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**AFOSR COE - Science of Electronics in Extreme Electromagnetic
Environments**

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Final Technical Report**

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September 28, 2021

Final Report on AFOSR/AFRL COE: Science of Electronics in Extreme Electromagnetic Environments

AFOSR Grant FA9550-15-1-0171

Period of Performance: 01 April 2015 – 30 June 2021

Program Managers: John Luginsland (AFOSR), Timothy Clarke (AFRL)

Principal Investigator: Edl Schamiloglu

ABSTRACT

This AFOSR/AFRL-funded Center of Excellence is led by the University of New Mexico with the University of Maryland a partner. This final report summarizes progress in the no-cost extension period following Year 6 and the Appendix include the annual reports from Years 1-6.

University of New Mexico and University of Maryland

The research tasks that are being investigated are listed below and brief updates are provided for each of them.

1. CMOS Injection Modeling and Experiments –

We focused on time-domain eye diagram analysis to develop a predictive model for bit error rates induced into digital systems due to RF/EMI interference. Experimental tests were performed to study the impact of EMI on the different parameters which define the digital “eye” diagram. Initial predictive models for the impact of EMI on eye diagram and bit error rate have also been developed, and its verification with experimental data is in progress. We also started working on incorporating nonlinear-device characterization of analog low noise amplifier circuits fabricated in 180 nm Si through TSMC.

2. E/O Injection Modeling and Experiments – A theoretical model for eye-diagram effects due to EMI injection in E/O modulators has been developed and is being validated through experiments.

3. CMOS Inverter Response under Stochastic Supply Signals – No research updates during this period except that manuscripts have been submitted for review.

4. Source Reconstruction – During this period we began preparation for experimental part of this work which will have two parts. The first will be in an anechoic chamber in which we will experimentally obtain near field measurements of a surrogate PCB (perhaps more than one) that is simple enough such that the measurements can be compared to simulations with CST. The PCB surrogate will likely start as a single trace, but will evolve to a larger receiver that, as a distributed source, will require the distributed

port (stochastic green's function (SGF)) formulation of the random coupling model (RCM). From this we use the measured data to solve for a distribution of $\vec{J}$ and $\vec{M}$ on the reconstruction surface. The second part of the experiment will be in the mode stirred cavity with the plane wave illuminated aperture. Here we will measure the statistical distribution of S_{21} and compare to the predictions from the SRM and from its interface with the RCM.

5. Quantum Dot Collaboration with UMD – The research this past year was focused on the development of a single photon emitter platform that could then be used as a baseline for EEMI studies. The studies included the growth of low-density quantum dot samples at specific wavelengths. A significant part of the effort was devoted to the incorporation of antimony in InAs quantum dots so that the emission wavelength of the dots could reach 1400 nm. This is important for the characterization lasers that are currently used in Prof. Waks's group. Successful growth of the samples was performed followed by single photon characterization. The one issue faced at UNM was the shutdown of the MBE laboratory from May 2020 to July 2020 with partial opening from August 2020 to December 2020 which significantly hampered the operations. This was particularly a problem for the reactors which need close to 24 Hr supervision and had to be shut down completely for several months. We have however been able to grow the necessary samples despite these disruptions.

6. Microcontroller Experiments – Edits were made to the manuscript submission based on the Editor's comments.

7. Deep Learning Estimation of Complex Reverberant Wave Fields with a Programmable Metasurface – Electromagnetic environments are becoming increasingly complex and congested, creating a growing challenge for systems that rely on electromagnetic waves for communication, sensing, or imaging, particularly in reverberating environments. The use of programmable metasurfaces provides a potential means of directing waves to optimize wireless channels on-demand, ensuring reliable operation and protecting sensitive electronic components. Here we introduce a technique that combines a deep learning network with a binary programmable metasurface to shape waves in complex reverberant electromagnetic environments, in particular ones where there is no direct line of sight. We applied this technique for wavefront reconstruction and control, and accurately determined metasurface configurations based on measured system scattering responses in a chaotic microwave cavity. The state of the metasurface that realizes desired electromagnetic wave field distribution properties was successfully determined even in cases previously unseen by the deep learning algorithm. Our technique is enabled by the reverberant nature of the cavity, and is effective with a metasurface that covers only ~1.5% of the total cavity surface area.

8. Wave Chaos Studies for Two-Dimensional Cavities Using the Random Coupling Model (RCM) and Other High Frequency Methods – Wave coupling within systems with irregular boundaries is a common phenomenon in many branches of science such as acoustics, vibrations, electromagnetics, and others. If the wavelength of the incident wave is small compared with the structure size, and the dynamics of the ray trajectories within the scattering region are chaotic, the scattering properties of the cavity will be extremely sensitive to small perturbations. These structures are then termed wave chaotic. Exact solutions of such systems are not feasible and various alternative methods are sought.

In the first part of this dissertation, such alternative methods are used to calculate the power delivered to a port in a two-dimensional wave chaotic enclosure. These methods are the ray tracing (RT), the Dynamical Energy Analysis (DEA) and the Power Balance methods (PWB). Particularly, the RT and DEA are used to calculate power received at an aperture and are compared with the established PWB. These results indicate that the RT and DEA are equivalent methods. Additionally, RT is compared with direct numerical simulations of the wave fields and found to be accurate if the wavelength is sufficiently small.

The Random Coupling Model (RCM) gives a statistical description of coupling of radiation in and out of large enclosures through localized and/or distributed ports. The RCM, in contrast to DEA, PWB, and

standard RT, includes both amplitude and phase information. It combines both deterministic and statistical information and makes use of wave chaos theory to extend the classical modal description of the cavity fields in the presence of boundaries that lead to chaotic ray trajectories. In the second part of this dissertation, a correction to the RCM termed the Short Orbit Formulation (SOF) is used to calculate successfully the impedance of a two-port wave chaotic enclosure in two dimensions using RT. Also, a directed beam approach was used to launch energy in a wave chaotic enclosure to break the so called 'random plane wave hypothesis', a fundamental basis of the RCM formulations. Results show that launching of such directed beams lead to enhanced short orbit effects which make the RCM inapplicable.

9. Device And Circuit Level EMI Induced Vulnerability: Modeling And Experiments Dissertation

– Electro-magnetic interference (EMI) commonly exists in electronic equipment containing semiconductor-based integrated circuits (ICs). Metal-oxide-semiconductor field-effect-transistors (MOSFETs) in the ICs may be disrupted under EMI conditions due to transient voltage-current surges, and their internal states may change undesirably. In this work, the vulnerabilities of silicon MOSFETs under EMI are studied at the device and the circuit levels, categorized as non-permanent upsets (“Soft Errors”) and permanent damages (“Hard Failures”).

The Soft Errors, such as temporary bit errors and waveform distortions, may happen or be intensified under EMI, as the transient disruptions activate unwanted and highly non-linear changes inside MOSFETs, such as impact ionization and Snapback. The system may be corrected from the erroneous state when the EMI condition is removed. We simulate planar silicon n-type MOSFETs at the device level to study the physical mechanisms leading to or complicate the short-term, signal-level Soft Errors. We experimentally tested commercially available MOSFET devices. Not included in regular MOSFET models, exponential-like current increases as the terminal voltage increases are observed and explained using the device-level knowledge. We develop a compact Soft Error model, compatible with circuit simulators using lumped (or compact-model) components and closed-form expressions, such as SPICE, and calibrate it with our in-house experimental data using an in-house extraction technique based on the Genetic Algorithm. Example circuits are simulated using the extracted device model and under EMI-induced transient disruptions.

The EMI voltage-current disruptions may also lead to permanent Hard Failures that cannot be repaired without replacement. One type of Hard Failures, the MOSFET gate dielectric (or “oxide”) breakdown, can result in input-output relation changes and additional thermal runaway. We have fabricated individual MOSFET devices at the FabLab at the University of Maryland NanoCenter. We experimentally stress-test the fabricated devices and observe the rapid, permanent oxide breakdown. Then, we simulate a nano-scale FinFET device with ultra-thin gate oxide at the device level. Then, we apply the knowledge from our experiments to the simulated FinFET, producing a gate oxide breakdown Hard Failure circuit model.

The proposed workflow enables the evaluation of EMI-induced vulnerabilities in circuit simulations before actual fabrication and experiments, which can help the early-stage prototyping process and reduce the development time.

Personnel Supported – UNM

Faculty: Balakrishnan, Dietz, Hemmady, Schamiloglu, and Zarkesh-Ha

Students: E. Dohme, Z. Abedi, S. Wang

Personnel Supported – UMD

Faculty: Balakrishnan, Dietz, Hemmady, Schamiloglu, and Zarkesh-Ha

Students: E. Dohme, Z. Abedi, S. Wang

Publications:

1. Benjamin W. Frazier, Thomas M. Antonsen, Jr., Steven M. Anlage, Edward Ott, “Deep Learning Estimation of Complex Reverberant Wave Fields with a Programmable Metasurface”, arXiv:2103.13500
2. I. Baum, C. Darmody, Y. Cui and N. Goldsman, “Effects of Fermi Pinning and Quantum Mechanisms on Leakage Current of 4H-SiC Schottky Diodes,” Submitted to Journal of Applied Physics, 2021.
3. Y. Zhao, H. Chalabi, and E. Waks, “A metasurface optical limiter”, manuscript in preparation.
4. M. Buyukkaya, C. Lee, S. Harper, and E. Waks, “Optical bistability and saturable gain in a nanophonic cavity coupled to quantum dots”, Manuscript in preparation.

Appendix – Years 1-6 Annual Reports



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March 22, 2016

Annual Report on AFOSR/AFRL COE: Science of Electronics in Extreme Electromagnetic Environments

AFOSR Grant FA9550-15-1-0171

Period of Performance: 01 April 2015 – 31 March 2016

Program Managers: Jason Marshall (AFOSR), Timothy Clarke (AFRL)

Principal Investigator: Edl Schamiloglu

ABSTRACT

The AFOSR/AFRL Center of Excellence on the Science of Electronics in Extreme Electromagnetic Environments was awarded in 2015 to the University of New Mexico. Predicting the effects of extreme electromagnetic interference (EEMI) on complicated modern CMOS-based computer electronics is a very challenging problem. Even in well-controlled laboratory experiments, there exist several variables that fall outside the domain of accessible knowledge of the target system. For instance, in the case of a typical personal computer, which comprises several electronic subsystems from different equipment manufacturers, the proprietary nature of the manufacturer's integration methodologies, subsystem operation, and interaction with other subsystems, curtails detailed understanding of the interaction of EEMI energy with electronics. Manufacturers are often even more tight-lipped about the specifics of the input conditions that drive their products to erroneously behave outside of their intended operating margins and impact software execution. Unfortunately, this happens to be at the crux of understanding the EEMI-induced disruption in computer electronics.

To spearhead the bridging of this intellectual chasm in predicting EEMI-induced upset of complicated electronic systems, our 6-year AFOSR Center of Excellence (COE) has assembled a distinguished team of scientists (both theoretical and experimental) with deep domain knowledge in the effects of EEMI on electronic devices, components, and systems, and in the development of high fidelity numerical modeling of coupled electromagnetic field-and-circuit field solvers. The University of New Mexico (UNM) and its partners at The University of Maryland (UMD) will leverage their prior expertise in this niche technical discipline to develop a suite of predictive models (validated through experimental testing) on fundamental CMOS devices, circuits, and printed circuit boards (PCBs) utilizing current CMOS technology as well as evolving future technologies. These predictive models could be used within the framework of a larger, comprehensive simulation environment to better understand the effects of EEMI on modern electronics.

The University of New Mexico and University of Maryland groups collaborate on this COE, initially in two areas: (i) Computational Electromagnetics and the Random Coupling Model



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(Zhen Peng, UNM and Tom Antonsen, UMD), and (ii) Investigation of Post-CMOS Optoelectronics for EMI Susceptibility (Ganesh Balakrishnan, UNM and Edo Waks, UMD). However, for the purposes of this Annual Report we separate the accomplishments of the two groups.

Preamble

The AFOSR/AFRL COE group at UNM meets biweekly to discuss progress. Invited to these are AFRL staff Timothy Clarke, Julie Lawrance, Hugh Pohle, Daniel Guillette, and Matt Landavazo. The UNM and UMD groups have been hosting monthly Skype meetings discussing progress.

Both the UNM and UMD groups presented at the DEPS Annual Symposium in Albuquerque in March 2016.

University of New Mexico

The UNM COE team includes: Ganesh Balakrishnan, David Dietz, Gregory Heileman, Sameer Hemmady, Zhen Peng, Edl Schamiloglu, Yang Shao, and Payman Zarkesh-Ha. In addition, several graduate students participate in the research: Nishchay Sule, Luis Valbuena, Mustafa Al Mashhdani, and Shen Lin.

The research tasks that are being investigated are listed below and brief updates are provided for each of them.

1. Effects of EEMI on VLSI Designs – Research and develop predictive physics-based models for electronic components stressed beyond their normal operating parameters due to direct injected electromagnetic interference.

The purpose of this project is to design and fabricate basic CMOS test structures using standard technology nodes to be used for EEMI testing and analysis. Our short term goal in the past year was to design the layout and tape out the baseline design to TSMC's 0.35 um CMOS process on Oct. 19, 2015, which was successfully achieved. The test chip was successfully designed and fabricated with 0.35um CMOS process. The chips, which contains basic logic gates as well as NMOS and PMOS devices, are currently under tests and evaluations. As soon as the tests are complete, the design of the next set of test chips using 130nm and 90nm technology nodes will be complete and submitted for fabrication in the next year report period. We have already finished the experimental testing of 0.5um CMOS chipset devices (which were previously fabricated by AFRL). We will be testing with the 0.35um process next. (*Test chip manufacture was financed through an AFOSR DURIP grant*).

2. Research and develop scaling laws for semiconductor CMOS technologies and identify trends.

This should emerge following the testing campaigns using the AFRL probe station and UNM's X-parameter analyzer. A testing laboratory has been established in L2 of the ECE Building. Testing will begin in April 2016 on the initial batch of test structures. (*Acquisition of an X-parameter analyzer was financed through an AFOSR DURIP grant*). This testing will inform the next round of test structures to be manufactured.



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3. Investigation of Post-CMOS Optoelectronics for EMI Susceptibility – Research the next generation electronic component technologies and investigate behavioral responses in the presence of electromagnetic interference.

