ONR Biannual OSPRES Review and Technical Interchange

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14. ABSTRACT

The ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAS Study (Grant Award No. N00014-17-1-3016) biannual review was held on 09DEC2020 via web conferencing (virtual, due to the COVID-19 pandemic). Sixteen briefs were given, 100+ individuals were invited, 70+ persons attended, and questions were captured via chat and orally. A summary of the briefs as well as questions and answers is provided in the executive summary.

15. SUBJECT TERMS

PCSS alternative, HPM, Antennas, Arrays, Pulsed Power, High Voltage

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ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAS Study

OSPRES Grant Goal: address and transition technologies and capabilities that enable the OSPRES Grant Objective using the OSPRES Grant Approach, while educating the next generation of pulsed power and defense minded, stewards, and innovators.

OSPRES Grant Objective: to execute high-risk, high-payoff efforts that mitigate, fill, or rectify one or more grand-challenge or elementary gaps or deficiencies needed to achieve a modular, scalable, and electronically steerable high power microwave (HPM) based defense system for the counter unmanned aerial system (cUAS) mission. The OSPRES HPM system and sub-system development/evaluation efforts are focused on the short-pulse high-average power space, and includes the kill chain considerations including the target and its responsivity to radiofrequency stimuli.

OSPRES Metrics of Success: developed technologies and capabilities that are published in the peer review, protected as intellectual property, and/or transitioned to the OSPRES Contract effort and beyond for integration with other DoD needs or dual-commercial-use, as enabling/integratable capability(ies).

OSPRES Grant Approach: A fail-fast philosophy is maintained, where if a technology or capability is deemed infeasible to be demonstrated or validated during the project period-of-performance, it shall be culled, results to date and basis of infeasibility documented, and the next major gap/deficiency area addressed by that part of the project sub-team. Students whose thesis depends on following through with a full answer during the life of the award will be given special dispensation to continue their work.

OSPRES Grant Security: All efforts should be fundamental and publically releasable in nature when taken individually. This report has been reviewed for operational security, compilation, proprietary and pre-decisional information concerns.

Administrative Introduction and Acknowledgements

The ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAS Study (Grant Award No. N00014-17-1-3016) biannual review was held on 09DEC2020 via web conferencing (virtual, due to the COVID-19 pandemic). Sixteen briefs were given, 100+ individuals were invited, 70+ persons attended, and questions were captured via chat and orally. A summary of the briefs as well as questions and answers is provided in the executive summary below.

The investigators wish to thank Humberto Gonzalez, Joseph Crow, and Jon Smith for organization/coordination of the review. Other thanks go out to the shop staff for fabrication, design, and troubleshooting support of the research as well as to our administrative support team, Leta Moler and Mallory Snyder, who work tirelessly to handle purchasing, tracking, scheduling, and an endless list of items that keep the program moving forward.

OSPRES Grant Agenda for DEC 09 2020

Fall 2020 Bi-Annual OSPRES Grant Review and Technical Exchange / Virtual 09 DEC 2020 / Distribution A				
CST	Presentation Title	Presenter	Tech Area	Tech Sub-Area
9:00 AM	Grant Objectives/Overview	Caruso/Paquette	Programmatic	OSPRES Grant
9:30 AM	Development of a US-based High-voltage Solid-state Switch	Azad/Khan	Prime Power	Compact HV Switching
9:50 AM	Si-PCSS Top Contact Optimization and Impact on Switch/Laser Requirements	Bellinger/Eifler/	Pulser	Device Physics
10:10 AM	GaN-PCSS: Direct RF Modulation	Kramer/Thompson	Pulser	Device Physics
10:30 AM	-- Break --			
10:40 AM	Energy Storage-Release and Compression Topology Considerations	Flippin/Labrada	Pulser	Device Physics
11:00 AM	Heat Transfer Potential and Pragmatism from Jet Impingement	Allen/Berg	Pulser	Thermal
11:20 AM	Fiber Laser Feasibility	Shepard	Pulser	Laser
11:40 PM	Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement	Bhamidipati	Pulser	Laser
12:00 PM	-- Break --			
12:30 PM	Challenges and progress toward low- and high- voltage D-NLTLs at 1 GHz	Gardner	Pulse Shaping	Pulse Forming Networks
12:50 PM	Antenna Element Survey for Reduced Aperture Area - UWB Arrays	Brasel/Durbhakula	Antenna	Array Elements
1:10 PM	Tradespace Analysis of ESA Array	Barman/Chatterjee	Antenna	Array and Array Elements
1:30 PM	FEKO <-> SPICE Tool Development/Validation	Bissen/Hamdalla/Hassan	RF Coupling	RF Model Building
1:50 PM	-- Break --			
2:00 PM	RF Coupling	Hassan	RF Coupling	Current Induction
2:20 PM	Localizing and Targeting UAS: A Review of Available Sensors	Fields/Klappa	ITTC	Targeting
2:40 PM	Engagement Level Heuristic Model Builds	Fields/Herrington	MLM/ELM	Model Building
3:00 PM	Feature Additions to UMKC-MAP Including Causal Inference	Luginsland	MLM/ELM	Platform Building
3:20 PM	-- Break --			
3:40 PM	-- Outside Evaluation/Suggestions of Sub-Efforts by Virtual Breakout Room --	Presenter Led Rooms		
4:10 PM	-- Breakout Summaries/Suggestions on Any-Effort to Full Audience --	Caruso	Programmatic	OSPRES Grant
4:40 PM	-- End --			

CST	Breakout Rooms	Mandatory Persons
3:40 - 4:10	Pulsed Charging Supply (HV Switch)	Khan, Azad, Roy
3:40 - 4:10	Photoconductive Solid-State Impulse Switching (Si, SiC, GaN)	Eifler, Bellinger, Thompson, Kramer
3:40 - 4:10	Non-phototriggered Solid-State Impulse Switching	Flippin, Labrada
3:40 - 4:10	Pulsed Laser Alternatives	Shepard, Morel, Bhamidipati
3:40 - 4:10	Pulse Forming Networks (D-NLTLs)	Fry, Gardner
3:40 - 4:10	Heat Transfer and Thermal Mitigation	Berg, Sobhansarbandi, Allen
3:40 - 4:10	All Things Antennas	Barman, Chatterjee, Durbhakula
3:40 - 4:10	RF Coupling	Hamdalla, Hassan, Bissen
3:40 - 4:10	Mission/Engagement Level Modeling and Identify/Track/Target/Classify	Klappa, Herrington, Fields, Tiller, Richman

*Breakout rooms will be available to select real-time during Zoom session

Acronyms

ONR: Office of Naval Research

UAS: Unmanned Aerial System

HPM: High Power Microwave

PCSS: Photo-Conductive Solid State Switch

UWB: Ultra Wide Band

ESA: Electrically Small Antenna

D-NLTL: Diode based Non-Linear Transmission Line

RF: Radio Frequency

Si: Silicon

LED: Light Emitting Diode

HV: High Voltage

DSRD: Drift Step Recovery Diode

GaN: Gallium Nitride

ASE: Amplified Spontaneous Emission

UHF: Ultra High Frequency

COTS: Commercial Off The Shelf

TCAD: Technology Computer Aided Design

SoTA: State of the Art

PFN: Pulse Forming Network

WBG: Wide Band Gap

GTEM: Gigahertz Transverse Electro-Magnetic

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1. OSPRES Grant Overview

Presented by Anthony Caruso

In FY20, the OSPRES Contract and OSPRES Grant programs support/coordinate with 70+ technical staff at UMKC, 20 administrative staff at UMKC, 30+ individuals from eight small businesses (two veteran owned small businesses), and 30+ individuals from across the Navy, Air Force, Kansas City FBI, Department of Energy and UK Ministry of Defense. 16 of the technical staff are undergraduate researchers, 28 graduate research assistants and 16 are faculty. The OSPRES Grant focuses on TRL 1-4 technology development in a Fail-Fast philosophy, pushing enabling technologies up to the OSPRES Contract and HPM community at large. Present categories of technology development include overcoming fundamental barriers to: electronic beam steering, HPM waveform tuning, inter-element time compensation for antenna array power input, heat transfer, array antenna physical aperture area, system volume as well as efficiency and monetary cost of the effector sub-systems. In the program so far, five efforts have been complete, eight projects sunset or culled, and ten projects are ongoing.

2. Development of a US-Based High-Voltage Solid-State Switch

Presented by: Wasekul Azad, GRA and Faisel Khan, Associate Professor

We have designed and fabricated a 4.8-kV-rated in-house high-voltage (HV) SiC switch that can be a direct and inexpensive replacement of the HV switch made by BEHLKE. The switch has been tested using a negative DC supply up to 2.5 kV, at a switching frequency up to 40 kHz, and a duty ratio up to 50%. The maximum voltage imbalance across the individual MOSFETs was measured as 40 V, which is much lower than the breakdown voltage rating of these 1.2 kV MOSFETs. We have designed and fabricated an in-house HV isolated gate driver (10 kV rated), because the commercially available gate drivers cannot provide isolations more than 5.7 kV. We have designed a power conditioning board for the Si-PCSS based pulse forming network (PFN) using a HV SiC switch made by BEHLKE, and the board was tested at a voltage level up to 4 kV and a repetition frequency up to100 kHz coupled with the Si-PCSS-based PFN. In addition, we have simulated a modular HV switch design in LTSpice which shows minimal voltage imbalance (<50 V) among individual MOSFETs.

Questions and Answers

1. Is the load impedance test surrogate representative of what the actual system impedance would be?

The objective of the in-house HV switch in terms of the OSPRES objective is to charge the transmission line, which can be primarily considered as a capacitive load (4-6 nF). The PCSS transfers the energy stored in the transmission line to the output load, which is close to 4-6 ohms, and therefore, the HV switch is not delivering power to the output load directly. During one of our initial experiments (at a DC voltage of 2 kV and a switching frequency of 20 kHz), we have used a dummy load which was composed of a 4.7 nF ceramic capacitor, a 12-ohm resistor bank, and an IGBT connected in parallel with the capacitor to closely emulate the behavior of the PCSS. The experimental results were in agreement with the result we expected. In addition to that, we have tested the in-house switch with the actual PCSS up to a voltage level close to 1 kV, and a repetition frequency up to 20 kHz. We achieved similar output across the load using this in-house switch compared to using the BEHLKE based HV switch.

2. If not, how will the test results and performance change for the real system?

As mentioned in the previous response, the in-house HV switch has been tested while coupled with the PCSS and with a dummy load (mimicking the PCSS) as a proof of concept. The primary challenge of the HV switch design is to ensure a rigorous voltage balancing across the individual switches inside the HV switch during both the ON and OFF states so that voltage stress across the individual switches does not exceed the threshold voltage rating of individual switch. We will test the latest iteration of the in-house switch (6.8 kV rated) driven by an in-house isolated gate driver with a resistive load. Once this test is successfully conducted, we will evaluate the switch's performance using the PCSS load.

3. Si-PCSS Top Contact Optimization and Impact on Switch/Laser Requirements

Presented by: Steven Bellinger, Staff Scientist and Jay Eifler, Staff Scientist

The top contact design of the Si-PCSS was optimized for reduced laser energy required for on-state switch resistance important for efficient source operation. Solar cell design principles were used in conjunction with TCAD simulations to determine the optimal top contact based on geometric considerations (laser windowing spacing). An analysis of the optimal spacing showed that a maximum 30% laser energy reduction was possible at the optimal spacing. Such a reduction allows flexibility in the design of compact, monetarily inexpensive laser systems, and helps enable modular/scalable HPM sources, higher TRL, and higher probability of fleet transition.

Question and Answer

1. How is flashover prevented?

Primarily by covering flashover surface with Silgard 184.

4. GaN-PCSS: Direct RF Modulation

Presented by: Heather Thompson, GRA and Noah Kramer, GRA

To achieve a smaller form factor and increased SWAP-C^2 capabilities for HPM pulse generation, a GaN:C photoconductive semiconductor switch (PCSS) system is proposed as its theoretical characteristics allow for higher operating temperatures and direct RF modulation, reducing the thermal management requirements and eliminating the need for a bulky, pulse-forming transmission line. Towards achieving direct RF modulation, a variable optical delay mirror stage was used to demonstrate nanosecond-scale pulse-to-pulse tunability of carbon-compensated GaN photoconductive semiconductor switches (GaN:C PCSSs) operating in linear mode. A 1.5 ns, 355 nm optical pulse passed through a 50/50 beam splitter; 50% took a direct path to trigger the first output pulse of the PCSS, and the other 50% passed through the optical delay stage, increasing the optical path length, before triggering the second output pulse of the PCSS. By varying the optical delay in 300 mm steps, the inter-pulse time delay was tuned from 3.75–5.77 ns. The first and second PCSS output pulses had similar on-state resistance and sub-nanosecond rise-times, but the second pulse had a reduced slew rate, possibly caused by the slight difference in charge voltage when the second pulse was triggered or by dispersion of the optical pulse as it traveled through the delay stage. Future studies include measurement of inter-pulse jitter, triggering a negatively charged PCSS with the delayed optical pulse for bipolar pulse generation, and measurements with a 70 ps laser to decrease the minimum inter-pulse time-delay.

Questions and Answers

1. What wavelength was used to trigger the GaN:C PCSS?

A 1064 nm laser pulse was passed through second and third harmonic generation stages to convert it to 355 nm. Any remaining 532 and 1064 nm components were removed by a bandpass filter.

2. Have you operated in avalanche mode or lock-on mode?

We have only been operating in linear mode; avalanche or lock-on mode is likely not advantageous for direct RF generation.

5. Correlation Studies Applied to a Semiconductor-Based Pulsed Power Source

Presented by: Nick Flippin, Research Consultant II

With the ability to fully characterize drift step-recovery diodes (DSRDs), from static characterization to pulse performance, we now have the ability to collect all of the empirical data to create a database. This database allows the user to run statistical analysis to find correlations between static characterization (IV and CV curves) to transient characterization (reverse recovery time measurements) to pulse performance (peak voltage, rise-time, pulse width, etc.). It was found that there is a strong statistical correlation between minority carrier lifetime and pulse width, which fits a 3rd degree polynomial function with an R value of ~0.8. More data is needed to better fill the prediction space to make more complete statistical correlations.

Questions and Answers

1. How many more diodes would you need to fill out the space?

I would estimate about triple the amount of data points to get the bare minimum to see well-defined trends.

2. Why did you choose the regression models you did?

After running multiple iterations, the regression model chosen was the best fit with the data we had.

*NOTE: Jordan Chaparro mentioned that logistic regression should not have been used as my data was continuous. He is correct: the logistic regression I mentioned was not correct, the model that was used was a generalized linear regression model.

3. Did you look at different predictors other than the ones in the presentation?

Yes, I had looked at all 18 predictors and ran multiple regression fits for all. These just happened to be the most interesting.

6. Heat Transfer Potential and Pragmatism from Jet Impingement

Presented by: Roy Allen, Lead Mechanical Engineer

Eclipsing the average-power compensation capabilities (<200 W) of traditional laminar-flowing dielectric-coolant based thermal management systems (TMSs), the latest jet-impingement TMS has shown, through numerical analysis, the ability to compensate >200 W (i.e., >200 MW/m^3 as cooling density) while maintaining a Si-PCSS to an average temperature of 42.4 °C (187% reduction from previous iteration, 30 °C less than laminar-flow TMS design) yet only requiring 420.1 psi (>350% reduction from previous iteration). Recent results indicate that achieving the desired average-power compensation capability of >1 kW (>1 GW/m^3) is within the art-of-the-possible and the JI-TMS design is expected to surpass the current state-of-the-art which traditionally requires the ancillary systems (e.g., chiller unit and fluid pump) consume equivalent power to that which is being compensated.

Questions and Answers

1. Why not use a thermal management fluid with more ideal cooling capabilities (s.c., increased thermophysical properties) like DI water or a DI-glycol mix?

For HPM-based sources that operate at high voltages, the potential for fluid leaks within the thermal management system poses a potentially hazardous combination for the end user should leaking occur. We concur that (and have looked into) using DI-water within the TMS system should overcome the potential hazard, however, DI water requires long-term replacement or advanced filtration techniques. We believe this additional ancillary system and maintenance requirement outweighs the fluid's performance tradeoffs at this time. From a broader impact perspective, both DI water and nanofluid alternatives are being considered at this time.

7. Fiber Laser Feasibility

Presented by: Scott Shepard, Research Tech. II

Our primary objective was to reduce the cost, size, and weight of the laser systems that trigger the PCSS. A pre-burst pumping scheme can reduce the (dominant) pump power costs by a factor of 40, with negligible amplified spontaneous emission (ASE) noise enhancement. A linear gain theory predicts that an optical amplifier of gain = 8×10^6 will produce ASE power = 3,960 x our spec. (on leakage current heat). We showed that gain saturation can suppress the ASE (for a system of gain = 8×10^6) by a factor of 9,525 in a staged design of different fiber cores enhancing saturation while remaining below damage thresholds. We additionally refined the nonlinear theory of ASE-induced timing jitter.

Question and Answer

1. How much timing jitter do you expect to see?

I have refined the nonlinear theory of ASE-induced timing jitter, but I have not had time to validate it yet.

8. Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

Presented by: John Bhamidipati, GRA

An unconventional multi-stage optical amplifier has been presented as a compact, inexpensive optical trigger alternative for PCSS-driven HPM systems that currently implement high average power laser systems with high SWaP-C^2 factor. The proposed optical amplifier implements an electrically triggered silicon drift step recovery diode (Si-DSRD) and optically triggered direct-bandgap gallium nitride photoconductive semiconductor switches (GaN-PCSSs) to drive laser diode (LD) and laser diode arrays (LDAs), respectively.

With a goal to minimize the number of amplification stages, the lock-on operation of a GaN-PCSS is being considered. The required output electric current, current gain, and optical energy per pulse have been determined via a feasibility study, and commercial off-the-shelf (COTS) optical sources needed to achieve the optical energies at each stage have been explored and down selected. Specific objectives for the initial part of the program as well as existing shortcomings have been presented, along with expected milestones for the near-future.

Comments:

1. The high gain mode has been observed in GaN and it is not a surface effect only. The lock-on field is ~4 kV/cm. I am doing testing on devices now.

Discuss with Jane Lehr to better understand GaN-PCSS's lock-on mode, and replicate their test environment/setup at UMKC for future GaN testing.

9. Challenges and Progress Toward Low- and High-Voltage D-NLTLs at 1 GHz

Presented by: Nicholas Gardner, GRA

Diode non-linear transmission line (D-NLTL) efforts are focused on increasing frequency production to the UHF regime through simulation/design process refinement. The most recent results include a prototype capable of frequency generation above 250 MHz as well as the documentation of several design considerations for D-NLTLs including suppression of reflections with proper line termination, and the role of diode type and line length in efficient high frequency production. Future studies will include optimizations to the 250 MHz prototype, continued identification of UHF diode candidates, fabrication of a voltage-biased D-NLTL for frequency tuning and bipolar excitations, as well as identification and characterization of diode parameters critical to UHF D-NLTL operation.

Questions and Answers

1. Have you tried TCAD for NLTL design?

It has been discussed for the purposes of including physical features such as board design and size, but we have not yet attempted or fully explored the use of TCAD.

2. How are you defining RF efficiency? It looks high. Can you explain?

RF efficiency is defined as the ratio of energy produced after a HPF to the energy injected into the line. In each case energy is the time integrated power waveforms. The theoretical limit is defined at 30% for RF efficiency with SOTA achieving about 10%. We have not yet fully measured it – rather we do a rule of thumb relation to the pulse modulation depth to get a feel for the efficiency – it is our goal to exceed 20% efficiency.

3. Is it RF conversion efficiency or energy efficiency?

RF conversion efficiency – how much energy in the desired RF regime as compared to the energy actually injected into the D-NLTL network.

10. Antenna Element Survey for Reduced Aperture Area - UWB Arrays

Presented by: Sadie Brasel, UGRA and Kalyan Durbhakula, Asst Research Professor

This effort carries out a tradespace study and analysis of down-selected single-element and array antennas in conjunction with scientific techniques (such as side lobe reduction, array configuration) to effectively reduce physical aperture area. The findings from the tradespace study will be compared against state-of-the-art UWB HPM antenna elements or arrays such as the balanced antipodal Vivaldi antenna (BAVA). In addition, tradeoffs between antenna metrics, such as bandwidth, peak gain, full-width half maximum (FWHM), ringing, power handling capability, physical aperture area, etc. will be reported for each down-selected single element and its array by varying design parameters.

A new effort was undertaken at the beginning of November 2020 to identify suitable antenna elements that meet the OSPRES grant requirements as well as possess UWB HPM capabilities. Since then, a rigorous literature survey has been carried out. Five different and minimally explored antenna elements were identified and compared against the BAVA using some pre-identified antenna metrics. A comparison table was presented. In particular, the comparison against the BAVA has highlighted two single antenna elements, the shark and Koshelov antennas, which possess great potential to eventually replace BAVA as the SOTA radiator for UWB HPM systems. In addition, scientific techniques such as side lobe reduction or a non-conventional array configuration have been identified to be applied to either single antenna elements or to an array to meet OSPRES grant targets.

Questions and Answers

1. Can you address power handling capability? Should it be in the main criteria/metric for tradespace analysis?

The power handling capability of the antenna will be determined by the peak power and average power of the input pulse and breakdown voltage of the dielectric material. The power handling capability criteria will be added to the initial antenna metrics analysis and for comparison to the state-of-the-art (SOTA). Advanced materials or high-permittivity materials can easily handle up to a few 10’s of kV per mm. High power connectors that can handle high peak-to-peak voltages are being looked into and are being developed/modeled by the lead mechanical engineer at MIDE.

2. Can you comment on why circular polarization is a con?

Helical and spiral antennas have an inherent circular polarization. The helical antenna design is a con in the context of the preferential linear polarization requirement for the OSPRES project; however, these antennas could be a great choice for space applications, or other projects for which circular polarization is more suitable.

11. Tradespace Analysis of Electrically Small Antenna (ESA) Array

Presented by: Bidisha Barman, GRA and Deb Chatterjee, Associate Professor

The primary goal of this work is to determine the extent to which the physical aperture size of an antenna array can be reduced, while maintaining performance over the UHF range (0.4–1 GHz), compared with present art HPM-capable antenna arrays.

A 15×15 planar array of microstrip ESAs (with an external ring of dummy elements), modeled in the UHF range (640–990 MHz) and having a radiating aperture area of 5.74 m^2, resulted in a maximum boresight gain of 27.76 dBi along with $\pm 60°$ beam steering capability from boresight.

With 30% aperture area reduction (by changing from square to hexagonal grid formation), which is equivalent to ≈50% reduction in number of antenna elements (from 225 to 114), the overall array gain reduced uniformly by 12% (from 27.76 dBi to 24.5 dBi) over 640-990 MHz, with no scan blindness observed in the visible region.

As a proof-of-concept to the array design methodology, a 3×3 array of microstrip ESAs (operating frequency = 3.75 GHz) has been built and tested in-house. Due to manufacturing defects, slight agreement has been achieved between the measured and simulated embedded element reflection coefficients. Note: Embedded element reflection coefficients are obtained by exciting only the required antenna element in the array, while the remaining elements are matched terminated.

Time domain analysis of the antennas (and array), subjected to non-ideal short input pulses, have been initiated.

Question and Answer

1. Will the microstrip patch antennas be able to handle high input peak power of 500 MW?

It has been shown via calculations that 2.4 W/cm^2 of power density can be achieved at a distance of 1 km from a 15×15 ESA microstrip patch antenna array, if the input peak power is 500 MW. This implies that the input peak power to each antenna element ≈2 MW. So far, the microstrip patch antennas have been designed on Rogers TMM-10i substrates, which are capable of handling tens of kilovolts of input peak power. Whether or not the TMM-10i substrates can withstand power in the MW range requires detailed analysis. We are currently investigating the power handling capabilities of the substrates through simulations, and the results will be furnished in the next report. Simultaneously, other substrates with high power handling capabilities (such as polyethylene) are being studied for designing antennas suitable for HPM transmissions in the UHF range.

12. FEKO <-> SPICE Tool Development/Validation

Presented by: Ahmed M. Hassan, Associate Professor

To achieve our goal of quantifying RF coupling to arbitrary wire configurations connected to nonlinear loads, we proposed to use the FEKO <-> SPICE Tool, which is based on the equivalent circuit approach. The approach is based on modeling the wiring system as a series of RLC circuits and using a SPICE solver instead of full-wave solvers to model RF Coupling. The FEKO <-> SPICE equivalent circuit approach is much faster than full-wave simulations and adds physical insight that allows us to predict RF coupling and select the optimum excitation that maximizes the voltage coupled to a load. We were able to quantify the variations in the equivalent circuit components with size, shape, and loads of the wire loop. We also validated our approach through experimental measurement. Finally, we presented a roadmap of future work, which consists of extending the FEKO <-> SPICE approach to the wires and integrated circuits typically found in UAVs.

Questions and Answers

1. Do you think that your approach will work for complex UAV systems?

Yes, the spice model is based on the full-wave calculations of the system's input impedance and not the TL approximation or any other approximation. Therefore, it can be scaled for complex systems similar to UAV wire configurations.

13. RF Coupling

Presented by: Mohamed Hamdalla, GRA

To achieve our goal of quantifying RF coupling to enclosed wires/electronics in dielectric/conducting enclosures with apertures, we have proposed the application of characteristic mode analysis (CMA) and machine learning to study enclosures comparable in size to the incident wavelength. We studied the shielding enhancement factor inside an empty enclosure, and we also calculated the coupled voltages to a simple wire/PCB model placed inside enclosures of different material compositions. We showed that dielectric enclosures could enhance coupling to the enclosed loads by >5 dB compared to free space, whereas PEC/CF frames can enhance coupling by more than 10 dB at high-quality resonances even with lossy dielectric FR4 substrates enclosed. We also proposed the use of the modified CMA to identify the critical frequencies that amplify the fields inside the enclosure. Finally, we presented a roadmap of future work that consists of developing a machine learning platform that predicts the effect of the enclosure on RF coupling to the enclosed wires/electronics. The machine learning platform will be tested using 10s of quadcopter shapes and COTS UAVs.

Questions and Answers

1. Did you introduce losses in your cavity simulations?

Yes, the model circuitry inside the cavity studied in the presentations contained an FR4 PCB with a loss tangent of 0.017 assigned to the dielectric layer.

2. What is the optimum excitation frequency for both shielded and unshielded cavities?

Based on our probability analysis of one UAV model, the resonance frequencies of the shielded cavities are critical. Also, the resonance frequencies of the dielectric and the PEC do not overlap at the voltage threshold of -45 dBV. Therefore, a relatively wide band signal that covers both the resonance frequencies of the dielectric and PEC shielded cavities should be optimal. This conclusion will be re-visited upon the study of more UAV shapes and materials.

14. UAS Localization and Targeting

Presented by: Paul Klappa, GRA and Travis Fields, PE, Associate Professor

Understanding and predicting performance of both red and blue actors is crucial to develop operationally relevant offensive or defensive technologies. The specific areas of interest include creating an analytical framework for DEW engagements, quantifying the COTS/GOTS identification and tracking performance of small UAS, and developing the optimal combination of tactics and strategy to defeat hostile targets. This relatively new research focus is already demonstrating the fundamental need for understanding DEW scenarios at the engagement level in order to better inform mission-level modeling efforts.

Questions and Answers

N/A

15. Engagement Level Heuristic Model Builds

Presented by: Shawn Herrington, GRA and Travis Fields, PE, Associate Professor

The requirements imposed on military defense systems places constrains on their development which can hamper their effectiveness in response to emerging threats. Subject matter expertise in the UAS sector, along with techniques borrowed from game theory, allows for high confidence predictions to be made about future threats. Information about the future threat space enables the development of high quality intelligence to be used throughout the development paradigm such that emerging defense technologies are equipped to face the most recently developed threat technologies and tactics.

Questions and Answers

1. (Michael Richman) Have you read the paper by John Tiller on the formalities of Tipping Point Analysis (referring to the tipping-point-like results presented in the presentation – the "space invaders" simulation).

(Shawn Herrington) Yes, we have seen the paper. [Michael emailed the paper as well for reference].

2. (Chip Grounds) John Tiller has talked about ping-pong analysis. Is there a way to validate this type of technique (against past predictions perhaps) in order to get an idea of the level of certainty in the predictions?

(John Tiller) Our ping-pong analysis isn't exactly the same as that presented by Shawn Herrington. Comparison against historical scenarios would be difficult considering that participants in the analysis would already know the outcome of the historical battle/game.

3. (Chip Grounds) We need to come up with ways to prove that our predictions are going to be high certainty and we need to figure out how to convince people.

(Shawn Herrington) By considering lower level characteristics (how fast is possible according to basic physics or mechanics?) rather than higher level mission functions (how will the red team use this tech?) we can make high fidelity predictions. The basic mechanics of the problem are less likely to transform overnight than other characteristics.

4. (John Luginsland) Commentary about irrational agents within the game and whether this is something important to consider. Many results bear out the adage that the most difficult poker opponent to face is a totally inexperienced player because they are unpredictable and may act in an irrational way.

5. (Chip Grounds) Does the field of economics offer any way to validate predictions?

(Shawn Herrington) I don't have any contemporary evidence but I will look into it. I will say that the concept of Nash Equilibrium was developed within the last 60 years with the specific intention of explaining behavior of players in the market that was not satisfactorily understood using existing explanations. And the concept of Nash equilibrium has proven useful in explaining many games since it was proposed.

(John Luginsland) Recent numerical results in a vast experiment seem to support the optimality of the Nash equilibrium concept.

16. Feature Additions to UMKC-MAP Including Causal Inference

Presented by: John Luginsland, Confluent Sciences and John Tiller, John Tiller Software

We have advanced the state-of-the-art in mission-level modeling (MLM) by exploiting and extending our physics-based wargaming tools. Our approach, which uses reduced order models with sufficient fidelity for a given task, allows a critical increase in the speed of evaluation of a given scenario, enabling both statistically valid evaluation of stochastic processes as well as higher level optimization tools to be wrapped around our wargames. This allows cost-risk tradeoffs in the deployment of HPM to be developed for counter-UAS defense against US Navy assets afloat. In particular, our modifications allow MLM to run roughly 20-200 times faster than the current state-of-the-art, with sufficient fidelity to answer the questions relevant to the Afloat HPM challenge. This allows more degrees of freedom and a wider range of scenarios to be studied and optimized. Additionally, our work this year improved the fidelity of the electromagnetic effects' models, advanced the artificial intelligence of both the defender and attacker forces, added exclusion zones and collateral damage models for both kinetic and non-kinetic defenders, and finally provided templates for optimization routines.

Questions and Answers

1. Describe the nature of the EM hardness model

Probability of effects based, can take in experimental data, or use a logistics model tuned to give soft, medium, hard.

2. Laser and HPM together – change requirements on HPM system?

Yes. Laser of long range but need dwell might get overwelmed by swarm, but now can imagine an HPM designed for area defeat – do not need gain but rather large area of effect. Shut down an area.

Appendix A: Slides of Briefs from 09 DEC 2020

FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

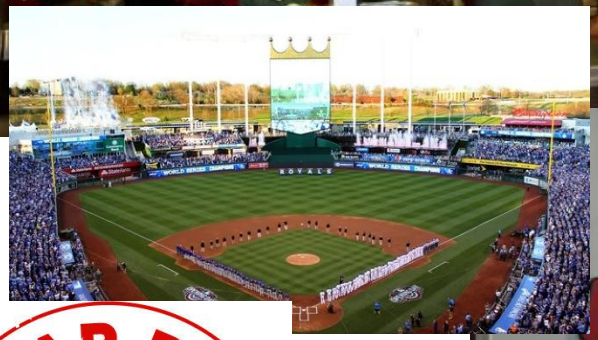
Bi-Annual Program Review

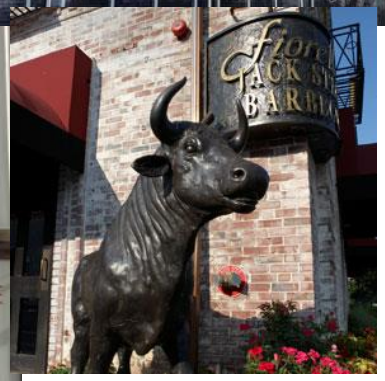
OSPRES Grant Overview
Paquette/Caruso, Coordinator/PI, UMKC-MIDE
816-738-5096/816-235-2505
paquettem@umkc.edu / carusoan@umkc.edu

09 DEC 2020 / 0900 - 0930
held via Zoom

Distribution A. Approved for public release.

Virtual KC OSPRES Review





OSPRES Fall 2020 Prog. Rev. and Tech. Exchange

Fall 2020 Bi-Annual OSPRES Grant Review and Technical Exchange / Virtual 09 DEC 2020 / Distribution A			
CST	**Presentation Title**	**Presenter**	**Tech A**
9:00 AM	[1] Grant Objectives/Overview	Caruso/Paquette	Progra
9:30 AM	[2] Development of a US-based High-voltage Solid-state Switch	Azad/Khan	Prime
9:50 AM	[3] Si-PCSS Top Contact Optimization and Impact on Switch/Laser Requirements	Bellinger/Eifler/	Pulser
10:10 AM	[4] GaN-PCSS: Direct RF Modulation	Kramer/Thompson	Pulser
10:30 AM	-- Break --		
10:40 AM	[5] Correlation Studies Applied to Semiconductor-based Pulsed Power Devices	Flippin/Labrada	Pulser
11:00 AM	[6] Heat Transfer Potential and Pragmatism from Jet Impingement	Allen/Berg	Pulser
11:20 AM	[7] Fiber Laser Feasibility	Shepard	Pulser
11:40 PM	[8] Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement	Bhamidipati	Pulser
12:00 PM	-- Break --		
12:30 PM	[9] Challenges and progress toward low- and high- voltage D-NLTLs at 1-GHz	Gardner	Pulse S
12:50 PM	[10] Antenna Element Survey for Reduced Aperture Area - UWB Arrays	Brasel/Durbhakula	Antenr
1:10 PM	[11] Tradespace Analysis of ESA Array	Barman/Chatterjee	Antenr
1:30 PM	[12] FEKO <-> SPICE Tool Development/Validation	Bissen/Hamdalla/Hassan	RF Cou
1:50 PM	-- Break --		
2:00 PM	[13] RF Coupling	Hassan	RF Cou
2:20 PM	[14] Localizing and Targeting UAS: A Review of Available Sensors	Fields/Klappa	ITTC
2:40 PM	[15] Engagement Level Heuristic Model Builds	Fields/Herrington	MLM/I
3:00 PM	[16] Feature Additions to UMKC-MAP Including Causal Inference	Luginsland	MLM/I
3:20 PM	-- Break --		
3:40 PM	-- Outside Evaluation/Suggestions of Sub-Efforts by Virtual Breakout Room --	Presenter Led Rooms	
4:10 PM	-- Breakout Summaries/Suggestions on Any-Effort to Full Audience --	Caruso	Progra
4:40 PM	-- End --		

OSPRES Fall 2020 Prog. Rev. and Tech. Exchange

Nine Tech Specific Breakout Rooms

3:00 PM	Feature Additions to UMKC-MAP Including Causal Inference	Luginsland	MLM/ELM
3:20 PM	-- Break --		
3:40 PM	-- Outside Evaluation/Suggestions of Sub-Efforts by Virtual Breakout Room --	Presenter Led Rooms	
4:10 PM	-- Breakout Summaries/Suggestions on Any-Effort to Full Audience --	Caruso	Programmatic
4:40 PM	-- End --		

CST	Breakout Rooms	Mandatory Persons
3:40 - 4:10	Pulsed Charging Supply (HV Switch)	Khan, Azad, Roy
3:40 - 4:10	Photoconductive Solid-State Impulse Switching (Si, SiC, GaN)	Eifler, Bellinger, Thompson, Kramer
3:40 - 4:10	Non-phototriggered Solid-State Impulse Switching	Flippin, Labrada
3:40 - 4:10	Pulsed Laser Alternatives	Shepard, Morel, Bhamidipati
3:40 - 4:10	Pulse Forming Networks (D-NLTLs)	Fry, Gardner
3:40 - 4:10	Heat Transfer and Thermal Mitigation	Berg, Sobhansarbandi, Allen
3:40 - 4:10	All Things Antennas	Barman, Chatterjee, Durbhakula
3:40 - 4:10	RF Coupling	Hamdalla, Hassan, Bissen
3:40 - 4:10	Mission/Engagement Level Modeling and Identify/Track/Target/Classify	Klappa, Herrington, Fields, Tiller, Richman
	***Breakout rooms will be available to select real-time during Zoom session**	

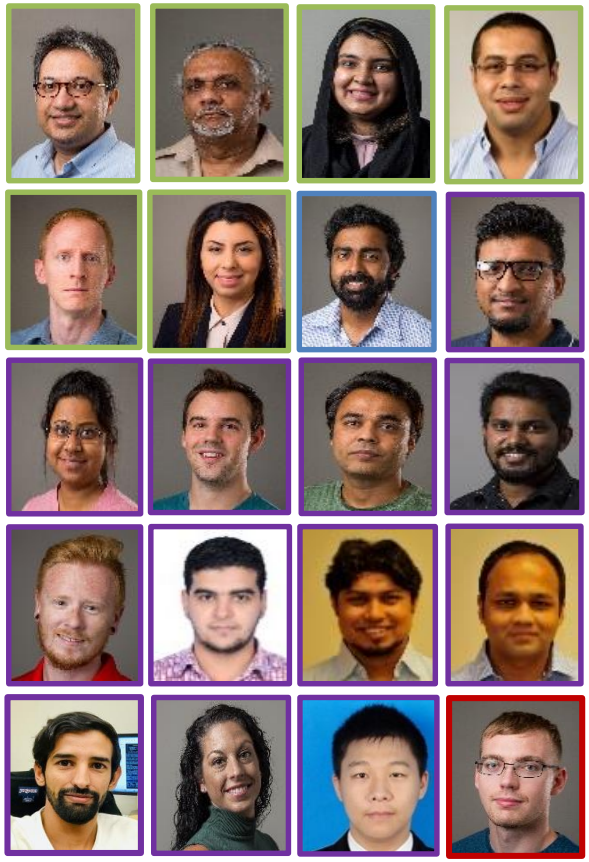
OSPRES *UM/MIDE Execution* Personnel (FY20)

OSPRES Grant Overview [~130/70]

OSPRES *Grant*

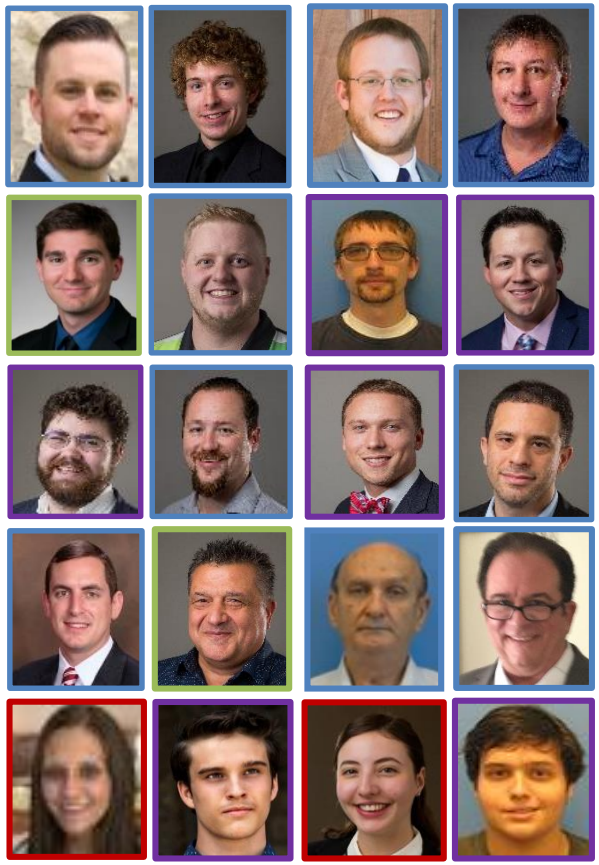
N00014-17-1-3016

30SEPT2017 – 29SEPT2022



F. Khan, Chatterjee, M. Khan, Hassan, Rulis, Sobhansarbandi, Durbhakula, Azad, Barman, Berg, Bhattarai, Bhamidipati, N. Gardner, Hamdalla, Hanif, Roy, Gwazani, Thompson, Xia, Utt (Hopfenzitz, Alsutan)

- UG Student
- Grad Student
- Staff
- Faculty

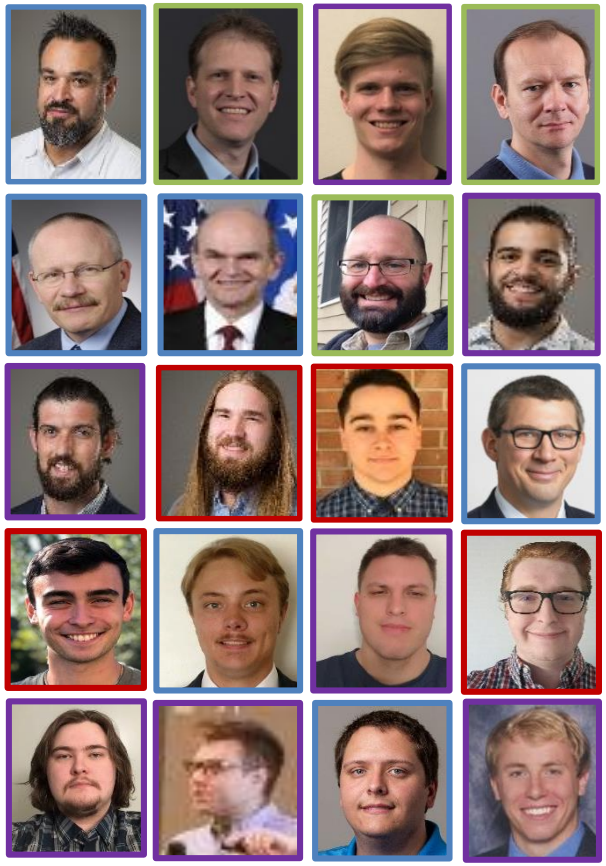


Allen, Bissen, Currie, Eifler, Fields, Flippin, Fry, Herrington, Kramer, Myers, Klappa, Richman, Smith, Doynov, Urton, Shepard, English, Spaeth, Brasel, Kovarik (Starke, Norris, S. Gardner, Taylor, Butler)

OSPRES *Contract*

N00014-18-C-1017

07MAR2018 – 07MAR2023



Beaudin, Beetner, Hunter, Khilkevich, Grounds, Hussey, Kovaleski, Labrada, A. Wagner, Landwehr, Reed, Kayrish, Snell, Evans, Smith, Karnes, Layman, Fazekas, S. Wagner, Gunter (Kruse, Cacy, Nimmer)

OSPRES *Subcontractor* Personnel (FY20)

OSPRES Grant Overview [20]

SARA – Barret Lamb, Robert Koslover, Jonathan Parson, Matt Wisher

RDT – Steve Bellinger

NanoEM – Kevin O'Connor

BAE – McGeehan, Yannick Morel

EHT – Tim Ziemba, James Prager, Ken Miller

ASR – Mike Abdalla, Mike Skipper

Metamagnetics – Anton Geiler, Michael Geiler

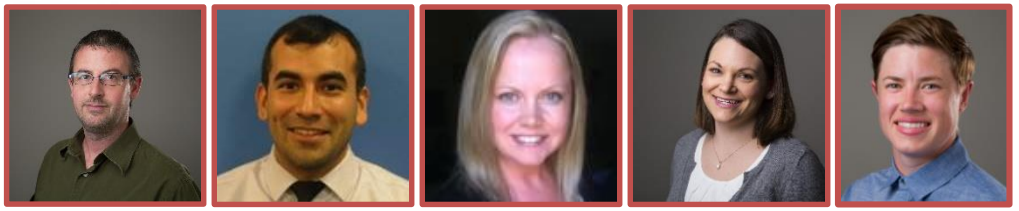
John Tiller Software – John Tiller, John Rushing (UAH), John Luginsland (CS)

OSPRES *Support* Personnel

OSPRES Grant Overview [10/10]

Logistics
Budget
Acquisition
Prog. Security

Crow
Gonzalez
Moler
Snyder
Dorsett



Prototyping

Dale
Newhook
Siegel
Verzella

Contracting
Post-Award

Owens
Daugherty
Winders
Brown
Jones

Bus. Dev.
Tech Trans.

Cottrell
Pederson
Anderson

Fac. Security
Pers. Security

Little
Carney
Battiston

Heather
Little

- UMKC-MIDE
- MU-SPA
- UMKC-ORS

OSPRES *Govt Partner* Personnel

OSPRES Grant Overview [30+]

ONR – Hoffman, McQuage, Kunapareddy

NSWC-DD – Walker, Chen, Chaparro, Cevallos

NRL – Schumer, Andreadis, Drikas, Croman, Meyerhofer, Dougherty

NSWC-PHD – Jaeger, Went, Went

LLNL – Voss, Conway

USASMDC – Rader, Lai

KC-NSC – Timpson, Byers

AFRL/SDPE/XZIC/RDHPS – Kanistros, Hoff

KC-FBI - Bakken

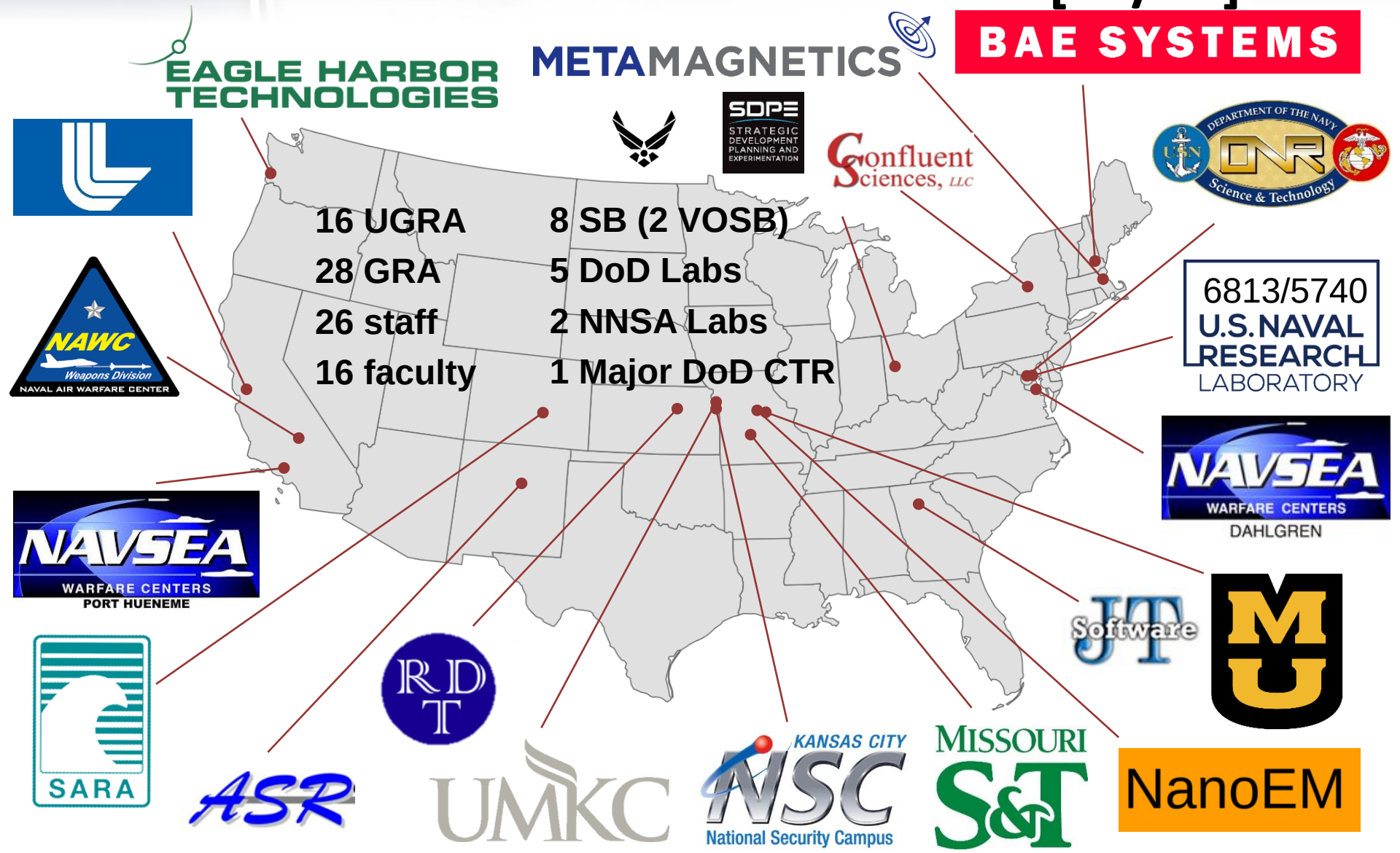
NAWCWD-CL – Higgins

DARPA-TTO – Nichols, Tun, Avicola

MOD-DSTL – Taylor, Hubbard

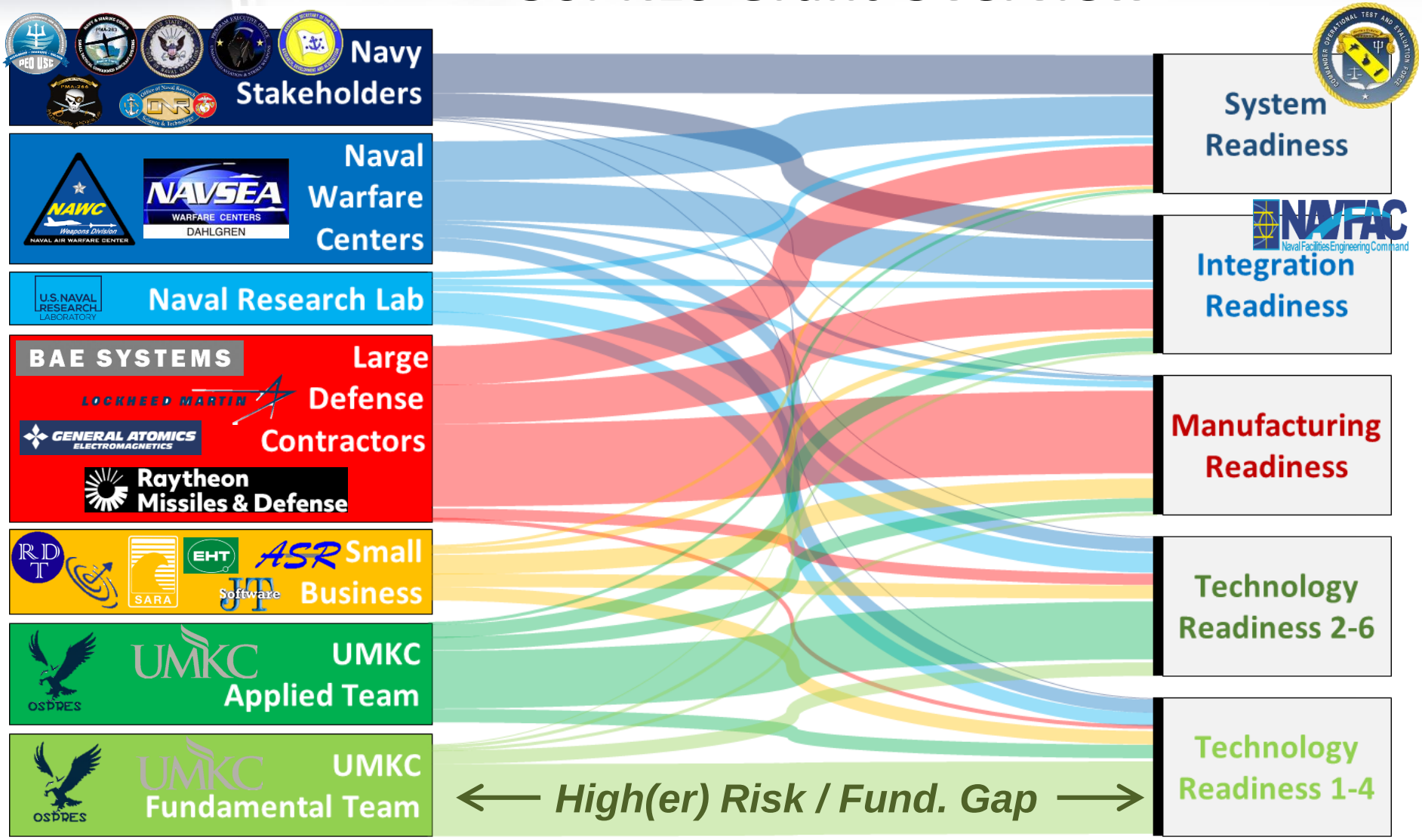
OSPRES Entities/Personnel (FY20)

OSPRES Grant Overview [14/16]



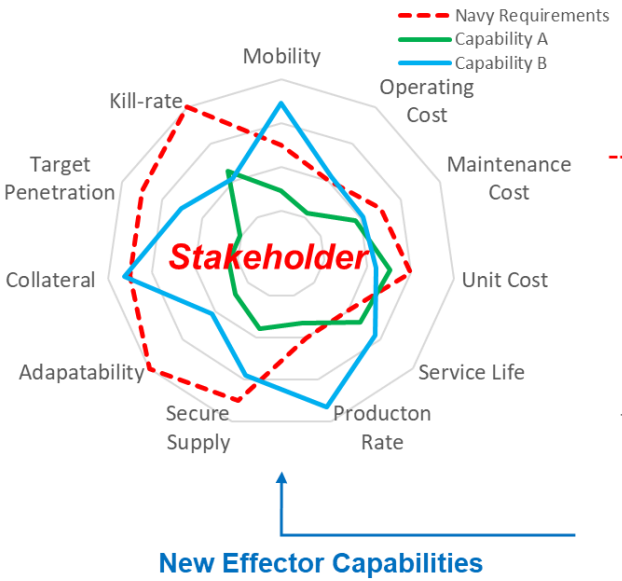
OSPRES: *Swim Lanes*

OSPRES Grant Overview

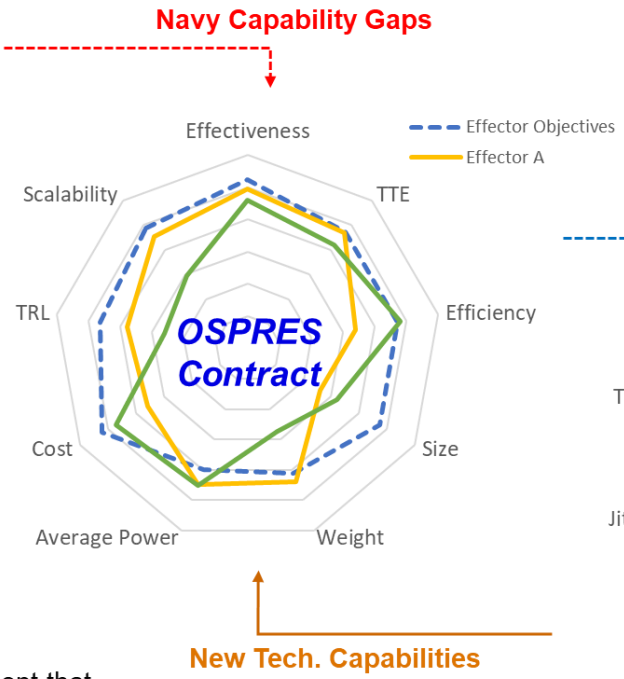


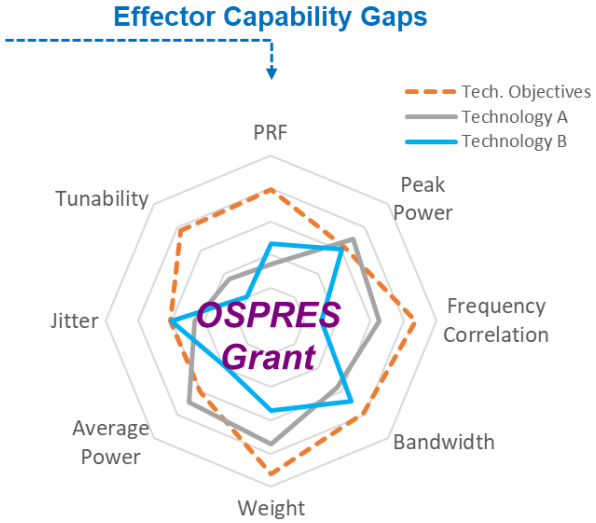
OSPRES: Gap/Deficiency *HOW*

OSPRES Grant Overview



OSPRES Grant:
UAS-HPM fundamental, high(er)-risk, enabling technology development that can be transitioned to the OSPRES Contract.





OSPRES Contract:
UAS-HPM pragmatic, effects-driven effector development that can be transitioned to fulfill Navy capability gaps

OSPRES FY20: HPM Gap/Deficiency *WHAT*

OSPRES Grant Overview

Overcome fundamental barriers to:

Electronic Beam Steering: up to ±60°

Tunable Waveforms: PW, PRF, f_c, BW

Inter-element Time Comp.: <10-ps

Heat Transfer: >500-W/cm^2

UHF Aperture Area: ≤Nom. L-band

System Volume: ≤Mk-15, 50, 100

↑***Range,*** ↑***Efficiency,*** ↓***Monetary Cost…***

OSPRES FY20: Gap/Deficiency *HOW*

OSPRES Grant Overview

Technical Approach(es) to:

Electronic Steering: control inter-element interaction / ↓ cascaded jitter

Tunable Waveforms: $\Delta L_{parasitic}$, $\Delta L_{element}$, $\Delta C_{element}$, $X_{dynamic}$

Inter-element Time Comp.: seed laser gain control, negative feedback / temp comp

Areal Heat Transfer: jet impingement and other turbulent flow considerations

UHF Aperture Area: electrically small tradespace eval, D/Q (directivity/qual-fact) ratio

System Volume: direct microwave modulation, non-phototriggered pulsers

1064-nm Laser SWaP-C: fiber laser, multi-stage optical amplifier

---

Management Approach (Ideal):

Fail Fast -> high/med-risk milestone-gates, sunset or transition and move to next*

*unless on PhD track

OSPRES: Fail Fast Approach - Status

OSPRES Grant Overview

On-going Sub-System Projects

- High-Average Power Fiber Laser ●
- Multi-stage Optical Amplifier ● ‡
- Engagement Level Model Development ● ● ● ‡
- UHF Arrays: Physical Aperture Area Reduction ● ‡
- HV-Solid State Charging Switch ● ‡
- RF Coupling ● ‡
- Drift Step Recovery Diode Optimization ● ‡
- Impulse Radiating Antenna Design ●
- Direct RF Modulation via UWBG-PCSS ● ‡
- Diode-based NLTL for f_c>400-MHz ● ‡

Sunset Projects

- Positive Feedback-NLTL ● ‡
- Minimally Dispersive Waves ●
- Multi-ferroic-NLTL ● ●
- *Ab Initio* → TCAD ‡
- Avalanche-based PCSS ●
- Gyromagnetic-NLTL ●
- Super Resolution from Deep Learning ●
- Multi-stage BPFTL ●

Completed Projects

- PCSS Top Contact Optimization ●
- Non-perturbing UAV Diagnostics ● ‡
- Noise Injection as HPM Surrogate ● ‡
- SiC:N,V Properties (w/ LLNL) ● ‡
- Adaptive Design-of-Experiments ● ‡

System-level Relationship

- ● Source Scalability/Modularity/SWaP-C^2
- ● Waveform Tunability
- ● Effects Prediction
- ‡ MS/PhD Project

OPSRES: Gap/Deficiency *HOW*

OSPRES Grant Overview

Future/Needed/Wish-List/Potential Projects

Co-axial Impedance Transformer (5 → 50-Ω)

High gain/power Ultra-low Jitter Seed Laser

Aging of UAV Autopilot Systems and Modules

Avalanche Transistor-based Pulsed Power

Vector Inversion Generators

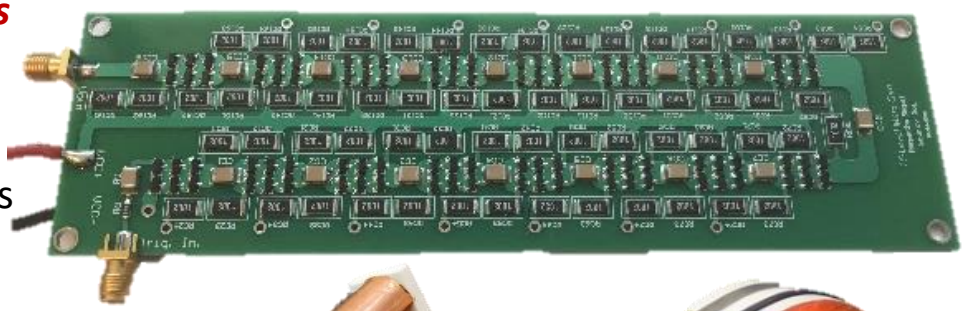
MOSFET-based Pulsed Power

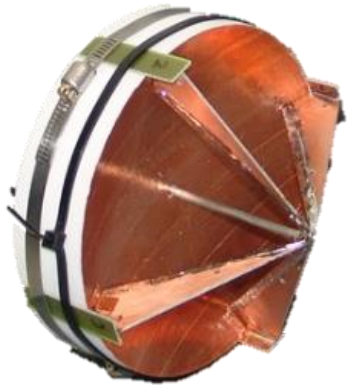
Packaging for Semiconductor-based Pulsed Power

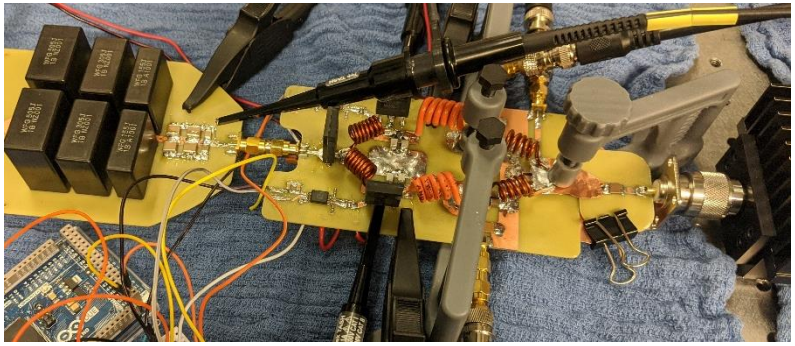
Avalanche Shaping/Sharpening

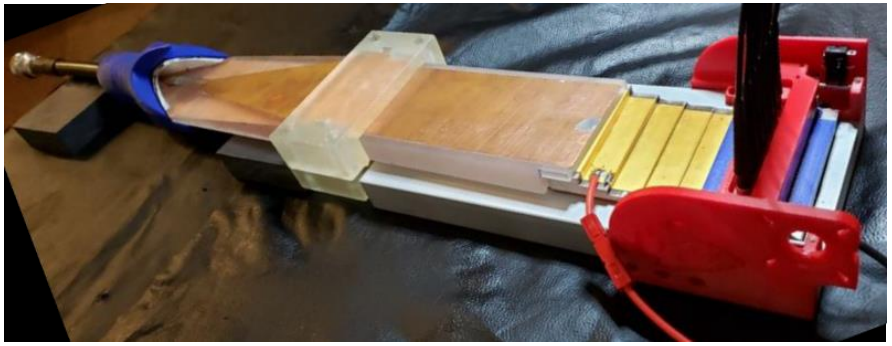
Large DoD Prime / GOV Defined

Many more……









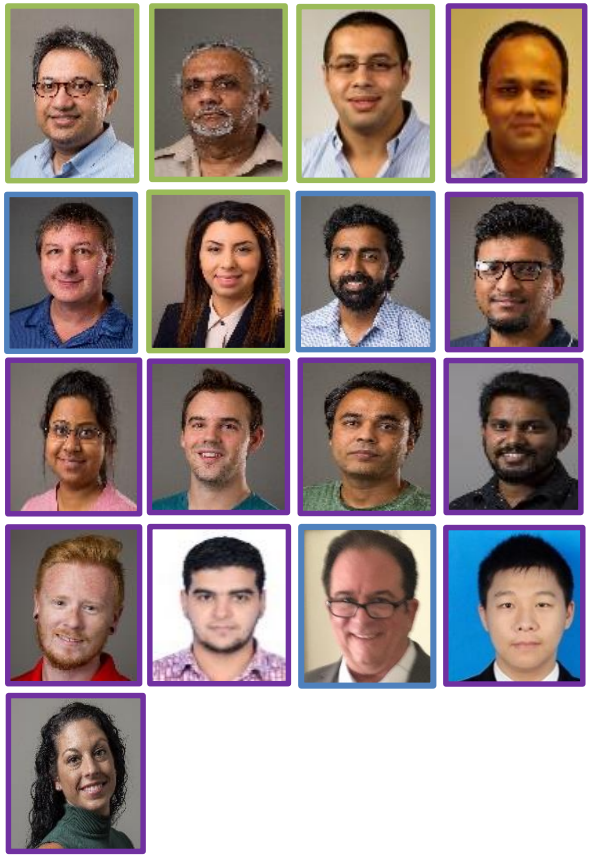
OSPRES *UM/MIDE Execution* Personnel (FY21)

OSPRES Grant Overview – Personnel Forward

OSPRES *Grant*

N00014-17-1-3016

30SEPT2017 – 29SEPT2022



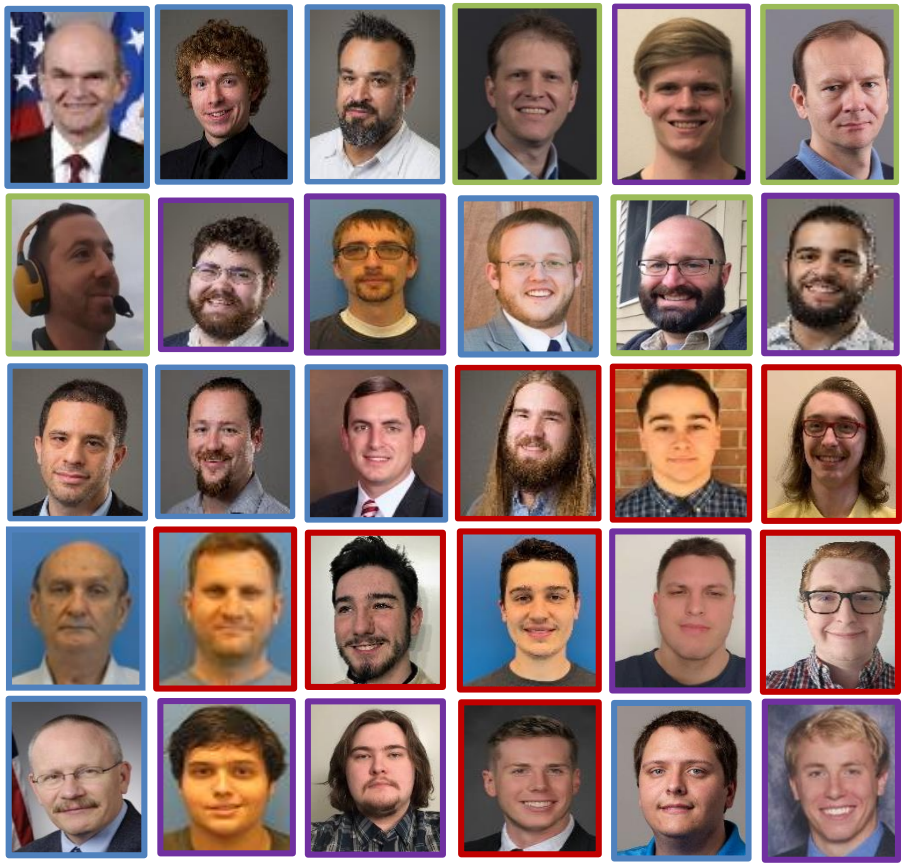
F. Khan, Chatterjee, Hassan, Roy, Eifler, Sobhansarbandi, Durbhakula, Azad, Barman, Berg, Bhattarai, Bhamidipati, N. Gardner, Hamdalla, Shepard, Xia, Thompson

Herrington, Brasel, Klappa, Allen, Fields

OSPRES *Contract*

N00014-18-C-1017

07MAR2018 – 07MAR2023



Hussey, Bissen, Beaudin, Beetner, Hunter, Khilkevich, Abdulrahim, Kramer, Fry, Currie, Kovaleski, Labrada, Richman, Myers, J. Smith, Landwehr, Reed, Grounds, Terry, Urton, Norris, Cacy, Chance, C. Smith, Karnes, Grounds, Kovarik, Layman, Mardikes, S. Wagner, Gunter

OSPRES: External Dissemination Summary

Conference Papers	27
Journal Papers	
Submitted	4
In-press	2
Published	1
External Presentations	
Posters	~50
Presentations	~70
Intellectual Property	
Disclosures	11
Provisional Patents	1
Non-Provisional Patents	0

N.B.: OSPRES Grant and Contract Combined

OSPRES: Graduates (as of DEC2020)

Program Graduates (14)

Lancaster (MS, LLNL)
Waleed (MS, KC-NSC)
Flippin (MS, SPT/UMKC)
Labrada (BS, UMKC)
Wagner (BS, UMKC)
Harp (MS, Small Business)
Renzelman (MS, KC-NSC)
Kramer (MS, UMKC)
Thompson (MS, UMKC)
Bissen (MS, UMKC)
Hauptmann (BS, UNL)
Xia (BS, MS&T)
Harmon (BS, MS&T)
Floyd (BS, NAWCAD)

FS20/SS21 Graduates (15)

Labrada (MS)
Wagner (MS)
Brasel (BS)
Roy (PhD)
Hanif (PhD)
Azad (PhD)
Fry (BS)
Kovarik (MS)
Fazekas (MS)
Herrington (PhD)
Klappa (PhD)
Smith (MS)
Layman (MS)
Stark (BS)
Landwehr (BS)

FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

Bi-Annual Program Review

Development of a US-based High-voltage Solid-state Switch

Faisal Khan, Associate Professor, MIDE-UMKC
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OSPRES: Prime Power and Conditioning Group

Development of a US-based High-voltage Solid-state Switch

Prime Power/Conditioning

- Power conditioning for pulse forming network
- In-house high-voltage (HV) switch design and fabrication

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End User

Pulse Forming Network

HPM generation using Si PCSS

Heather Thompson
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End User

GaN:C PCSS

HPM generation using GaN:C PCSS

Roy Allen
Lead Mechanical Engineer

Mechanical support team

Thermal Management of PCSS

Ensuring adequate cooling for PCSS and HV switch

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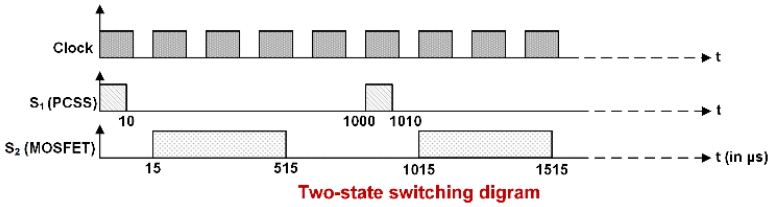
Development of a US-based High-voltage Solid-state Switch

- While generating HPM, power loss due to the lack of power conditioning can affect the efficiency of a linear-mode PCSS based pulse forming network (PFN).
  - Incoming current during the recombination time of the PCSS causes power loss
- A two-state switching mechanism facilitated by an HV switch can minimize the power loss associated with the PCSS based PFN, thereby increasing system efficiency.
  - First state: Transmission line (TL) is charged through HV switch
  - Second state: TL is discharged through the PCSS triggered by a laser
- Commercially available HV switches (e.g., switches made by German manufacturer BEHLKE) are expensive, have long lead time, require liquid cooling system for a switching frequency greater than 10 kHz, and require multiple ancillary DC supplies.
- Developing an in-house modular HV (~10-kV) switch built from commercially available inexpensive 1700V MOSFETs can become a direct and inexpensive replacement to the HV switches made by BEHLKE.
- This HV switch is an integral part of an energy efficient and compact PCSS based PFN that can reliably generate HPM to counteract enemy drones, thereby, keeping the ship afloat.

HV switch (BEHLKE made)



Two-state switching digram

Two state switching scheme

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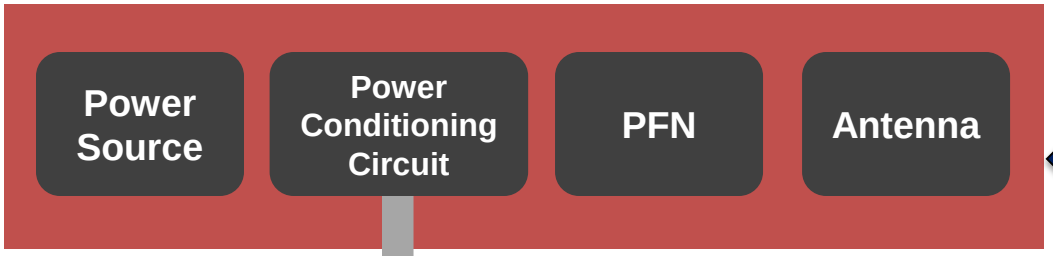

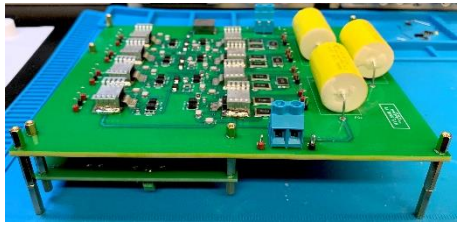

Power conditioning is needed for an efficient PCSS System

- In-house modular HV switch uses inexpensive COTS MOSFETs and an in-house HV (~10 kV) isolated gate driver
  - COTS components reduce the cost of the switch, in-house design decreases the lead time of a complete switch fabrication
  - Modularity and scalability of HPM System improved
  - Higher TRL and fleet transition probability improved

ONR HPM Program Key Research Criteria - II

Development of a US-based High-voltage Solid-state Switch

Qualitative Criteria:

Goal I: Design and develop an inexpensive in-house modular HV solid-state switch using COTS components

State-of-the-art (SOTA): Direct liquid cooled HV switches made by BEHLKE (e.g., HTS-151-30)

Deficiency in SOTA: HV switches from BEHLKE are expensive, have long lead time, require liquid cooling and multiple ancillary voltage supplies, thereby contributing to the increase in size.

Proposed Solution: Design and demonstrate modular high-voltage (~10-kV) and fast (PRF = 100-kHz) solid-state switches using a combination of series and parallel-connected commercially available inexpensive discrete MOSFETs and custom high-voltage (~10-kV) isolated gate drivers.

Program outcome: We have designed and fabricated an in-house 4.8 kV rated HV switch and a 10 kV rated isolated gate driver. We will design a modular 10 kV HV switch, which can be driven by the in-house isolated gate driver.

ONR HPM Program Key Research Criteria - I

Development of a US-based High-voltage Solid-state Switch

Quantitative Criteria/Metrics for HPM source improvement:

Parameter of Research	SOTA	Threshold	Objective	Expected Results
Repetition Rate	100 kHz	110 kHz	300 kHz	200 kHz
Ancillary Supplies	3	3	1	1
Cooling Method	Liquid	Liquid	Forced air	Forced air
Cost	>$5,000	>$4,500	<$1,000	~ $1,000
Volume	1890 cm^3	~ 800 cm^3	< 800 cm^3	~ 800 cm^3

Research Parameter/Metric Context Description:

1. **Repetition Rate:** SOTA BEHLKE made HV switches (~15 kV rated) have a maximum repetition rate close to 100 kHz when fitted with direct liquid cooling. Our research focus is to develop an in-house HV switch (~10 kV rated) that can operate at a repetition frequency close to 300 kHz.
2. **Ancillary Supplies:** SOTA BEHLKE made HV switches (~15 kV rated) require 3 DC power supplies to operate beyond 10 kHz switching frequency (e.g., HTS-151-30) that increases system size, cost and affect system portability. Our research focus entails developing a single gate driver based HV switch that require only one DC power supply.
3. **Cooling Method:** Direct liquid cooling is required to operate SOTA BEHLKE switch once the switching frequency exceeds10 kHz. Our research focuses on incorporating forced-air cooling up to an operating frequency close to 100 kHz.
4. **Cost:** BEHLKE switches are expensive, for instance, a single unit of HTS-151-30 costs close to $5,000. Our in-house HV switch will be made from inexpensive COTS components, thereby minimizing the expense.
5. **Volume:** SOTA BEHLKE made HV switches (~15 kV rated) occupies an area close to 1890 cm^3 without taking the space required to fit the liquid cooling system into account. We aim to limit the volume of the HV switch with attached heatsinks within 800 cm^3.

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Development of a US-based High-voltage Solid-state Switch

- **Risks**
  - EMI coupling to the gate signal at high voltage (~10 kV or higher) and high repetition frequency (>100 kHz) leading to switch malfunctioning and failure
  - Voltage overshoot due to the fast switching speed of the SiC MOSFETs may cause false turn-ON
  - Failure of an individual MOSFET leading to a cascaded failure of the HV switch
- **Payoffs**
  - A modular, inexpensive and compact HV switch built from inexpensive COTS components
  - Customizable for different level of voltages facilitated by the modular design of the switch as required by different applications to avoid overdesign and optimize cost.
- **Challenges**
  - Ensuring rigid control over voltage balancing among individual MOSFETs inside the HV switch
  - Suppressing time delays between the turn-ON time of individual MOSFETs to mitigate unwanted voltage stress
  - Measuring conducted EMI associated with the switch and ensuring adequate shielding

HPM: Broader Impact

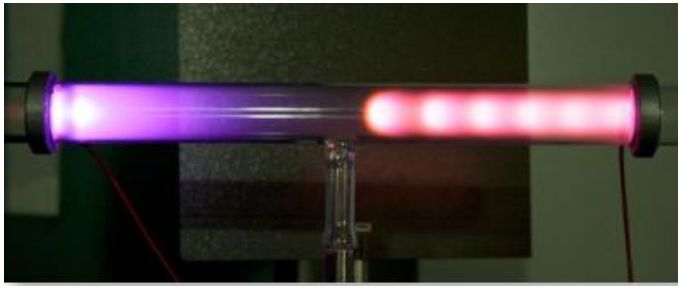
Development of a US-based High-voltage Solid-state Switch

- This in-house HV switch can help to construct a compact PFN using a linear-mode PCSS.
- This in-house HV switch can be used in multitude of applications, for instance, fast capacitor charging systems, electrostatic precipitators, atmospheric plasma production, large particle accelerator, fusion science, medical devices for cancer therapies to name a few.

Electron beam driver

Electrostatic precipitator

Particle accelerator



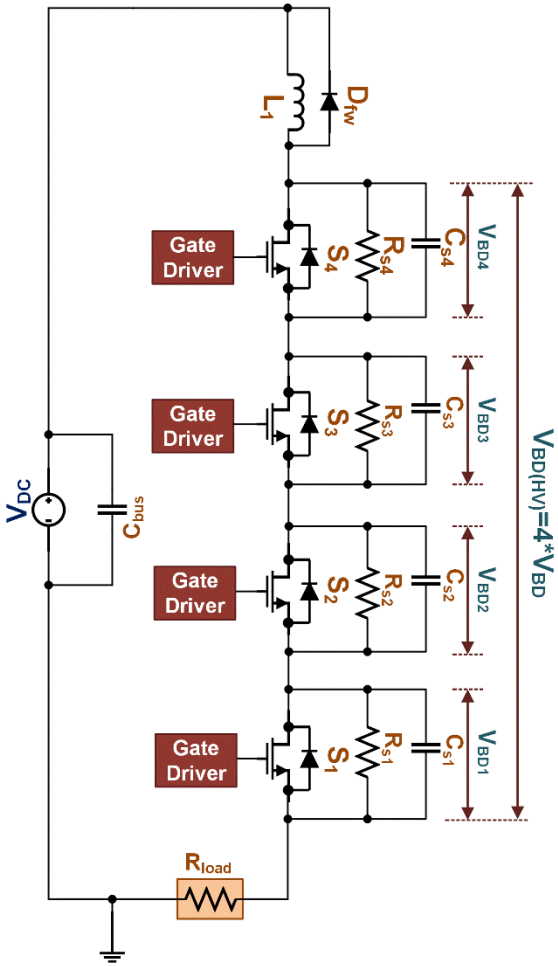
High voltage plasma discharge

High voltage food treatment

HPM: Sub-Project Research Objective

Development of a US-based High-voltage Solid-state Switch

- Breakdown voltage of COTS discrete MOSFETs is limited to 4.5 kV, thereby not suitable for HV applications (>4.5 kV). Our research effort to develop an HV switch by stacking inexpensive COTS MOSFETs in series using a single gate driver topology can solve this existing problem.
- Introducing modularity in the HV switch design to optimize cost and minimize overdesign
- Characterizing the reliability of the HV switch to use it in commercial space in future
  - Estimating the change in the effective $R_{DS\text{-}ON}$ of the switch with aging
- Developing an HV (~10 kV rated) isolated gate driver became necessary to test our in-house HV switch as commercial HV isolated gate drivers are limited by the voltage rating (< 5.7 kV).

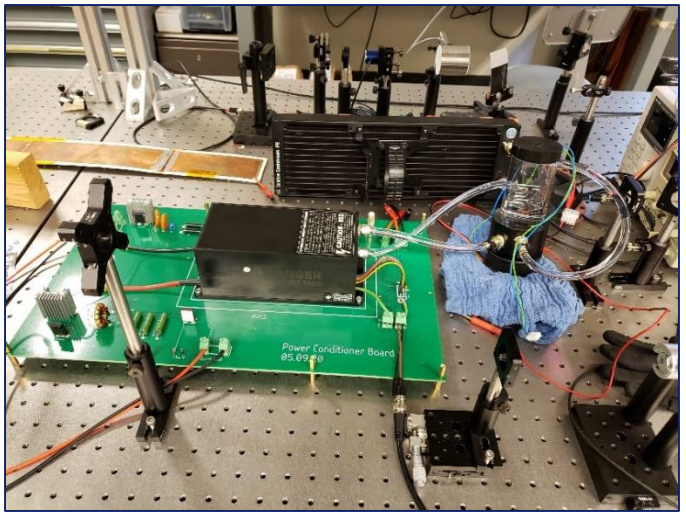


Series connection of switches

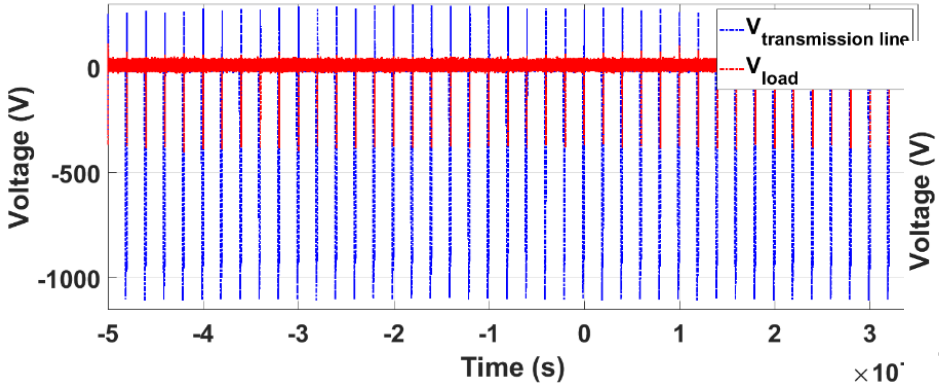
HPM: Technical Discussion/Progress

Development of a US-based High-voltage Solid-state Switch

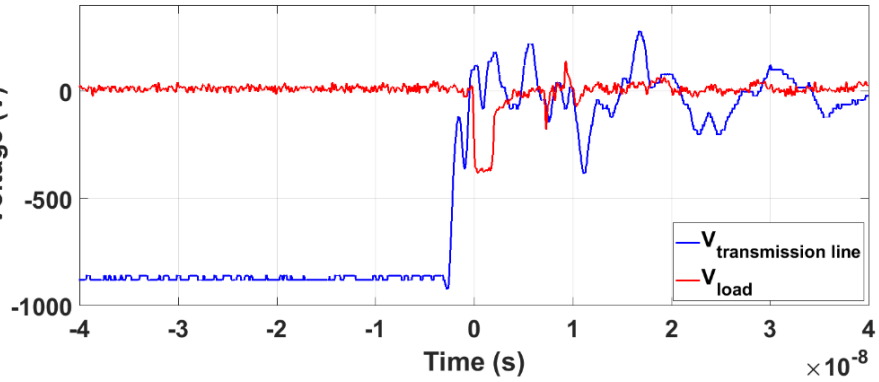
In-house power conditioning board using a HV switch (HTS-151-30) from BEHLKE



Experimental setup using the power conditioning board and liquid cooling system for the BEHLKE switch



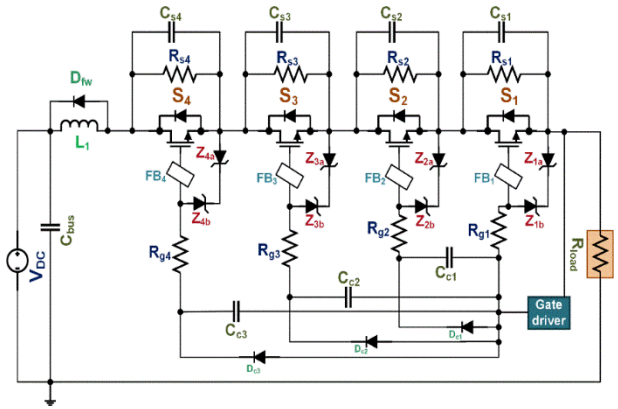
Measured voltages at different points of the transmission line using the power conditioning board using BEHLKE HV switch (V_{DC}= 1 kV, f= 50 kHz)



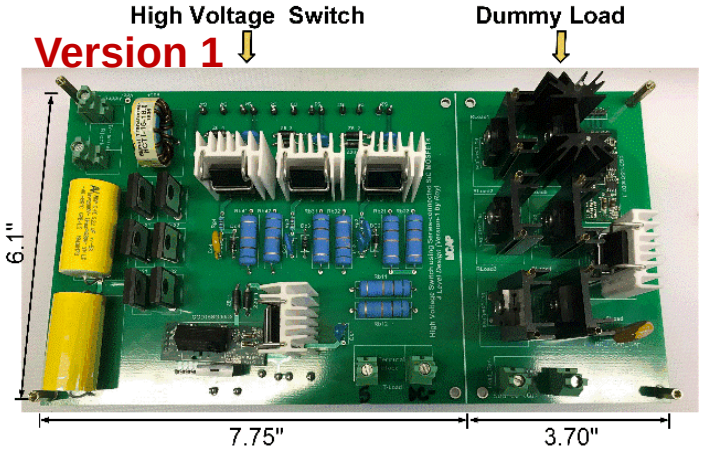
Zoomed version of the switching transients at different points of the transmission line using the power conditioning board (V_{DC}= 1 kV, f=50 kHz)

HPM: Technical Discussion/Progress

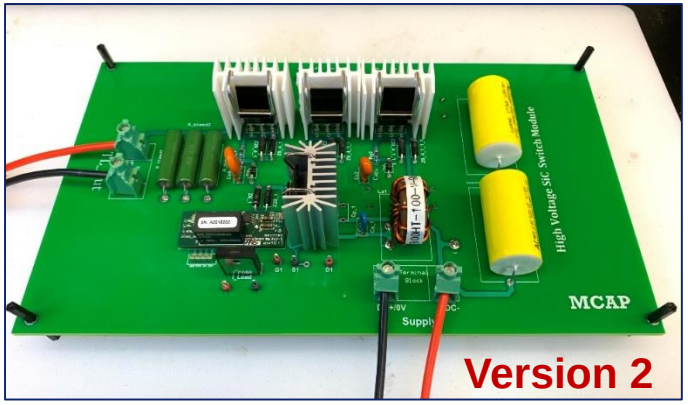
Development of a US-based High-voltage Solid-state Switch



Schematic of a single gate driver-based 4.8 kV HV switch with an IGBT controlled load



A single gate driver-based in-house HV switch (4.8 kV rated) compatible with positive DC power supply

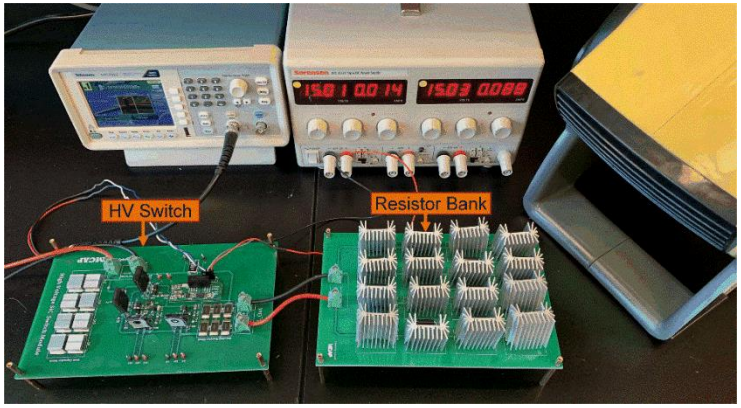


Prototype of a four-stage 4.8 kV rated HV switch compatible with negative DC power supply

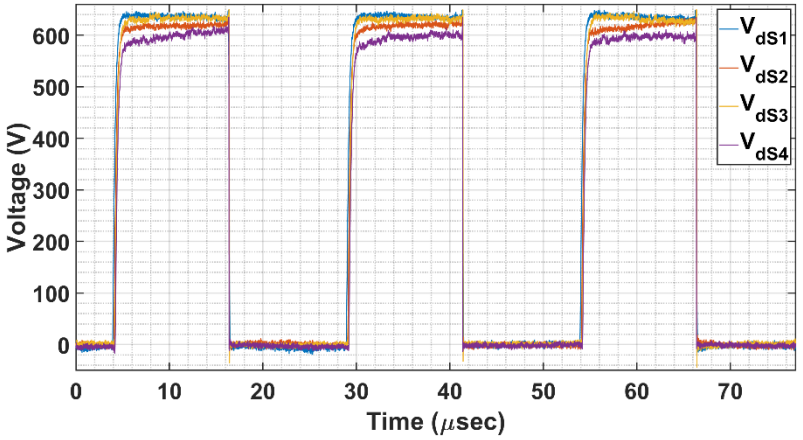
Prototype of a four-stage 4.8 kV rated HV switch with SMD components

HPM: Technical Discussion/Progress

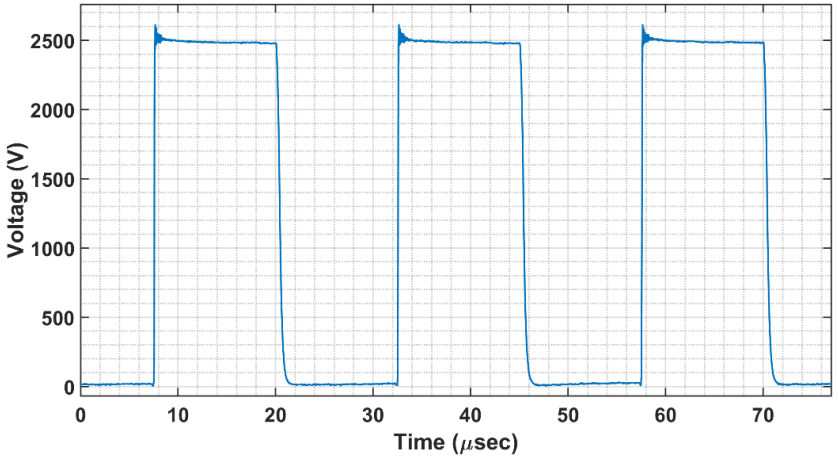
Development of a US-based High-voltage Solid-state Switch



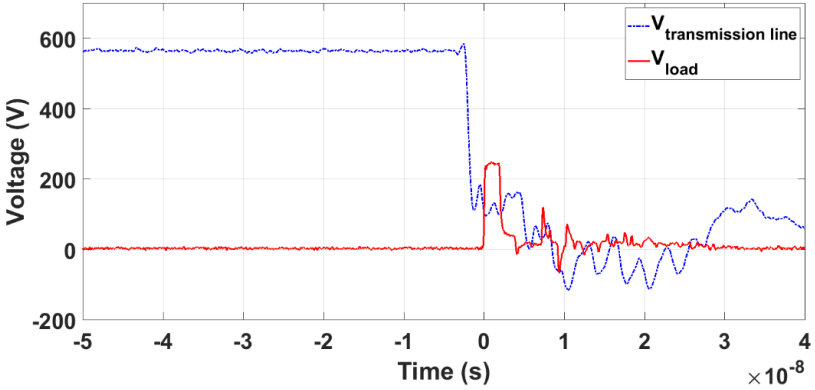
Experimental setup



Experimental drain-source voltages across the four individual MOSFETs (V_{DC}= 2.5 kV)



Voltage measured across 3.2 kΩ resistive load (f_{sw}= 40 kHz, D= 50%)

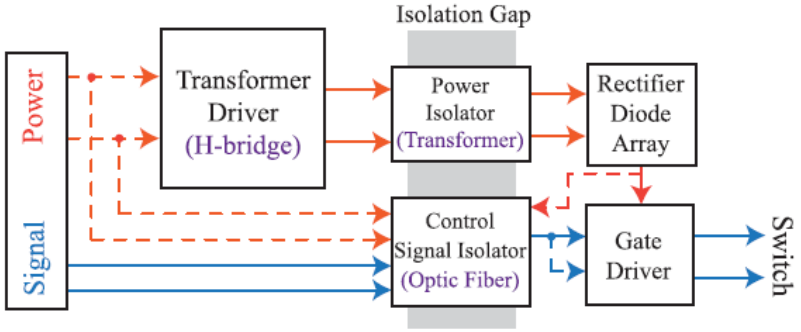


Zoomed version of the switching transients at different points of the transmission line using the in-house HV switch (V_{DC}= 600 V)

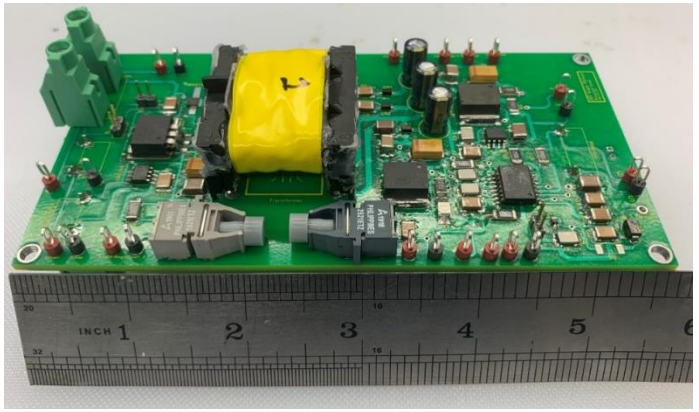
HPM: Technical Discussion/Progress

Development of a US-based High-voltage Solid-state Switch

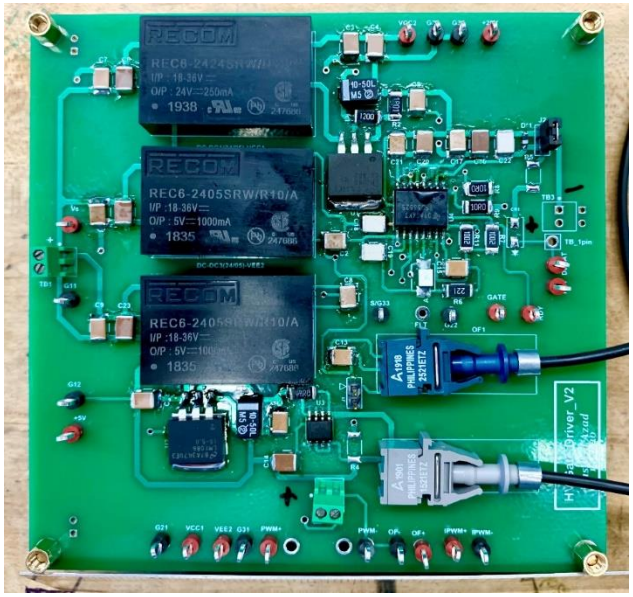
Version 3



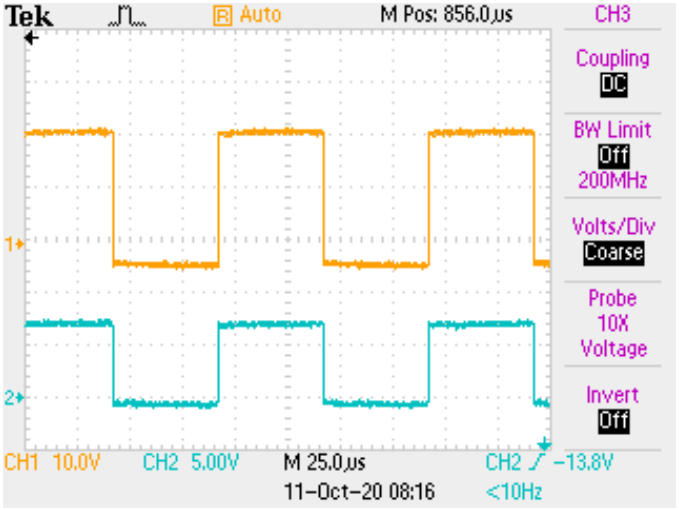
Schematic of a HV isolated gate driver with fiber optic isolation



Initial prototype of a HV (~15 kV rated) isolated gate driver



Second prototype of the HV (~15 kV rated) isolated gate driver

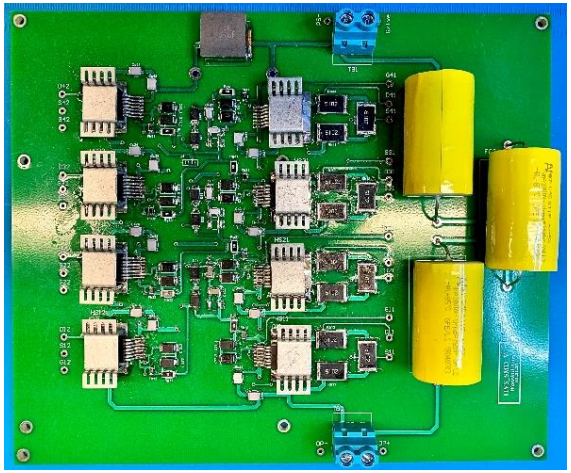


Gate drive signals (Cyan- input PWM signal, Yellow- level shifted gate driver signal)

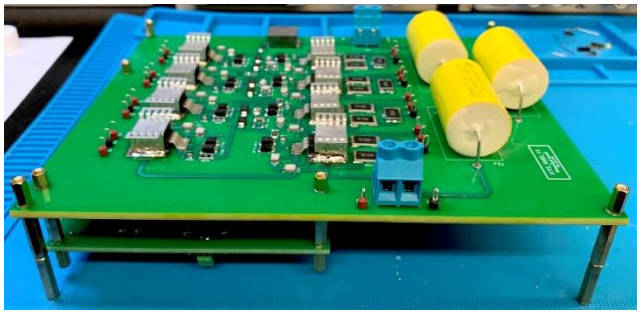
HPM: Technical Discussion/Progress

Development of a US-based High-voltage Solid-state Switch

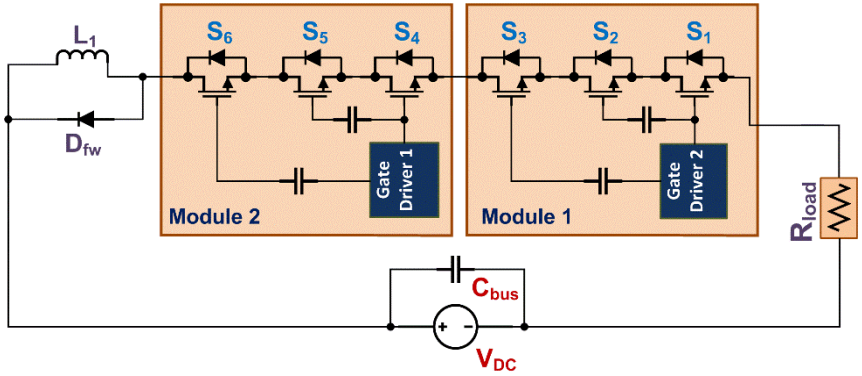
Version 3



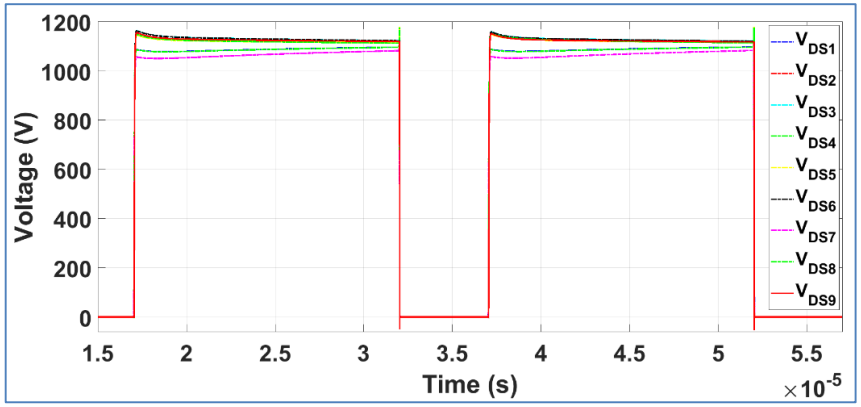
Prototype of the 6.8 kV rated SMD MOSFET based HV switch



Prototype of the 6.8 kV rated SMD MOSFET based HV switch with integrated gate driver (connected back to back)



Proposed modular architecture



Simulated voltages across the drain-source terminals of the series-connected MOSFETs for a resistive load (V_{DC}=10kV)

HPM: Research Objective Progress/Findings

Development of a US-based High-voltage Solid-state Switch

- A power conditioning board using a HV (15 kV rated) SiC switch made by BEHLKE has been designed and successfully tested while coupled with the PCSS up to a DC supply voltage of 3 kV and switching frequency up to 50 kHz.
- An in-house 4-stage HV switch has been successfully tested up to a DC supply voltage of 2.5 kV and switching frequency up to 50 kHz.
- An in-house 10 kV rated isolated gate driver has been designed, fabricated and tested successfully. Fiber optic isolators has been incorporated in the gate driver module to provide robust, noise-immune, high voltage isolation to TTL control signals with easy-to-use plastic fiber.
- The fast rise and fall times and low jitter associated with the fiber optic isolators are ideal for applications that require precision timing.
- A modular HV switch will be designed and tested at a DC supply voltage close to 10 kV using the in-house HV switch we have developed to optimize cost and minimize overdesign.
- The switching parameters of this HV switch (e.g., turn-ON, turn-OFF time, reverse recovery time, energy loss during switching transients, etc.) will be characterized using double pulse test.

HPM: New Ideas / Opportunities

Development of a US-based High-voltage Solid-state Switch

- The team has explored multiple HV switch topologies, balancing technics, cost reduction methods, modularity and simplified architectures.
- The next step is complete modular design, which will enable us to stack multiple HV modules to increase the operating voltage of the stack as a linear function of the number of modules. This is something unique and can give us enhanced reliability.
- The present design is low-cost, has optical isolation, and provides necessary voltage balancing. It also has less stringent ancillary voltage requirements, compared to commercial solutions. These features could be exploited to use these switches in utility applications such as high voltage dc (HVDC) transmission.
- Other than HPM sources, HV MOSFETs could be used in many other applications such as fast capacitor charging systems, electrostatic precipitators, atmospheric plasma production, large particle-accelerator, fusion science and so on.

HPM: Conclusions

Development of a US-based High-voltage Solid-state Switch

Task 1. Designing, fabricating and testing a four-stage SMD MOSFET based HV switch (6.8 kV rated) using the 10 kV rated in-house isolated gate driver at a supply voltage up to 5 kV and switching frequency up to 100 kHz. [Status- *Ongoing*]

Task 2. Designing, fabricating and testing a modular six-stage (two modules) HV switch (~12 kV rated) driven by two in-house gate drivers. [Status- Will be started after Task 1 is completed]

Task 3. Characterization of the HV switch using double pulse test. [Status- Will be started after Tasks 1 and 2 are completed]

Task 4. Designing a modified version of the power conditioning board using HV SiC switch made by BEHLKE incorporating improved EMI protection, surge protection, short circuit protection etc. [Status- Will be started shortly after more data collection using the first BEHLKE prototype]

FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

Bi-Annual Program Review

Si-PCSS Top Contact Optimization and TCAD Informed p-i-n Advances
Steven Bellinger, Staff Scientist, RDT
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09 DEC 2020
held via Zoom

Distribution A. Approved for public release.

OSPRES: Semiconductor Device Physics Team

PCSS Modeling, Simulation, Design and Optimization

Semiconductor Device Physics Team works immediately with the Laser Group and Si-PCSS-BPFTL Team in designing and optimizing the Si-PCSS top contact

Laser Group

Scott Shepard, MIDE Research Tech II

Top contact spacing optimized for laser requirements

Semiconductor Device Physics Team

Jay Eifler, Team Lead, MIDE Staff Scientist, Physics PhD

Noah Kramer, PCSS researcher, Physics PhD Candidate

John Bhamidipati, Switch Evaluation, Physics PhD Student

Heather Thompson, GaN Testing and Development, Physics PhD Student

Metallization patterns for Si-PCSS designed and optimized

Si-PCSS-BPFTL Team

Spencer Fry, MIDE Staff

Adam Wagner, MS Student

John McGeegan, BAE

Steve Bellinger, RDT, PhD

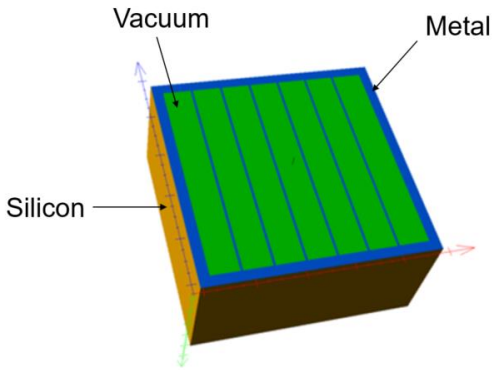
OSPRES: Semiconductor Device Physics Team

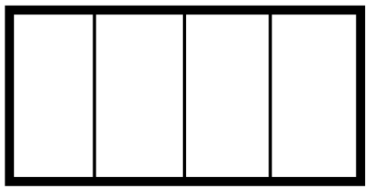
Si-PCSS Top Contact Optimization

Laser size has long been the Achilles heel of linear-mode PCSS-based systems.

Scalable and modular systems to place on Naval vessels must be small, lightweight, have minimal cooling requirements and be monetarily inexpensive.

Reduced laser energy for required on-state resistance (R_{on}) through optimized PCSS top contacts is one major way toward meeting the laser SWaP-C^2 objective.





Top contact (PCSS)

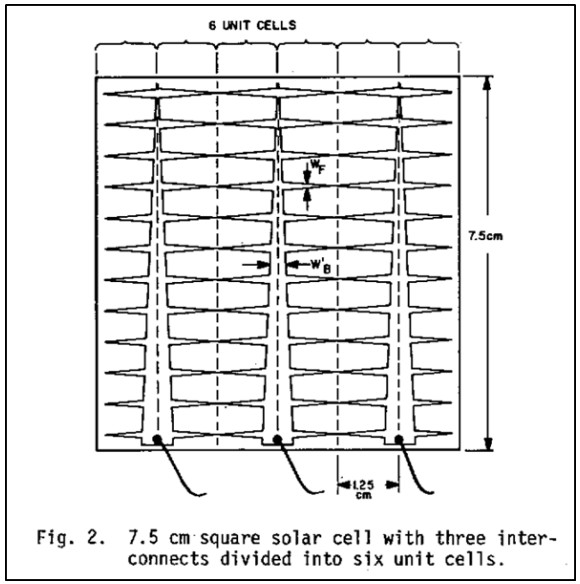
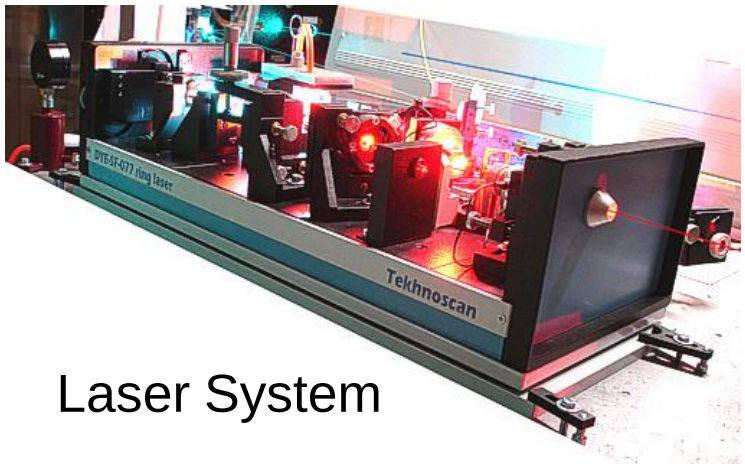


Fig. 2. 7.5 cm square solar cell with three interconnects divided into six unit cells.

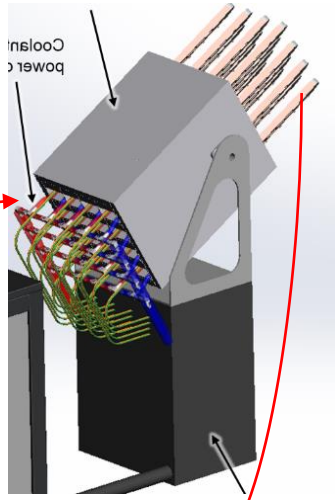
Solar cell top contact

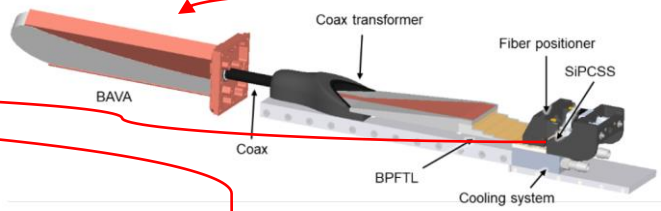


Laser System

OSPRES: Semiconductor Device Physics Team

Si-PCSS Top Contact Optimization





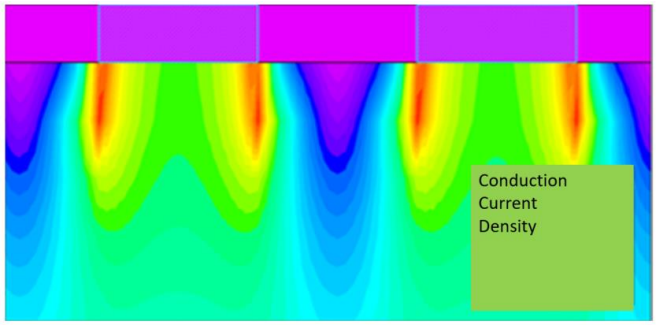
Optimized top contacts are needed for efficient PCSS System

-> PCSS top contacts require optimization to reduce required laser energy

-> Reduced laser energy requirement leads to a smaller and/or lower cost laser

-> Modularity and scalability of HPM System improved

-> Higher TRL and fleet transition probability improved



ONR HPM Program Key Research Criteria - II

Si-PCSS Top Contact Optimization and its Impact on Switch/Laser Requirements

Qualitative Criteria:

Goal I: Reduce required laser energy by at least 10% using Si-PCSS top contact design

State-of-the-art (SOTA): Top contact geometry using metal current filaments from solar cells

Deficiency in SOTA: Not optimized for PCSS and its operation

Proposed Solution: TCAD modeling of Si-PCSS including its application circuit for optimal top contact design optimization using improved photogeneration model with doping dependent free-carrer absorption (DDFA)

Program outcome: Maximum 30% reduction in required laser energy affecting laser system SWaP-C^2 for improved modularity/scalability and higher TRL and fleet transition probability

Goal II: Optimize doping profile of Si-PCSS considering top contact design

State-of-the-art (SOTA): High p-doping for ohmic contact and voltage holdoff

Deficiency in SOTA: PCSS p-doping not optimized with optimal top contact design

Proposed Solution: TCAD DDFA modeling of Si-PCSS including its application circuit for optimal p-doping of Si-PCSS considering tradeoffs with voltage holding and ohmic contact

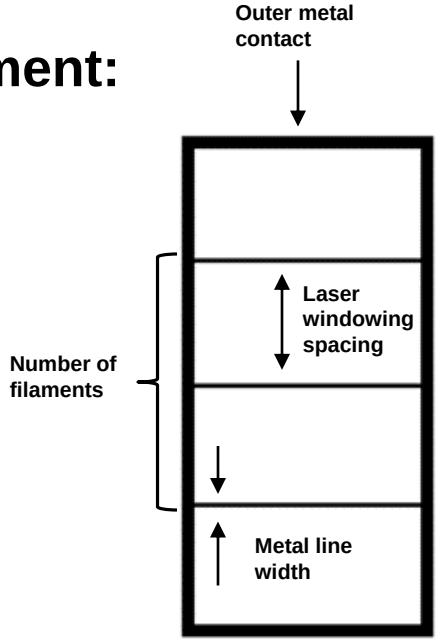
Program outcome: Further possible reductions in required laser energy affecting laser system SWaP-C^2 for improved modularity/scalability and higher TRL and fleet transition probability

ONR HPM Program Key Research Criteria - I

Si-PCSS Top Contact Optimization and its Impact on Switch/Laser Requirements

Quantitative Criteria/Metrics for HPM source improvement:

Quantitative Criteria/Metric	Representative Values
Percent laser energy reduction	10% - 30%
Laser energy difference at fixed R_{on}	< 30 µJ
Laser windowing spacing	10 µm - 1000 µm
Metal line width	10 µm
Number of filaments	< 1000s
Incident laser energies	1 uJ – 1000 uJ
On-state resistance (R_{on})	< 1 Ω



Research Parameter/Metric Context Description:

1. **Percent laser energy reduction (E_{per}):** E_{20} is the laser energy at some R_{on} for 20 µm spacing, E_{wid} is wider spacing energy required at same R_{on}, positive percent gives reduction
2. **Laser energy difference at fixed R_{on} (ΔE_{Ron}):** the numerator in E_{per} equation, necessary to compare at one R_{on} value which necessitates two laser energies and therefore a difference, not constant across R_{on} as with E_{per}
3. **Laser windowing spacing**: gap between metal filaments crossing the length of the switch to let in laser light, metal width limited by cost of manufacturing
4. **Incident laser energies:** 50 uJ – 100 uJ, stable and deliverable to switch
5. **On-state resistance:** subohm, depends on load resistance for PFN efficiency, static resistance of PCSS after laser illumination until charge storage time

$$E_{per} = \frac{E_{20} - E_{wid}}{E_{20}} * 100\%$$

For example:

30% reduction using 100 uJ laser energy gives 30 uJ laser energy reduction (for some R_{on} and spacing)

Note: Laser energies are per pulse and uniform top-hat spatial profile

HPM: Sub-Project Research Objective

Si-PCSS Top Contact Optimization and its Impact on Switch/Laser Requirements

Objective: Significantly reduce required laser energy by at least 10% from designing and optimizing Si-PCSS top contact

Current practice in solar cell community: Larger solar cell top contact design methods employ theoretical, SPICE and simplified TCAD simulation methods to optimize top contact for desired device performance

Origin of TCAD PCSS method: Using the same theoretical considerations as for solar cells and TCAD, optimal top contact patterns were developed for PCSS

Scientific community impact: TCAD can be successfully used in smaller solar cell and PCSS top contact design

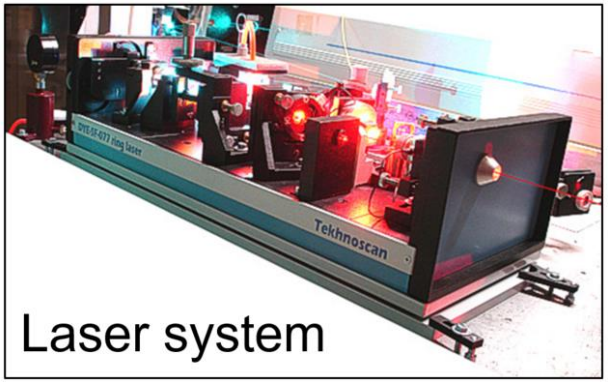
HPM: Research Objective Progress/Findings

Si-PCSS Top Contact Optimization and its Impact on Switch/Laser Requirements

–29% maximum laser energy reduction at optimal spacing (29 uJ of 100 uJ)

– Optimal top contacts lessen the pump power cost of laser systems by reducing required laser energy output

–Reduced laser energy requirement gives increased flexibility in designing compact laser systems



Laser system

–P-side doping concentration linearly related to on-state resistance at optimal spacing (we must minimize P-doping with considerations for voltage holding and ohmic contacts, implies well-known V_{max} vs R_{on} tradeoff)

HPM: Conclusions

Si-PCSS Top Contact Optimization and its Impact of Switch/Laser Requirements

–Si-PCSS top contact design show 29% maximum reduction in required laser energy when using the optimal spacing

–Laser energy reduction enables compact and/or lower cost laser solutions enabling modularity and scalability, higher TRL and fleet transition probability

–Non-provisional patent being sought, drafting for journal publication, transferred to OSPRES contract

–Additional TCAD studies for doping optimization with top contact, possible geometric effects, application to vertical SiC and GaN PCSS, and thermal effects on cooling optimization

–Increased computational resources for TCAD have arrived

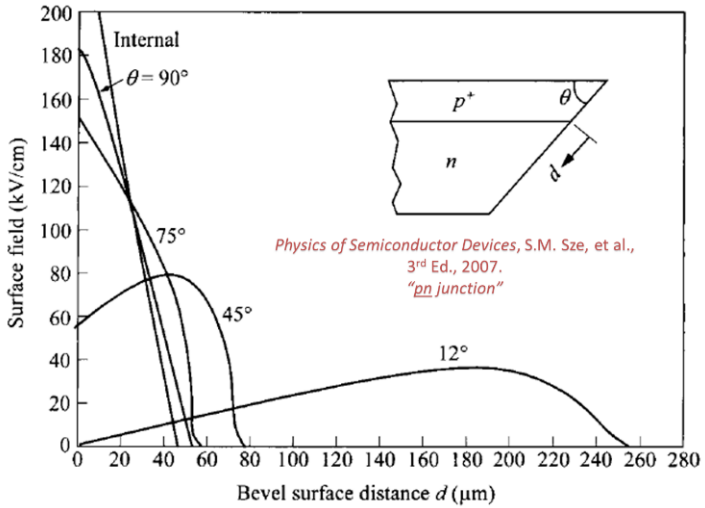
Si-PCSS Diode Optimization

Diode Structure and Edge Passivation of Si-based PCSS devices are the two most important features of voltage hold-off capability.

PCSS diodes for pulsed power applications must be compact, high voltage holding, small leakage current, have minimal cooling requirements and be monetarily inexpensive.

Reduced electric field within the Si-PCSS and passivation of dangling bonds at the Si-PCSS diode edge through optimized PCSS diode junction depth and device geometry is one major way toward meeting the peak PCSS holding-voltage objective for inexpensive Silicon-based HPM switches.

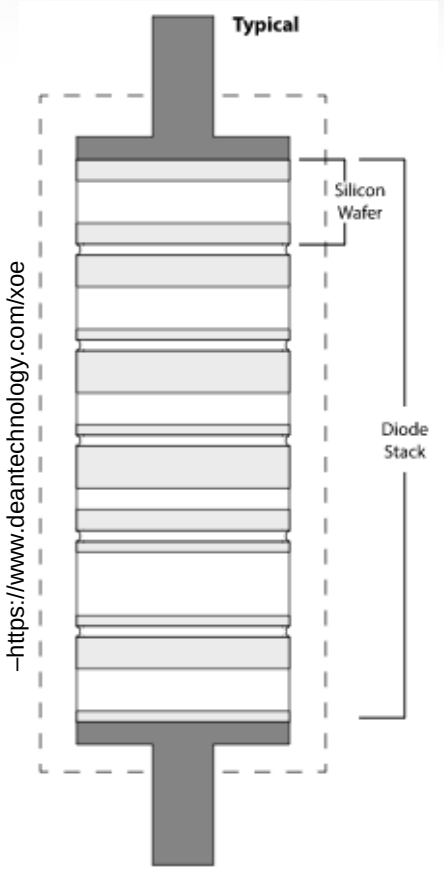
Edge Bevel & Passivation (PCSS)



Edge Electric Field

ONR HPM Program Key Research Criteria - II

Si-PCSS Diode Optimization and its Impact on HPM Requirements



Qualitative Criteria:

Goal I: Increase holding voltage of Si-PCSS by adjusting diffused junction profile;

State-of-the-art (SOTA): Low-voltage single element diode stacked to gain holding voltage;

Deficiency in SOTA: Not optimized for PCSS and its operation;

Proposed Solution: TCAD model of Si-PCSS diffused junction and simulate internal electric field strength. Changing the diffused depth and profile of junction will affect electric field in bulk Si;

Program outcome: Develop a design that can be manufactured and reduces the peak electric fields within the diode.

Goal II: Increase holding voltage of Si-PCSS by adjusting diode geometry;

State-of-the-art (SOTA): Low-voltage single element diode stacked to gain holding voltage;

Deficiency in SOTA: Not optimized for PCSS and its operation;

Proposed Solution: TCAD model of Si-PCSS edge geometry of diode and simulate electric field strength at edge. Consider dielectric materials for passivation at edge to hold edge voltage;

Program outcome: Develop a design that can be manufactured and reduces the peak electric fields at diode edge.

ONR HPM Program Key Research Criteria - I

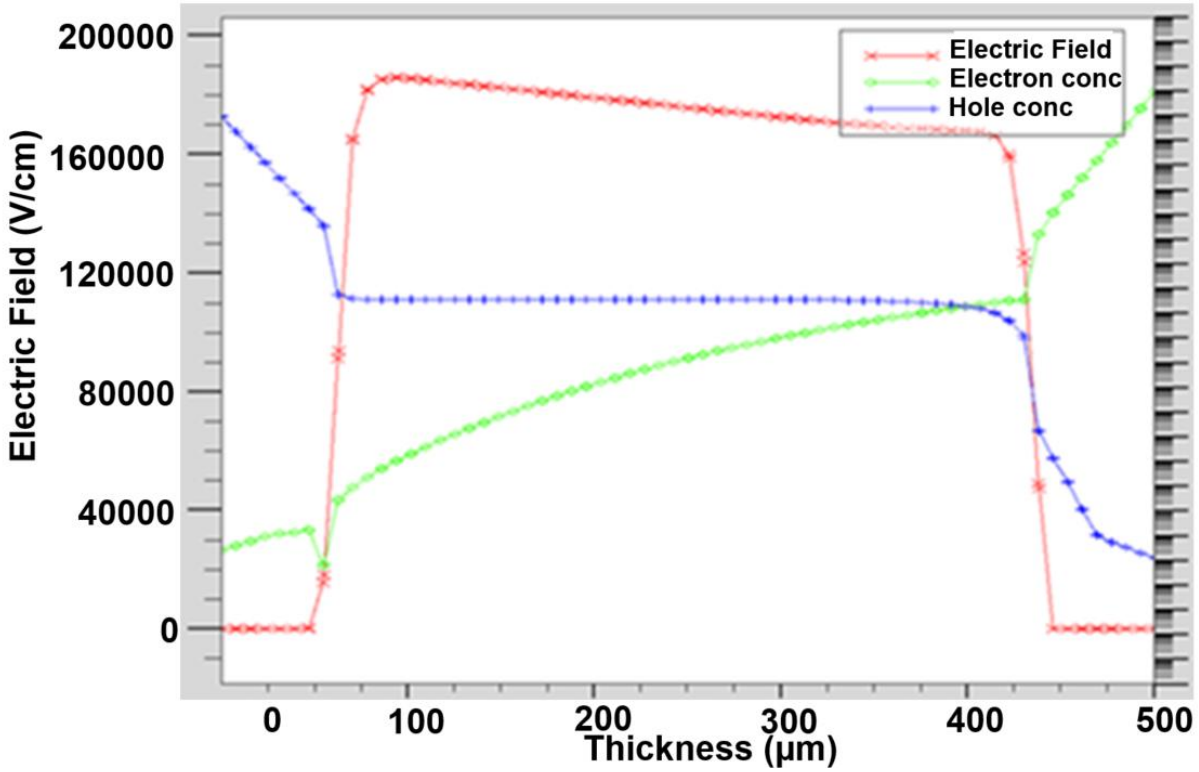
Si-PCSS Top Contact Optimization and its Impact HPM Requirements

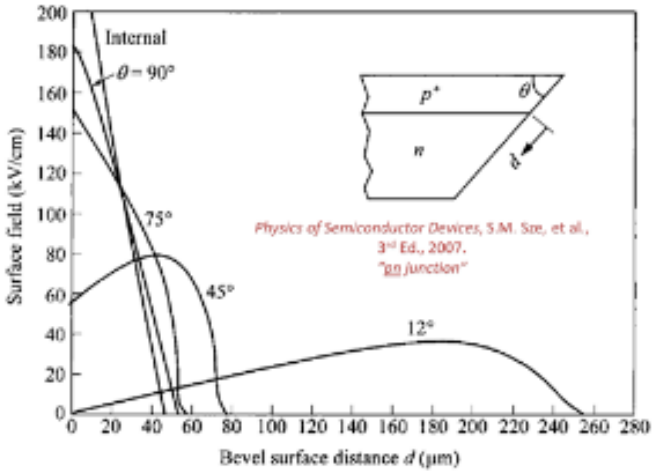
Quantitative Criteria/Metrics for HPM source improvement:

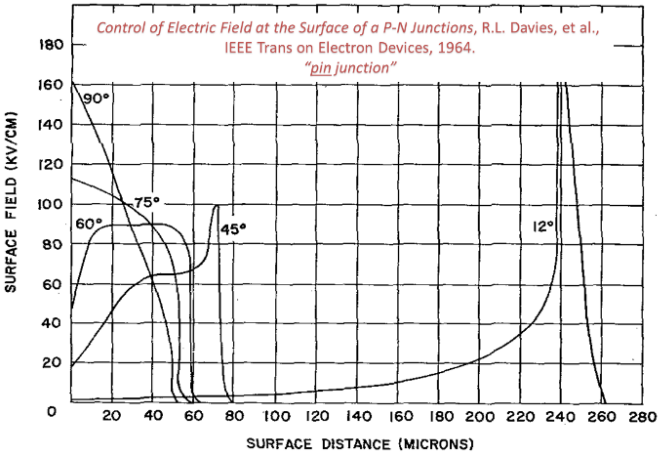
Research Parameter/Metric Context Description:

1. **High Voltage Increase (HV):** COTS single diode holding voltage ~1200VDC. Increase to 10KVDC per single element.
2. **Diffused Diode Junction:** Peak and diffused dopant concentration, p+ and n+ {cm^{-3}}, versus depth in bulk semiconductor.
3. **Diode Geometry**: Singulated diode edge profile and area (shape). **θ** varies from straight edge (90°) to bevel (45°). **d** is length of edge which is dependent on bulk thickness of Si diode.

Vertical Electric Field Profile TCAD (red)







HPM: Sub-Project Research Objective

Si-PCSS Diode Optimization and its Impact on HPM Requirements

Objective: Significant 1200 V to 10 kV increase in DC voltage holding of Si-based PCSS diode requires junction dopant profile and singulation-edge profile optimization to minimize electric field.

Current practice in high voltage community: Beveled edge and deep-graded junction dopant design methods employ theoretical and simplified TCAD simulation methods to optimize dopant depth profile and concentration and beveled edge for desired device performance.

Origin of TCAD PCSS method: Using the same theoretical considerations as for planar diode electric field and TCAD, optimal dopant profile and beveled edge were developed for PCSS.

Scientific community impact: TCAD can be successfully used for Si-based high voltage diode design and performance simulation.

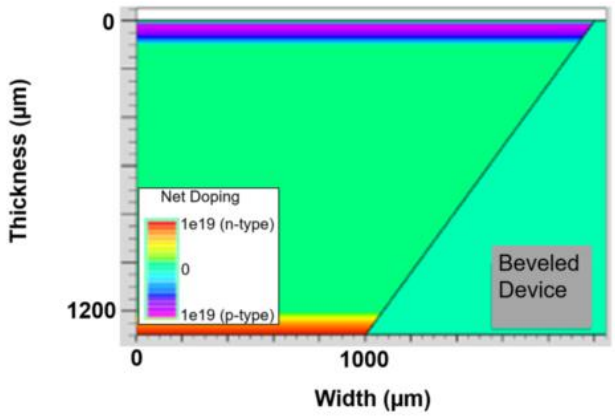
Si-PCSS Diode Optimization and its Impact on HPM Requirements

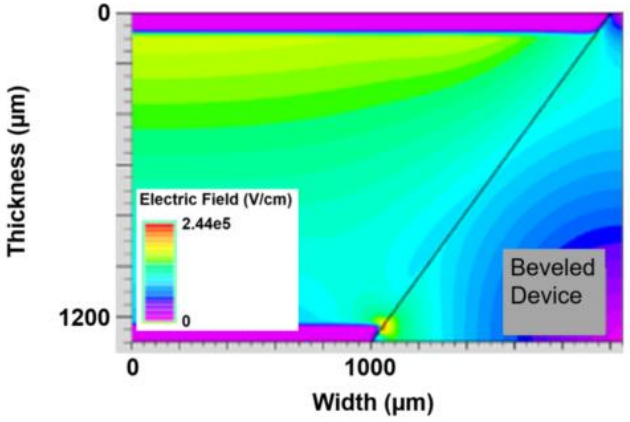
–10x possible holding voltage increase at optimal dopant diffusion and edge bevel/passivation.

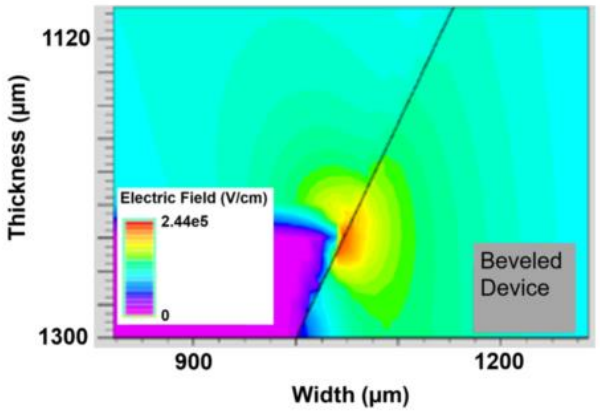
–Higher voltage per Si-PCSS diode increases power delivered to driven HPM component.

–Increased Si-PCSS voltage holding requirement leads to more compact pulsed power systems with increased power to driven components.

–Bevel shape important for reducing peak electric field at most sensitive region of diode – the singulation edge.







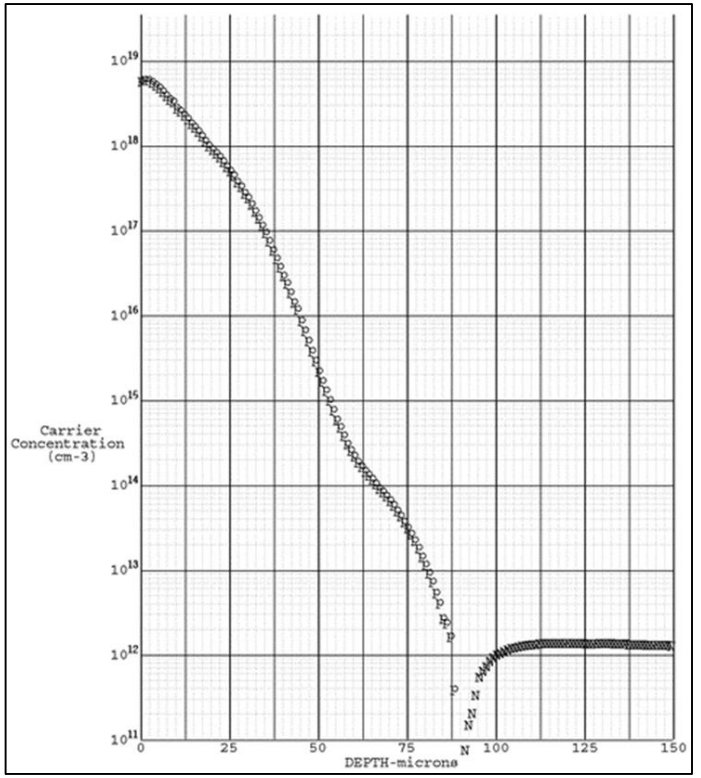
HPM: Conclusions

Si-PCSS Diode Optimization and its Impact of HPM Requirements

–Si-PCSS diode junction profile and singulation edge design simulation optimizes the diffusion profile and edge geometry based on various semiconductor types and parameters.

–Additional TCAD studies for doping optimization with top contact design, varying edge passivation materials to drain off fixed charge on surface, and factor manufacturability into dopant profile and singulation edge geometry.

–Currently comparing and validating empirical “as built” Si-PCSS devices to TCAD models.



FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

Bi-Annual Program Review

GaN-PCSS: Direct RF Modulation
Heather Thompson, GRA, UMKC
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09 DEC 2020
held via Zoom

Distribution A. Approved for public release.

OSPRES: GaN:C PCSS

Direct RF Modulation Considerations

Certain Navy vessels are smaller requiring even more concern for payload amounts, thus necessitating a cUAS system with a more compact form factor.

Sea Fighter (FSF-1)

https://en.wikipedia.org/wiki/List_of_current_ships_of_the_United_States_Navy

USS Henry M. Jackson

https://www.military.com/daily-news/2020/10/23/video-shows-us-navy-experimenting-drones-make-deliveries-submarine.html

Counter Drone System

https://defense-update.com/20191025_repmus19.html

N-AUDS – Naval/Maritime Defense

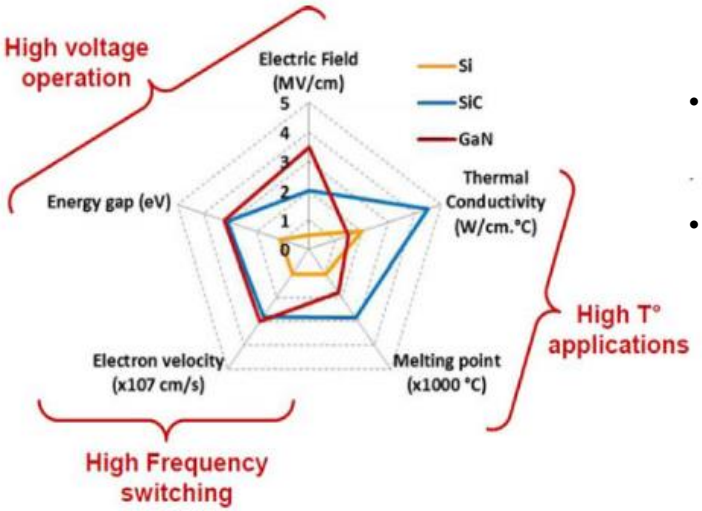
https://liteye.com/products/counter-uas/

OSPRES: GaN:C PCSS
Direct RF Modulation Considerations

Photoconductive Semiconductor Switch (PCSS) for High Power Electromagnetic (HPEM) System

Benefits:

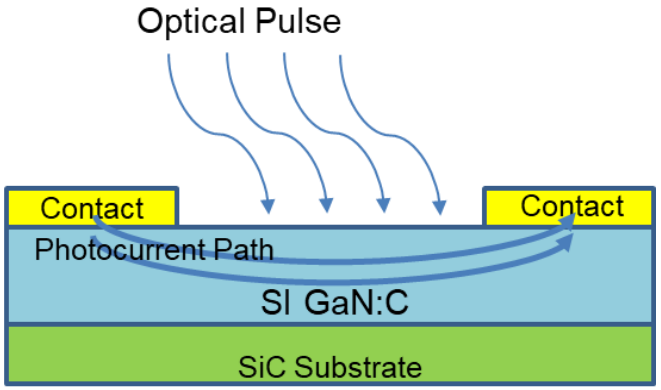
- Optical coupling of control circuits
- Compact devices
- Low switching jitter
- Fast rise and fall times
- Isolation of device from EMI effects



https://digitalrepository.unm.edu/cgi/viewcontent.cgi?article=1439&context=ece_etds

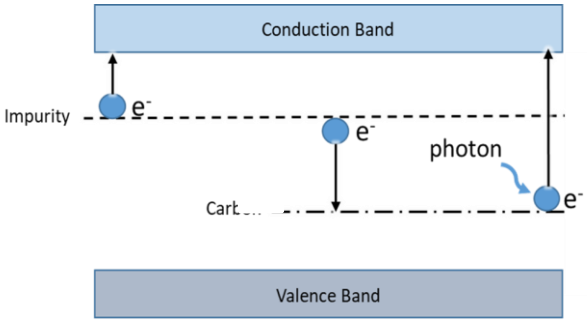
- Silicon (Si) is commonly used due to its maturity and low cost.
- As applications need higher frequency switching, operating temperatures, and operating voltages, wide-bandgap materials must be considered.

Lateral PCSS Schematic



Carbon Compensation:

- C Concentration – 10^{17}-10^{18} cm^{-3}
- Off-state resistivity of >10^{10} Ω-cm
- On-state resistivity of ~10^{-3} Ω-cm

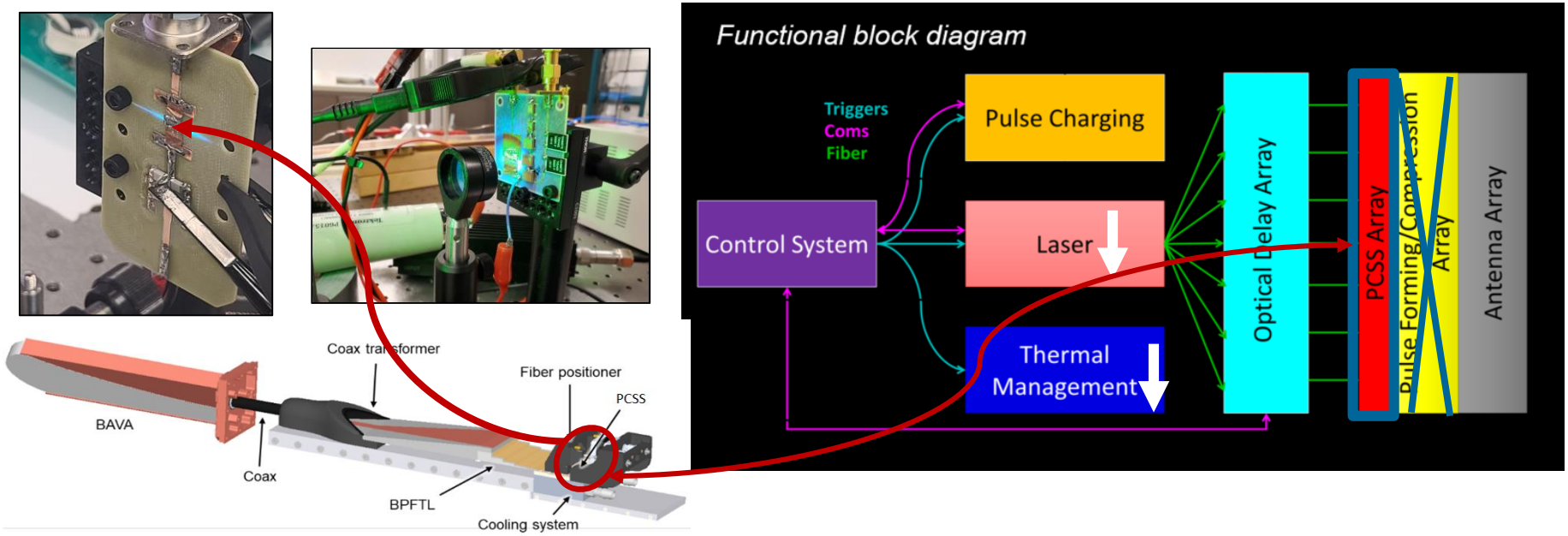


OSPRES: GaN:C PCSS

Direct RF Modulation Considerations

Problem: Need for a more compact, cost-effective RF pulse generation cUAV system for Navy afloat missions on smaller vessels and vehicles.

Proposed Solution: Replace silicon PCSS with gallium nitride (GaN) PCSS to increase efficiency, reducing device size and thermal requirements; GaN's theoretical material properties allow for higher operating voltages, center frequencies, and operational temperatures, while also eliminating the need for pulse-shaping transmission lines through direct RF modulation using a laser/photon source.



OSPRES: GaN:C PCSS

Direct RF Modulation Considerations

Eliot Myers
Assistant Director of Research

Jay Eifler
SDP Team Lead, MIDE Staff Scientist

Semiconductor Device Physics Team

Noah Kramer
iPhD Candidate

Heather Thompson
iPhD Student

Thermal Management
Losses in Device
Generation Rate
Device Surface Area

John Bhamidipati
iPhD Student

Laser
Optical Energy
Pulse Width
Wavelength
Beam Shaping
Repetition Frequency

Source - PCSS
Material: Si, SiC, GaN:C
Operating Voltage
Peak Power Out
Carrier Concentration
Carrier Saturation Velocity
Geometry: Lateral vs Vertical
Current Density

Antenna

Effects

Pulse Charger

Distribution A

OSPRES: GaN:C PCSS

Direct RF Modulation Considerations

Risks:

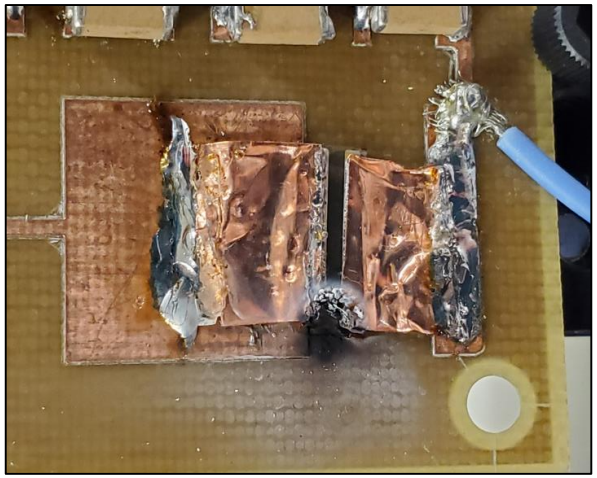
- Immature manufacturing → mainly lateral geometry devices increasing chance for surface flashover (without encapsulation or enclosure)
- Recovery time (ones-to-tens-of-ns) → may lead to device heating and increased DC content when generating RF (period on the same order as recovery time)

Payoffs:

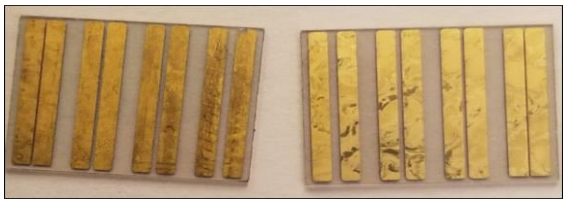
- Compact, tunable RF source
- Reduced SWAP-C[2]
- Reduced cooling requirements
- Increased efficiency
- Higher center frequency

Challenges:

- Limited operating voltages with lateral geometries
- High cost of material → Increased cost may balance out with reduction in size, system components (thermal, pulse-forming), and reduced payload requirements.



Possible Flashover on GaN:C PCSS



1 cm GaN:C-PCSS

1 cm Si-PCSS

Size comparison of OSPRES PCSS devices

7 cm Si-PCSS

ONR HPM Program Key Research Criteria

Direct RF Modulation Considerations

Qualitative Criteria:

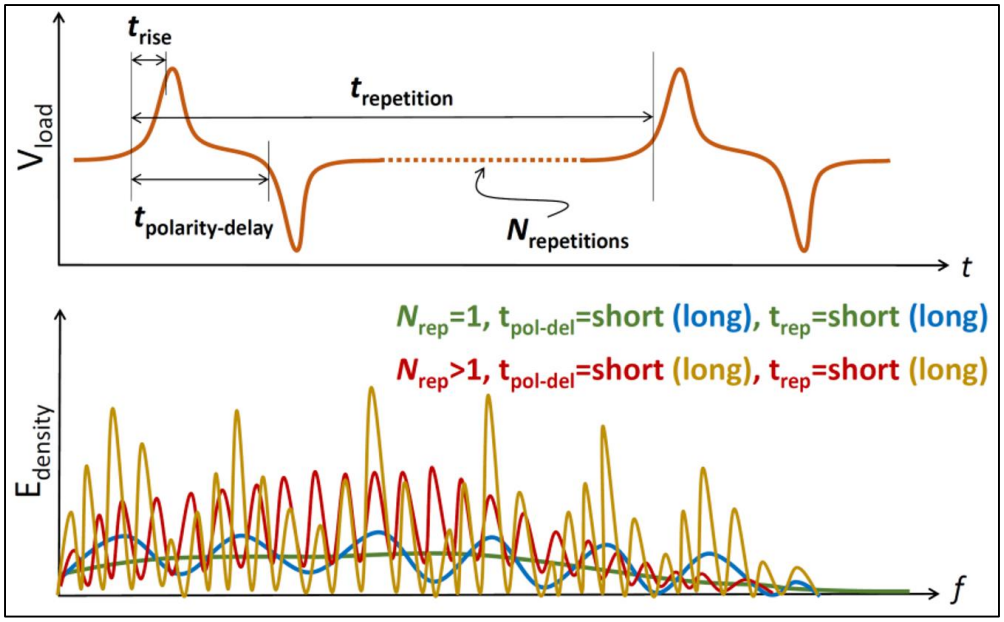
Goal: Reduce size and cost of PCSS RF generation system

State-of-the-art (SOTA): Narrow bandgap (Si) PCSS

Deficiency in SOTA: Large laser system, bulky pulse forming transmission line (~3 ft long), and increased thermal management needs

Proposed Solution: Direct RF modulation of GaN:C linear PCSS using laser source driving device

Program outcome: A cUAS system with a compact form factor and reduced cost



- Output pulse with GaN:C is laser dependent (i.e. follows the characteristics of the incident laser/photon source).
- Can use time separation to vary frequency content
- Can achieve quicker rise-time and shorter pulse width using a different laser (ps or fs laser)

ONR HPM Program Key Research Criteria

Direct RF Modulation Considerations

<u>Quantitative</u> Criteria/Metrics for HPM source improvement:

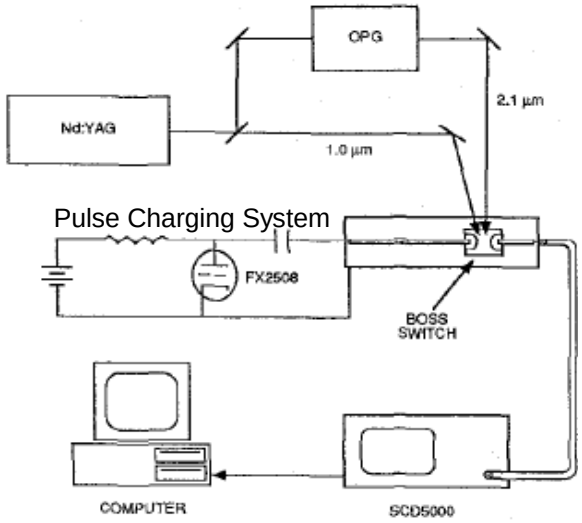
Parameter	SOTA (Si-PCSS)	Proposed (GaN:C-PCSS)	Parameter Description
Breakdown Field (V/cm)	$3*10^5$	$3.3*10^6$	N/A
Cooling System Capacity (W/cm^2)	500		Based on current cooling requirements of Si-PCSS
Incident Energy per Output Power (μJ/MW)	25	6.67	Incident laser energy as a function of PCSS output power, based on 4 MW output
Device Area (cm^2)	1-7	<1	Based on current OSPRES PCSS devices
Operating Temperature (°C)	<160	500	Operating temperature for GaN:C PCSS will be limited based on PCB components
Recovery time	μs Scale	ps - ns Scale	Recovery time for GaN:C is laser and material dependent
Saturation Velocity (cm/s)	$1*10^7$	$2.5*10^7$	N/A
Max Operating Frequency (GHz)	3.8	>12	N/A

HPM: Technical Discussion/Progress

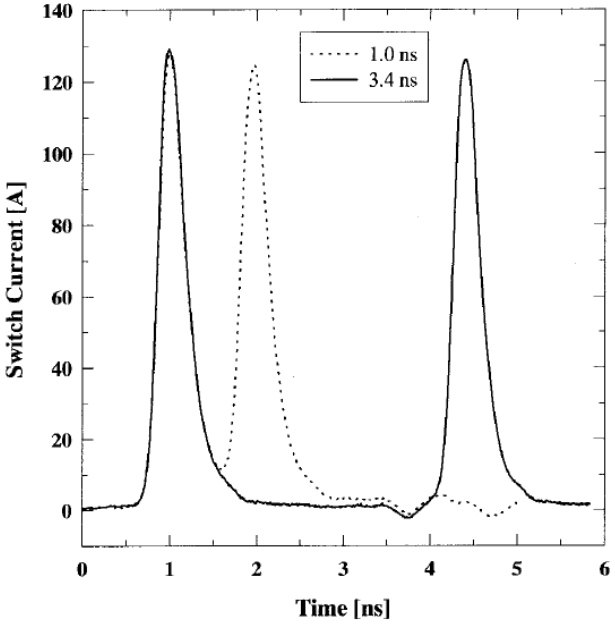
Direct RF Modulation Considerations

GaAs Bulk Optically Controlled Semiconductor Switch (BOSS)

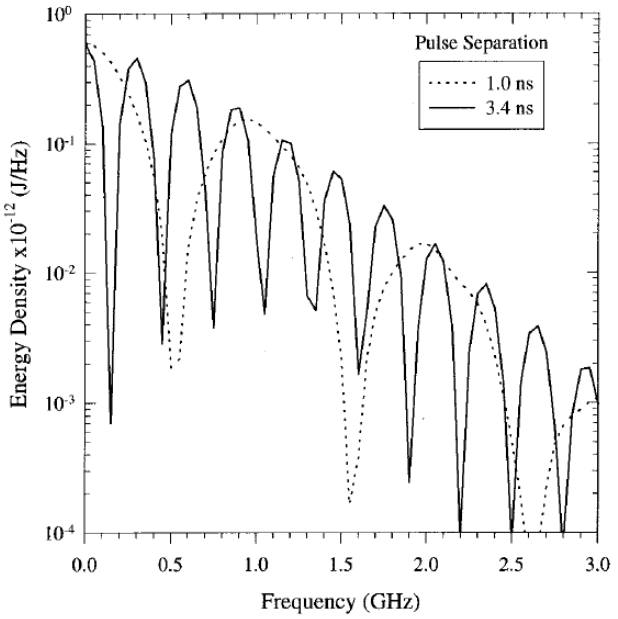
Test Setup



Two-burst Output at 16 kV



Energy Density Fourier Spectra



1 GHz – 1 ns pulse separation

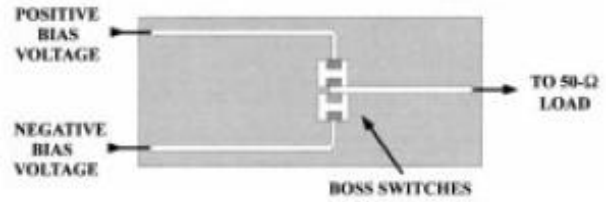
290 MHZ – 3.4 ns pulse separation

Stoudt, D. C., Richardson, M. A., & Peterkin, F. E. (1997). Bistable optically controlled semiconductor switches in a frequency-agile RF source. *IEEE Transactions on Plasma Science*, *25*(2), 131–137. https://doi.org/10.1109/27.602483

HPM: Technical Discussion/Progress

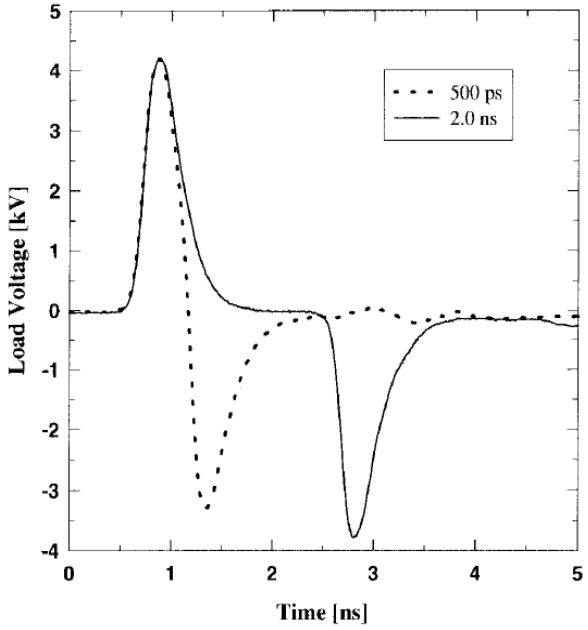
Direct RF Modulation Considerations

Microstrip Layout

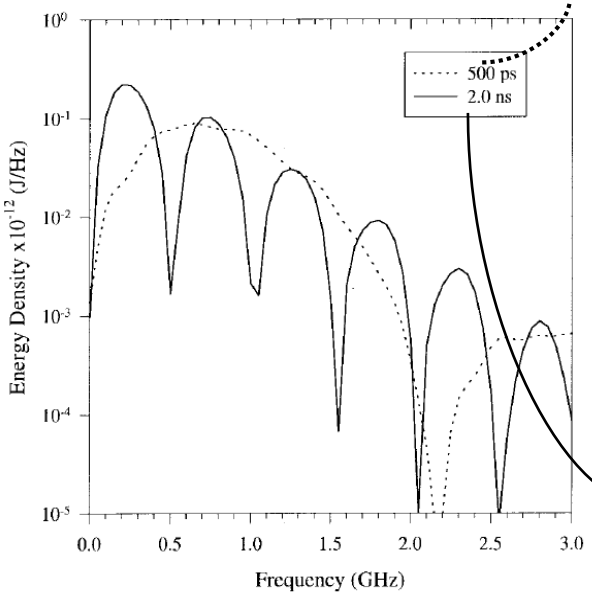


- Reduction in non-radiating DC content by activating second switch before the first one fully turned off (minor reduction in negative voltage)
- Time delay between two pulses determine spectrum envelope shape

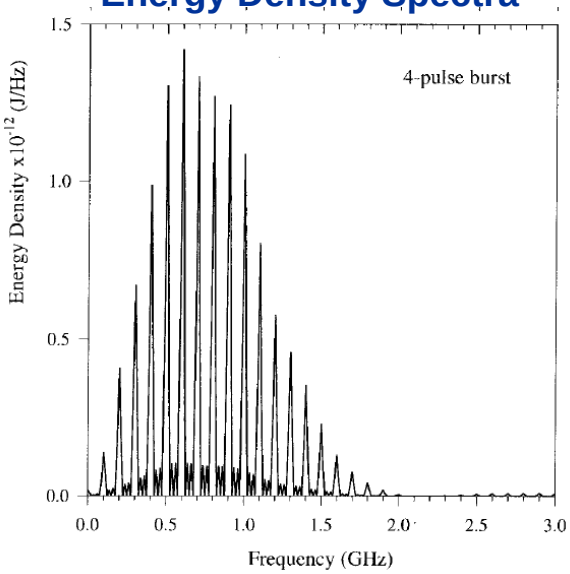
GaAs BOSS Output

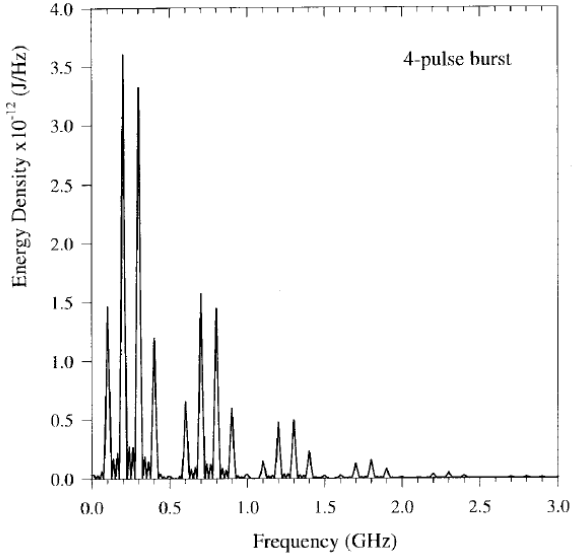


Fourier Spectra



Energy Density Spectra





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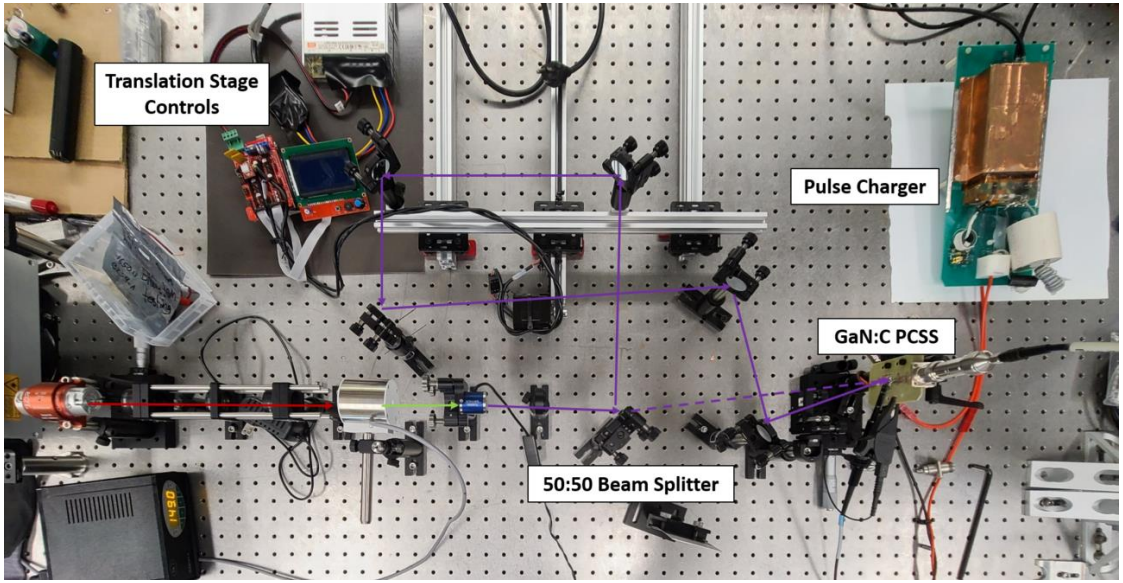
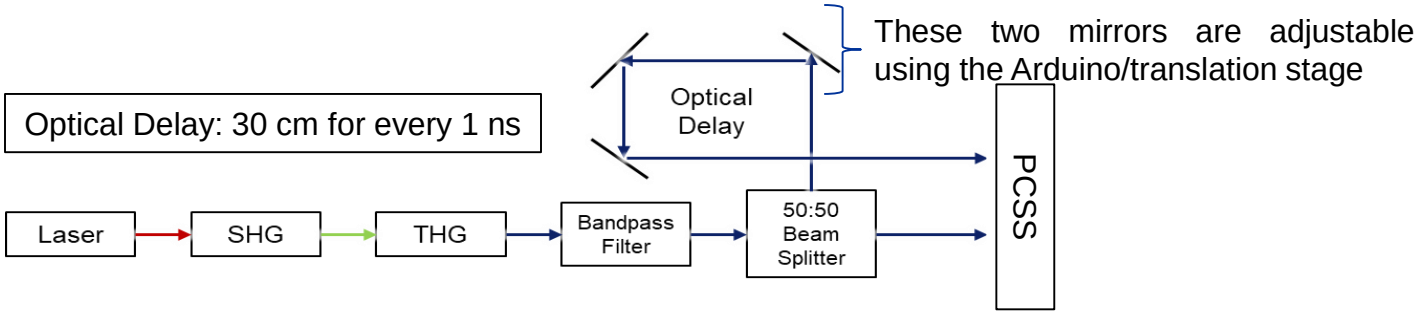
HPM: Technical Discussion/Progress

Direct RF Modulation Considerations

Optical Delay Setup



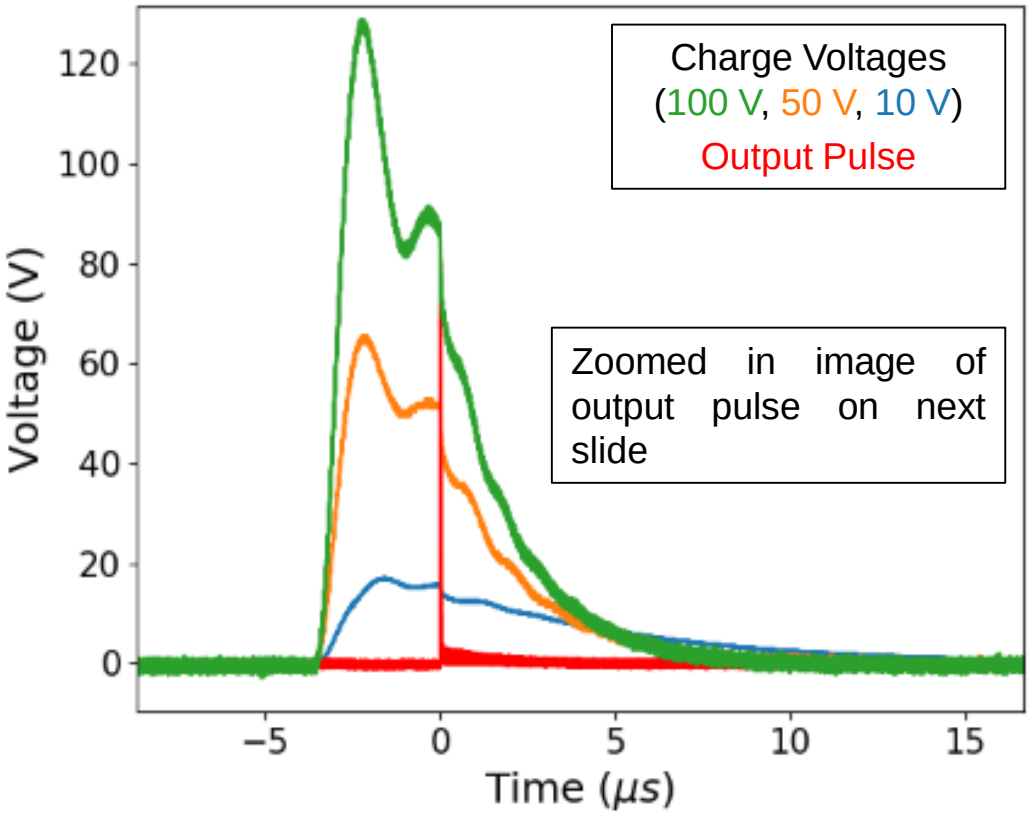
Optical Delay Schematic



HPM: Technical Discussion/Progress Cont'd

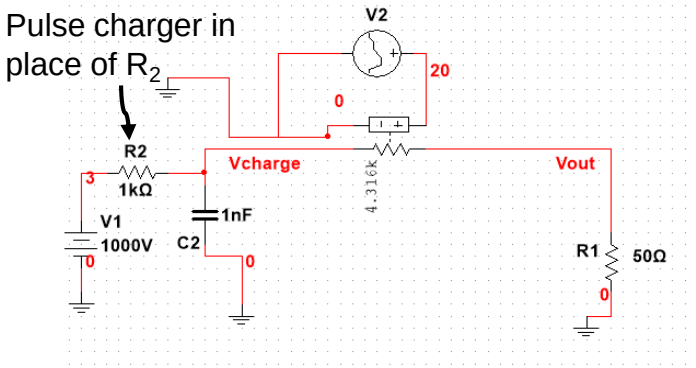
Direct RF Modulation Considerations

Zoomed out image of GaN:C charge voltage using pulse charger



Pulse Charger

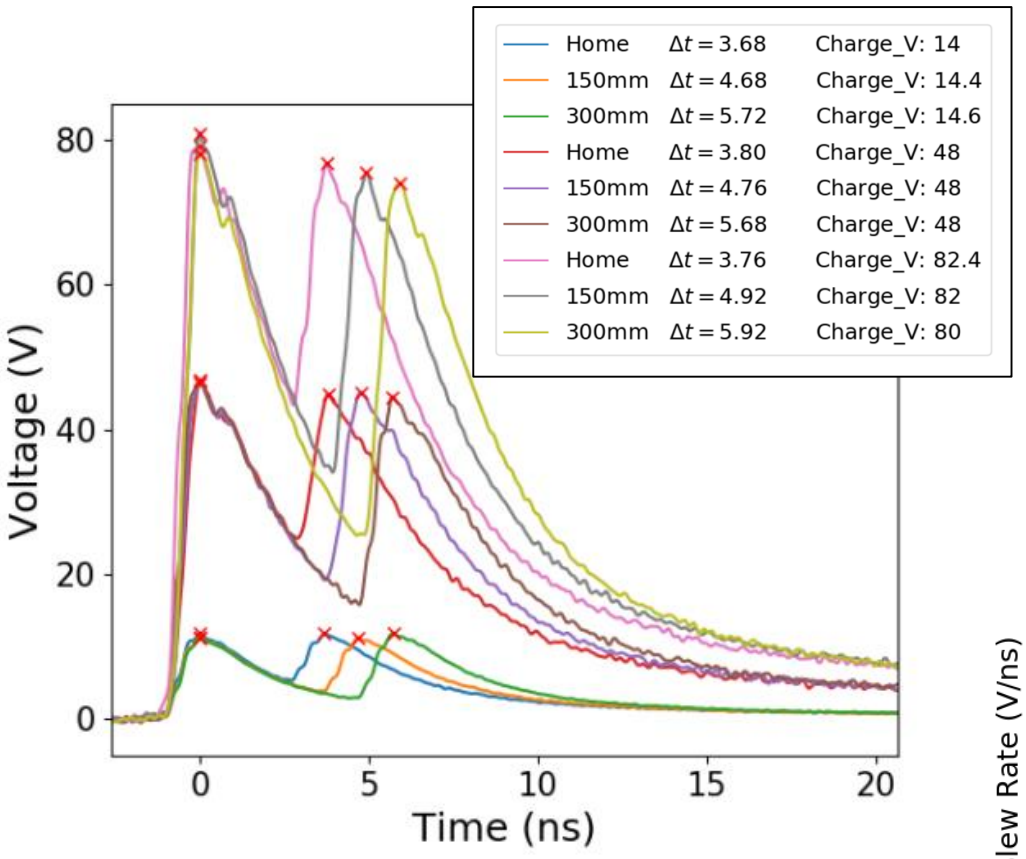
GaN PCSS Circuit



HPM: Technical Discussion/Progress Cont'd

Direct RF Modulation Considerations

Optical Delay at Different Charge Voltages



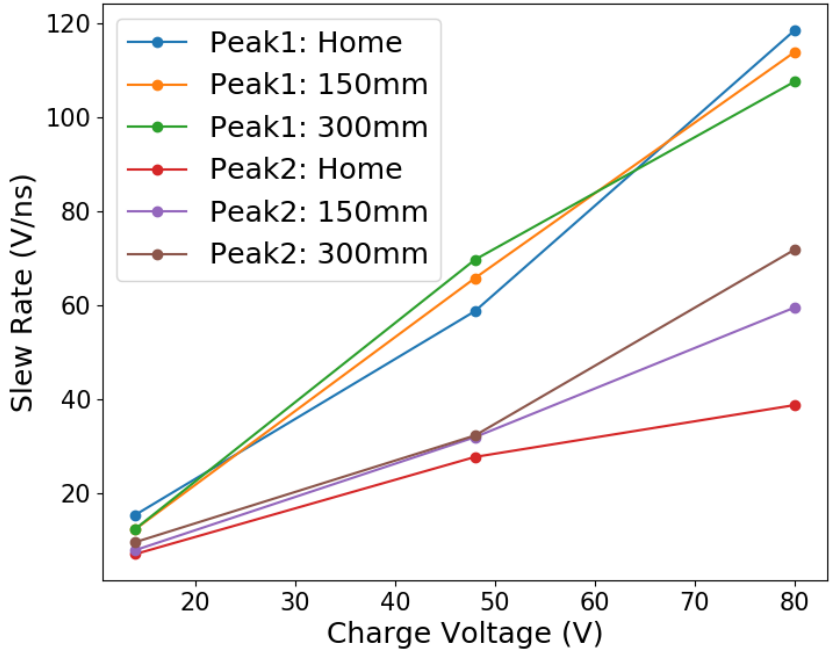
Average Δt:

- Home 3.75 ns
- Home + 150 mm 4.77 ns
- Home + 300 mm 5.77 ns

Avg R_{on} Differences (peak 1 and peak 2):

- 10 V: 1.14 Ω
- 50 V: 2.14 Ω
- 100 V: 2.70 Ω

Slew Rate by Charge Voltage



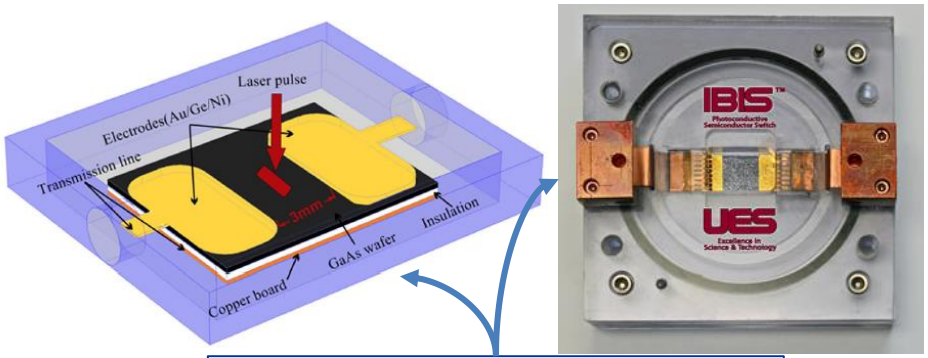
HPM: Future Work

Direct RF Modulation Considerations

Jan 2021:

High-voltage operation (ones-of-kV to start)

- Use Sylgard-184 to prevent flashover
- Repeat using SF6 and compare results



GaAs PCSS SF6 Chambers

Feb 2021:

RF unipolar modulation using wedge laser

Pulse Width: <1.5 ns
Pulse Energy: Up to 2 mJ
Rep Rate: Up to 2 kHz

April 2021:

RF bipolar modulation

- Using two GaN:C PCSSs
- Source a negative power supply

May 2021:

Complete study of recovery as a function of:

- gap lengths
- incident energies
- operating voltages

June 2021:

Repeat unipolar and bipolar RF modulation using the neoLASE (quicker rise time & shorter pulse width)

Pulse Width: 70 ps
Pulse Energy: Up to 250 µJ
Rep Rate: Up to 80 MHz

HPM: Sub-Project Research Objective

Direct RF Modulation Considerations

Pursuit of this goal will yield information that will benefit the scientific community, such as:

How do dopants affect:

- Carrier lifetime
- Breakdown field
- Responsivity
- Rise-time

Recovery time as a function of:

- Gap lengths
- Incident energies
- Operating voltages

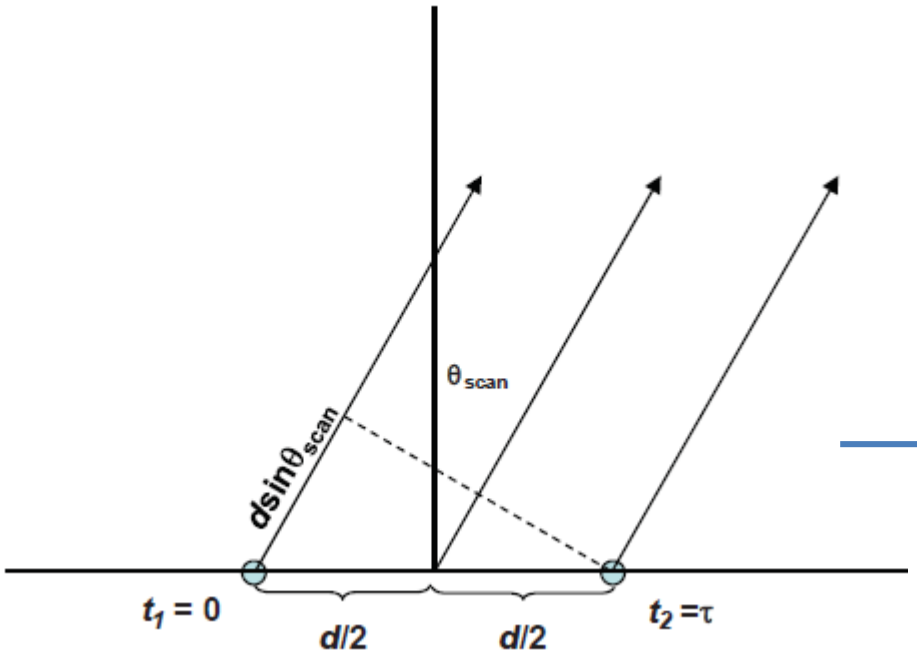
Agile RF frequency content:

- Time delay between pulses
- Operating voltages
- Bipolar vs unipolar modulation

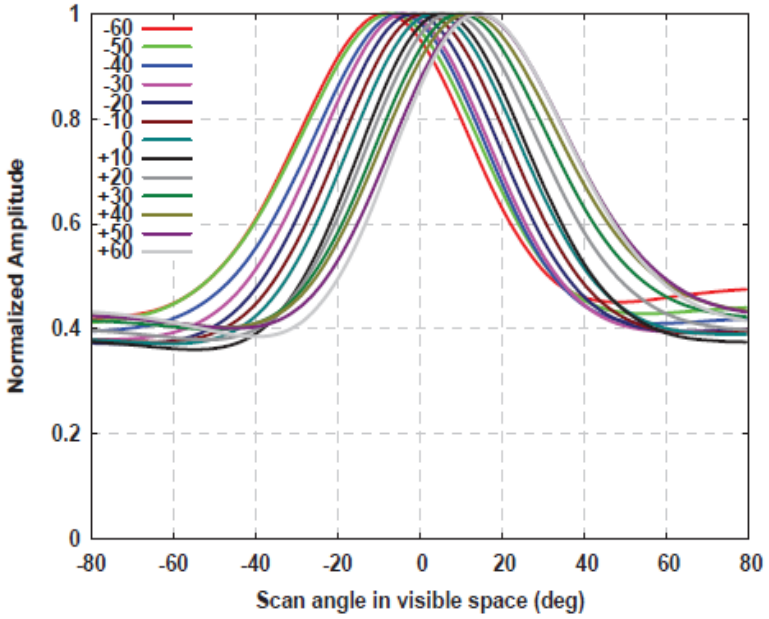
HPM: New Ideas / Opportunities

Direct RF Modulation Considerations

Time Delay RF Beam Steering



Steering Angle Example



- Time delay adjusted so that wave-fronts add constructively in far-field
- Can add additional devices for greater steering and power
- Study of jitter between devices necessary for optimal steering

https://www.spiedigitallibrary.org/conference-proceedings-of-spie/7311/73110X/Demonstration-of-enhanced-emission-and-time-delay-beam-steering-using/10.1117/12.819149.short

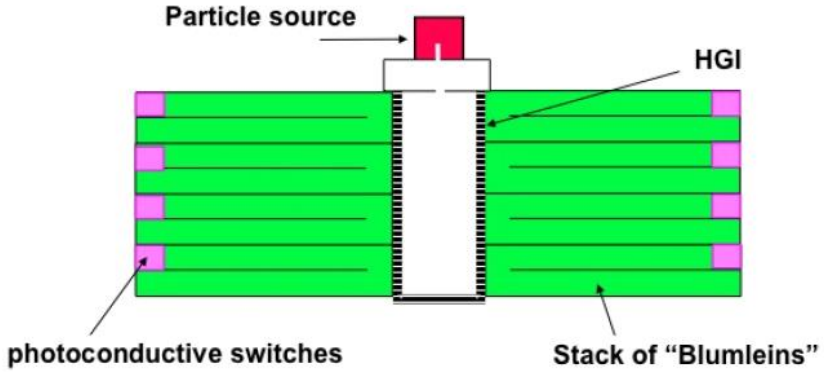
HPM: Broader Impact

Direct RF Modulation Considerations

RF Communication

Particle accelerator (Dielectric Wall Accelerator)

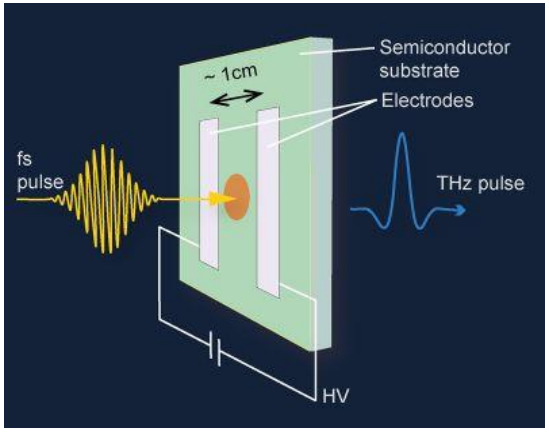
→ X-ray radiography and proton therapy



https://www.worldscientific.com/doi/epdf/10.1142/S1793626809000235

GaN Based Radar

THz generation in a more compact form and higher power for medical imaging



http://qcmd.mpsd.mpg.de/index.php/Broadband-Time-resolved-terahertz-spectroscopy.html

HPM: Conclusion

Direct RF Modulation Considerations

Goal: Reduce size and cost of PCSS RF generation system

Proposed Solution: Replace silicon PCSS with gallium nitride (GaN) PCSS to increase efficiency, reducing device size and thermal requirements; GaN's theoretical material properties allow for higher operating voltages, center frequencies, and operational temperatures, while also eliminating the need for pulse-shaping transmission lines through direct RF modulation using a laser/photon source.