This topic is in collaboration with UMD. UNM and UMD have identified double-gate FinFETs as the next generation device that warrants study. Two additional technologies that will play a critical role in future electronics have been identified. The technologies are: III-V/Silicon integrated optoelectronics and quantum dot (QD) single photon emitters. The former is a critical technology for silicon photonics while the latter will be used extensively in quantum computation and cryptography. The effort is coordinated with Prof. Edo Waks at UMD, with UNM providing epitaxial materials and devices and the UM providing characterization results. In the present year, self assembled InAs quantum dots were grown on GaAs and InP substrates and were investigated extensively. While InAs on GaAs quantum dots are excellent emitters for wavelengths up to about 1.3 μm , InAs nanostructures on InP emit light in the wavelength region from 1450 nm to 2000 nm, including technologically important wavelengths such as the fiber optic telecommunication wavelength of 1550 nm. This makes the QDash technology very relevant to this COE where the aim is to provide single photon emission at 1.55 μm . However, InAs nanostructures grown on lattice matched $(\text{Al}_x\text{Ga}_{1-x})_{0.47}\text{In}_{0.53}\text{As}$ buffers on InP substrates do not form quantum dots – they form asymmetric structures that have been called quantum dashes. The elongation of the QDs could be an issue in the fabrication single sources. Thus the effort in year 1 has been spent on optimizing InAs QDs at 1.55 microns and to reduce the density of the QDs to demonstrate single photon emission. We have managed to grow high-quality elongation suppressed QDashes and have also demonstrated single photon emission from such structures - this is the first demonstration of such an effect.

Future consideration will be given on the importance of the Shannon-von Neumann-Landauer (SNL) limit on emerging electronics and EMI susceptibility.

4. Investigate and develop impact of EM interference on software processes and elemental firmware architectures.

We are interested in studying how EEMI affects different software layers in computing systems. There are a few publications that describe how a perturbation at certain points in an IC wafer (microcontroller, FPGA, processor) produce a repetitive fault in the execution of a program, but these papers did not report the component of the processor that was affected (the ALU, bus, program counter, etc.). We first would like to relate faults in assembler instructions with components of a processor. To study this issue, we have been working to build a simple 4-bit processor from scratch (via simulation) using only logic gates and flip-flops. The plan is to perturb its components while executing certain algorithms (e.g., prime number generation, encryption, etc.). We have already built the ALU, the registers, the program counter, the program memory and RAM, the instruction register and the clock. The next step involves devising the assembly language instructions the processor will use. The faults will be introduced notionally.

5. Investigate and develop innovative algorithms to fuse deterministic computational EM algorithms with stochastic EM models for coupling into complicated cavities.

The main achievements of year 1 by the UNM CEM group are three-fold:



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(1) Hierarchical multi-scale computational algorithms for high-definition IC and electronic systems. The technical ingredients include an augmented multi-component multi-solver method via hierarchical skeletonization, and an optimized Schwarz method aiming for scalable convergence in iterative solutions. The hierarchical electronic systems are decomposed into multiple sub-systems. Each sub-system adapts different simulation strategies and algorithms. These individual simulation tools are seamlessly integrated to achieve high-fidelity system-level solutions.

(2) Investigation of high-resolution deterministic CEM solution for electronics in large PEC enclosures. The proposed solver includes the following ingredients: (i) a new multi-trace electric field boundary integral equation formulation; (ii) a direct solver with Schur complement for DDM linear system of equations; (iii) high order basis functions for high-resolution discretization. A validation example using two monopoles inside a large PEC cavity was conducted and measured by Prof. Schamiloglu's group. We observe excellent agreements between results obtained by computation and measurement. Such agreement was not available or reported by other groups in the literature.

(3) A new stochastic dyadic Green's function method for wave interaction with wave-chaotic media (in collaboration with Prof. Antonsen at UMD), which quantitatively describes the universal statistical properties of chaotic systems through random matrix theory. It also leads to a seamless integration of deterministic and stochastic formulation for the statistical characterization of in-situ IC electronics in short-wavelength wave-chaotic enclosures. The implementation and validation of this method is on-going and will be reported in the near future.

6. Research frameworks for uncertainty quantification and investigate the origin of "randomness" in EMI interaction with electronic devices and software processes.

In the direction of examining possible avenues of ingress of probabilistic behavior of devices and gates operating beyond the designed-for EM-environment regimes, we have examined several papers that present deterministic models of signal time delay, t_D , in a single inverter, as well as in chains of inverters, subject to voltage perturbations in the power supply V_{dd} driving the inverter(s) and have begun to incorporate into the those models possible stochastic perturbations of V_{dd} to infer corresponding stochastic deviations in t_D . Some of these time delays will be disruptive and others not depending upon allocated device design noise margins so that the probabilistic behavior for disruption may also be quantified. In Year 2 we intend to extend and refine these models.

Publications: No publications based on the COE research have appeared in print in Year 1.



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University of Maryland

Principal Investigator – Thomas Antonsen, Jr.

The UMD COE team includes: Steven Anlage, Thomas Antonsen, Jr., Neil Goldsman, Ed Ott, and Edo Waks. In addition, several graduate students participate in the research: Tystan Koch, Ke Ma, S. Aghaeimeibodi, and Z. Luo.

Researchers and students at UMD are engaged in a number of basic studies relevant to the operation of electronic equipment in extreme electromagnetic environments as part of the collaborative COE sponsored by AFOSR and AFRL. Broad areas include: basic mathematical characterization of field distributions in systems, measurement of EM coupling in different topologies, and effect of extreme electromagnetic environments on future semiconductor and optoelectronics devices. Within these broad areas the following specific studies are highlighted:

a) Distribution of electromagnetic wave energy on networks

Quantum graphs-consisting of nodes connected by bonds that support waves have been studied extensively in the physics community as tractable models of wave chaotic behavior. We have considered the electrical analog, in which the bonds represent transmission lines and the nodes contain either discrete circuit elements or intricate circuit elements best represented by arbitrary scattering matrices. Including these extra degrees of freedom at the nodes leads to phenomena that do not arise in the simpler graph models already studied. We have investigated theoretically the properties of eigen-frequencies and eigen-functions on these graphs, and related these to the statistical description of voltages on the transmission lines when driving the network externally. The theoretical predictions are currently being compared with measurements on simple networks.

b) Statistics of fields in systems with both regular and chaotic ray trajectories

A wave chaos description of fields requires that the corresponding ray dynamics in the geometric optics be such that almost all orbits diverge exponentially from each other. This is not the case in enclosed regions with parallel walls for example. Our current effort is to find a simple geometry where there are both regular and chaotic regions of ray phase space. We have identified a “Four Arcs” geometry and accompanying parameters for which there are generic intermingled chaotic and non-chaotic regions. We are now in the process of developing a solution method for the fields in the wave dynamic case that will allow us to make detailed comparisons with an appropriately modified random coupling model.

c) Using computational electromagnetics codes to determine Random Coupling Model parameters

Calculating the coupling of electromagnetic energy through an aperture into a large enclosure is complicated due to interference between waves entering the aperture and waves reverberating in the enclosure. A first principles calculation of this phenomena requires resolving all details of the aperture and the enclosure. Use of the Random Coupling Model will obviate resolving the details of the enclosure. However, there is as yet a prescription for combining a CEM calculation of an unbacked aperture with the RCM. We are working with Zhen Peng of UNM to develop such a prescription. A mathematical formulation of the technique has been developed and plans are



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underway to implement this approach in one of the UNM CEM codes. At the same time a student at Maryland is developing a simplified, two-dimensional problem to test the method. Solution of this problem is critical to developing a simulation methodology that allows design engineers to make use of the RCM approximation in assessing the effect of apertures in enclosures.

d) Extracting model parameters from complex systems,

The random coupling model (RCM) has been successfully demonstrated as a method to characterize the electromagnetic coupling between ports in large complex enclosures. The model characterizes the system in terms a statistical impedance matrix. In its formulation, it has the advantage of requiring only the loss parameter of the enclosure and the radiation impedance at each of the ports for a full statistical description of the coupling between the ports. However, a challenge remains in finding a practical method to measure the radiation impedance, especially at a port with significant localized power loss. We have developed practical techniques to measure the radiation impedance of the port and the loss parameter. In the case of a lossy port in the complex enclosure, a generalized antenna model is adopted, and the radiation efficiency of the antenna is used to modify RCM's impedance matrix description. The method has been verified with calculations and validated by measurements.

e) Experiments on field distributions in scaled geometries, (ONR funded)

We are now extending the RCM to include consideration multiple connected enclosures, each of which is ray chaotic. However, to test the RCM under increasingly realistic scenarios requires experimental facilities currently beyond our means at UMD. To address this problem the UMD group has received an ONR-DURIP grant to develop a scaled-down electromagnetic test setup. Tests will be performed on four types of predictions, namely induced voltages on components in chains of connected enclosures, and induced voltages in enclosures that are illuminated through an irregular aperture. In addition we will study, in support of the CoE effort, the statistics of induced voltages in the very common situation of enclosures with mixed regular and chaotic behavior.

f) Application of density functional theory to determine the effect of radiation and defects on characteristics of a new class of FETs,

Unwanted electromagnetic signals can couple to micro-devices and nano-devices via printed circuit board traces. MOS Gate Oxides are especially vulnerable to induced terminal voltages in the presence of these signals. Modern oxide layers are very thin and can have defects (Oxygen Vacancies), which enhance the vulnerability of circuits to. Calculation of the behavior of these vacancies requires a quantum mechanical treatment. We have used Density Functional Theory (DFT), plus related modeling tools, to calculate defect states on the atomic level. As a result of these calculations, a transient Arrhenius type model was developed that uses DFT QM Atomic Structure and State results to quantify charging. The model correctly quantifies MOSFET threshold voltage shifts due to gate voltage bias stress.



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g) Effects in high-performance photonic interconnects based on novel materials.

We have developed silicon compatible SiN photonic waveguides coupled to 2D materials. We have fabricated the passive devices, demonstrated waveguiding, and shown that these waveguides are highly insensitive to HPM excitation. We have coupled monolayer WSe₂ to SiN waveguides and demonstrated injection of light emission into the waveguide with high efficiency. We have also developed 2D heterostructures with electrical contacts in order to electrically inject carriers to generate light emission.

Publications: No publications based on the COE research have appeared in print in Year 1.



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Program Managers: Jason Marshall (AFOSR), Timothy Clarke (AFRL)

Principal Investigator: Edl Schamiloglu

ABSTRACT

This AFOSR/AFRL-funded Center of Excellence is led by the University of New Mexico with the University of Maryland a partner. The Year 2 review will be held in Albuquerque, NM on Thursday, March 23, 2017. This report summarizes progress in Year 2.

University of New Mexico

The UNM COE team includes: Ganesh Balakrishnan, David Dietz, Gregory Heileman, Sameer Hemmady, Zhen Peng, Edl Schamiloglu, Yang Shao, and Payman Zarkesh-Ha. In addition, several graduate students participate in the research: Sadhvikas Addamane, Shen Li, Nishchay Sule, Luis Valbuena, and undergraduate Desmond Awungayi.

The research tasks that are being investigated are listed below and brief updates are provided for each of them.

1. Effects of extreme electromagnetic interference (EEMI) on VLSI design – Research and develop predictive physics-based models for electronic components stressed beyond their normal operating parameters due to direct injected electromagnetic interference.

The purpose of this portion of the project is to design and fabricate basic CMOS test structures using standard technology nodes to be used for EEMI testing and analysis. Over the past year, we designed and fabricated wafers containing elemental semiconductor devices – NMOS, PMOS, inverters, inverters with electrostatic discharge (ESD) protection, ring counters and buffers using 1x and 10x device scales. Also, the same circuit topologies were replicated in the 350 nm, 180 nm, 130 nm, 90 nm, and 65 nm TSMC processes. All test circuits were tested and found to be operational. In addition, we performed direct injection testing for input and power supply injection using cw excitation with frequencies spanning 100 MHz to 4 GHz, and power levels from -30 dBm to +30 dBm. The variation in the transfer characteristics of these individual devices was captured. We also developed



Department of Electrical & Computer Engineering

predictive models for describing the scaling laws for NMOS devices and inverter sections.

2. Effects of EEMI on software execution – Research and develop predictive models to characterize the functional (software) upset of digital electronics due to physical interaction of EEMI with underlying circuitry (collaboration between Professor Hemmady and Professor Antonsen, UMD).

The purpose of this project is to develop a predictive model describing functional software upset of a complicated digital electronic system due to EEMI influence. We focus on the use of microcontrollers, which serve as ideal surrogates for large, more complicated digital systems. In addition, we developed a FPGA-based experimental framework to reproducibly inject glitches into the clock stream and power supply of the microcontroller, while it is executing specific software instructions. We studied the statistical behavior of software glitches and are developing a stochastic, Markov based modeling framework to predict software behavior as a function of injected glitch parameters. This work is performed in collaboration with UMD.

Another portion of this work seeks to find a way to write resilient code for EEMI environments. We want to have a predictive model of how the different states of a computation changes under EEMI. In addition to the Markov chain approach we are looking at this through a Turing machine approach (can EEMI be used to change a computer from performing one set of instructions to a completely different set of instructions?) and as a hybrid automata. Two manuscripts are being prepared for submission: one on a 4-bit processor testbed for software predictive models and one on the consequences of targeted extreme EEMI on software execution.

3. Investigate and develop innovative algorithms to fuse deterministic computational electromagnetic algorithms with stochastic electromagnetic models for coupling into complicated cavities (collaboration between Zhen Peng's CEM group, Professor Schamiloğlu's group, and Professor Antonsen, UMD).

The main achievements of year 2 by the UNM Computational Electromagnetics (CEM) group are three-fold:

(1) First-principles analysis and verification tools for complex electronic systems ranging from circuit, package, board and system levels. The emphasis is placed on advancing parallel algorithms that are provably scalable, and facilitating a design-through-analysis paradigm for emerging and future electronic systems. The advancements answer the following fundamental questions: (i) how do we exploit the natural hierarchy in electrical systems during the modeling and simulation? (ii) can both the simulation capability and modeling fidelity of electromagnetic field-based simulators scale with the exponential growth in computing power? (iii) how to reduce the computational complexity for the multi-scale simulation of complex electronic systems?

The work has advantages over the existing approaches in three aspects: (i) the use of an adaptive and scalable geometry-aware domain decomposition (DD) method to conquer the



Department of Electrical & Computer Engineering

geometric complexity of physical domains. This work not only leads to scalable convergence in DD iterations, but also simplifies the preparation of electromagnetic analysis-suitable models from electrical computer-aided design layouts. (ii) a hierarchical coarse-grained method to reduce the computational complexity for multi-scale modeling of electronics. The multi-level skeletonization is employed to construct effective basis functions, the so-called skeletons, with individual sub-systems of different scales. (iii) this work also serves as a basis for parallel and scalable computational algorithms to reduce the time complexity via advanced high performance computing (HPC) architectures. A hybrid Message Passing Interface (MPI)/OpenMP parallel implementation of the proposed framework is developed and tested on shared and distributed memory supercomputers.