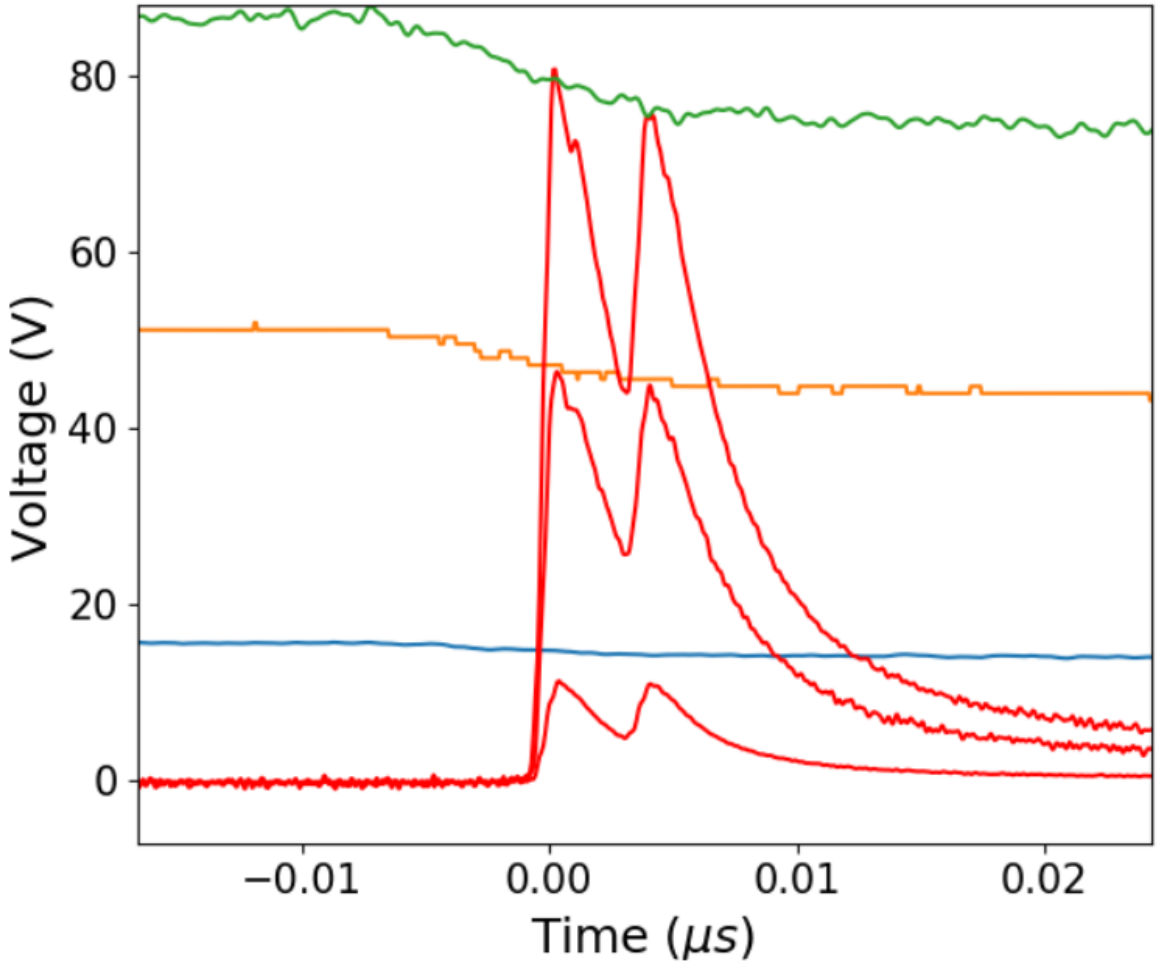
Progress:

- Replaced limiting circuit component on PCB with pulse charger to work towards HV operation
- Demonstrated tenability using GaN:C with spatial optical delay

Next Steps:

- Demonstrate multi-kV operation using GaN:C PCSS (1800 V currently)
- Show direct unipolar and bipolar RF generation with GaN:C
- Use neoLASE to achieve faster rise times and shorter pulse widths and higher switching frequencies

Extra Slides



FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

Bi-Annual Program Review

Correlation Studies Applied to a Semi-Conductor-Based Pulsed Power Source

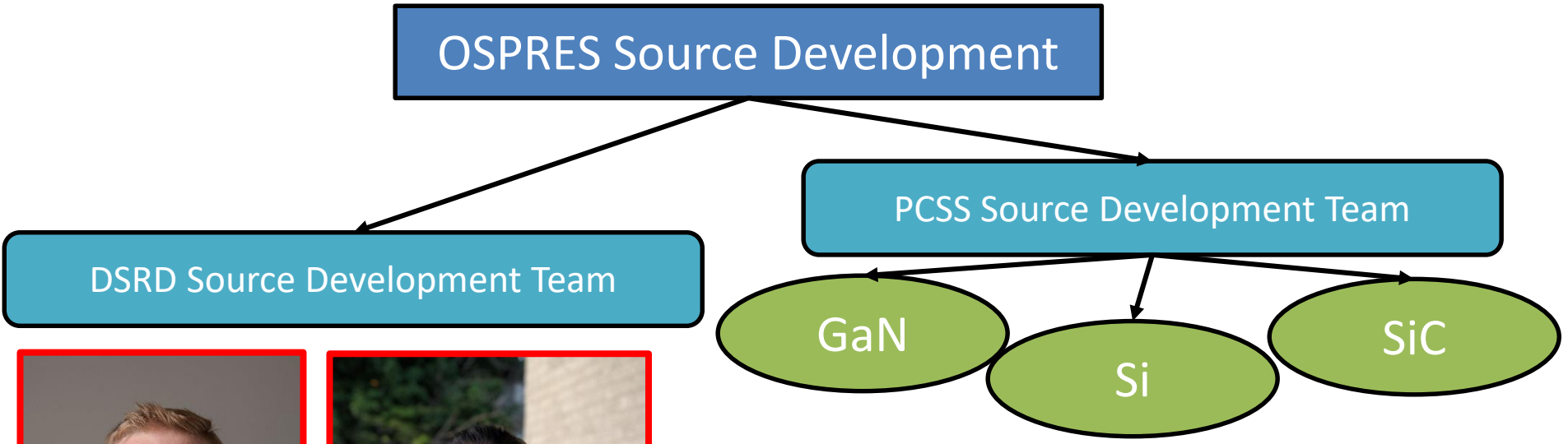
Nick Flippin, Research Consultant II, MIDE
flippinn-secure@umsystem.edu

09 DEC 2020
held via Zoom

Distribution A. Approved for public release.

OSPRES: DSRD Source Team

Drift Step-Recovery Diode Source Development



Nick Flippin
Research
Consultant II

Dario Labrada
Graduate Research
Assistant

Ancillary Team Members

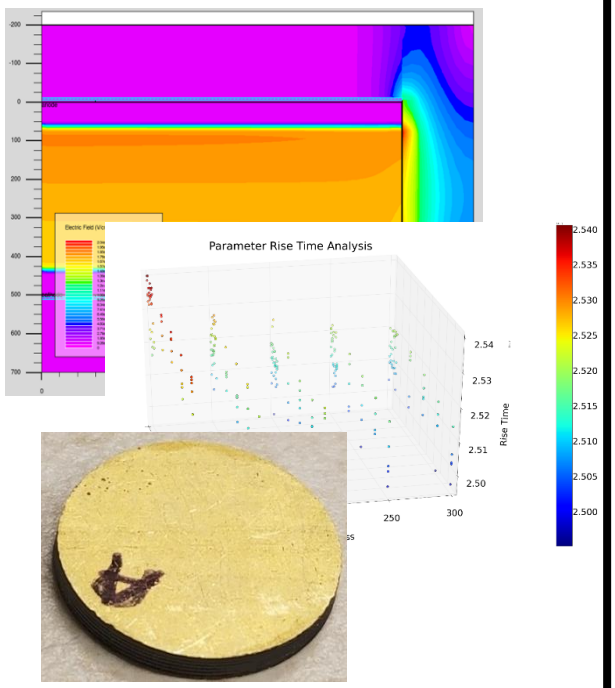
Noah Kramer

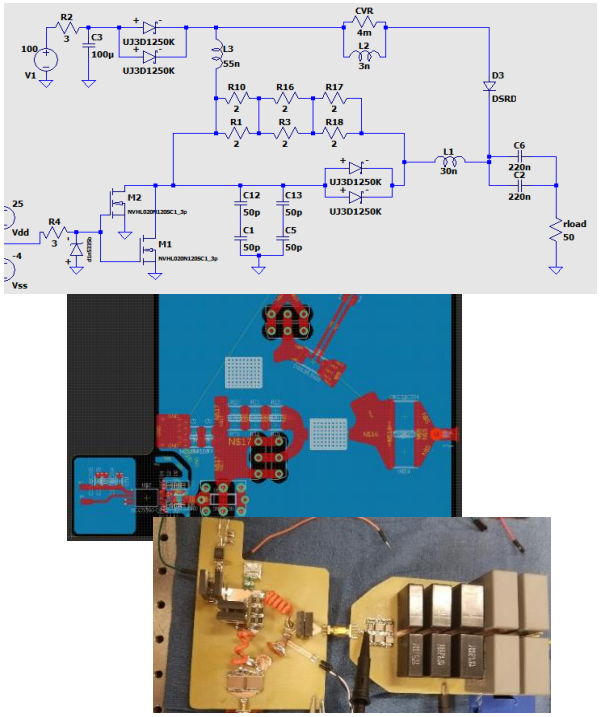
OSPRES: DSRD Source Team

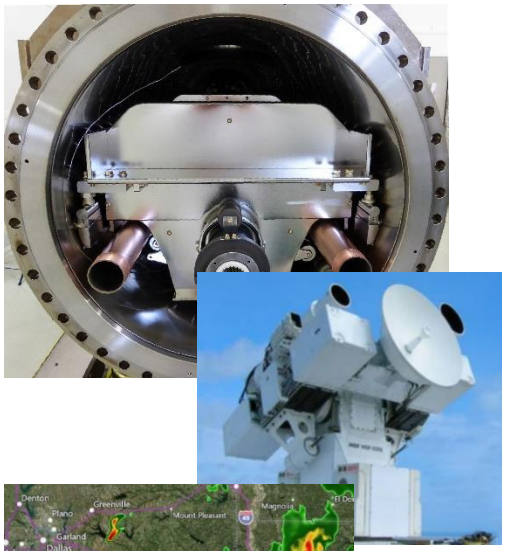
Drift Step-Recovery Diode Source Development

- **Main Objective:** *Use statistical learning methods to optimize and improve theoretical understanding for drift step-recovery diodes (DSRDs) and DSRD- based systems for high power RF applications.*

DSRD component design	DSRD pulse circuit design	DSRD system design







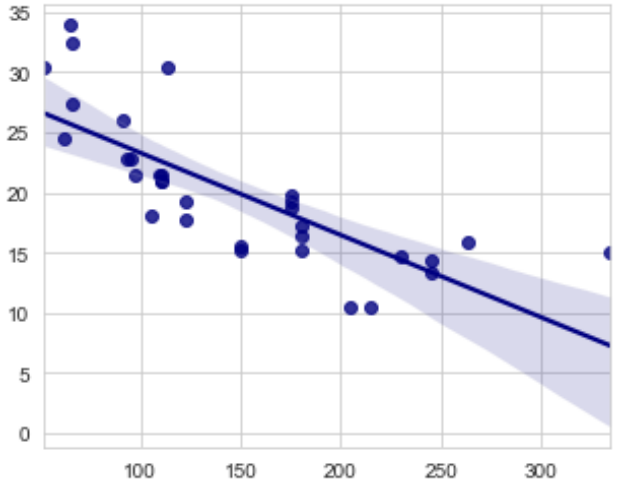
OSPRES: Statistical Learning Definitions

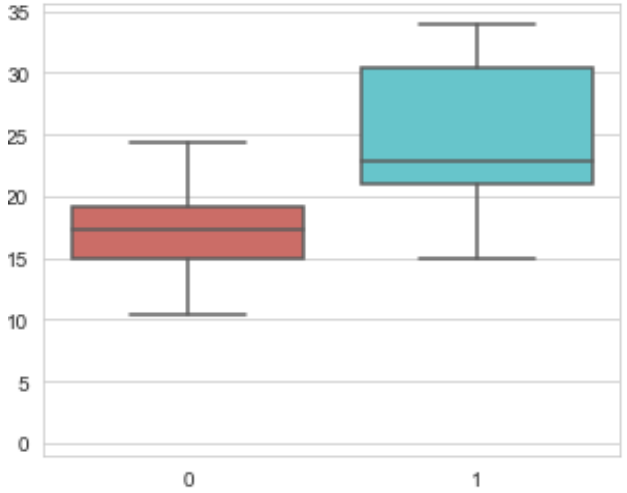
Drift Step-Recovery Diode Source Development

- **What is statistical learning?**
  - A framework for machine learning that utilizes statistical analysis to find solutions to the problem of finding predictive functions to best fit and describe data.

Supervised	Unsupervised
Uses input and output variables	Takes only input data
CHALLENGE: Parsing/classifying large datasets	CHALLENGE: Output is not known

- **Regression V. Classification?**

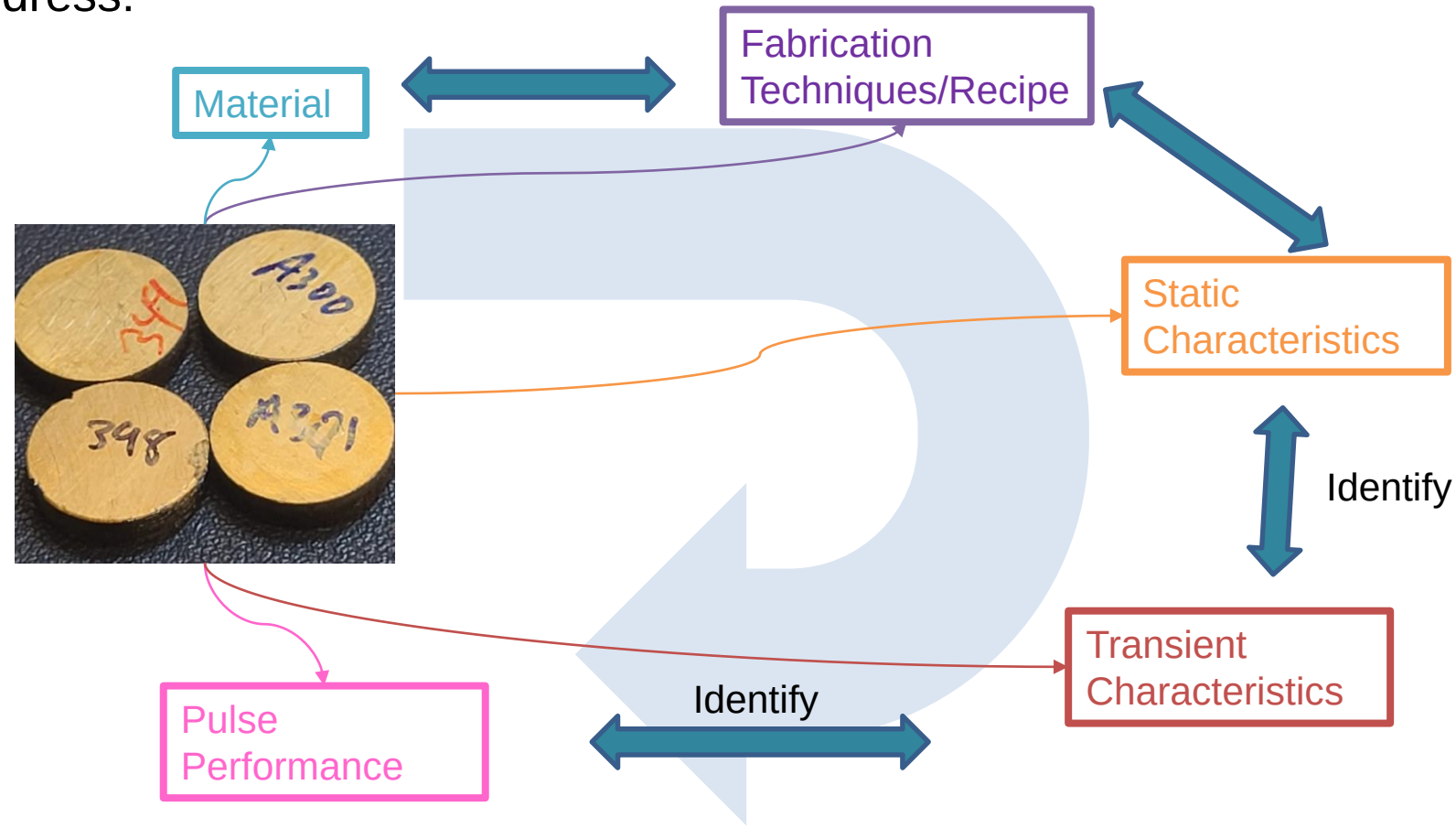




OSPRES: Technology Deficiency

Drift Step-Recovery Diode Source Development

Despite successful engineering of DSRDs that can interrupt kA's of current in sub-nanosecond time scales, there are questions we wish to address:



OSPRES: Technology Deficiency

Drift Step-Recovery Diode Source Development

Despite successful engineering of DSRDs that can interrupt kA's of current in sub-nanosecond time scales, there are questions we wish to address:

Material

Fabrication Techniques/Recipe

Can we **correlate** the three using statistical learning?

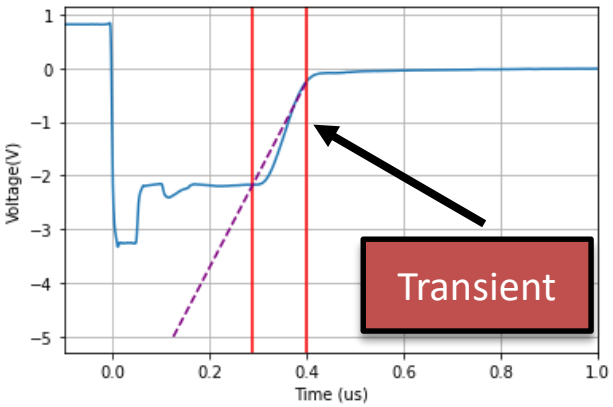
Static Characteristics

Transient Characteristics

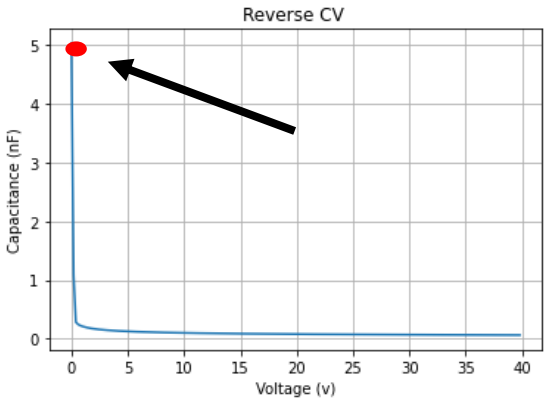
Pulse Performance

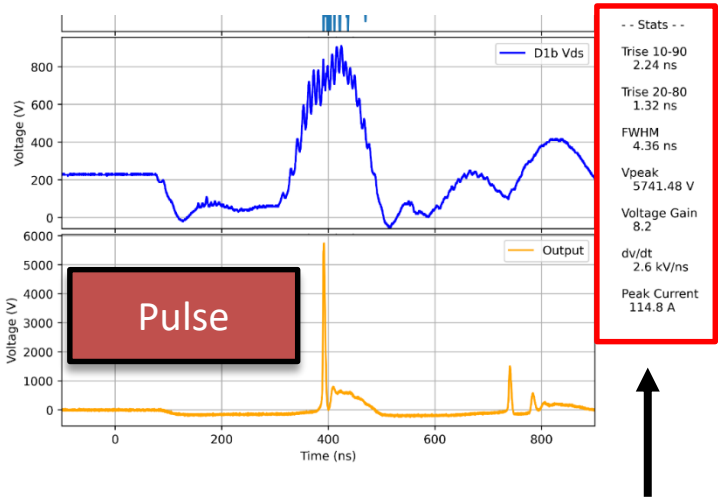
OSPRES: Addressing the Deficiencies

Drift Step-Recovery Diode Source Development



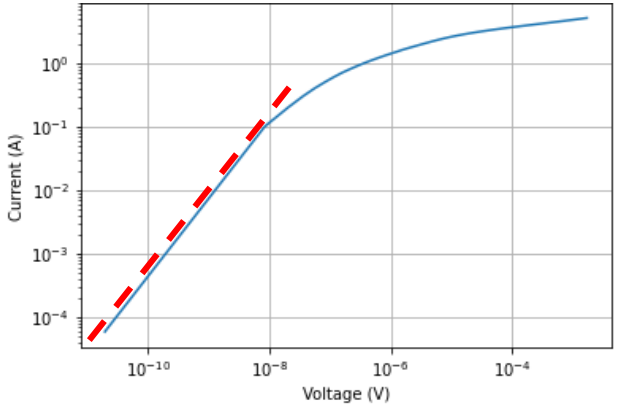
By selecting values (static, transient, pulse values) we can build a database of parameters (that can be added to)





python™

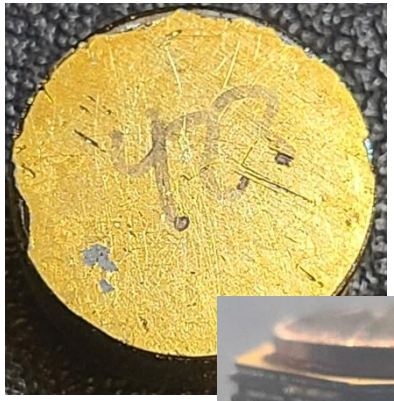
R

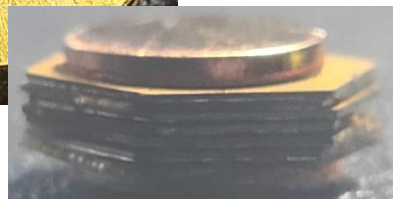


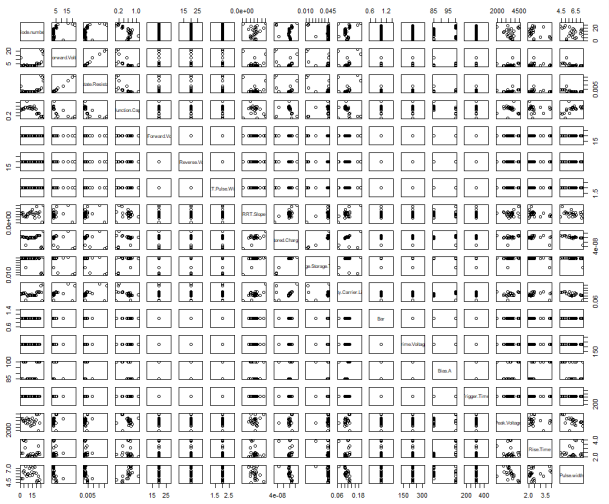
We select the orthogonal elements we believe to be correlated to the pulse data (i.e. RRT slope and rise time) and use regression and cross validation to validate statistically significant correlations.

ONR HPM Program Key Research Criteria - II

Drift Step-Recovery Diode Source Development







Qualitative Criteria:

Goal I: Optimize pulse performance of drift step-recovery diodes (DSRDs) using statistical quantitative analysis.

State-of-the-art (SOTA): Independent agencies using different characterization methods to determine quality of DSRDs being made.

Deficiency in SOTA: Optimization criteria relies heavily on simulation (with mixed results) and/or device characterization that has not been correlated to pulse performance.

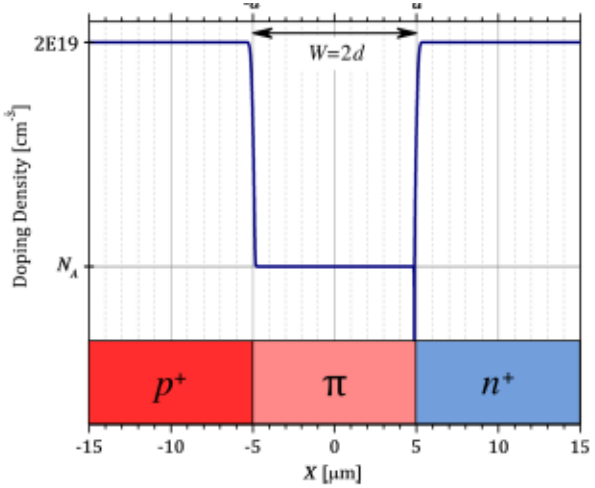
Proposed Solution: Collect and analyze all characterization data from all DSRDs in current inventory, find trends between static testing results and pulse results, relate trend back to manufacturing techniques.

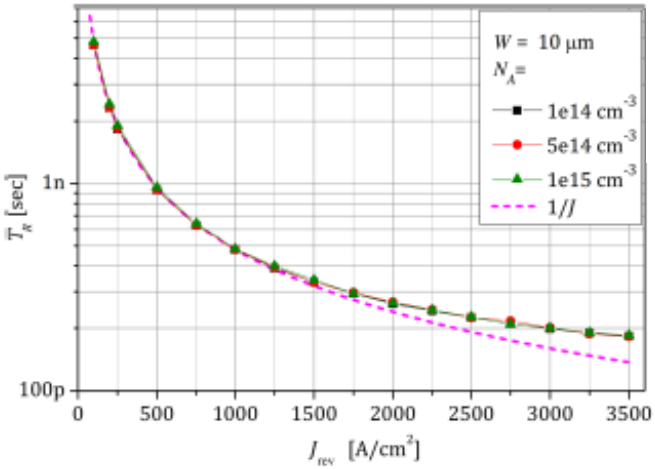
Program outcome: Of the DSRDs UMKC has on hand, all have been characterized (static & pulse), trends are currently being investigated using Python and R.

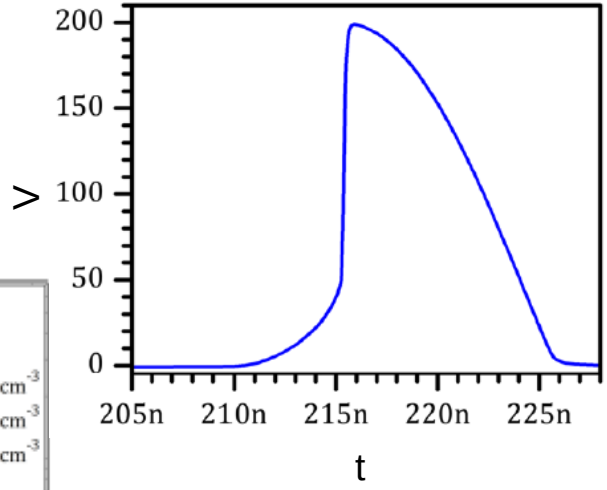
ONR HPM Program Key Research Criteria - I
Drift Step-Recovery Diode Source Development

<u>Quantitative</u> Criteria/Metrics for HPM source improvement:

Previously, **using simplified modeling techniques with TCAD tools**, investigations of pulse characteristics and static characteristics have been performed. Correlations were found between doping profile and current density by looking at the fast current interruption in the pulse data.





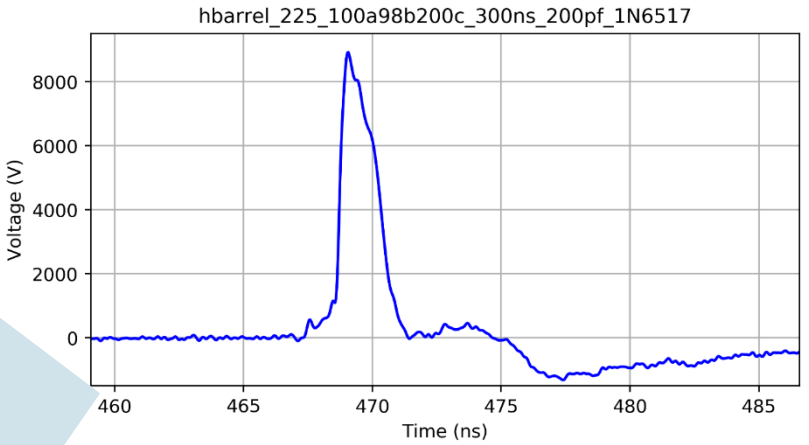


[1] Y. Sharabani, Y. Rosenwaks, and D. Eger, "Mechanism of fast current interruption in p-π-n diodes for nanosecond opening switches in high-voltage-pulse applications," *Phys. Rev. Appl.*, vol. 4, no. 1, pp. 1–14, 2015.

HPM: Sub-Project Research Objective

Drift Step-Recovery Diode Source Development

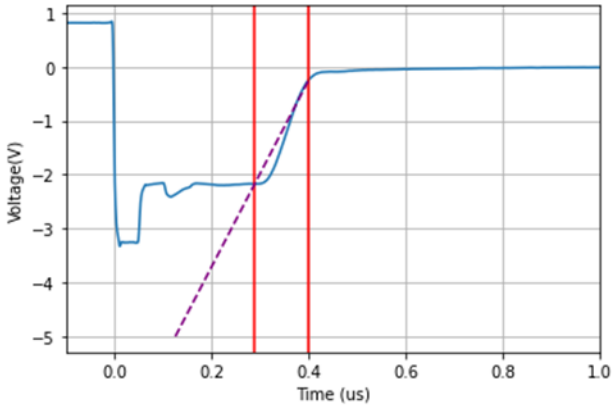
Scientific Objective: *Inform* DSRD design and fabrication techniques that will *optimize* the pulse performance in terms of: rise-time, peak voltage, FWHM, PRF, BRF and efficiency.



Pulse Performance

Static Characterization

DSRD Fabrication

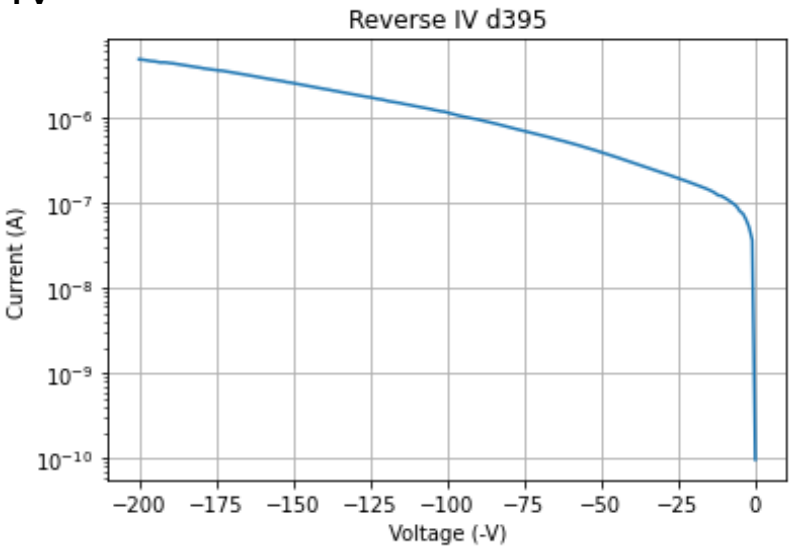


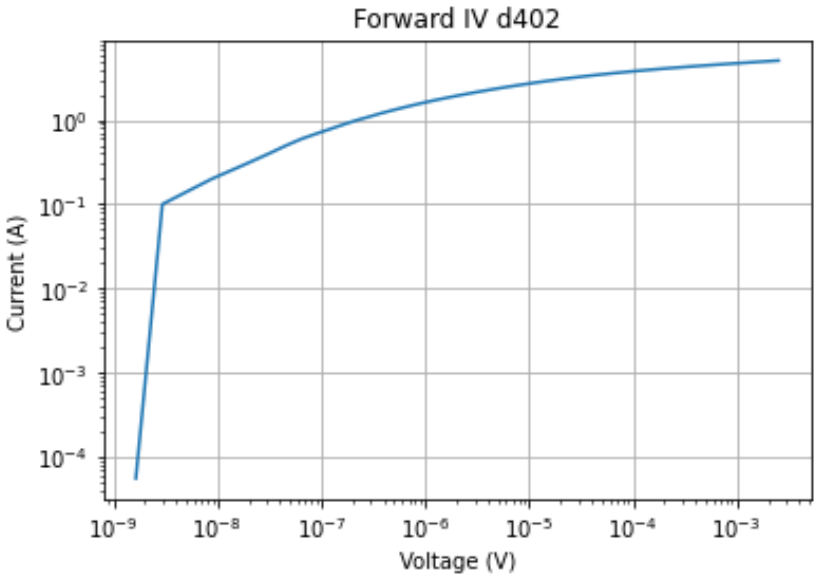
By finding a correlation between typical static characterization measurements, and pulse performance, we can make an educated inference between DSRD fabrication techniques and pulse performance.

HPM: Technical Discussion/Progress

Drift Step-Recovery Diode Source Development

IV





Focusing on the IV characteristics of a diode we can look at several characteristics:

- Turn-on Voltage
- Leakage Current
- Reverse Breakdown
- Space Charge limited current (in progress)
- On-state resistance

HPM: Technical Discussion/Progress

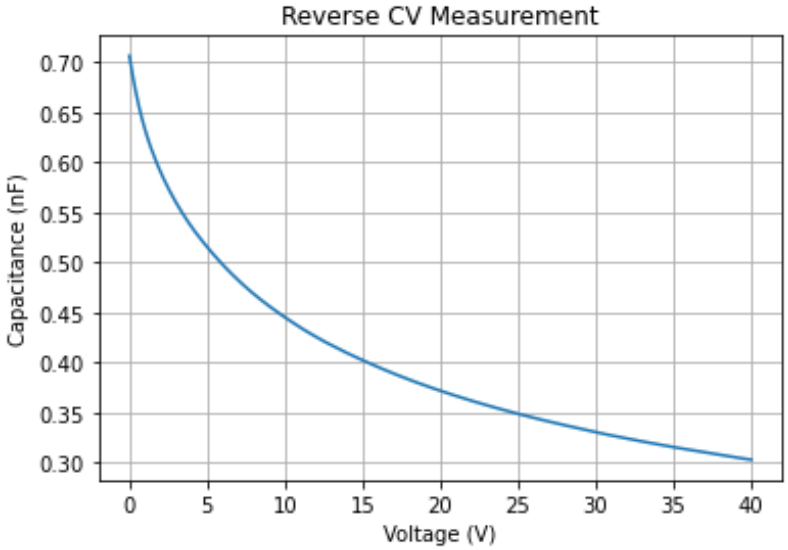
Drift Step-Recovery Diode Source Development

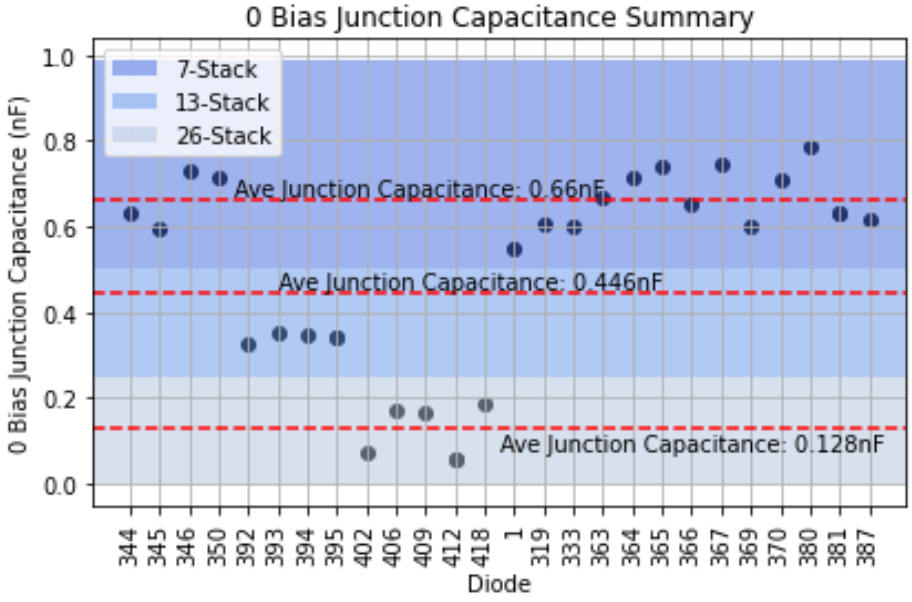
CV

The CV data provides 0-bias junction capacitance. Using this we can:

- cluster our findings,
- determine the average capacitance of each cluster,
- use the average capacitance to predict how many die are stacked in a device.
- use the summary plot below to try to make a qualitative correlation.

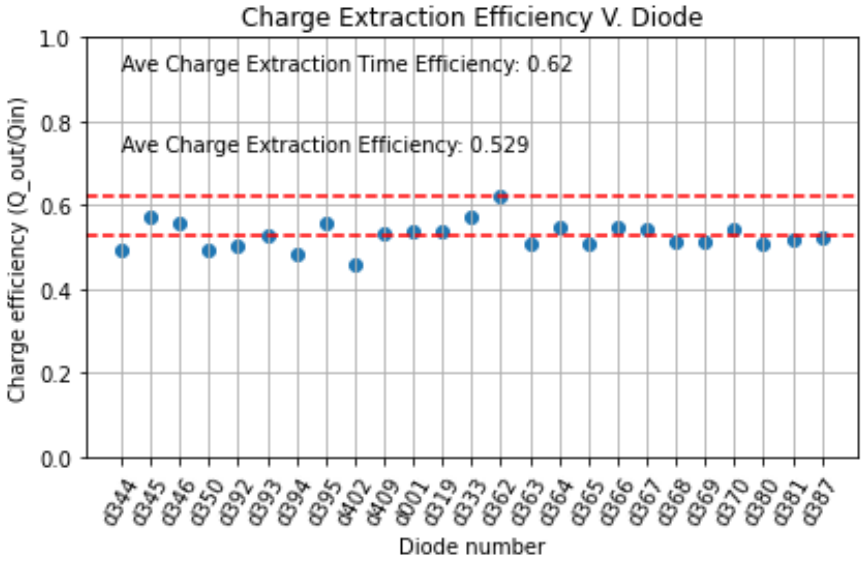
Ultimately this information has been used to create a more accurate SPICE model.





HPM: Technical Discussion/Progress

Drift Step-Recovery Diode Source Development

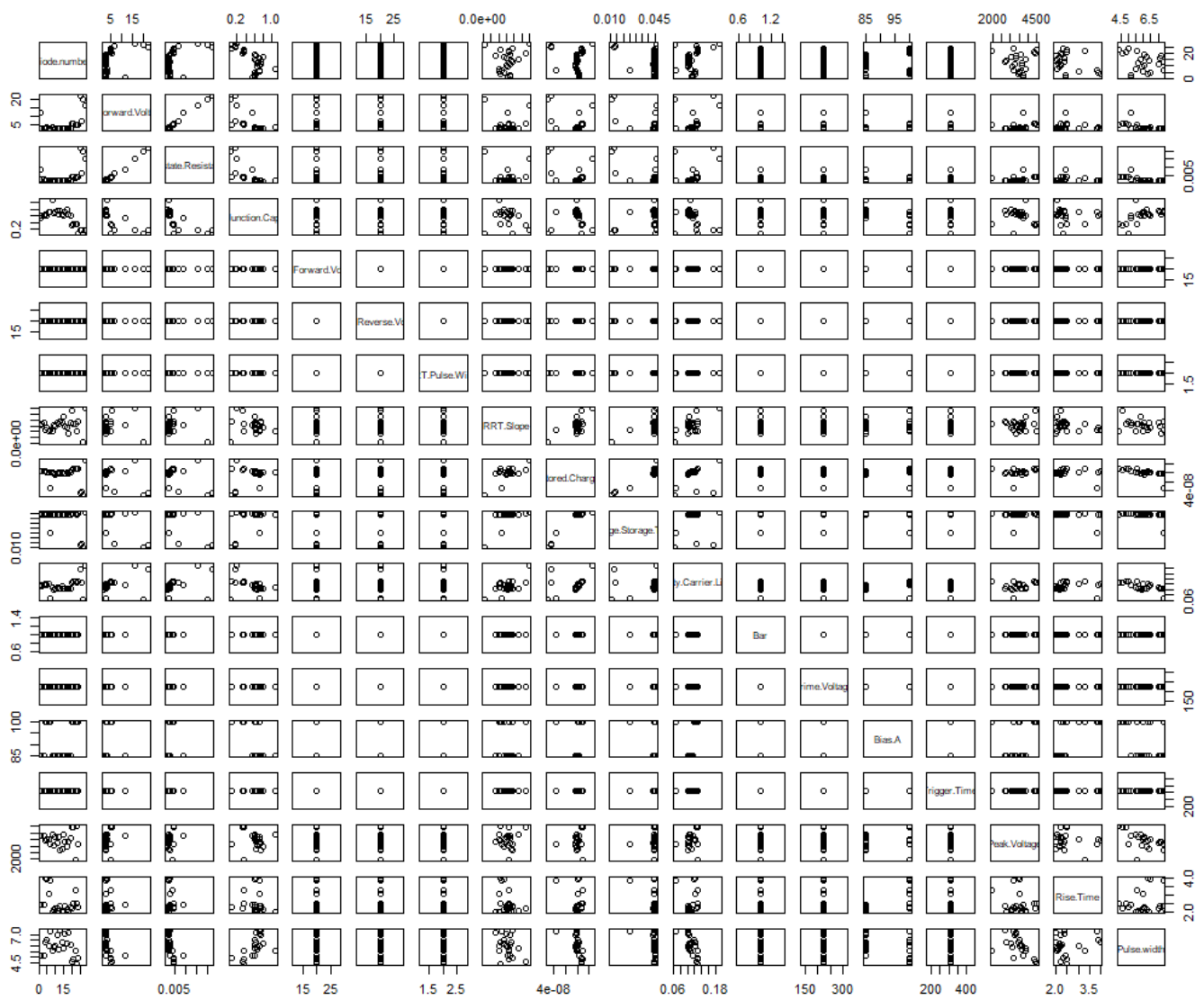


- Forward Pulse Width
- RRT Slope
- Stored Charge
- Charge Storage Time
- Charge Extraction Efficiency
- Charge Extraction Timing (what percent of the forward pump is the charge storage time)

By looking at the charge extraction efficiency (found using RRT data), and relating this to the forward and reverse pumping of the DSRD we can fine tune the L and C in the pulse circuit.

HPM: Research Objective Progress/Findings

Drift Step-Recovery Diode Source Development



Collect DSRD Characterization Data

Create Database of Inventory

Apply Statistical Analysis Methods

*** Currently data set is too small to generate any meaningful conclusions

HPM: Research Objective Progress/Findings

Drift Step-Recovery Diode Source Development

Collect DSRD Characterization Data

Create Database of Inventory

Apply Statistical Analysis Methods

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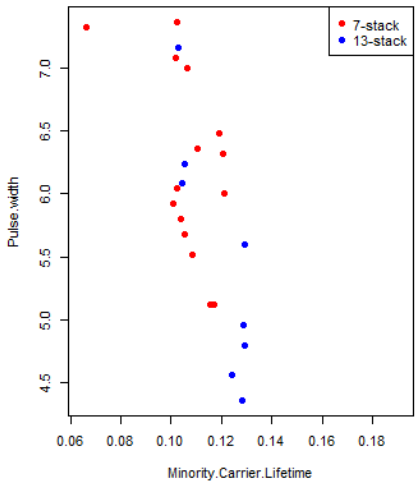
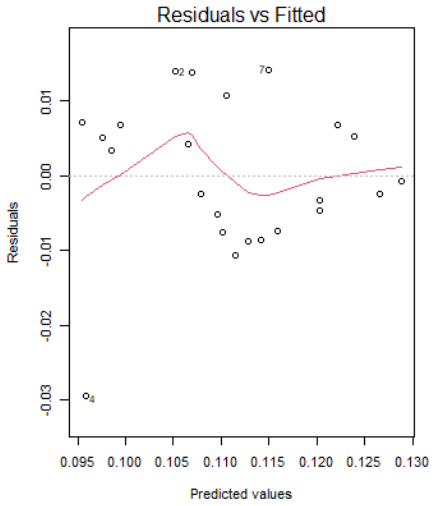
HPM: Research Objective Progress/Findings

Drift Step-Recovery Diode Source Development






```
Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  0.177217   0.015075  11.756 1.06e-10 ***
Pulse.width -0.011112   0.002507  -4.432 0.000231 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

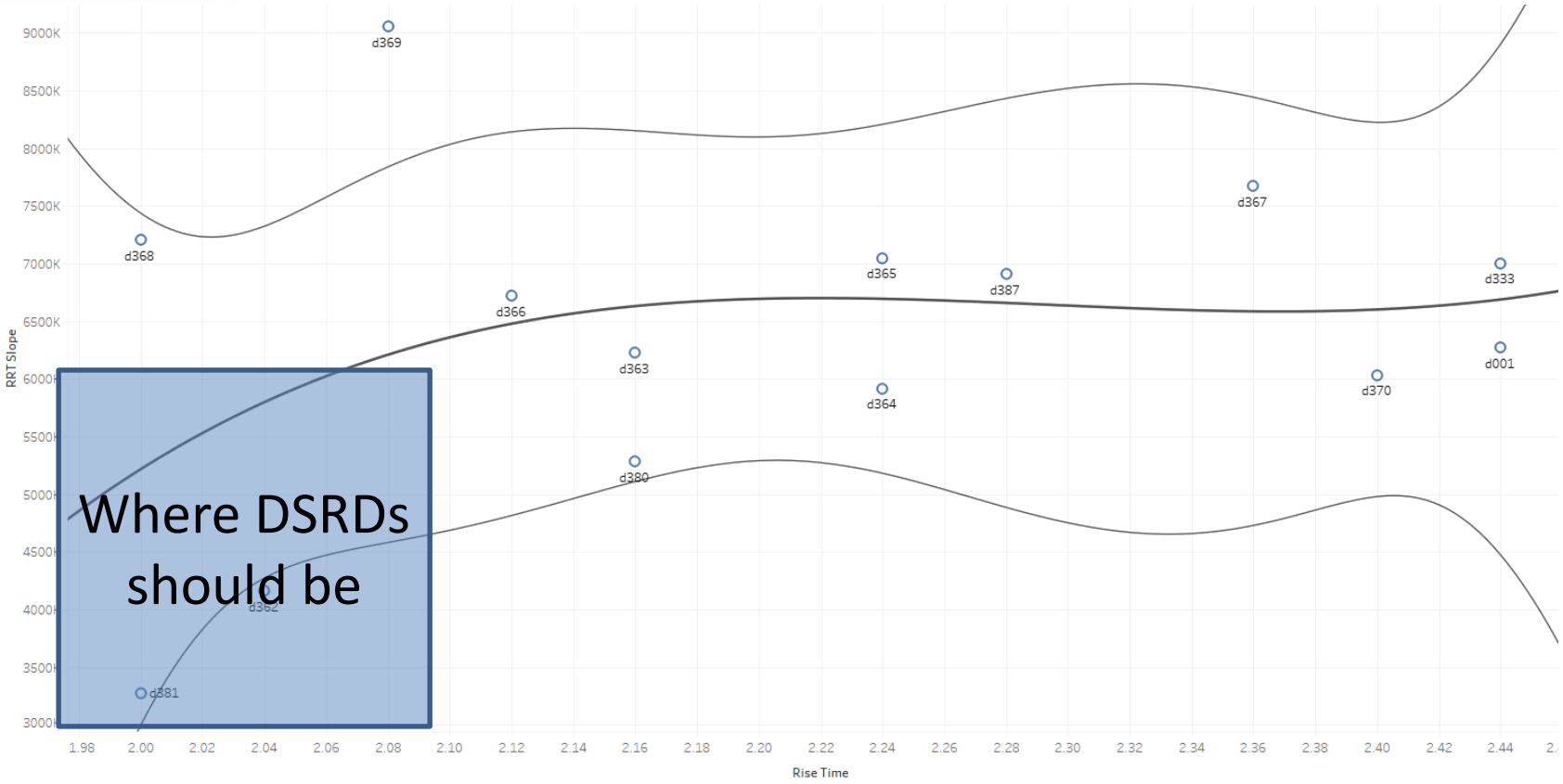
Based on the scatter matrix on the previous slide we can determine which parameters (along the diagonal) appear to be correlated to each other.

Here **Minority Carrier Lifetime** (found using reverse recovery measurements) has a **strong (statistically significant) correlation** with **Pulse Width** (found using pulse testing).

The next step would be using this model to predict the pulse width from a minority carrier lifetime value (this value depends heavily on the doping profile of the diode)

HPM: Research Objective Progress/Findings

Drift Step-Recovery Diode Source Development



Here the reverse recovery slope and pulse rise time are plotted (for LLNL 7-stacks). The fit is a 3 degree polynomial function that appears to fit the data relatively well (only 2 data points are out of the confidence interval). However, this model is based on a **data set that is extremely small** and has a **very low statistical significance** (little to no correlation).

HPM: New Ideas / Opportunities

Drift Step-Recovery Diode Source Development

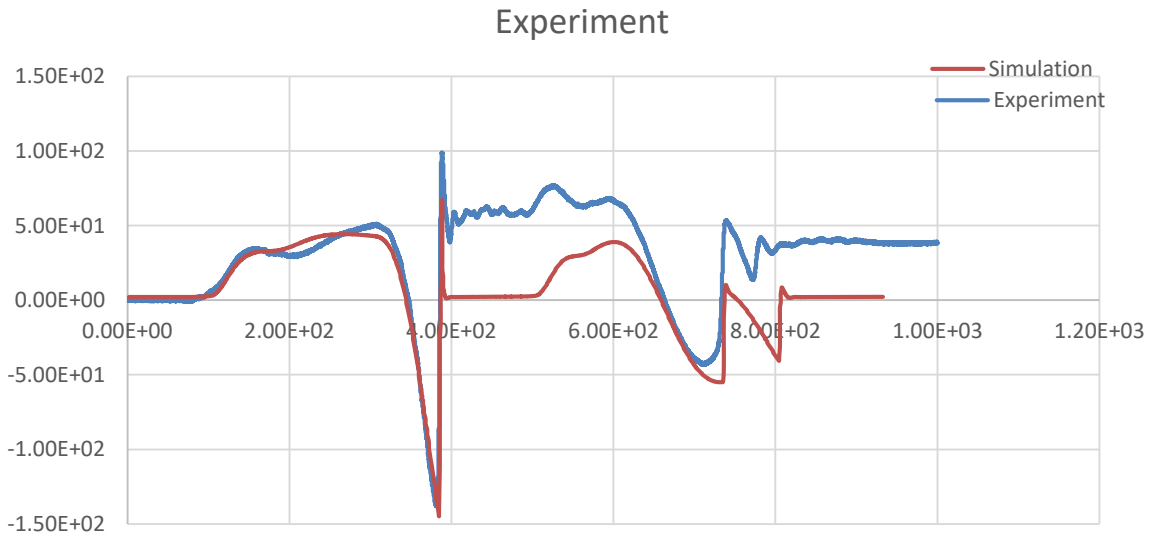
What can we do with this new approach?

Guess and Check?

Incomplete models in simulations

Statistically backed manufacturing leading to higher yields and LESS uncertainty of diode performance.

More realistic models that improve circuit design.



HPM: Conclusions

Drift Step-Recovery Diode Source Development

As of **Today**:

We have 28 diodes in our data set, with 18 measured/recorded values. Very few correlations can be made with the limited amount of data points.

Next Steps:

Option 1: Expand our data set to include **important manufacturing details** (i.e. material type, intrinsic impurity concentration, thickness, bonding method, etc.)

Option 2: Expand our data set to include **ALL DSRDs** from all manufacturers and increase the number of data points we have to make clearer correlations.

Resources Needed:

- More diodes for testing,
- More manufacturing information,
- Universal test matrix, everyone can perform and add to the DSRD database.

Milestones:

- Build statistical analysis tool for widespread use
- Add manufacturing data including: resistivity, FZ or CZ, material concentrations (O, C, S), dicing method, bonding method, etc.
- Make final optimization recommendations to improve DSRD peak voltage to 15-20 kV, and voltage rise rates of 10kV/ns.

FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

Bi-Annual Program Review

Heat Transfer Potential and Pragmatism from Jet Impingement

Roy Allen, Lead Mechanical Engineer, MIDE
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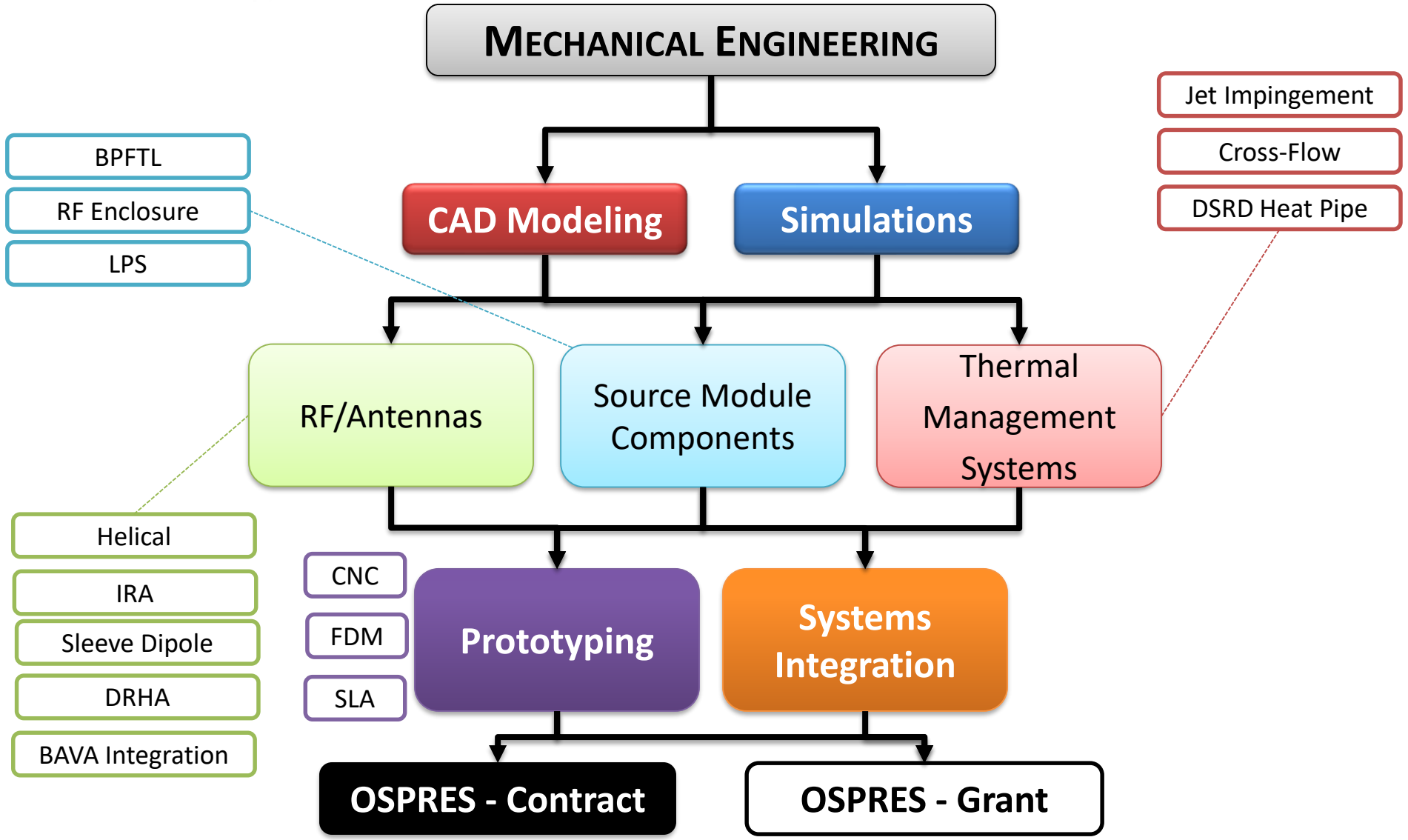
09 DEC 2020
held via Zoom

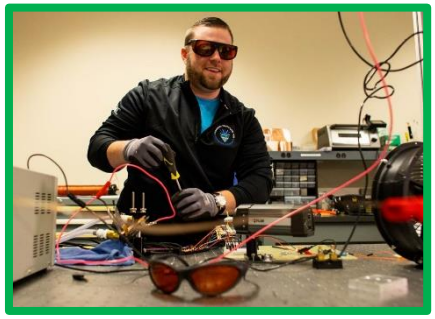
Distribution A. Approved for public release.

OSPRES: Mechanical Engineering Group



OSPRES: Thermal Management Group

Jet Impingement - TMS



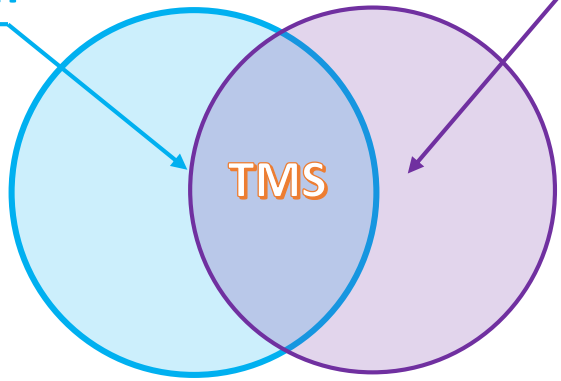
Roy Allen
Lead Mechanical Engineer

Sarvenaz Sobhansarbandi
Asst. Prof. of Mechanical Engineering

Jordan Berg
Master Student

Modeling and Experimentation

- ✓ Modeling of the TMS with SolidWorks
- ✓ Device fabrication



Modeling and Thermal Analysis

- ✓ Modeling of the TMS with ANSYS Fluent
- ✓ Thermal Analysis of HTF with DSC and TGA
- ✓ TMS Design/Materials Optimization

OSPRES: Thermal Management Group

Jet Impingement - TMS

What is the necessity of increased cooling performance?

- Goal: Increasing Naval assets protection efficacy at range with HPM-based sources.
  - Requires increasing at least one of the HPM source's waveform parameters (e.g., PRF, shot count).
  - Results in an increase in average power.

- What's the catch? Traditional, laminar-flow-based cooling technologies are limited in their ability to compensate average-power dissipation >1-kW (i.e., >1-GW/m3 as cooling density) – specifically, the thermal load byproduct – of HPM-based sources within electronically-steered arrays;

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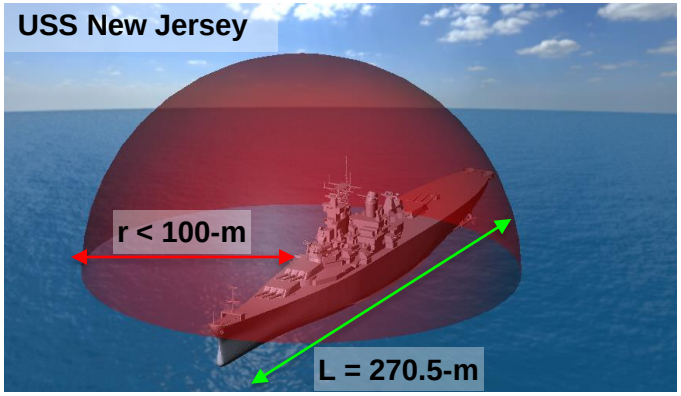
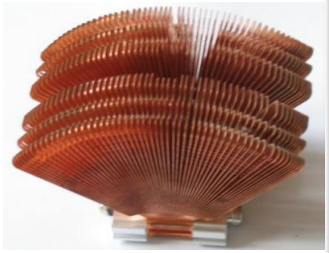
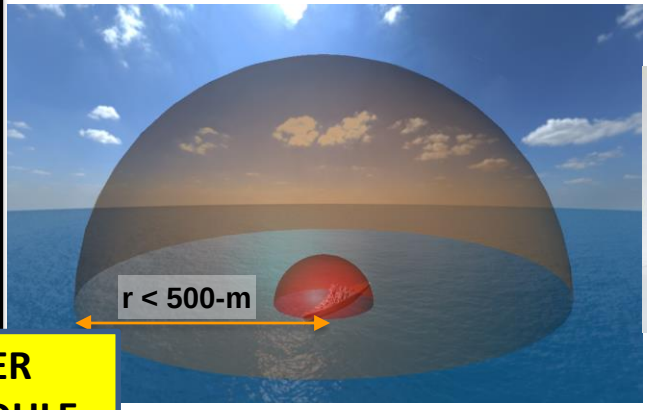
Jet Impingement - TMS

TMS Class 1: Passive Cooling
< 10-W (0.1-W/cm^3) < 100-m



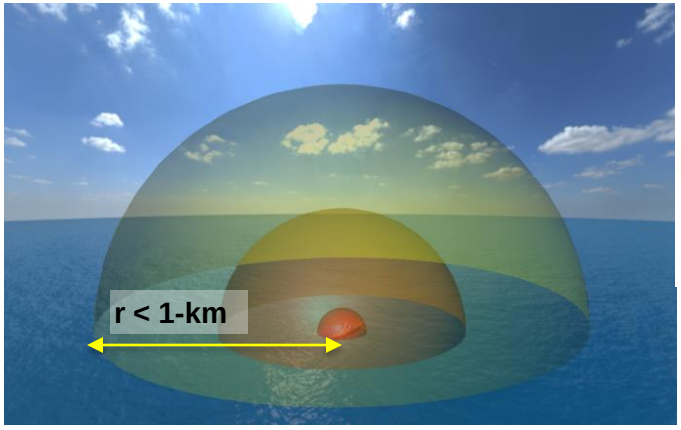


TMS Class 2: Passive Multi-Phase
< 100-W (1-W/cm^3) < 500-m



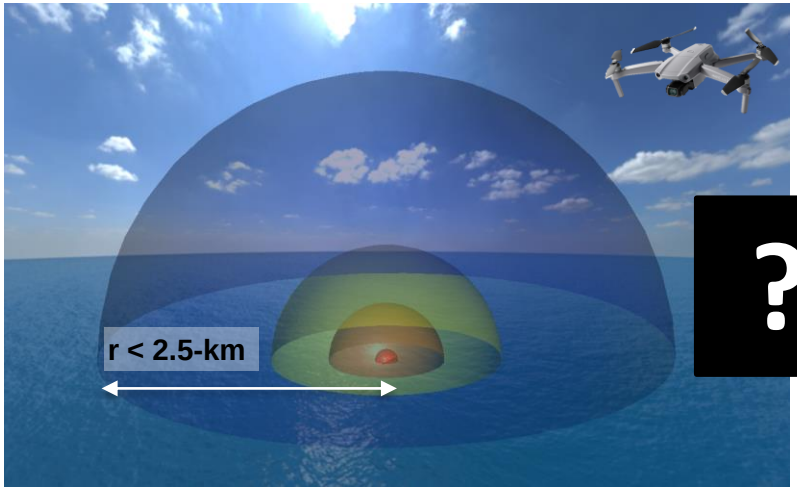
PER MODULE BASIS

TMS Class 3: Active Single-Phase/Laminar
< 500-W (5-W/cm^3) < 1-km



Traditional TMS's methods limit

TMS Class 4: Active S-P Turbulent
>1-kW (10-W/cm^3) > 2.5-km



ONR HPM Program Key Research Criteria - I

Jet Impingement - TMS

Qualitative Criteria:

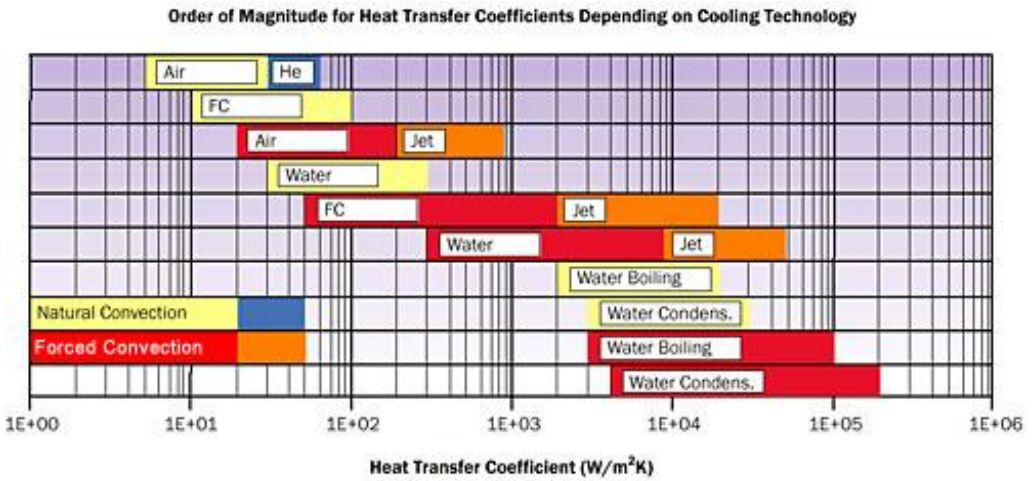
Primary Goal: Develop a JI-based TMS to compensate average-power dissipation >1-kW (i.e., >1-GW/m3 as cooling density).

State-of-the-art (SOTA): high-power electronics employing JI-TMS's have achieved 10's-of-kW of average-power handling capabilities.

Deficiency in SOTA: chiller/pump system's require extreme pressures (100's-of-psi) to achieve optimal flowrate performance and cooling metrics, low SWaP-C[2] fidelity for Navy afloat missions.

Proposed Solution: develop a JI-TMS to handle > 1-kW while maintaining HPM-based solid-state source temperature < 80°C, while not exceeding 100's of psi within the system.

Program outcome: *Our current progress suggests a pressure drop reduction by a factor of at least 3, with a possible PCSS temperature of* 53°C *at 200 Watts average power.*



OSPRES: Thermal Management Group

Jet Impingement - TMS

Risks:

- JI requires pumping fluid at high-pressures (> laminar-flow systems of equivalent size) which can be increase susceptibility for leaks to occur.
- Chiller/pump unit's volume may counteract SWaP fidelity (i.e., the higher the pressure the bigger the pump).

Payoffs:

- Increase cooling form-factor (> 1-GW/m^3) to 5× > traditional cooling techniques.
- The JI-TMS can be scaled & affixed to cool any heated surface.

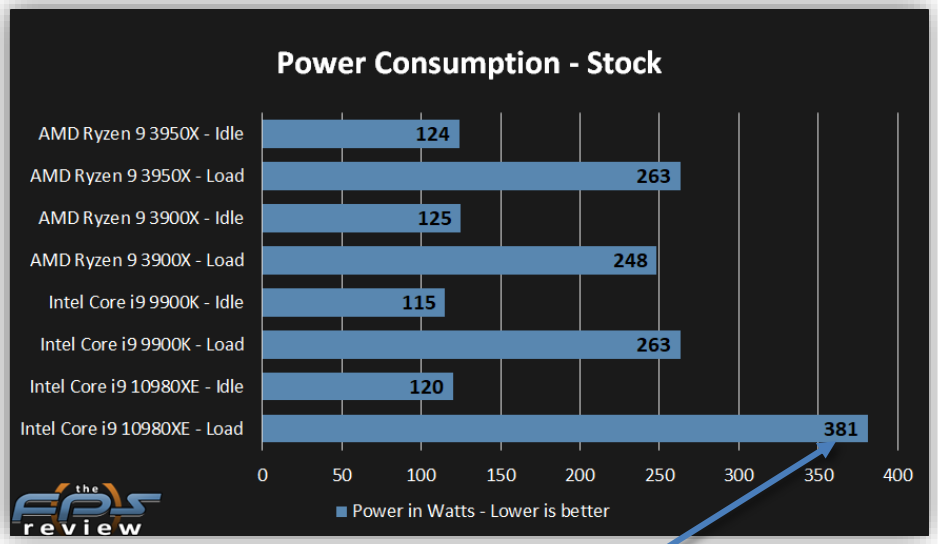
Challenges:

- Minimizing pressure drop requirements while maintaining or improving cooling performance and without increasing system's volume.

HPM: Broader Impact

Jet Impingement - TMS

- ✓ Creating a high-performance liquid cooled TMS could be used for many high-power-density electronics, especially next gen CPU's and GPU's.
- ✓ CPU and GPU clock speed is analogous to HPM Burst Profile



A Major Limiting Factor for chip performance is the thermal limitation.

Sooner rather than later, **more powerful cooling will be necessary to increase performance**

Over 350 Watts needed for CPU heat dissipation!

Lower heat flux than the SiPCSS

- ➢ Along with semiconductors and chips, **any surface** that exceeds a desired temperature can utilize the deigned JI-TMS to maintain desire operating conditions.

HPM: Sub-Project Research Objective

Jet Impingement - TMS

So, **what** is our primary objective?

Understand and implement the highest performance cooling technologies with a SWaP-C optimization mindset

Pressure

Viscosity

Geometry

Materials

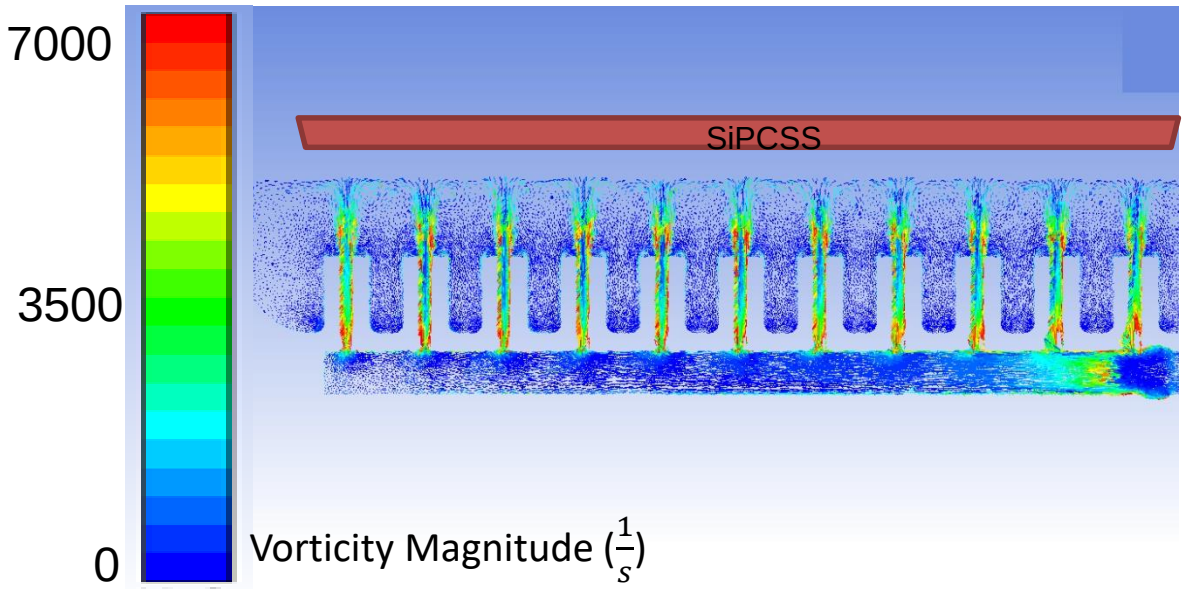
With proper knowledge and practice, we can push the SOTA toward modular designed TMS with $^{GW}/_{m^3}$ cooling densities.

OSPRES: Thermal Management Group

Jet Impingement - TMS

This Time Last Year

Property	Magnitude	Units
Pressure Drop	>> 1,500	PSI
Vorticity	7000	$1/s$
Convective heat transfer coef.	2200	$\frac{w}{m^2 \cdot K}$
Max. PCSS Temperature @ 200 W	67.85	°C



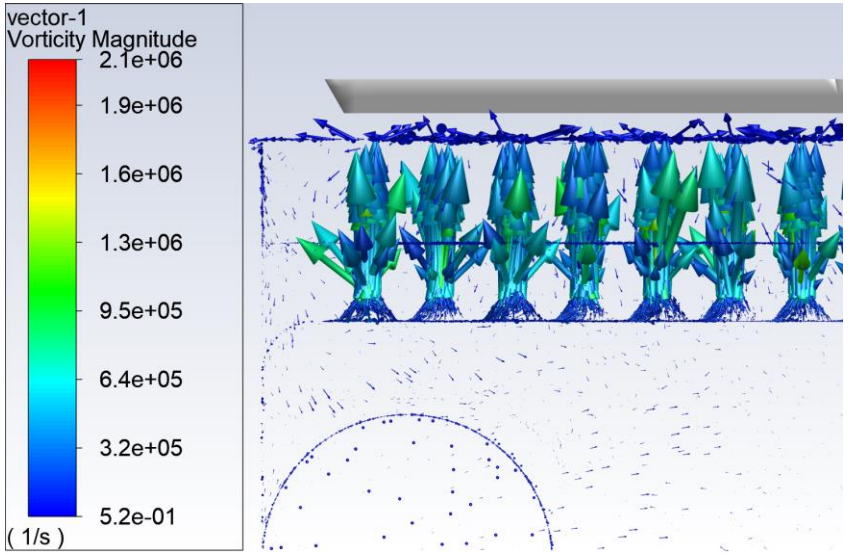
- The preliminary TMS geometry from previous year **does not achieve**:
  - a convective heat transfer coefficient indicative of jet impingement systems (> 40k $\frac{W}{m^2 K}$)
  - A reasonably achievable pressure drop

OSPRES: Thermal Management Group

Jet Impingement - TMS

Most Recent Progress

Property	Last Year	Current	Improvement
Pressure Drop (PSI)	>>1,500	420.1	>350 %
Vorticity ($\frac{1}{s}$)	7,000	$2.2 \cdot 10^6$	31,428 %
Convective heat transfer coefficient ($\frac{W}{m^2K}$)	2,200	28,742	1,306 %
Max. PCSS Temperature @ 200 W (°C)	67.85	53.37	219 %
Avg. PCSS Temperature @ 200 W (°C)	60	42.42	187 %



- While the pressure loss across the system is still large, it is roughly an order of magnitude less that before.
- Fluid domain appears to achieve true JI and turbulent characteristics.

Average switch temperature is nearly 30℃ lower than the threshold temperature!

This leaves excess performance for an increase in the HPM average power

HPM: Research Objective Progress/Findings

[SUB-PROJECT TITLE]

Significant Milestones

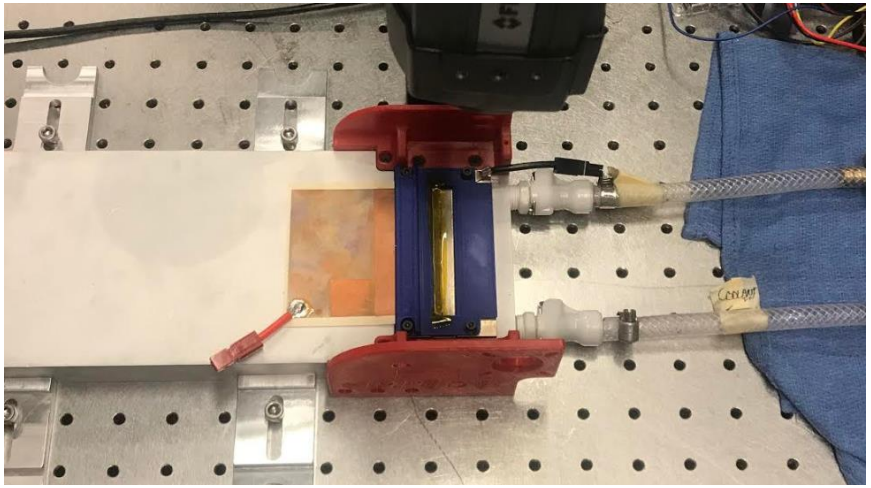
- ✓ Achieved pressure reduction by a factor of greater than 3
- ✓ Current design likely meets threshold PCSS temperature goal of 80℃ by a large margin
- ✓ While utilizing a viscous dielectric HTF, a ‘true’ jet impingement system has been designed

Significant findings

High degree of accuracy in CFD results as compared to experimental results

While pressure is a necessary evil, it can be drastically optimized

Discrepancy in manufacturer-reported values of thermal properties of HTF



Jet Impingement - TMS

Next Steps

- Utilize the optimal turbulence models and other simulation parameters deduced from past iteration's analysis to numerically analyze the redesigned JI-TMS parametrically.
- **Experimentally** verify the simulation results by generating a new prototype of the JI-TMS and testing its performance capabilities.
- Perform thermal analysis of various HTFs with different percentages of nanoparticle additives.
- Import highest performance HTF into simulations to gauge system reaction.

Possible Routes

- Generate an operational-space model to understand and predict how specific HPM-based source's waveform parameters effect the transient time-to-overheat (*time in which a device-under-load exceeds its maximum operating temperature*).
- Include performance HTF in experimental studies and compare finding with base fluid results.

Jet Impingement - TMS

Thank you for your time!

Any Questions?

FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

Bi-Annual Program Review

Fiber Laser Feasibility
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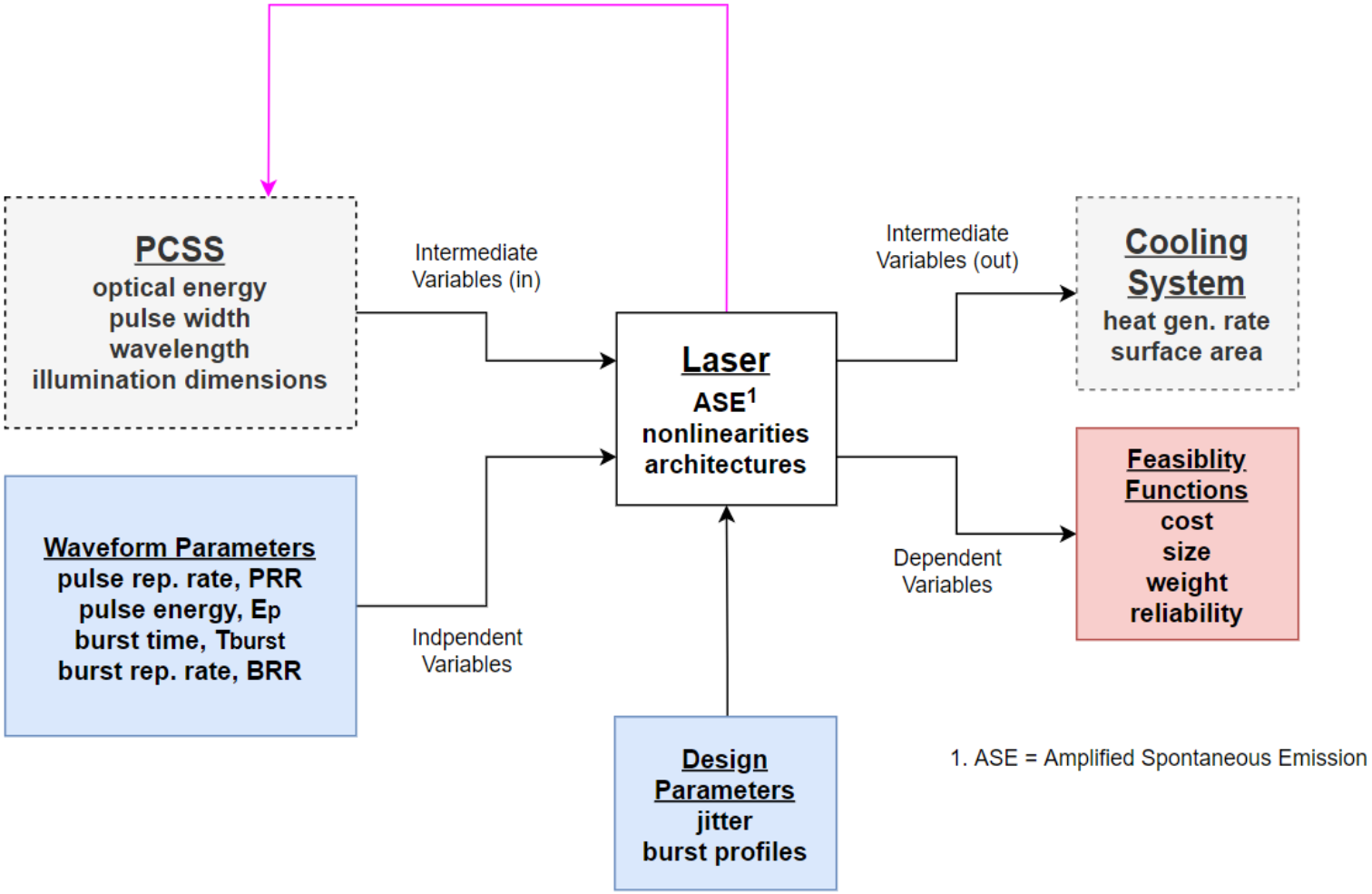
09 DEC 2020
held via Zoom

Distribution A. Approved for public release.

OSPRES: Lasers and Optics Support

Fiber Laser Feasibility



OSPRES: Lasers and Optics Support

Fiber Laser Feasibility

Laser size and costs have long been the Achilles heal of PCSS-based systems.

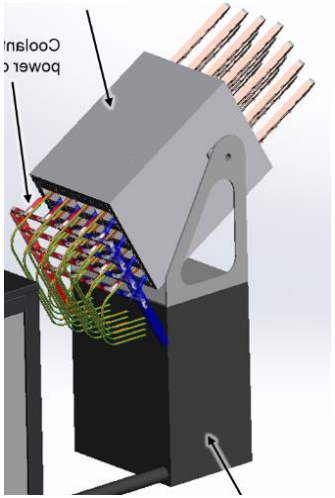
Scalable and modular systems to place on Naval vessels must be small, lightweight, have minimal cooling requirements and be monetarily inexpensive.

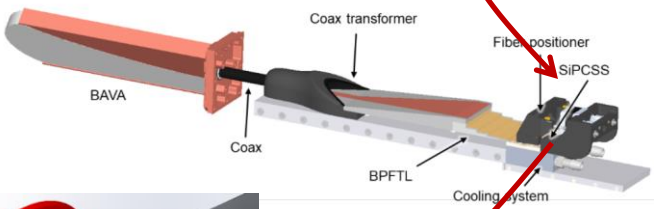
Fiber Lasers comprised of optical fiber amplifiers, fed by a low-power stable seed laser diode, can offer a cost-effective, low-weight and small-volume solution. Larger surface areas of active media also diminish the cooling requirements.

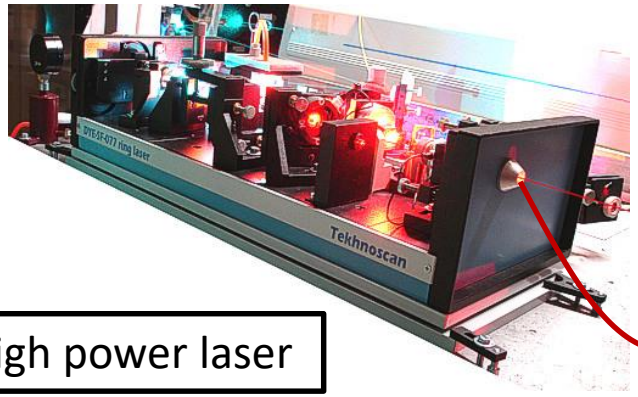
⇒

OSPRES: Lasers and Optics Support

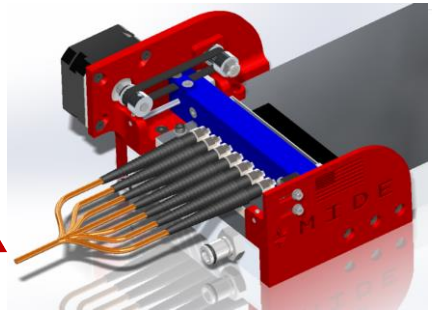
Fiber Laser Feasibility







High power laser



Triggers the PCSS

ONR HPM Program Key Research Criteria

Fiber Laser Feasibility

Qualitative and Quantitative Criteria:

Goal I: Reduce the dominant laser cost, of pump power systems, by a factor of 2.

State-of-the-art (SOTA): Ytterbium-doped fiber amplifiers optimized for LIDAR and cutting.

Deficiency in SOTA: Optical pump power system costs are prohibitive by a factor of 2.

Proposed Solution: A pre-burst optical pumping scheme to reduce costs by more than 2.

Program outcome: Simulations reveal that our technique can reduce optical pumping power costs by a factor of 40, with tolerable pre-burst ASE enhancement.

[UMKC invention disclosure filed 02JUN2020]

Example: high performance laser of 240 uJ/pulse at 500 kHz rep. rate

originally at 173 K$ in pump power costs could be pumped for only 4.3 K$.

It breaks the “pump power cost bottleneck.”

ONR HPM Program Key Research Criteria

Fiber Laser Feasibility

Qualitative and Quantitative Criteria:

Goal II: Develop a low timing-jitter fiber laser system.

State-of-the-art (SOTA): Ytterbium-doped fiber amplifiers optimized for LIDAR and cutting.

Deficiency in SOTA: Amplified spontaneous emission (ASE) noise and nonlinearities in fiber lasers create timing-jitter thereby limiting steerability.

Proposed Solution: Exploiting gain saturation to suppress the ASE while increasing the mode diameter of each fiber amplifier stage to mitigate nonlinearities.

Program outcome: Simulations show this can suppress ASE by 3 orders of magnitude, while each amplifier stage remains below damage thresholds.

[UMKC invention disclosure filed 14SEP2020]

OSPRES: Lasers and Optics Support

Fiber Laser Feasibility

The major **Risk** in our **goal I** solution of cutting cost by pumping outside the burst time is: **the ASE will increase** (since pumping while inversion not dropping from pulses).

But the **Payoff** is huge: **a factor of 40 is transformative.**

The major **Challenges** are:

1) keeping pre-burst ASE enhancement below spec.

2) material T1 time constant long enough to store pump

[Ytterbium-doped silica fiber amplifiers should suffice.]

OSPRES: Lasers and Optics Support

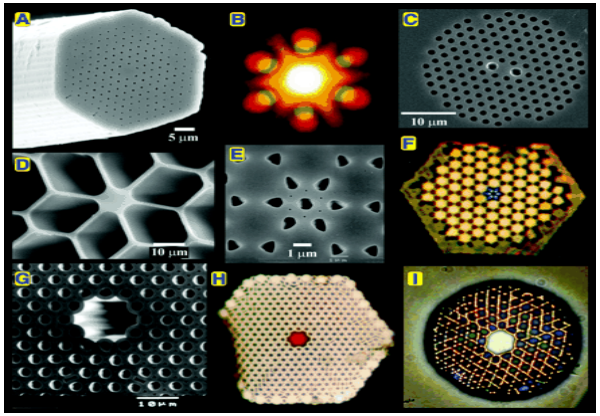
Fiber Laser Feasibility

The major **Risk** in our **goal II** solution of suppressing ASE via gain saturation (while increasing the mode diameter at each stage) is: **that gain saturation will also distort the optical pulse shape.**

But the **Payoff** is huge: **3 orders of magnitude.**

The major **Challenges** are:

to utilize dispersion and nonlinearities to improve pulse shape and minimize timing-jitter



[Adding a photonic crystal fiber stage should suffice.]

HPM: Broader Impact

Fiber Laser Feasibility

The broader impacts of our developments lie in the dual use of this technology in three areas.

Laser cutting industries will certainly benefit from a lower-cost high-power fiber laser.

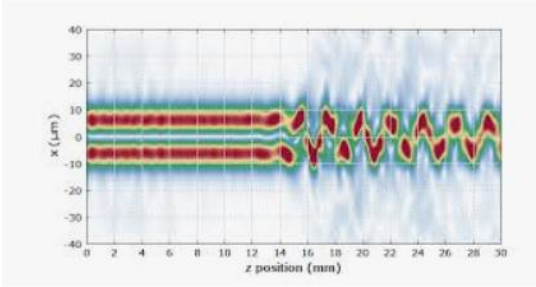
Our work on reducing ASE and nonlinear distortions in fiber amplifiers will also benefit **telecommunications.**

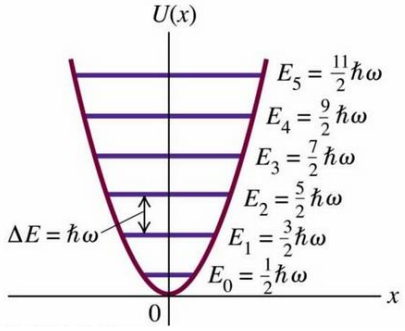
Higher intensity optical **power transmission** over fiber might lead to the transmission of energy over secure optical networks (immune to EMP).

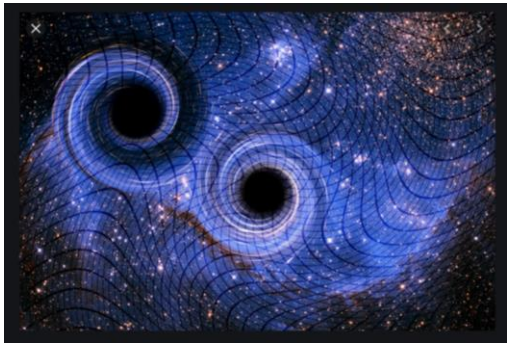
HPM: Sub-Project Research Objective

Fiber Laser Feasibility

Scientific objectives of this work include fundamental issues of **power transfer** in general. For example, the power limit imposed by self-focusing in media might be circumvented via photonic crystal structures by guiding fields in air-gaps. Fundamental issues on **quantum noise** arise in our work as ASE stems from the zero-point fluctuations of the vacuum state. Our study of its interaction with nonlinear systems and influence on phase and timing measurements have impacts in the **quantum metrology** community.







HPM: Technical Discussion/Progress

Fiber Laser Feasibility

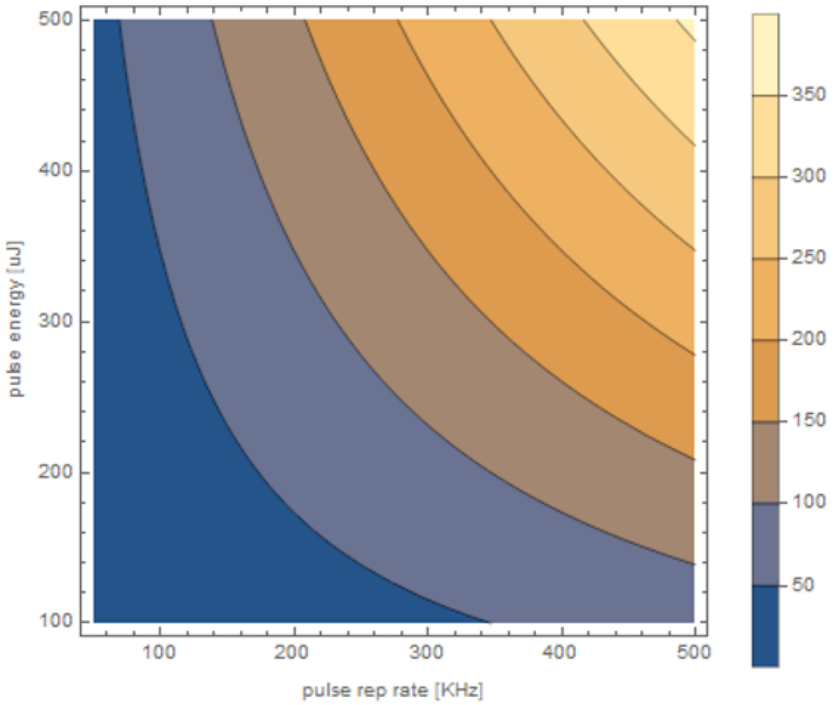
Pump Power Cost [in K$]

- e.g., at 240uJ and 500kHz we'd have
  - 172.8 K$ for that Pave = 120 W case

c = 1.44 Pave

c in [K$] COTS

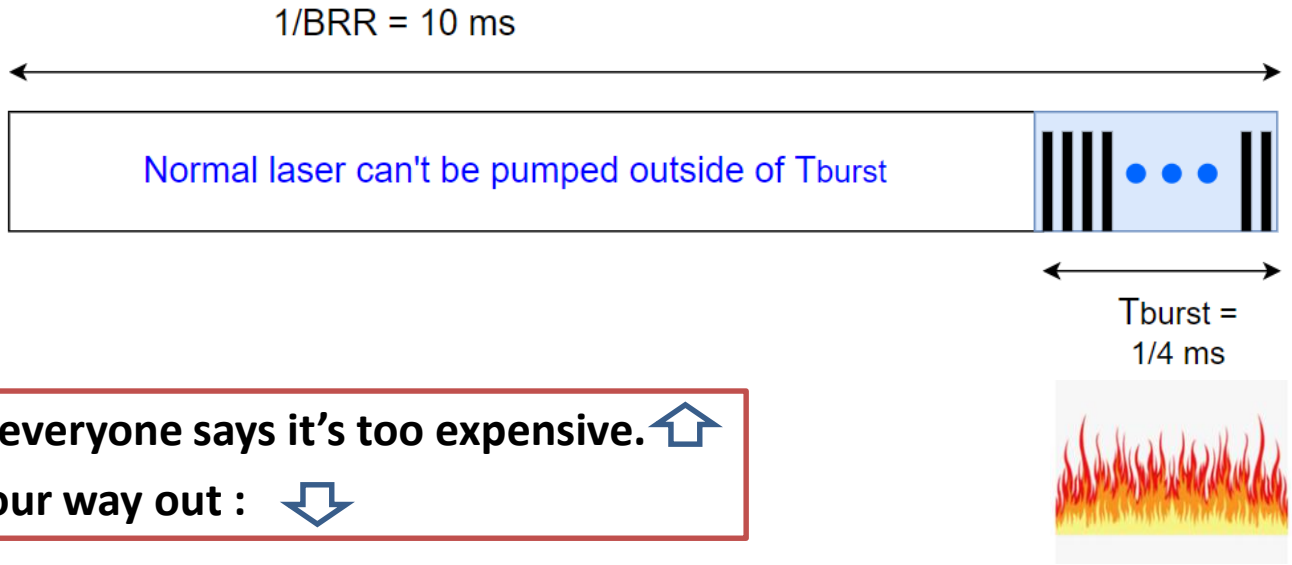
Pave in [W]



Pave = PRR Ep

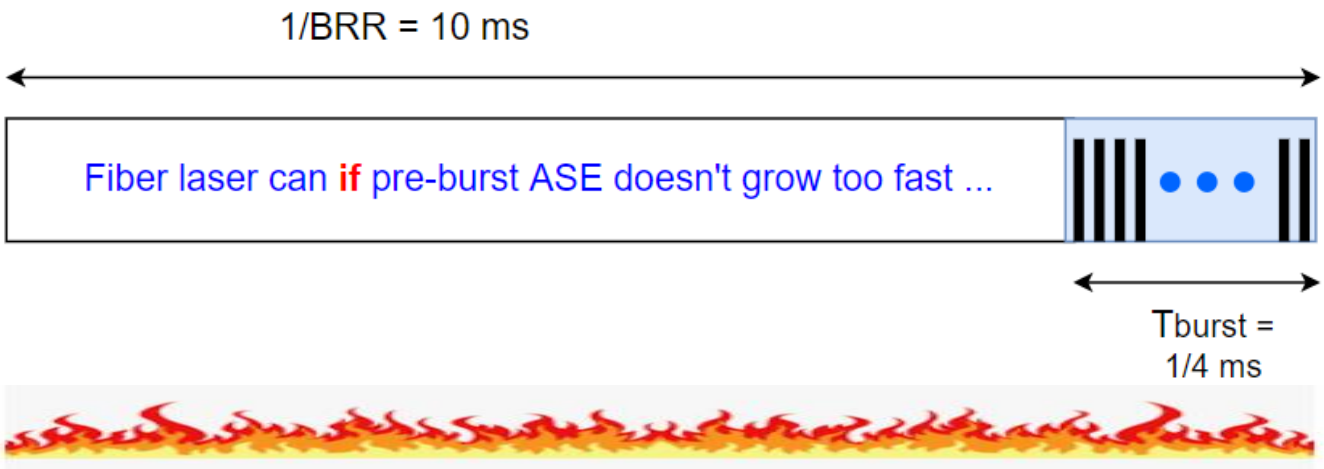
HPM: Technical Discussion/Progress

Fiber Laser Feasibility



That's why everyone says it's too expensive.

But here's our way out :



HPM: Technical Discussion/Progress

Fiber Laser Feasibility

- @ burst rep.rate = 100Hz there's 10,000 usec (10 ms) per burst
  - which is huge w.r.t. Tburst = 250 usec
- Now Ed = N Ep of interest and Ed = (Pave)(Tburst)
  - for classic example (like our Neolase) of Ep = 240uJ and N=125
  - Ed = 30 mJ which is also = (120 W) (250 usec)
- To supply that we only need Pbr = (30 mJ)/(10ms) = 3 W !!

Bottom line ⇒

- Like a "gigantic pulse" or "Q-gated" laser
  - we build for a long time then "let 'er rip"
  - then nonlinearities clobber us but at least we've a way out of the pump cost bottleneck

HPM: Technical Discussion/Progress

Fiber Laser Feasibility

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Bottom line ⇒

- Like a "gigantic pulse" or "Q-gated" laser
  - we build for a long time then "let 'er rip"
  - then nonlinearities clobber us but at least we've a way out of the pump cost bottleneck

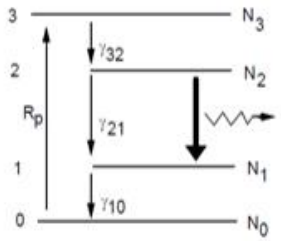
Trick only works because:

1) we can hold pump power for 10 ms and
2) our ASE doesn't grow much in 10 ms

HPM: Technical Discussion/Progress

Fiber Laser Feasibility

THE EQUATIONS



$$\frac{d}{dt}N_2 = -\frac{N_2}{\tau_L} - 2^*\sigma v_g N_2 n_L + R_p$$
$$\frac{d}{dt}n_L = -\frac{n_L}{\tau_p} + 2^*\frac{\sigma v_g}{V}N_2\left(n_L + \frac{1}{V}\right).$$

$\gamma 10$ *is fast so* $N1 \sim 0$

BECOME =>

$$\frac{d}{dt}g = -\frac{g - g_0}{\tau_L} - \frac{gP}{E_{sat}}$$
$$\frac{d}{dt}P = -\frac{1}{\tau_p}P + \frac{2g}{T_R}(P + P_{vac}).$$

THE CONSTANTS

g_0 = initial gain, linearly proportional to the pumping rate/pump power

T_p = cavity loss time constant (or loss per length in fiber amp)

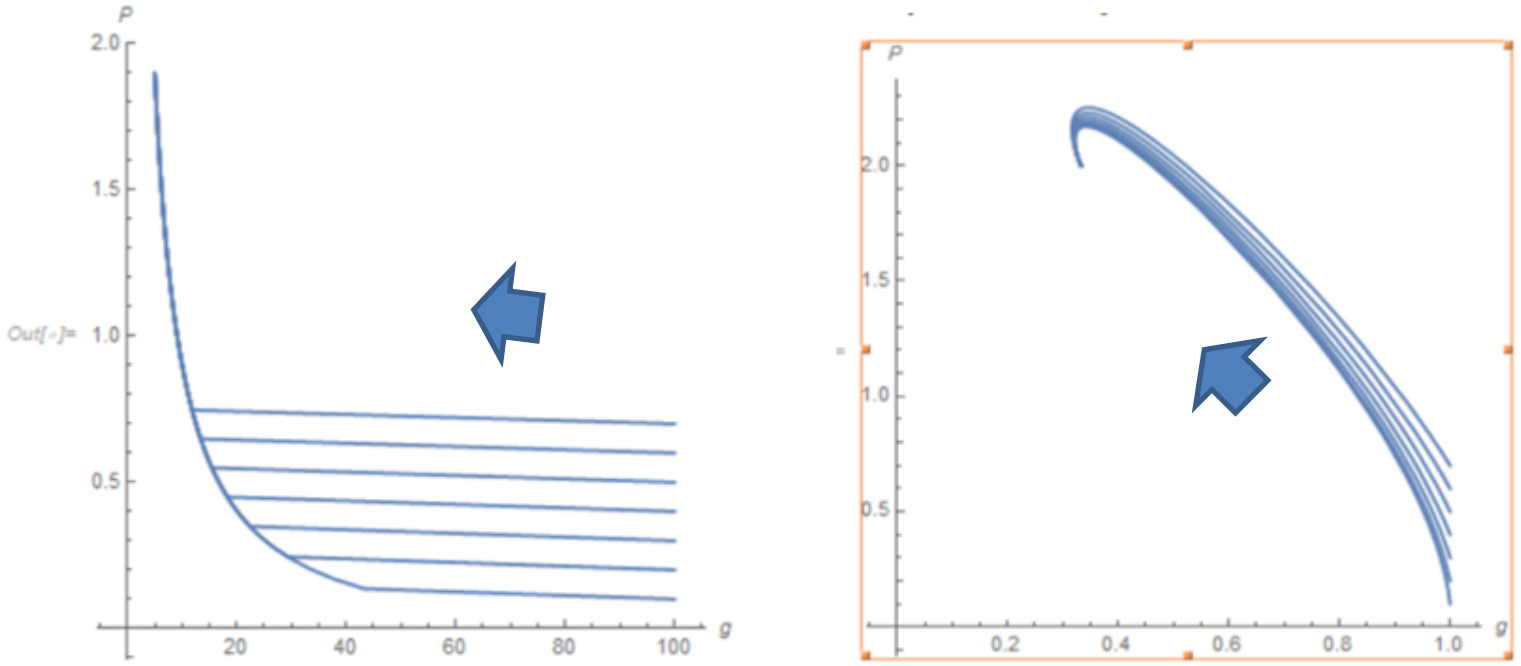
$E_{sat} = P_{sat}\,T_L$ where T_L = "T1" = "T_{sp}" = spontaneous decay rate time constant

and P_{vac} = ½ (h f) BW > 1 nW at 1064 nm is what turns into ASE

HPM: Technical Discussion/Progress Cont'd

Fiber Laser Feasibility

SATURABLE GAIN MODEL HAS ONLY ONE STABLE CRITICAL POINT
P = Output Power g = Gain



Gain and power converge to the unconditionally stable (gcp, Pcp)
First plot more typical (P doesn't overshoot for typical constants)

HPM: Technical Discussion/Progress Cont'd

Fiber Laser Feasibility

Model showed pre-burst ASE tolerable ☺

But then we found a different

POTENTIAL PROBLEM

Linear gain theory says

Pase = h f (G-1) BW

At 1064 nm with a 1 nm optical BW

that's 49.5 nW (G-1)

With G = 8 x 10^(6) we'd be over the 100 uW "limit"

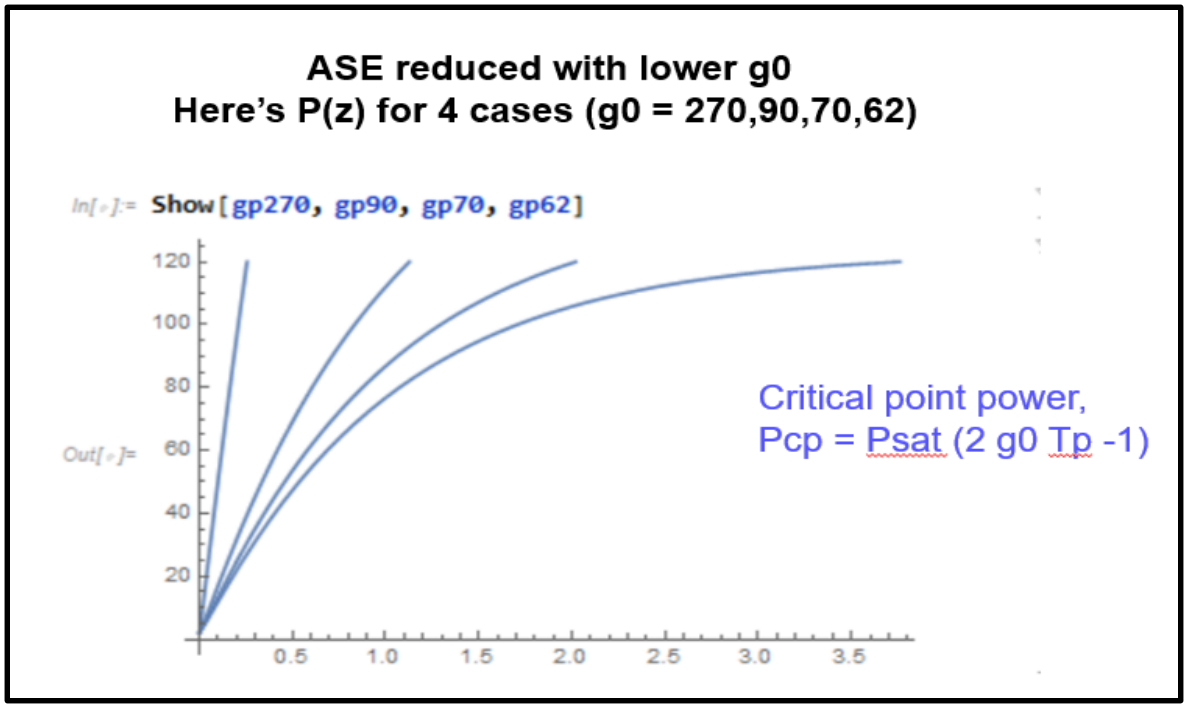
(for heating due to ASE-induced PCSS leakage current)

by a factor of 3960 !

HPM: Technical Discussion/Progress Cont'd

Fiber Laser Feasibility

But our gain isn't linear – it saturates !



Lowering g0
lowers P_{cp}
but fiber longer

We can also lower $P_{sat} = I_{sat} A_{eff} \sim d^2$
where d = fiber core diameter

So…

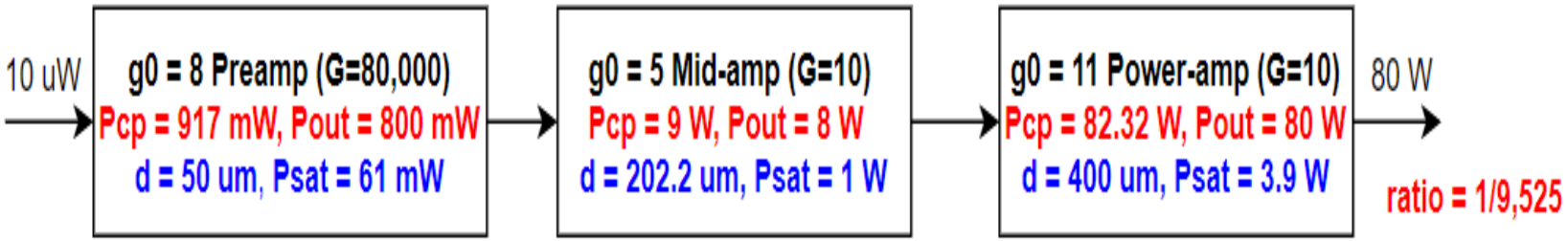
HPM: Technical Discussion/Progess Cont'd

Fiber Laser Feasibility

now … have a practical design example

for G = 8 x 10^6 case

which beats the factor of 3960



– **ASE suppressed by 9525**

– we lowered Pcp via g0 and Psat (via mode diameter d)

– while keeping d above damage thresholds in each stage

HPM: Research Objective Progress/Findings

Fiber Laser Feasibility

Primary findings:

- A pre-burst pumping scheme can reduce the (dominant) pump power costs by a factor of 40, with negligible ASE enhancement.

- A linear gain theory predicts that an optical amplifier of gain = 8 x 10^6 will produce ASE power = 3,960 x our spec. (on leakage current heat).

- Showed that gain saturation can suppress the ASE (for a system of gain = 8 x 10^6) by a factor of 9,525 in a staged design of different fiber cores enhancing saturation while remaining below damage thresholds.

- Refined the nonlinear theory of ASE induced timing-jitter.

HPM: Conclusions

Fiber Laser Feasibility

The work is incomplete, yet remains feasible and a provisional patent (possibly two) should be filed soon. Next steps include: cost reduction analyses for various burst profiles and fiber media – including photonic crystal fiber (PCF) filled with various gasses; pulse dynamic studies including the effects of gain saturation vs the dispersion engineering capabilities of PCF; and the assessment of the impact of fiber nonlinearities on pulse shaping, timing-jitter and damage thresholds.

FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

Bi-Annual Program Review

Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

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09 DEC 2020
held via Zoom

Distribution A. Approved for public release.

Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

HPM Mission Expectation:

Modular systems aboard active naval fleet must be structurally robust, lightweight and inexpensive (to fabricate and operate) with minimal spatial footprint.

Fundamental deficiency in HPM systems:

- Heavy, bulky and expensive laser systems required for linear-mode PCSS-based systems.
- Need for non-linear SHG/THG optics for conventional lasers (1064 nm) to trigger WBG solids (GaN/SiC).

Fig: *neoLase picosecond laser system*

OSPRES: Modeling and WBG Materials Team

Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

The Context

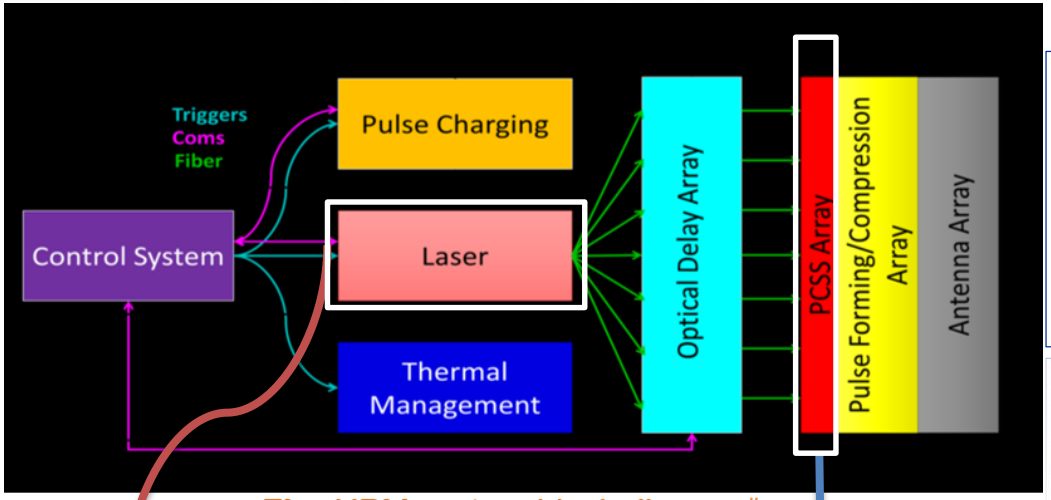

Fig: *HPM system block diagram#*

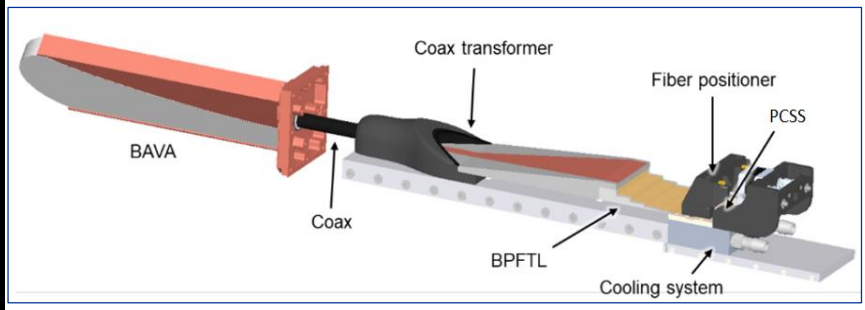

Fig: *HPM system functional diagram*

Fig: *neoLase picosecond laser system*

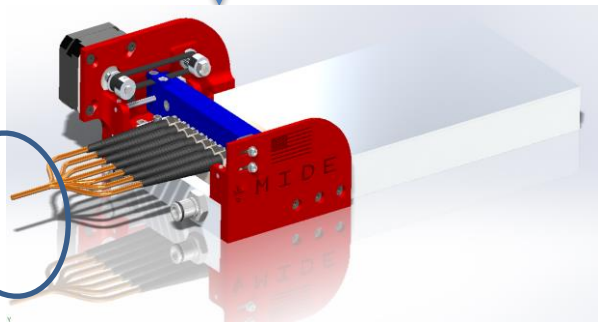

Fig: *Laser feed to PCSS**

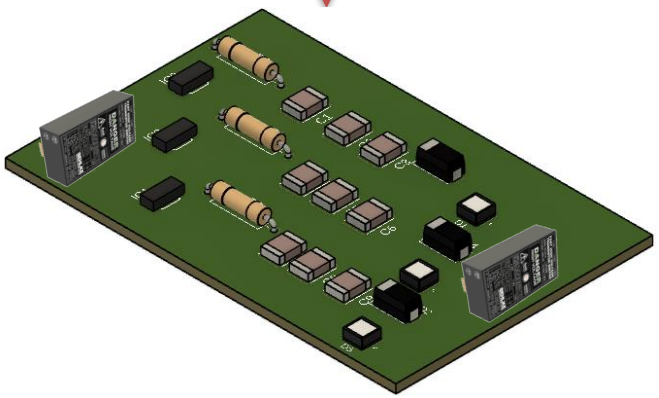

Fig: *Proposed alternative design*

OSPRES: Modeling and WBG Materials Team

Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

Eliot Myers
Asst. Dir. Research

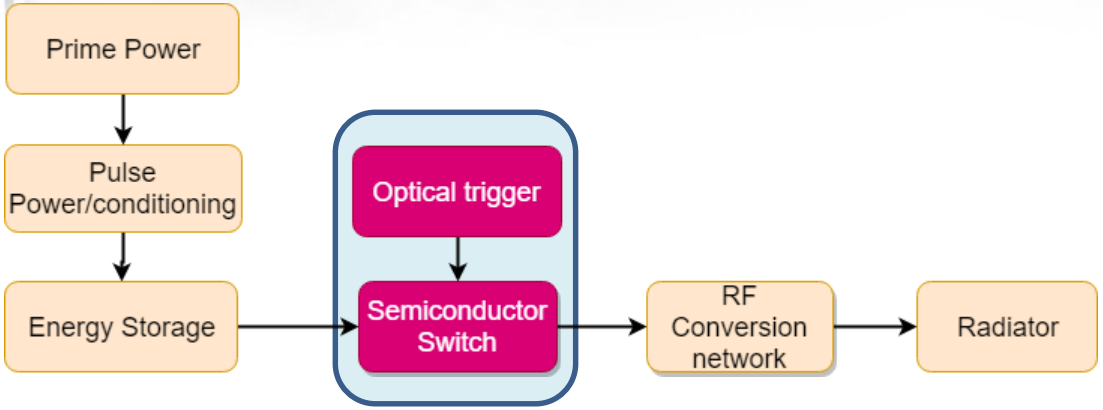

Fig: *HPM system block diagram*

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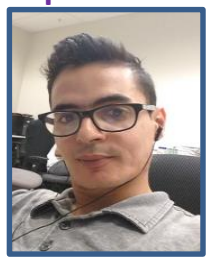
GaN computational team



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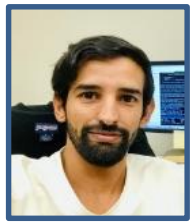

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Paul Rulis
Associate Professor

- Staff
- Grad Student
- Faculty

ONR HPM Program Key Research Criteria - II

Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

Qualitative Criteria

Goal: Improve HPM system's affordability and portability (SWaP-C^2 factor) by replacing conventional laser systems with laser diode (array) based alternative optical trigger subsystem.

State-of-the-art (SOTA):

High average power picosecond pulsed lasers up to 50 W output power with a optical amplifier gain factor up to 40 dB (~10,000x power) with laser amplifier.

Deficiency in SOTA:

(i) High laser system volume: >1100 cm^3/W and (9.65 cu-ft)

(ii) cost per optical energy output: >$800/μJ (>$120,000 /system)

Proposed Solution:

Multi-stage cascaded optical amplifier powered by laser diodes (arrays) and GaN-PCSS as a compact, inexpensive laser replacement capable of high temperature (~175°C) operation.

Program outcome: A compact, inexpensive laser alternative without a need for an external amplifier

ONR HPM Program Key Research Criteria - I

Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

Quantitative Criteria/Metrics for Optical source improvement:

Parameter	SOTA	Objective	Expected Results	Parameter description
Weight	125 lbs*#	10-15 lbs	~90% lower	Laser module, controller, and chiller (no amp.)
Volume	9.65 cu-ft	1.08 cu-ft (19.75”x11”x 8” pelican case)	~89% lower	Cumulative volume of the equipment involved
Power	15 W @1064 nm	Up to 1200 W avg. QCW @ 808 nm		Unamplified laser output power
Cost	>$120,000	~$15,000	~90% lower	In reference to neoLase picosecond laser system
Pulse energy	250 µJ @1064 nm	> 750 µJ (808 nm & 1064 nm JOLD-1000-QANN-10A LD stack)	300% higher	peak energy per pulse from the source
Repetition rate	Up to 80 MHz	50 – 80 MHz	similar	at ~50% duty cycle, ~70-100ps FWHM

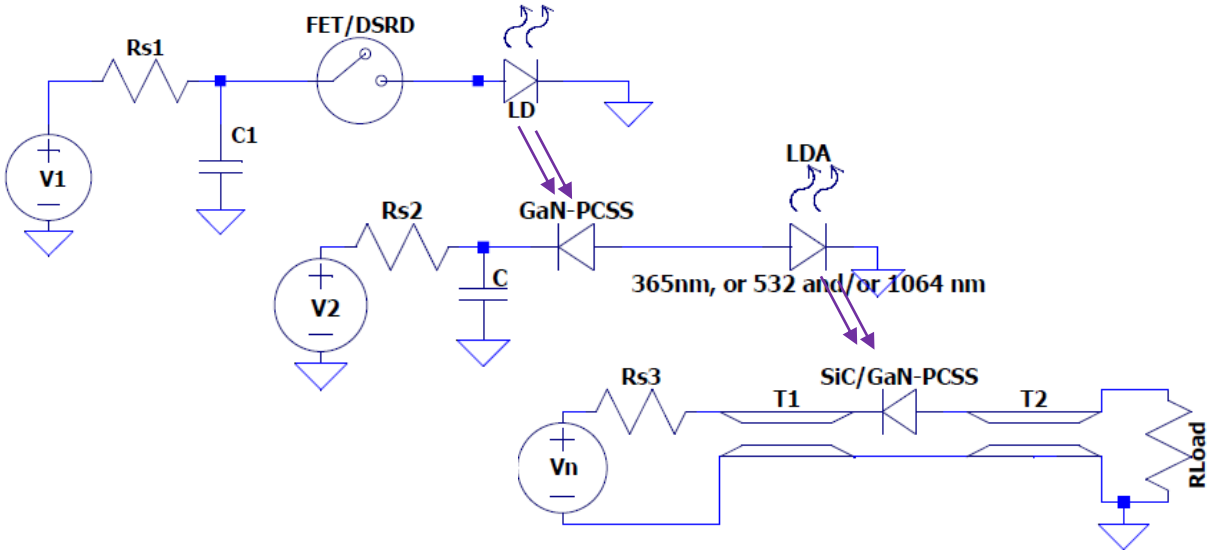
** Calculated from neoLase system and industrial chiller specs.*

(seed laser & amplifier + driver + industrial chiller)

HPM: Technical Discussion/Progress

Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

The WHATs



Stage I:

Laser diode driven by Si-based FET/DSRD

Stage II:

Laser diode (array/stack) driven by lock-on /linear GaN-PCSS triggered by from *stage I* optical output.

Note: LDA wavelength depends on source driver needs.

Current sources:

Si-DSRD

GaN:C PCSS

Optical sources:

Laser diode module

Laser diode array (LDA)

Pulse charger/ HV switch

HPM: Sub-Project Research Objective

Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

Specific objective:

- Exploit WBG materials' high breakdown & operational-temperature threshold, and direct bandgap (DBG)-specific lock-on mode to miniaturize ultrafast switches without compromising output currents.

- Study GaN's lock-on/avalanche mode characteristics and its dependence on circuit parameters, and fabrication parameters such as dopants, and their concentrations.

Contribution to scientific community:

- Quantification of photoconductivity properties of GaN with repeatability

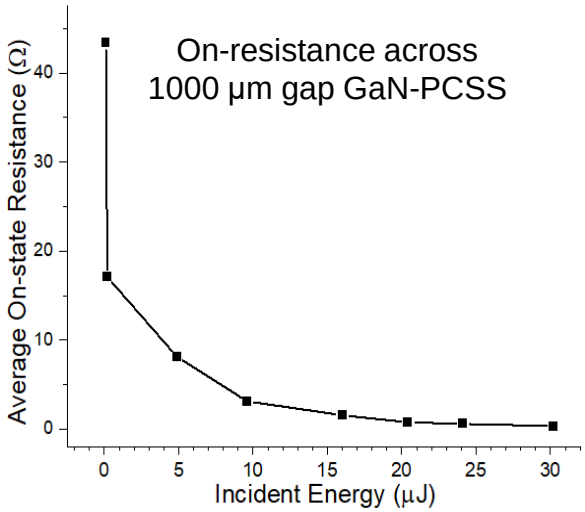
- Broadened trade-space in industrial, medical, and communications applications with portable, inexpensive high power laser

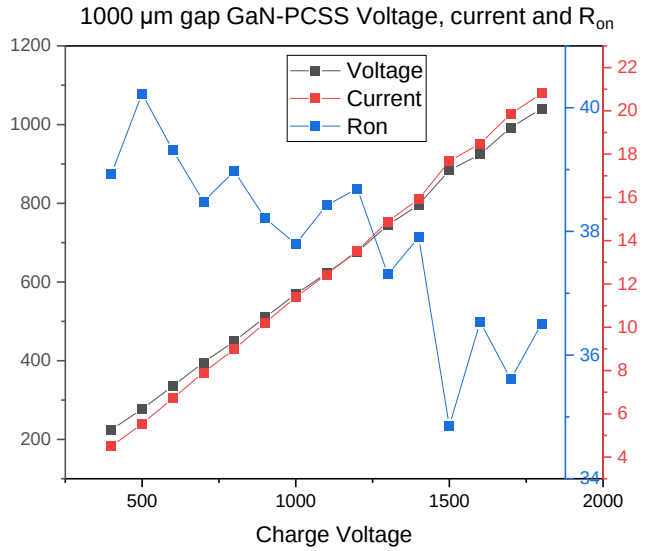
HPM: Sub-Project Research Objective

Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

GaN properties and Metrics:

Property	Si	GaN	4H-SiC
E_g (eV)	1.12	3.45	3.26
Electron mobility (cm^2/V-s)	1.4E+3	1E+3	1E+3
Hole mobility (cm^2/V-s)	450	350	115
Ecrit (V/cm)	3E+5	3.3E+6	2.2E+6
dielectric constant	11.7	5.35	9.66
Thermal Conductivity (W/m-K)	1.5	1.3	4.9
Saturation velocity (cm/s)	1E+7	2.5E+7	2.2E+7
Density (g/cm^{-3})	2.33	6.15	3.16
Specific Heat ($J\ g^{-1}°C^{-1}$)	0.7	0.49	0.69





GaN-PCSS metrics required:

- <100 ps rise- and fall-times
- ~400 mA/pulse for initial stages and >1-2 A/pulse for the final
- >2 kV voltage hold-off

Takeaway:

- GaN:C PCSS Lab testing has exhibited linear mode; lock-on mode has not been observed even at 1800 V bias (E_{device}= 18kV/cm).
- > 20 µJ per pulse is required to attain mΩ-order on-state resistance

Credits: GaN testing data by Heather Thompson

HPM: Technical Discussion/Progress

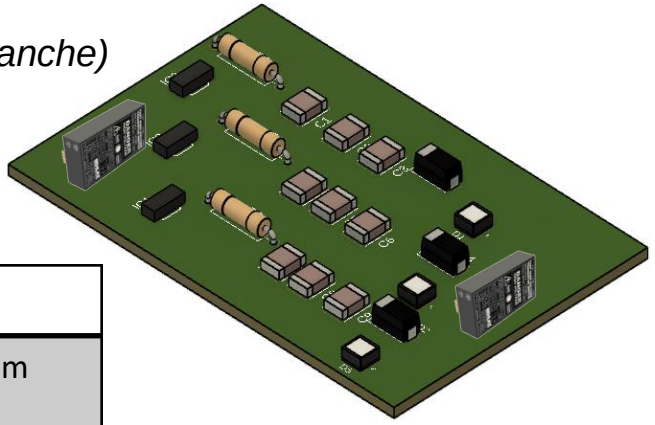
Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

The HOWs

Operational requirements:

1. Positive gain of 10^x is required at each stage – *non-linear (lock-on/avalanche)*
2. UV-A optical sources to avoid SHG optics
3. > 20 µJ per pulse is required to attain mΩ-order on-state resistance

   [1 µJ of 365nm per pulse- I_{out}= 0.28µA (linear mode)]



	Initial Stage	Final Stage
Source	365-375 nm LD	808 or 980 nm LDA (365-375 nm preferred)
COTS model	USHIO HL37013MG	JOLD-1000-QANN-10A
Power	250mW pulsed	up to 1200 W QCW
FWHM	<110 ps	trigger dependent
PRR	>50 MHz	
Oper. parameters	5 V, 370 mA	

Goal: *To limit number of stages to a minimum (2; 3 at most)*

HPM: Technical Discussion/Progress

Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

Literature:

- High-gain triggering observed in GaAs, GaN and InP [DBG], but not in Si, SiC, GaP, or C (diamond) [IBG].
- Persistent conductivity observed beyond the duration of the laser pulse until sustaining field fell below 3kV/cm in GaN device.

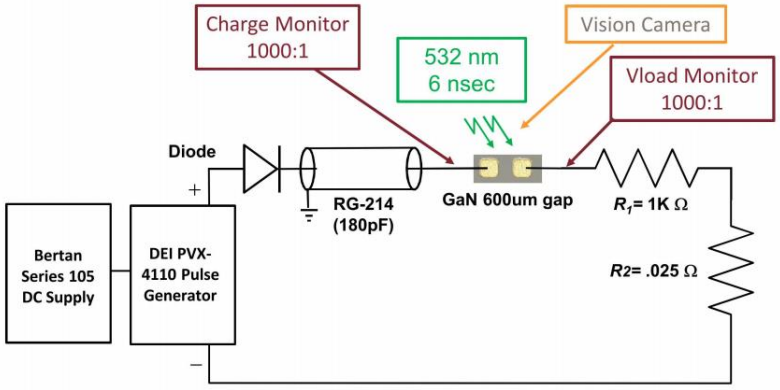


Fig: SNL GaN-PCSS test setup

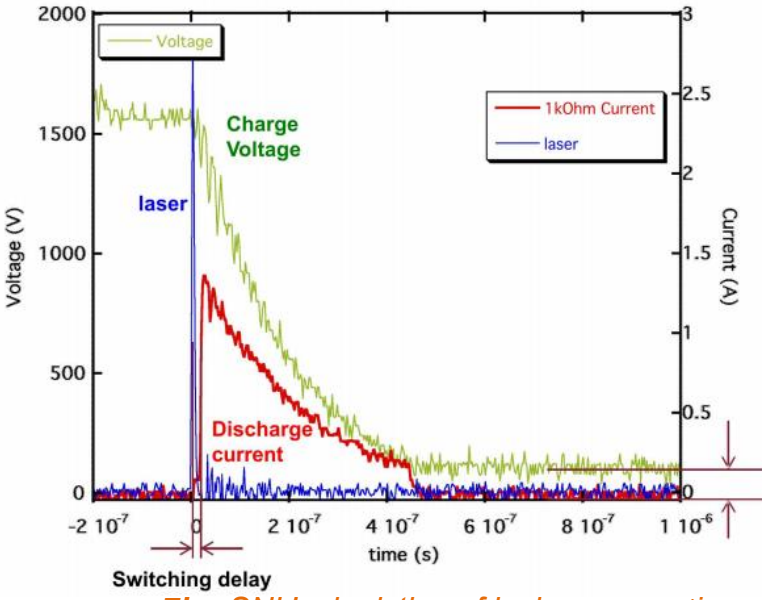


***Fig:** SNL's depiction of lock-on operation*

The dilemma:

- ❑ High-gain switching not observed under FC-70 (Fluorinert). Is high-gain just a surface effect?

*E. A. Hirsch *et al.*, "High-Gain Persistent Nonlinear Conductivity in High-Voltage Gallium Nitride Photoconductive Switches," *2018 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, Jackson, WY, USA, **2018**, pp. 45-50, doi: 10.1109/IPMHVC.2018.8936660.

Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

Risks, Payoffs, and Challenges

Risks:

(i) Inducing non-destructive avalanche mode in GaN-PCSS (unsuccessful so far)

(ii) Reduced overall system control and PRR range with avalanche mode

(iii) Potential need for research in laser diodes (arrays) due to unavailability of COTS high power pulsed laser diodes

Payoffs:

(i) Reduction in system-size and -cost by an order (or two orders) of magnitude;

(ii) Enable higher safe operating temperatures (>150°C) ➔ reduced cooling requirements

Challenges:

(i) Reduction in electronic bandgap, breakdown threshold, saturation velocity and carrier mobility at high operating temperatures – *find alternatives to enhance carrier mobility*

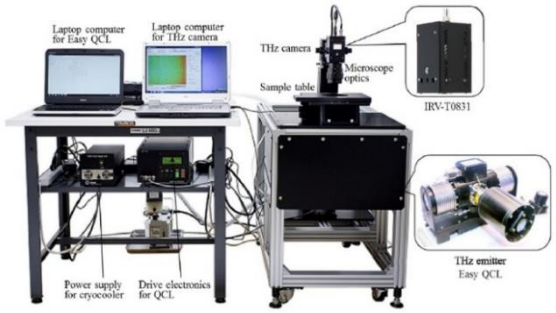
(ii) Engineering issues for thermal management, interconnects, and packaging

(iii) Increased complexity for higher cascaded stages – *Limit no. of stages to 2, at most 3*

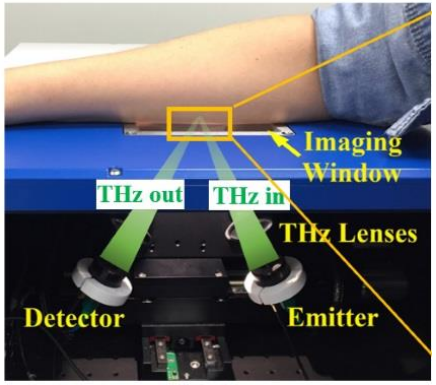
HPM: Broader Impact

Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

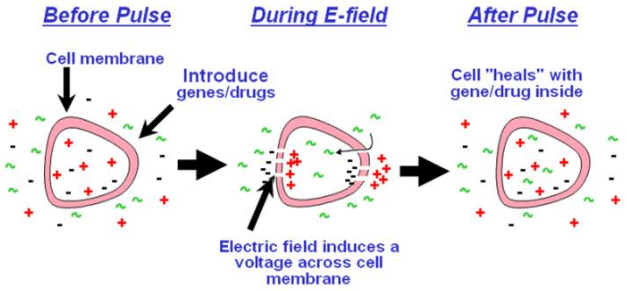
Medical diagnosis:



Cancer Imaging: Compact THz imaging sources

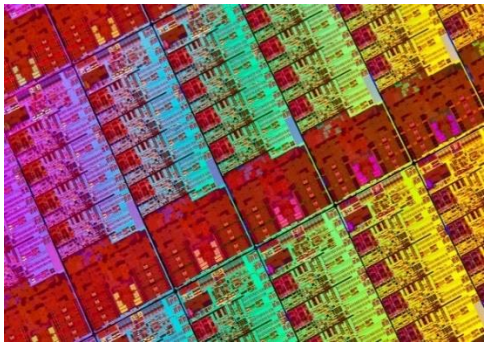


non-invasive superficial organ imaging



Electroporation-enhanced vaccine delivery

Manufacturing:



Maskless laser photolithography

Laser cutting

HPM: New Ideas / Opportunities

Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

- Explore alternatives in fiber amplifiers (optical pumping) for final stage in the event of failed lock-on mode, where SiC-PCSS can be implemented for thermal superiority.
- Does responsivity and impurity concentration influence conduction mode? To what extent can GaN's responsivity be manipulated?
- Implement lock-on in the initial stages and linear-mode in the final to minimize jitter? – with an intermediate filter
- UV-A laser diode array (InAlGaN) modeling

HPM: Conclusions

Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

Status: The feasibility study (numerical) along with initial test data collection for GaN-PCSS have been completed. Modeling is underway for GaN-PCSS alongside SiC-PCSS as a fall-back option.

Hurdles: Unavailability of COTS UV-A LDAs (~365 -375 nm), prompting additional attention to modeling and sim.

Next Steps:

- Model and simulate GaN-PCSS to corroborate lab test data and literature
- Explore the options without high-gain mode of operation, implementing fiber lasers

Milestones:

- GaN- and SiC-PCSS TCAD modeling and transient simulations, lab testing and characterization – Apr/May 2021
- Proof-of-concept test with two-stage system implementing GaN-PCSS to verify positive gain from each stage – Jul/Aug 2021
- Complete initial LDA modeling for 365-375nm using Silvaco TCAD and COMSOL – Sep/Oct 2021

Thank you!

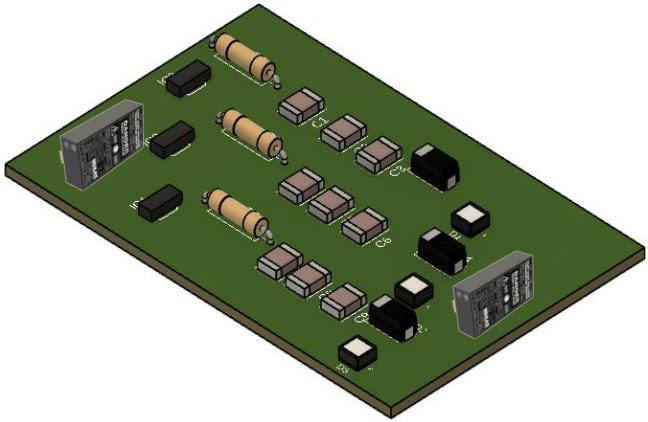
HPM: Technical Discussion/Progress

Multi-Stage Optical Amplifier as an Inexpensive Laser Replacement

The HOWs

Initial Stage

Source	365-375 nm LD
COTS models	PicoQuant LDH-IB-375-M; Nichia NDU4116; USHIO HL37013MG
Power	35 mW; 70 mW; 250mW pulsed
FWHM	<110 ps
PRR	>50 MHz
Oper. parameters	5.4 V, 110 mA; 5 V, 370 mA



Final Stage

Source	808 or 980 nm LDA *(365-375 nm preferred)*
COTS models	JOLD-1000-QANN-10A
Power	up to 1200 W QCW
FWHM	trigger dependent
PRR	N/A

Goal: *To limit number of stages to a minimum (2; 3 at most)*

Feasibility of fabrication: Edge-emitting or VCSELs?

FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

Bi-Annual Program Review

Challenges and progress toward low- and high- voltage D-NLTLs at 1 GHz

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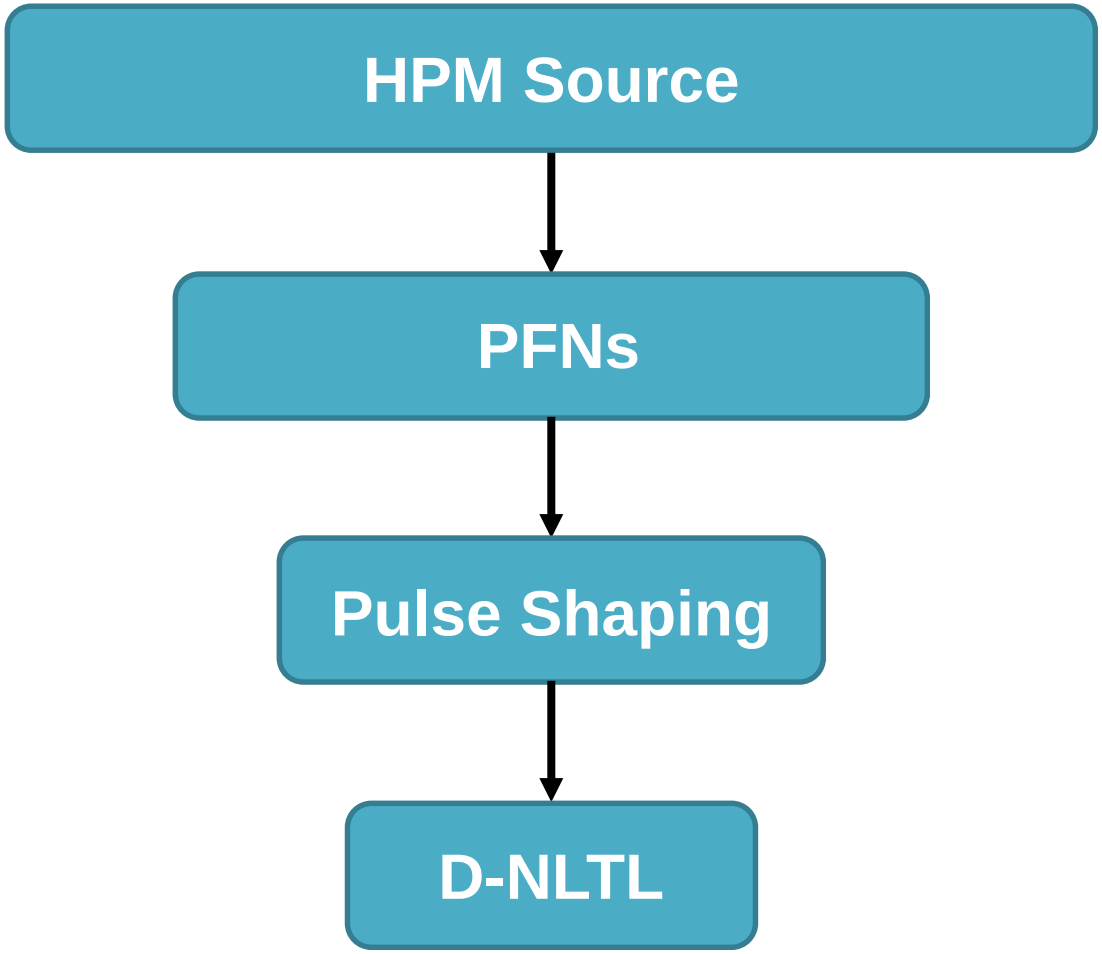
09 DEC 2020
held via Zoom

Distribution A. Approved for public release.

OSPRES: Pulse Forming Networks

D-NLTLs



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OSPRES: Pulse Forming Networks

D-NLTLs

The environment of a naval vessel necessitates all systems be optimized with respect to system size, weight, and cost.

Traditional systems capable of HPM generation (klystrons, relativistic magnetrons, etc.) are large, costly, and require the use of several auxiliary systems for operation.

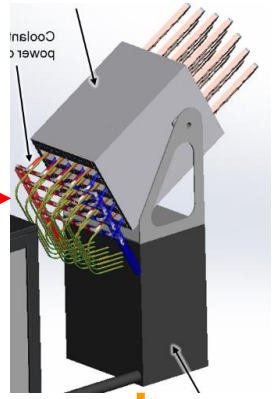
Overall system size, weight, and cost can be optimized using a diode based nonlinear transmission line (D-NLTL) as a pulse shaping network for the conversion of pulsed energy to the UHF regime.

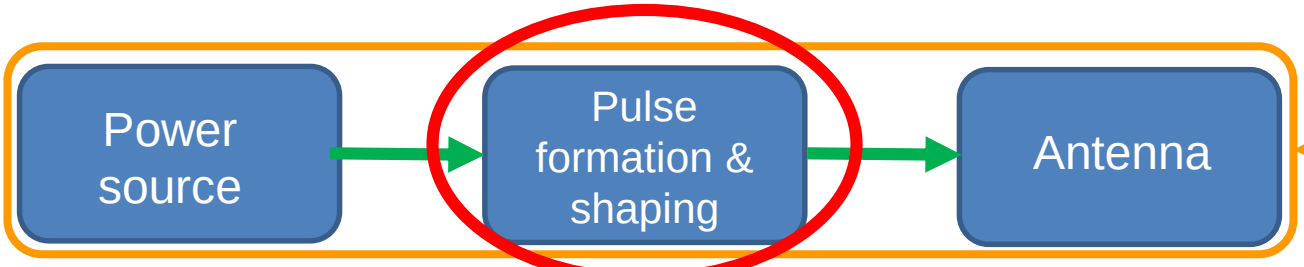
Klystron

Diode based nonlinear transmission line

OSPRES : Pulse Forming Networks

D-NLTLs





Single module in array

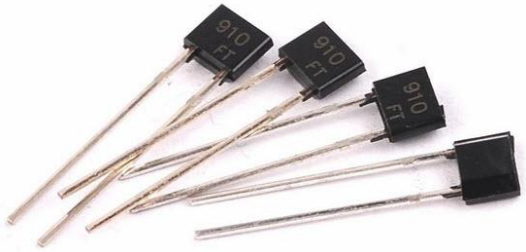
D-NLTL Role:

- Reduces size, weight, and cost of pulse shaping component of HPM system
- Reductions allow for more flexibly in design of other HPM system components

HPM: Broader Impact

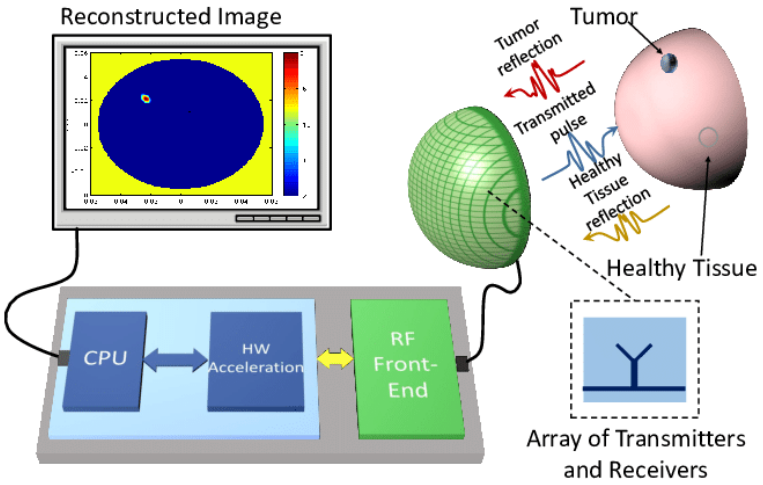
D-NLTs

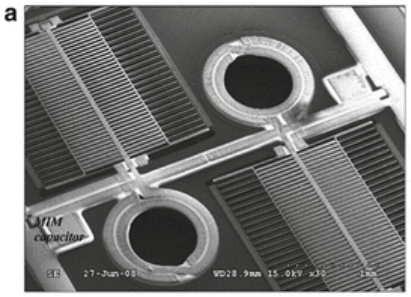
Satellite Communications

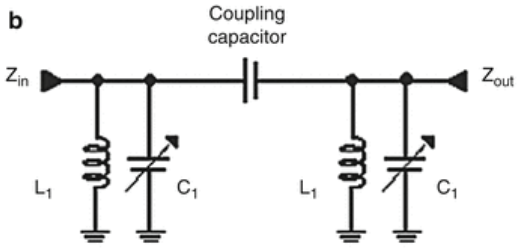


Improvements in HV varactor design

RF and Microwave Imaging







Improvements to HV tuning applications

HPM: Sub-Project Research Objective

D-NLTLs

Objective: Increase the center frequency generation capabilities of the D-NLTL network beyond 1 GHz in a compact, low cost, modular/scalable package.

ONR HPM Program Key Research Criteria - II

D-NLTLs

Qualitative Criteria:

Goal I: Increase the center frequency generation of D-NLTL to UHF (0.5-1.5 GHz) regime

State-of-the-art (SOTA): D-NLTL prototypes have documented center frequencies of up to 0.4 GHz.

Deficiency in SOTA: Simulations indicate achievable frequencies in the single GHz range. However, simulations need to be refined to better match measurements at frequencies above 0.1 GHz.

Proposed Solution: Determine what parameters need to be introduced into simulations for improved prediction of D-NLTL behavior.

Program outcome: D-NLTL prototype capable of UHF operation with reductions in trial by error design

Goal II: Develop metrics for identifying COTS diode models and/or design considerations for custom diodes capable of UHF operation in a D-NLTL.

State-of-the-art (SOTA): Diode selection for sub-UHF NLTL applications is based on reverse bias max potential, low signal capacitance, and the rate of capacitance decrease with signal strength.

Deficiency in SOTA: At UHF and above frequency response, relaxation time, or device degradation can become significant with respect to NLTL performance. There exists little documentation for the effect of each on NLTL performance.

Proposed Solution: Construct a set/database of guiding parameters for determining optimal diode candidates for UHF D-NLTL operation.

Program outcome: Reduction in trial by error D-NLTL design.

ONR HPM Program Key Research Criteria - I

D-NLTL

<u>Quantitative</u> Criteria/Metrics for D-NLTL improvement:

Parameter of Research	Definition	SOTA	Threshold	Objective
Center Frequency	Peak power/voltage in frequency domain. Estimated by the time between successive solitons	400 MHz	500 MHz	1 GHz
Bragg Frequency	The cutoff frequency of the NLTL. Estimated by the 10-90 rise time.	500 MHz	> 500 MHz	> 1 GHz
RF efficiency	Ratio of radiated/post HPF energy to injected energy. Estimated by the ratio of the pulse modulation depth to V_{pk}	10%	20%*	> 20%
Q_{VM} (cm^3 ▪ g)	Product of NLTL volume and mass used to determine device mobility.	n/a**	50 – 1,000	< 500
Bandwidth (%)	$\% = 100\frac{f_u - f_l}{f_c}$ calculation is preformed for -3 and -5 dB of F_C	n/a**	31 (-3dB) 53 (-5dB)	30 (-3dB) 50 (-5dB)

** Theoretical max is 30% for a single pulse ** Has not been reported on to my knowledge*

OSPRES : Pulse Forming Networks

D-NLTLs

Challenges

- **Power limited by V_R**
  - Well defined problem
  - COTS $V_R \leq 10^1$ kV
  - Solution: Diode stacks
  - Solution: Line parallelization
- **Simulations need further refinement**
  - Not well defined
- **Frequency limited by diode properties**
  - Not well defined

Risks

- **Stacks of diodes increase peak power but decrease efficiency**
- **Nonlinearity mechanism may not be capable of GHz frequency generation**
- **Pulses with amplitudes > V_R can damage device**

Payoff

- **D-NLTL cost, weight, and size allows for greater flexibility in the design of other system components**
  - Pulse source
  - Antenna
- **A Mobile RF source capable of compact applications**
  - Aboard a UAV
  - Hand-held
  - Satellites

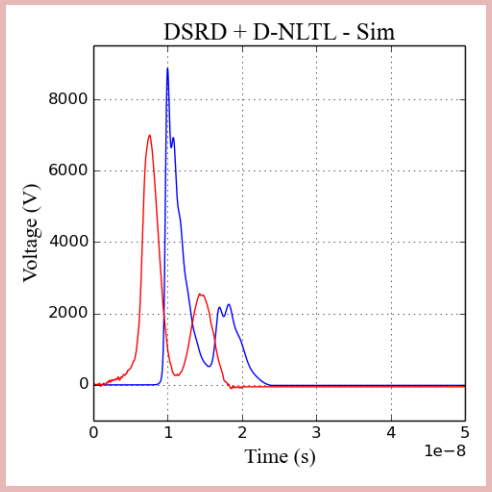
HPM: Technical Discussion/Progress

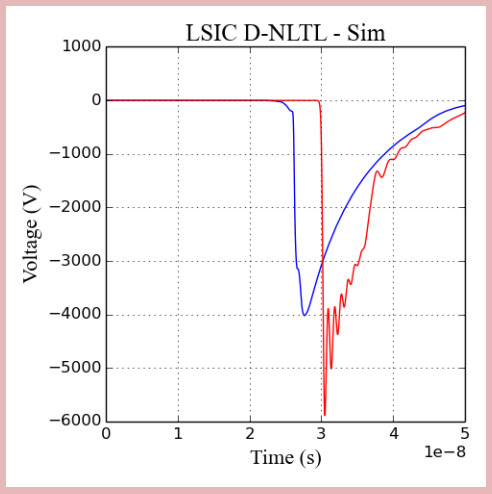
D-NLTLs – HV GHz Designs

Prototype

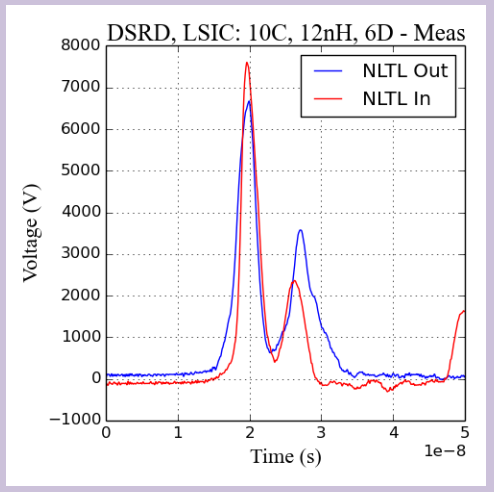
Diode Model	LSIC2SD1 20C10
# Cells	10
# Diodes/Cell	8
Cell Inductance	12.5 nH

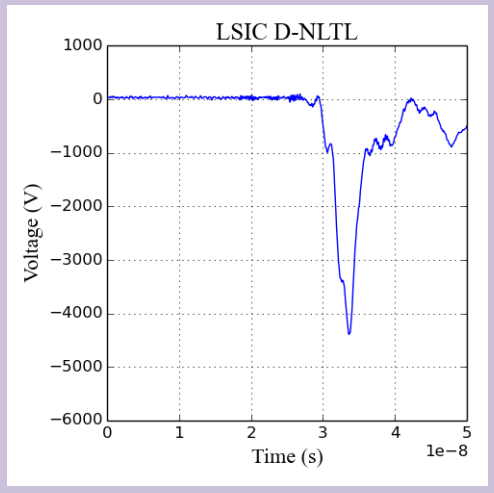
Sims/Intended behavior





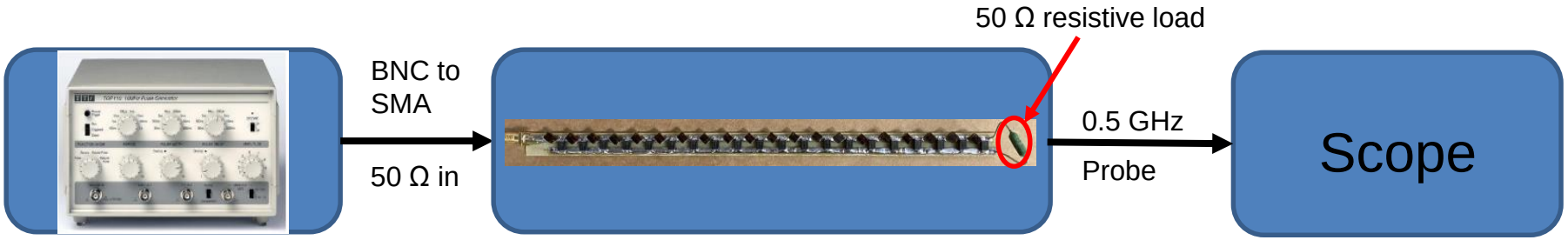
Measurements

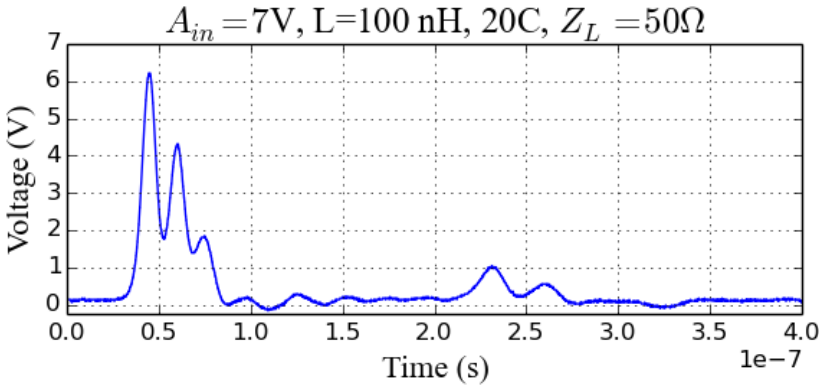


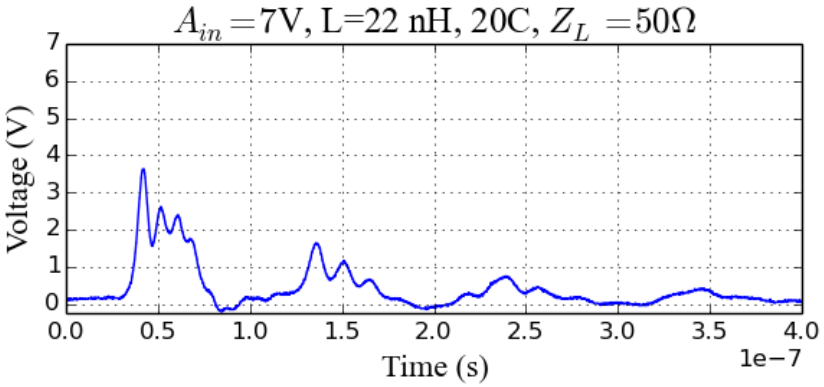


HPM: Technical Discussion/Progress

D-NLTLs – SS22T3G







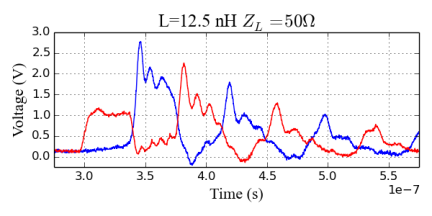
100 nH Cell Inductance	
Fc (MHz)	66.5
Rise (ns)	7.6
Vpk (V)	6.21

22 nH Cell Inductance	
Fc (MHz)	105
Rise (ns)	7.44
Vpk (V)	3.626

HPM: Technical Discussion/Progress

D-NLTLs – SS22T3G

Problem 1: At low L reflections at the Line-Load interface significantly distort waveform.



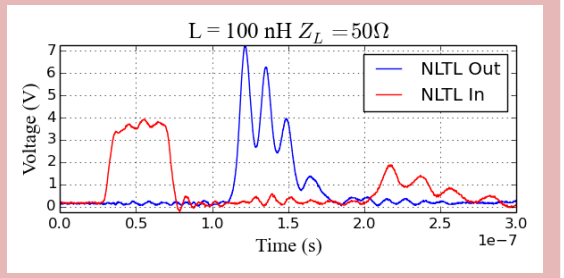
Problem 2: A dynamic Line capacitance introduces a dynamic impedance.

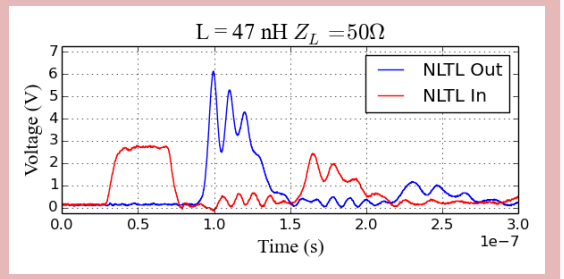
Idea/Solution: Terminate line with an impedance equal to Z_{avg} calculated as:

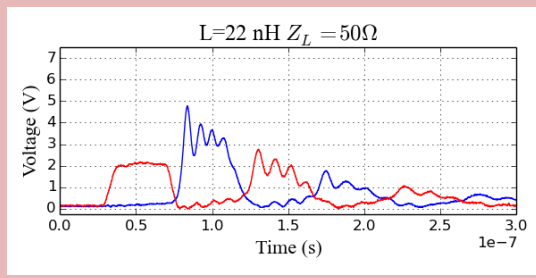
$$Z_{avg} = \sqrt{L/C_{avg}}$$

$$C_{avg} = \frac{1}{V_{max}} \int_0^{V_{max}} C(V)dV$$

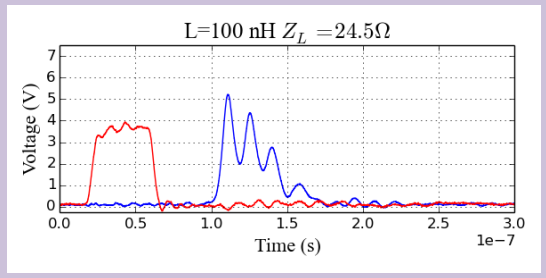
50 Ω Load

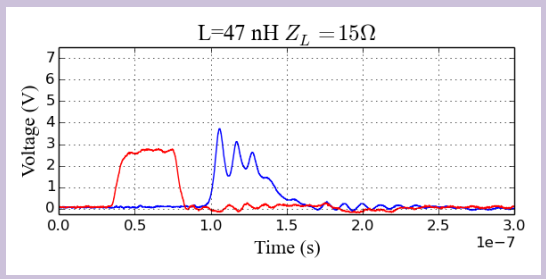


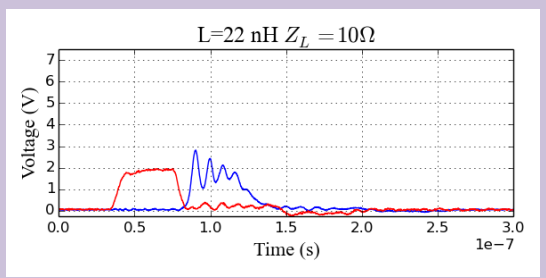




Z_{avg} Load

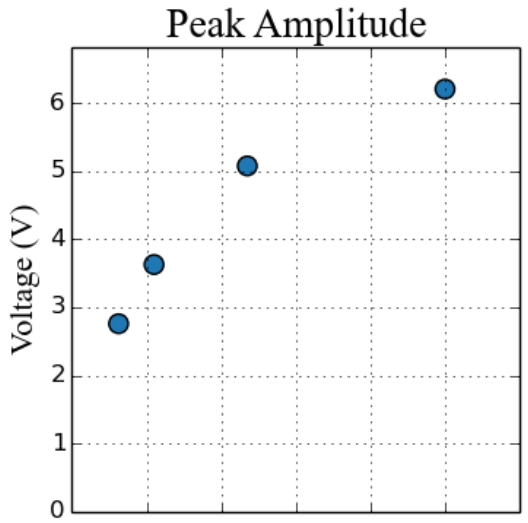


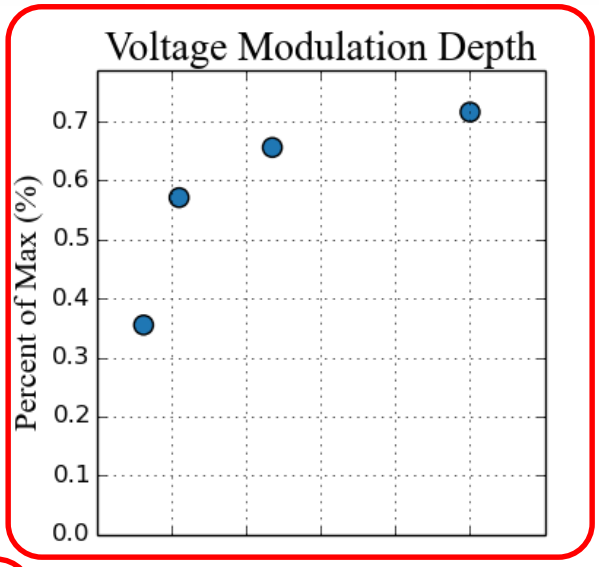


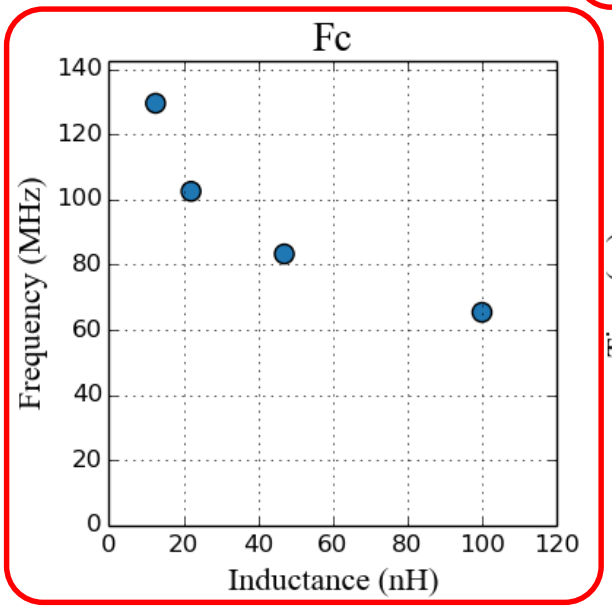


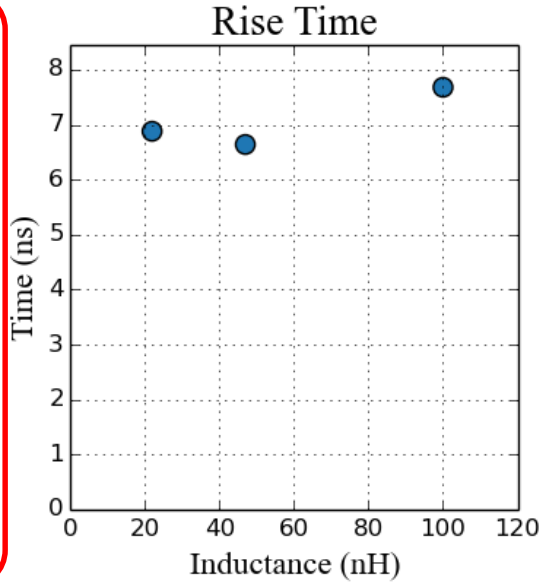
HPM: Technical Discussion/Progress

D-NLTLs – SS22T3G









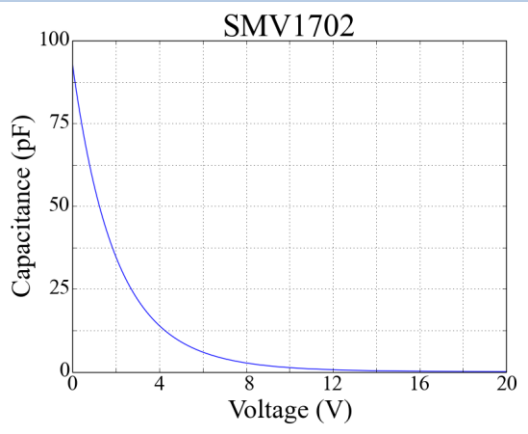
HPM: Technical Discussion/Progress

D-NLTLs – SMV1702

Diode Choice

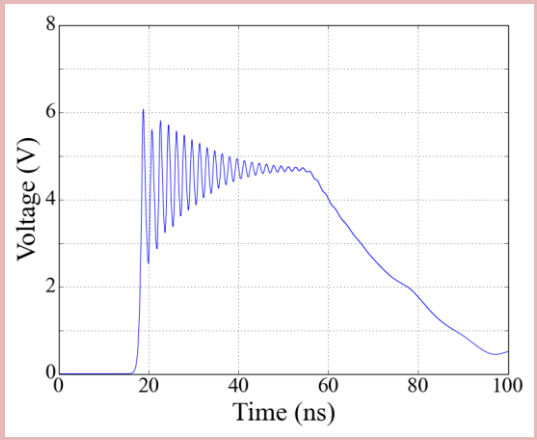
Selection Criteria:

- C_{j0} of 100 – 200 pF
- Order of magnitude drop over a 5-10V operation rage
- V_R of 10 - 20 V



Lossless Sim

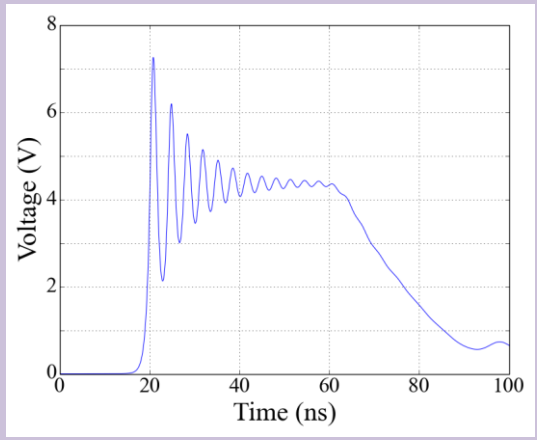
Line Specs	
# Cells	40
Cell L (nH)	22
# Diodes/Cell	1
Load (Ω)	50



Measurements	
Fc (MHz)	526
Rise (ns)	1.02
Vpk (V)	6.06

Lossy Sim

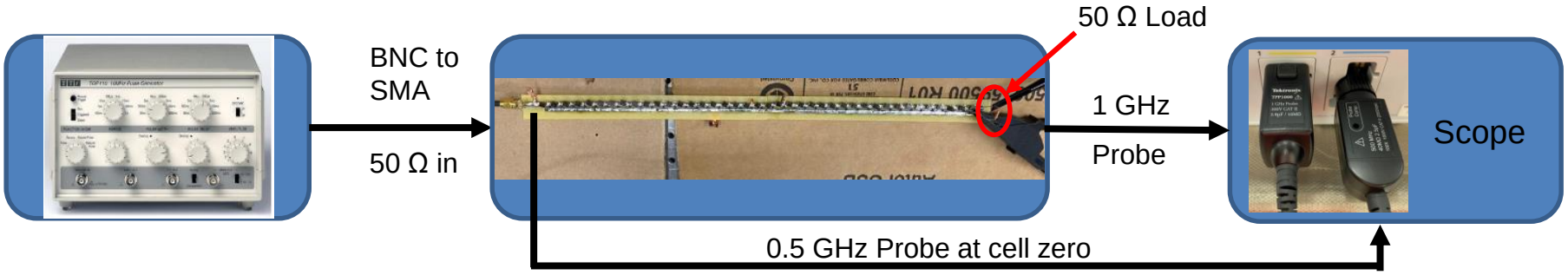
Sources of Loss	
L Parallel C (pF)	2.2
L Series R (mΩ)	5.6
D Series L (nH)	1.5
D Parallel C (pF)	10.36



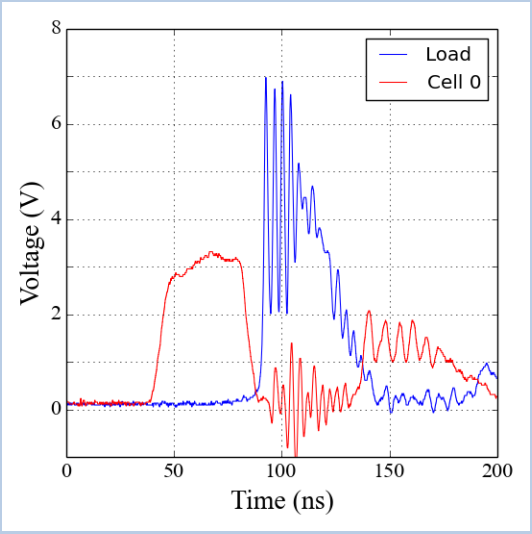
Measurements	
Fc (MHz)	251
Rise (ns)	1.75
Vpk	7.26

HPM: Technical Discussion/Progress

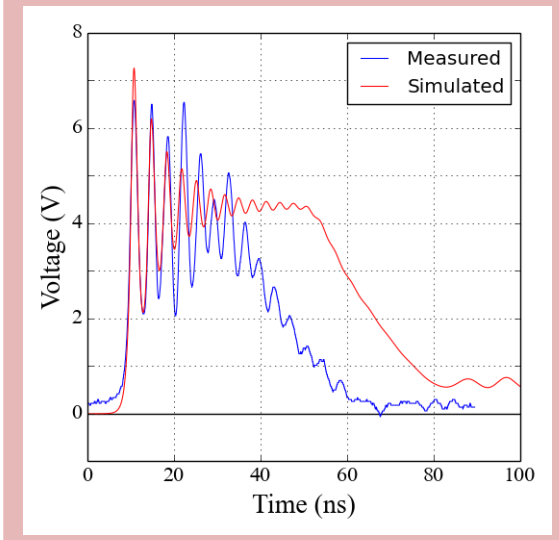
D-NLTLs – SMV1702



Measurement



Sim Comparison



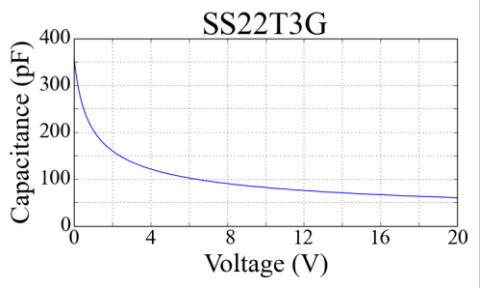
Details

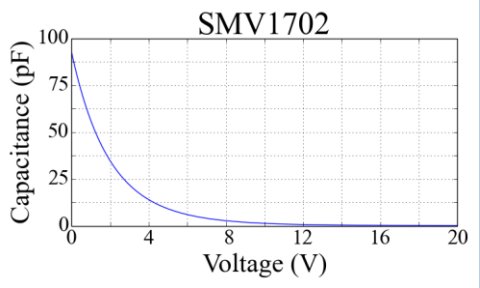
	Meas	Sim
F_C	253	251
rt (ns)	2.28	1.75
V_{pk}	6.94	7.26
VMD (%)	64	71

HPM: Technical Discussion/Progress

D-NLTLs – Next steps in UFH push

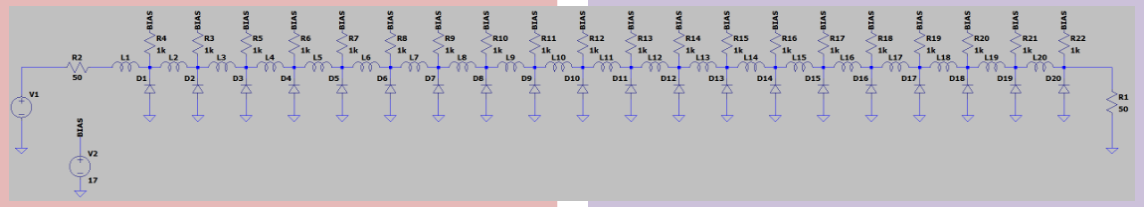
Continued Device Search and Refinement



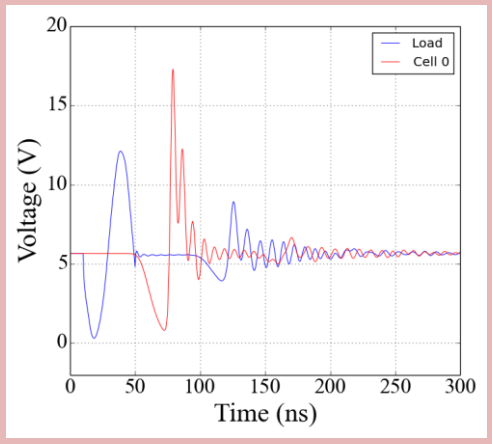


- C_{j0} < 100 pF
- Refinements to SMV line
  - Lowest possible Inductance
  - Resistive load v SMA

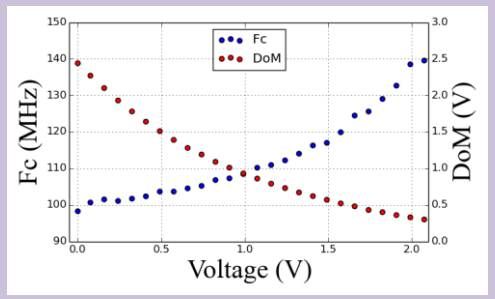
Bipolar Excitation

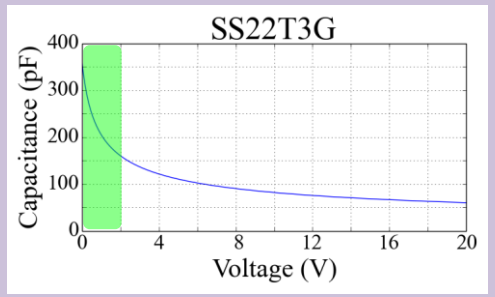


- Bias diodes to the negative polarity amplitude of the bipolar pulse
- Greater frequencies generated from the same pulse amplitude.



Frequency Tuning





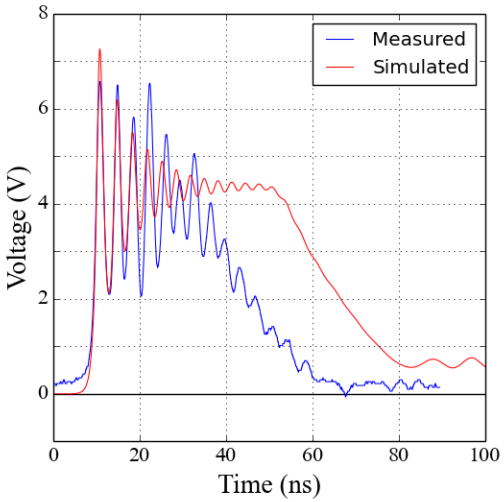
HPM: Research Objective Progress/Findings

NLTL – Summary

Progress

Frequency Generation:

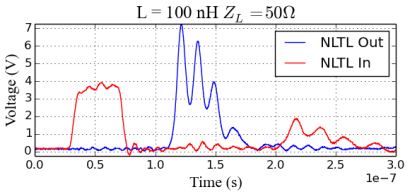
– Fc = 253 MHz, rt = 2.28 ns (F_{bragg}~ 440 MHz)

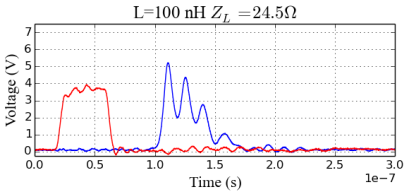


Design Considerations:

– Reflections are minimized with $Z_{load} = Z_{avg}$

– Soliton width and line length must be optimized





Unexpected Results:

– Diode model and line length have a more prominent effect on center frequency and efficiency than inductance

HPM: Conclusions

D-NLTL – Next Steps/Future work

Status: Ongoing

Future Work:

- Continued increase of Line frequency to 0.5 – 1.5 GHz with a goal of 1 GHz
- Identification and characterization of Diode parameters affecting NLTL Frequency Generation for device selection and fabrication
- How are networks best simulated to avoid trial and error?

Next Steps:

1. Optimize SMV1702 Line
2. Fabricate/test voltage biased NLTL (Bipolar & Tunable)
3. Begin Characterizing Diode factors
4. Multi-diode testing

QUESTIONS?

EXTRA SLIDES

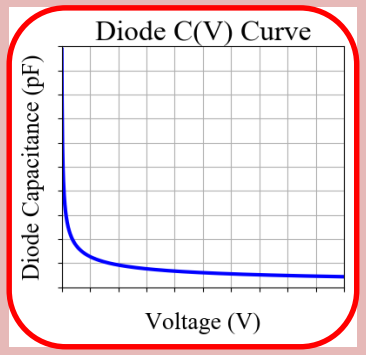
HPM: Technical Discussion/Progress

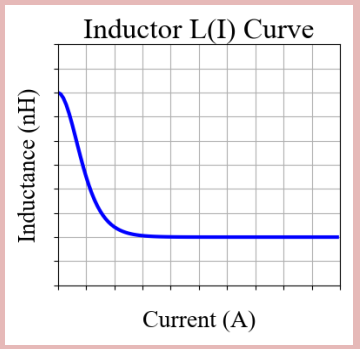
D-NLTLs – Theory/Overview

Propagation rate (Lumped Element)

$$v = \frac{1}{\sqrt{LC}}$$

Nonlinear Component Characteristic curve





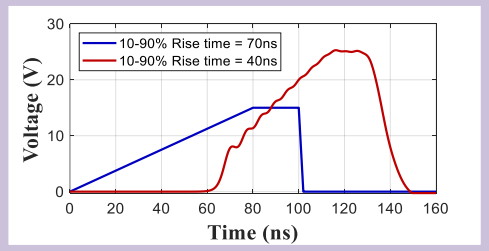
Signal Rise Time & Rise Time Reduction

$$\Delta T = n\left(\sqrt{(LC)_i} - \sqrt{(LC)_f}\right)$$

$tr_{in} \gg \Delta T$

Rise time reduced by ΔT

$-\Delta T \sim 30ns$

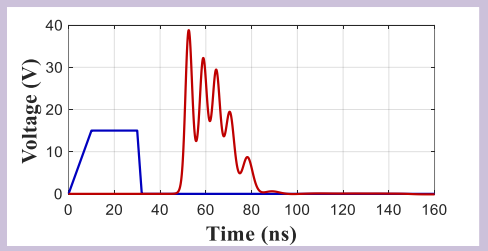


$tr_{in} \ll \Delta T$

Rise time reduced to $0.35\frac{1}{\pi\sqrt{LC_f}}$

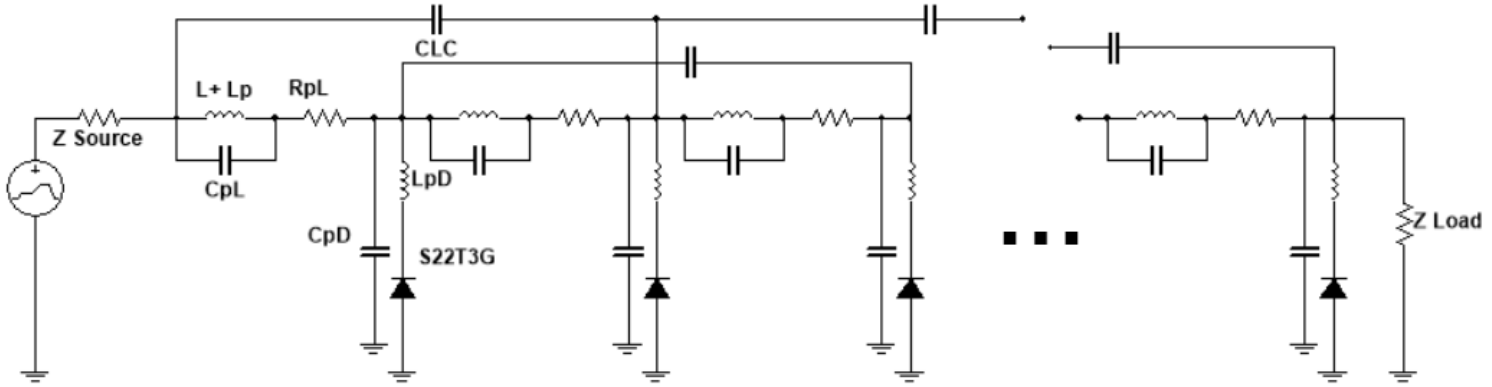
Shockwave forms

Shockwave + Dispersion from LE structure = Soliton

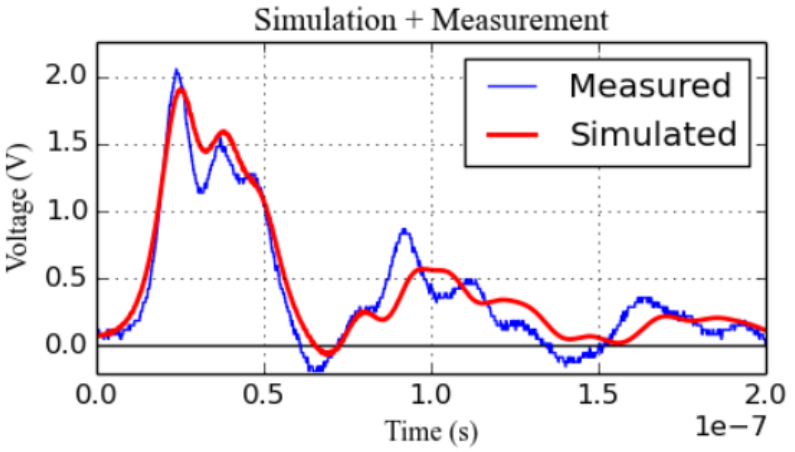


HPM: Technical Discussion/Progress

D-NLTLs – SS22T3G – Sim/Meas Matching

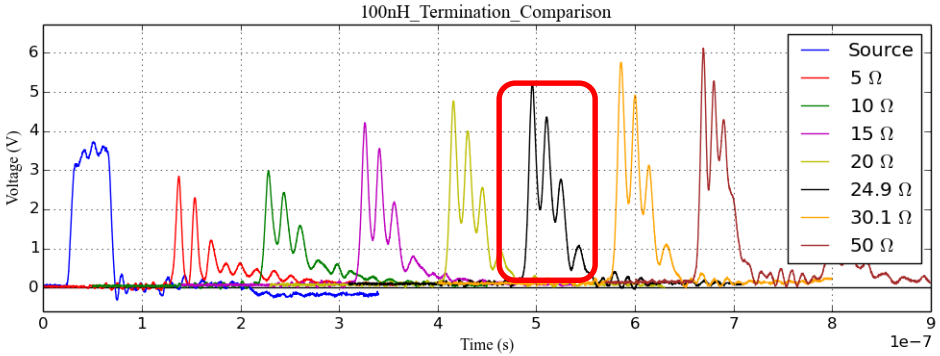


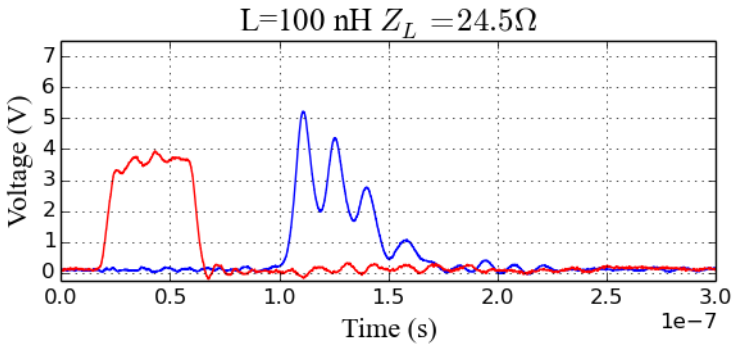
Abbreviation	Name	Value
L + Lp	Inductance + Parasitic L	47nH + 2nH
CpL	Inductor Parallel Capacitance	2.2 pF
RpL	Inductor Series Resistance	5.6 mΩ
CpD	Diode Parallel Capacitance	6 pF
LpD	Diode Series Inductance	1.5 nH
CLC	Cross Link Capacitors	15 pF
Z Source	Source Impedance	45 Ω

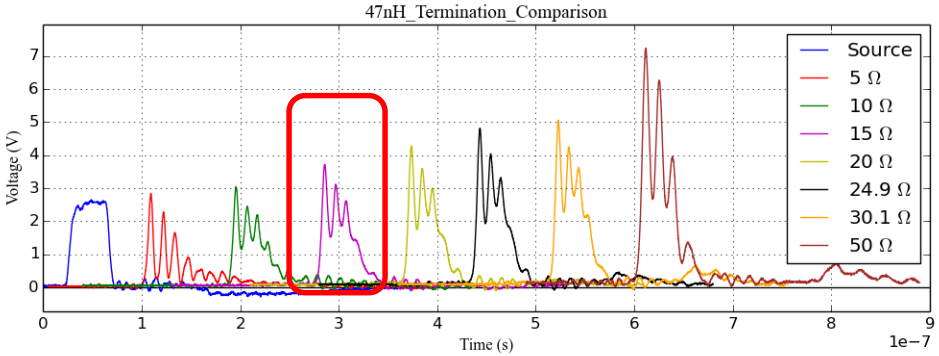


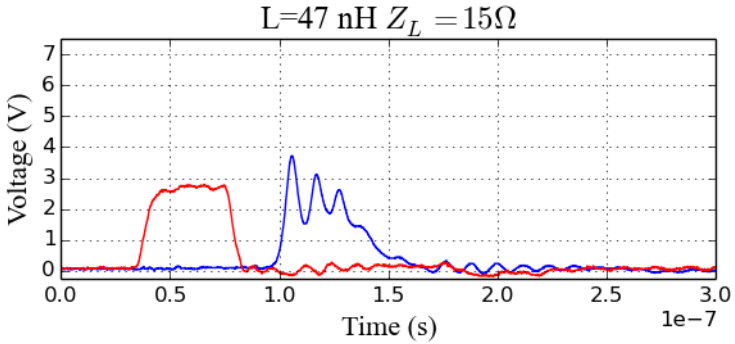
HPM: Technical Discussion/Progress

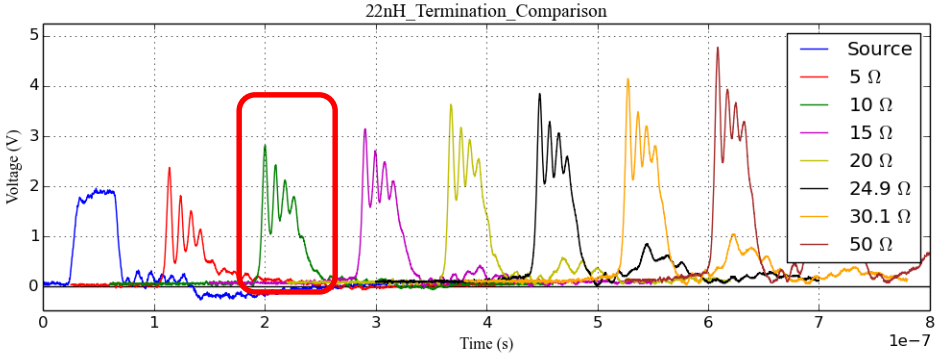
D-NLTLs – SS22T3G – Line/Load matching

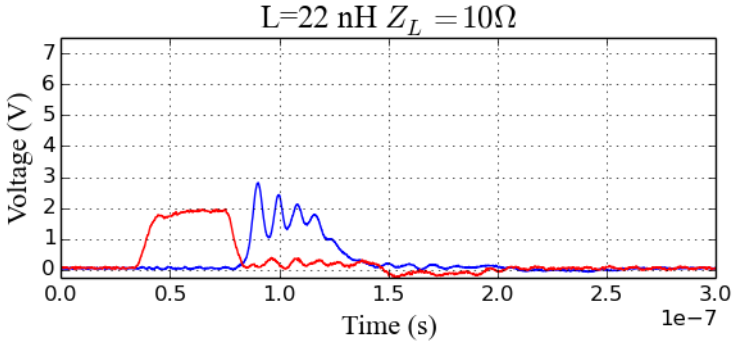






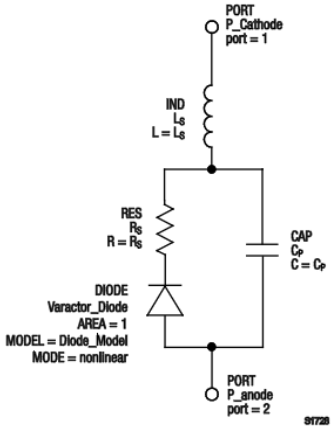


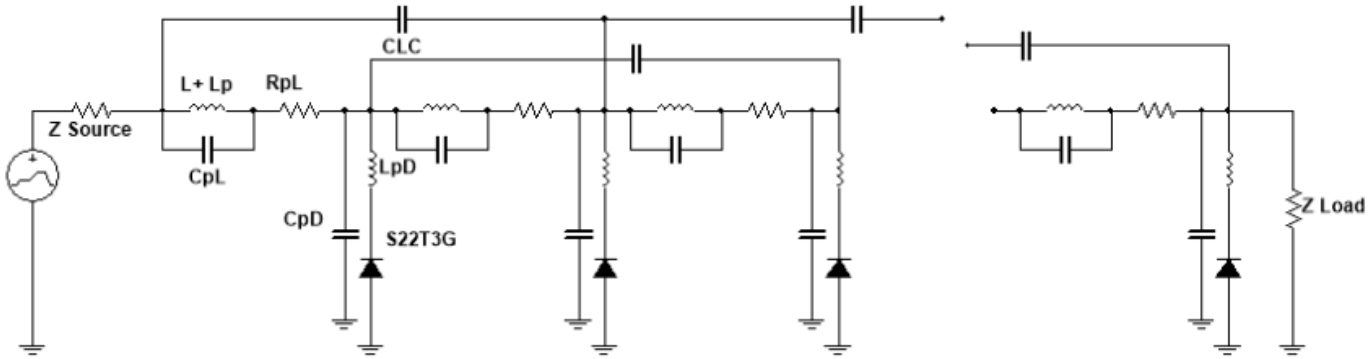




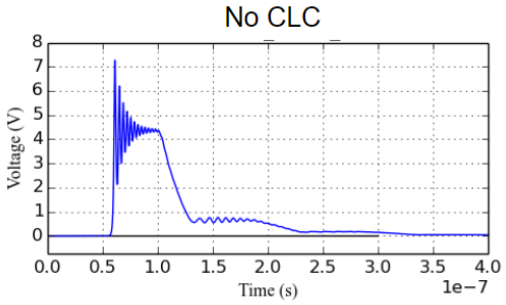
HPM: Technical Discussion/Progress

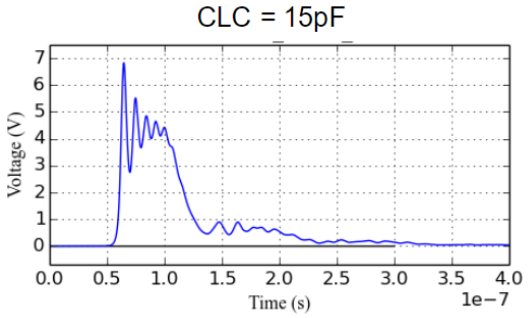
D-NLTLs – SMV1702 – Loss Simulations





Abbreviation	Name	Value
L	Inductance + Parasitic L	22 nH
CpL	Inductor Parallel Capacitance	2.2 pF
RpL	Inductor Series Resistance	5.6 mΩ
CpD	Diode Parallel Capacitance	10.36 pF
LpD	Diode Series Inductance	1.5 nH
CLC	Cross Link Capacitors	Varied
Z Source	Source Impedance	50 Ω





	lossless	No CLC	CLC = 15pF
Fc (MHz)	526	251	77
Rise (ns)	1.02	1.75	4.63
Vpk	6.06	7.26	6.83

FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

Bi-Annual Program Review

Antenna Element Survey for Reduced Aperture Area - UWB Arrays

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Distribution A. Approved for public release.

09 DEC 2020
held via zoom

OSPRES: Antenna Team

Antenna Element Survey for Reduced Aperture Area UWB Arrays

1. Pulse parameters, tradespace study requirements

2. Tradespace study data and tradeoffs between metrics

3. Measure, verify and carry forward important results to OSPRES contract for further refinement

UMKC/MIDE
Antenna TEAM

OSPRES: Antenna Team

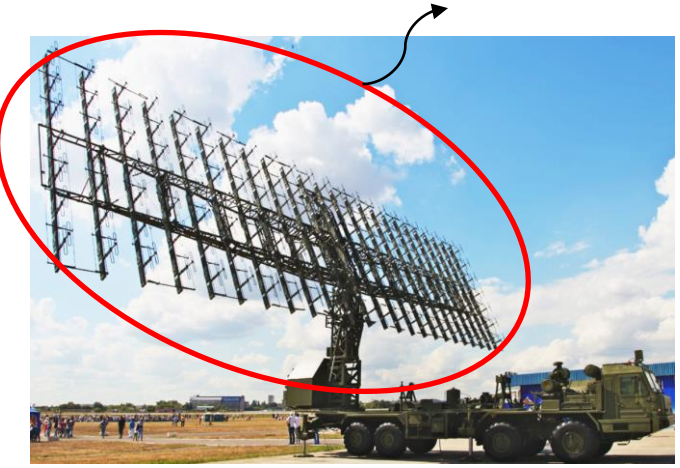
Antenna Element Survey for Reduced Aperture Area UWB Arrays

1. Increasing physical aperture area has been the de facto solution for designing UWB HPM system array antennas to accommodate frequencies in the UHF (300 MHz to 1 GHz) range and to withstand high voltages.

2. A survey has been carried out to identify antenna elements that satisfy UWB HPM system requirements.

3. Tradespace study and analysis on minimally studied/explored 5 UWB HPM antenna elements in conjunction with certain scientific techniques (ex: side lobe reduction, sunflower pattern configuration, enhancing beam steering capabilities) to reduce physical aperture area ('x%' reduction) with negligible change to certain antenna metrics ('y%' change to gain).

1. Physical aperture area



https://pmrpressrelease.com/military-antenna-market-by-type-frequency-platform-and-application-and-forecast-report/

2. Antenna element survey

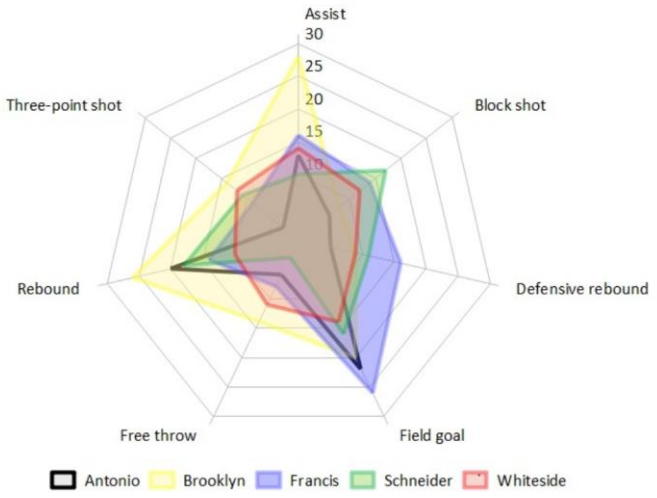
A. Frequency independent antennas

B. Aperture antennas

C. Reflector antennas

D. Travelling wave antennas

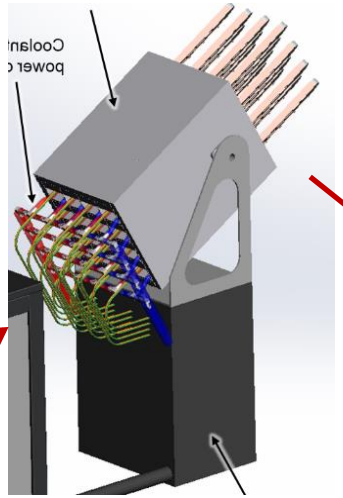
3. Tradespace analysis (a spider plot)

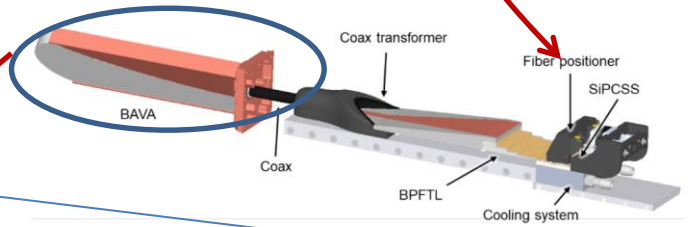


https://www.edrawmax.com/radar-chart/

OSPRES: Antenna Team

Antenna Element Survey for Reduced Aperture Area UWB Arrays





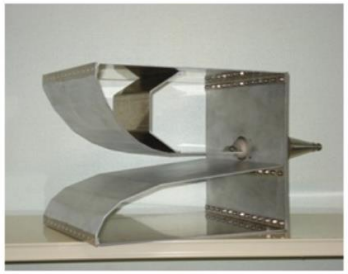
Other UWB HPM antennas

Valentine antenna

Double ridge guided horn antenna

Impulse radiating antenna

Koshelov antenna



ARRAY

ONR HPM Program Key Research Criteria - I

Antenna Element Survey for Reduced Aperture Area UWB Arrays

Research Parameter/Metric Context Description:

1. Physical aperture area
2. Effective aperture area
3. Aperture efficiency
4. Center frequency
5. Bandwidth
6. Realized gain
7. Directionality
8. E-plane, H-plane patterns
9. Half-power beamwidth
10. Side lobe levels
11. Electronic Beam Steering
12. Mutual coupling
13. Peak/Avg. power
14. Pulse shape (Mono./Diff./Bipolar)
15. Radiated E-field
16. Waveform dispersion
17. rE/V
18. Pulse width
19. Rise time
20. Fidelity factor
21. Envelope
22. Pulse repetition frequency
21. Impulse response/Transfer function
22. Full width half maximum (FWHM)
23. Effective radiated power (ERP)
24. Polarization
25. Energy density
26. Energy pattern
27. Ringing
28. Breakdown voltage
29. Profile, Cost, Manufacture difficulty

<u>Quantitative</u> Criteria/Metrics for UWB HPM antenna improvement:

Antenna element type	Frequency dependent dimensions (single element)	Bandwidth	Peak gain	Directionality		FWHM	Ringing	Electronic Beam steering	Aperture efficiency	Effective Radiated Power (ERP)
				E-plane	H-plane					
Balanced antipodal Vivaldi antenna (BAVA)	-	25:1	≈ 8 dBi	Dir.	Dir.	Low (≈ 135 ps)	Low (≈ 150 ps)	Y	> 90 %	Input power (dBm) + peak gain-2.15 dBi

ONR HPM Program Key Research Criteria – II

Antenna Element Survey for Reduced Aperture Area UWB Arrays

<u>Qualitative</u> Criteria:

Goal I: Build a library of tradespace study data for minimally studied UWB HPM antenna elements

State-of-the-art (SOTA): BAVA and TEM horn antenna

Deficiency in SOTA: Large physical aperture size

Proposed Solution: A rigorous tradespace study using computational electromagnetics (EM) solvers on selected UWB HPM antennas with an emphasis on aperture area reduction

Program outcome: An antenna element that meets the performance of SOTA with reduced aperture size

OSPRES: Antenna Team

Antenna Element Survey for Reduced Aperture Area UWB Arrays

- **Risks:** Reaching theoretical limits therefore achieving only few percentage of physical aperture area reduction, incomplete literature review
- **Payoffs:** a massive digital library of tradespace data for multiple antenna elements with reduced aperture area
- **Challenges:** Developing an effective process or work-plan to regularly analyze the incoming data from various antenna element simulations.

HPM: Broader Impact

Antenna Element Survey for Reduced Aperture Area UWB Arrays

Broader impact from this effort could help future ONR projects with immediately choosing an appropriate antenna element based on the project's threshold and objective UWB HPM antenna requirements.

Application of low-power UWB single element antenna or an array antenna in 5G communications, body area networks which can take advantage of the reduced physical aperture area while retaining UWB metrics.

HPM: Sub-Project Research Objective

Antenna Element Survey for Reduced Aperture Area UWB Arrays

Macro Level Objectives:

1. To perform comprehensive tradespace study and analysis on 5 individual antenna elements.

2. Identify, understand and implement scientific technologies that can help improve electronic beam steering capability, side lobe reduction thereby effectively contributing to physical aperture area reduction.

HPM: Technical Discussion/Progress

Antenna Element Survey for Reduced Aperture Area UWB Arrays

Taxonomies of antenna elements which can be used to reduce physical aperture of an UWB HPM array ?

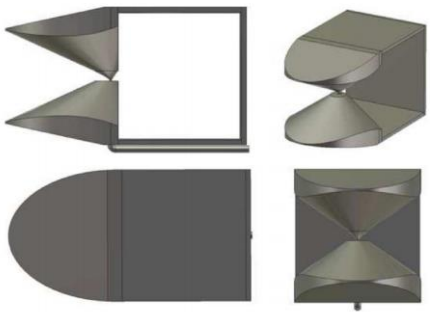
Some taxonomies:

a. Wide frequency band (500 MHz or more) or cover the short pulse frequency spectrum
b. Withstand high peak to peak input voltages for a range of pulse repetition frequency (10's kHz to 100's kHz)
c. Directive in E-plane and H-plane
d. Electronically steerable

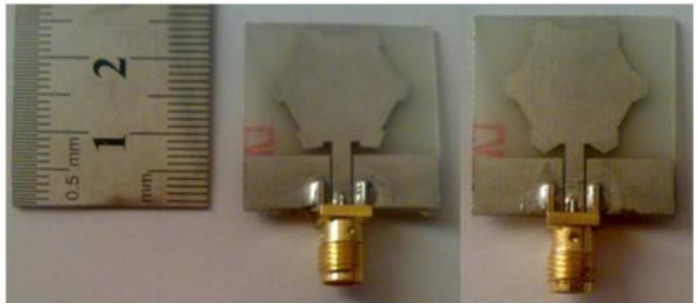
HPM: Technical Discussion/Progress

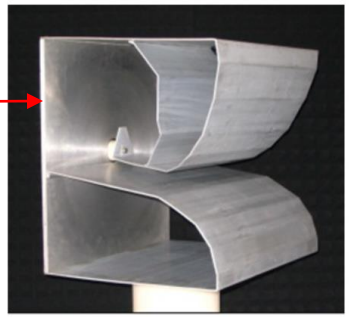
Antenna Element Survey for Reduced Aperture Area UWB Arrays

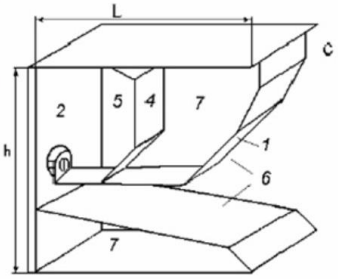
Based on the taxonomies, single/individual antenna element types are identified for UWB HPM applications:



1. Aperture coupled Vivaldi, antipodal Vivaldi antenna
2. Shark antenna
3. TEM horn (Flare, Exponential, K) and double ridge guide horn
4. Log-periodic dipole (con: dispersive, low power handling capability)