(2) Quantitative statistical electromagnetic analysis of antennas and electronics in complicated enclosures. Characterizing the EMI and microwave effects on antennas and electronics within large complicated enclosures (e.g. computer box, reverberation chamber, aircraft fuselage) is an important and challenge problem. In the high-frequency regime, wave solutions inside these enclosures show strong fluctuations that are extremely sensitive to the exact geometry of the enclosure, the location of internal electronics, and the operating frequency. The response of one configuration of the enclosure may not be useful in predicting that of a nearly identical enclosure. Furthermore, real-world EMI with electronic systems also involves a very high degree of uncertainty. The electromagnetic source, propagation/interference path, and targets of interest are often unknown. Therefore, it necessitates a statistical characterization of the EMI and system behavior.

This work presents a different methodology comparing to existing methods in the literature. A hybrid deterministic and stochastic formulation is proposed, in which small components (electronics, antennas, etc.) in the computational domain are modeled using first-principles and large portions (cavity enclosures, scattering environments, etc.) are modeled statistically. The key ingredients are a non-overlapping domain decomposition (DD) formulation, and a stochastic Green's function method that quantitatively describes the universal statistical property of chaotic systems through random matrix theory (RMT).

The work seamlessly integrates the universal statistical properties of the chaotic environments and the site-specific features within a comprehensive statistical analysis framework. Furthermore, it establishes a surrogate modeling capability, which generates the statistical electromagnetic interference in nearly real-time while retaining the underlying first-principles analysis.

(3) Validation and verification of the proposed computational framework. To evaluate the feasibility of the proposed work, we have carried out a number of experimental verification and validation (in collaboration with Ghadeh Hadi, Sameer Hemmady, and Edl Schamiloglu) studies. In a representation exploration we considered a complicated 3D aluminum box. The paddle-wheel mode stirrer is used to generate an ensemble of measurements. Two X-band waveguide (WG) antennas mounted on the opposite walls are used as the transmitter and receiver. The electromagnetic fields inside the box exhibit strong fluctuations due to a mix of



Department of Electrical & Computer Engineering

regular cavity eigenmodes and chaotic eigenmodes. This work successfully predicts the probabilistic in-situ performance and co-site interference between two antennas. We observe very good agreement comparing computational results and measurements.

4. Investigate EEMI effects on optoelectronics through multi-physics analysis

Due to the high transmitting volume and speed of network traffic on the internet: video streaming, clouding computing, and the Internet of Things (IOT), fiber-optic laser transmitters will continue to be one of the major research focus areas in the next decade. The objective of this work is to investigate and develop computational models to predict laser transmitter behavior in the presence of EEMI. The advancements will lead to a comprehensive multi-physics analysis toolset for a variety of optoelectronics.

This year we focused on the following developments:

(i) Investigation of a time domain multi-physics solver hybridizing first-principles electromagnetic models and laser diode behavior models.

The laser diode is extremely sensitive to electrostatic discharge, high current levels and current spikes. These currents may be induced intentionally or unintentionally by electromagnetic interference. The developed time domain solver seamlessly integrates the rigorous solution of Maxwell subsystem and non-linear behavior modeling of optical subsystem through the circuit-field relations. It can accurately characterize the induced RF currents on the laser diode pins.

(ii) Measurement of laser diode I-V curve with various injected RF currents.

We purchased 5 types of optoelectronic components. All of them are TO-can packages, and we plan to extend the testing to the butterfly package in the next year. The components are ready for two sets of tests. One set is 980 nm lasers and silicon detectors, and another set is 1550 nm telecom lasers and InGaAs. We finished the I-V curve measurements on one laser transmitter with injected RF currents with frequency varying from 10 MHz – 100 MHz and power from -20 dBm to 18 dBm. We will extend our present experimental capability to test more laser diode parameters and conduct more testing on other laser diodes.

(iii) Development of a predictive model for laser diode behavior with RF currents.

From the measurement data we observe that the injected RF currents indeed affect the I-V curve cut-off voltage. Measurement data show that RF current at lower frequency and higher power level affect the cut-off voltage the most. Simulations show that the RF current at this level will increase the bit error rate of transmitted data.

5. Photonic interconnects and future devices: Effects of EEMI on single photon emitters (collaboration between Professor Balakrishnan's group and Professor Waks' group at UMD).



Department of Electrical & Computer Engineering

In a collaborative effort between Prof. Waks' group at UMD and Prof. Balakrishnan's group at UNM quantum dot-based samples were grown with ultra-low dot density that are ideal for the fabrication of single photon devices. The molecular beam epitaxy of the devices was conducted at UNM followed by patterning using an e-beam writer and subsequent optical characterization done at UMD. There were significant results this year, with the first demonstration at UNM of single dot emission from telecom-wavelength 1.55 μm InAs quantum dots grown on InP. This has, in the past, been a challenge due to the difficulty in realizing and isolating single dots for InAs on InP substrates. With the successful realization of single dot emitters at 1.25 μm and 1.55 μm we envision device fabrication in the coming year followed by studies to understand the effects of EEMI on such devices.

6. Research frameworks for uncertainty quantification and investigate the origin of "randomness" in EEMI interaction with electronic devices and software processes.

We have developed an analytic model for a single inverter to compute the stochastic signal time delay, t_D , resulting from a stochastic power supply V_{dd} driving the inverter as well as to compute the probability of failure of any digital circuit employing only a single inverter. We have also extended this model to a pair of inverters; the formalism used for the pair is extendable to any number of inverters and we will so extend it fully in Year 3. As an early result in this direction, we have also derived an expression for the probability of failure of a circuit containing a very large ("infinite") number of inverters in a special case of our formalism; we will as well in Year 3 explore the extension of this result to other cases. We will also begin to investigate stochastic behavior to other logic gates as a consequence of stochastic V_{dd} .

UNM Publications – Journals Published

1. A. Sadhvikas, A. Mansoori, N. Dawson, C. Hains, R. Dawson, and G. Balakrishnan, "Emission Wavelength Control in InAs (Sb) Quantum Dashes-in-a-Well Structures," J. Vac. Sci. Technol. B (Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena), vol. 34, 02L103 (2016).
2. Z. Peng, Y. Shao, H.-W. Gao, S. Wang, and S. Lin, "High-Fidelity, High Performance Computational Algorithms for Intra-System Electromagnetic Interference Analysis of IC and Electronics," IEEE Trans. Compon. Packag. Manuf. Technol., Invited paper for IEEE T-CPMT Special Topics Section on "Address Signal and Power Integrity in Future Generation Systems," DOI:10.1109/TCPMP.2016.2636296, 2017 [published early access on-line].
3. H.-W. Gao, Z. Peng, and X.-Q. Sheng, "A Geometry-Aware Domain Decomposition Preconditioning for Hybrid Finite Element-Boundary Integral Method," in IEEE Trans. Antennas Propag., doi: 10.1109/TAP.2017.2670533, 2017 [published early access on-line].

UNM Publications – Conference Papers Published

1. S. Lin, Z. Peng, and T. Antonsen, "A Quantitative Statistical Analysis of In-Situ IC and



Department of Electrical & Computer Engineering

Electronics in Complex and Wave-Chaotic Enclosures, 2016 IEEE MTT-S International Microwave Symposium (IMS) (2016) 10.1109/MWSYM.2016.7540274.

2. A. Wang, H.-W. Gao, Y. Shao, and Z. Peng, "Scalable Full-Wave Algorithms for Signal Integrity Analysis of 3D ICs and Packages," 2016 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting, Puerto Rico, USA, June 2016.

3. S. Lin, Z. Peng, and T. Antonsen, "Multi-Scale Modeling and Stochastic Analysis of IC and Electronics in Complex and Wave-Chaotic Enclosures," 2016 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting, Puerto Rico, USA, June 2016.

4. Y. Shao, S. Wang, and Z. Peng, "Exploring High-Fidelity Modeling and Multi-Scale Simulation Methods for EMI/EMC Analysis of IC and Electronics," 2016 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting, Puerto Rico, USA, June 2016.

5. H.-W. Gao, Z. Peng, and X.-Q. Sheng, "A Multi-Scale Surface Integral Equation Domain Decomposition Method for High-Fidelity Electromagnetic Simulation," 2016 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting, Puerto Rico, USA, June 2016.

6. Z. Peng, "High-Performance Surface Integral Equation Solvers Towards Extreme-Scale Electromagnetic Computation," 2016 SIAM Annual Meeting, Boston, Massachusetts, USA, July 2016.

7. S. Lin, Z. Peng, and T.M. Antonsen, "A Hybrid Method for Quantitative Statistical Analysis of In-situ IC and Electronics in Complex and Wave-chaotic Enclosures," 2016 Progress In Electromagnetic Research Symposium (PIERS), Shanghai, China, 8–11 August (2016), pp. 2503-2510.

8. Z. Peng, "Domain Decomposition Methods in Wave Chaotic Analysis," SIAM Conference on Computational Science and Engineering, Atlanta, Georgia, USA, February 2017.

Awards and Recognition

Zhen Peng receive 5 honors in 2016-2017:

2017 Young Investigator Training Program Awardee of the 21st IEEE Workshop of Signal and Power Integrity

2016, International Union of Radio Science (URSI) Asia-Pacific Radio Science Conference Young Scientist Award

2016 University of New Mexico ECE Department's Distinguished Researcher Award

2016 Young Investigator Training Program Awardee of the 20th IEEE Workshop of Signal and Power Integrity



Department of Electrical & Computer Engineering

2016 Best Poster Paper Award of the 20th IEEE Workshop of Signal and Power Integrity

Edl Schamiloglu received a 2016 Institute of Physics (UK) Outstanding Reviewer Award for Journal of Physics D: Applied Physics

University of Maryland

Principal Investigator – Thomas Antonsen, Jr.

The UMD COE team includes: Steven Anlage, Thomas Antonsen, Jr., Neil Goldsman, Ed Ott, and Edo Waks. In addition, several graduate students participate in the research: Tystan Koch, Ke Ma, S. Aghaeimeibodi, Z. Luo, Bisrat Addisie, Farasatul Adnan, Min Zhu, Zhiyuan Fu.

Researchers and students at UMD are engaged in a number of basic studies relevant to the operation of electronic equipment in extreme electromagnetic environments as part of the collaborative COE sponsored by AFOSR and AFRL. Broad areas include: basic mathematical characterization of field distributions in systems, measurement of EM coupling in different topologies, and effect of extreme electromagnetic environments on future semiconductor and optoelectronics devices. Within these broad areas the following specific studies are highlighted:

a) Distribution of electromagnetic wave energy on networks

An experimental setup consisting of a microwave network is used to simulate quantum graphs. The random coupling model (RCM) is applied to describe the universal statistical properties of the system with and without time-reversal invariance. The networks which are large compared to the wavelength, are constructed from coaxial cables connected by T junctions, and by making nodes with circulators time-reversal invariance for microwave propagation in the networks can be broken. The results of experimental study of microwave networks with and without time-reversal invariance are presented both in frequency domain and time domain. With the measured S-parameter data of two-port networks, the impedance statistics and the nearest-neighbor spacing statistics are examined. Moreover, the experiments of time reversal mirrors for networks demonstrate that the reconstruction quality can be used to quantify the degree of the time-reversal invariance for wave propagation.

b) Statistics of fields in systems with both regular and chaotic ray trajectories

Mixed systems are systems for which ray trajectories in the enclosure may be chaotic or regular depending on the initial conditions for the ray. The RCM assumes all ray trajectories are chaotic. Past work of ours on a particularly shaped two-dimensional cavity showed that the statistics of impedance matrices were modified when both chaotic and integrable trajectories were present. However, that shape was not typical in that the regions in phase space of integrable and regular trajectories were distinct. The more generic situation is that the regions are intertwined. We are now considering a model that has this property. The Method of Moments has been implemented to solve the Helmholtz equation in a 2D cavity. This is an essential step in order to obtain the numerical eigenfrequencies and eigenmodes of the mixed system 2D cavities we are interested in. We need the eigenfrequencies and eigenmodes to check if the Random Coupling Model gives the correct prediction of the cavity impedance probability distribution or not.



Department of Electrical & Computer Engineering

As a starting point, we choose to solve the potential field in a unit circle, with the boundary condition being zero potential value on the boundary. Given this setup, we should be expecting to get the eigenfrequencies and eigenmodes the same as the well-known solution for TM modes in a circular waveguide. We have since generalized to the case of a cavity whose perimeter is defined by two pairs of circular arcs with different radii. The lengths of the arcs and their radii of curvature is selected such that the tangent vector to the perimeter is a continuous function as one travels around the perimeter. The next step is to add ports and measure impedance statistics.

c) Using computational electromagnetics codes to determine Random Coupling Model parameters

Calculating the coupling of electromagnetic energy through an aperture into a large enclosure is complicated due to interference between waves entering the aperture and waves reverberating in the enclosure. A first principles calculation of this phenomena requires resolving all details of the aperture and the enclosure. Use of the Random Coupling Model will obviate resolving the details of the enclosure. However, there is as yet a prescription for combining a CEM calculation of an unbacked aperture with the RCM. We are working with Zhen Peng of UNM to develop such a prescription. A mathematical formulation of the technique has been developed and plans are underway to implement this approach in one of the UNM CEM codes. As a first step in the process of merging the RCM with a computational electromagnetics code (CEM) we have considered the model 2D problem of an aperture backed by a section of waveguide. This problem can be solved numerically using HFSS. The section of waveguide may be extended to infinity, the radiation case, terminated with a boundary condition representing an enclosure with regular trajectories, or terminated with a boundary condition as stipulated by the RCM. This will allow comparison of these three possibilities in a computational setting.

d) Experimental Tests of the RCM to determine its regime of validity,

The random coupling model (RCM) has been successfully demonstrated as a method to characterize the electromagnetic coupling between ports in large complex enclosures. The model characterizes the system in terms a statistical impedance matrix. In its formulation, it has the advantage of requiring only the loss parameter of the enclosure and the radiation impedance at each of the ports for a full statistical description of the coupling between the ports. However, a challenge remains in finding a practical method to measure the radiation impedance, especially at a port with significant localized power loss. We have developed practical techniques to measure the radiation impedance of the port and the loss parameter. In the case of a lossy port in the complex enclosure, a generalized antenna model is adopted, and the radiation efficiency of the antenna is used to modify RCM's impedance matrix description. The method has been verified with calculations and validated by measurements. We are currently determining the lower frequency limit of the RCM. Measurements have been made down to the frequency range of the lowest 50 modes of the cavity. At this frequency finite sample size becomes the dominant limitation.

e) Experiments on field distributions in scaled geometries, (ONR funded)

We are now extending the RCM to include consideration multiple connected enclosures, each of



Department of Electrical & Computer Engineering

which is ray chaotic. However, to test the RCM under increasingly realistic scenarios requires experimental facilities currently beyond our means at UMD. To address this problem the UMD group has received an ONR-DURIP grant to develop a scaled-down electromagnetic test setup operated at a reduced temperature to maintain the correct scaling for resistive losses. Tests have been performed on this setup at a frequency such that the volume is 450 wavelengths on each dimension. Issues being addressed include modifications of the RCM to account for quasi-optical coupling losses in this small wavelength regime.

f) Application of density functional theory to determine the effect of radiation and defects on characteristics of a new class of FETs,

Unwanted electromagnetic signals can couple to micro-devices and nano-devices via printed circuit board traces. MOS Gate Oxides are especially vulnerable to induced terminal voltages in the presence of these signals. Modern oxide layers are very thin and can have defects (Oxygen Vacancies), which enhance the vulnerability of circuits to. Calculation of the behavior of these vacancies requires a quantum mechanical treatment. There are two basic mechanisms for device damage and various subsets of these damaging processes: Gate oxide damage and Device damage due to joule heating induced by excessive voltage and currents in the MOSFET conducting channel between the source and the drain. We have used Density Functional Theory (DFT), plus related modeling tools, to calculate these mechanisms and assess their relative importance.

g) Effects in high-performance photonic interconnects based on novel materials.

We have developed silicon compatible SiN photonic waveguides coupled to 2D materials. We have fabricated the passive devices, demonstrated waveguiding, and shown that these waveguides are highly insensitive to HPM excitation. We have coupled monolayer WSe₂ to SiN waveguides and demonstrated injection of light emission into the waveguide with high efficiency. We have also developed 2D heterostructures with electrical contacts in order to electrically inject carriers to generate light emission. Recently, Halide perovskite semiconductors have emerged as prominent photovoltaic materials since their high conversion efficiency and promising light emitting materials in optoelectronics. In particular, easy-to-fabricated colloidal perovskite nanocrystals based on CsPbX₃ quantum dots have been intensively investigated. Their luminescent wavelength can be tuned precisely by their chemical composition and size. This opens new applications, including light-emitting diodes and optical amplifiers, due to their promising performance as emitters. We have demonstrated the Purcell enhancement effect of CsPbBr₃ perovskite nanocrystals by coupling them to an optimized photonic crystal nanobeam cavity. This is a first crucial step towards realization of integrated on-chip coherent light sources with low energy consumption for robust optical interconnects.

UMD Journal Publications Published

1. B. Xiao, T.M. Antonsen, E. Ott, and S.M. Anlage, "Focusing Waves at an Arbitrary Location in a Ray-Chaotic Enclosure Using Time-Reversed Synthetic Sonas," Phys. Rev. E 93, 052205 (2016).
2. B. Xiao, K. Lai, Y. Yu, T. Ma, G. Shvets, and S.M. Anlage, "Exciting Reflectionless Unidirectional Edge Modes in a Reciprocal Photonic Topological Insulator Medium," Phys. Rev.



Department of Electrical & Computer Engineering

B 94, 195427 (2016).

3. D. Zhang, M. Trepanier, T. Antonsen, E. Ott, and S.M. Anlage, “Intermodulation in Nonlinear SQUID Metamaterials: Experiment and Theory,” *Phys. Rev. B* 94, 174507 (2016).

4. J. Gil Gil, Z. Drikas, T. Andreadis, and S.M. Anlage, “Prediction of Induced Voltages on Ports in Complex, 3-Dimensional Enclosures with Apertures, using the Random Coupling Model,” *IEEE Trans. Electromag. Compat.* 58, 1535-1540 (2016).

5. K. Lai, T. Ma, B. Xiao, S. Anlage, and G. Shvets, “Experimental Realization of a Reflections-Free Compact Delay Line Based on a Photonic Topological Insulator,” *Scientific Reports*, vol. 6, 28453 (2016).

6. D.P. Ettisserry, N. Goldsman, and A.J. Lelis. “Role of Oxygen Vacancies in Short-and Long-Term Instability of Negative Bias-Temperature Stressed SiC MOSFETs,” *IEEE Trans. Electron Dev.*, vol. 64, 1007 (2017).

UMD Publications – Conference Papers Published

1. F. Cangialosi, T. Grover, P. Healey, T. Furman, A. Simon, and S.M. Anlage, “Time Reversed Electromagnetic Wave Propagation as a Novel Method of Wireless Power Transfer,” 2016 IEEE Wireless Power Transfer Conference (WPTC), pp. 1-4 (2016).

2. S. Roman, R. Gogna, and S.M. Anlage, “Selective Collapse of Nonlinear Time Reversed Electromagnetic Waves,” 2016 IEEE Wireless Power Transfer Conference (WPTC), pp. 1 – 4 (2016).

3. S. Lin, Z. Peng, and T. Antonsen, “A Quantitative Statistical Analysis of In-Situ IC and Electronics in Complex and Wave-Chaotic Enclosures, 2016 IEEE MTT-S International Microwave Symposium (IMS) (2016) 10.1109/MWSYM.2016.7540274.

4. S. Lin, Z. Peng, and T.M. Antonsen, “A Hybrid Method for Quantitative Statistical Analysis of In-situ IC and Electronics in Complex and Wave-chaotic Enclosures,” 2016 Progress In Electromagnetic Research Symposium (PIERS), Shanghai, China, 8–11 August (2016), pp. 2503-2510.

Awards and Recognition

Edward Ott received three major honors during 2016-2017:

2016 Citation Laureate in Physics (Thompson-Reuters) [for “a control theory of chaotic systems”]

2017 Lewis Fry Richardson Medal [for “pioneering contributions to the theory of chaos”]

2017 Jurgen Moser Award [for “seminal work in chaos theory and the dynamics of physical systems”]



Department of Electrical & Computer Engineering

Tom Antonsen received the 2016 IEEE John R. Pierce Award for Excellence in Vacuum Electronics



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Annual Report on AFOSR/AFRL COE: Science of Electronics in Extreme Electromagnetic Environments

AFOSR Grant FA9550-15-1-0171

Period of Performance: 01 April 2017 – 31 March 2018

Program Managers: Jason Marshall (AFOSR), Timothy Clarke (AFRL)

Principal Investigator: Edl Schamiloglu

ABSTRACT

This AFOSR/AFRL-funded Center of Excellence is led by the University of New Mexico with the University of Maryland a partner. The Year 3 review was held in College Park, MD on Friday, March 16, 2018. This report summarizes progress in Year 3.

University of New Mexico

The research tasks that are being investigated are listed below and brief updates are provided for each of them.

1. Microcontroller Investigations – Over the past year, we refined our experiment to allow us to inject RF pulses into the microcontroller and analyze the contents of its internal registers. From our previous setup, we used the UART register on the microcontroller to obtain information about internal registers. Since the microcontroller only has one UART register, we had to perform several read/writes and data transfers into and out of the UART register to accomplish transferring all the register contents on the output bus. There was significant possibility of overwriting effects-data stored in the registers during these transfers. To overcome this limitation, we decided to incorporate the JTAG On-Chip Debugging (OCD) capability. We revised our experiment to allow us to inject a RF pulse into a specific instruction executing on the microcontroller, and then examine the contents of the JTAG boundary scan registers right after the injection of the RF pulse. In this manner, we can study how internal register contents are altered due to RF pulse injection. We then studied the behavior of erroneous register contents as a function of the instruction being executed. Our analysis shows that the contents of the internal registers can be perturbed in a statistical manner which conforms with a Markov Chain model for representing software upset.

Future Work: We will work on refining our experimental setup and developing theoretical Markov Chain models to describe and validate (through experiments) the interaction of RF pulses

with software instructions.

2. CMOS Injection Experiments – Over the past year, we focused on developing predictive models for describing the influence of RF injection on the Large Signal Operating Point (LSOP) I-V Curves of MOSFET devices, which were fabricated through MOSIS in the first year of the COE effort. The experimental data collected through the second and third year was used to validate the theoretical models developed. In specific, we developed low-frequency models for MOSFET with drain-side injection; MOSFET with gate-side injection; Inverter with input-side injection; Inverter with supply-side injection. These models were then compared with experimental data to show good agreement. Models were also developed to extend these low-frequency models into scaling laws for the peak injection strength that these MOSFET devices could sustain before damage. These scaling models were then also validated through experiments. Finally, the low-frequency models were extended to higher frequency models taking into account parasitic impedances within the devices.

Future Work: We will focus on experimentally validating the high frequency models as well as developing models for nonlinear responses of the devices under RF injection.

3. First-Principles Mathematical Model for the Statistical Wave Analysis of Antennas and Electronics in Complicated Enclosures – The research work in Year 3 is centralized around first-principles mathematical model for the statistical wave analysis of antennas and electronics in complicated enclosures.

Characterizing the electromagnetic interference (EMI) and microwave effects on antennas and electronics within large complicated enclosures (e.g. computer box, reverberation chamber, aircraft fuselage) is an important and challenge problem. In the high-frequency regime, the complex boundary of the enclosure can lead to high modal density and high modal overlap. Wave solutions inside these enclosures show strong fluctuations that are extremely sensitive to the exact geometry of the enclosure, the location of internal sensors and electronics, and the operating frequency. Minor differences in the detailed configuration of the system, or small numerical errors in the computation, can result in significantly different EM field distributions within the enclosure.

One significant outcome of our Year 1&2 research is a stochastic integral equation – Green’s function (SIE-GF) method. The SIE-GF method leads to a new statistical model, which interprets the universal properties of wave-chaotic systems through the random matrix theory (RMT). Nevertheless, most real-world EM systems often involve mixed chaotic and regular wave dynamics. Those non-chaotic dynamical features result in deviations from universality and ergodicity, which in turn limits the applicability of the RMT. Therefore, it is of great practical importance to rigorously study and incorporate these non-universal effects, which motivates the theme of this work.

The Year 3 research focuses on the quantitative statistical analysis for complicated EM systems exhibiting mixed integrable (regular) and non-integrable (chaotic) dynamics. The key research objective is to integrate the universal statistical properties predicted by the RMT with the non-chaotic dynamical aspects. To accomplish this goal, we have developed a hybrid deterministic and stochastic formulation incorporating component-specific characteristics, investigated an in-situ SGF addressing the site-specific short-orbits, and designed a Lorentzian-weighted frequency averaging to predict the system-specific ensemble behavior. The work leads to a comprehensive statistical analysis framework for general complex EM systems, and establishes an imperative design-under-chaos capability expected to have a big impact in the engineering discipline.

This theoretical framework has been validated through experiments performed by Ghadeh Hadi, Sameer Hemmady, and Edl Schamiloglu.

4. Investigate EEMI Effects on Optoelectronics through Multi-Physics Analysis – The purpose of this research is to investigate predictive models to analyze EEMI effect on laser diode behavior. In order to accurately measure the laser diode I-V characteristics with injected RF currents, we have designed and fabricated a printed circuit board with installed diode components. Measurement results show that the RF current at high power level significantly affects the cut-off voltage and current-voltage (I-V) curve of the laser diode.

We have developed three predictive models to analyze the laser diode behavior with various injected RF currents: (1) predictive model of small RF injection current, (2) predictive model of large RF signal analysis, and (3) predictive model of large RF injection currents at high frequencies. After first establish the diode baseline equation, the predicted models successfully simulate the diode behavior with injected RF currents at small power level, large power level and high frequencies, respectively.

To leverage the machine learning capabilities, we have built a deep neural network model to learn the diode I-V pattern with various inject RF current power level and frequencies.

The planned work in the near-term includes: (1) current predictive model is based on TO-can laser diode, we will also work on VCSEL diode models, (2) we will extend the measurements for X parameter analysis of diodes, (3) better and more accurate machine learning algorithms will be explored.

5. Photonic Interconnects and Future Devices – Effects of EEMI on single photon emitters (collaboration between Professor Balakrishnan's group and Professor Waks' group at UMD).

During the previous year, we were able to successfully fabricate single photon emitters at telecom-wavelength 1.55 μm from InAs quantum dots grown on InP at UNM. Building on these results, this year we focused on realizing single photon emitters at different wavelengths ranging from 0.9 μm to 2 μm . In order to span such a long wavelength range, we have explored the use of InAs nanostructures (quantum dots or quantum dashes) on a variety of substrates including GaAs, InP and metamorphic buffers with varying lattice constants. The samples were grown using molecular beam epitaxy (MBE) in Prof. Balakrishnan's group at UNM. They were then packaged and shipped to UMD, where Prof. Waks' group worked on processing these samples and characterizing them optically. To isolate single (or a few) nanostructures and to enhance their emission, photonic crystal cavities were fabricated with three missing holes in the center (L3 cavity). Using these samples, there were significant results this year with the realization of single photon emission around 1.25 μm and 900 nm. With these results, we envision the fabrication of devices in the coming year which will lead the way to understanding the effects of EEMI on single photon emitters.

6. Research Framework for Uncertainty Quantification and Investigate the Origin of "Randomness" in EEMI Interaction with Electronic Devices and Software Processes –

We have developed an analytic model for a single CMOS inverter to compute the stochastic signal time delay, t_D , resulting from a stochastic power supply V_{dd} driving the inverter gate or resulting from a stochastic external EM disturbance inducing a voltage on that gate; and to compute as well the probability of failure, as a consequence of such gate voltage, of any digital circuit employing only a single such inverter. We have also extended this model to a pair of CMOS inverters in the general case when the V_{dd} 's on the two inverter gates are not necessarily (but may be) statistically independent; the formalism used for the pair is extendable to any number of CMOS inverters and we have begun that extension. As an early result in this direction, we have also derived an expression for the probability of failure of a circuit containing a very large ("infinite") number of CMOS inverters in a special case of our formalism; we have also continued to explore the extension of this result to other cases. We will in Year 4 begin to investigate stochastic behavior to other CMOS logic gates, formed *via* combinations of inverters,

as a consequence of stochastic V_{dd} .

7. Effects on Software Execution – During the last year we focused on the development of the predictive model with hybrid automata, including the dynamical system descriptions (which includes EEMI) of components such as inverters (transistors) provided by Dr. Zarkesh-Ha and Dr. Schamiloglu. We are regarding the hybrid automata to have fixed discrete states that matches the execution states of the 4-bit processor developed before. These fixed states execute the software written in memory. When the hybrid automata executes the code, there is an instruction label output associated with each execution cycle, then the complete running of the program produces an execution path. In the presence of EEMI, this execution path is altered and for the time being we are treating the time of the EEMI injection to be a random variable.

We have also done the following consideration: given a particular execution path P , we want another execution path P' for which we establish the (continuous) state conditions (set) S required to happen on P to become P' . We are working on the reachability problem: go backwards on the discrete states to determine the state subspace such that when the execution takes place, the hybrid automata is inside set S .

We have also studied how EEMI injection on the clock signal cascades through the system. We created a ring oscillator with Dr. Zarkesh-Ha's model of an inverter under low frequency noise injection and connected the oscillator to both synchronous and asynchronous frequency dividers. All this is done in a simulation environment. We observed that the injected noise signal does move through the components and arrives to the control matrix. The control matrix is the component in charge of coordinating the execution stages of the processor mentioned at the beginning.