5. Spiral antenna (con: circular pol.)
6. Helical antenna (con: difficult to steer and circular pol.)
7. Full and half Impulse radiating antenna, lens IRA
8. Centered and offset reflectors
9. Fractal antennas (good fidelity factor)
10. Bowtie antenna (con: omnidirectional in H-plane)
11. Monocone antenna (con: omnidirectional in H-plane)
12. Koshelov antenna (withstand > 460 kV peak to peak)
13. Leaky wave antenna (high directivity, difficult to steer)
14. Valentine antenna







HPM: Technical Discussion/Progress

Antenna Element Survey for Reduced Aperture Area UWB Arrays

Antenna element type	Dimensions (single element)	Bandwidth	Peak gain	Directionality		FWHM	Ringing	Aperture efficiency
				E-plane	H-plane			
BAVA (SOTA)	-	> 25:1	8 dBi	Dir.	Dir.	Low (≈ 135 ps)	Low (≈ 150 ps)	> 90%
Spiral antenna	D = λ/π	10:1	7.5 dBi	Dir.	Dir.	Around 200 ps	Around 250 ps	40% to 50%
Shark antenna	λ/3.52 × λ/3.36 × λ/1.91	10:1	7 – 8 dBi	Dir.	Dir.	Lower than vivaldi	Unknown	Unknown
Koshelov antenna	-	6:1	6 – 8 dBi	Dir.	Dir.	Unknown	Unknown	85% (energy efficiency)
Fractal antenna	-	2:1	4 - 6 dBi	Dir.	Dir./Omni	Assuming low (100 to 200 ps) due to good fidelity factor reported in literature	Assuming low due to good fidelity factor	> 90%
Leak wave antenna	0.83λ (length, 1D)	≈ 2:1 or less	7 – 8 dBi	Dir.	Dir.	Higher than Vivaldi	Higher than Vivaldi	50% to 60%

Distribution A

HPM: Technical Discussion/Progress

Antenna Element Survey for Reduced Aperture Area UWB Arrays

Other scientific techniques that can be used to try and reduce physical aperture area

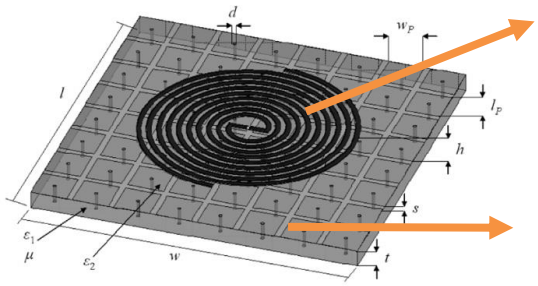
- Inductive loading (magnetic materials or planar meandering) [23]
- Dielectric loading [23], Dielectric embedding [7]
- Resistive terminations (to reduce reflections/ringing but reduces efficiency)
- Subarray overlapping (to reduce sidelobes) [27]
- Electromagnetic band-gap (EBG) ground plane [19]
- Array configuration (square, rectangular, triangular, hexagonal, sunflower [25] etc.)
- Defected ground structures (mutual coupling reduction) [24]
- Beveling and creating slots (increases impedance BW) [21]
- Frequency dependent notches (to reduce impedance BW and creates pass/stop band characteristics) [6,20]
- Iterative projection method (side lobe reduction) [30]
- Dielectric/Metamaterial lens
- E-plane vs H-plane array and subarray placements [29]

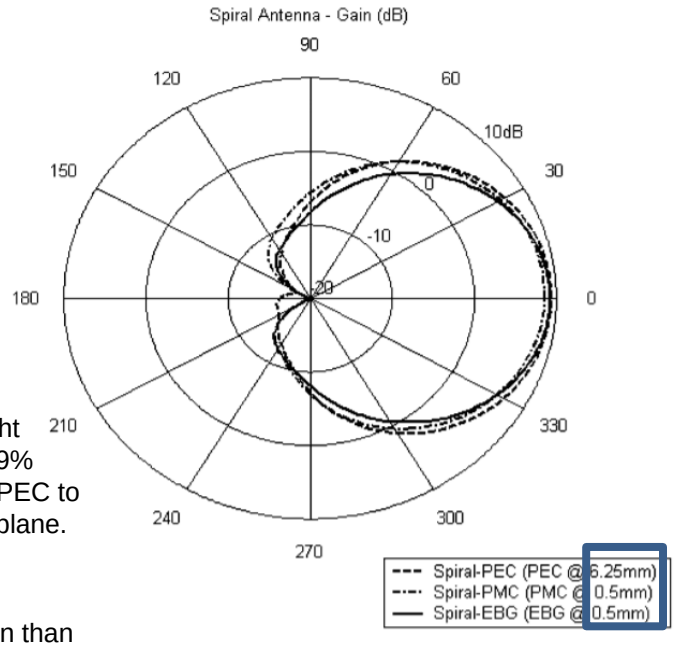
HPM: Technical Discussion/Progress

Antenna Element Survey for Reduced Aperture Area UWB Arrays

How an EBG or non-conventional array configuration can help with aperture area reduction ?

PEC, PMC vs EBG ground plane

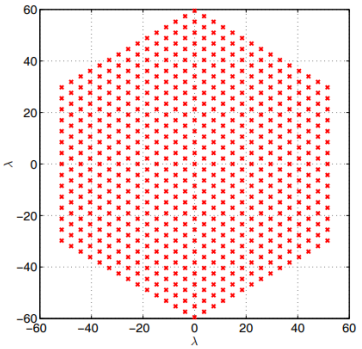




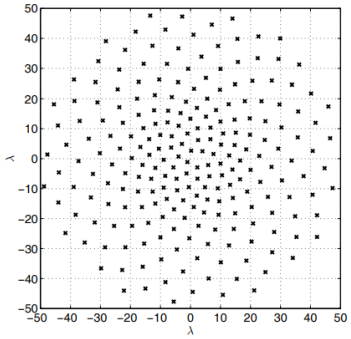
Antenna height reduced by 69% moving from PEC to EBG ground plane.

Lower back-lobes/radiation than PEC.

Regular v. Sunflower array configuration



Regular (631 elements)



Sunflower (230 elements)

TABLE II

COMPARISON BETWEEN THE CONFIGURATIONS

array lattice		regular	tapered sunflower
sub-array excitations		Taylor	constant power
	required	achieved	
EOC gain no scan	43.8dBi	44.8dBi	44.5dBi
SLL 1 no scan	20dBi	20dBi	19.5dBi
SLL 2 no scan	25dBi	13.8dBi	20dBi
SLL 3 no scan	30dBi	30dBi	20dBi
EOC gain scan	43.8dBi	43.9dBi	43.7dBi
SLL 1 scan	20dBi	20dBi	20dBi
SLL 2 scan	25dBi	20dBi	23.5dBi
SLL 3 scan	30dBi	38.5dBi	23.5dBi
aperture eff %		89.4%	91.6%
aperture radius		60λ	50λ

HPM: Research Objective Progress/Findings

Antenna Element Survey for Reduced Aperture Area UWB Arrays

Specific progress :

A broad investigation into various individual antenna elements that offer potential to reduce the physical aperture area while allowing electronic beam steering

Significant findings :

Identified 5 antenna elements that were minimally studied in the literature in relation to UWB HPM requirements.

1. Shark antenna
2. Koshelov antenna
3. Leaky wave antenna
4. Fractal antenna
5. Spiral antenna

HPM: New Ideas / Opportunities

Antenna Element Survey for Reduced Aperture Area UWB Arrays

A novel trade-space tool that can compare different antenna metrics for a class of pre-defined antenna elements in relation to user defined antenna requirements and UWB HPM pulses.

HPM: Conclusions

Antenna Element Survey for Reduced Aperture Area UWB Arrays

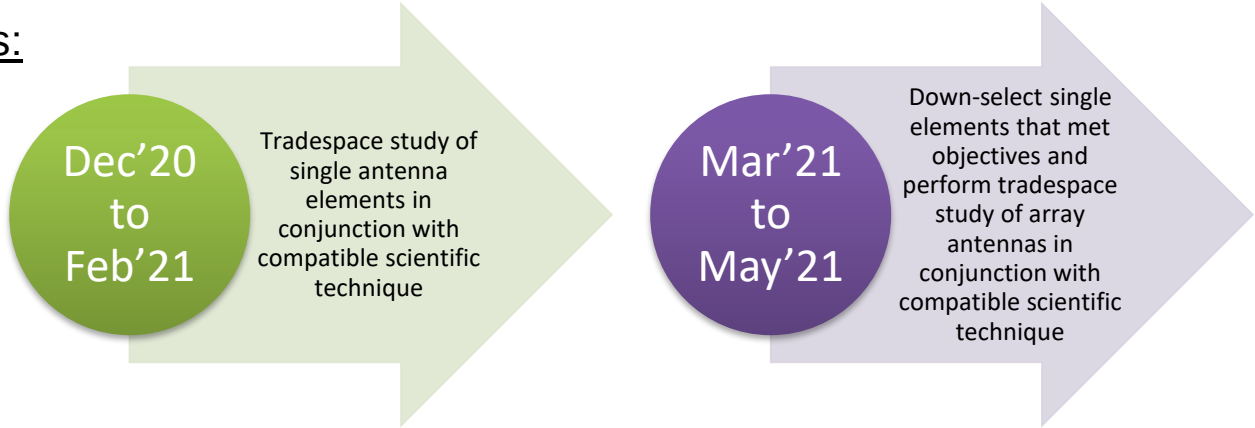
Next steps:

1. Develop and implement tradespace study steps specific to each down-selected antenna element.
2. Identify antenna elements from step 1 that showed promising aperture area reduction results and build an array.
3. Develop and implement tradespace study tasks in particular to array identified in step 2.
4. Understand pros and cons of each scientific technique in their application to UWB single element and/or array.
5. Assess and analyze step 3 results and pick scientific techniques from step 4 that can be integrated and studied for aperture area reduction.

Resources Needed:

1. Have been identified internally and are being currently addressed. Nothing significant to highlight in this review meeting.

Mini-milestones:



HPM: References

Antenna Element Survey for Reduced Aperture Area UWB Arrays

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Thank you.

Any questions ?

–Distribution A

HPM: Technical Discussion/Progress

Antenna Element Survey for Reduced Aperture Area UWB Arrays Electronic Beam Steering

In an antenna array, the time delay that determines the final waveform depends on both the element spacing and scan angle.

$$s(t,\phi) = f(t,\phi) * \sum_{n=0}^{N-1} \delta(t - n\Delta t - \tau_n) = \sum_{n=0}^{N-1} f(t - n\Delta t - \tau_n, \phi),\ \Delta t = \frac{d\sin\phi}{c}$$

$$P_{energy}(\phi) = \int_0^{\infty} |s(t,\phi)|^2 dt$$

$$P_{peak}(\phi) = \mathrm{Max}\{s(t,\phi)\}$$

$$P_{cross}(\phi) = \int_0^{\infty} s(t,\phi) b(t) dt$$

Three observations can be made from the results. (1) The beam width of the main lobe for each pattern will be narrowed by increasing the number of antenna elements, or the element spacing. (2) Given an array configuration, the peak value pattern has the narrowest beam width for the main lobe, and the lowest sidelobe level, while the cross correlation pattern has the widest beam and the highest sidelobe level. (3) The sidelobe level increases with element spacing.

FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

Bi-Annual Program Review

Tradespace Analysis of ESA Array

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09 DEC 2020
held via Zoom

Distribution A. Approved for public release.

OSPRES: Antenna Group

Tradespace Analysis of ESA Array

Supervising

Modeling & Analysis

Fabrication & Testing

Goals/ Targets

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Sr. Research Specialist

Kalyan C. Durbhakula
Asst. Research Professor

OSPRES: Antenna Group
Tradespace Analysis of ESA Array

- High gain and wideband antennas at UHF range have large physical size.
- Antenna arrays required to be placed on Naval vessels must meet SWaP considerations (i.e., Small in size, Light weight and capable of HPM transmissions).

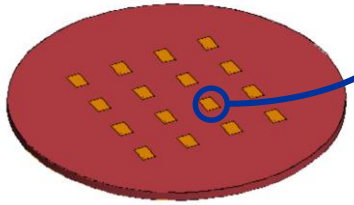
A radar antenna at UHF range

Too big for Naval Vessels

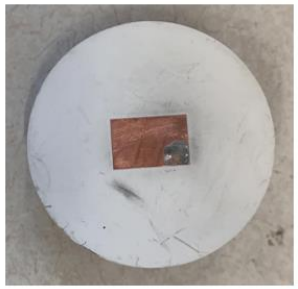
- A method to reduce physical aperture area is to use Electrically Small Antenna (ESA) elements in an array, and arrange them in proper grid formation (eg., hexagonal or triangular) – with the aim to achieve comparable performance with conventional antenna arrays.

OSPRES: Antenna Group
Tradespace Analysis of ESA Array

Using microstrip ESA elements can reduce the physical aperture size of the phased array while maintaining comparable performance w.r.t conventional arrays.

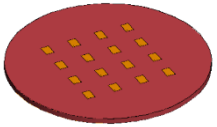


Lightweight microstrip patch antenna array.

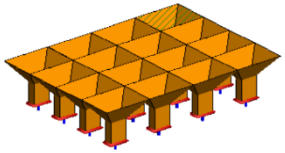


Coaxial probe-fed Microstrip Patch Antenna

An Example	4x4 ESA Array	4x4 Horn Antenna Array
Operating Frequency (MHz)	815	815
Radiating Aperture Area (m^2)	0.24	8.5
Gain (dBi)	14.0826	25.963



ESA Array



Horn Antenna Array

97% aperture area reduction → 46% gain reduction.

ONR HPM Program Key Research Criteria - I

Tradespace Analysis of ESA Array

Qualitative Criteria:

Goal: Determining the extent to which the physical aperture size of an antenna array can be reduced, while maintaining performance over the UHF range (0.4 – 1 GHz), compared with present art - HPM capable antenna arrays.

State-of-the-Art (SOTA): Ultra wideband antennas for HPM transmissions (such as Horn, Reflector, Vivaldi, etc.) are used as elements in a phased array to obtain high gain and power density at the required engagement range.

Deficiencies in SOTA: Achieving high gain and wide bandwidth from antenna arrays at low frequency comes at the cost of large physical aperture size.

Proposed Solution: Using ESAs as Array Elements to reduce physical aperture size; followed by optimization of the design in terms of both near-field (Quality Factor → Bandwidth) and far-field (Directivity) parameters, simultaneously, via D/Q ratio.

Program outcome: ESA microstrip patch antenna array (5.73 m^2 radiating aperture area) have been designed to operate in the UHF range (640 – 990 MHz), having gain (27.76 dBi) and steering capability (0 to $\pm 60°$) comparable to established antennas.

ONR HPM Program Key Research Criteria - II

Tradespace Analysis of ESA Array

Quantitative Criteria:

Parameters	Definitions	Expected Value
2:1 VSWR Bandwidth	The range of frequencies within which the VSWR of the antenna < 2.	600 – 1000 MHz (50%)
Gain	The ratio of the radiation intensity in a given direction to the radiation intensity that would be produced if the power accepted by the antenna were isotropically radiated.	≥ 30 dBi
Effective Aperture Area	A theoretical value which is a measure of how effective an antenna is at receiving power.	-
ERP	Relative gain of a transmitting antenna w.r.t max. directivity of a half-wave dipole multiplied by the net power accepted by the antenna from the connected transmitter.	
Half Power Beamwidth	Angle between the two directions in which the radiation intensity is one-half the maximum value.	< 10°
Beam Diameter	The radiation spot size at a target which is related to the antenna's beam width and target range.	-
Beam Steering	Changing the direction of the major lobe of a radiation pattern.	0 to ±60°

HPM: Sub-Project Research Objective

Tradespace Analysis of ESA Array

- Determining the extent to which the physical aperture size of the antenna array can be reduced, while maintaining performance (in peak power density, bandwidth and electronic beam steerability of short pulses) over the UHF range; Comparing with present art - HPM capable antenna arrays.

Targeted Frequency Range: 0.6 – 1 GHz

Steering Range: ±60° from boresight

HPM: Technical Discussion/Progress

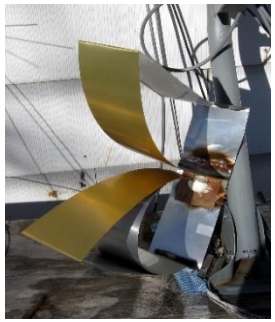
Tradespace Analysis of ESA Array

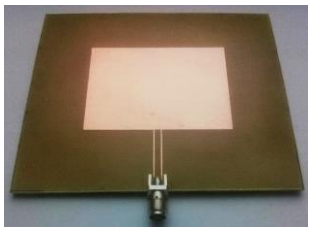
Step - I
- Design single Antenna Element at UHF range.

Step - II
- Select Lattice Type.
- Integrate the designed antenna elements to model a phased array.

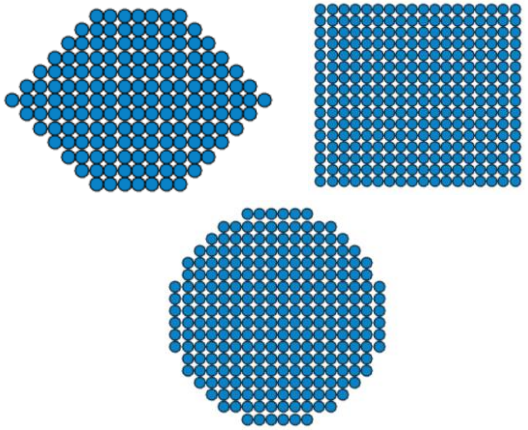
Step - III
- Tradespace analysis of the array.

Step - IV
- Build and test a minimum viable validation prototype.



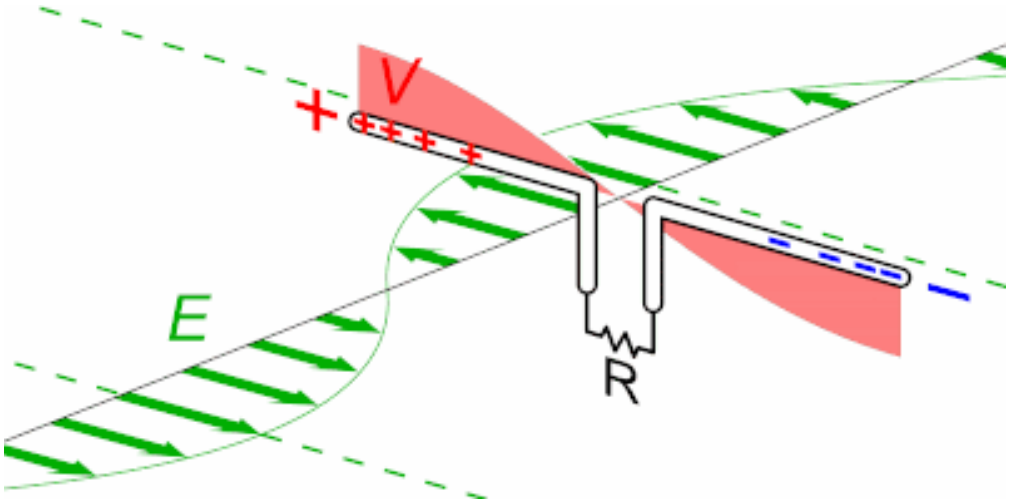


Common Antennas Elements used in Phased Arrays



Lattice Types

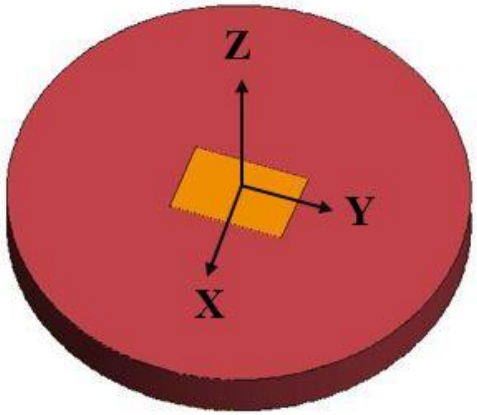
I: Antenna Element Design



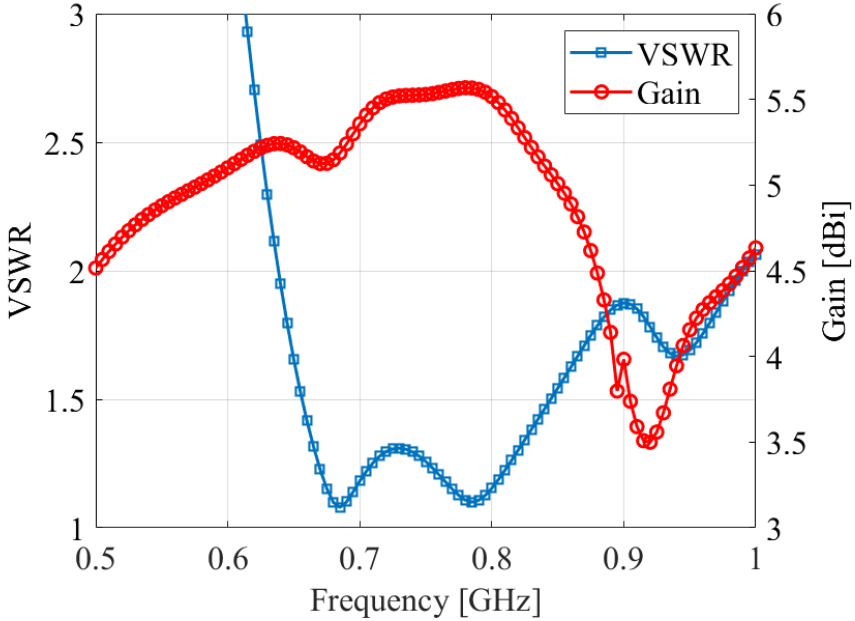
Electrically Small Microstrip Patch Antenna Design at UHF region

- A general method to achieve > 35% impedance bandwidth from coaxial probe-fed microstrip patch ESAs has been developed [1].
- Using this method, an antenna element is modeled at UHF range.
- Substrate used: 26.67 mm (1.05") thick TMM-10i ($\varepsilon_r = 9.8, \tan\delta = 0.002$) from Rogers Corp.

Parameters	Values
L (mm)	41.37
W (mm)	62.05
r_p (mm)	2
r_g (inch)	4.21
(x_p, y_p) (mm, mm)	(13.79, 20.685)



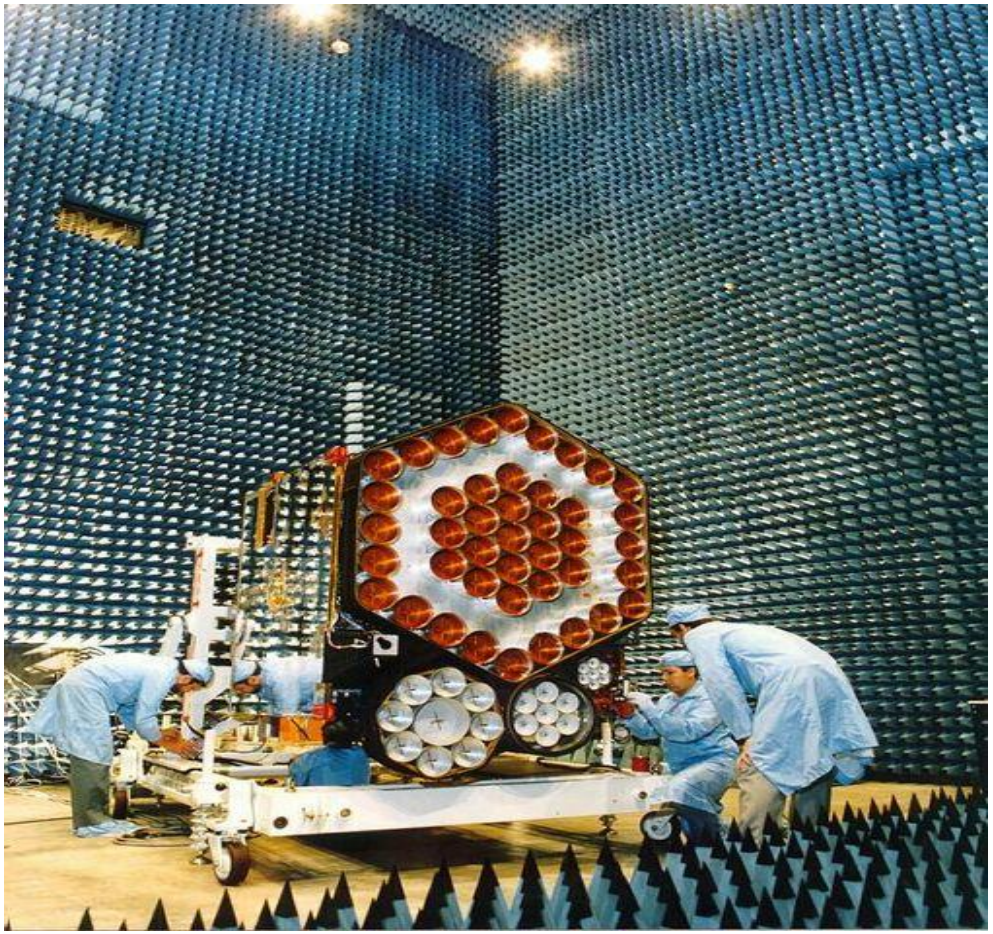
Simulation Model of the Antenna



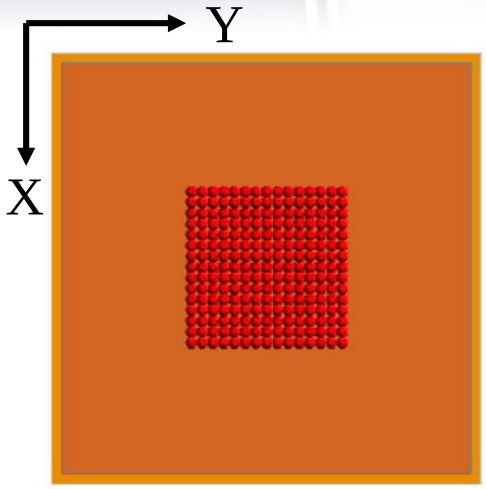
% BW	Max. Gain (dB)	ka
43.27	5.67	0.67

[1] B. Barman, K. C. Durbhakula, B. Bissen, D. Chatterjee and A. N. Caruso, "Performance Optimization of a Microstrip Patch Antenna using Characteristic Mode and D/Q Analysis," *2020 XXXIIIrd General Assembly and Scientific Symposium of the International Union of Radio Science*, Rome, Italy, 2020, pp. 1-4.

II: Array Design

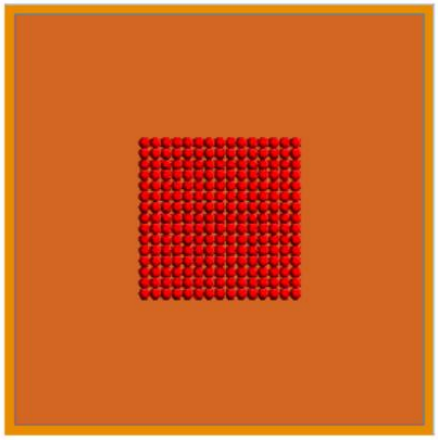


Planar Array of Microstrip ESAs

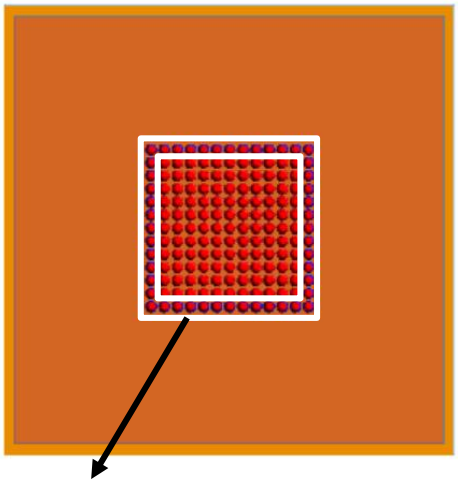


- 15 × 15 Array modeled on infinite ground plane.
- Inter-element spacing:
  $d = 0.5\lambda$
- λ calculated at 814.4 MHz.

Degradation in Radiation Pattern observed at high frequency end.



- 15 × 15 Array modeled on infinite ground plane.
- Inter-element spacing [2]:
  $d = 0.485\lambda_h$
- λ_h calculated at 990.6 MHz.

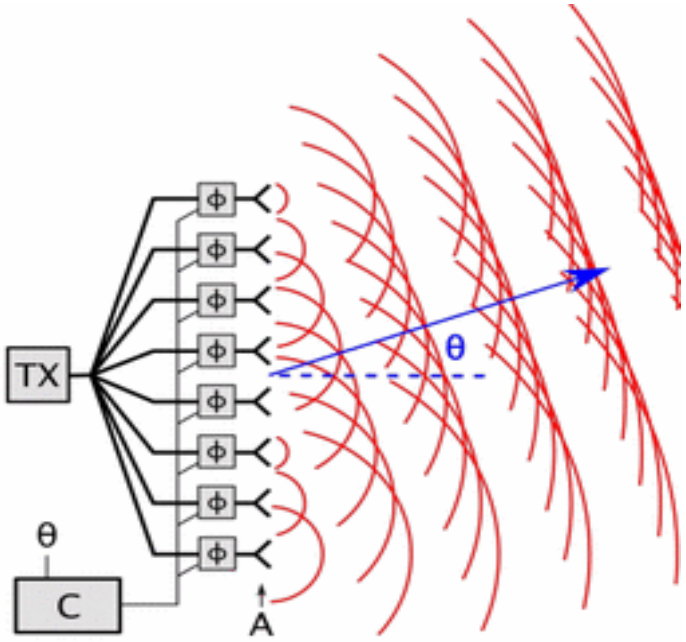


- A ring of dummy elements placed around the 15 × 15 Array.
- $d = 0.485\lambda_h$
- λ_h calculated at 990.6 MHz.

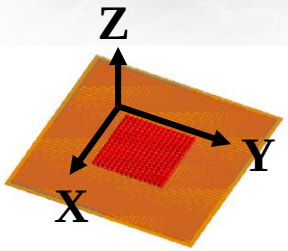
Radiation Pattern improved at high frequency end.

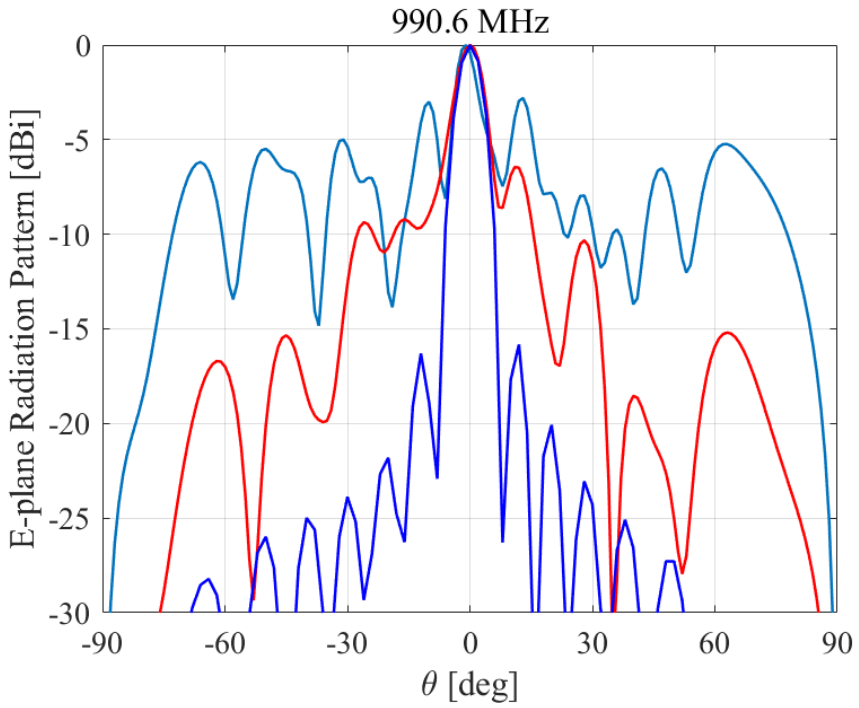
[2] S. K. Rao and C. Ostroot, "Design Principles and Guidelines for Phased Array and Reflector Antennas," *IEEE Antennas and Propag. Mag.*, Vol. 62, No. 2, pp. 74-81, April 2020.

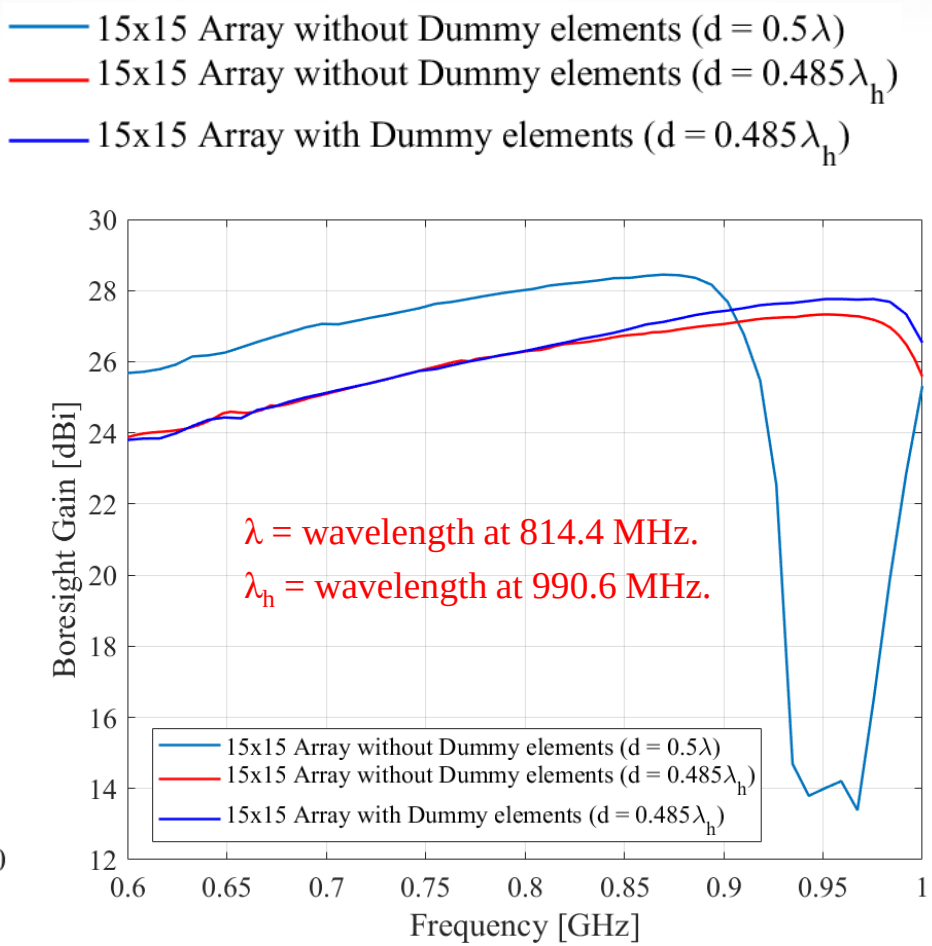
III: Tradespace Analysis of the Array of ESA Microstrip Patches



Radiation Pattern & Array Boresight Gain

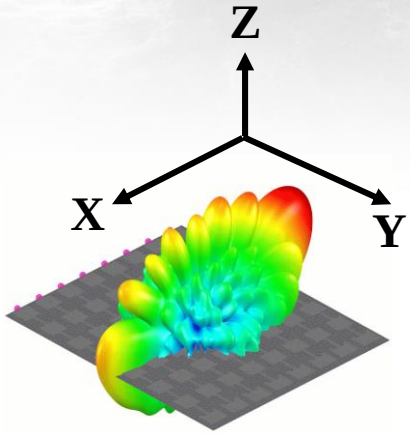




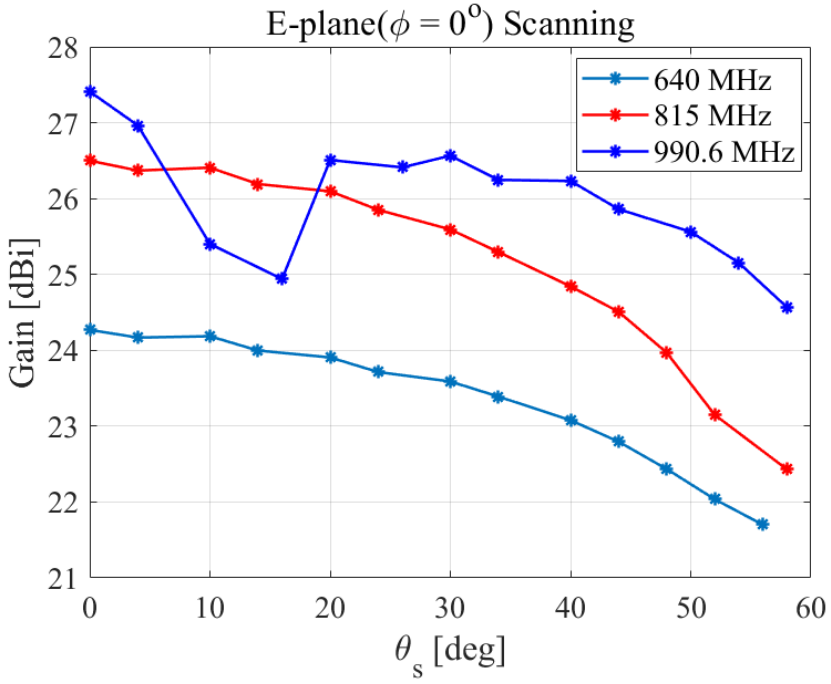


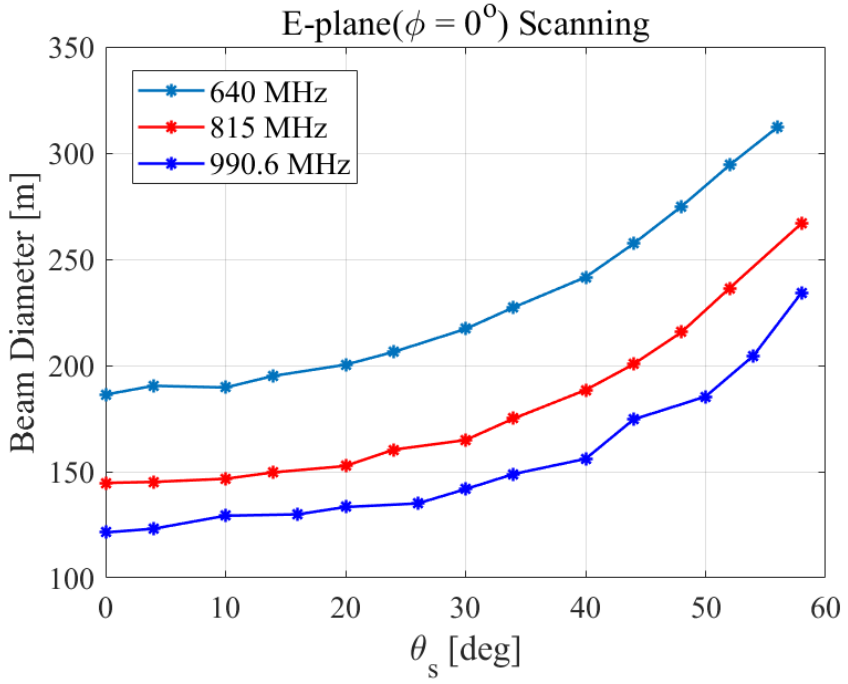
- Use of dummy elements with $d = 0.485\lambda_h$ significantly improves radiation pattern at 990.6 MHz.
- Array Models have been simulated on infinite ground plane to reduce computation time.

Beam Steering in XZ-plane or E-plane



The main beam of the 15×15 array (with a ring of dummy elements) and $d = 0.485\lambda_h$ (λ_h calculated at 990.6 MHz) is steered from 0 to $\pm 60°$ over the UHF region.



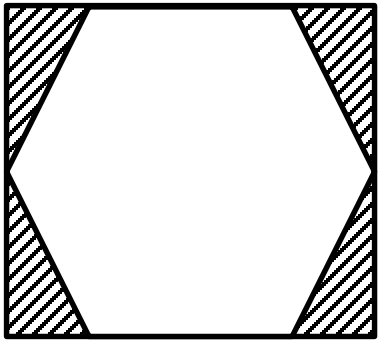


θ_s = Steering angle from zenith

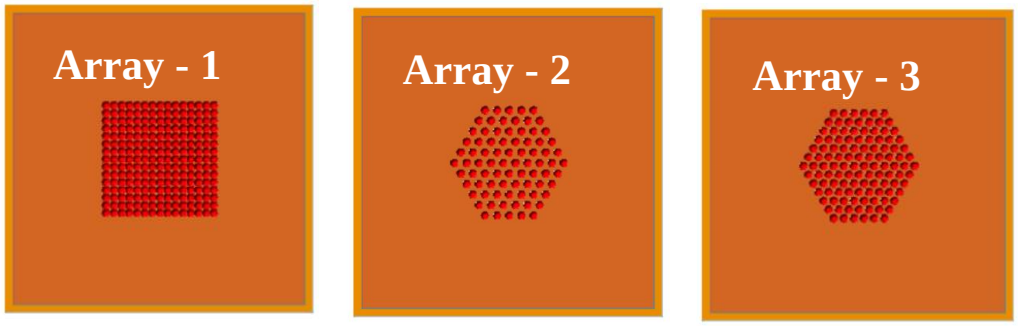
[3] J. T. Tatum, "Radio Frequency, Directed Energy Weapon Design Tool," *DSAIC Journal*, vol. 5, no. 4, pp. 20-23, Fall 2018.

Array Aperture Area Reduction

- Array model transformed from square to hexagonal lattice as shown (Elements in the shaded area removed) → ≈ 30% Aperture Area Reduction.



Transforming from Square to Hexagonal Lattice.

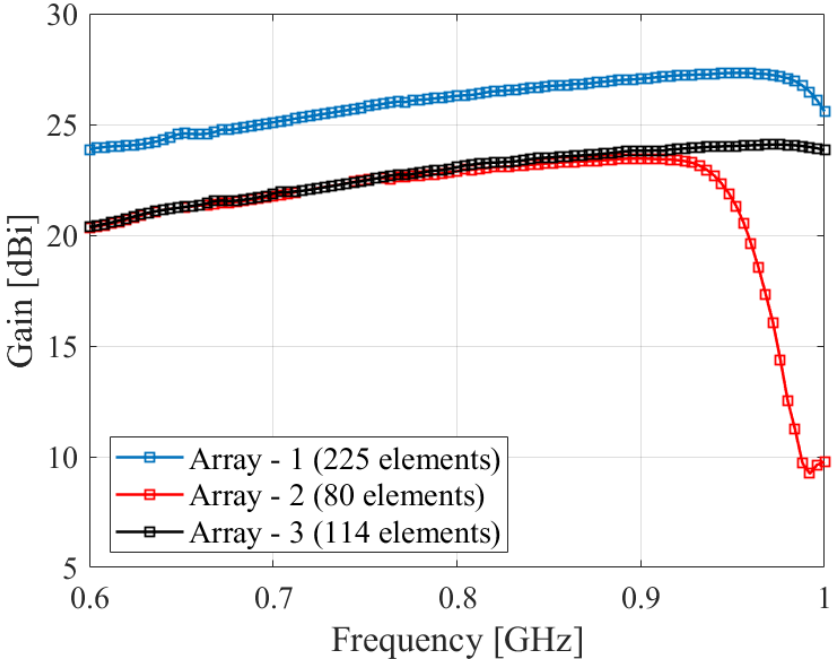


Simulation Models of the Arrays on infinite ground plane

Array #	Aperture Area (m^2)	Inter-element spacing (d)	Total No. Elements
1	4.43	$0.485\lambda_h$	225
2	≈ 3.10	$0.6\lambda_h$	80
3	≈ 3.10	$0.5\lambda_h$	114

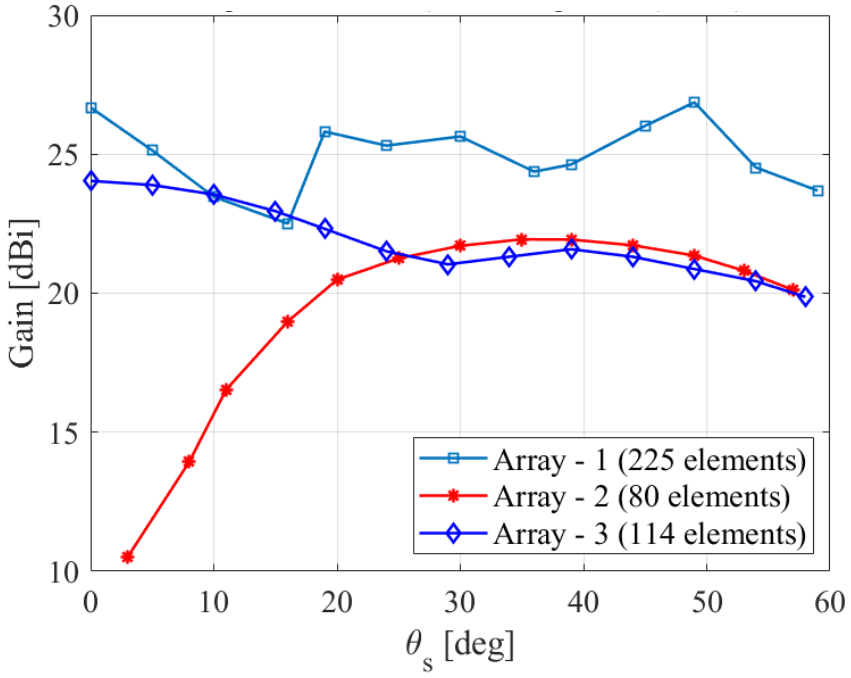
Effect of Aperture Area Reduction on Array Parameters

Gain vs. Frequency



- ✓ **With ≈ 30% aperture area reduction (≡ 49.3% reduction in the total # of array elements from 225 to 114), array gain reduces uniformly by 3 dB across the entire frequency range.**

Beam Steering in E-plane at 990.6 MHz



- ✓ **No drop in gain is observed for Array-3 as the main beam is steered from 0 to ±60° within 640 MHz – 990.6 MHz.**

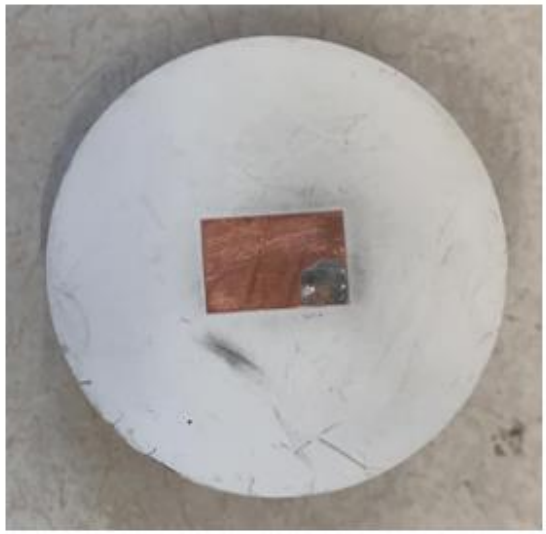
IV: Experimental Validation

Experimental Validation: Single Antenna Element

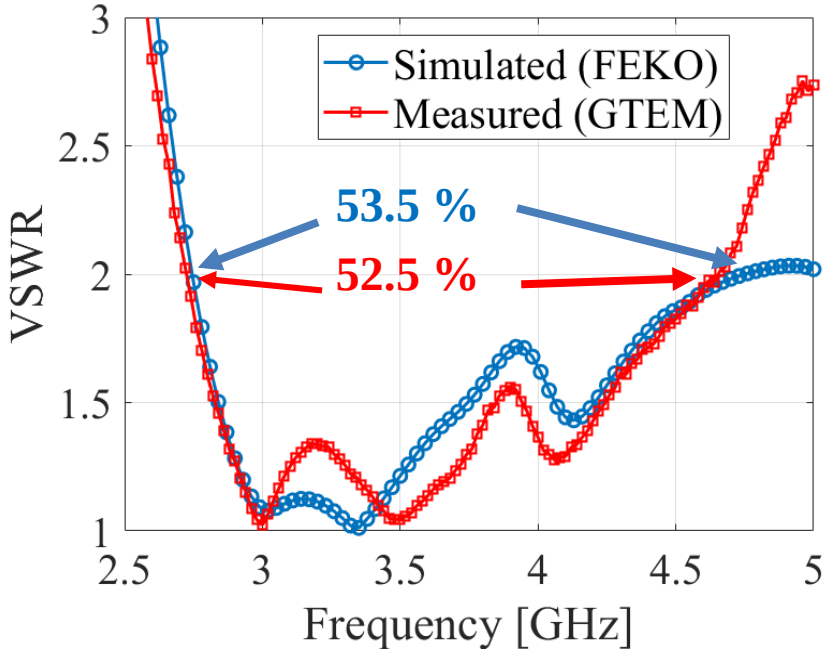
- Due to unavailability of proper substrate panel sizes from the vendors required in the UHF region, the design methodology is validated at 3.75 GHz first.
- Substrate Used: 6.35 mm (0.25”) thick TMM-10i (free sample from Rogers Corp.)

Simulated Results						
Ground Plane	f_L (GHz)	f_c (GHz)	f_U (GHz)	% BW	Max. Gain (dB)	ka
Circular	2.745	3.75	4.75	53.50	5.65	0.68

Parameters	Values
L (mm)	9.61
W (mm)	14.42
r_p (mm)	0.6
r_g (mm)	23.5
(x_p, y_p) (mm, mm)	(3.20, 4.80)

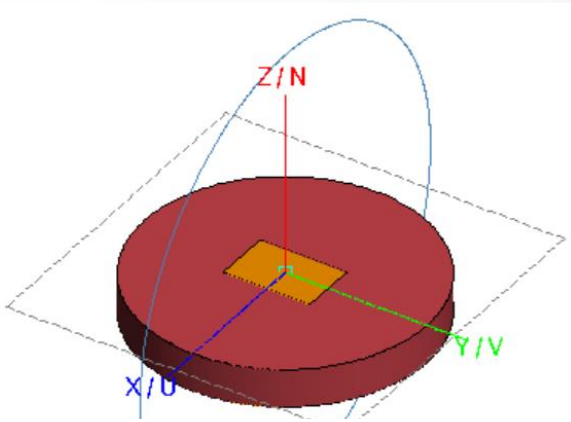


Fabricated Prototype

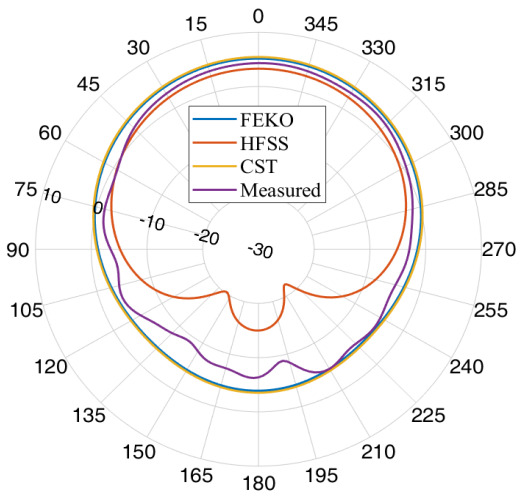


Experimental Validation of Antenna Element

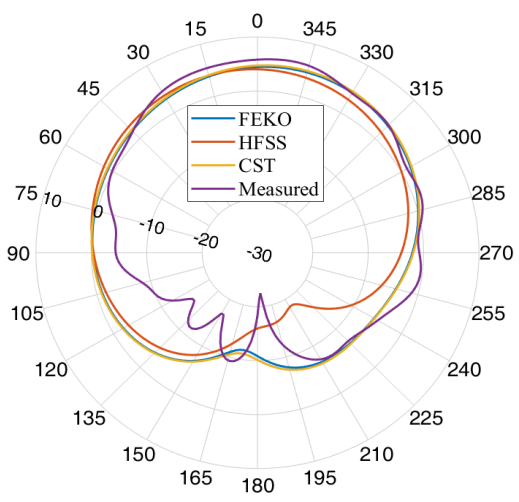
- Simulated and Measured Radiation Patterns are compared in the E- or XZ- plane.
- Simulated Data obtained via FEKO, CST and HFSS.
  - ✓ FEKO and CST: Method of Moment (MoM)
  - ✓ HFSS: Finite Element Method (FEM)
- Measured data obtained from Honeywell.



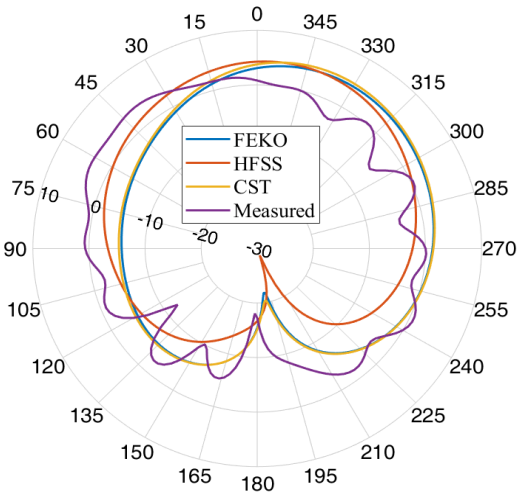
E- or XZ- plane
($\phi = 0°$)



2.745 GHz



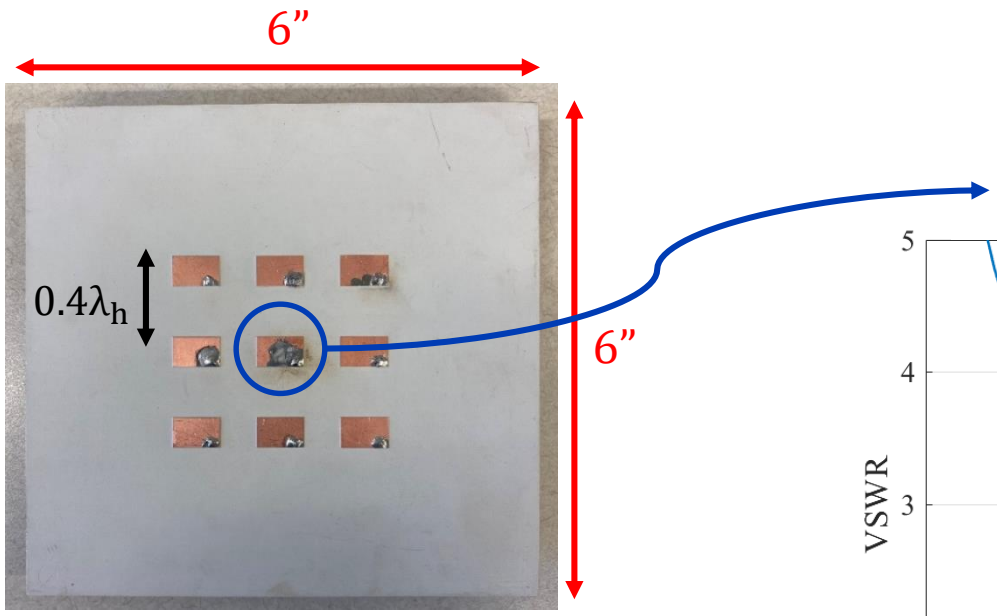
3.7475 GHz



4.75 GHz

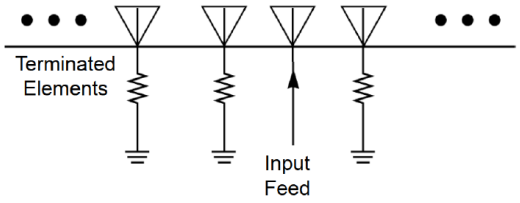
Experimental Validation of Array:
Measured and Simulated Embedded Element VSWRs

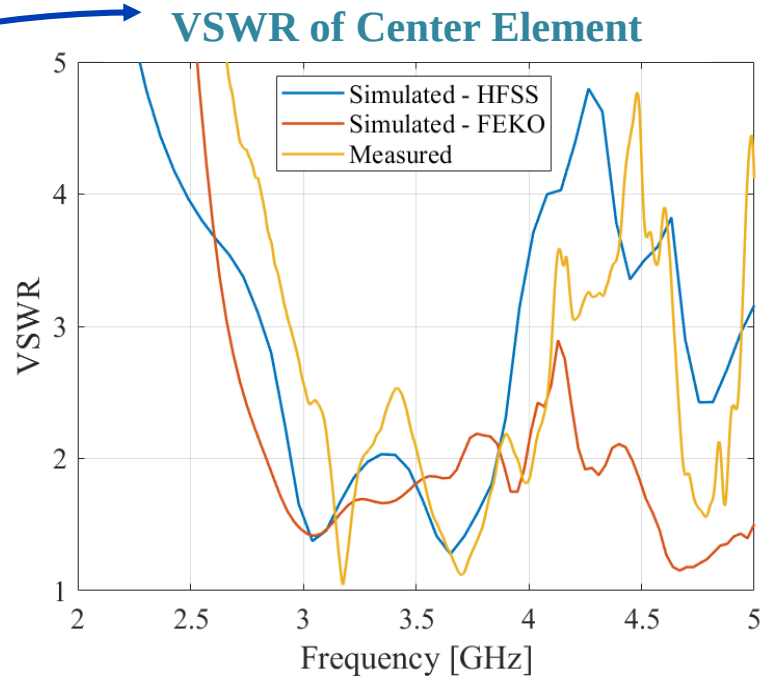
- n^{th} embedded element VSWR is obtained by feeding only the n^{th} element, while all other elements are terminated in matched loads.



Fabricated Prototype of a
3×3 array ($f_c = 3.75$ GHz)

(λ_h calculated at 4.75 GHz)





- The measured and the simulated data have slight resemblance.
- The disagreement between measured and simulated results is due to manufacturing defects.

HPM: Research Objective Progress/Findings

Tradespace Analysis of ESA Array

Significant Findings:

Array	Antenna Aperture Area $L \times W$ (m^2)	Boresight Gain $G^R(\theta,\phi)$ (dBi)	Input Peak Power to the Array (P_{in}) (MW)	Power Density: $S(\theta,\phi) = \frac{1}{4\pi}\frac{P_{in}}{R^2}G^R(\theta,\phi)$ (W/cm^2)	
				@ R = 1 km	@ R = 2 km
15 × 15 with Dummy Elements	2.38 × 2.41 = 5.7358	27.76	100	0.4752	0.1188
			500	2.3761	0.5940

- With 30% reduction in the aperture area (≈50% reduction in # of elements), the gain drops by <= 3.5 dBi without any scan blindness spotted as the main beam is steered from boresight to ±60° in the range 640 MHz to 990 MHz.

HPM: New Ideas / Opportunities
Tradespace Analysis of ESA Array

- Microstrip Patch antennas have the inherent drawback of narrow bandwidth.
- A new method has been found, where the antenna impedance bandwidth can be significantly increased by strategically placing the coaxial - feed probe along the patch diagonal.
- A interesting problem would be to investigate why the microstrip patches yield such a huge bandwidth.

HPM: Conclusions/Future Work

Tradespace Analysis of ESA Array

- Tradespace analysis of ESAs by optimizing antennas (and arrays) in terms of directivity (or gain) and impedance bandwidth simultaneously, via D/Q technique is being pursued.
- Further investigations into the effect of array aperture area reduction on different array parameters must be conducted.
- Investigations into ESA array designs on substrates suitable for high power handling capabilities (such as Ceramic or Polyethylene) – to achieve better performance for HPM transmissions at UHF range.

FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

Bi-Annual Program Review

FEKO <-> SPICE Tool Development/Validation

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09 DEC 2020
held via Zoom

Distribution A. Approved for public release.

OSPRES: Research Team

FEKO <-> SPICE Tool Development/Validation

RF COUPLING

Computational EM Modeling

Mohamed Hamdalla
PhD Student

Benjamin (Bear) Bissen
PhD Student

Experimental EM Measurements

Big Data Acceleration of EM Codes

Khulud Alsultan
PhD Student

→ Effects Team

- General RF Coupling Guidelines/Trends
- Guidance for Experimental Measurements
- Explanations to Experimental Observations
- Predict optimum pulsed excitation

MISSOURI S&T

Ahmed M Hassan
Assoc. Professor

Praveen Rao
Assoc. Professor

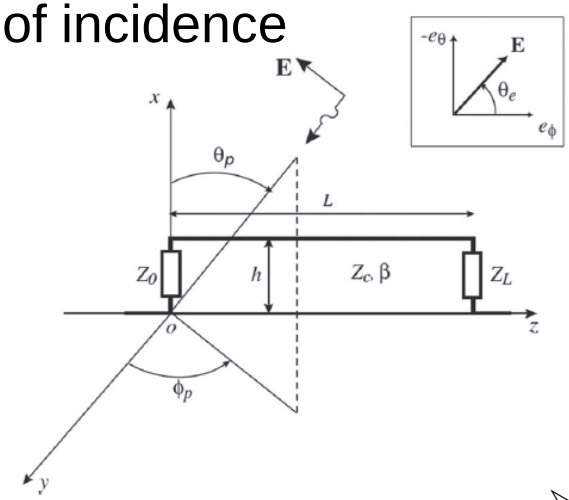
Anthony N Caruso
Professor

OSPRES: RF Coupling Revisited

FEKO <-> SPICE Tool Development/Validation

- RF Coupling to a Device Under Test (DUT) is affected by:

1. **Properties of the device:** Wire/trace shapes, sizes, loads, environment
2. **Properties of the excitation:** frequency, BW, PRF, polarization, angles of incidence



Random variable X_i	Mean μ_{X_i}	Coefficient of variation δ_{X_i}	Case 1
$X_1 = L$ (m)	4.2	10%	Lognormal / $\mathbb{R}_+^*$
$X_2 = h$ (m)	0.02	10%	Lognormal / $\mathbb{R}_+^*$
$X_3 = d$ (m)	0.001	5%	Lognormal / $\mathbb{R}_+^*$
$X_4 = Z_L$ (Ω)	1,000	20%	Lognormal / $\mathbb{R}_+^*$
$X_5 = Z_0$ (Ω)	50	5%	Lognormal / $\mathbb{R}_+^*$
$X_6 = a_e$ (V/m)	1	20%	Lognormal / $\mathbb{R}_+^*$
$X_7 = \theta_e$ (rad)	$\pi/4$	57.7%	Uniform / $[0\,;\pi/2]$
$X_8 = \theta_p$ (rad)	$\pi/4$	57.7%	Uniform / $[0\,;\pi/2]$
$X_9 = \phi_p$ (rad)	π	57.7%	Uniform / $[0\,;2\pi[$
$X_{10} = f$ (MHz)	30	9.6%	Uniform / $[25\,;35]$
$X_{11} = \alpha$ (-)	0.0010	28.9%	Uniform / $[0.0005\,;0.0015]$

- To cover the parameter space, 1 billion calls to the solver were needed to accurately calculate failure probability
- UAVs have a bigger parameter space and solver requires hours/days
- **Prohibitive to explicitly measure/simulate all possible UAV permutations**

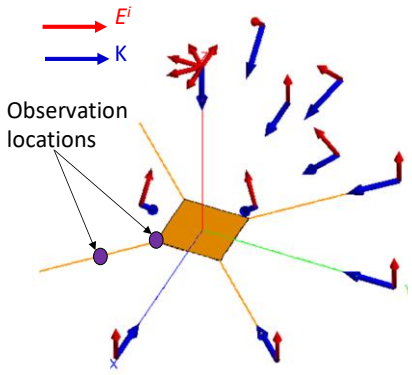
A. Kouassi *et al.*, "Reliability and Sensitivity Analysis of Transmission Lines in a Probabilistic EMC Context," *IEEE Trans. on EMC*, vol. 58, no. 2, pp. 561-572, 2016.

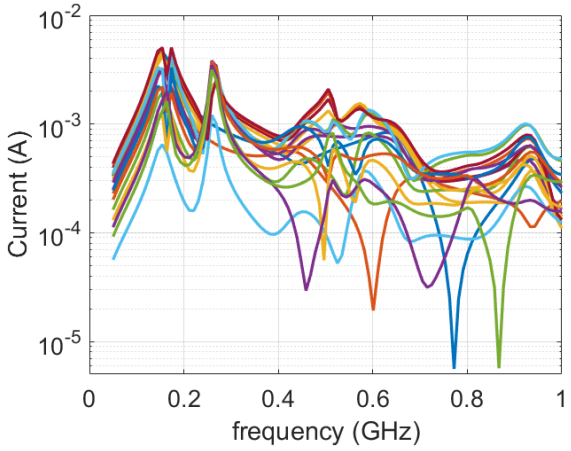
OSPRES: RF Coupling Revisited

FEKO <-> SPICE Tool Development/Validation

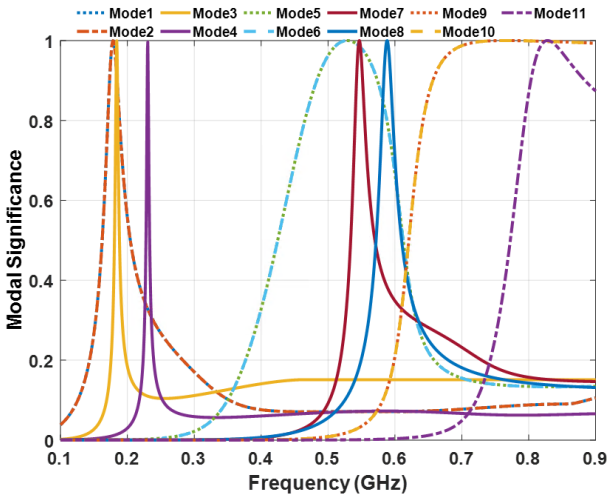
Use the characteristic mode analysis and the equivalent circuit approach to narrow the parameter space.

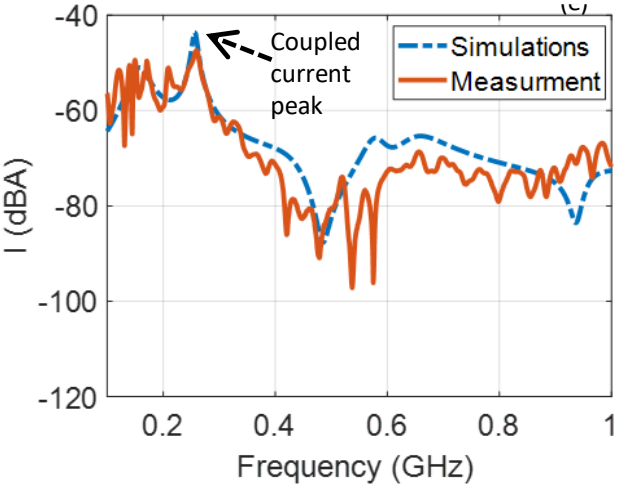
Effects Team:
Guide experimental measurements,
Predict effects





Antennas Efforts:
Identify all possible UAV coupling pathways to accurately determine gain, frequency, and radiation characteristics of the antenna



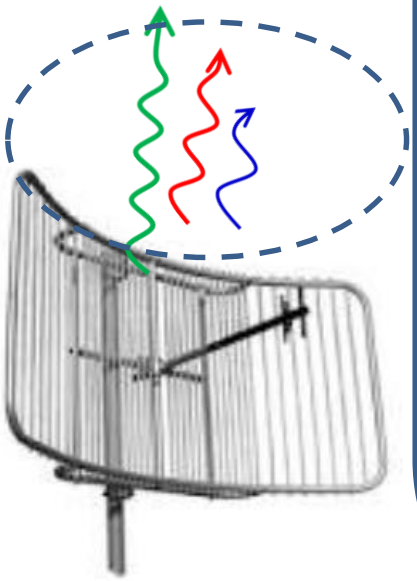


HPM: Future Proposed Efforts

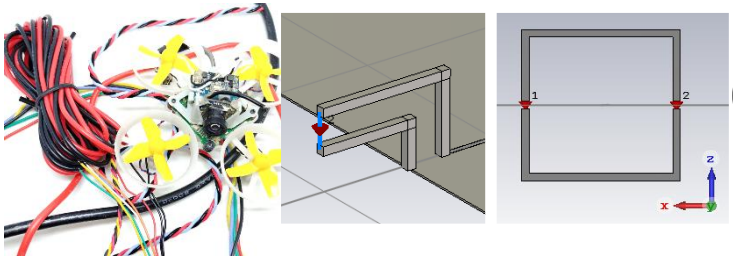
RF Coupling Collaboration

=

Source of Interference



Wires **(UMKC & MS&T)**



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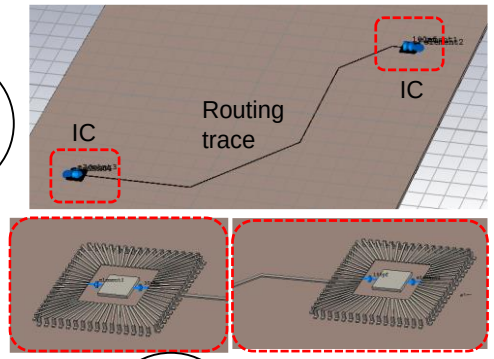
PCB Traces **(MS&T)**



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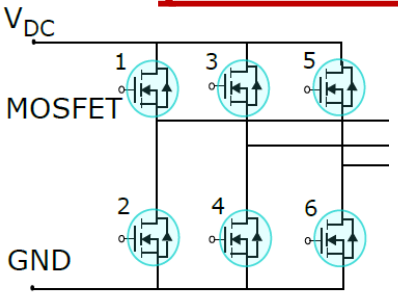
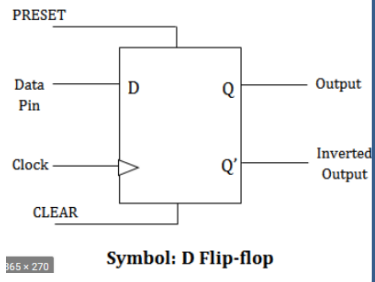
Predict Effects

Load Susceptibility **(UMKC & MS&T)**





Equivalent Circuit

DPI and TEM illumination

Frame, Enclosure, Wrapping **(UMKC)**

\+

(a) Aluminum foil.

ONR HPM Program Key Research Criteria - II

FEKO <-> SPICE Tool Development/Validation

Qualitative Criteria:

Goal I: Quantify RF coupling to arbitrary wire systems connected to nonlinear loads

State-of-the-art (SOTA): Simple wire shapes with mostly linear loads. Only a limited set of pulsed excitations were considered

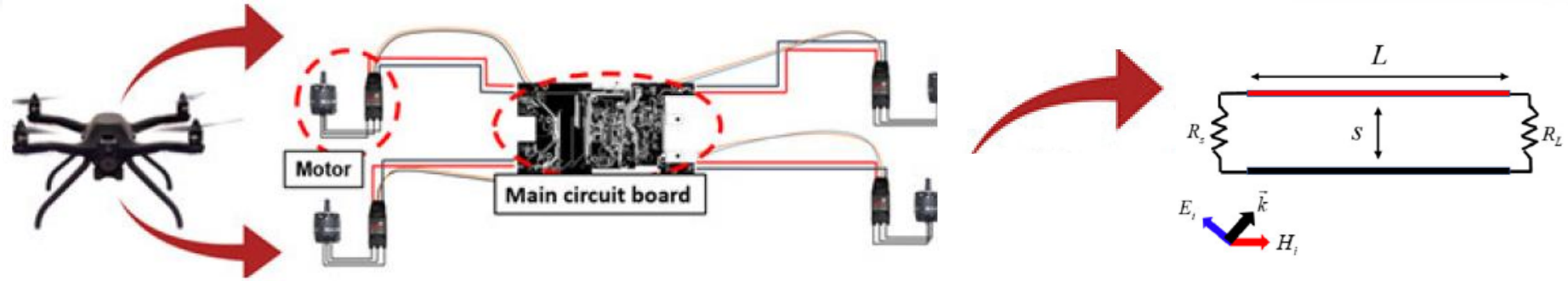
Deficiency in SOTA: (i) limited range of wire shapes/sizes, (ii) limited nonlinear components, (iii) lack of an accurate predictive technique to identify the optimum pulse to maximize the coupled voltage to a load

Proposed Solution: Use the equivalent circuit approach (FEKO <-> SPICE) as an accurate computationally efficient approach

Program outcome: (1) Identify UAV coupling pathways due to different wire systems, (2) Quantify the variation in the RF Coupling with variations in UAV wire shape, size, and loads, (4) Generate Re-visited RF coupling trends (5) Predict effects for different pulse properties (frequency, BW, PRF) and select optimum pulse for desired effect.

ONR HPM Program Key Research Criteria - I

FEKO <-> SPICE Tool Development/Validation



Parameter of Research	SOTA	Threshold	Objective
Wire Configuration	Simple 1-3 wire structures or loops	**Lengths:** 5 cm – 40 cm **Types:** N wire configurations **Curvature:** Straight rectangular, circular square shaped wire loops	**Lengths:** 5 cm – 40 cm **Types:** 1*x Data cables, AUX cables, Power cables **Curvature:** Meandered wires with 1 cm – 5 cm persistence length
Nonlinear loads	Simple diodes	Power limiters, amplifiers, transistors, diodes	UAV DC Power Module, Electronic Speed Controller, Pulse Width Modulator
Pulsed Excitations	Canonical pulses	Double Exponential, Damped Sinusoidal, Gaussian, Practical pulses and Pulse Repetition frequencies	Predict optimum pulses

S. Kim *et al.*, "Electromagnetic Signature of a Quadcopter Drone and Its Relationship With Coupling Mechanisms," *IEEE Access*, vol. 7, pp. 174764-174773, 2019,

OSPRES: RF Coupling Revisited

FEKO <-> SPICE Tool Development/Validation

- **Risks**

Practical wire configurations are computationally expensive to simulate → Use Big Data tools to accelerate computational models

RF Coupling Trends in practical wire configurations may be difficult to identify → Machine Learning Identification/classification

- **Payoffs**

An intelligent computationally efficient RF coupling predictive tool to wires

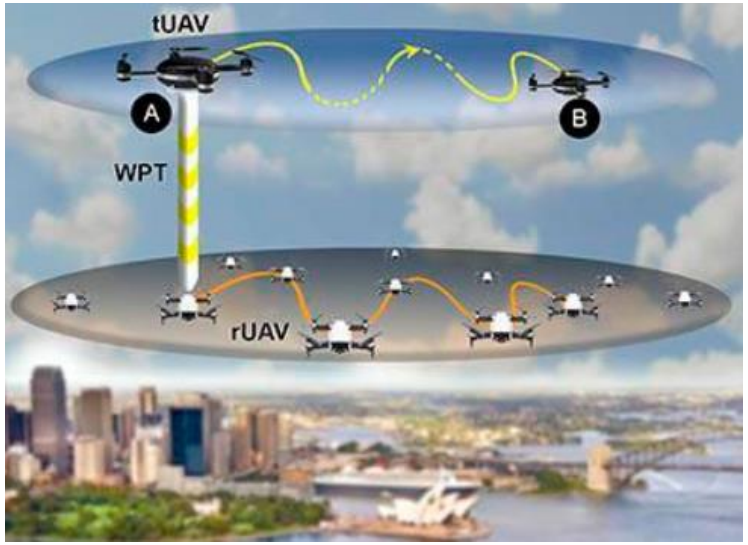
- **Challenges**

Time to adapt the proposed FEKO-SPICE approach for all wire configurations of interest and time needed to validate simulations experimentally to fully trust conclusions.

HPM: Broader Impact

FEKO <-> SPICE Tool Development/Validation

- RF coupling guidelines developed can be used to predict the performance of UAVs when they fly in a congested wireless spectrum such as near cellular base station

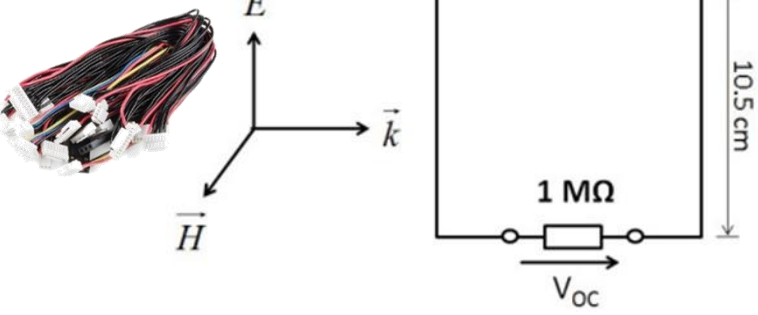


- High power pulses can be used for the wireless charging of UAVs to extend their flight time beyond their battery capacity

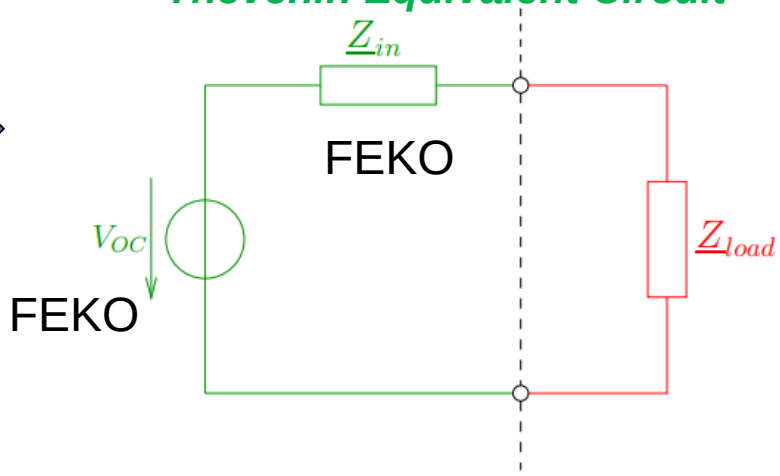
HPM: Technical Discussion/Progress Cont'd

Equivalent Circuit Approach

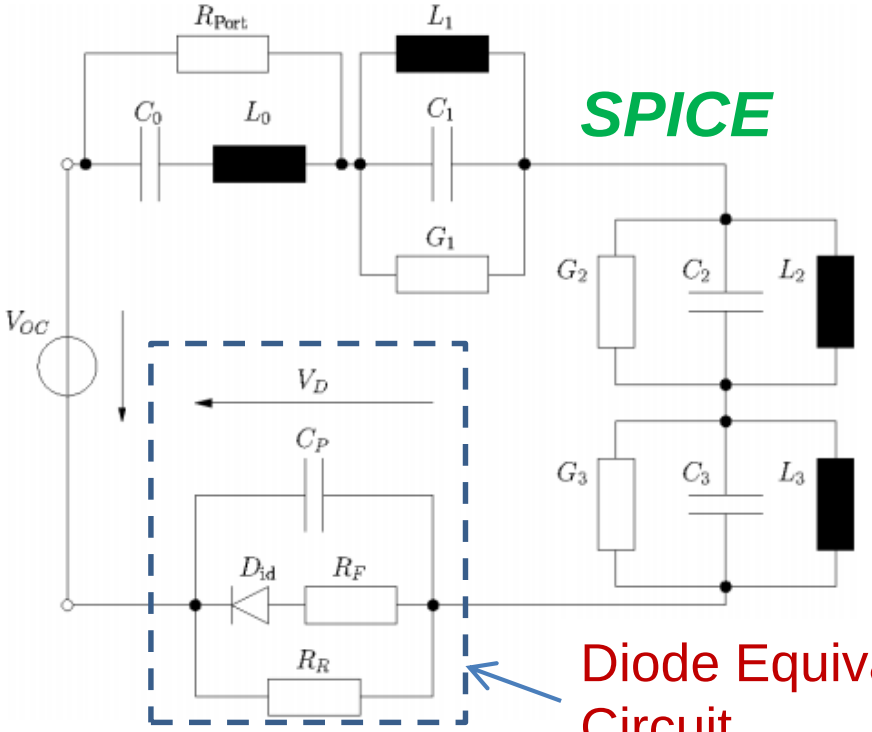
Wire configuration



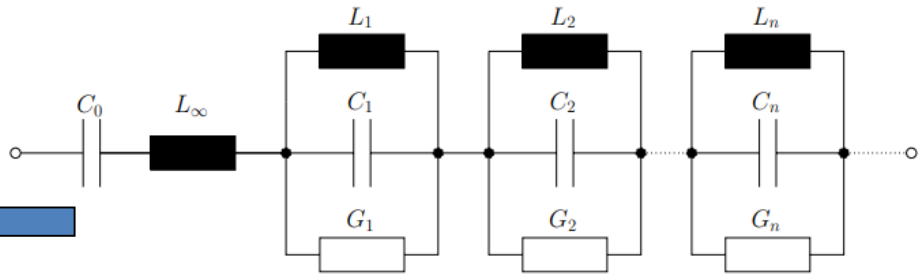
Thevenin Equivalent Circuit



SPICE



Diode Equivalent Circuit

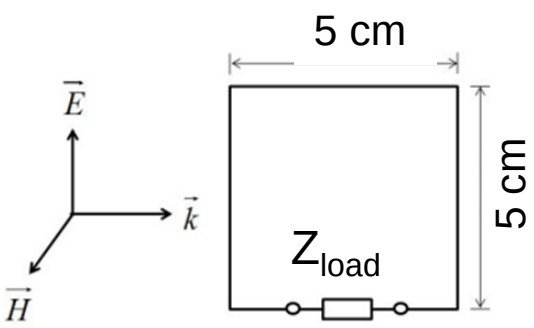


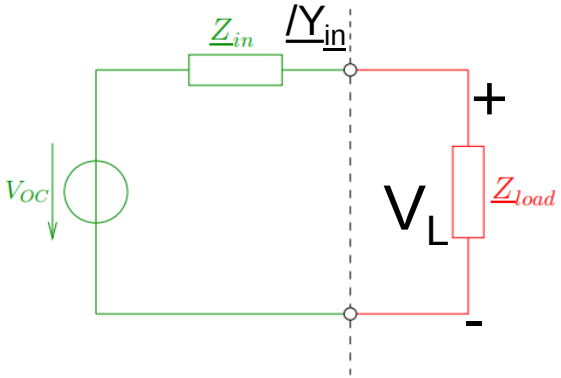
RLC representation of Z_{in}

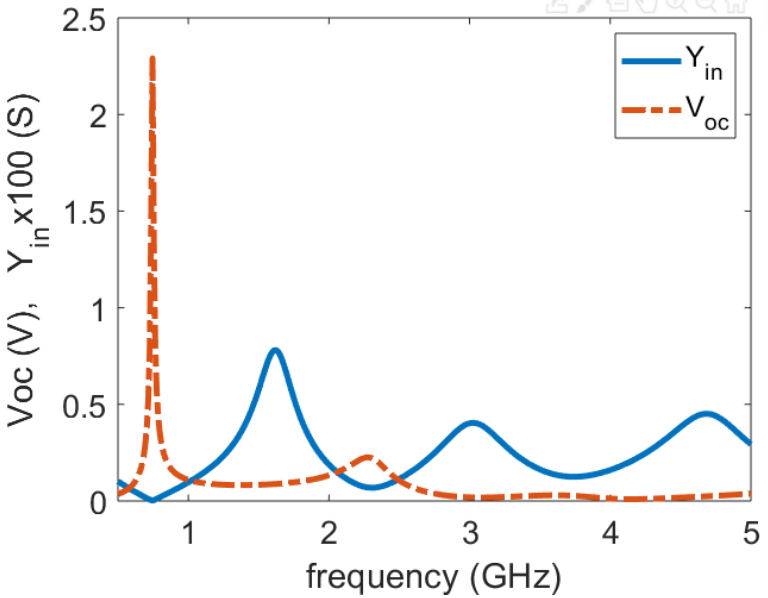
R. Michels, M. Willenbockel and F. Gronwald, "A Parametric Study of an Energy Storage Effect due to Nonlinear Components and HPEM-Excitation," *2019 International Symposium on Electromagnetic Compatibility - EMC EUROPE, Barcelona, Spain*, pp. 59-64, 2019

HPM: Technical Discussion/Progress Cont'd

Equivalent Circuit Approach







The pulse center frequency that will maximize coupling to the load?

- It depends on Y_{in}, V_{oc}, and Z_{load}
- For small $Z_{load} << Z_{in}$: $V_L \approx Z_{load} * V_{oc} * Y_{in}$
- For large $Z_{load} >> Z_{in}$: $V_L \approx V_{oc}$

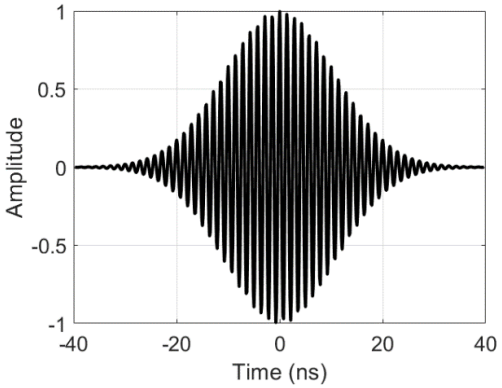
Using the above guidelines we can identify the optimum pulse to maximize coupled voltage to the load of interest.

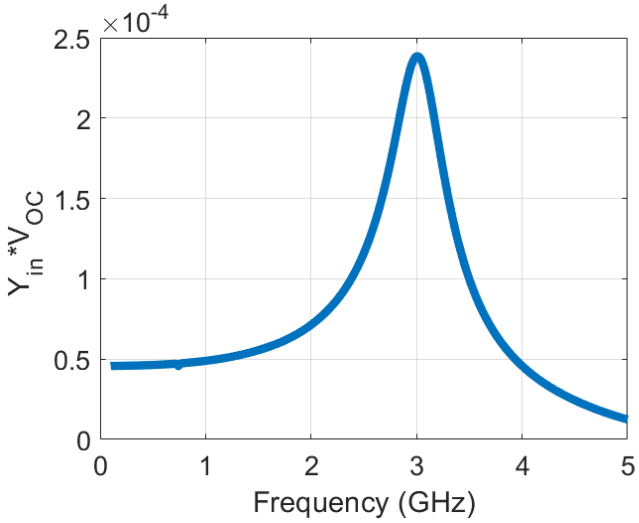
HPM: Technical Discussion/Progress Cont'd

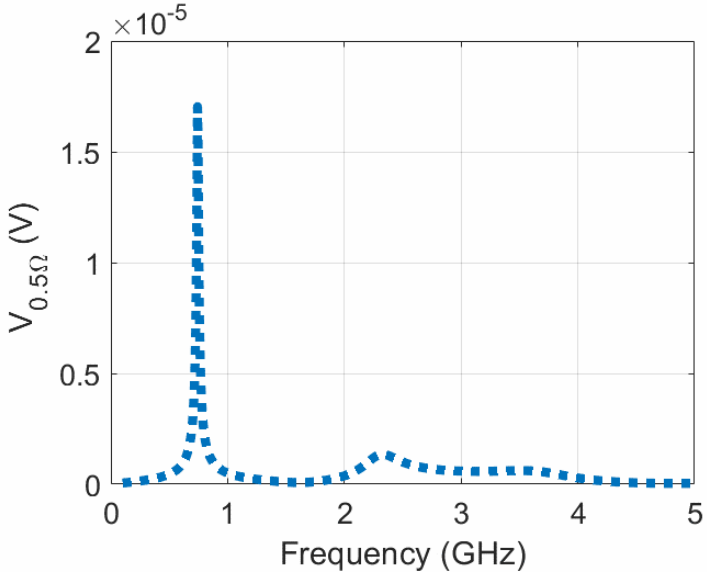
Equivalent Circuit Approach

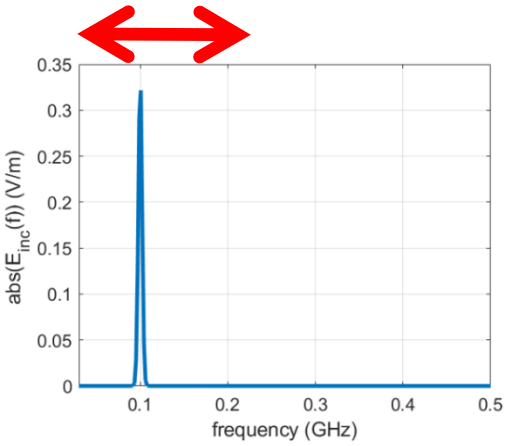
Small Load: (Z_L = 0.5 Ω)

Gaussian sinusoidal pulses with varying center frequency



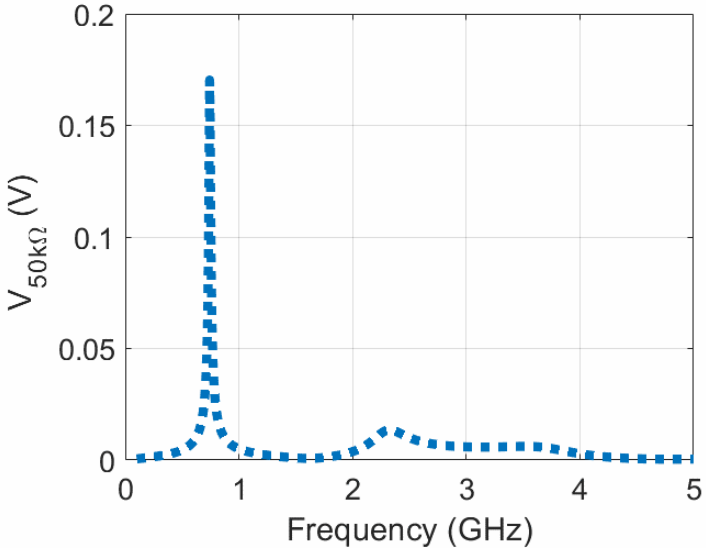






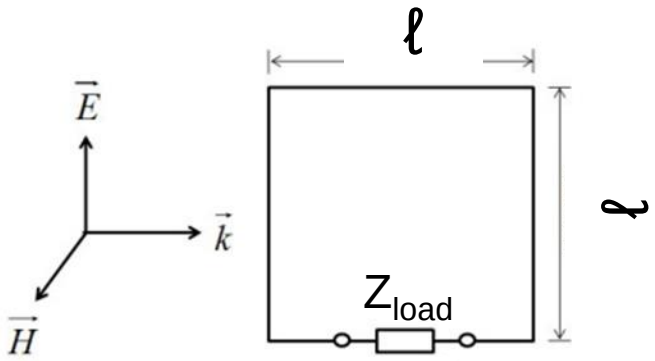
Large Load

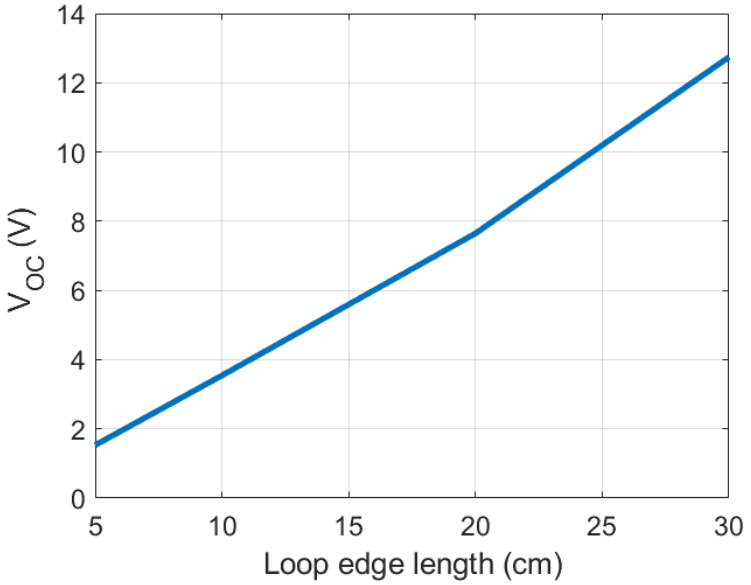
Z_L = 5 kΩ

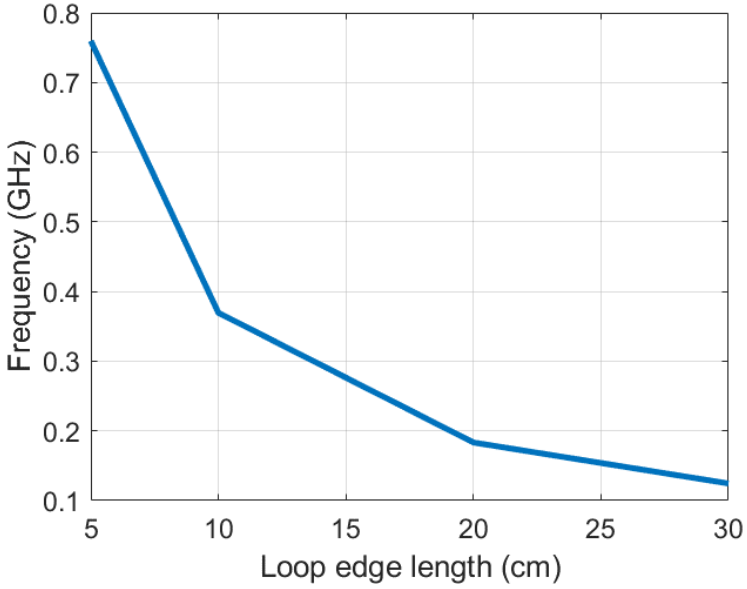


HPM: Technical Discussion/Progress Cont'd

Wire Loop Size







- The resonance frequency scales as:

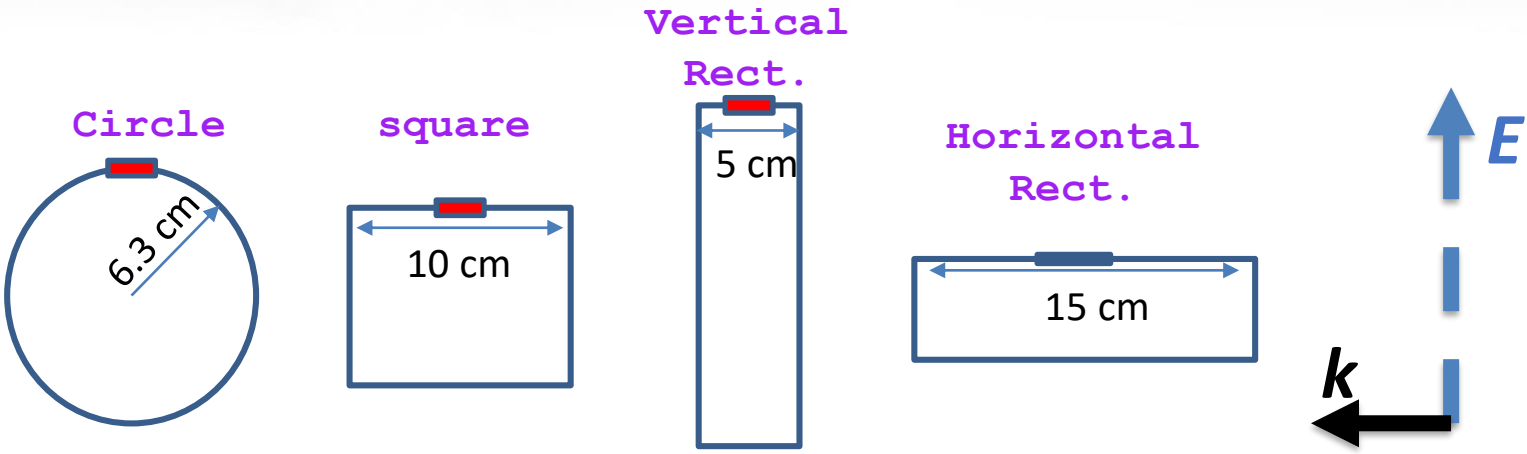
$$f = \frac{c}{2 * \ell}$$

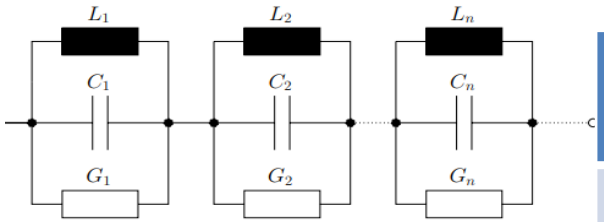
- The V_{oc} scales linearly with ℓ

HPM: Technical Discussion/Progress Cont'd

Wire Loop Shape

All loops have the same contour length of 40 cm





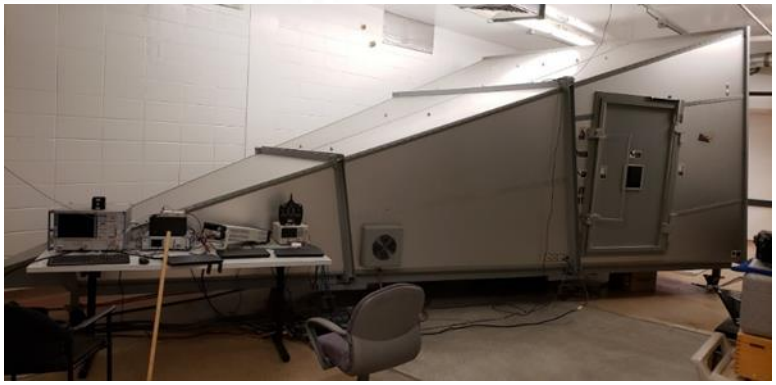
Z_{in}

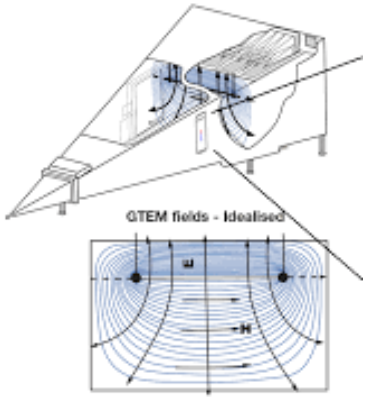
- Circuit elements vary within a narrow range except for R
- Help in quantifying the effect of shape on RF coupling

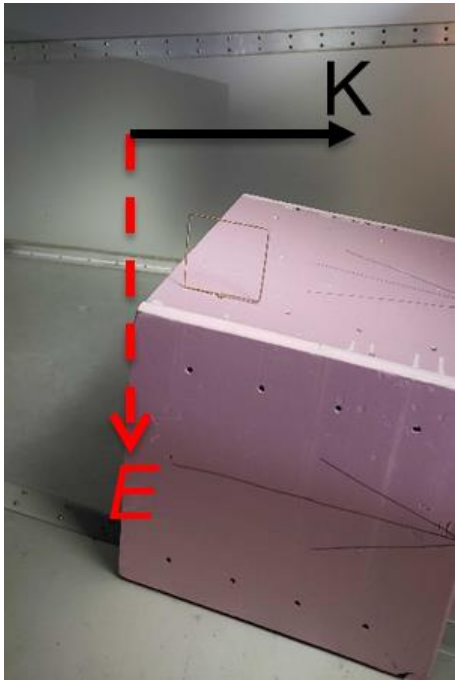
Element	Circle	Square	Vertical Rect.	Horizontal Rect.
R1 (kΩ)	80.48	91.48	222.97	64.51
C1 (pF)	0.3563	0.3545	0.3697	0.3647
L1 (nH)	527.24	503.92	484.69	472.598
R2 (kΩ)	4.4	4.675	21.02	2.608
C2 (pF)	0.4	0.4152	0.4082	0.3573
L2 (nH)	49.156	46.401	48.381	56.349

HPM: Technical Discussion/Progress Cont'd

Experimental Validations

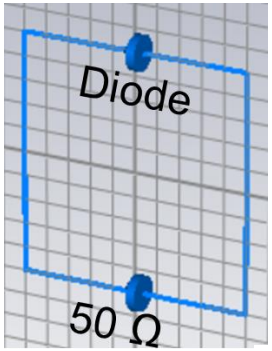


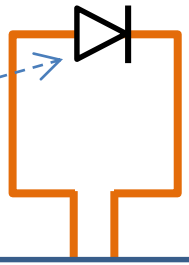




Arbitrary Waveform Generator

Broadband Amplifier





Wire loop

Oscilloscope

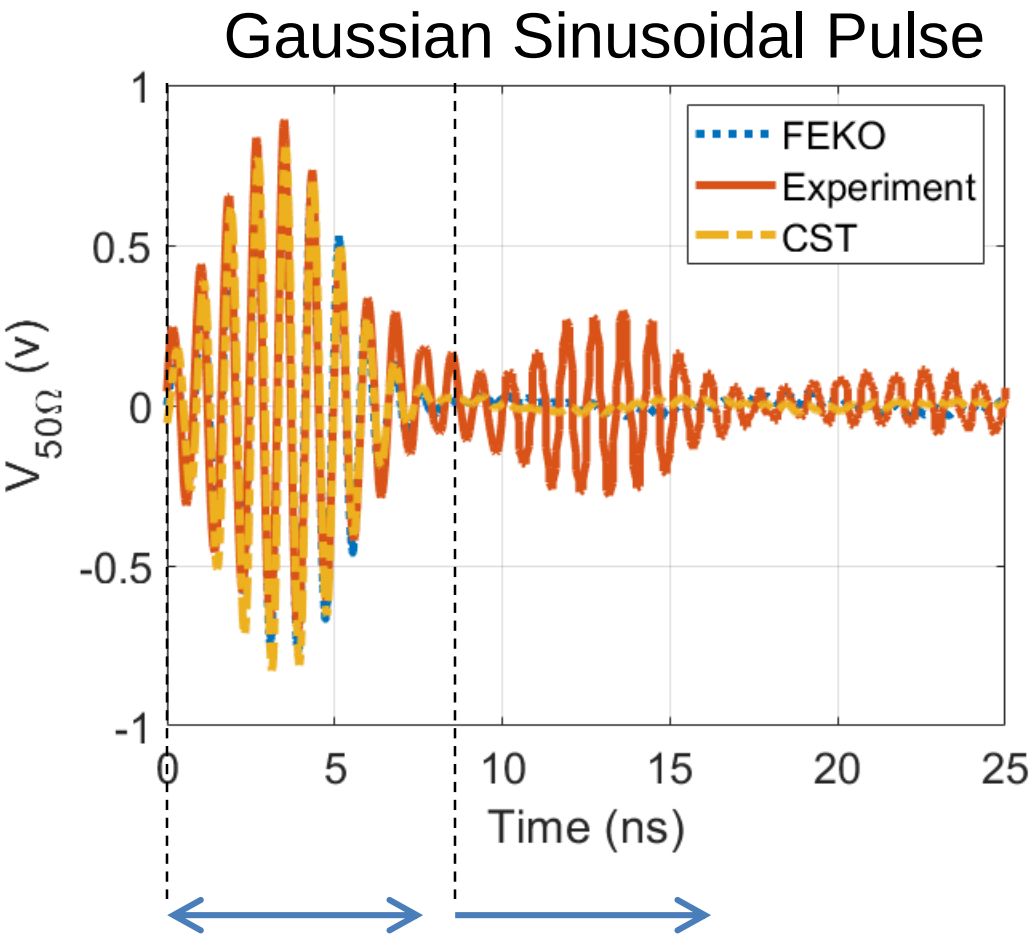
Pulse Distorted by Amplifier

The top load can be varied but the bottom load is fixed to 50 Ω (the input impedance of the oscilloscope)

Distribution A

HPM: Technical Discussion/Progress Cont'd

Experimental Validations: Different Pulsed Excitations



Effects measurements in GTEM may suffer from multiple reflections not present in free space measurements

Distribution A

HPM: Research Objective Progress/Significant Findings

- The equivalent circuit approach was validated using 2 independent computational techniques and experimentally

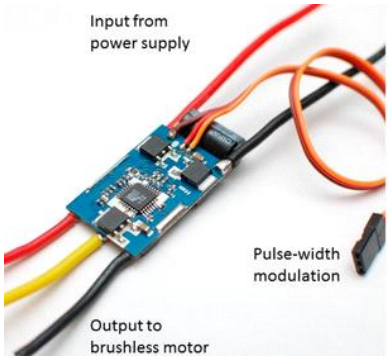
- The following trends were quantified:
    1. Variations in equivalent circuit components with size of the loop
    2. Variations in equivalent circuit components with shape of the loop
    3. Variation in response with load properties

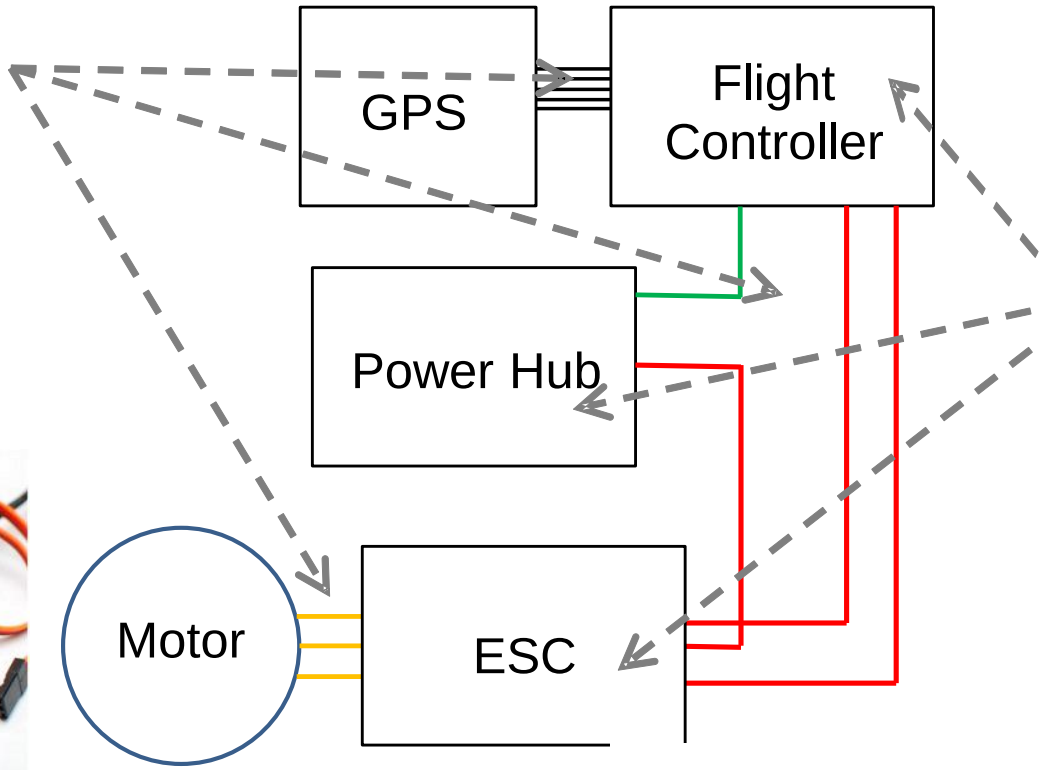
HPM: Future Proposed Efforts

Road Map

Wires:

Sizes, Shapes, Number of wires



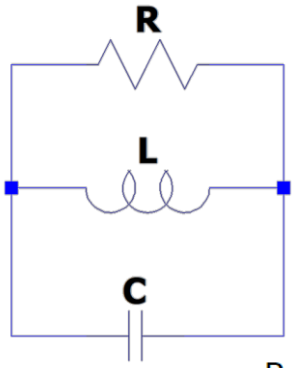


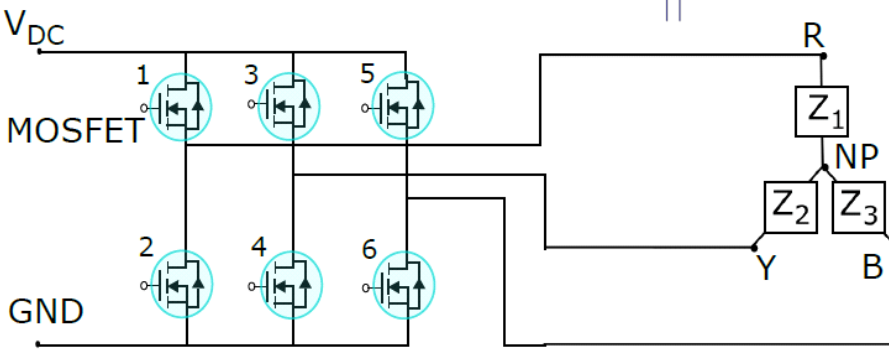
Loads:

Linear: RLC

Nonlinear: diodes, LNA, ESC, etc

(1)

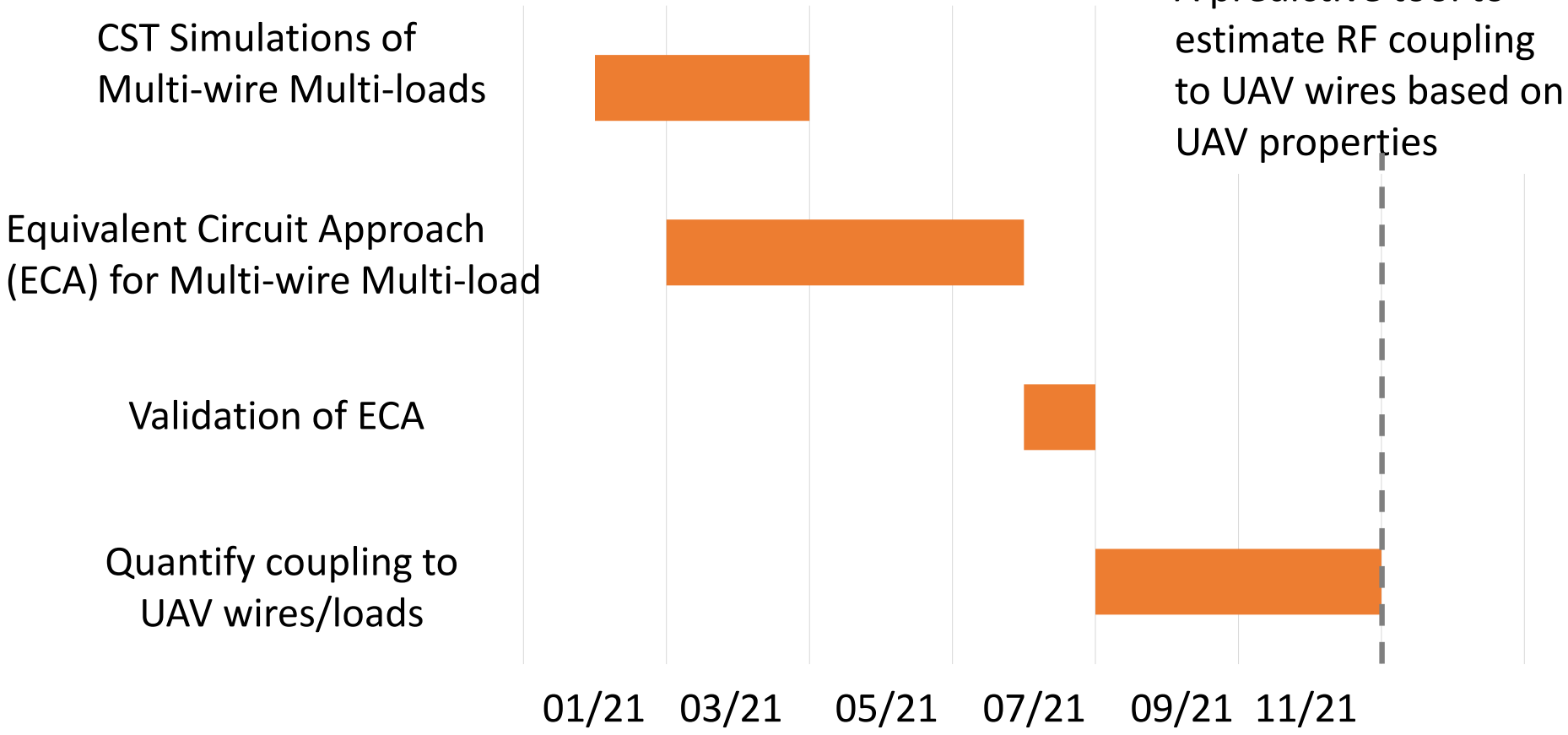




HPM: Future Proposed Efforts

Road Map

Milestone:
A predictive tool to estimate RF coupling to UAV wires based on UAV properties



Distribution A

HPM: Conclusions
FEKO <-> SPICE Tool Development/Validation

- The FEKO <-> SPICE equivalent circuit approach was validated in multiple independent ways and was capable of quantifying and predicting RF coupling to wire loops with nonlinear loads
- The scaling of circuit components with loop size, loop shape, and load properties were quantified
- Future work, will be to study more practical wire configurations to quantify/predict effects.

Acknowledgements

This work is supported by Office of Naval Research Grants:

- ONR grant # N00014-17-1-2932
- ONR grant # N00014-17-1-3016

Distribution A

Backup Slides

Distribution A

OSPRES: RF Coupling Revisited

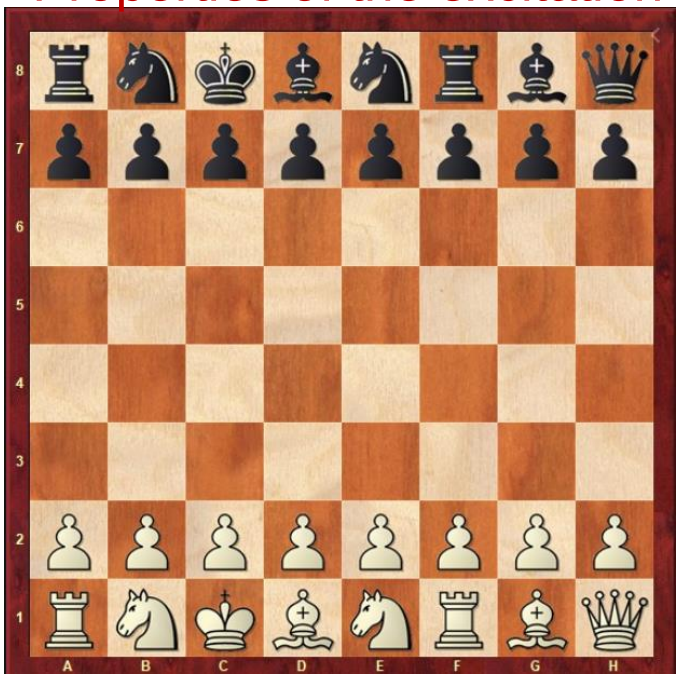
FEKO <-> SPICE Tool Development/Validation

- RF Coupling to practical systems/devices is affected by:

1. **Properties of the system:** Wire/trace shapes, sizes, loads environment
2. **Properties of the excitation:** frequency, BW, PRF, polarization, angles of incidence

#	Possibilities
1	20
2	400
3	8902
4	197,742
5	4,897,256

Properties of the excitation



Properties of the system

Goal:

1- Win the game: predict effects, find optimum excitation to create the desired effect

2- Can not calculate all possibilities (Use RF Coupling Analysis to Guide Covering the Parameter Space)

"Half the variations which are calculated in a tournament game turn out to be completely superfluous.– Jan Timman

OSPRES: RF Coupling Revisited

FEKO <-> SPICE Tool Development/Validation

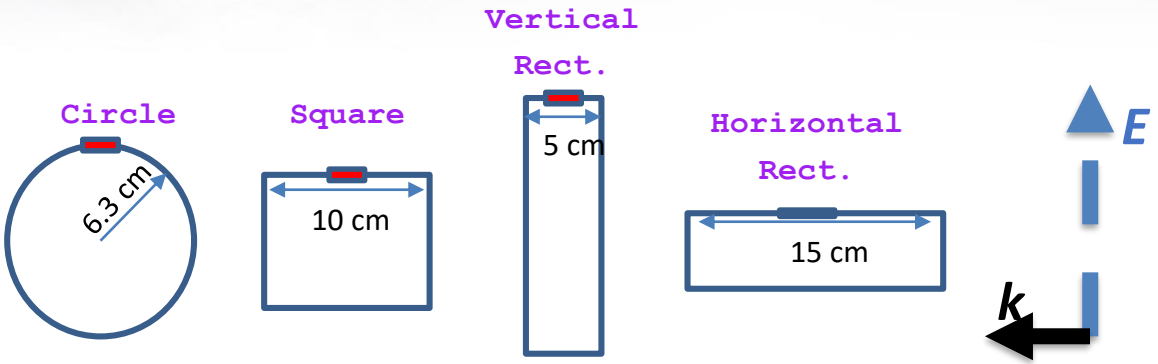
- RF Coupling to practical systems/devices is affected by the excitation characteristics: frequency, polarization, pulse bandwidth, pulse repetition frequency, etc
- Current models are mainly:
  1. Based on simple systems → extrapolating conclusions to practical devices will be inaccurate
  2. Statistical in nature → cannot predict the outcome of a specific measurement in a specific situation
  3. Too specific to one system and therefore any small change in the system will significantly alter the conclusions
- **Challenge:** ***How to revisit previous RF Coupling guidelines to extend their validity to more complex/practical systems without restricting their applicability to a limited set of devices/systems.***

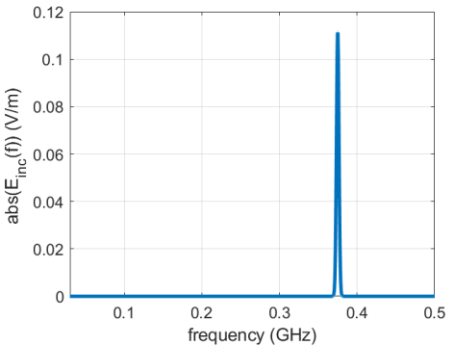
HPM: Technical Discussion/Progress Cont'd

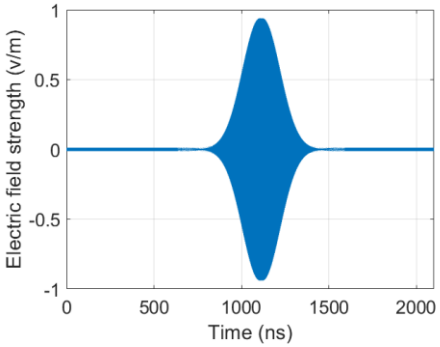
Wire Loop Shape

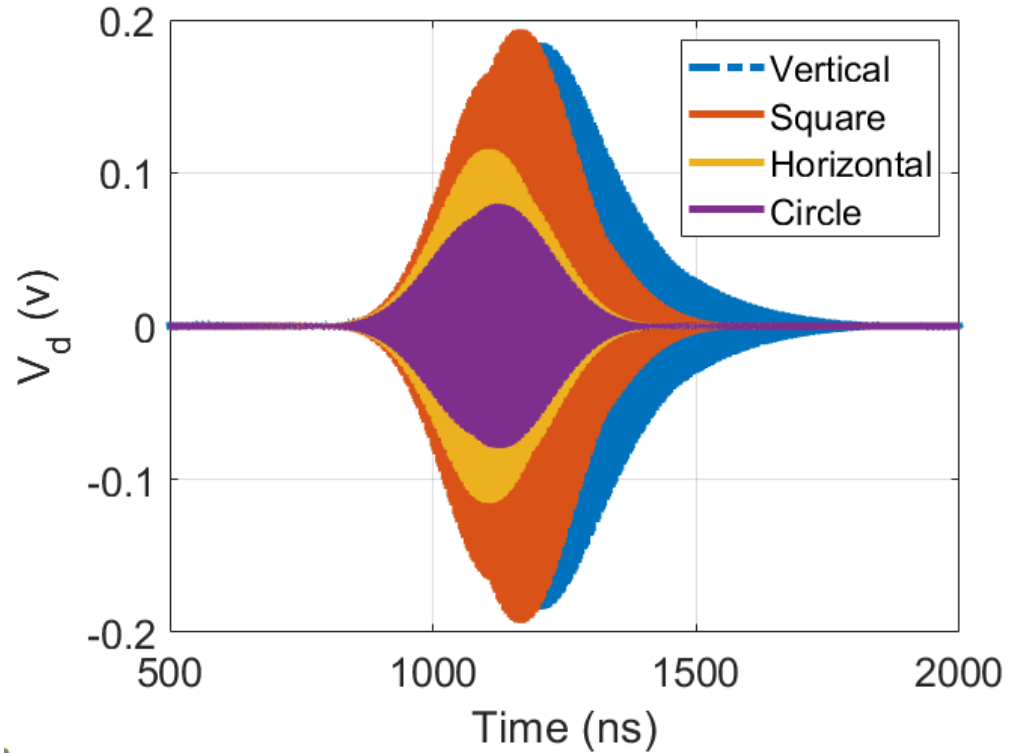
Excitation specs:

- Gaussian Pulse
- Resonance frequency: 0.375 GHz
- Bandwidth: 1%







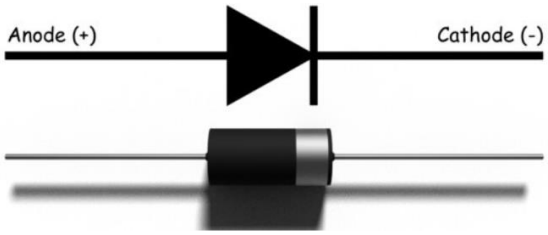


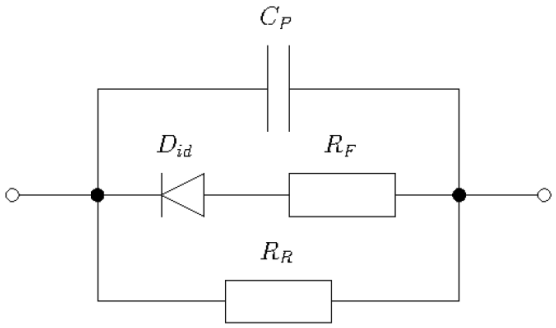
Distribution A

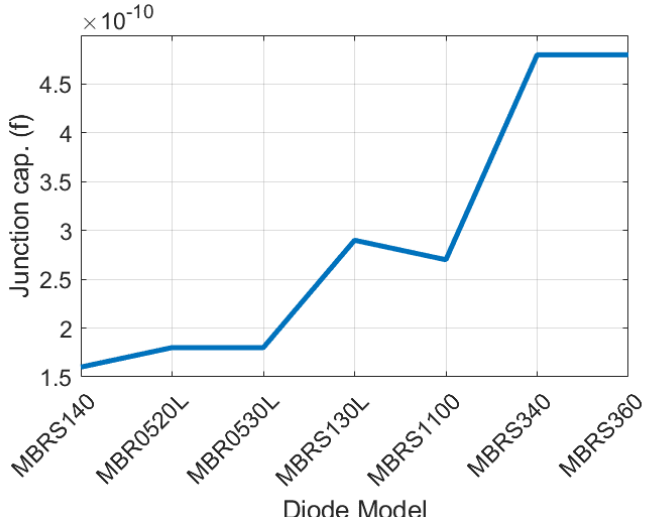
HPM: Technical Discussion/Progress Cont'd

Different Diodes

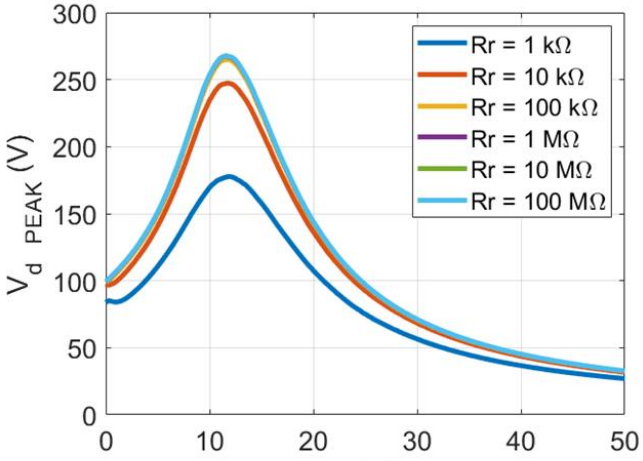
Modeling RF Coupling to different practical diodes by varying the values of the equivalent circuit components







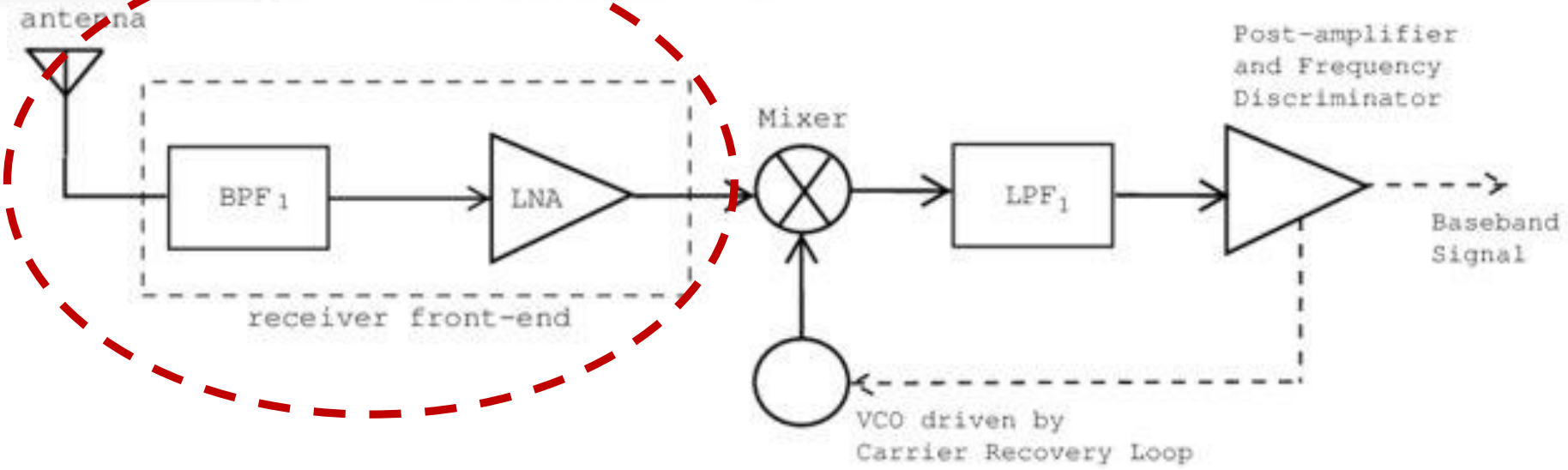
- Diode was connected to a square wire loop
- Increasing R_r increases the coupled voltage up to a limit
- Voltage peaks at a certain C_p based on wire loop properties



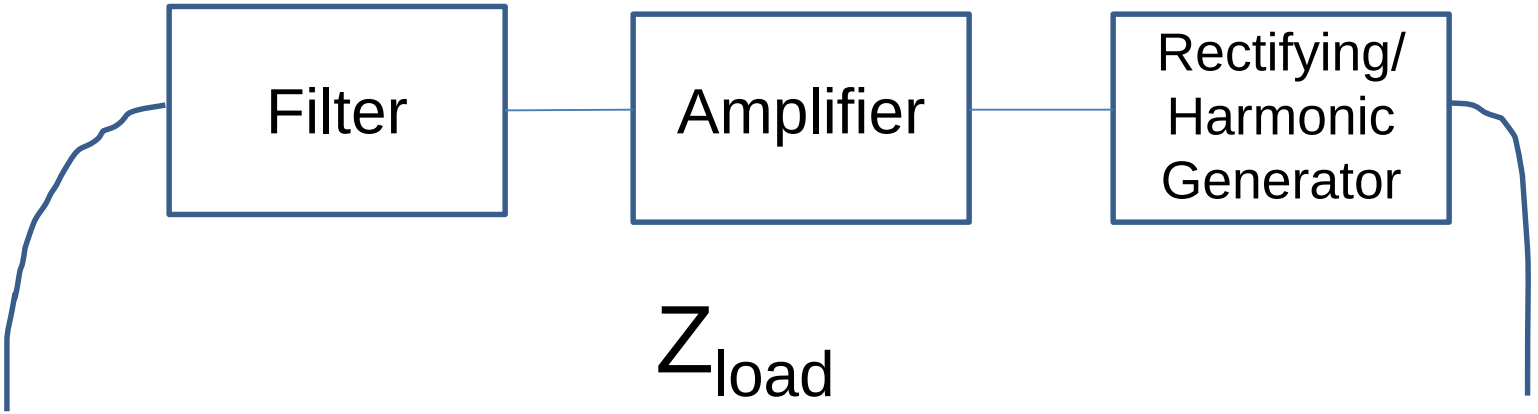
Distribution A

HPM: Technical Discussion/Progress Cont'd

Different Loads



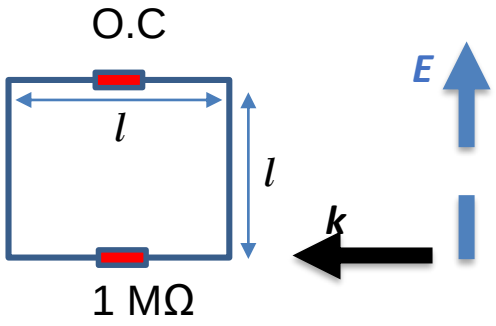
Generic Load:



Distribution A

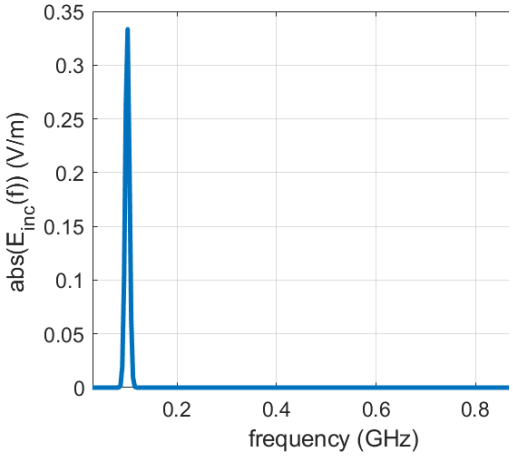
HPM: Technical Discussion/Progress Cont'd

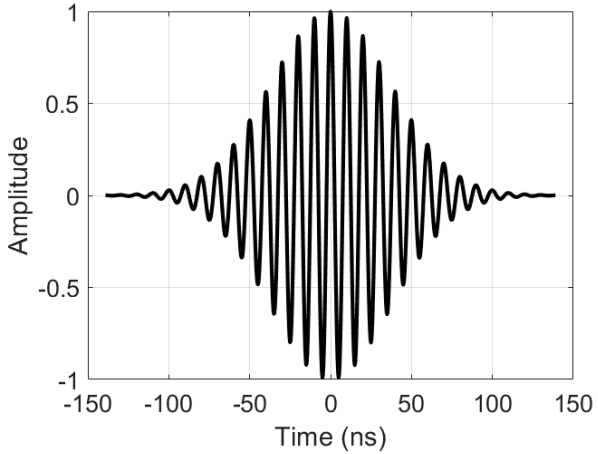
Different Loads

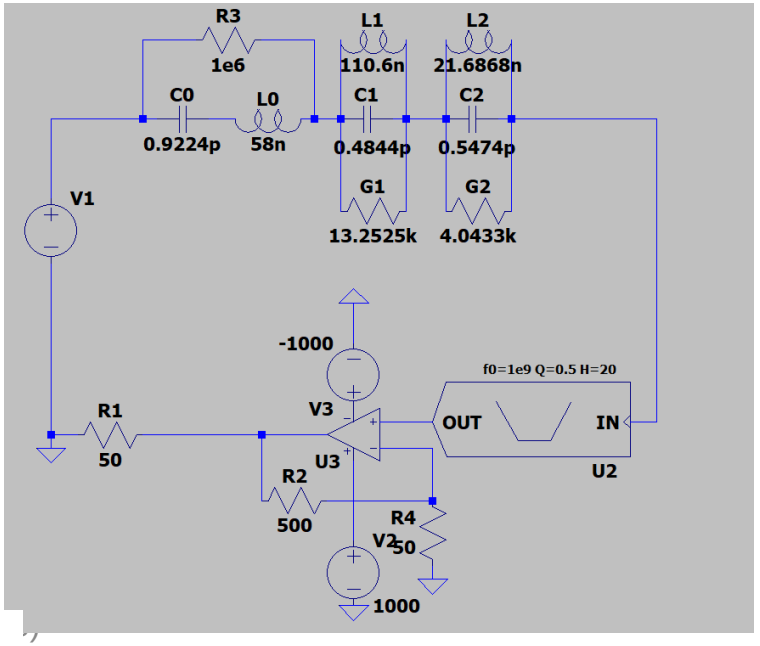


- *L = 10 cm*
- *Wire radius = 0.25 mm*
- *Bandpass filter specs:*
- *Resonance frequency = 1 GHz*
- *Quality factor = 0.5*
- *Gain = variable.*

- ***Excitation specs:***
- *Gaussian pulse*
- *Center frequency 0.1 GHz*
- *Bandwidth : 10%*

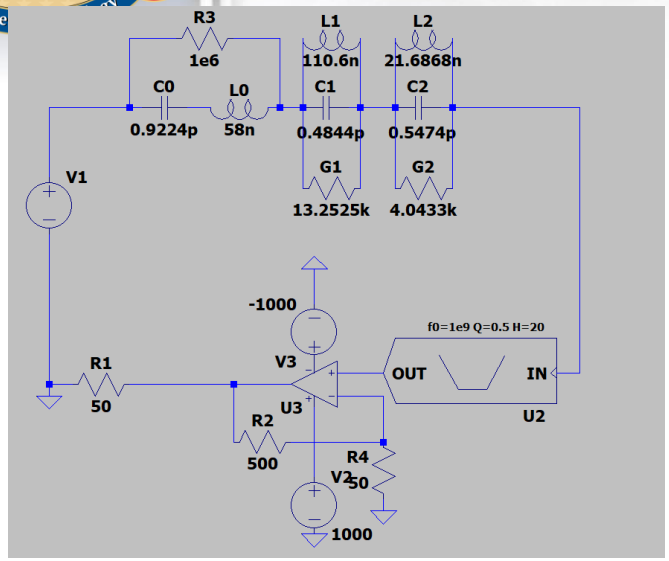




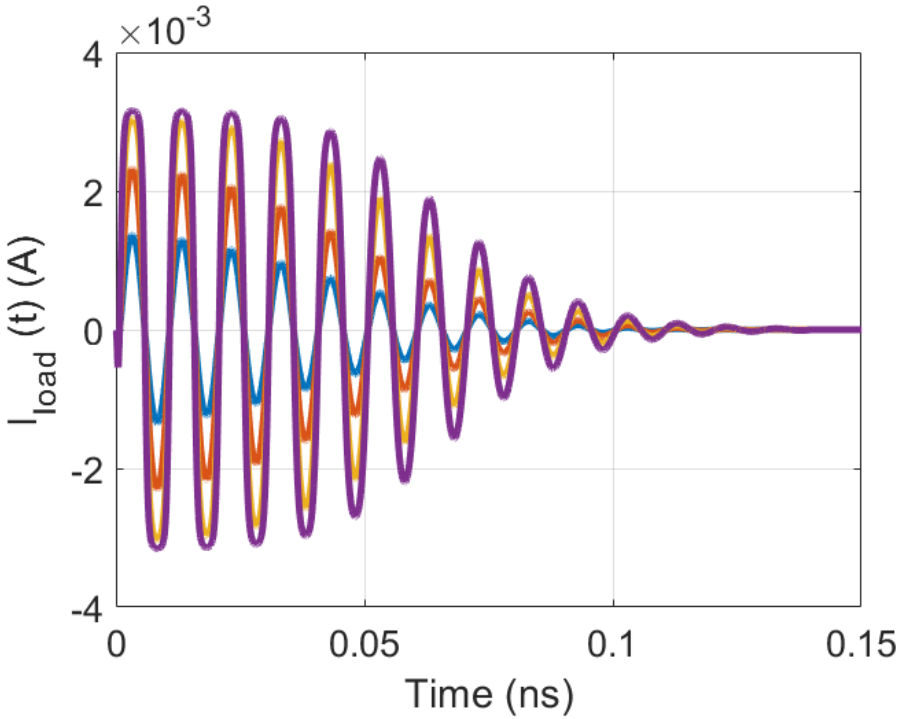


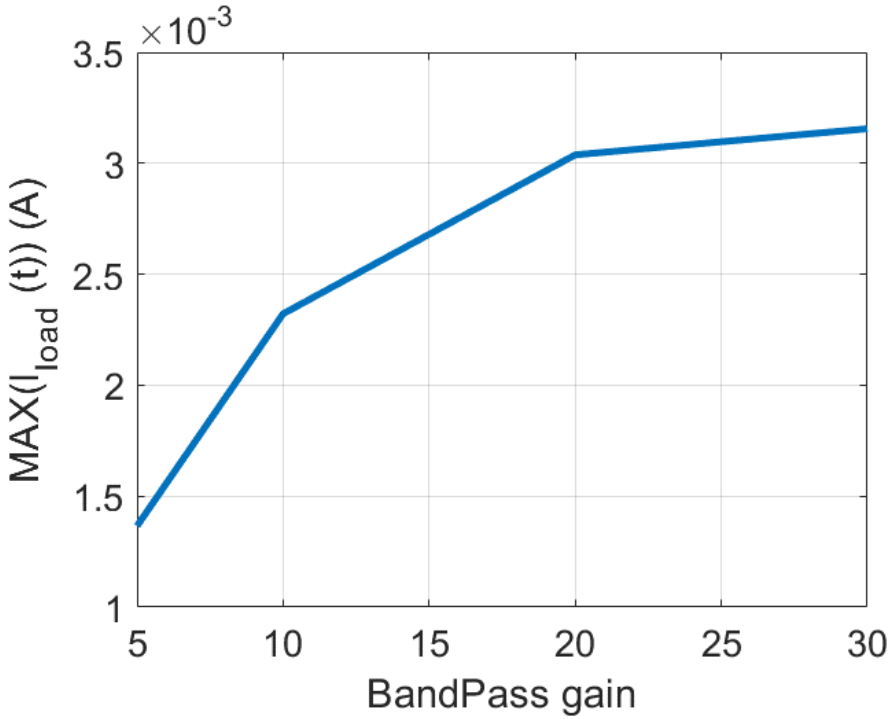
HPM: Technical Discussion/Progress Cont'd

Different Loads



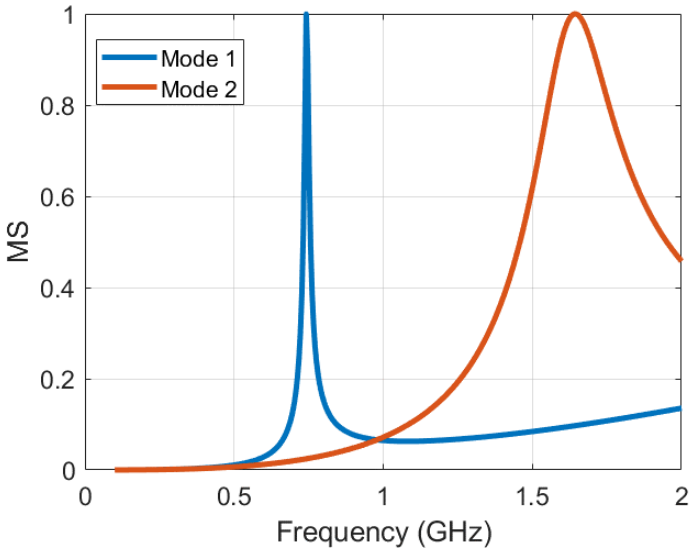
Load current will saturate beyond a certain gain level

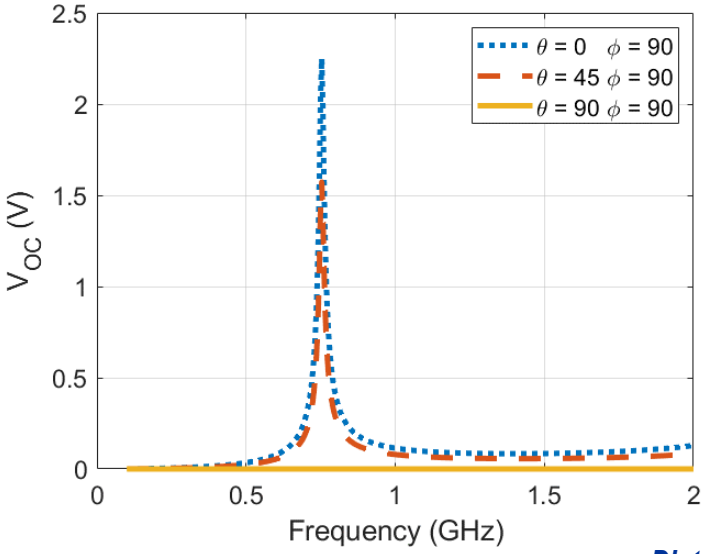




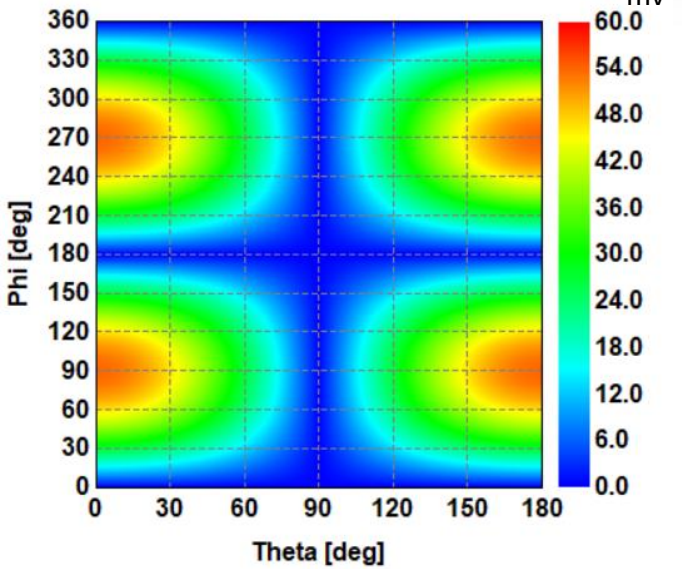
–CMA PREDICTIONS for VOC

$l = 5$ cm

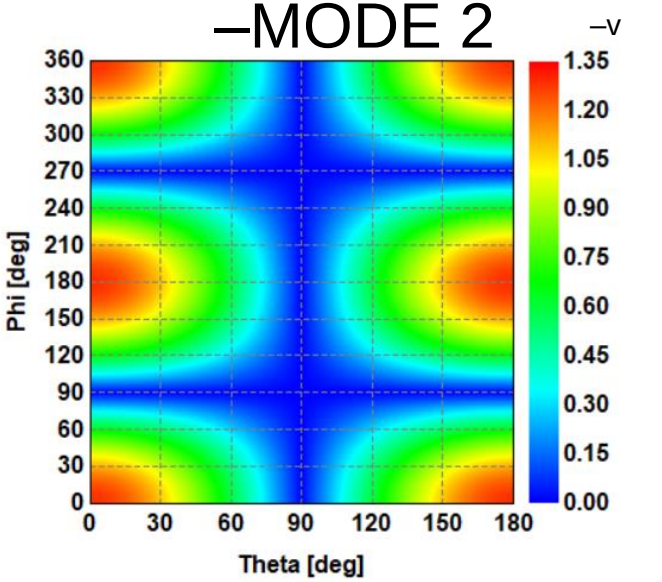




–MODE 1



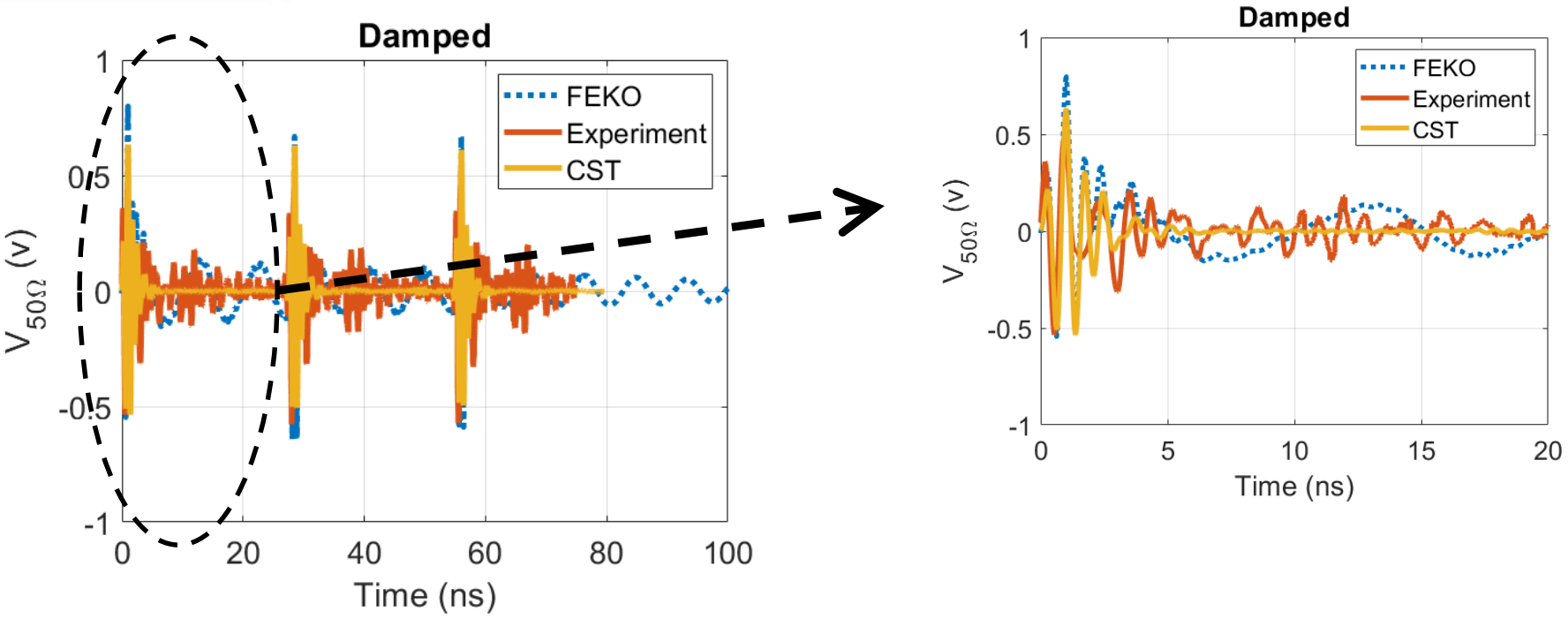
–MODE 2



Distribution A

HPM: Technical Discussion/Progress Cont'd

Experimental Validations



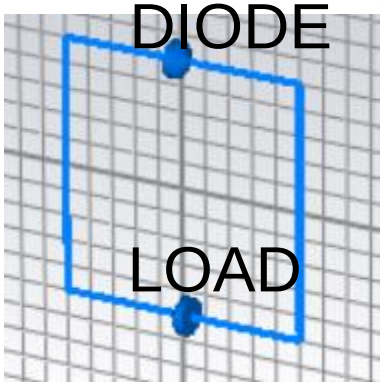
- Two independent computational electromagnetics techniques, CST and FEKO
- Excellent agreement with experimental measurements validates the approach

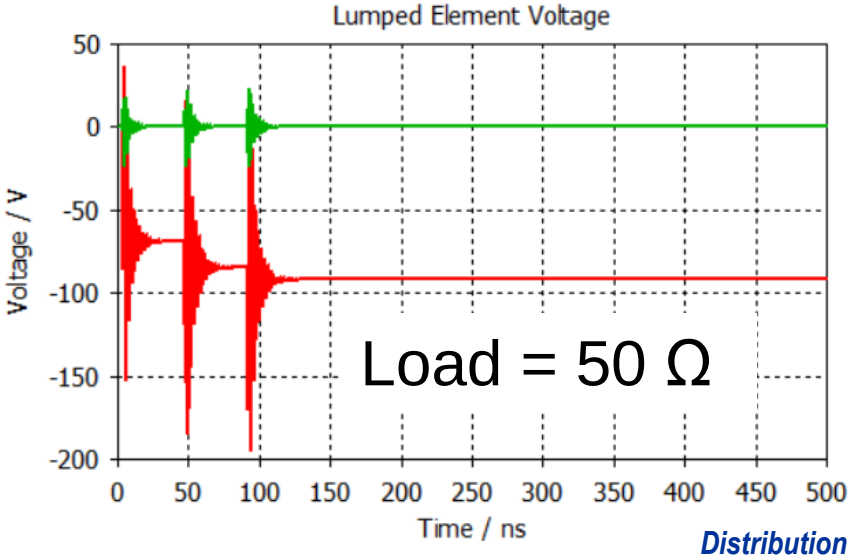
Distribution A

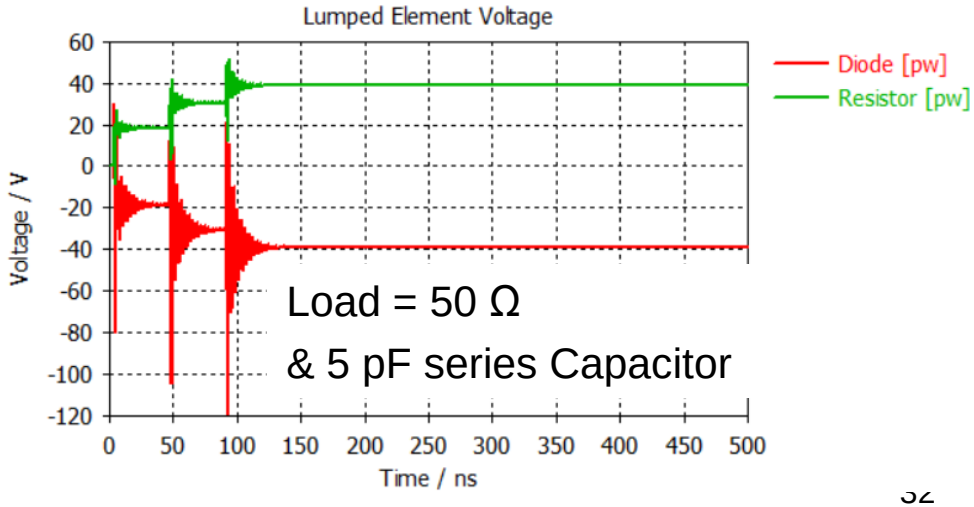
HPM: Technical Discussion/Progress Cont'd

Experimental Validations: Demonstrating voltage buildup

- Voltage buildup needs a large time constant, either large R and large C in Load
- R is limited to 50 Ω, the input impedance of the oscilloscope port
- If C is introduced, series to the 50 Ω oscilloscope port, voltage buildup can be experimentally observed as predicted by simulations below
- Parasitic capacitance exist in practical components







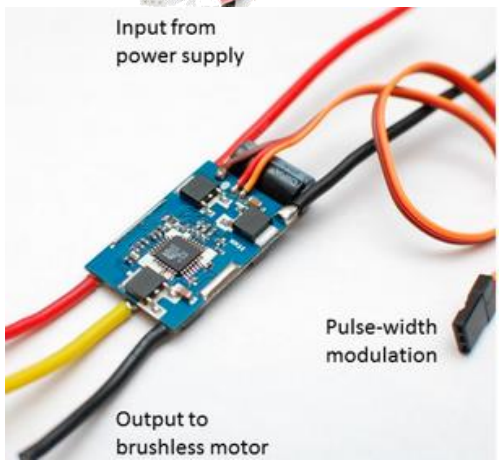
Distribution A

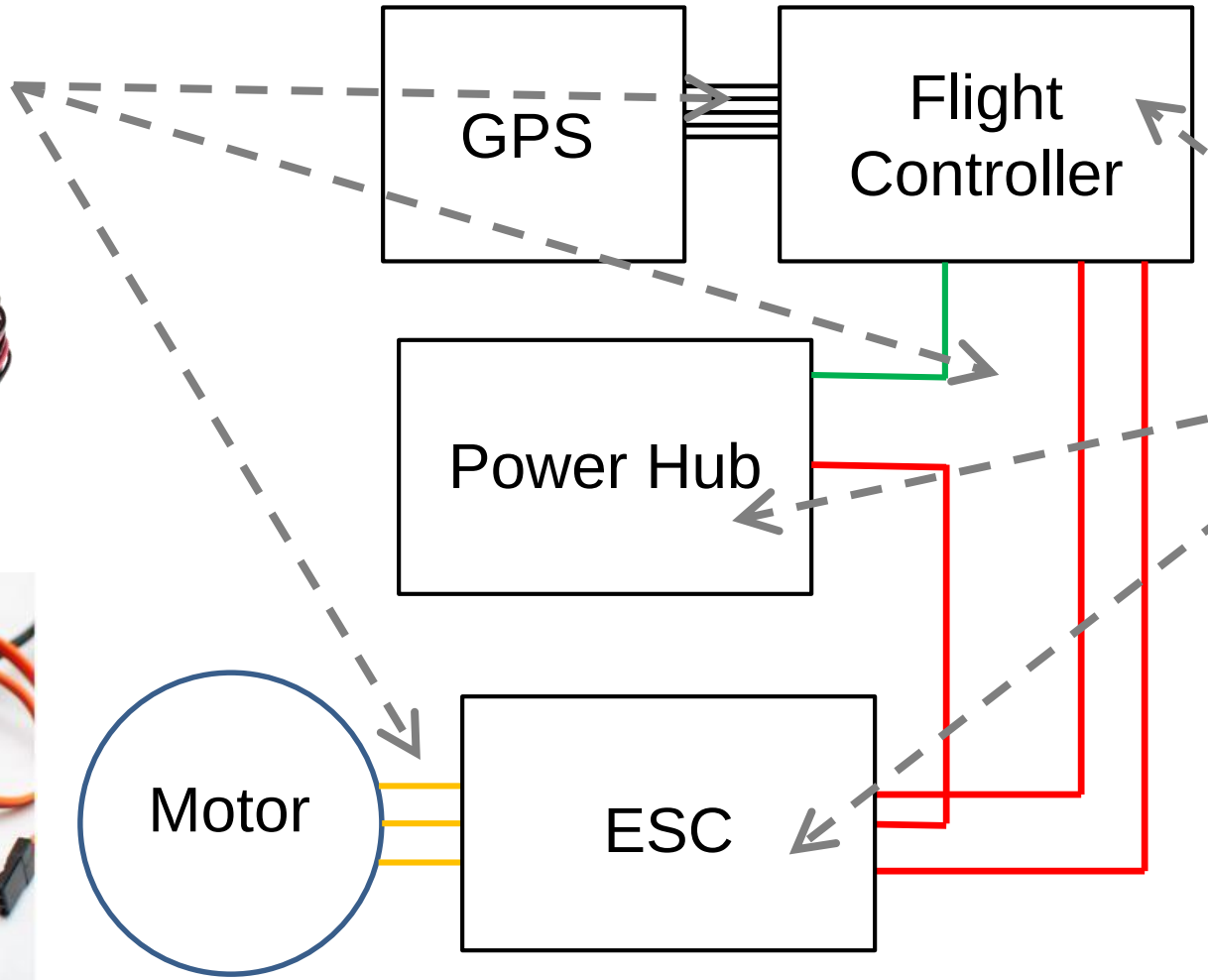
HPM: Future Proposed Efforts

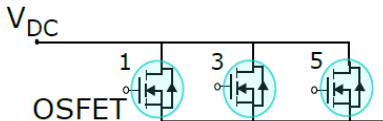
Road Map

Wires:

Sizes, Shapes,
Number of wires







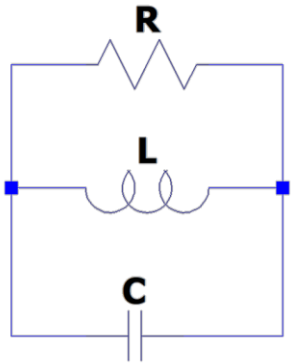
HPM: Future Proposed Efforts

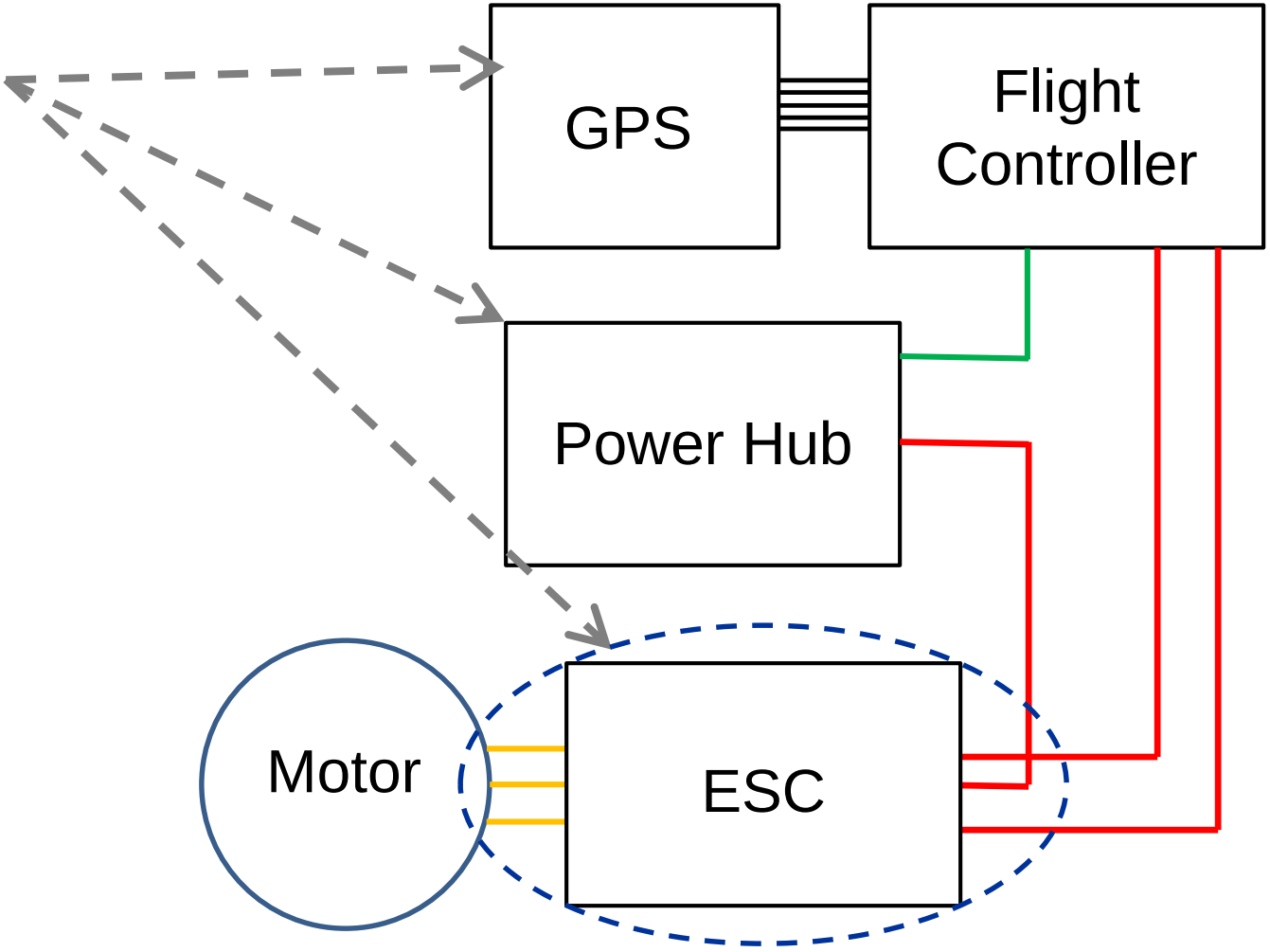
Road Map

Loads:

Linear: RLC

(1)

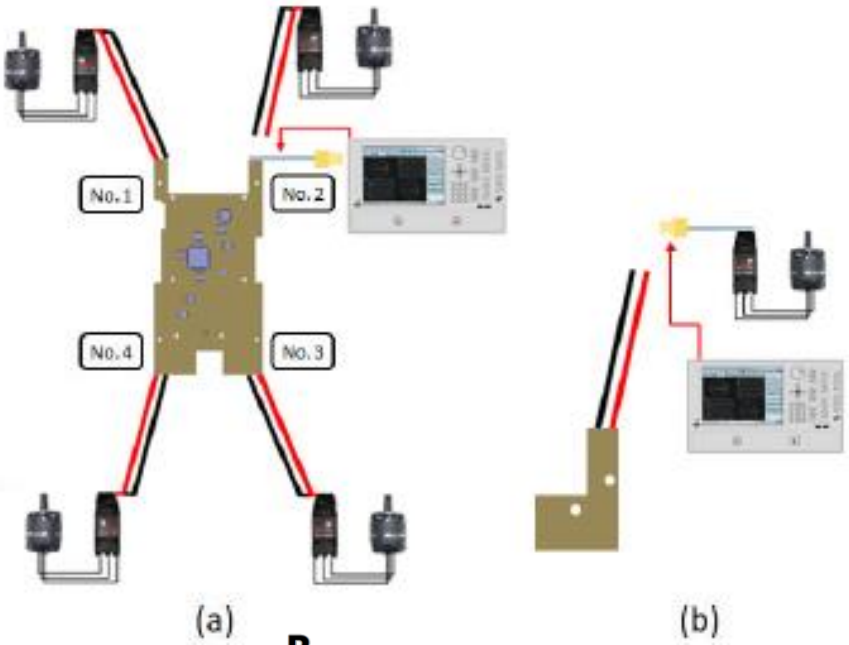




HPM: Future Proposed Efforts
Road Map

Loads:

Linear: RLC



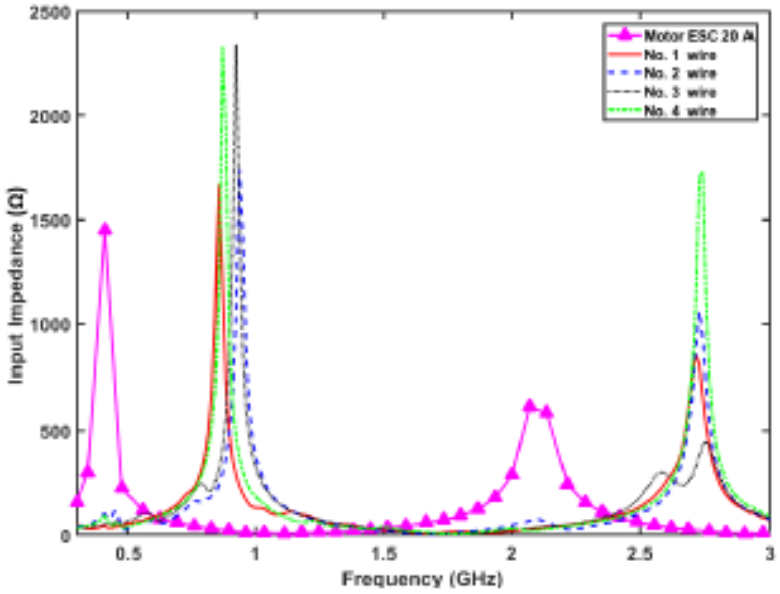
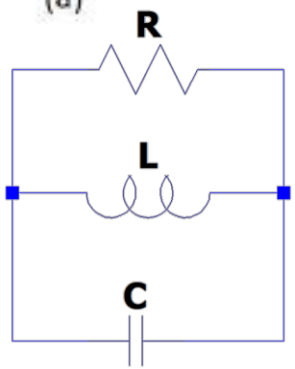


FIGURE 5. Input impedances for PCB side for wires 1 to 4 and motor side.

(1)



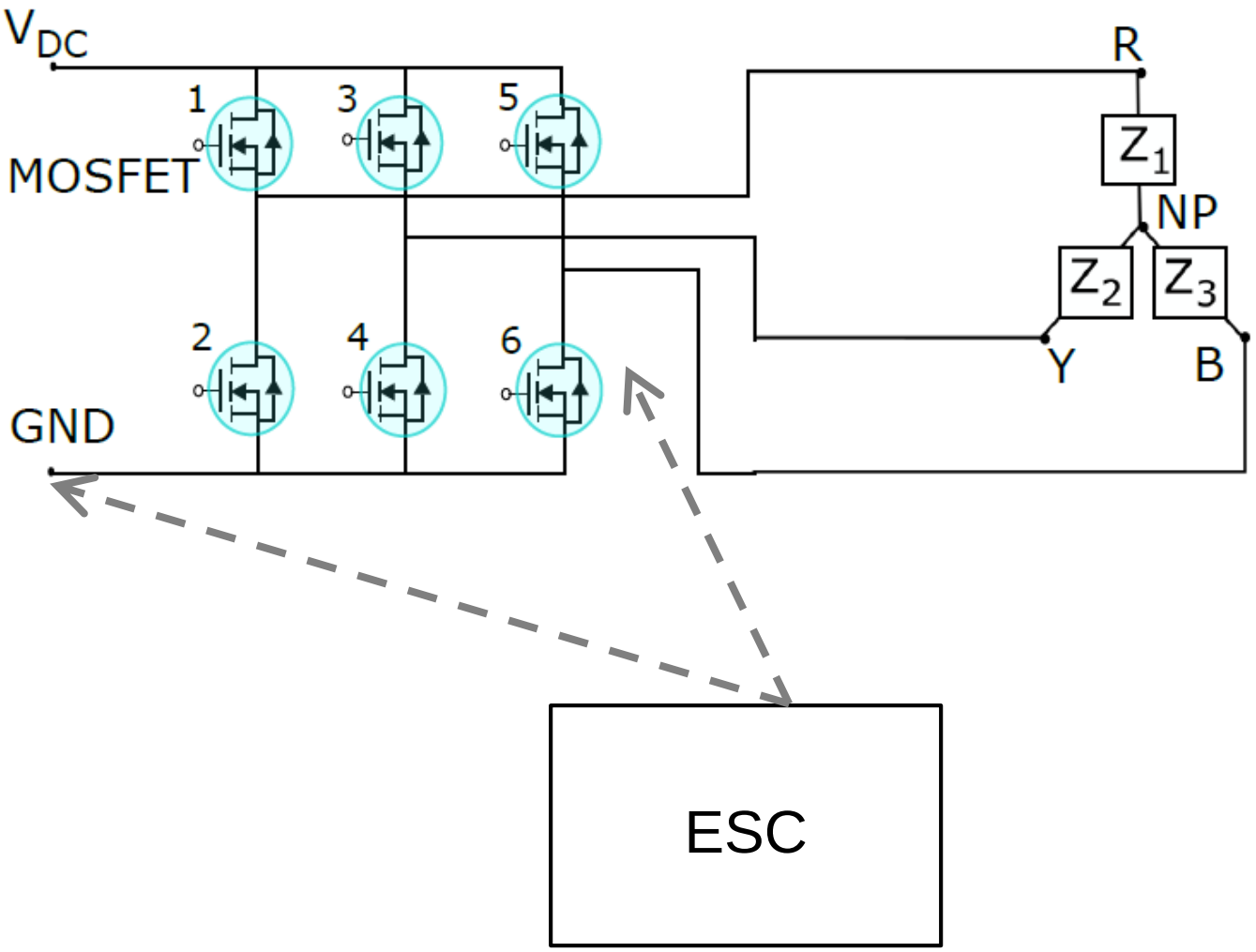
S. Kim *et al.*, "Electromagnetic Signature of a Quadcopter Drone and Its Relationship With Coupling Mechanisms," *IEEE Access*, vol. 7, pp. 174764-174773, 2019,

HPM: Future Proposed Efforts

Road Map

Loads:

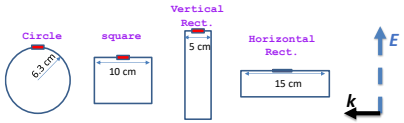
Nonlinear:
diodes, LNA, ESC, etc



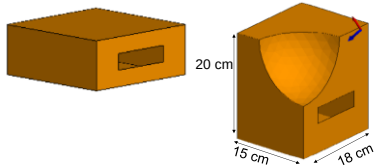
RF Coupling Research Configurations

- Most configurations below were experimentally verified
- For each configuration guidelines were developed e.g. optimum coupling frequency, angle of incidence, polarization, and optimum pulse excitations
- Quantitative analysis of the importance of how important is each factor e.g. shape, load.

Single unterminated wire, arbitrary shape free space

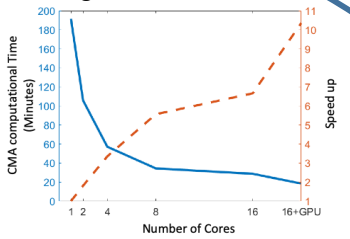


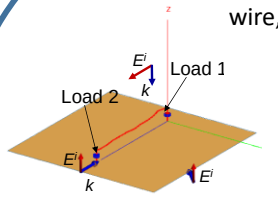
Wire loops, terminated, arbitrary shape free space



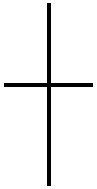
Wires in a perforated enclosure

Big data acceleration

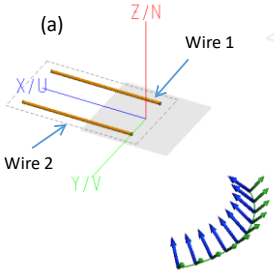




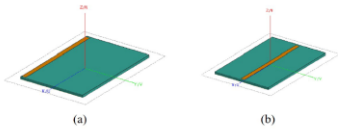
Single terminated wire, arbitrary shape, above ground plane



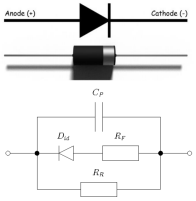
Two intersecting wires feeding same load

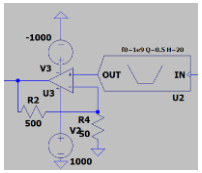


Coupling to 2-3 wires



Coupling to PCB traces, terminated, of arbitrary shapes at different location on board

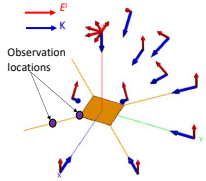


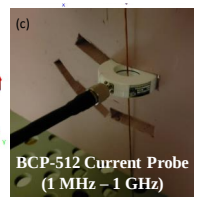


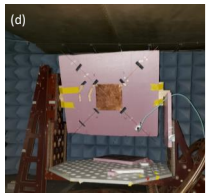
Different Nonlinear Loads

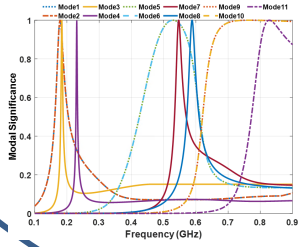
OSPERES cUAV Research

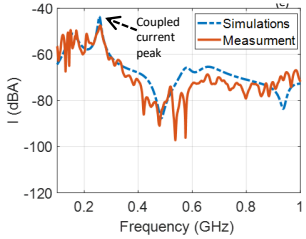
Quadcopter Model Version 0



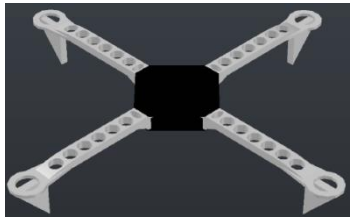


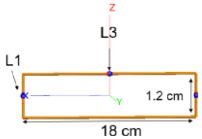


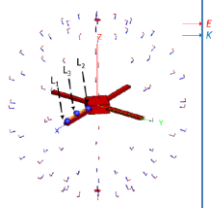


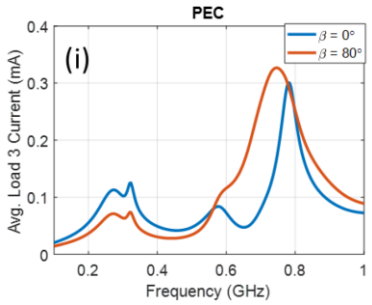


Quadcopter Model Version 1

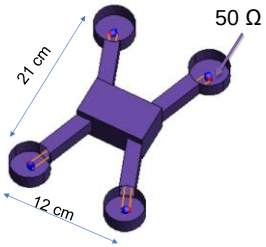


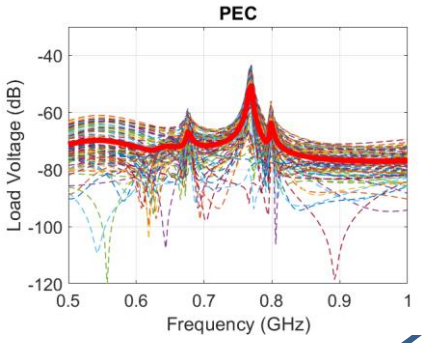






Quadcopter Model Version 2





FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

Bi-Annual Program Review

RF Coupling

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09 DEC 2020
held via Zoom

Distribution A. Approved for public release.

OSPRES: Research Team

FEKO <-> SPICE Tool Development/Validation

RF COUPLING

Computational EM Modeling

Mohamed Hamdalla

PhD Student

Benjamin (Bear) Bissen

PhD Student

Experimental EM Measurements

Big Data Acceleration of EM Code

Khulud Alsultan

PhD Student

Effects Team

- General RF Coupling Guidelines/Trends
- Guidance for Experimental Measurements
- Explanations to Experimental Observations
- Predict optimum pulsed excitation

MISSOURI S&T

Ahmed M Hassan

Assoc. Professor

Praveen Rao

Assoc. Professor

Anthony N Caruso

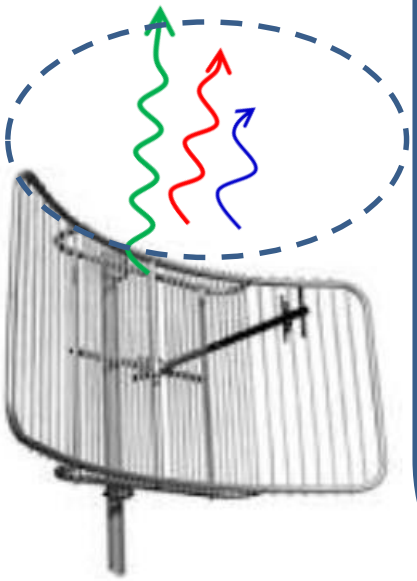
Professor

HPM: Future Proposed Efforts

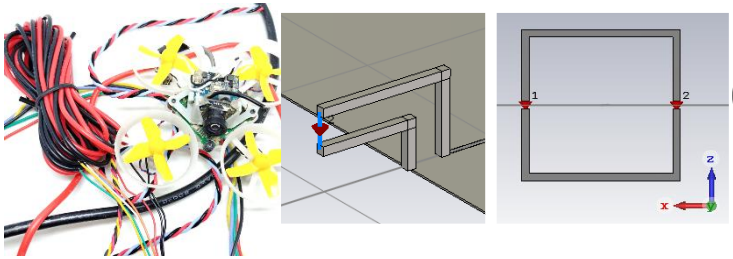
RF Coupling Collaboration

=

Source of Interference



Wires **(UMKC & MS&T)**



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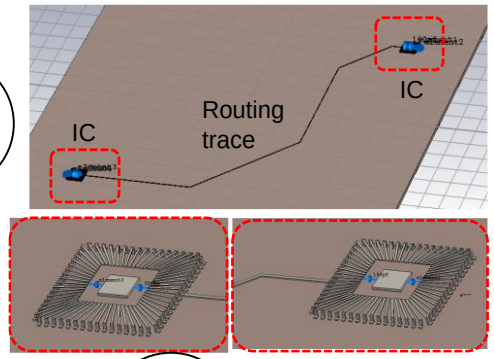
PCB Traces **(MS&T)**



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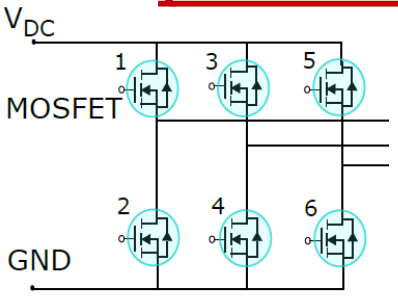
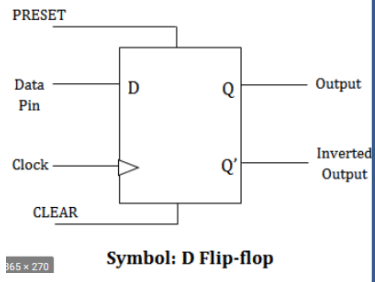
Predict Effects

Load Susceptibility **(UMKC & MS&T)**





Equivalent Circuit

DPI and TEM illumination

Frame Enclosure Wrapping **(UMKC)**

+

(a) Aluminum foil.

ONR HPM Program Key Research Criteria - II

RF Coupling to Enclosed Wires/ICs

Qualitative Criteria:

Goal I: Quantify RF coupling to enclosed wires/electronics in dielectric/conducting enclosures with apertures.

State-of-the-art (SOTA): *Simple enclosures/apertures, Random Coupling Model (RCM)*

Deficiency in SOTA: Only simple enclosures/apertures are modeled/measured. RCM valid for high frequencies, with respect to enclosure size, and provides statistics not a specific measurement in a specific situation.

Proposed Solution: Use computational modeling, CMA, and Machine Learning to study enclosures comparable in size to incident wavelength

sUAVs ~ 0.5 m - 1 m enclosures, f ~ 0.1 GHz - 3 GHz (λ ~ 3 m – 0.1 m)

Program outcome:

(1) Generate trends on how the shape/material of enclosure affect RF coupling

(2) A trained ML platform for predicting effects on wires and integrated circuits in UAV enclosures

ONR HPM Program Key Research Criteria - I

RF Coupling to Enclosed Wires/ICs

Quantitative

Parameter of Research	SOTA	Threshold	Objective
Study Enclosures with apertures similar in shape/size Quadcopter sUAVs	Simple shapes, not relevant to sUAV	10s of sUAVs geometries L (m) = 0.5:0.25:1.5 W(m) = 0.25:0.1:0.5 $\theta = 0°, 45°, 60°$	5-10 COTS sUAVs
Material Properties	Perfect Electric Conductors (PEC)	PEC, plastics, Carbon fiber variations	New Composite Materials, Wrapping

Normal Enclosures

Enclosures caused by EM Shielding Attempts

(a) Aluminum foil.

M. Graswald et al., "DEFEATING UAVS THROUGH NOVEL HPEM EFFECTORS," *31ST INTERNATIONAL SYMPOSIUM ON BALLISTICS HYDERABAD*, INDIA, NOVEMBER 4–8, 2019

OSPRES: RF Coupling Revisited

RF Coupling to Enclosed Wires/ICs

- **Risks**

Practical enclosure are computationally expensive to simulate → Use Big Data tools to accelerate computational models

RF Coupling Trends in practical wire configurations may be difficult to identify → Machine Learning Identification/classification

- **Payoffs**

An intelligent computationally efficient predictive tool to quantify the effect of perforated enclosures

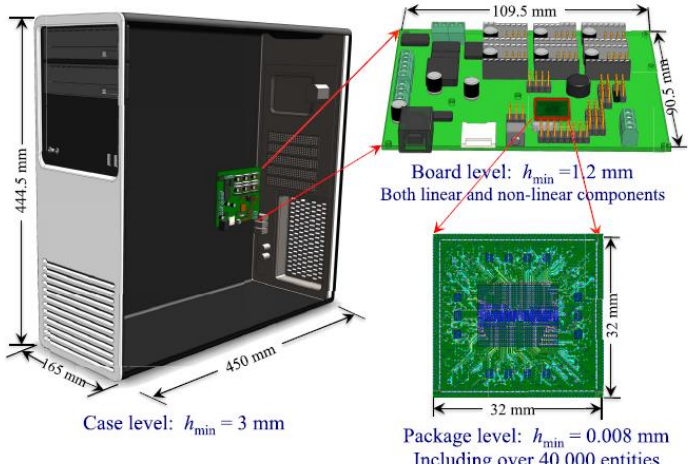
- **Challenges**

Computational simulation of one quadcopter enclosures requires a computational time in the order of hours (9 hours for the configuration in this presentation). Big data acceleration and parallel computing is needed to simulate 10s of configurations.

HPM: Broader Impact

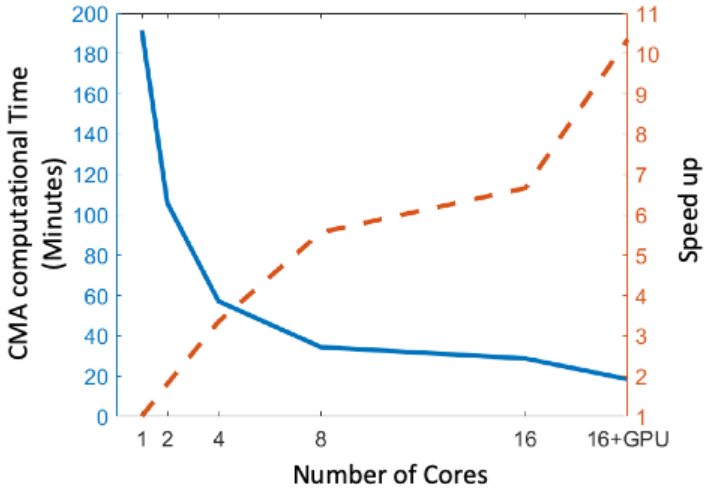
RF Coupling to Enclosed Wires/ICs

- The broader impact of this approach is that it can be used to guide interference to various non-sUAV enclosures e.g. other vehicles, computer casings etc.



Z. Peng *et al. IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 7, no. 5, pp. 653-668, May 2017.

Big data acceleration



- Merge of Big Data tools and Computational Electromagnetics has the potential to advance both fields

HPM: Sub-Project Research Objective

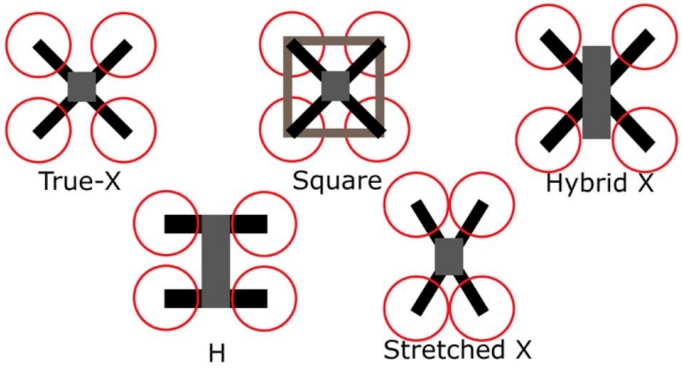
RF Coupling to Enclosed Wires/ICs

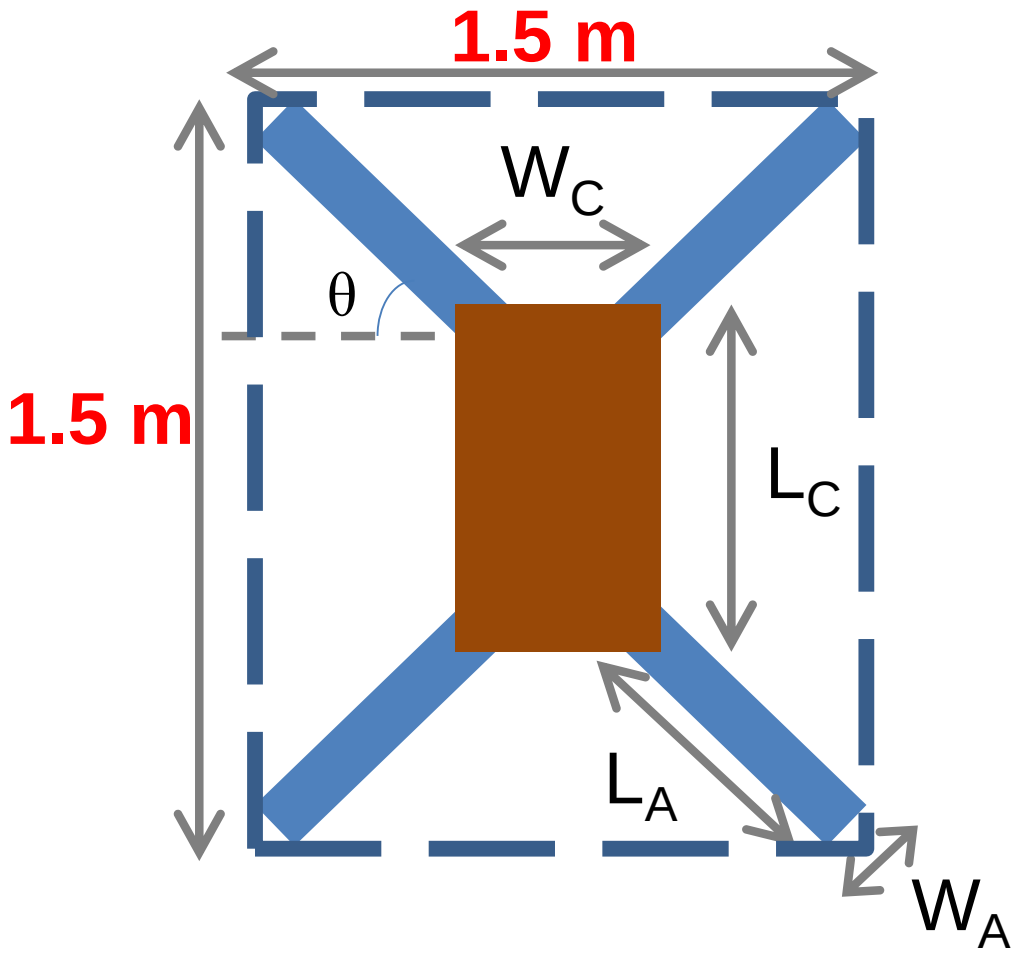
Use the full-wave simulations and Characteristic Mode Analysis (CMA) to:

- Identify the fundamental modes of the enclosure, current distribution, and the field pattern of each mode.
- Predict the worst-case RF coupling scenarios
- Scan sUAV quadcopter enclosure sizes, shapes, and common materials

HPM: Technical Discussion/Progress

Identification of sUAV enclosures



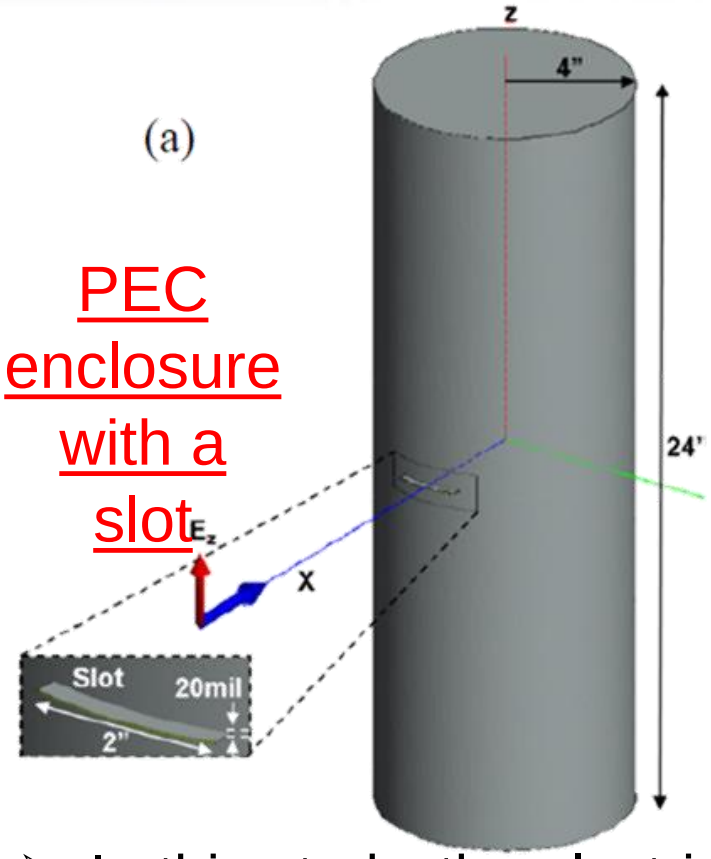


- We will focus on quadcopters to confine their shape variations.
- **Goal:** develop a generic model and test its conclusion on COTS sUAV shapes

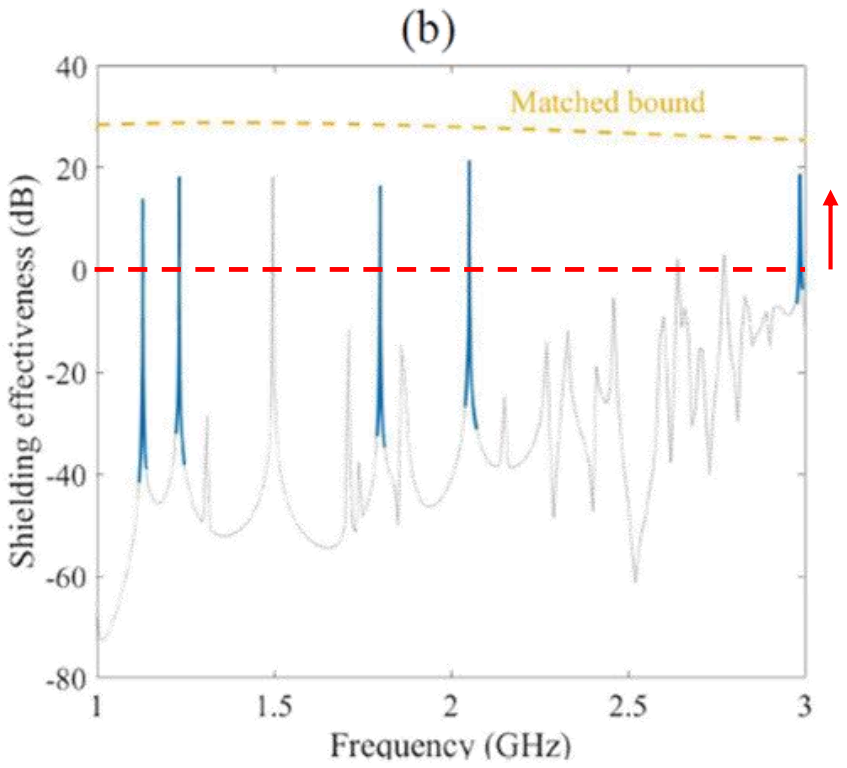
9 geometrical parameters
+ Material + Apertures

HPM: Technical Discussion/Progress Cont'd

Metallic Enclosure with Slot



PEC enclosure with a slot



SE > 0 dB

Indicate cavity amplifying incident field

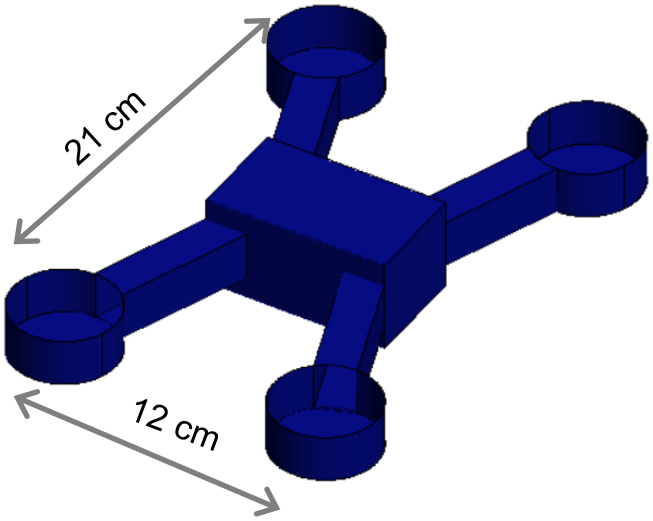
- In this study, the electric field inside the center of the cavity was compared to the incident field and the Shielding Effectiveness (SE) calculated.

$$SE\ (dB) = 20\ \log_{10} \frac{E_{in}}{E_0}$$

S. Campione et al., "Modeling and Experiments of High-Quality Factor Cavity Shielding Effectiveness," *2019 International Applied Computational Electromagnetics Society Symposium (ACES)*, Miami, FL, USA, 2019, pp. 1-2.

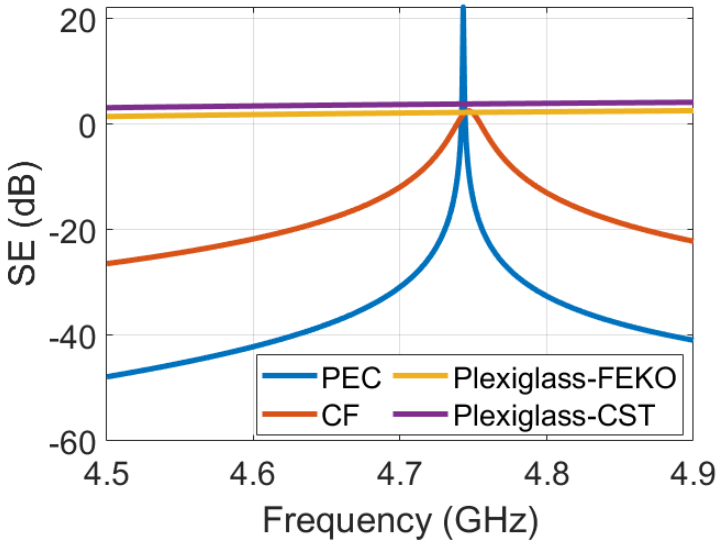
HPM: Technical Discussion/Progress Cont'd

SE of UAV Frames of Different Materials



Three materials were considered:

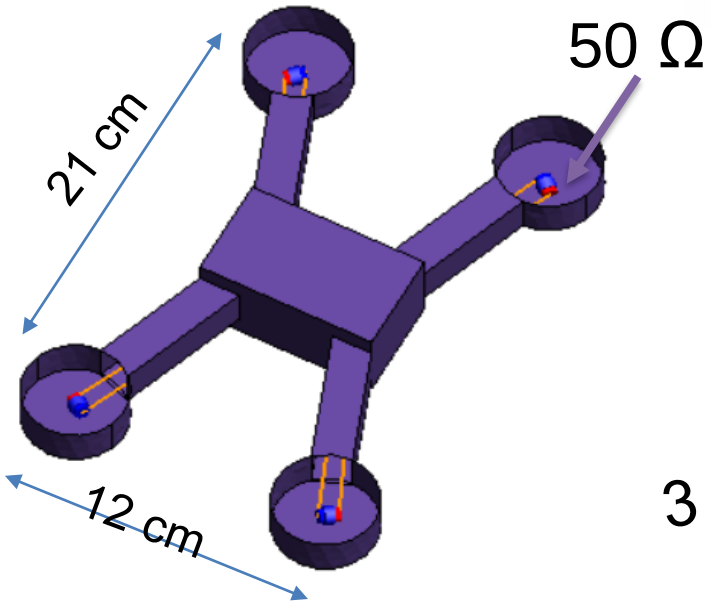
1. **PEC**
2. **Carbon Fiber Composite:** Polymer ε_r =3, Fibers σ = 1000 S/m
3. **Plexi-glass** ($\varepsilon_r = 2.6$, $\tan\delta = 0.0057$, thickness = 5 mm)



- Lossy dielectric UAV enclosures, Plexiglass, enhance coupling to enclosed wires and electronics by ~ 5 dB, over a wide range of incident field directions compared to free space;
- Perforated PEC and Carbon fiber UAVs shield by more than 20 dB on average except at the resonance frequencies where they amplify the coupling by ~ 5-20 dB over a narrow bandwidth.

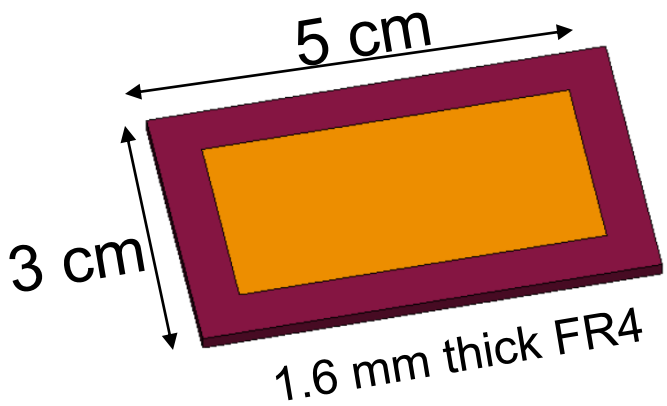
HPM: Technical Discussion/Progress Cont'd

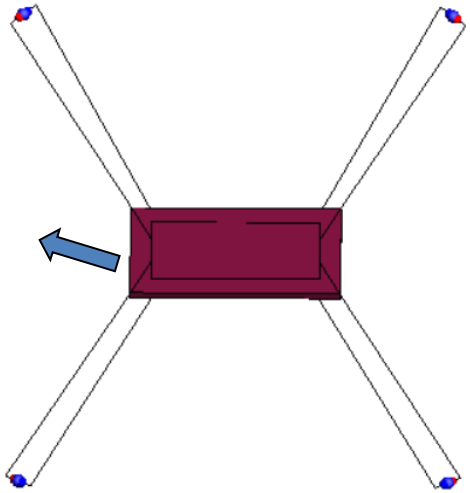
Coupling to enclosed wires

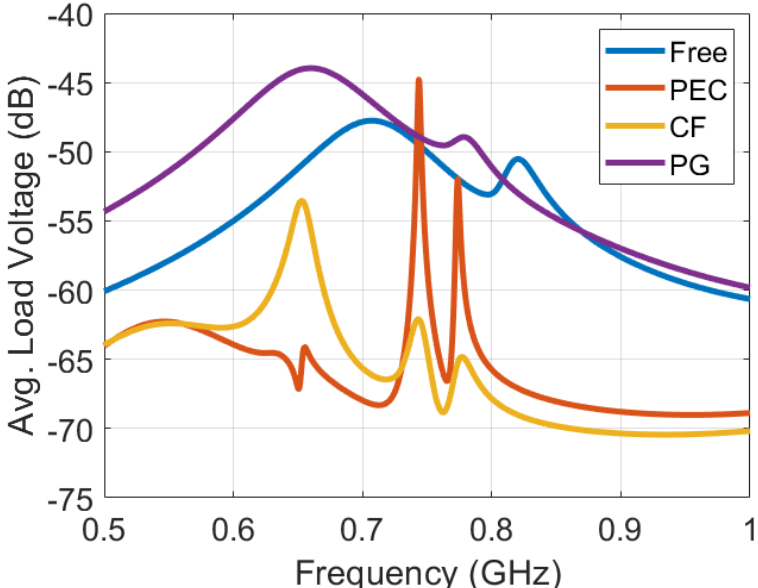


Angles of incidence were varied such as:

$0 < \theta < 180°$ and $0 < \varphi < 90°$ in $5°$ steps





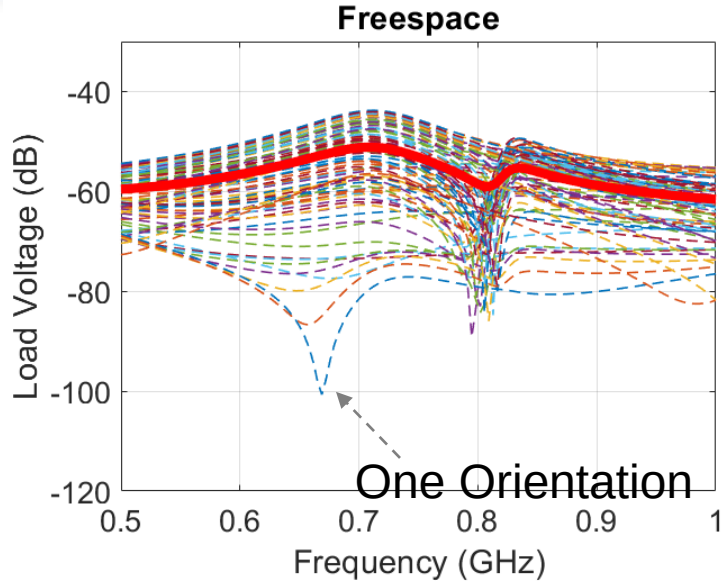


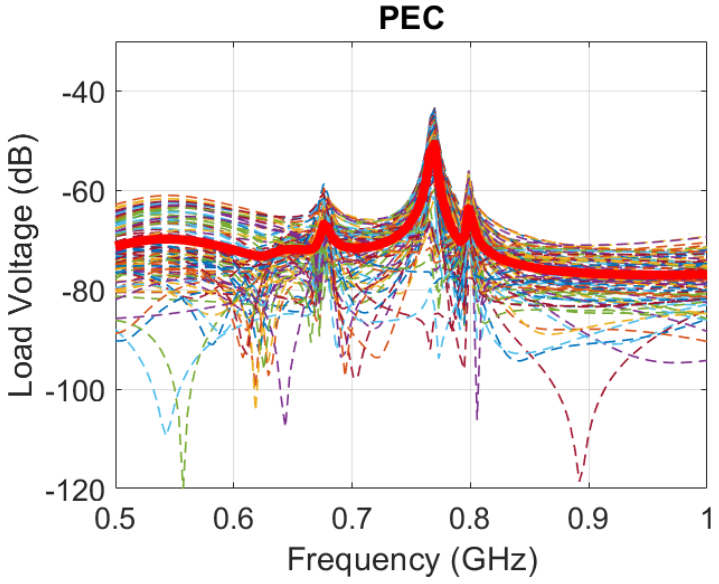
- At the resonance frequencies, shielding can be compromised (e.g. CF frame 0.66 GHz)
- For PEC, fields are amplified in comparison to free space at 0.75 GHz and 0.77 GHz
- Dielectric frames amplify the voltage by > 5dB and shift resonances to lower frequencies

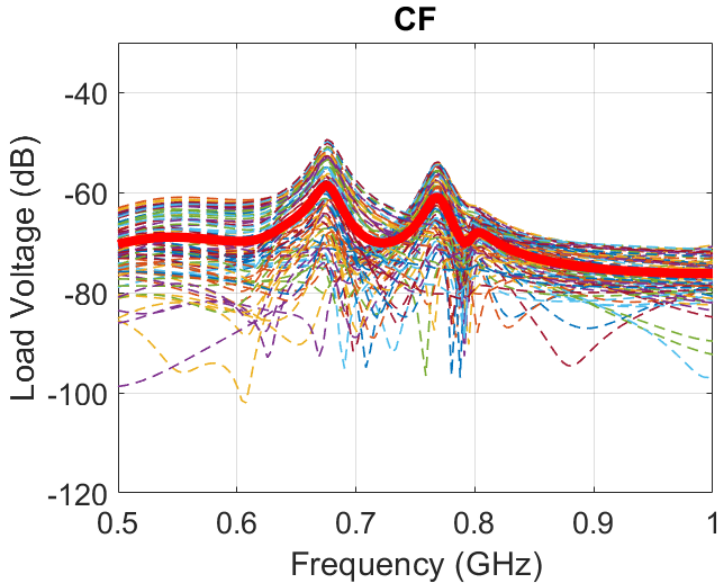
Distribution A

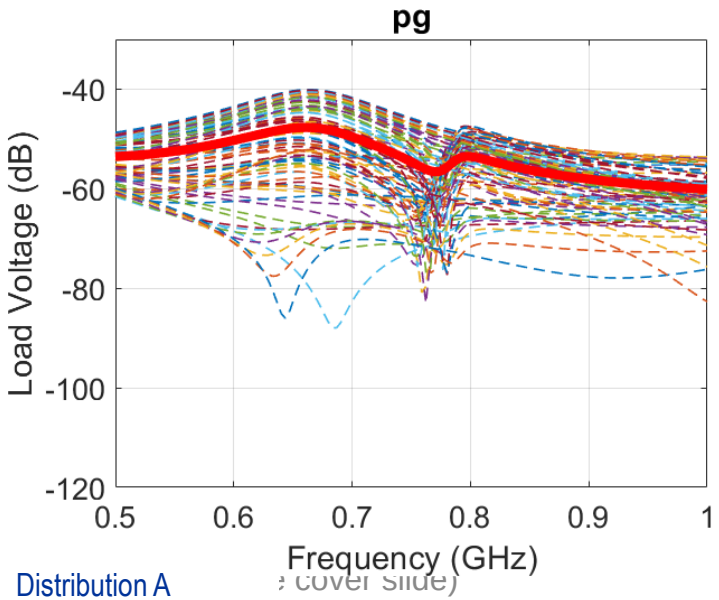
HPM: Technical Discussion/Progress Cont'd

Variations in Coupled Voltage with Angles of Incidence (Orientation)







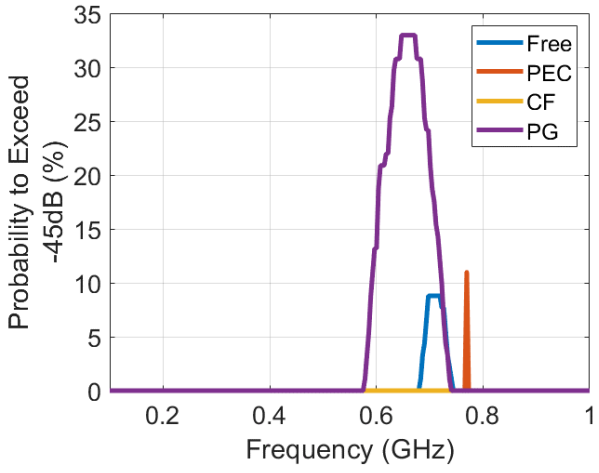


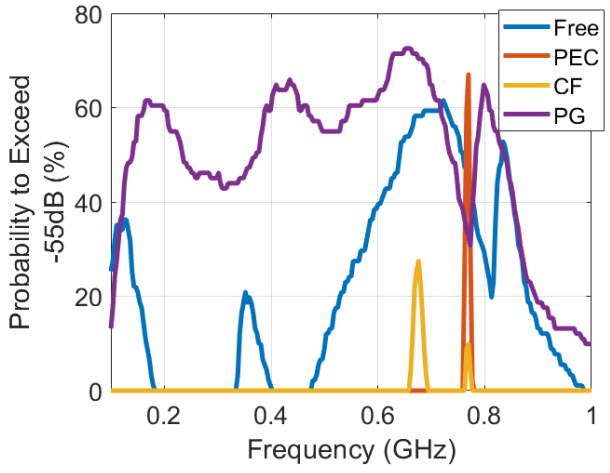
- CF does not have the sharp resonances of PEC but yields comparable shielding
- Given the variations in the coupled voltage with orientation, we can calculate the probability of the voltage exceeding a certain threshold

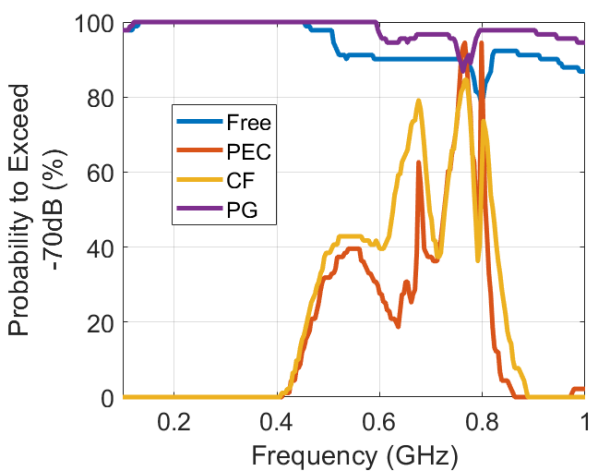
Distribution A

HPM: Technical Discussion/Progress Cont'd

Coupling to enclosed wires







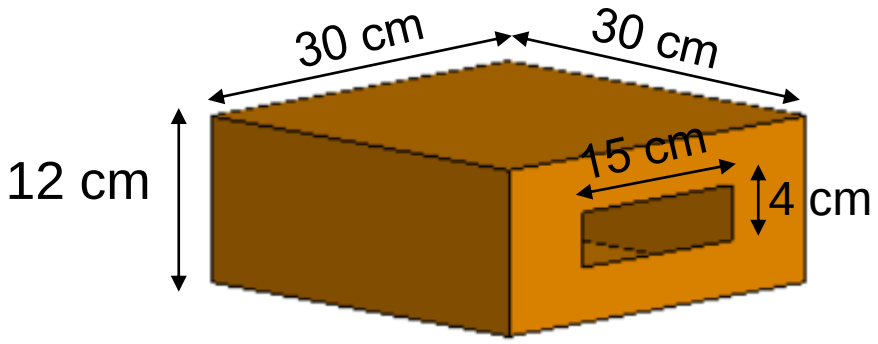
- Previous results were achieved using incident plane waves at continuous frequencies
- However, the results can predict the optimum pulse, to maximize the coupled voltage, by designing the pulse's BW to overlap with the frequencies where the probability is highest.
- **Future work, will investigate the variation in the above statistics with the shape/size of the enclosure**

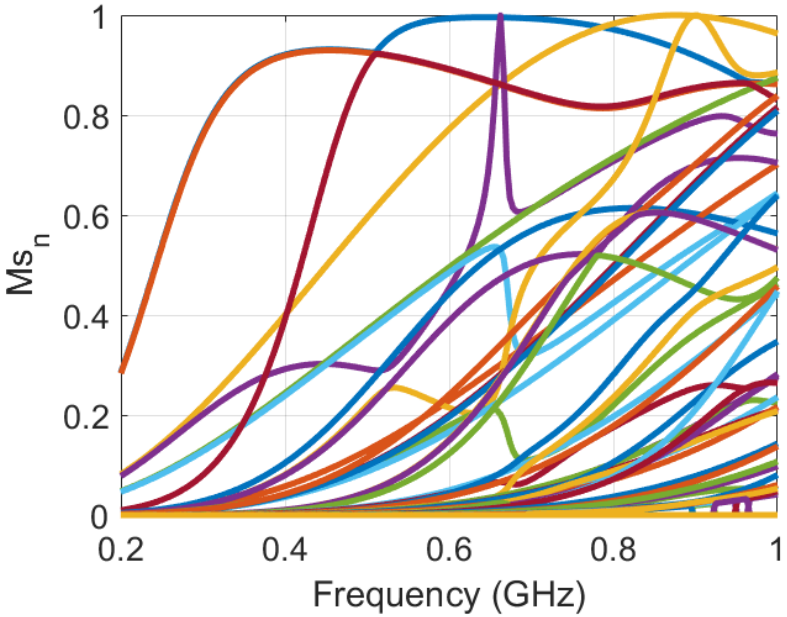
Distribution A

HPM: Technical Discussion/Progress Cont'd

CMA of Metallic Enclosure with a Slot

- The resonance frequencies of non-canonical shapes can not be estimated by closed form formulas
- Characteristic Mode Analysis (CMA) provides the modal significance which can be used to identify the resonance frequencies.



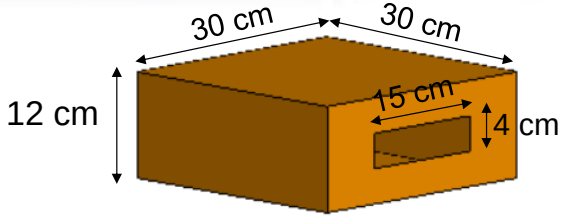


- Too many modes, some irrelevant to enclosed electronics. How to classify?

Distribution A

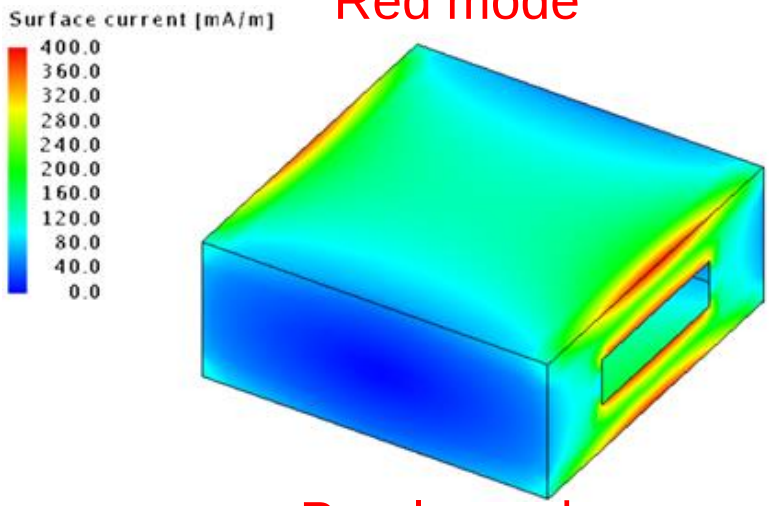
HPM: Technical Discussion/Progress Cont'd

CMA of Metallic Enclosure with a Slot

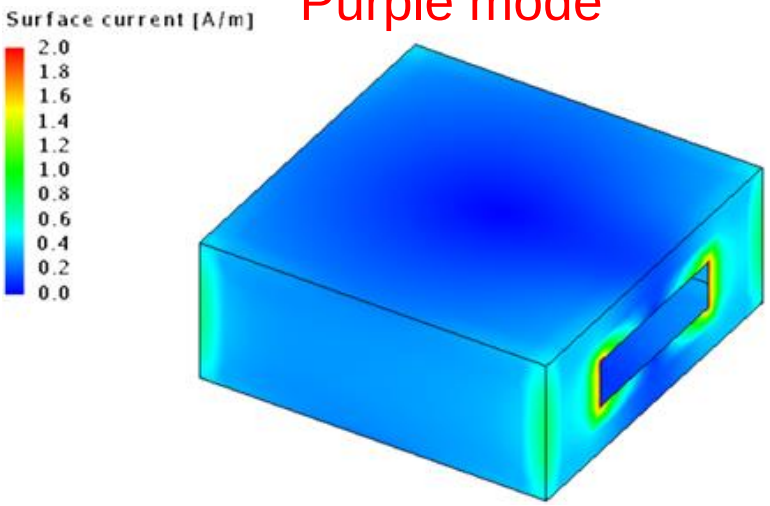


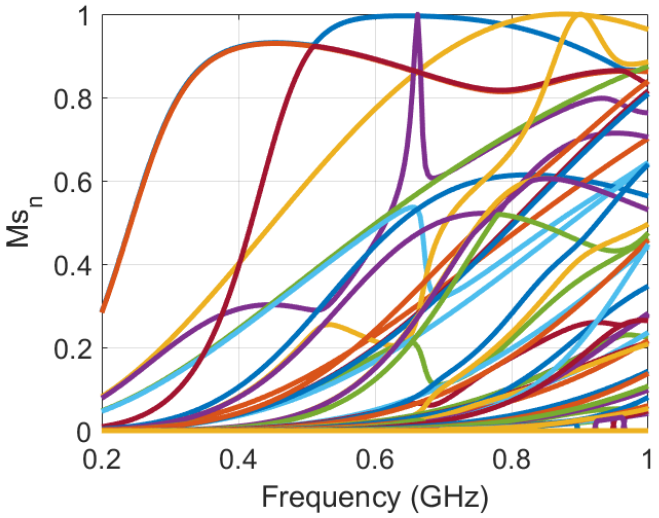
- Some modes at their resonance have a higher maximum amplitude
- **Hypothesis:** These modes are the modes which create standing waves and amplify the field inside the enclosure

Red mode



Purple mode





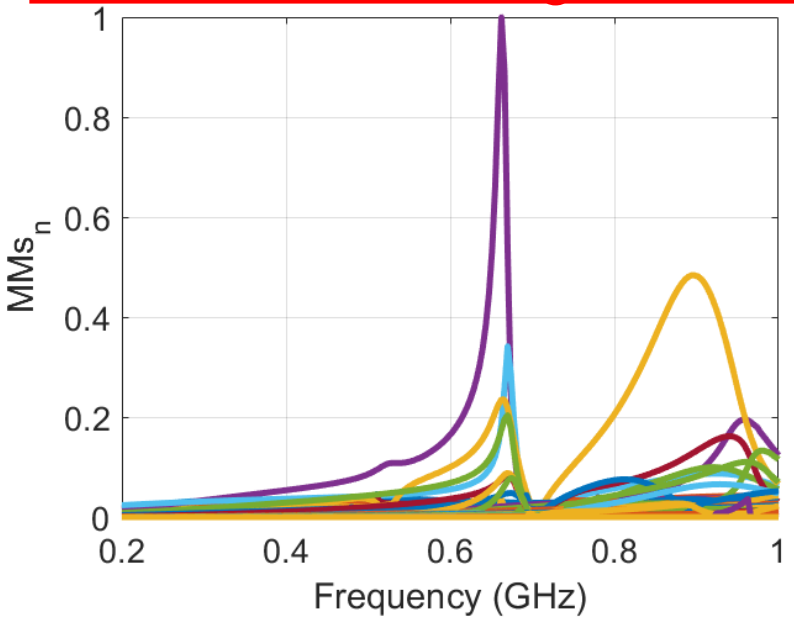
Define $MMS(n) = MS\ (n) * max\{|\boldsymbol{J_n}|\}$

Distribution A

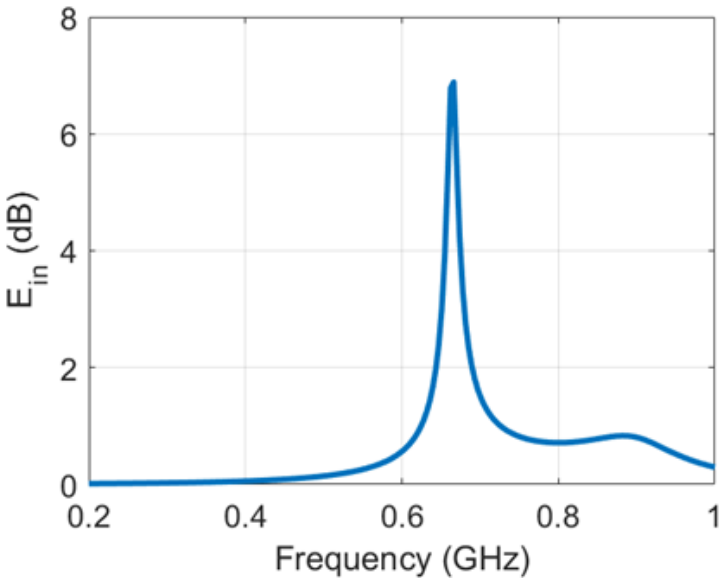
HPM: Technical Discussion/Progress Cont'd

CMA of Metallic Enclosure with a Slot

Modified Modal Significance



Field at the center of the cavity

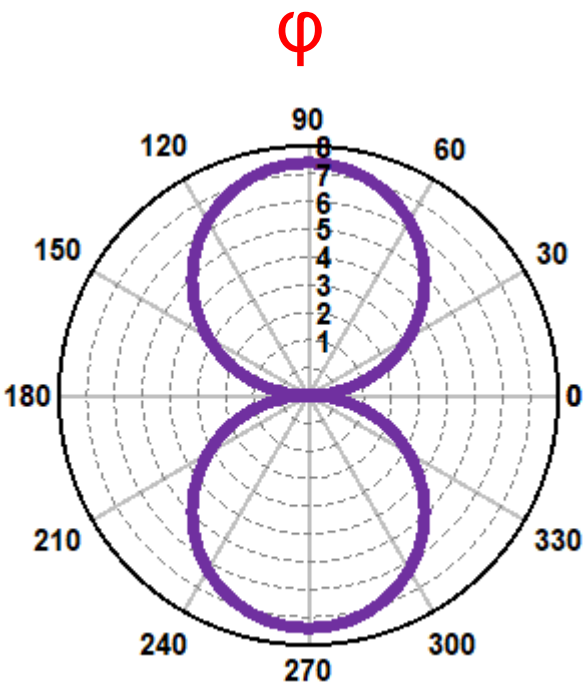


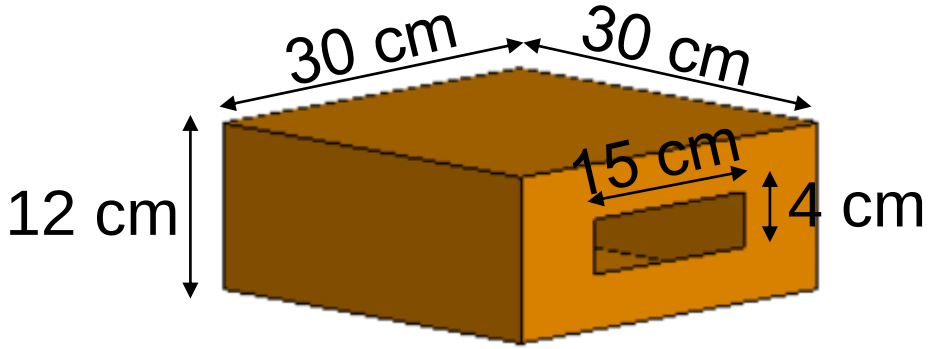
- MMS provides an indication of modes that amplify the field inside the enclosure
- Other modes predominantly radiate outside of the enclosure → Therefore, are not expressed in MMS

Distribution A

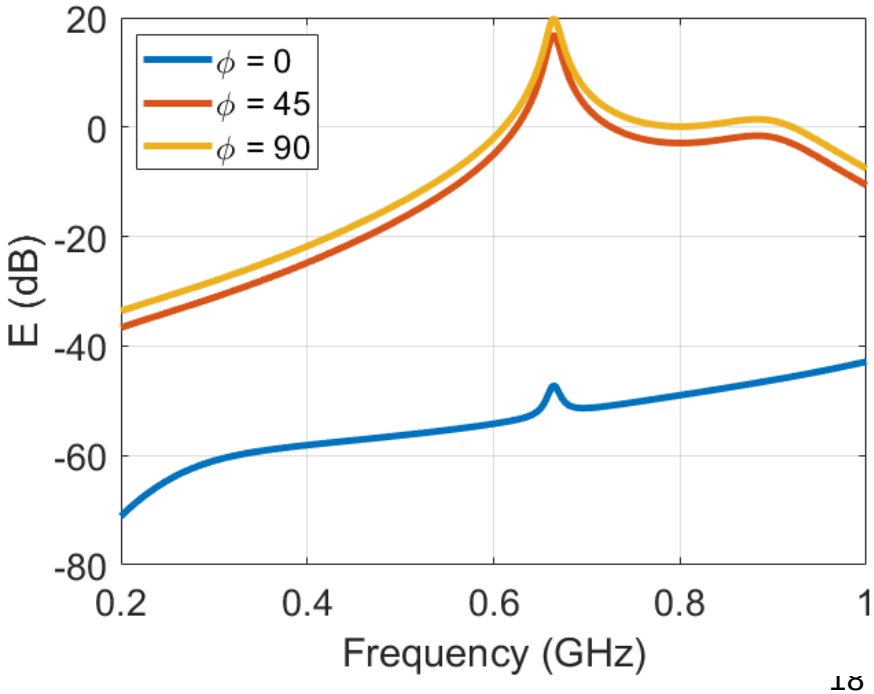
HPM: Technical Discussion/Progress Cont'd

Mode Radiation Characteristics





Field at the center of the cavity



- Modal fields can be used to identify optimum coupling angles
- Or to calculate the statistics of the coupled voltage for a randomly oriented target

Distribution A

HPM: Research Objective Progress/Significant Findings

- Even dielectric enclosures can enhance coupling to the enclosed loads by > 5 dB in comparison to free space
- PEC/CF frames can lead to high quality resonances even with lossy dielectric FR4 substrates enclosed.
- Optimum frequencies can be identified for shielded/covered frames

(a) Aluminum foil.

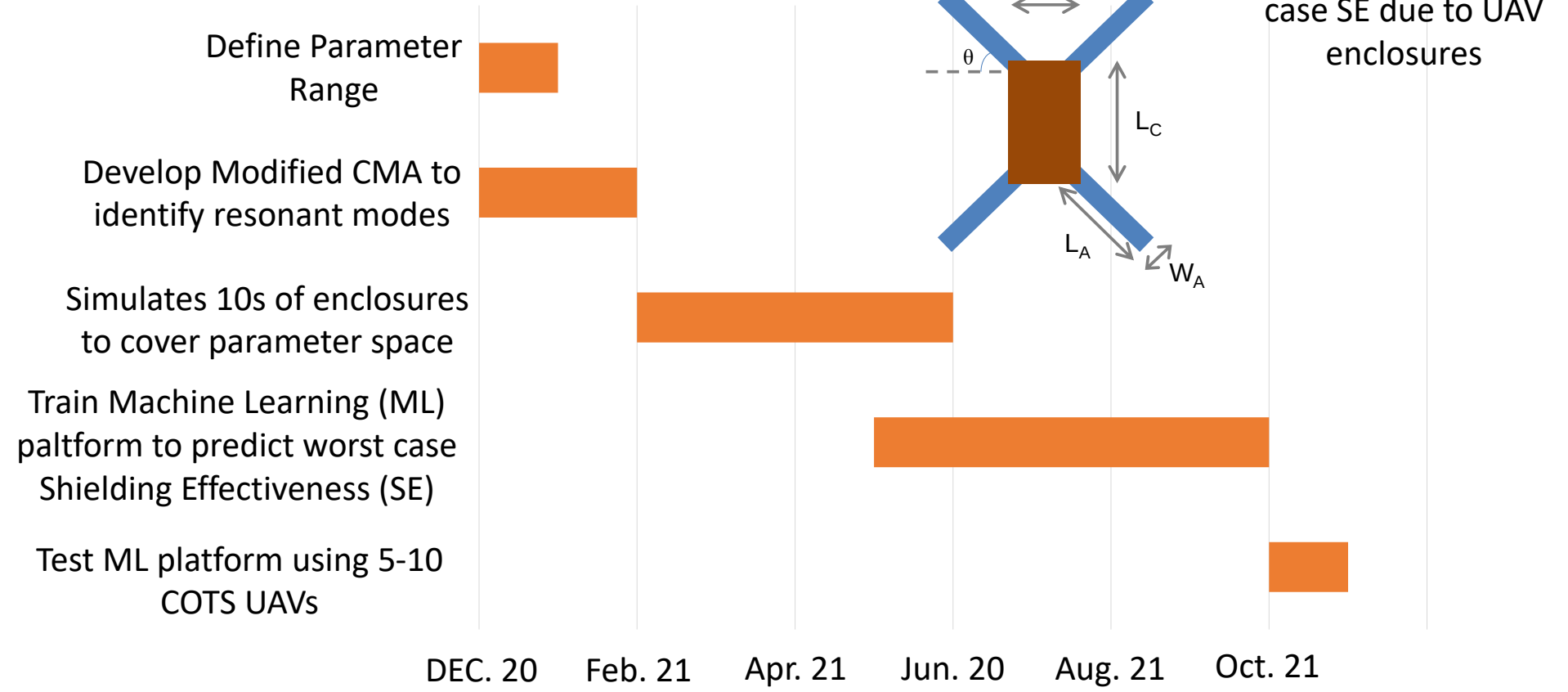
(b) Wrap shield.

HPM: Future Proposed Efforts

Road Map

Milestone 1:
AWPL paper on Modified CMA

Milestone 2:
A trained ML platform for predicting worst case SE due to UAV enclosures



HPM: Conclusions
FEKO <-> SPICE Tool Development/Validation

- The susceptibility of most wires and electronics to electromagnetic interference is typically measured/assessed in free space.
- We studied the shielding effectiveness and the coupled voltages to wires/loads enclosed in perforated enclosures of different materials
- Lossy dielectric UAV can enhance coupling by 5 dB
- PEC and Carbon fiber UAV enclosures increase shielding effectiveness by more than 20 dB except at the resonance frequencies of the enclosure where shielding will be compromised or coupling can be even increased by ~ 5-20 dB over a narrow bandwidth
- Analysis can be used to provide general guidelines about how the enclosure increases/decreases shielding effectiveness.
- Analysis can also be used to identify optimum coupling frequencies based on shape/size and material of enclosure.

Acknowledgements

This work is supported by Office of Naval Research Grants:

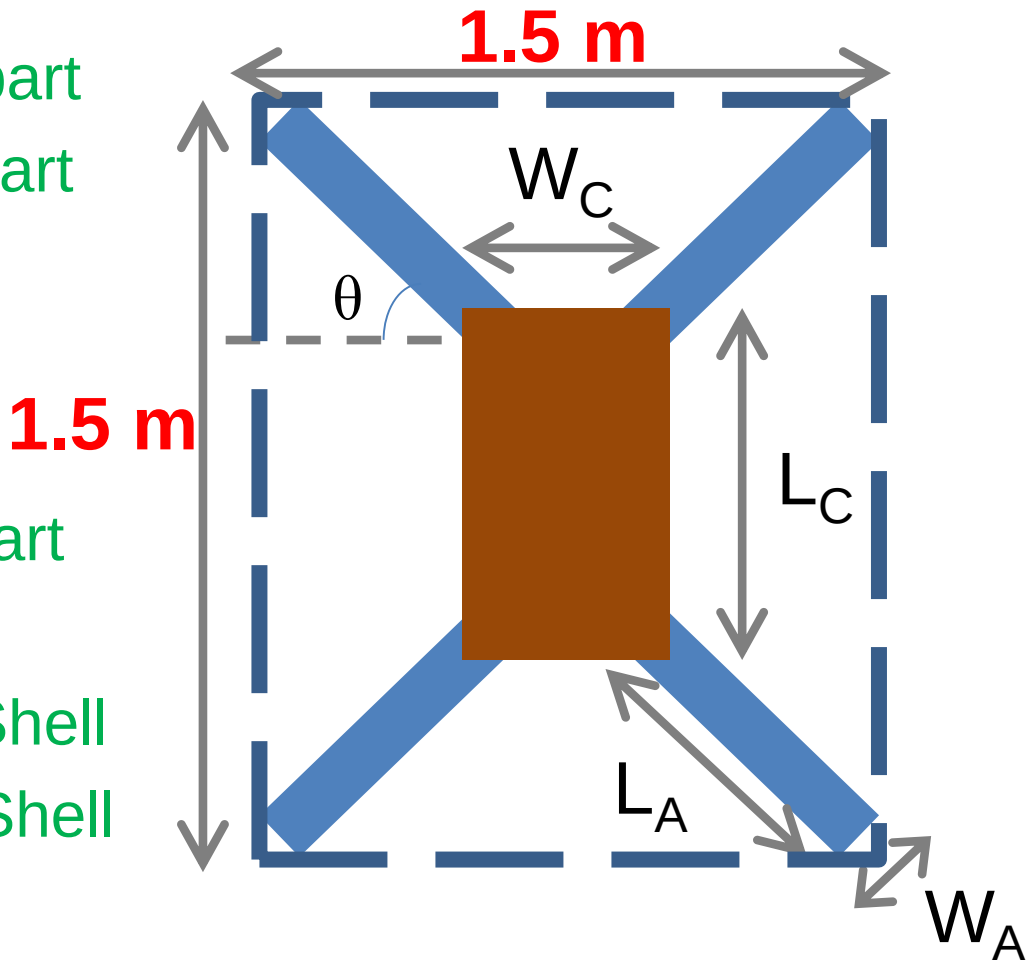
- ONR grant # N00014-17-1-2932
- ONR grant # N00014-17-1-3016

HPM: Technical Discussion/Progress

Identification of sUAV enclosures

Parameters to Vary:

1. L_C: Length of Central part
2. W_C: Width of Central part
3. L_A: Length of Arm
4. W_A: Width of Arm
5. θ: Arm angle
6. H_A: Height of central part
7. H_C: Height of Arm