Personnel Supported

Faculty: Balakrishnan, Dietz, Heileman (U. Kentucky), Hemmady, Peng, Schamiloglu, Shao, and Zarkesh-Ha

PostDocs: Sathvikas Addamane, Ghadeh Hadi

Students: Sathvikas Addamane, Ghadeh Hadi, Rusmir Bilalic, Joe Chen, Maxim Vitovski, Luis Valbuena, Nishay Sule, Zahra Abidi, Desmond D. Awungayi, Troy Powell

UNM Publications – Journals

1. H.-W. Gao, Z. Peng, and X.-Q. Sheng, "A Coarse-Grained Integral Equation Method for Multi-Scale Electromagnetic Analysis," IEEE Transactions on Antennas and Propagation, vol. 66, no. 3, pp. 1607-1612, March 2018.
2. Z. Peng, Y. Shao, H.-W. Gao, S. Wang, and S. Lin, "High-Fidelity, High-Performance Computational Algorithms for Intra-System Electromagnetic Interference Analysis of IC and Electronics," IEEE Transactions on Components, Packaging and Manufacturing Technology, Invited Paper for Special Topics Section on Addressing Signal and Power Integrity in Future Generation Systems. vol. 7, no. 5, pp. 653-668, May 2017. (Best Paper Award among papers published in the Transactions during the previous year.)
3. H.-W. Gao, Z. Peng, and X.-Q. Sheng, "A Geometry-Aware Domain Decomposition Preconditioning for Hybrid Finite Element-Boundary Integral Method," IEEE Transactions on Antennas and Propagation, vol. 65, no. 4, pp. 1875-1885, April 2017.
4. S. Addamane, A. Mansoori, N. Dawson, D.M. Shima, T.J. Rotter, C.P. Hains, L.R. Dawson,

G.T. Wang and G. Balakrishnan, "Photoluminescence-Based Comparison of Optical Properties of Stranski-Krastanov (S-K) InAs/GaAs Quantum Dots and InAs/InP Quantum Dashes," Appl. Phys. Lett. (under review).

5. D. Dietz, "Stochastic Propagation Delay Through a CMOS Inverter as a Consequence of Stochastic Power Supply Voltage, Part I: Model Formulation," IEEE Trans. Electromagn. Compat., to appear (2018).

6. D. Dietz, "Stochastic Propagation Delay Through a CMOS Inverter as a Consequence of Stochastic Power Supply Voltage, Part II: Modeling Examples," IEEE Trans. Electromagn. Compat., to appear (2018).

UNM Publications – Conference Papers

1. S. Lin and Z. Peng, "A Novel Stochastic Wave Model Statistically Replicating Reverberation Chambers," 26th Conference on Electrical Performance of Electronic Packaging and Systems, (Best Student Paper Award), San Jose, California, USA, October 2017.

2. S. Wang and Z. Peng, "Space-Time Parallel Computation for Time-Domain Maxwell's Equations," 2017 International Conference on Electromagnetics in Advanced Applications (ICEAA), (ICEAA IEEE-APWC Awards Finalist), Verona, Italy, September 2017.

3. S. Lin and Z. Peng, "Fusion of First-Principles and Statistical Analysis in Complex Electronics Systems," XXXII General Assembly and Scientific Symposium of the International Union of Radio Science (URSIGASS 2017), (Invited Talk), Montreal, Canada, August 2017.

4. Z. Peng, Y. Shao, and S. Lin, "First-Principles Modeling and Statistical Characterization of Wireless Channels in Complex Electromagnetic Environments," XXXII General Assembly and Scientific Symposium of the International Union of Radio Science (URSIGASS 2017) (Invited Talk) Montreal, Canada, August 2017.

5. S. Wang and Z. Peng, "A Space-Time Parallel Domain Decomposition Method for High Fidelity Electromagnetic Analysis," 2017 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting, San Diego, California, USA, July 2017.

6. S. Lin, Z. Peng, and T. Antonsen, "Quantitative Statistical Analysis with Physics-based Surrogate Modeling for Wave Chaotic Systems," 2017 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting, (Honorable Mention Award in Student Paper Competition), San Diego, California, USA, July 2017.

7. Y. Shao and Z. Peng, "Supercomputing-Enabled First-Principles Analysis of Wireless Channels in Urban Environments," 2017 International Microwave Symposium (IMS), (entered into the best IMS Advanced Practice Paper) Honolulu, Hawaii June 2017.

8. Z. Peng and S. Lin, "EM-CAD for Complex Electronics Systems: A Journey from Order to Chaos," 2017 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization for RF, Microwave, and Terahertz Applications, (Invited Talk), Sevilla, Spain, May 2017.

9. Z. Peng, "Geometry-Aware Domain Decomposition Methods in High-Fidelity Electromagnetic Design," 2017 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization for RF, Microwave, and Terahertz Applications, Sevilla, Spain, May 2017.

10. S. Lin, Z. Peng, and T. Antonsen, "Fusion of First-Principles and Statistical Analyses in

Complex Electronics Systems,” 21th IEEE Workshop on Signal Integrity and Power Integrity (SPI2017) (Young Investigator Training Program Awardee), Baveno, Italy, May 2017.

11. D. Awungayi, N. Sule, P. Zarkesh-Ha, E. Schamiloglu, S. Hemmady, “Developing Predictive Scaling Laws for Large Signal RF Response of Elemental MOSFET Devices,” Presented at the ASIAEM Conference, Bangalore, India, July 2017.

12. N. Sule, T. Powell, S. Hemmady, and P. Zarkesh-Ha, “Predicting the Tolerance of Extreme Electromagnetic Interference on MOSFETs,” submitted to IEEE Computer Society Annual Symposium on VLSI (ISVLSI), July 2018.

13. T. Powell, N. Sule, S. Hemmady, and P. Zarkesh-Ha, “Predictive Model for Extreme Electromagnetic Compatibility on CMOS Inverters,” submitted to the International Symposium and Exhibition on Electromagnetic Compatibility (EMC Europe), August 2018.

14. E. Schamiloglu *et al.*, “Recent Advances in High Power Microwave Sources and the Science of Electronics in Extreme Electromagnetic Environments at the University of New Mexico,” in Proceedings of the 2017 International Conference on Electromagnetics in Advanced Applications (ICEAA), Verona, Italy, 11-15 Sept 2017 (2017).

15. L. Valbuena, G. Heileman, S. Hemmady, and E. Schamiloglu, “A Testbed for Simulating Electromagnetic Effects on Software Execution,” IEEE International Conference on Circuits and Systems, Nalanchira, Thiruvananthapuram, Kerala, India, December 2017.

16. G. Hadi, S. Hemmady and E. Schamiloglu, “Predicting the Nature of Electromagnetic Field Fluctuations in Random Interconnections of Large Complicated Cavities,” Proc. APS/URSI 2017 (San Diego, CA, July 9-14, 2017).

17. G. Hadi, S. Hemmady, and E. Schamiloglu, “Developing a Statistical Topological Approach using Wave-chaos for Electromagnetic Effects (STUWEE),” Presented at the ASIAEM Conference, Bangalore, India, July 2017.

UNM Publications – Technical Reports

1. D. Dietz and T. Clarke, *A Model for Microcontroller Functionality Upset Induced by External Pulsed Electromagnetic Irradiation*, AFRL-RD-PS-TN-2016-0003, Air Force Research Laboratory, Directed Energy Directorate, Kirtland Air Force Base, NM 87117-5776 (2016).

2. D. Dietz, *Quantifying Propagating Uncertainties in Computer Code Chains*, AFRL-RD-PS-TN-2017-0003, Air Force Research Laboratory, Directed Energy Directorate, Kirtland Air Force Base, NM 87117-5776, *to appear* (2018).

Awards and Recognition

Zhen Peng received the following honors in 2017-2018:

- 2018, National Science Foundation CAREER Award, Project Title: CAREER: Physics-Oriented Statistical Wave Analysis Integrating Order and Chaos
- 2018, Best Transaction Paper Award - IEEE Transactions on Components, Packaging and Manufacturing Technology
- 2017, IEEE Albuquerque Section’s Outstanding Young Engineer Award
- 2017, 21st IEEE Workshop on Signal and Power Integrity (SPI2017) Young Investigator Training Program Awardee
- 2017, 26th Electrical Performance of Electronic Packaging and System Best Paper Award, “A Novel Stochastic Wave Model Statistically Replicating Reverberation Chambers”

Payman Zarkesh-Ha received the following honor in 2017-2018:

- Recipient of 2017 Innovation Award from STC at UNM, April 2017

Edl Schamiloglu received the following honor in 2017-2018:

- 2017: University of New Mexico Senior Faculty Research Excellence Award

UNM Students Who Graduated

- Sadvikas Addamane (PhD, Optoelectronics) – he is a postdoc at UNM
- Ghadeh Hadi (PhD, Engineering) – she joined Verus Research
- Rusmir Bilalic (PhD, Engineering) – he is at AFRL/RV

University of Maryland

8. Nonlinear Wave Chaos and Second Harmonic Fields

Concepts from the field of wave chaos have been shown to successfully predict the statistical properties of linear electromagnetic fields in electrically large enclosures. The Random Coupling Model (RCM) describes these properties by incorporating both universal features described by Random Matrix Theory and the system-specific features of particular system realizations. In an effort to extend this approach to the nonlinear domain, we added an active nonlinear frequency-doubling circuit to an otherwise linear wave chaotic system, and we measured the statistical properties of the resulting second harmonic fields. We developed an RCM-based model of this system as two linear chaotic cavities coupled by means of a nonlinear transfer function. The harmonic field strengths are predicted to be the product of two statistical quantities and the nonlinearity characteristics. Statistical results from measurement-based calculation, RCM-based simulation, and direct experimental measurements were compared and showed good agreement over many decades of power.

9. Features and Statistics of S-Parameters in Nonlinear Wave Chaotic Systems

The Random Coupling Model (RCM) has been shown to successfully predict the statistical properties of linear wave chaotic cavities in the highly over-moded regime. It is of interest to extend the RCM to strongly nonlinear systems. Besides the statistics of harmonics we recently studied, we examined measurements of the nonlinear S-parameters in two nonlinear systems. One system is a diode-loaded $\frac{1}{4}$ -bowtie quasi-2D microwave cavity where the diodes act as point nonlinearities in a wave chaotic system. Another is a cut-circle quasi-2D microwave cavity, which is made of Pb plated copper. In the superconducting state, the cavity is very nonlinear. By taking advantage of the high power (up to +35 dBm) vector network analyzer (VNA), we observed that the S-parameters are power dependent. Some features, such as time reversal symmetry breaking, hot spot statistics, nonlinear impedance etc. are observed in these nonlinear systems. The goal is to determine how RCM needs to be modified to quantitatively explain these features.

10. Assessing the Effects of RF Interference on Maintenance of Coherence of a Group of Drones

This past year we have initiated a program studying the effects of RF interference on the maintenance of coherence in a group of drones. We consider a group of N -drones that fly together in a spatially localized group (a ‘flock’). We assume that spatial localization is made possible by RF communication between the flock members. Our goal is to assess how this process might be degraded by RF interference, possibly launched as a disruptive attack on the drone flock. Our

beginning work on this project addresses the issue of how the drones can autonomously regulate their direction of flight so as to ensure that they are all going in the same direction. To this end, we have formulated and studied a generic model (based on the well-known Kuramoto model). In this model, each drone receives RF signals from all the other drones in the flock, allowing it to deduce the average direction of flight of the other drones, which it then uses as a basis of deciding how to adjust its own direction of flight. A surprising result of this study is that there is a basic qualitative difference between flocking in two dimensions (e.g., drones moving on a land surface) and flocking in three dimensions (as for flying drones): In two dimensions, the RF signal strength K must exceed a critical value $K_c > 0$ in order to maintain any degree of orientational coherence in the direction of drone motion, while in three dimensions some degree of coherence is maintained for any signal strength $K > 0$. In addition, we have shown that the effect on our model of interfering RF noise is to lower K , and, based on the previous result, this might be expected to have a more dramatic effect on two-dimensional flocking as compared to three-dimensional flocking. A paper on this work is in preparation for publication. In the coming year we will add further aspects to our model to increase its real-world relevance, e.g., consideration of spatial coherence in addition to motion orientation coherence.

11. Wave Chaotic Properties of Cascaded Complex Enclosures

Predicting the power transmission of interconnected enclosures, is of keen interest to various communities. Here we utilized Random Coupling Model (RCM) to explain the wave chaotic properties of the cavity cascade system. We determined loss parameters and found agreement between the statistical properties of the experimental normalized impedance and the RCM predictions. We used the scaling properties of Maxwell's equations to create a scaled-down cavity which preserves the loss parameter of the full scale cavity. Experiments showed that the statistics of the single cavity impedance matrix elements for full scale and scaled enclosures match. We next studied the transmission of the multi-cavity cascade system with cavities connected by apertures. By describing the coupling between cavities through apertures, we were able to produce predictions for the statistics of the impedance for cascaded cavities. We made estimates of the radiation admittance for apertures both experimentally and theoretically, which permitted us to complete a quantitative theoretic model for the cavity cascade systems' statistical properties.

12. Photonic Interconnects and Future Devices

Photonic interconnects using low dimensional materials (Waks group): We investigated black phosphorus as a potential opto-electronic material for photonic interconnects. We developed a fabrication recipe to create a gated black phosphorus PN junction on silicon, and were able to observe diode rectification behavior. The junction was found to be extremely sensitive to voltages and burned very easily. We are now looking at other materials that may be more robust and could be useful for optical interconnects. We have also been studying non-reciprocal coupling of low dimensional materials via spin-orbit interactions.

13. Effects of EEMI on Single Photon Emitters (Collaboration between Professor Balakrishnan's Group and Professor Waks' Group at UMD)

In a collaborative effort between Prof. Waks' group at UMD and Prof. Balakrishnan's group at UNM quantum dot-based samples were grown with ultra-low dot density that are ideal for the fabrication of single photon devices. The molecular beam epitaxy of the devices was conducted at UNM followed by patterning using an e-beam writer and subsequent optical characterization done at UMD. This year we successfully grew and characterized quantum dot samples emitting at 1100 nm and 900 nm. The 1100 nm emitting dots showed clear narrow resonances consistent with single photon emitters. The 900 nm dots showed dim and broad emission suggesting that quantum dots were degraded. We are pursuing various modifications to the growth process to

create improved dot emission at 900 nm and also to push the emission to 1300 nm and 1500 nm where they are suitable for telecommunication wavelengths.

14. Experimental Study of Quantum Graphs with Simple Microwave Networks: Non-universal Features

Quantum graphs provide a setting to test the hypothesis that all ray-chaotic systems show universal wave chaotic properties. Here, an experimental setup consisting of a microwave coaxial cable network was used to simulate quantum graphs. The networks, which are large compared to the wavelength, are constructed from coaxial cables connected by T junctions. The distributions of impedance statistics were obtained from experiments on an ensemble of tetrahedral networks. The random coupling model (RCM) was applied in an attempt to uncover the universal statistical properties of the system. Deviations from RCM predictions have been observed in that the statistics of diagonal and off-diagonal impedance elements are different. Waves trapped due to multiple reflections on bonds between nodes in the graph most likely cause the deviations from universal behavior in the finite-size realization of a quantum graph.

15. Statistics of Signals on Networks of Cables

The impedance matrix for an arbitrary passive network of transmission lines was developed mathematically and it was shown that it can be represented as a sum over modes of the isolated network with resonant denominators at complex frequencies corresponding to those normal modes. This is the first step in the derivation of an RCM for networks. However, it was shown theoretically that there are departures of the fluctuation levels on networks from RMT type statistics. That is, the random plane wave hypothesis does not apply to networks. We have developed an alternate hypothesis that is being tested. The alternate hypothesis accounts for the effect of modes partially trapped on the branches of a network between two nodes with large reflection coefficients. The statistics of the fluctuations in this case show in comparison with Gaussian statistics.

16. Heuristic Treatment of Finite Resolution Effects in DEA

The DEA computes EM energy densities on a spatial grid that is made of tetrahedra in 3D and triangles in 2D. The presence of the grid can artificially scatter waves. An assessment of numerical diffusion and scattering in the DEA algorithm has been made and is being compared with numerically generated solutions. So far agreement is good and the heuristic theory can indicate when numerical scattering will pollute DEA results. Further, we formulated the phase space density evolution equations in a way that connects them to geometric optics solutions and includes the coupling of radiation due to ports that are described by known radiation impedances. This is an alternative to the Dynamical Energy Analysis (DEA) approach favored by the Nottingham group.

17. Nanoscale Device Level Modeling of EMI Induced Vulnerability

In response to the recommendations of the program management, in the last year we investigated soft-error in nanoscale electronics. With soft-error, the electronics is typically not permanently damaged from EMI, but bit errors are introduced, or circuit latch-up occurs, which requires the system to be re-booted. We focused our soft-error effort on silicon CMOS because almost all electronics are of this type. The standard transistor type is a MOSFET, which can experience soft-error due to impact ionization. If a voltage that is approximately two times the standard operating level is induced on a supply rail from electromagnetic coupling, the electric field internal to the MOSFET will greatly increase and can cause impact ionization. Under these circumstances, electrons gain sufficient energy to collide with the crystal lattice to generate electron-hole pairs and thereby generate excess currents at drain and body contacts of the device. By itself, this generation of parasitic currents can be detrimental by giving rise to unexpected voltage build-ups which can cause bit errors in digital circuits and signal errors in analog circuits. However, even

more critical is the problem of positive feedback that is associated with impact ionization that greatly enhances this parasitic effect. The structure of CMOS transistors is such that inside the device, in addition to the MOSFET structure, there is an intrinsic, parasitic bipolar junction transistor (BJT). When impact ionization occurs, this parasitic BJT can turn on, and thereby give rise to a large parasitic current gain that amplifies the initial impact ionization current by an order of magnitude or more. When this happens additional terminal current arises and leads to circuit errors. Even more problematic is that the increased current can lead to the snap-back phenomenon, where so much parasitic current is produced that the field internal to the device collapses. As a result, the voltage across the MOSFET will get latched into low-voltage state, and digital logic will no-longer function. When this occurs, the only thing that can be done to resume operation is to re-boot the system.

In our work this year we developed a methodology for modeling these latch-up and snap-back phenomena. We first identified this problem, and then achieved numerical solutions to the partial differential semiconductor equations to simulate impact ionization inside MOSFETs. Next, we developed a lumped model equivalent circuit of the MOSFET and its intrinsic parasitic BJT using the distributed simulations as a guide. We developed a voltage dependent expression for the impact ionization currents and input it into the lumped model as a voltage-dependent current source. With the current source in place, we evaluated the lumped model using a circuit simulator (SPICE), and showed that the model could generate the snap-back phenomenon, as well as the introduction of bit errors. The model can be used to help predict under what conditions these errors in CMOS electronic circuits will occur as a result EMI coupling.

Personnel Supported

Faculty: Antonsen, Ott, Anlage, Waks, Goldman

Students: Cai, T., Koch, T., Ma, K., Aghaeimeibodi, S., Luo, Z., Addissie, B., Adnan, F., Darmody, C., Cui, Y., Fu, Z., Zhou, M., Ma, S., Chandra, S., Ghutishvili, T.

Publications

1. Cai, T., Dutta, S., Aghaeimeibodi, S., Yang, Z., Nah, S., Fourkas, J. T., & Waks, E. (2017). Coupling Emission from Single Localized Defects in Two-Dimensional Semiconductor to Surface Plasmon Polaritons. *Nano Letters*, 17 (11), 6564–6568. <https://doi.org/10.1021/acs.nanolett.7b02222>
2. Aghaeimeibodi, S., Kim, J.-H., & Waks, E. (2017). Near-infrared Emission from Defect States in Few-layer Phosphorene. *arXiv Preprint arXiv:1706.10189*.
3. Yang, Z., Pelton, M., Fedin, I., Talapin, D. V., & Waks, E. (2017). A room temperature continuous-wave nanolaser using colloidal quantum wells. *Nature Communications*, 8. <https://doi.org/10.1038/s41467-017-00198-z>
4. Yang, Z., Pelton, M., Bodnarchuk, M. I., Kovalenko, M. V., & Waks, E. (2017). Spontaneous emission enhancement of colloidal perovskite nanocrystals by a photonic crystal cavity. *Applied Physics Letters*, 111, 221104. <https://doi.org/10.1063/1.5000248>
5. Coherent oscillations of driven rf SQUID metamaterials, Trepanier, M, Zhang, DM , Mukhanov, O, Koshelets, VP , Jung, P , Butz, S, Ott, Antonsen, TM, Ustinov, AV, Anlage, SM, PHYSICAL REVIEW E **95**, 050201, DOI: 10.1103/PhysRevE.95.050201 (2017).
6. Nonlinear wave chaos: statistics of second harmonic fields, Zhou, M, Ott, E, Antonsen, TM, Anlage, SM , CHAOS **27**, 103114, DOI: 10.1063/1.4986499 (2017).
7. Experimental Study of Quantum Graphs with Simple Microwave Networks: Non-Universal

Features, Fu, Z, Koch, T, Antonsen, TM, Ott, E, Anlage, SM, ACTA PHYSICA POLONICA A 132, 1655-1660, DOI: 10.12693/APhysPolA.132.1655 (2017).

8. Extraction of the Coupling Impedance in Overmoded Cavities, Bisrat Addissie , John Rodgers, and Thomas Antonsen, submitted to wave Motion (2018).

Conference Presentations

1. Science of Electronics in Extreme EM Environments: AFRL/AROSR Center Activities, T. M. Antonsen Jr., InnoWave 2017 Innovations in Wave Modeling, Nottingham UK 12-14 July 2017.

2. Innovative Ways to Understand Electromagnetic Properties of Complex Systems, S. Anlage, InnoWave 2017 Innovations in Wave Modeling, Nottingham UK 12-14 July 2017.

3. Features and Statistics of S-parameters in Nonlinear Wave Chaotic Systems, Min Zhou, Edward Ott, Thomas Antonsen, Steven Anlage, Abstract F47.00008, APS, March Meeting, Los Angeles CA, 2018.

4. Quantitative Statistical Analysis with Physics-based Surrogate Modeling for Wave Chaotic Systems, Lin, Shen; Peng, Zhen; Antonsen, Thomas, International Symposium of IEEE-Antennas-and-Propagation-Society / USNC/URSI National Radio Science Meeting Location: San Diego, CA Date: JUL 09-14, 2017

Awards/Honors

Waks became a Fellow of the APS

Antonsen was promoted to Distinguished University Professor

Ott was awarded the 2017 Lewis Fry Richardson Medal at the European Geosciences Union Meeting in Vienna, Austria, April, 2017., and gave the 2017 Jurgen Moser Award Lecture at the Society for Industrial and Applied Mathematics Meeting in Snowbird, Utah, May, 2017



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March 31, 2019

Annual Report on AFOSR/AFRL COE: Science of Electronics in Extreme Electromagnetic Environments

AFOSR Grant FA9550-15-1-0171

Period of Performance: 01 April 2018 – 31 March 2019

Program Managers: Jason Marshall (AFOSR), Timothy Clarke (AFRL)

Principal Investigator: Edl Schamiloglu

ABSTRACT

This AFOSR/AFRL-funded Center of Excellence is led by the University of New Mexico with the University of Maryland a partner. The Year 4 review was held in Albuquerque, NM at the Lobo Rainforest on Thursday, March 21, 2019. This report summarizes progress in Year 4.

University of New Mexico

The research tasks that are being investigated are listed below and brief updates are provided for each of them.

1. Microcontroller Investigations – Over the past reporting period, we have continued our research effort into understanding the impact of EEMI pulses on the software execution of instructions on an elementary microcontroller. We have identified that there is a relationship between the onset and width of the incident EEMI pulse, and the natural clock-cycle timing of the microcontroller. By studying this relationship further, we have shown that there are regimes where this ascribed relationship varies with the type of instruction being executed. We attribute these regimes to be software-instruction-cycle dependent. We have developed a probabilistic model using conditional probabilities to show the probability that a software script, comprising a series of different instruction cycles, will successfully execute /be affected due to EEMI injection. Experimentally, we have demonstrated this clock-cycle-to-EEMI relationship utilizing a FPGA board and an elementary microcontroller. In addition, we have also demonstrated that such effects can occur for RF injections as well. For future work, we are studying the dependence on register contents and whether it has an impact on this relationship. Finally, all our experimental results this year have focused on clock-side EEMI injection. While we attempted to also study power supply-side EEMI injection, our experimental attempts this year have not been successful due to the inherent capacitance of the PCB that houses the microcontroller. We propose to develop new low-capacitance PCBs in this coming year and continue our research on power-supply-side EEMI injection.

2. CMOS Injection Experiments – The focus of our research activity in the past year was to complete high frequency response models for RF injection in a single device as well as inverter gate which were fabricated through MOSIS in the first year of the COE effort. We successfully demonstrated that our frequency response models for various RF injection scenarios fit very well with experimental data. In addition to this effort, and to continue our investigation on other impacts of RF injection, we have also developed a new analytical model that predicts and characterizes the impact of Electromagnetic Interference (EMI) on the leakage current of CMOS integrated circuits. We found that the impact of RF injection on leakage current is the leakage current is very sensitive to the RF injection power. For example, a small (340 mV or 0.6 dBm) of peak noise can increase the leakage current by factor of 1000. This work was done in collaboration with Prof. Thomas Antonsen at UMD. We have also initiated time-domain experiments to characterize the signal integrity of CMOS inverter chains due to RF injection on the input and supply terminals. In addition, we are also investigating nonlinear characterization of NMOS/PMOS devices due to RF injection.

Future Work: Upon completion of our predictive modeling of linear high frequency response of CMOS devices, we will focus on experimental and mathematical modeling of non-linear high frequency responses. In addition, we will also look into other aspects of RF injections, including data transmission in inverter chain as well as frequency of ring oscillators that have already been fabricated in our test chips. We will utilize the data from our ongoing time-domain and nonlinear characterization experiments to develop high frequency models for CMOS upset.

3. First-Principles Mathematical Model for the Statistical Wave Analysis of Antennas and Electronics in Complicated Enclosures – The research work by UNM CEM group Year 4 is centralized around first-principles mathematical and statistical model for information transmission in complex multipath environments. The work extends our stochastic Green's function theory and algorithms from confined systems to complex scattering environments.

Electromagnetic field theory provides the fundamental physics of wireless communications. Over the past decades, electromagnetic theory has played a significant role in the design, performance assessment, and deployment planning of wireless devices and systems. Meanwhile, military and civilian communication and sensor systems are expected to take place in increasingly congested, contested, and competitive environments. Among many other scenarios, communication in wave-chaotic environments is a topic of both fundamental and practical importance. Applications include indoor radio channels, dense urban cells, transmission through diffusive random media, and disordered media, etc. A key challenge emerging is to understand the governing physics of propagation channels in wave-chaotic environments, which is critical for the characterization and assessment of information transmission.

Based on the stochastic wave models we investigated in Years 1-3, the Year 4 research presents a novel mathematical/statistical model analyzing the information transmission in multipath, chaotic environments. It rigorously characterizes the antenna mutual coupling, and resolves the transmitting, propagation, and receiving correlations in the wave propagation. Such model does not appear to be available in the literature. The work has diverse applications to wireless experimentation, time-reversal experiments, wavefront shaping, and sensing and targeting.

4. Investigate EEMI Effects on Optoelectronics through Multi-Physics Analysis – In Year 3, we studied the EEMI effect on laser diode electric characteristics with various injected RF currents. We proposed three models to predict the laser diode's current-voltage (I-V) curve for (1) small RF injection current, (2) large RF signal analysis, and (3) large RF injection currents at high frequencies. This year we continue to work on predictive models to analyze EEMI effect on Vertical-Cavity Surface-Emitting Lasers (VCSELs) behaviors.

Compared to conventional edge-emitting semiconductor lasers, VCSEL is a type of laser diode that its laser beam emits perpendicular from the top surface. There are several advantages of

using VCSELs. Edge-emitters cannot be tested until the end of the production process, while VCSELs can be tested at several stages throughout the process to check if it's function correctly. Because VCSELs emit from the top surface, it's suitable for monolithic one-dimensional and two-dimensional integration. VCSEL's applications include optical computer mice, fiber optic communications, laser printers, face identification units, smart glass, etc.

Typical VCSELs have relatively severe heating and so it has strong thermally dependent electrical and optical parameters. Beside considering the electric characteristics for laser diodes, we need to consider important effects including light versus current characteristics and its thermal dependence. The goal of the research is to investigate a compact optoelectronic predictive model to characterize VCSELs behavior with RF injections through multi-physics analysis.

VCSELs' electrical, optical and thermal characteristics are measured under various injected continuous wave (CW) currents at different DC bias. Measurement results show that the RF current at high power level significantly affects the cut-off voltage and I-V curve of the laser. From the measured current-light (I-L) curves, we observe the effect of carrier leakage at high power RF current injections, which shows by the optical output power roll over and then complete turn-off of the laser.

We have developed a rate-equation-based thermal predictive model to analyze the VCSEL behavior. The model introduced a temperature dependent offset current to account for carrier leakage in the active region.

- (1) It can be used to predict VCSELs' electrical, thermal and optical characteristics respect to different input current, voltage, light output and ambient temperature.
- (2) The predictive model can accurately model the light output power turns on, rolls over and turns off when injected current increases in the measurement data.
- (3) It also predicts significant reduction in the maximum output power and slope efficiency when the ambient temperature increases.