8. T_A: Thickness of Arm Shell
9. T_C: Thickness of Arm Shell
10. Apertures
11. Material



UAV Sizes and Operating Classifications

- UAV are classified according to its size, shape and material.
- For size, they are categorized as follow:

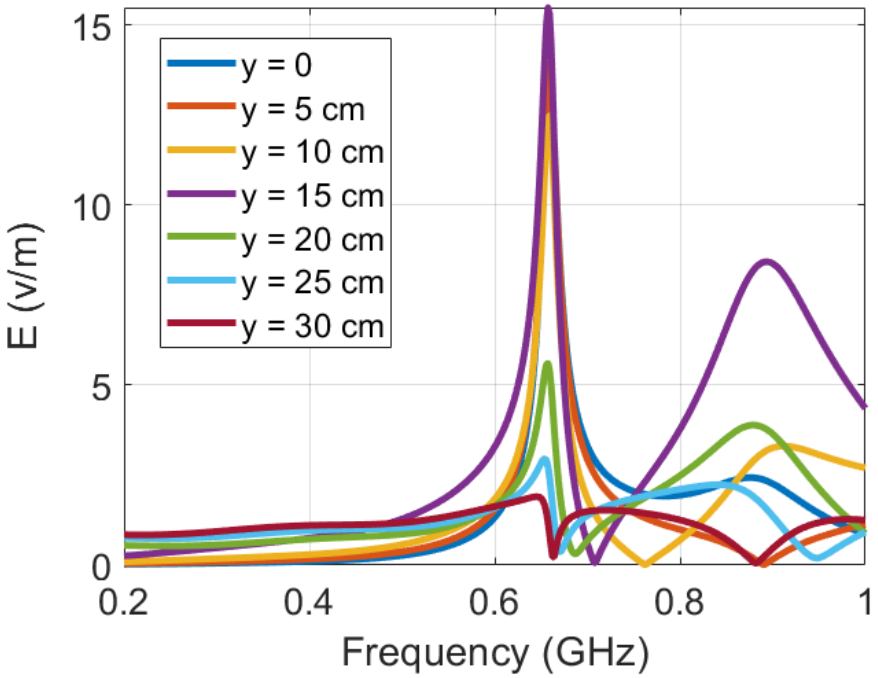
Class	Mass	Size	Altitude	Range	Endurance
Micro	< 0.2 lb	< 10 cm	<50 ft	0.1-0.5 Km	<1 hr.
Mini	< 0.2-1 lb	10 – 30 cm	<100 ft	0.5-1 Km	<1 hr.
Very small	2-5 lb	30 – 50 cm	<1000 ft	1-5 Km	1-3 hr.
Small	5-20 lb	0.5 -2 m	1000-5000 ft	10-100 Km	0.5-2 hr.

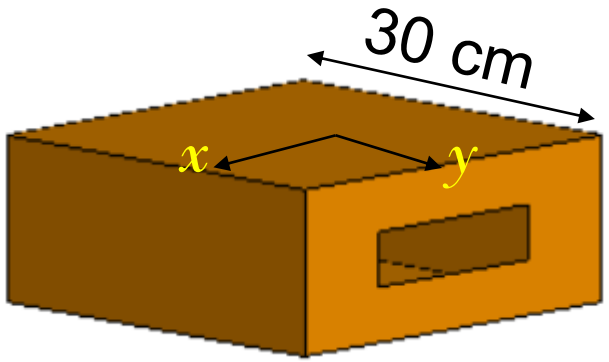
- We will focus on Micro - Small UAVs: (1) Practical relevance, (2) Feasible Computational Full-wave Analysis, (3) Conclusions can be scaled to larger UAV sizes.

[1]Unmanned Aircraft Design: A Review of Fundamentals

HPM: Technical Discussion/Progress Cont'd

CMA of Metallic Enclosure with a Slot





Different modes cause field maxima at different locations

FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

Bi-Annual Program Review

UAS Localization and Targeting

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09 DEC 2020
held via Zoom

Distribution A. Approved for public release.

OSPRES: Strategic Threat Assessment Group

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Strategic Threat Assessment Group

Target Detection & Tracking for cUAS

Tom Cacy
Undergraduate Research Assistant

Trade Study Analysis

Tim Layman, B.S.
Graduate Research Assistant

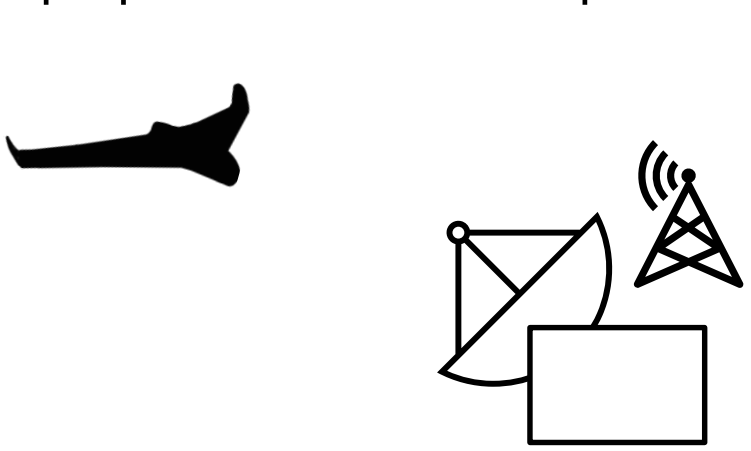
Air-to-Air Navigation Strategy

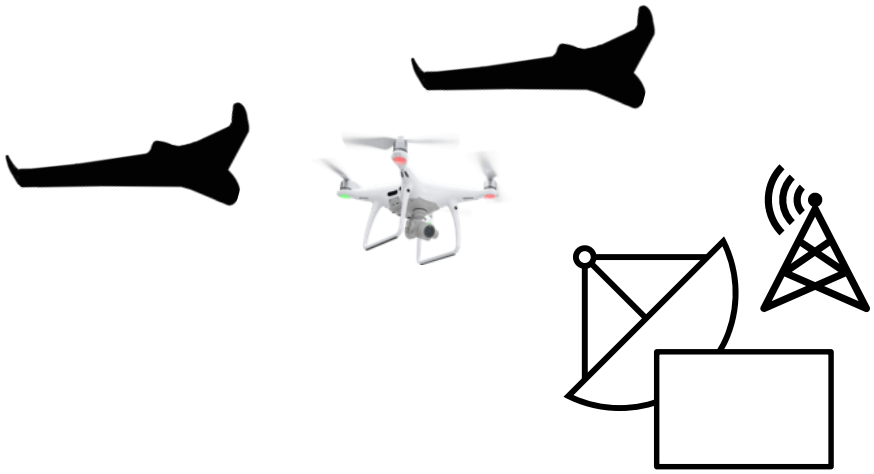
UAS Localization & Targeting

DEW systems require targeting and tracking to effectively engage targets.

The method at which a target is engaged depends heavily on the capabilities of the tracking system (accuracy, FOV, multi-target vs single-target, etc).

Efficient DEW integration with tracking-based systems effectively prepares for more complex engagement scenarios.





OSPRES: Strategic Threat Assessment Group

UAS Localization & Targeting

Main Types of Detection and Tracking Systems:

Electro-Optical & Infrared (EO/IR)

- Visible & infrared wavelengths
  - Mid-wavelength and long-wavelength infrared
- Fixed and Gimbal-based

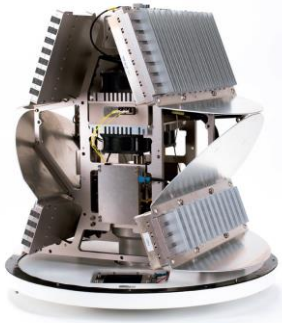
FLIR
Star SAFIRE® 380-HDc

L3HARRIS
WESCAM MX™-RSTA

FORTEM
TrueView® Radar

Radar

- Microwave wavelength
- Radar Cross Section (RCS)
- Transmitter and Receiver
- AESA or PESA



ROBIN
IRIS® Radar

OSPRES: Strategic Threat Assessment Group

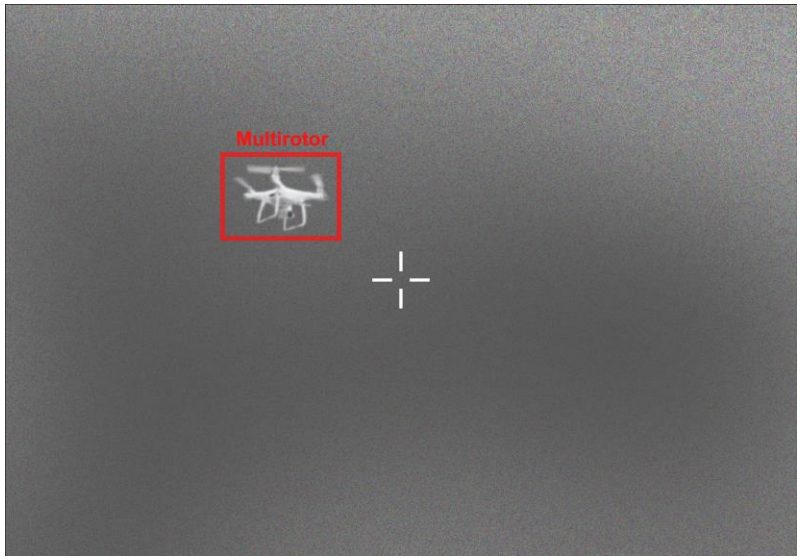
Engagement Scenarios

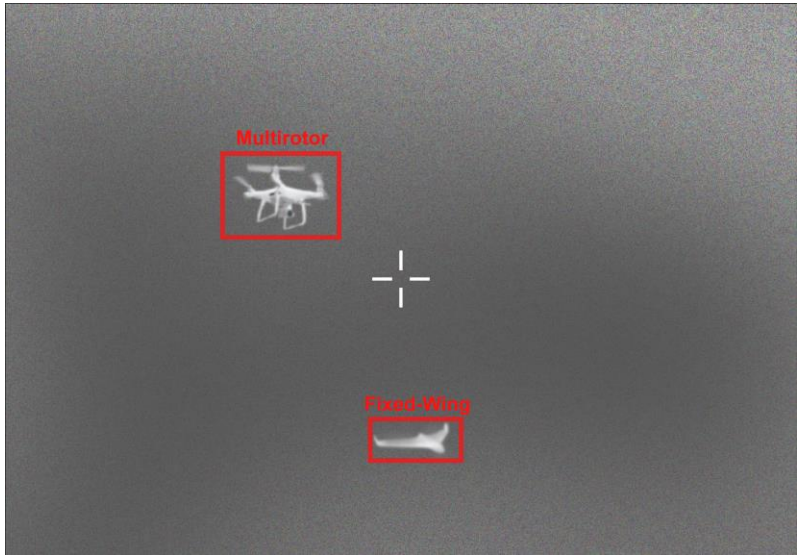
EO/IR Detection:

- C2 Integration
- Multi-target detection and Tracking within a field of view (FOV).
- FOV limited but able to mechanically adjust

Considerations:

- Background (terrain, sun, infrastructure)
- Split Targeting
- Line of sight (LoS)
- Triangulation for range
- Actual object size
- Atmospheric conditions



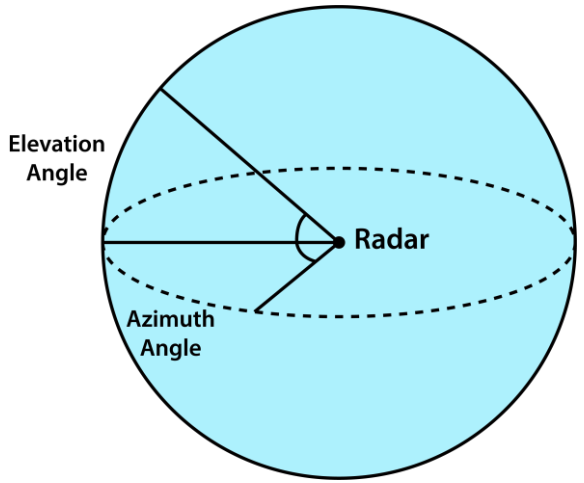


OSPRES: Strategic Threat Assessment Group

Engagement Scenarios

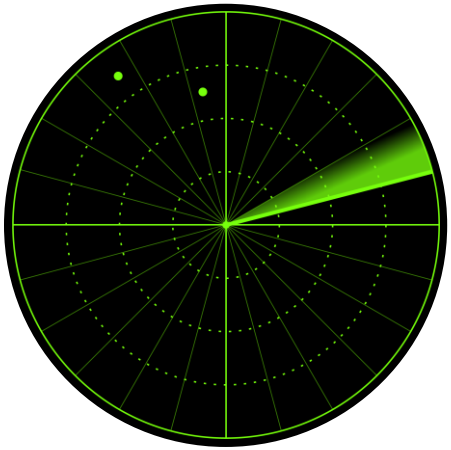
Radar Detection:

- C2 Integration
- Multi-target detection and Tracking.
- FOV can be limited & reconfigurable
- Azimuth and elevation detection.



Considerations:

- Rotation & refresh rate
- Power fluctuations from environmental conditions
- Target size and RCS
- Grouped targets
- Jamming
- Low flying clutter



OSPRES: Program Key Research Criteria - I

UAS Localization & Targeting

Goal I:

Detection/tracking system integration with ground-to-air system through command and control (C2).

State-of-the-art (SOTA):

Many tracking systems are available and integrate with C2.

Deficiency in SOTA:

Each tracking system has different capabilities (range, accuracy, FOV, etc.).

Proposed Solution:

Comparative analysis for each available system.

Program outcome:

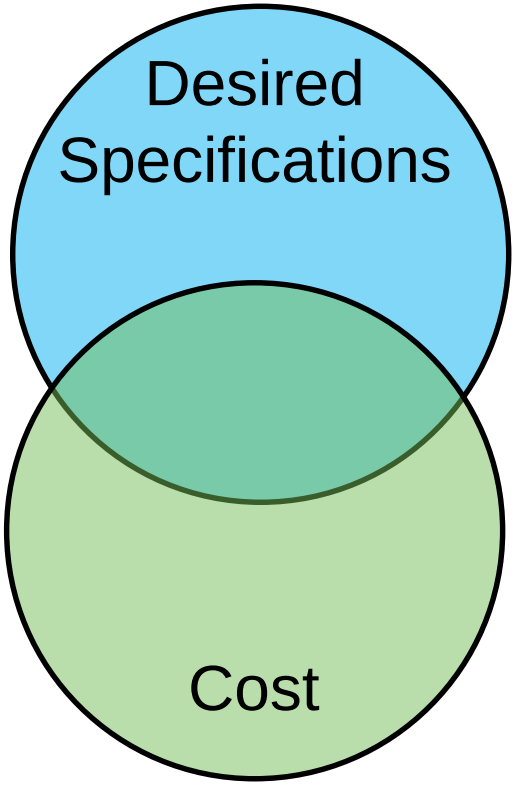
Compilation of detection systems and specifications that achieve C2 integration.

OSPRES: Detection/Tracking Systems

UAS Localization & Targeting

	System	Company	Range, km	FOV, degrees	Update, Hz	Frequency Band
Radar	TrueView R30	Fortem Technologies	6 km (1 m^2)	120x120	NA	NA
	TrueView R20		1.5 km (1 m^2)	120x40	8	NA
	Bridgemaster E	Northrop Grumman	NA	NA	NA	X & S-band
	aCHR	RADA	7 km (mini UAV)	120x90	NA	S-Band

	System	Company	Range, km	FOV, degrees
EO/IR	Ranger III LR	FLIR	8	11x8.2
	STAR SAFIRE III		25	25x25
	Recon V		10	NA
	MTS	Raytheon	NA	NA



Why focus on what exists?

–Need system capabilities to make important design decisions (mechanical versus electrical steering).

–System design not limited to ideal assumptions

OSPRES: Program Key Research Criteria - II

UAS Localization & Targeting

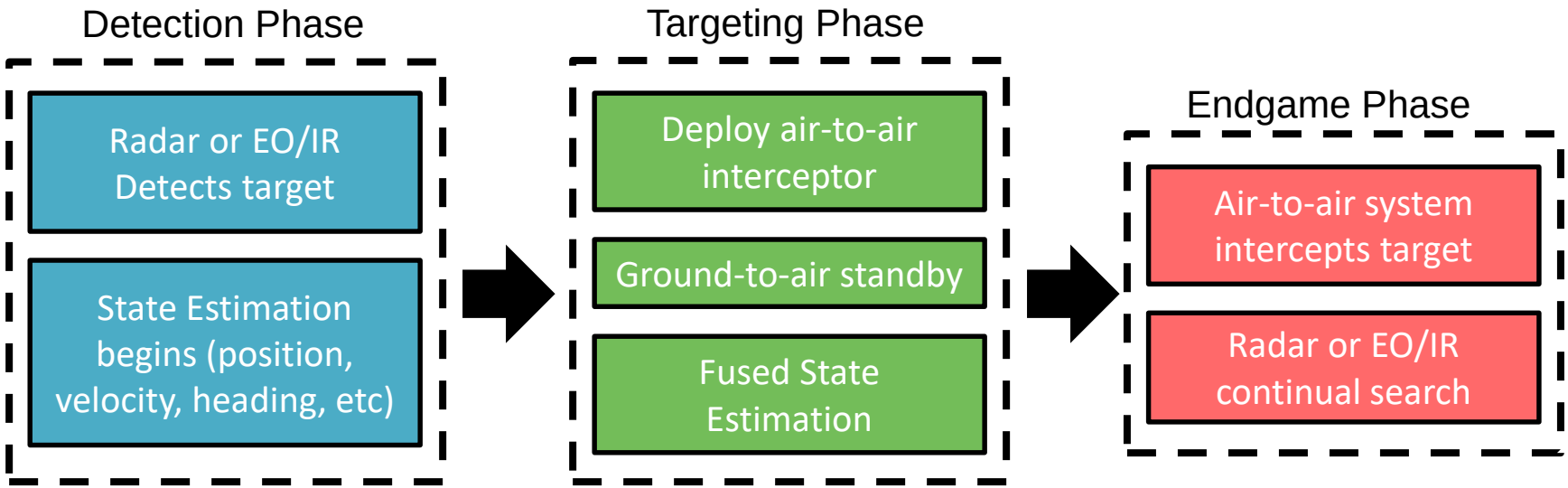
Goal II: Develop improved engagement tactics for multi-targets and multiple interceptors

State-of-the-art (SOTA): Ground-to-air systems combined with detection/tracking systems.

Deficiency in SOTA: This approach may not be the most effective. Short-range and long-range systems may be more effective.

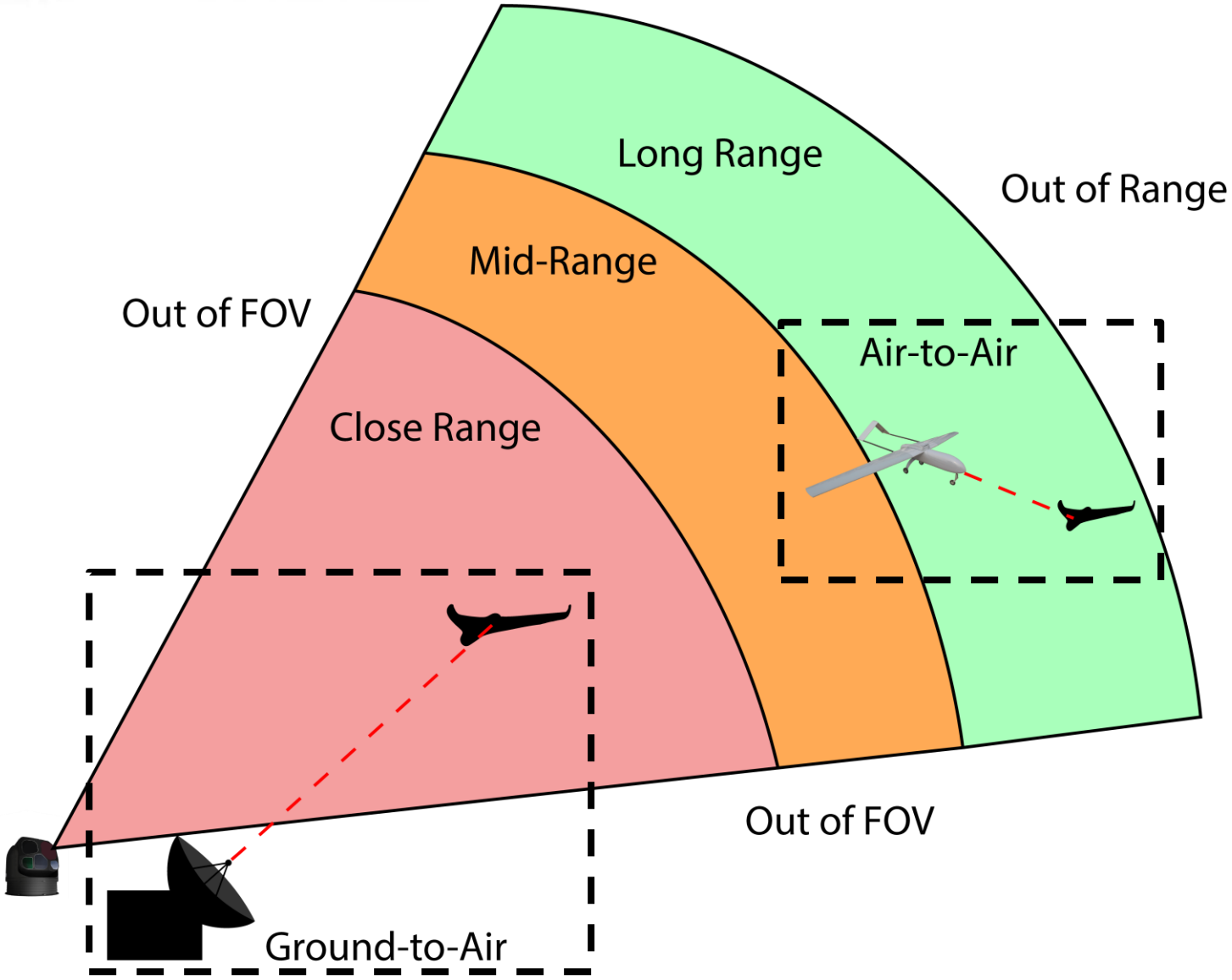
Proposed Solution: Integrate ground-to-air system and air-to-air interceptor with the detection/tracking system.

Program outcome: Effective implementation of localization algorithms for air-to-air system. Effective combination of ground-to-air and air-to-air systems for engagement scenarios.



OSPRES: Ground-to-Air & Air-to-Air

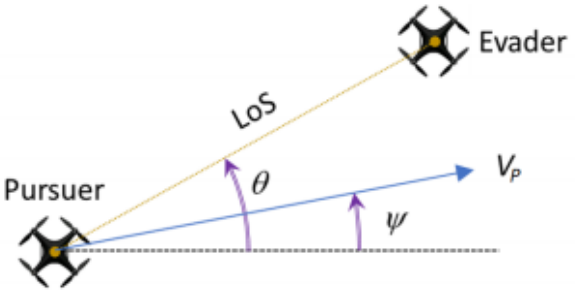
UAS Localization & Targeting



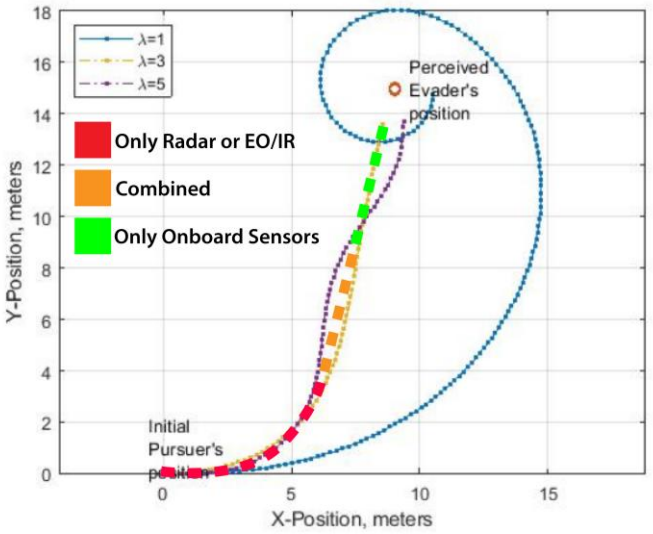
OSPRES: Air-to-Air & Ground-to-Air
Combined Engagement Scenarios

Air-to-Air Interceptor:

- Proportional Navigation (PN) control law
  - Line of Sight navigation
- State Estimation
  - Optical Sensor (onboard) and detection sensor (EO/IR or Radar)
  - KF, EKF, UKF state estimation algorithms.
  - Provide better estimates of desired states $(\dot{\theta}, \theta, \psi)$



$$\dot{\psi}_{cmd} = \lambda\dot{\theta}$$



λ=1, λ=3, and λ=5 paths.

OSPRES: Conclusions & Next Steps

UAS Localization & Targeting

Conclusions

–Detection/Tracking systems have a wide range of capabilities, costs, and performance that will affect the efficacy of a ground or aerial-based system.

–Navigation and engagement strategies must be coordinated with the Identification Tracking Targeting and Classification (ITTC) system in order to maximize the capabilities in a cost space.

–Combining ground-to-air DEW systems with air-to-air DEW systems may result in more effective engagements.

Next Steps

Physical Systems:

- Determine which physical detection system will be used to integrate with Command and Control.
- Explore improved estimation algorithms with available sensors.

Simulation:

– Target state estimation using EO/IR or Radar parameters.

– Combined Target state estimation using EO/IR or Radar coupled with observer/interceptor

  - This may be broken into interceptor phases

FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

Bi-Annual Program Review

OSPRES Grant Overview

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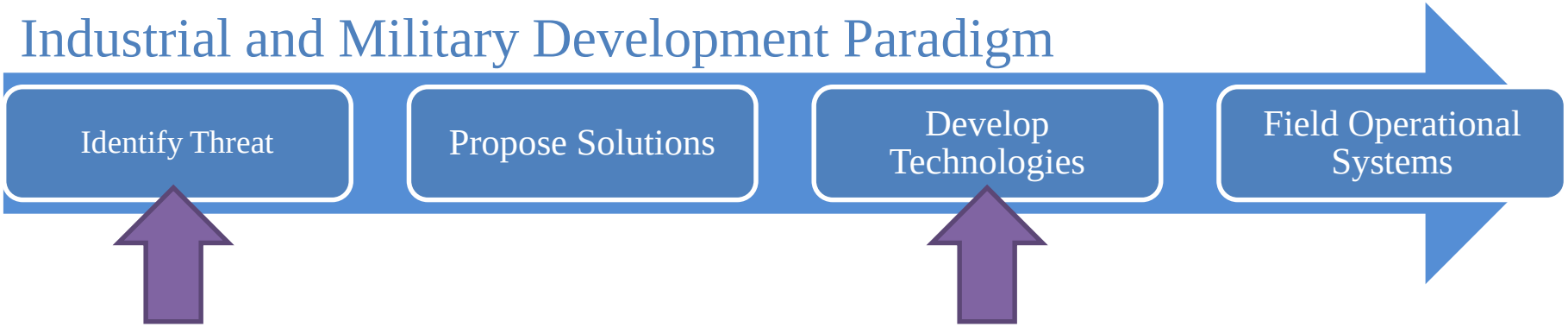
09 DEC 2020 / 1440
held via Zoom

Distribution A. Approved for public release.

OSPRES: Mission Level Modeling

How do we fit in?



Before Development Begins

- Observe and report on the current state of the art
- Anticipate new technologies
- Predict future targets

During Testing and Evaluation

- Develop surrogates
- Implement vignettes (tactics)

Bottom Line

- High quality intelligence at planning and development phases
- Robust testing programs (realistic evaluation of capabilities)
- Increased first-day lethality of operational systems
- Operational systems ready for future threats

OSPRES: Mission Level Modeling

Are we fighting a fair fight?

U.S. Navy photo by Mass Communication Specialist 2nd Class Ridge Leoni

Typical Development Paradigms

Industrial and Military: 3-15 years

- Identify Threat
- Propose Solutions
- Develop Technologies
- Field Operational Systems

Consumer and High-Tech: 1-3 years

- Predict Consumer Interest
- Develop Technologies
- Release Products
- Over-the-Air Improvements, Ongoing Testing

Apple Inc.

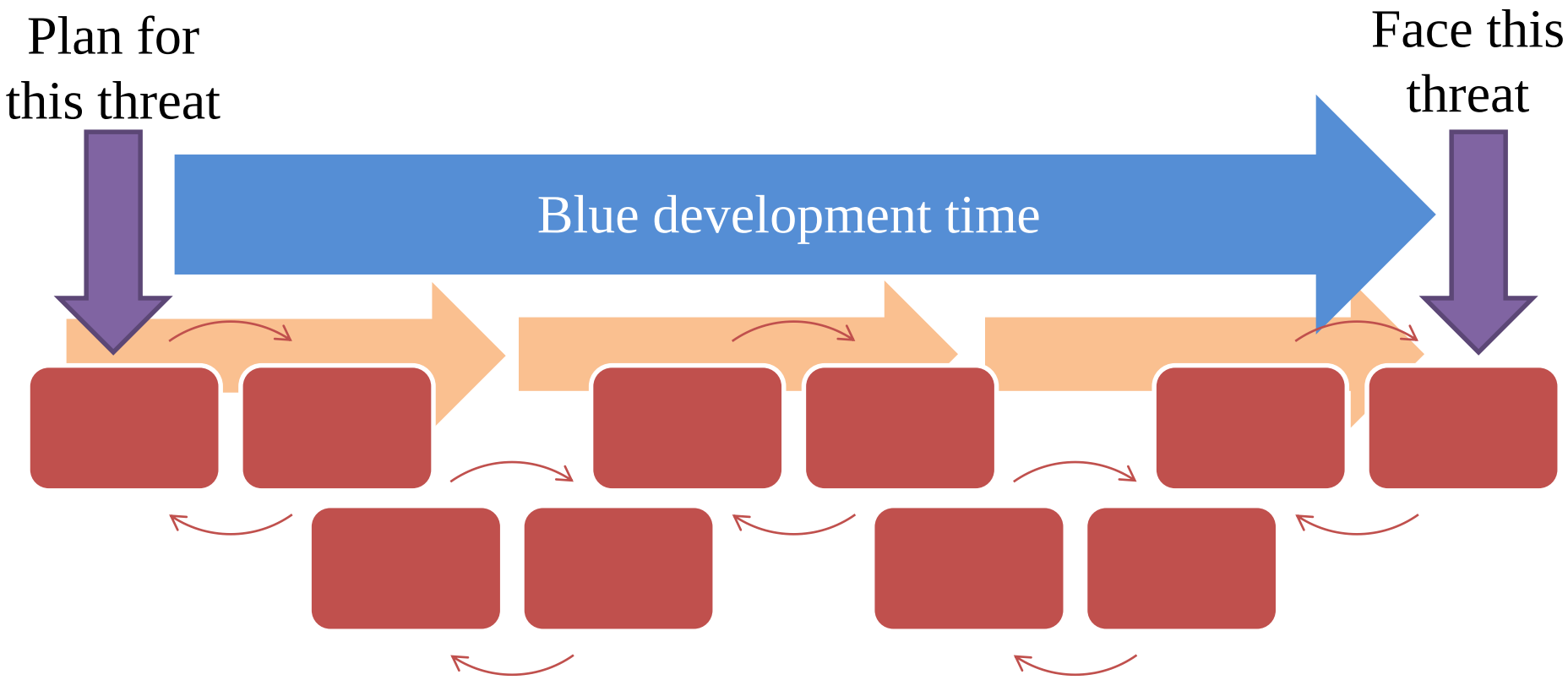
Ad-hoc: 6-60 days

- Identify Opportunities, Improvise Requirements
- Implement, Test, and Develop Solutions

Public Domain

OSPRES: Mission Level Modeling

React, Respond, Repeat



Red Development:

Agile, cyclical, inexpensive, can use latest consumer technology

Blue Development:

Slow, periodic, expensive, uses oldest technology

OSPRES: Mission Level Modeling

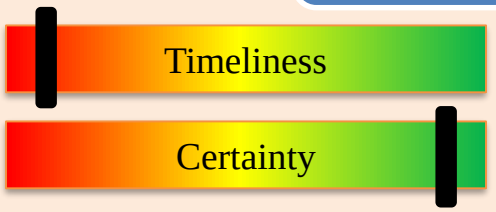
How do we go on Offense?

Leverage Engineering Subject Matter Expertise:

- Correlate publications with market viability
- Gas engine testing, RF hardening
- Karnes, Smith, Herrington

Current Paradigm:

- Trade study
- Drone database
- Klappa, Smith, Cacy



Observe: What is online now?

Anticipate: What is about to be online?

Predict: What is possible in the future?

Expected Future Threats

How does this work?

- Blue/red capabilities and blue/red tactics
  - Game theory
  - Herrington

OSPRES: Mission Level Modeling

Beyond Whack-a-Mole

Game Theory

- Studies behavior of firms operating within a common market (could be chess, could be oil futures, could be cryptocurrency exchange)
- The players are red and blue, the market is the battlefield
- Basic characteristics can be predicted: "How likely is red agility to double in the next decade?"

Game Theory

Predict: What is possible in the future?

Distil down to basic characteristics

Inventory Blue Capabilities

- Beam width
- PK
- Slew rate
- Protection area
- Detection radius
- Time to effect

Inventory Red Capabilities

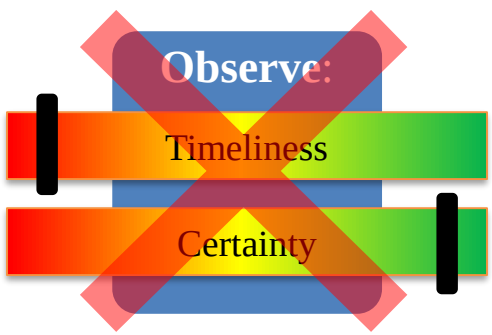
Distil down to basic characteristics

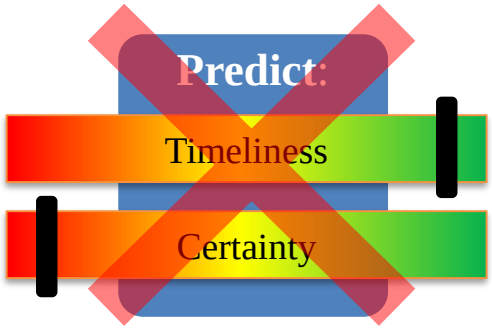
- Swarm size
- Speed
- Agility
- RF susceptibility
- Mission type
- Damage propensity

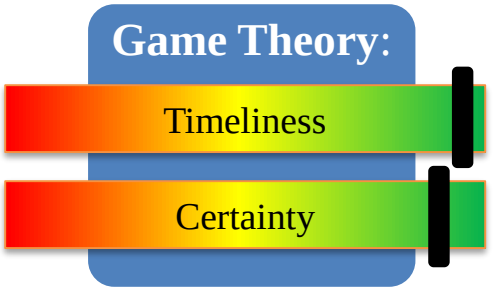
OSPRES: Mission Level Modeling

The Game Theory Approach

We want to predict future threats before they occur

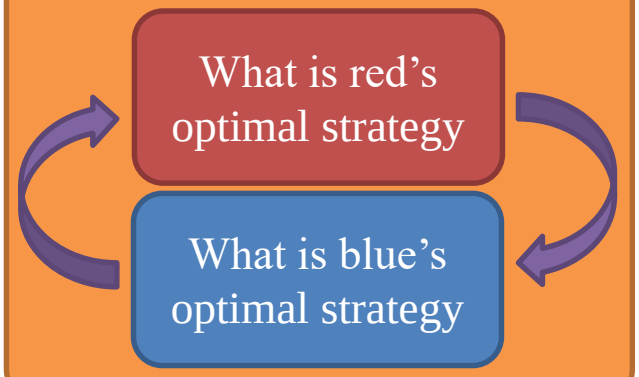






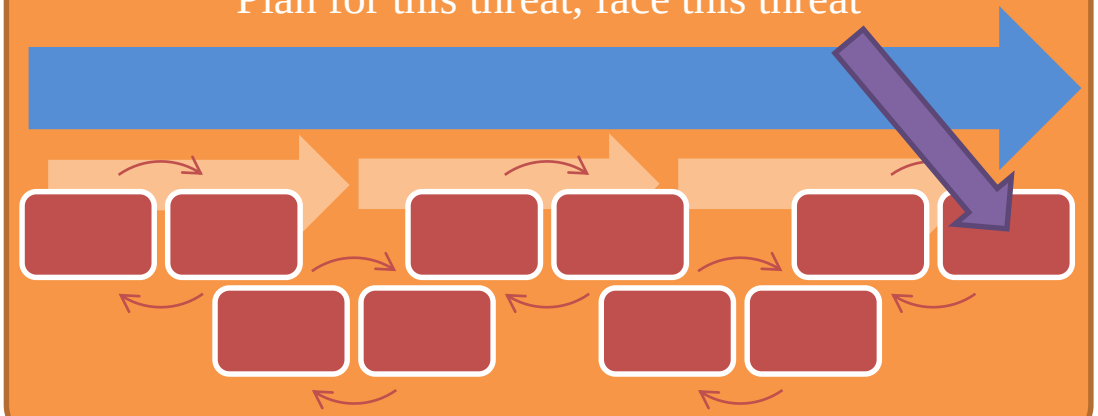
Certainty:

Strategy "ping-pong"



Timeliness:

Plan for this threat, face this threat



OSPRES: Mission Level Modeling

Technology Timeline Example

2000 2005 2010 2015 2020

2002
Terrain Following Research Paper
Netter, T. & Francheschini, N.

14 years

2002-2008
UAV Swarm Research Paper
Et. Al. & How, J.

11-17 years

2007
Vision –Based Obstacle Avoidance
Watanabe, Y, Calise, A., Johnons, E.

12 years

2009
Vision Tracking Research Paper
Kendoul, F. Fantoni, I., & Nonami, K.

6 years

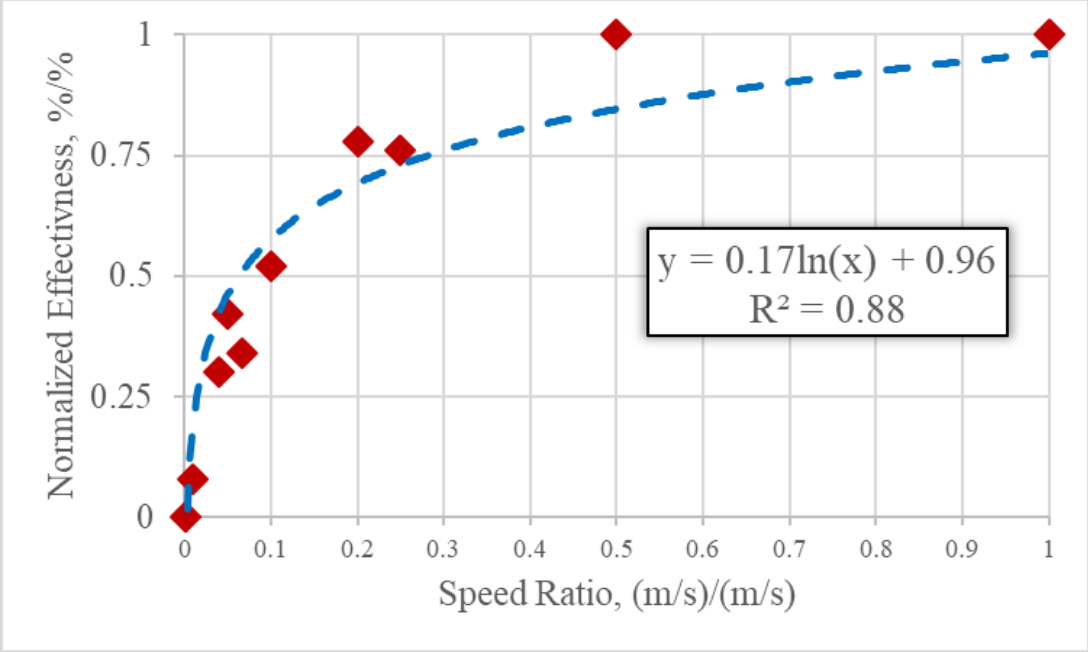
OSPRES: Mission Level Modeling

Numerical Study Example (Pt. 1)

OSPRES: Mission Level Modeling

Numerical Study Example (Pt. 2)

- For simplified case, 50% is "worst-case"
  Doubling aggressor speed reduces effectiveness by 24%
- Effectiveness reduced by around 50 percentage points when aggressor speed increases by 5 times

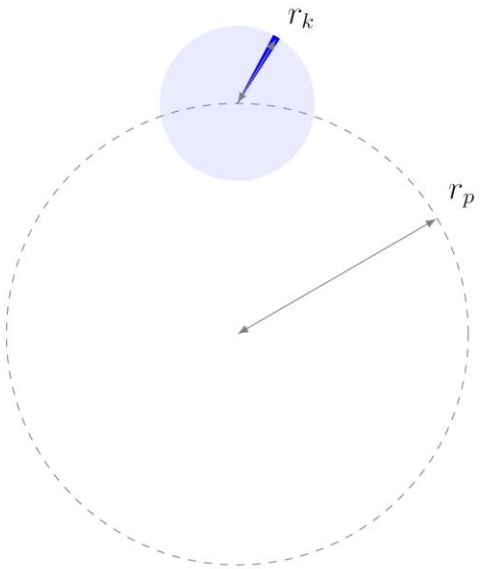


Speed Ratio	Normalized Effectiveness	Effectiveness
1.000	1.00	100%
0.500	1.00	100%
0.250	0.76	88%
0.200	0.78	89%
0.100	0.42	76%
0.067	0.34	67%
0.050	0.22	71%
0.040	0.30	65%
0.010	0.08	54%
0.001	0	50%

OSPRES: Mission Level Modeling

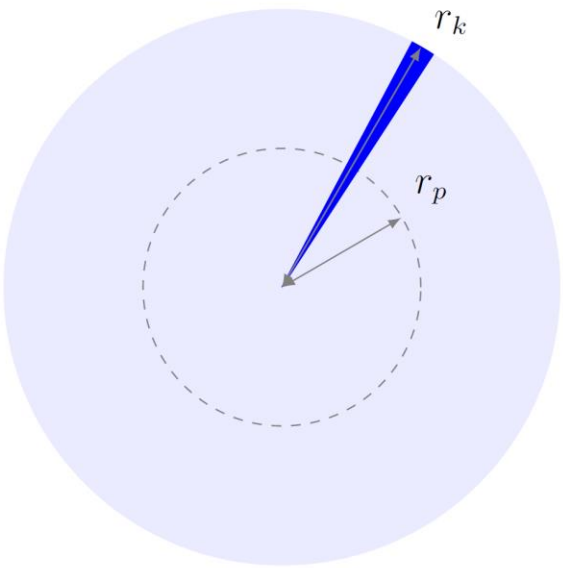
Analytical Approach (Pt. 1)

Coastline protection, hunter-killer, (multiple effectors)



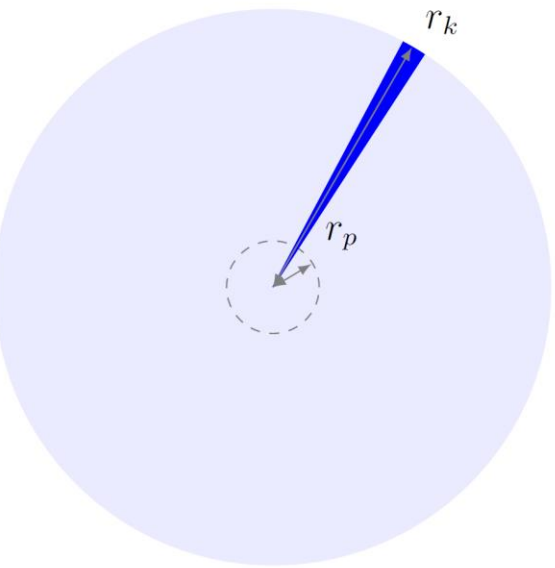
(a) Kill radius much smaller than protection radius ($r_k \ll r_p$).

Afloat/base protection (single effector)



(b) Kill radius and protection radius of similar magnitude ($r_k \approx r_p$).

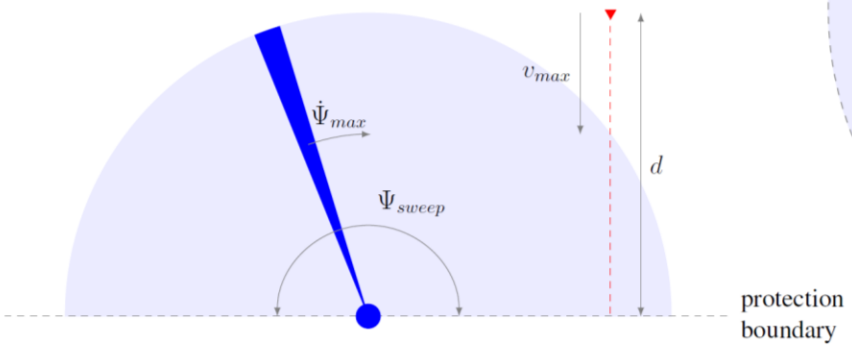
Afloat/base protection (single effector)



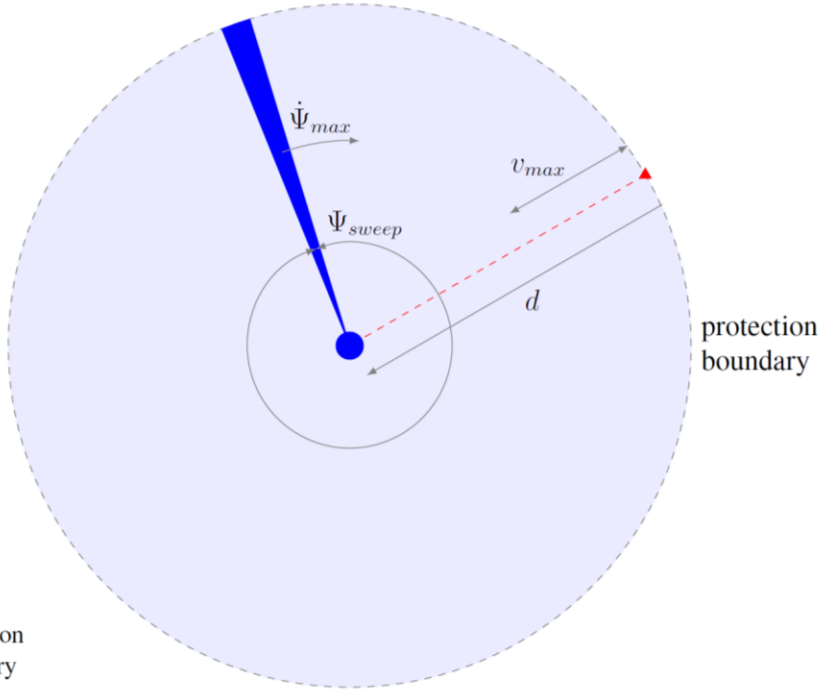
(c) Kill radius must larger than protection radius ($r_k \gg r_p$).

OSPRES: Mission Level Modeling
Analytical Approach (Pt. 2)

These different scenarios have mathematical equivalence.



(a) 180° Scenario.



(b) 360° Scenario

Minimum angular speed required to guarantee victory against all single evader engagements:

$$\dot{\Psi}_{max} \geq \frac{\Psi_{sweep} d}{v} \qquad \dot{\Psi}_{max} \geq \frac{\pi d}{v}$$

OSPRES: Mission Level Modeling
Analytical Approach (Pt. 3)

A Simple Game

- Blue protects a prize. The cost of losing the prize is 100,000
- The cost to blue of defending the prize is 100.
- Any red attack is unlikely to succeed but is less expensive than any blue defense.
- If red attacks successfully the cost is 1. If red attacks unsuccessfully the cost is 11.
- Optimality is satisfied according to Pareto for scenario (N,N): (0,0)

Pareto Optimal

Best overall payoff (sum individual payoffs, find the maximum)

Why would red choose to play?

Red chooses to play (Yes or No)

Blue chooses to play **Blue** (Yes or No)	Red: *Y*	Red: *N*
Y	-100, -11	-100,0
N	-10100, -1	0, 0

Blue payoff

Red Payoff

Optimal Solution

OSPRES: Mission Level Modeling
Analytical Approach (Pt. 4)

The Modified Game

- Red likes to see blue suffer (wins 20 anytime blue expends resources)
- Payoffs have been summed with the payoffs in the last example
- Pareto optimality satisfied by (N,N):(0,0)
- Nash optimality satisfied by (Y,Y):(-100,9)

We have not considered risk attitudes

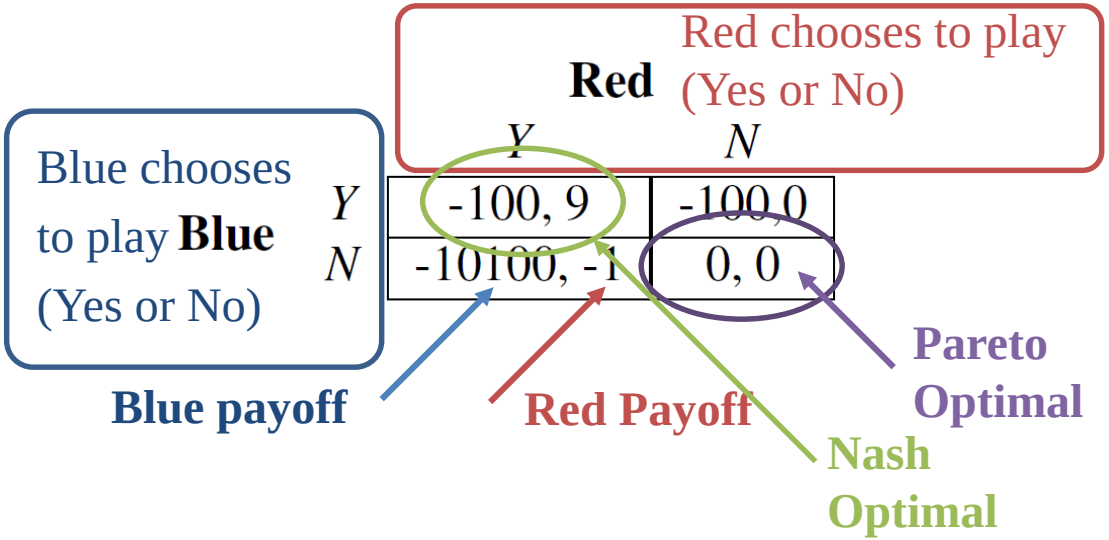
We have not considered incomplete information

Pareto Optimal

Best overall payoff (sum individual payoffs, find the maximum)

Nash Optimal

If any player can improve his outcome by changing his move, he will do so



OSPRES: Mission Level Modeling
Analytical Approach (Pt. 5)

Another Game

- Blue always plays but a self-defense action may be successful or unsuccessful
- The expected payoff
- Can red be convinced not to play the game at all?

Red chooses to play (Yes or No)

Blue always plays, self-defense can be Successful or Unsuccessful

Blue \ Red	Y	N
S	-100, 9	-100,0
U	-10100, -1	0, 0

Blue payoff **Red Payoff** **Nash Optimal**

Payoff for red loss times probability it will occur

Payoff for red victory times probability it will occur

$$0 > 9p - 1(1-p)$$

$$0 > 9p - 1 + p$$

$$p < 1/10$$

Red will choose not to play anytime the chance of red winning is less than 10%

OSPRES: Mission Level Modeling

Current Status of Model Refinements

Goals

- Build surrogates for evaluation programs (includes RF hardening, structural improvements, etc. to increase realism of red team)
- Inform red and blue tactics for operational and in-development programs
- What are the future weaknesses?

Major Challenges

- Analytical results may be limited in scope
- How to reduce the problem space?
- How to quantify performance under non-guaranteed conditions?
- Incomplete information

Unexpected Results

- Mathematical equivalence of some scenarios reduces problem space
- Some characteristics can be eliminated at the analytical phase

FY19-20 Combined

ONR Short Pulse Research, Evaluation and non-SWaP Demonstration for C-sUAV Study (OSPRES Grant)

Bi-Annual Program Review

Feature Additions to UMKC-MAP Including Causal Inference

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09 DEC 2020
held via Zoom

Distribution A. Approved for public release.

OSPRES: Mission Level Modeling

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-Team leader
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-Scenario analysis

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-Detection and tracking issues
-Code development
-Computing advice

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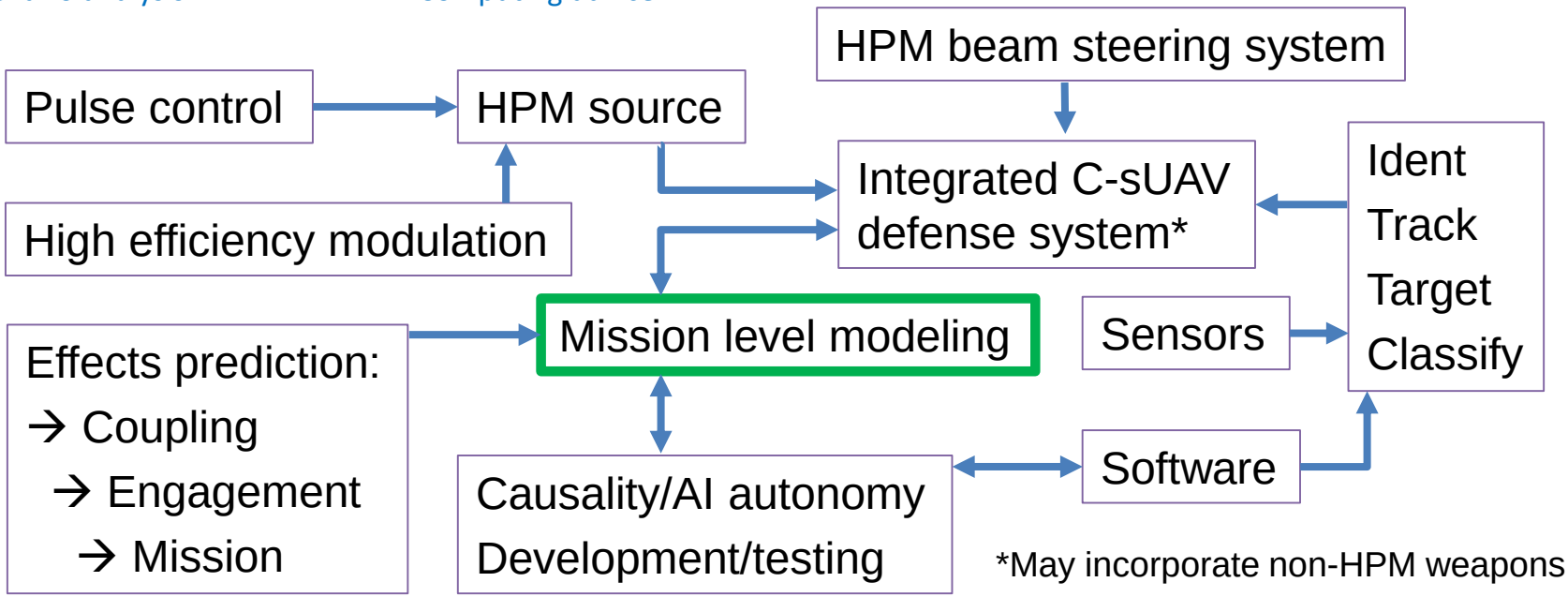
Senior Scientist, Confluent Sciences
-Translating physics to wargames
-Sensor models

Michael Richman
Postdoc., MIDE
-Scenario analysis
-Optimization



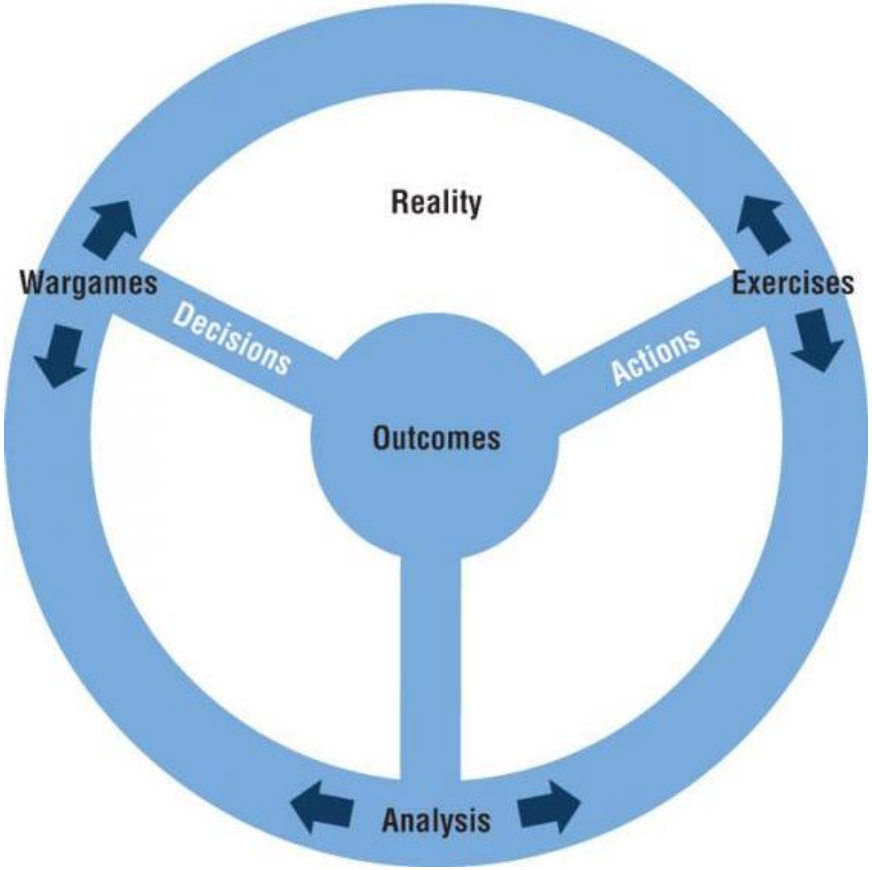
OSPRES: Mission Level Modeling

What Deficiency Do We Rectify?

- In afloat and other situations, we provide an understanding of the:
  - impact of current research on future capabilities.
  - risks and outcome tipping points.
  - effectiveness of various HPM configurations against likely threats.

- We facilitate monetary-cost-sensitive:
  - optimization of both design and use of HPM weapons.
  - construction of a scenario library that can aid in the determination of both procurement decisions and asset-mix selections.*

*Asset mixes may incorporate non-HPM C-sUAV weapons.



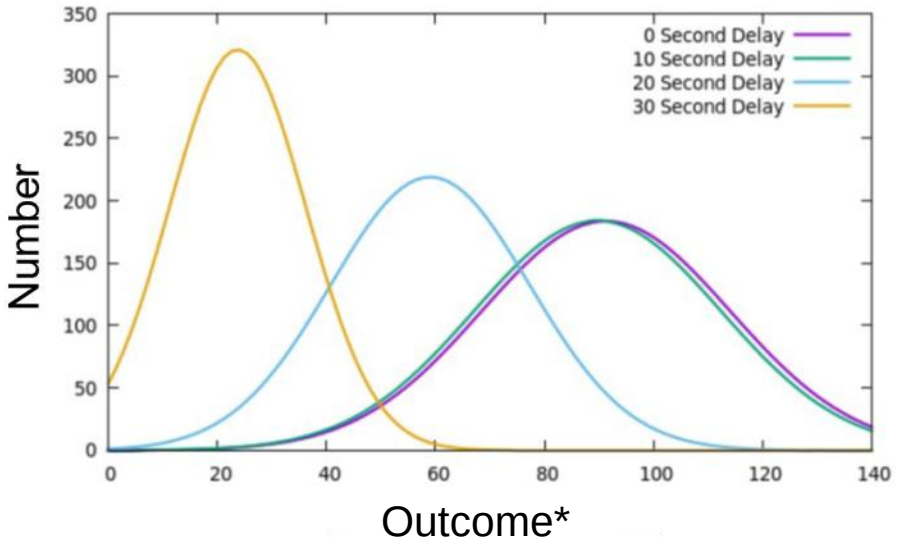
Perla's Cycle of Research.

https://wargamingcommunity.wordpress.com

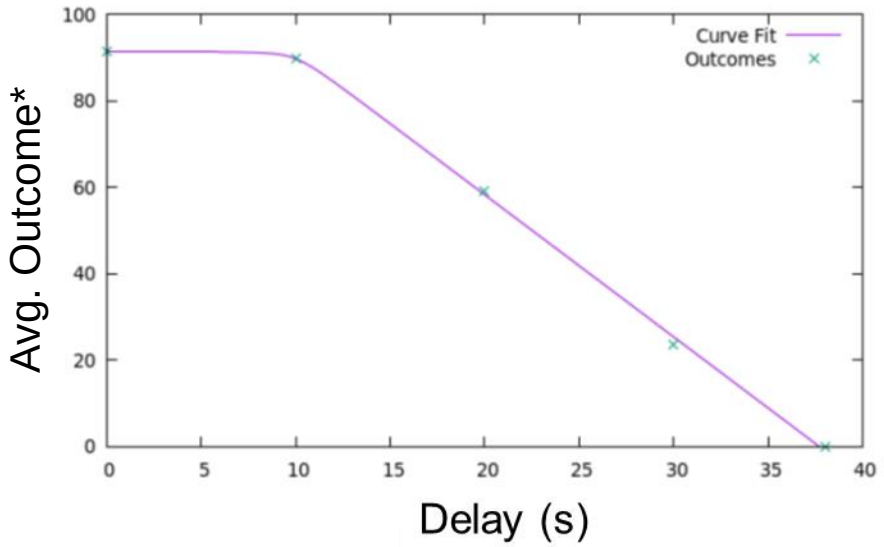
OSPRES: Mission Level Modeling

How Do We Fit In?

- Aggregate results of example scenarios demonstrate expected outcome and risk.
- Changes to critical parameters illustrate the impact of those changes.
- Tipping points associated with parameters can be discovered and understood.



Impact of command delay in initiating defenses.



Tipping point analysis of command delay.

*Outcome = 10 × (# of aggressors neutralized).

ONR HPM Program Key Research Criteria - II

Mission Level Modeling

Qualitative Criteria:

Goals:

I: Inform (1) design of HPM weapon systems, (2) their use, and (3) procurement decisions.

II: Identify possible enemy countermeasures and corresponding friendly countermeasures.

III: Identify the impact of technology innovations on outcomes,

e.g., what outcome changes result from adding HPM to a C-sUAV force mix?

State-of-the-art (SOTA):

MAP, AFSIM, MAST, Builder, COMET Application Suite for Mission Modeling & Simulation?, Suppressor?, EADSIM?, RF POLAND and Threat Evaluation?

Deficiency in SOTA:

Due to computational intensity, inadequately adapted for searching the large permutation space for tipping points, risk assessment, causal factors, and optimization purposes.

Proposed Solution:

Enhance MAP's realism and versatility, e.g., enhance sensor models, integrate 3D models, provide large-scale-optimization-compatible parameter access to inform optimization and causality studies.

Program outcome:

Monetary-cost-sensitive realization of optimized HPM weapon systems and their use.

ONR HPM Program Key Research Criteria - I

Mission Level Modeling

<u>Quantitative</u> Criteria/Metrics for HPM source employment:

1. Expected scenario-dependent outcome
   e.g., large or small amount of collateral damage?

2. Risk variation associated with aggregate results
   e.g., chance that the number of leakers is 2x that which is considered most likely?

3. Tipping point for a given parameter range
   e.g., command delay in initiating defenses?

4. Change in expected outcome for a given change in parameter.
   e.g., how does sensor placement affect possible outcomes?

5. Pareto-efficient outcomes and the variables that provide them.*
   e.g., what tactic best minimizes Blue damage for a set level of tolerated collateral damage?

*Pareto efficiency:
a situation where no single preference criterion can be improved without diminishing at least one other such criterion.

OSPRES: Mission Level Modeling

Payoffs, Risks, Challenges

Payoffs

- Facilitates optimization of OSPRES efforts.

  e.g., mechanical vs. electronic steering for HPM effectors?

Risks

- Wargaming provides preliminary results that may change when analyzed in more detail.
- Assumptions of enemy threats and countermeasures may not hold up.

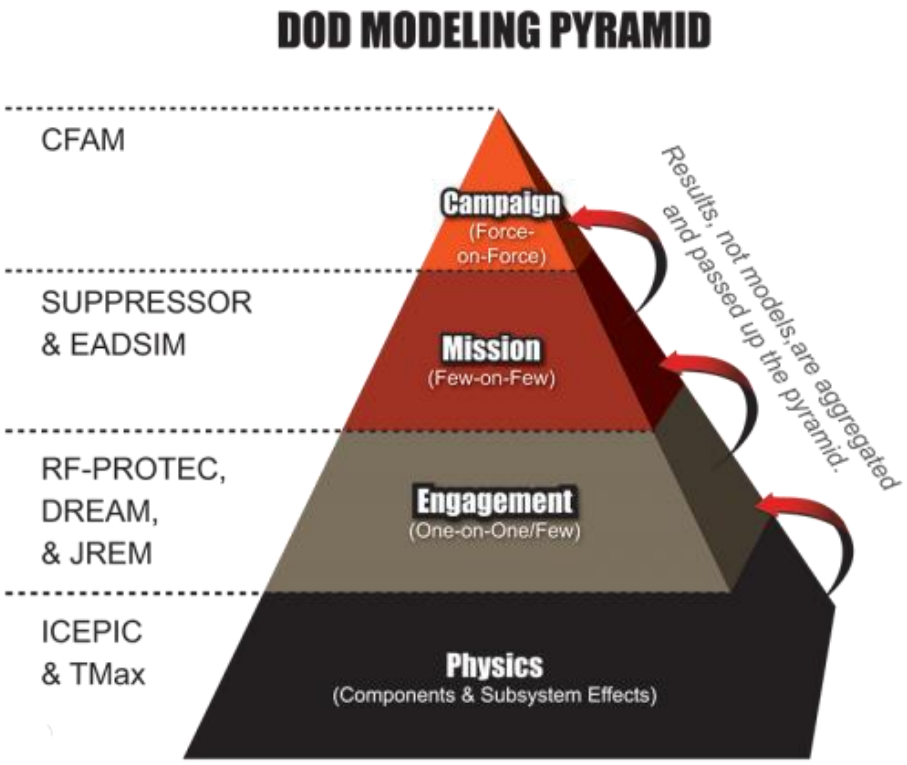
Challenges

- Some scenarios and some analysis may exceed practical computing capabilities.

  e.g., $O(n^3)$ outcome space + stochastic nature → full space sampling possibly precluded.

- Modeling of research implementations requires knowledge of fundamental behavior.

  e.g., RF coupling probability of effect.

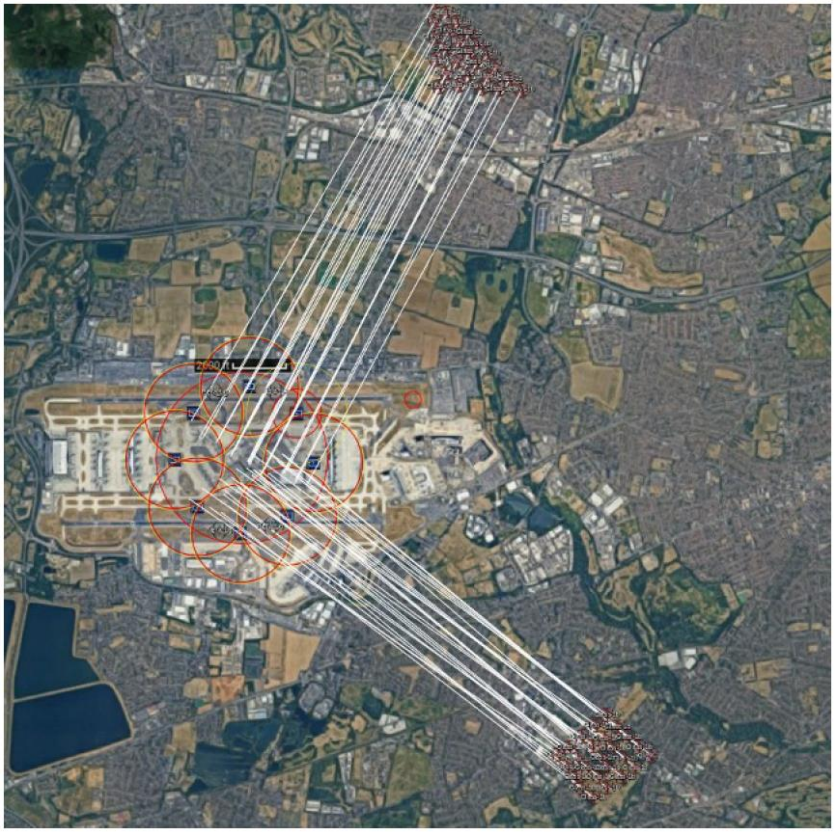


Tatum, *DSIAC Journal*, 1, 20, 2014.

Mission Level Modeling
Broader Impact

Results and platform have relevance to other services and contexts:

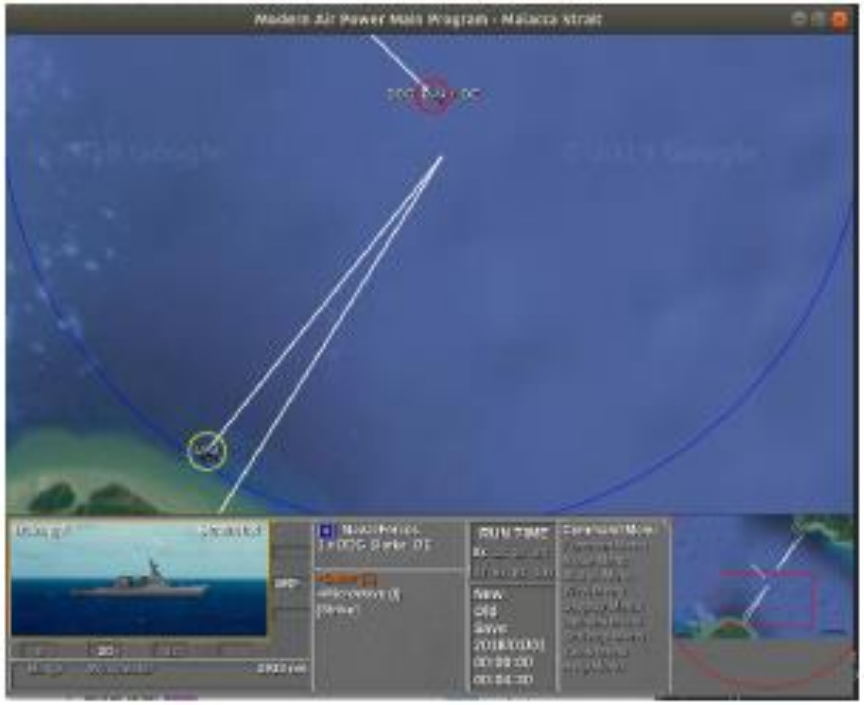
- land.
- airborne land.
- airborne afloat.
- civilian airport defense.
- special events (e.g., World Series).
- critical infrastructure (e.g., powerplants).
- *offensive* operation planning.
- etc.



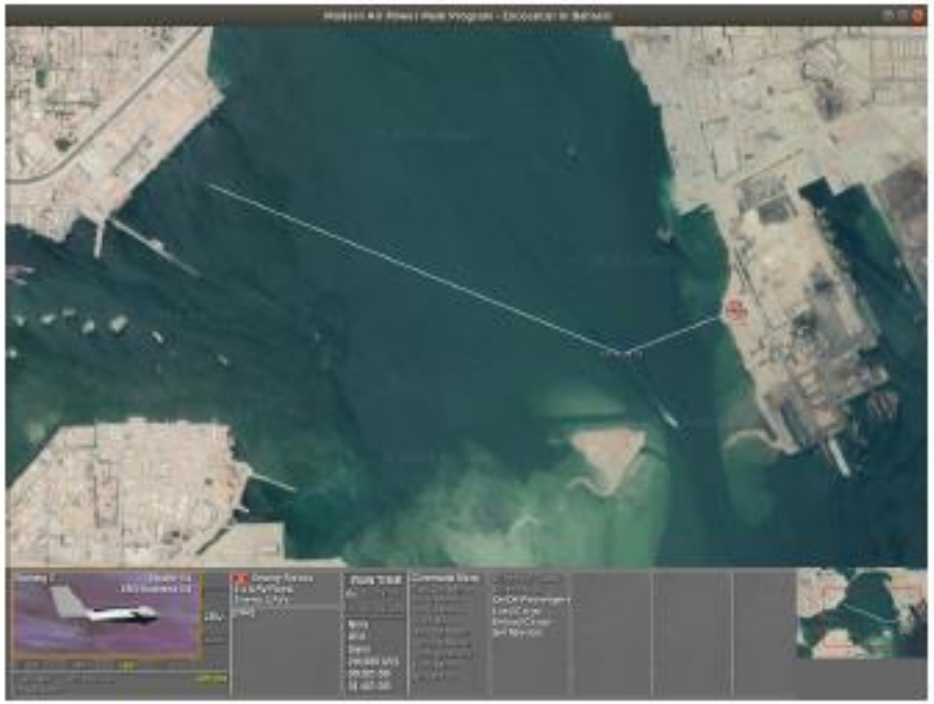
Mission Level Modeling

Sub-Project Research Objective

Using computer wargames, physics-based modeling, and mathematical analysis, determine optimal designs and implementations of HPM defenses in specific scenarios.



Open water scenario.



Constrained operations scenario.

Mission Level Modeling
Technical Discussion/Progress

- Analysis conducted into:
  - the benefits of HPM and laser ship defenses both separately and combined.
  - ship defenses against fixed-wing UAVs in port traversal scenario.
- Comparison of the effectiveness of distributed HPM defenses versus single more powerful defense.
- Tipping Point analysis of HPM defenses relative to number of attacking UAVs.
- Analysis of the impact of defensive command delays in the outcome of UAV attacks.
- Investigations into the impact of collateral shore damage relative to HPM and other defenses.

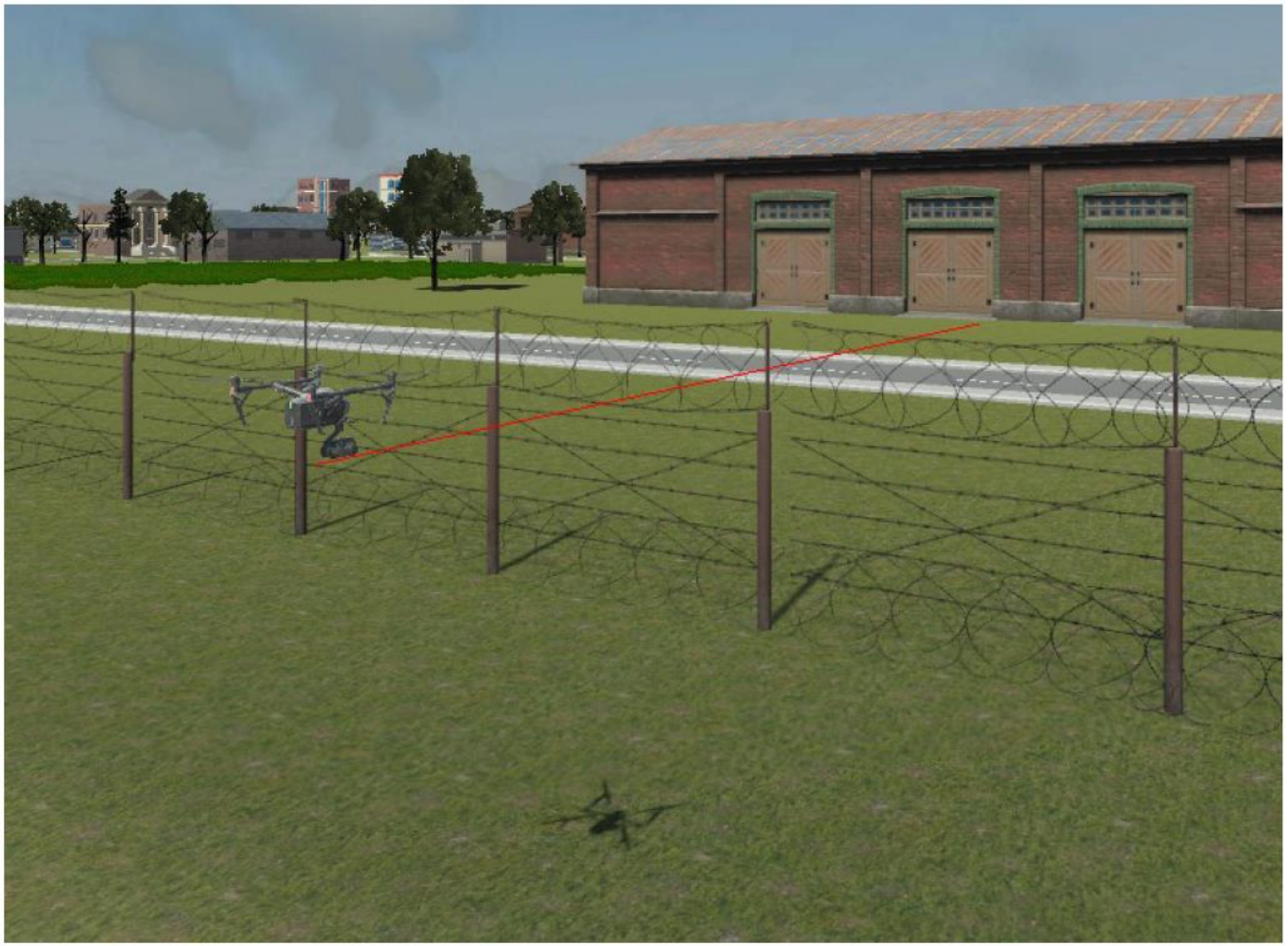
Mission Level Modeling
Significant Progress

- Craft electromagnetic hardness feature added to MAP.
- MAP modified to support the concept of exclusion zones in UAV defense.
- Hunter–Killer UAV concept added to MAP database.
- MAP's AI enhanced to better support Hunter–Killer scenarios.
- Programs enhanced to capture collateral damage and other outcome metrics.
- Templates developed and refined to support variability of parameters associated with platforms, weapons, and tactics.
- Optimization interface program developed.
- Integrated MAP with numerical optimization algorithms.
- To facilitate increasing MAP's realism, reports written on:
  - detection and tracking issues for swarming targets.
  - sensor models.
  - calibration of sensor models for C-sUAV.
- Initiated development of a more detailed version of MAP that supports analysis of line-of-sight-related issues.

Mission Level Modeling

New Ideas / Opportunities: 3D

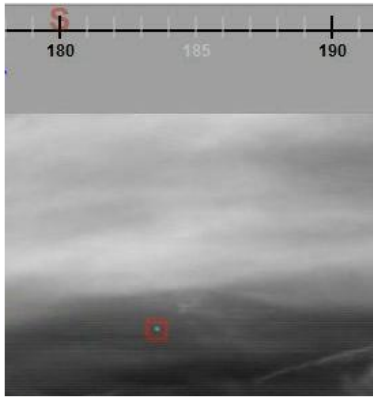
New 3D simulations will enhance tactical detail (e.g., line of sight, terrain following).

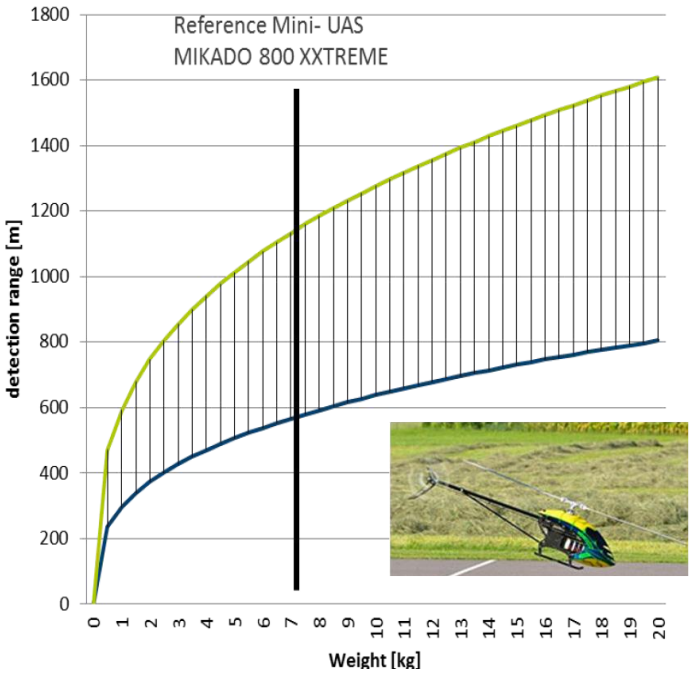


Mission Level Modeling

New Ideas / Opportunities: Enhanced Sensor Models

- ***Opportunity: Higher fidelity modeling of the kill chain, with realistic timelines, sensor/shooter coupling, and features of decision making.***
- Calibrated new sensor modeling will provide enhanced simulation of complex scenarios.
  - Discrimination and target ID.
- Modern sensors use signal processing to dramatically enhance the sensitivity to small signals – parameterized by SNR and "time."
  - Holds for both EO/IR and radar systems.





Radar

$$SNR = \frac{P_r}{N_o} = \frac{P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 R^4}\left(\frac{G_p L}{k_B T_s B_n}\right)$$

$$SNR(dB) = MDS(dB) - 40\log\left(\frac{R}{R_{max}}\right) + 10\log(N) - 10\log(L(\vec{x})) - 10\log(k_B T_S B_n)$$

$$N = PRF * dwell_time$$

EO/IR

$$Irradiance = Source * 10^{-A}$$

$$A = \sum_{i=1}^{N} \varepsilon_i \int_o^L c_i(z)dz$$

$$SNR = \frac{A_{optics} T_{int} Irradiance(Watts)}{Noise}$$

TIME

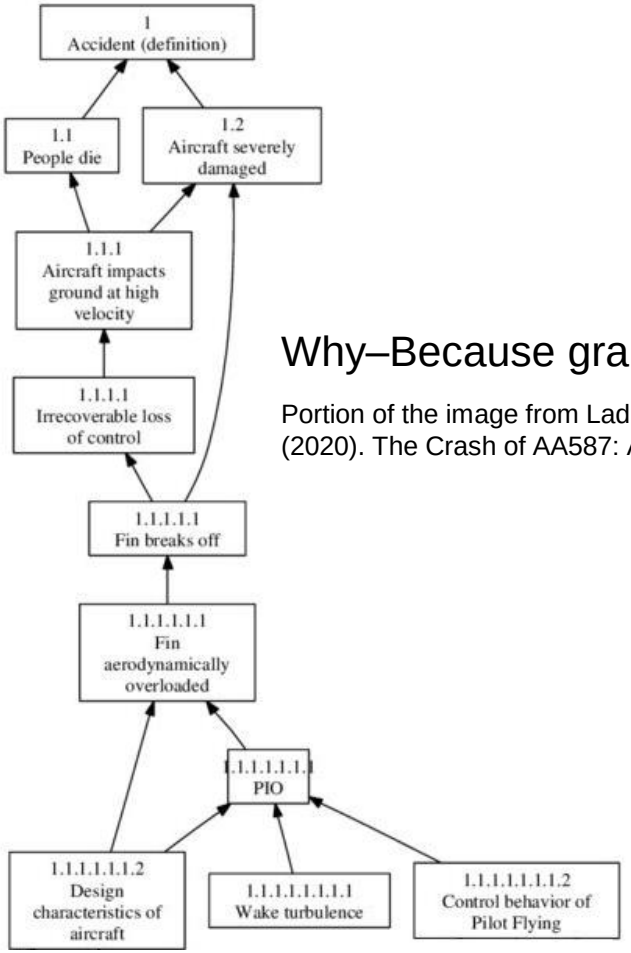
Mission Level Modeling

New Ideas / Opportunities: Causality

Causality analysis of outcomes enhances current impact studies associated with critical parameters and provides new insight into the “why” of observed outcomes.

2021 Wargaming-Context Milestones:

1. Determine how to interpret causality in the context of outcomes (by Mar.).
2. Determine how parametric experiments implement the concept of independent testing and the Pearl do operator (by Mar.).
3. Develop new metrics and numerical value generation relative to causality (by Jun.).
4. Analyze how it is possible to determine the causal effect of mediating variables as opposed to independent variables (by Sep.).
5. Develop software that extracts causal relationships analogous to decision tree analysis (by Dec.).



Why–Because graph.

Portion of the image from Ladkin, P. (2020). The Crash of AA587: A Guide.

Mission Level Modeling
Conclusions

- Mission level modeling is providing insight into the impact of current HPM research and informing leadership of the potential for new developments in HPM weaponry.

- New mathematical analysis and new weapon system modeling will improve the quality of future mission level modeling in this effort and others associated with future warfare analysis.