5. Photonic Interconnects and Future Devices – Effects of EEMI on single photon emitters (collaboration between Professor Balakrishnan's group and Professor Waks' group at UMD).

Prior to this year, we were able to successfully realize single photon emission from InAs nanostructures (quantum dots and quantum dashes) around telecom wavelengths of 1.3 and 1.55 μm . During this year, we focused on increasing the efficiency of transmission and control of photons by integrating the single photon sources with a photonic crystal and distributed Bragg reflectors (DBRs). This is a critical step towards fabricating practical quantum systems which in turn will lead the way to understanding the effects of EEMI on single photon emitters. Towards this goal, multiple quantum dot-based samples were grown using molecular beam epitaxy (MBE) at UNM. In order to be compatible with existing characterization equipment, the emission wavelength of the quantum dots was to be tuned to 900-1000 nm at 4 K. After exploring multiple options (submonolayer QDs, GaSb QDs, QDs on metamorphic buffers), we chose to grow InGaAs QDs due to the ease of tuning emission wavelength by changing the $\text{In}_x\text{Ga}_{1-x}\text{As}$ composition. The samples were then shipped to Prof. Waks' group at UMD for optical characterization and further processing. With these results, we intend to be able to fabricate on-demand single photon emitters and then study the effect of EEMI on these devices.

6. Research Framework for Uncertainty Quantification and Investigate the Origin of "Randomness" in EEMI Interaction with Electronic Devices and Software Processes –

We are continuing to develop analytic models to compute the stochastic signal propagation time delays through collections of CMOS inverters resulting from a stochastic power supply V_{dd} driving the inverter gates or resulting from a stochastic external electromagnetic disturbance

inducing voltages on those gates; and to compute as well the probability of failure, as a consequence of such gates' voltages, of any digital circuit employing such inverters. We have this year completed this development for a pair of CMOS inverters for the general case when the V_{dd} s on the two inverter gates are not necessarily (but may be) statistically independent and have completed a manuscript detailing this work for submission in Year 5. We have also further progressed on the extension of our models to any number of CMOS inverters. Also, in Year 5 we will continue that extension as well as begin to investigate stochastic behavior of CMOS logic gates formed via combinations of inverters, as a consequence of stochastic V_{dd} .

In a separate but related effort we have developed an analytic model to compute the stochastic drain-source current through a single MOSFET as a consequence of (possibly) simultaneously stochastic gate-source and drain-source voltages, and to compute as well for that MOSFET the probability of its functional failure as a consequence of such stochastic gate and drain voltages; we have completed a manuscript detailing this work for submission in Year 5.

7. Effects on Software Execution – During the last year we have focused on completing essential dynamics modules of the predicting hybrid automata model, that is, we have worked on formulating a tractable model for the (data) flip-flop gate. This model is derived from a study on the metastability of first order flip-flops and it is combined with concepts of artificial potential fields and window(ing) functions. This flip-flop model has been conceived under the premise of avoiding the “curse of dimensionality” present on the approaches studied about calculation of backwards/forwards reachable sets. We have the model implementation done in MATLAB but we are currently migrating it to T-Spice.

We have conducted the analysis of backwards reachability on the available (realistic) models for the inverter and NOR gate. We have found that the time propagation is very small (~ 3 orders of magnitude) compared with the period of the clock signal. This has motivated us to look for a different Hamilton-Jacobi equation that involves more phenomena. The original form of the Hamilton-Jacobi equation only has a convection term. We believe that the inclusion of a convection term could provide more insight. We are making the implementation on a common toy model to have comparison material.

We have also been identifying critical modules for each of the instructions of the 4-bit simulated processor to establish the regions inside the set of all the trajectory orbits that deters the instruction to be executed. We will call these collections of subset as $\mathcal{S}$. Now we have all the models that we need. Then, for some software execution path $\mathbf{P}$ and a $\mathbf{P}'$, we employ a particular element of $\mathcal{S}$ depending on the difference between $\mathbf{P}$ and a $\mathbf{P}'$, and execute the calculation of backward/forward reachable sets.

Personnel Supported

Faculty: Balakrishnan, Dietz, Heileman (U. Kentucky), Hemmady, Peng, Schamiloglu, Shao, and Zarkesh-Ha

PostDocs: S. Addamane

Students: S. Lin, E. Dohme, J. Chen, M. Vitovsky, L. Valbuena, N. Sule, Z. Abidi, S. Wang

UNM Publications – Journals

1. B. MacKie-Mason, Y. Shao, A. Greenwood and Z. Peng, “Supercomputing-Enabled First-Principles Analysis of Radio Wave Propagation in Urban Environments,” IEEE Trans. Antennas Propag., vol. 66, 6606 – 6617, 2018 (Special Issue on Radio Wave Propagation).

2. D. Dietz, "Stochastic Propagation Delay Through a CMOS Inverter as a Consequence of Stochastic Power Supply Voltage, Part I: Model Formulation," IEEE Trans. Electromag. Compat., vol. 61, 226-232, 2019.
3. D. Dietz, "Stochastic Propagation Delay Through a CMOS Inverter as a Consequence of Stochastic Power Supply Voltage, Part II: Modeling Examples," IEEE Trans. Electromag. Compat., vol. 61, 233-241, 2019.
4. S. Wang, Y. Shao, and Z. Peng, "A Parallel-in-Space-and-Time Method for Transient Electromagnetic Problems," IEEE Trans. Antennas Propag. (accepted and to appear in 2019).
5. M. Vitkovsky, T. Antonsen, S. Hemmady, "Progress in Developing Predictive Models for Erroneous Software Behavior of Embedded Digital Logic Due to Electromagnetic Interference," in preparation for IEEE Trans. Electromag. Compat. (2019).
6. D. Dietz, "Stochastic Propagation Delay Through a Pair of CMOS Inverters as a Consequence of Stochastic Power Supply Voltage, Part I: Model Formulation," in preparation for IEEE Trans. Electromag. Compat. (2019).
7. D. Dietz, "Stochastic Drain-Source Current through a MOSFET as a Consequence of Simultaneously Stochastic Gate-Source and Drain-Source Voltages," in preparation for IEEE Trans. Electromag. Compat. (2019).

UNM Publications – Conference Papers

1. S. Wang and Z. Peng, "High-Performance Surface Integral Equation Solvers Towards Extreme-Scale Electromagnetic Modeling and Simulation," 2018 International Applied Computational Electromagnetics Society (ACES) Symposium (Denver, CO, March 2018). (*Best Student Paper Award*)
2. S. Lin and Z. Peng, "A Novel Stochastic Integral Equation Method for Wireless Communication in Diffuse Multipath Environments," 2018 International Applied Computational Electromagnetics Society (ACES) Symposium (Denver, CO, March 2018). (*Best Student Paper Award Finalist*)
3. Z. Peng, S. Lin, E. Schamiloglu, and T. Antonsen, "A Stochastic Green's Function Method for Wave Propagation in Chaotic Environments," 12th European Conference on Antennas and Propagation (EUCAP 2018) (London, UK, April 2018). (*Invited contribution for Convened Session: Fundamental Challenges and Novel Methodologies in the Next-Generation Computational Electromagnetics*)
4. N. Sule, T. Powell, S. Hemmady, and P. Zarkesh-Ha, "Predicting the Tolerance of Extreme Electromagnetic Interference on MOSFETs," Proc. IEEE Computer Society Annual Symposium on VLSI (ISVLSI) (Hong Kong, China, July 08-11, 2018).
5. S. Lin and Z. Peng, "First-Principles Statistical Model of Communication Through Wave-Chaotic Environments," IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting (2018 IEEE AP-S/USNC-URSI) (Boston, MA, July 2018). (*Honorable Mention Award in Student Paper Competition*)
6. S. Wang and Z. Peng, "Breaking the Scaling Limit: A Parallel-in-Space-and-Time Method for Transient Electromagnetic Problems," IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting (2018 IEEE AP-S/USNC-URSI) (Boston, MA, July 2018).
7. O. Noakoasteen, S. Wang, and Z. Peng, "Emulation of Transient Electrodynamical Physics via Deep Neural Networks," IEEE International Symposium on Antennas and Propagation and

USNC-URSI National Radio Science Meeting (2018 IEEE AP-S/USNC-URSI) (Boston, MA, July 2018).

8. M. Vitkovsky, T. Antonsen, S. Hemmady, “Progress in Developing Predictive Models for Erroneous Software Behavior of Embedded Digital Logic Due to Electromagnetic Interference,” Proc. AMEREM 2018 (Santa Barbara, CA, August 27-31, 2018).

9. T. Powell, N. Sule, S. Hemmady, and P. Zarkesh-Ha, “Predictive Model for Extreme Electromagnetic Compatibility on CMOS Inverters,” IEEE International Symposium and Exhibition on Electromagnetic Compatibility (EMC Europe) (Amsterdam, Netherlands, August 27-30, 2018).

10. S. Lin, E. Dohme, and Z. Peng, “A Stochastic Green’s Function - Integral Equation Method for Communication in Diffusive Multipath Environments,” Proc. ICEAA 2018 (Cartagena des Indias, Colombia, September 10-14, 2018). (*ICEAA IEEE-APWC Best Paper Award*)

11. L. Valbuena, G.L. Heileman, S. Hemmady, and E. Schamiloglu, “Predicting Deviations in Software Execution Paths Due to EMI Injection via Reachable Sets and Random Delays,” Proc. ICEAA 2018 (Cartagena des Indias, Colombia, September 10-14, 2018).

12. Z. Abedi, S. Hemmady, T. Antonsen, E. Schamiloglu, and P. Zarkesh-Ha, “Electromagnetic Compatibility in Leakage Current of CMOS Integrated Circuits,” submitted to the IEEE International Symposium and Exhibition on Electromagnetic Compatibility (EMC Europe), August 2019.

UNM Publications – Other Presentations

1. M. Vitkovsky, T. Antonsen, S. Hemmady, “Predictive Models for Erroneous Software Behavior of Embedded Digital Logic Due to Electromagnetic Interference,” ONR-OSPRES Review (Kansas City, MO, 2018).

2. Z. Abedi, S. Hemmady, T. Antonsen, E. Schamiloglu, and P. Zarkesh-Ha, “Progress in RF injection experiments on CMOS Integrated Circuits,” ONR-OSPRES Review (Kansas City, MO, 2018).

UNM Publications – Technical Reports

1. D. Dietz, *Quantifying Propagating Uncertainties in Computer Code Chains*, AFRL-RD-PS-TN-2018-0002, Air Force Research Laboratory, Directed Energy Directorate, Kirtland Air Force Base, NM 87117-5776, 101 pages, 24 May 2018.

Awards and Recognition

- 2018 “A Stochastic Green’s Function - Integral Equation Method for Communication in Diffusive Multipath Environments,” received **Best Paper Award** at International Conference on Electromagnetics in Advanced Applications (ICEAA) and IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC) (Shen Lin, Evelyn Dohme and Zhen Peng).
- 2018, **1st place in the student paper competition**, “A Space-Time Domain Decomposition Method for High-fidelity Electromagnetic Simulation,” 2018 International Applied Computational Electromagnetics Society (ACES) Symposium (Shu Wang and Zhen Peng).

- 2018 “First-Principles Statistical Model of Communication Through Wave-Chaotic Environments” received **honorable mention award in Student Paper Competition** at 2018 IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting (Shen Lin and Zhen Peng).
- 2018 27th Conference on Electrical Performance of Electronic Packaging and System **Best Student Paper Finalist**, “Parallel-in-Space-Time Analysis of Electromagnetic Interference in Electronics” (Shu Wang and Zhen Peng).
- 2018 “Quantitative Statistical Analysis for Wave Propagation in Chaotic Environments: A Stochastic Green’s Function - Integral Equation Method” **Student Paper Competition Finalist** in 2nd International Union of Radio Science (URSI) Atlantic Radio Science Meeting (Shen Lin, Zhen Peng and Thomas Antonsen).
- 2018: Edl Schamiloglu receives UNM.STC Creativity Award for patent award.
- 2019: Edl Schamiloglu receives UNM.STC Creativity Award for patent award.

UNM Students Who Graduated

- None

University of Maryland

8. Photonic Interconnects and Future Devices

Photonic interconnects using low dimensional materials (Waks group): Coupling single photon emitters to surface plasmons provides a versatile ground for on chip quantum photonics. However, achieving good coupling efficiency requires precise alignment of both the position and dipole orientation of the emitter relative to the plasmonic mode. We demonstrate coupling of single emitters in the 2-D semiconductor, WSe₂ self-aligned with propagating surface plasmon polaritons in silver-air-silver, metal-insulator-metal waveguides. The waveguide produces strain-induced defects in the monolayer which are close to the surface plasmon mode with favorable dipole orientations for optimal coupling. We measure an average enhancement in the rate of spontaneous emission by a factor of 1.89 for coupling the single defects to the plasmonic waveguide. This architecture provides an efficient way of coupling single photon emitters to propagating plasmons, which is an important step towards realizing active plasmonic circuits on chip.

Plasmonic nanostructures provide an efficient way to control and enhance the radiative properties of quantum emitters. Coupling these structures to single defects in two-dimensional materials provides a particularly promising material platform to study emitter–plasmon interactions because these emitters are not embedded in a surrounding dielectric. They can therefore approach a near-field plasmonic mode to nanoscale distances, potentially enabling strong light–matter interactions. However, this coupling requires precise alignment of the emitters to the plasmonic mode of the structures, which is particularly difficult to achieve in a site-controlled structure. We present a technique to generate quantum emitters in two-dimensional tungsten diselenide coupled to site-controlled plasmonic nanopillars. The plasmonic nanopillar induces strains in the two-dimensional material, which generate quantum emitters near the high-field region of the plasmonic mode. The electric field of the nanopillar mode is nearly parallel to the two-dimensional material and is therefore in the correct orientation to couple to the emitters. We

demonstrate both an enhanced spontaneous emission rate and increased brightness of emitters coupled to the nanopillars. This approach may enable bright site-controlled nonclassical light sources for applications in quantum communication and optical quantum computing.

9. Combining the Finite Element Method (FEM) and the Random Coupling Model (RCM) for Quasi 2D Cavities

The Random Coupling Model (RCM) is a method for making statistical predictions of induced voltages and currents for objects and components contained in complicated (ray-chaotic) over-moded enclosures and subjected to RF fields. On the other hand, the Finite Element Method (FEM) is a widely used computational method that solves the wave equations numerically. We showed a combination of the two methods where we considered an aperture backed by a wave chaotic cavity. The FEM gridding is usually required for the entire geometry. But in this work, we showed that one can grid the region close to the aperture while rest of the cavity can be modeled by the RCM. We modeled a quasi 2D cavity with an aperture. This was done in the commercial software HFSS. Perfectly Matched Layers (PMLs) were placed on one side of the aperture, while on the other side the boundary was treated as a port and the fields were represented in modes.

We determined numerically the power through the aperture without simulating the entire cavity, only the aperture. The influence of the cavity was described by the RCM. In particular, the scattering matrix relating the modes on the cavity side of the aperture were simulated by the RCM. We excited the cavity side of the aperture with each of the 25 modes and recorded the far field patterns at the PML. We then used these profiles and the principle of reciprocity to find the current on the port for an incident plane wave from outside the cavity and found the admittance matrix on the aperture side of the port. This allowed us to calculate the power coupled into the cavity for various types of cavities.

10. Statistics of Fields in Nonlinear Wave Chaotic Systems

Nonlinearity in electromagnetic systems is manifested as harmonic generation and amplitude dependent responses. We studied the statistics of harmonics excited by a source in a nonlinear wave system by adding an active frequency multiplier to the 1/4-cavity microwave billiard. To create amplitude dependent responses, we introduced different sources of nonlinearity into the cavity. Observing nonlinearity usually requires that we be in the high amplitude regime, hence a high power vector network analyzer (VNA) is implemented to measure the S- parameters up to $\sim +40$ dBm.

We showed the results of the nonlinear S- parameters in two nonlinear systems. One system is a diode-loaded 1/4-bowtie microwave cavity where the diode acts as a point nonlinearity in a wave chaotic system. By attaching the diode to the excitation port, we observed the statistics of the impedance change substantially with the excitation power. We also found that the short orbits between the port and a nearby wall were strongly modified. Other unexpected changes were also observed. We found that many of these changes were due to the fact that the admittance of the diode changes with the excitation power. The nonlinear diode competes with the cavity admittance, substantially altering the response of the system. By implementing the lossy port model extension of the RCM, the results were well explained by the changing radiation efficiency of the diode-loaded port. This configuration may have potential application in protecting electronic circuits from EMI.

Another source of nonlinearity in microwave billiards is the nonlinear surface impedance $Z = R + iX$ of a material on the interior surface of the cavity. In particular we considered nonlinear superconducting materials coating the walls of a cavity. A cut-circle quasi-2D microwave cavity, which is made of Pb-plated copper, can present nonlinear boundary conditions at temperatures T

$< T_C$, where $T_C = 7.2$ K. We have previously characterized the linear response properties of this extremely low loss system ($\alpha = 0.02$) at 6.6 K using an in-situ broadband cryogenic calibration technique. By putting the cavity in a dilution refrigerator, the base temperature reached 500 mK, allowing us to enter a strongly nonlinear regime. The power dependent S-parameters showed that the cavity has a mainly resistive nonlinear response. The quality factor, Q , of many of the modes decreased as input power increased.

Applying the RCM, we found that the impedance statistics also changed with power. The results of this analysis may give insight into the statistical properties of generic nonlinear systems. Furthermore, as a complement to the nonlinear resistive superconducting billiard, we also proposed an experiment on a TiN-coated Si wafer cut-circle billiard, where the TiN superconducting films are reported to have a dominant nonlinear reactive response.

11. Wave Chaotic Properties of Cascaded Complex Enclosures

The RCM predicts the statistical properties of waves inside a cavity by using Random Matrix Theory and also incorporating system specific features, which can be determined by structure dimensions and material properties. Previously, studies of 2-port single cavity experiments have been conducted. Statistical properties, such as the probability density function of the impedance matrix elements were in good agreement with RCM predictions.

Since arranging full sized cavities ($\sim 1\text{m}^3$ per cavity) is difficult in regular-sized rooms, we used the scaling relationship from Maxwell's equations to obtain a scaled-down-in-size cavity system, while preserving the loss parameter of the full-scale cavity. Experiments showed that the statistics of the single cavity two-port impedance matrix elements for full scale and scaled enclosures that have the same loss parameter matched with each other.

We next studied the transmission properties for a multi-cavity cascade system. The cavities were connected by circular or rectangular shaped apertures. We studied the trans-impedance and the input impedance of the cavity system. To model these quantities, we used the RCM to characterize the single cavities within the cavity-cascade chain. To establish the theory for connected cavities, we adopted the theory proposed by Gradoni et al., that characterizes an aperture by an admittance matrix based on expansion of fields in modes of the aperture cross section. This approach is still being tested, and results are being compared with those of other theories.

12. Assessing the Effects of RF Interference on Maintenance of Coherence of a Group of Drones

The Kuramoto model, originally motivated by the dynamics of many interacting oscillators, has been used and generalized for a wide range of applications involving the collective behavior of large heterogeneous groups of dynamical units whose states are characterized by a scalar angle variable. One such application in which we are interested is the alignment of velocity vectors among members of a drone swarm. Despite being commonly used for this purpose, the Kuramoto model can only describe swarms in 2 dimensions, and hence the results obtained do not apply to the often-relevant situation of swarms in 3 dimensions. Partly based on this motivation, we studied the Kuramoto model generalized to D dimensions, focusing on the 3-dimensional case. We show that in 3 dimensions, as well as for all odd dimensionality, the generalized Kuramoto model for heterogeneous units has dynamics that are remarkably different from the dynamics in 2 dimensions. In particular, for odd D the transition of the time asymptotic equilibrium state to coherence occurs discontinuously as the coupling constant K is increased through zero, as opposed to the $D=2$ case (and, as we will show, also the case of even D) for which the transition to coherence occurs as K increases through a positive critical value K_c . In addition, we have shown that the effect on our model of interfering RF noise is to lower K , and, based on the previous result, this might be expected to have a more dramatic effect on two-dimensional swarm

coherence as compared with three-dimensional coherence.

13. Graph Treatment of Electromagnetic Topology

The problem of understanding how electromagnetic waves couple to and propagate through complex structures such as buildings, aircraft, and ships is very challenging. A number of approaches have treated the problem in terms of scalar energy flow through interconnected compartments. These methods ignore wave effects (e.g. interference), and therefore provide only a mean-field description of energy distribution. We want to extend these approaches by including wave propagation effects and interference to understand deviations from the mean.

Quantum graphs provide a setting to formulate a more complete model of energy propagation in complex structures. Such graphs are a natural outcome of the electromagnetic topology approach. There is a hope that the statistical properties of wave and energy distribution on these graphs can be understood using an approach based on the RCM.

We employed an experimental setup consisting of a microwave coaxial cable network. The networks, which were large compared with the wavelength of excitations, were constructed from coaxial cables connected by T junctions. The distributions of impedance values from an ensemble of tetrahedral networks were measured. The RCM was applied in an attempt to uncover the universal statistical properties of the experimental data obtained from this system. Deviations from RCM predictions were observed in that the statistics of diagonal and off-diagonal impedance elements were different. It is argued that because of the small size of the networks used here there will be deviation from random matrix predictions.

We have extended these simple microwave networks by replacing the T-junctions with quasi-two-dimensional microwave cavities that display wave chaotic properties. This models realistic scenarios in which overmoded enclosures are interconnected through multiple ports, including cables, apertures and waveguides (ducts). We will next relate the results of these experiments to the general question of how to estimate induced voltage statistics on electronics deep inside a network of complex enclosures.

14. Nanoscale Device Level Modeling of EMI Induced Vulnerability

Vulnerability of modern nanoscale and microscale electronics to EMI is being investigated. The investigation has focused on the key elements of Silicon CMOS device vulnerability. The most common electronic devices are metal oxide silicon field effect transistors (MOSFETs), which represent approximately 99% of the semiconductor transistors in operation today. Most integrated circuits are composed of MOSFETs. Our work focus entails studying and quantifying the vulnerability of MOSFETs to EMI, with respect to both soft and hard error. Soft errors typically cause devices to malfunction, which in turn give rise to circuit errors and system crashes. These errors are not permanent and typically require a system reboot. Hard errors are permanent and occur when nanoscale devices are permanently damaged causing circuit failure. We have been focusing our attention on three likely mechanisms of failure that can result due to EMI induced voltage spikes that can propagate as unintended input onto MOSFET terminals. Two of these mechanisms are oxide dielectric breakdown and thermal breakdown, which are typically permanent effects. We are also looking at EMI induced internal voltage spikes as another mechanism which lead to soft error, especially the snap-back and latch-up phenomena. Our earlier work on these mechanisms was largely theoretical where we developed distributed and lumped device and circuit models to help explain the phenomena. At the device level, we solve the Semiconductor Partial Differential Governing Equations to quantify what occurs internally to the MOSFET device if an EMI-induced voltage spike occurs on one of its terminals. The spike will generate a large internal electric field, which can cause impact ionization and even avalanche multiplication giving rise to very large internal current densities, and therefore unstable internal

voltage levels, and Joule heating. We have developed methodologies to model all of these phenomena with the goal of not only explaining the events but have predictive capabilities as well.

To help verify and improve our model development, as well as to gain additional insight, we have devoted considerable time to developing experiments to induce these device effects on the laboratory bench. Specifically, we have designed and fabricated numerous silicon MOS devices using the nanofabrication cleanroom facility at the University of Maryland. Since we made the devices ourselves, we have detailed knowledge of the internal structure, which removes guesswork from the input of our simulations. In addition, since we have the fabrication capability, we can design new devices of different geometry to calibrate the EMI-induced effects. Using our bench setup for testing the effects of voltage spikes on the MOSFET devices that we fabricated, we have been focusing on hard error due to dielectric breakdown where data indicates that oxide fields of 8MV/cm are required.

In the future, more data will be taken, and the mechanisms of failure resulting from large terminal voltage spike application will be simulated to verify models with experimental data. Device structures will be varied to help determine how EMI vulnerability is affected by MOSFET geometry and feature size.

Personnel Supported

Faculty: Antonsen, Ott, Anlage, Waks, Goldsman

Students: T. Cai, S. Aghaeimeibodi, Z. Luo, F. Adnan, C. Darmody, Z. Cui, M. Zhou, S. Ma, S. Chandra, T. Ghutishvili, R. Chalabi

Publications

1. M. Zhou, E. Ott, T.M. Antonsen, Jr., and S.M. Anlage, "Scattering Statistics in Nonlinear Wave Chaotic Systems," arXiv:1812.06789.
2. B. Xiao, T.M. Antonsen, E. Ott, Z.B. Drikas, J. Gil Gil, and S.M. Anlage, "Revealing Underlying Universal Wave Fluctuations in a Scaled Ray-Chaotic Cavity with Remote Injection," Phys. Rev. E, vol. 97, 062220, 2018.
3. B. Addissie, J. Rodgers, and T. Antonsen, "Extraction of the Coupling Impedance in Overmoded Cavities," Wave Motion (in press).
4. S. Chandra, M. Girvan, and E. Ott "Continuous versus Discontinuous Transitions in the D-Dimensional Generalized Kuramoto Model: Odd D is Different," Phys. Rev. X, vol. 9, 011002, 2019 (Featured in Physics - Extending the Kuramoto Model to Arbitrary Dimensions, January 3rd, 2019).
5. S. Chandra and E. Ott, "Observing Microscopic Transitions from Macroscopic Bursts: Instability-Mediated Resetting in the Incoherent Regime of the D-Dimensional Generalized Kuramoto Model", accepted for publication in Chaos (arXiv: 1902.05159).
6. S. Chandra, M. Girvan, and E. Ott "Complexity Reduction Ansatz for Systems of Interacting Orientable Agents: Beyond the Kuramoto Model," submitted to Chaos and awaiting referee review (arXiv: 1809.00783).
7. S. Dutta, T. Cai, M.A. Buyukkaya, S. Barik, S. Aghaeimeibodi, and E. Waks, "Coupling Quantum Emitters in WSe₂ Monolayers to a Metal-Insulator-Metal Waveguide," Appl. Phys. Lett., vol. 113, 191105, 2018.

8. T. Cai, J.H. Kim, Z. Yang, S. Dutta, S. Aghaeimeibodi, and E. Waks, "Radiative Enhancement of Single Quantum Emitters in WSe₂ Monolayers Using Site-Controlled Metallic Nanopillars," *ACS Photonics*, vol. 5, 2018.
9. M. Vitkovsky, T. Antonsen, S. Hemmady, "Progress in Developing Predictive Models for Erroneous Software Behavior of Embedded Digital Logic Due to Electromagnetic Interference," in preparation for *IEEE Trans. Electromag. Compat.* (2019).

Conference Papers

1. M. Zhou, B. Xiao, E. Ott, T. Antonsen, and S. M. Anlage, "The Generalization of Wave Chaos to Nonlinear Systems," 2018 2nd URSI Atlantic Radio Science Meeting (AT-RASC), Meloneras, 2018, pp. 1-1. doi: 10.23919/URSI-AT-RASC.2018.8471640.
2. S. Ma, "Wave Chaotic Properties of Cascaded Complex Enclosures," *Proc. AMEREM 2018* (Santa Barbara, CA, August 27-31, 2018).
3. M. Zhou, "Features and Statistics of S-parameters in Nonlinear Wave Chaotic Systems," *APS March Meeting* (Los Angeles, CA, March 5-9, 2018).
4. M. Zhou, "Statistics of Fields in Nonlinear Wave Chaotic Systems," *Proc. AMEREM 2018* (Santa Barbara, CA, August 27-31, 2018). (Best Student Paper Award)
5. L. Chen, E. Ott, T. Antonsen, and S. Anlage, "Quantum Graph Treatment of Electromagnetic Topology," *Proc. AMEREM 2018* (Santa Barbara, CA, August 27-31, 2018).
6. M. Vitkovsky, T. Antonsen, S. Hemmady, "Progress in Developing Predictive Models for Erroneous Software Behavior of Embedded Digital Logic Due to Electromagnetic Interference," *Proc. AMEREM 2018* (Santa Barbara, CA, August 27-31, 2018).
7. S. Anlage, "Wave Chaotic Properties of Cascaded Complex Enclosures," *Proc. AMEREM 2018* (Santa Barbara, CA, August 27-31, 2018).
8. S. Anlage, "Topologically Protected Photonic Modes in Composite Quantum Hall/Quantum Spin Hall Waveguides," 49th Winter Colloquium on the Physics of Quantum Electronics (Snowbird, UT, 8 January 2019).
9. S. Anlage, "Unique Applications of Time-Reversed Electromagnetic Waves," 2018 IEEE International Symposium on Electromagnetic Compatibility, Signal and Power Integrity (Long Beach, CA, 30 July 2018).
10. S. Anlage, "Demonstration of a Bi-Anisotropic Meta-Waveguide Quantum Hall Analog," IEEE Photonics Society Summer Topical Meeting on Non-Hermitian and Topological Photonics (Waikoloa, HI, 10 July 2018).
11. S. Chandra, "Generalized Kuramoto Model in D dimensions: Discontinuous Transitions and Implications for Swarms," *Dynamics Days 2018* (Denver, CO, January 4-6, 2018).

Other Presentations

1. S. Anlage, "When Waves Meet Chaos: A Clash of Paradigms," Physics Colloquium, Temple University, Philadelphia, PA, USA, 14 January 2019.
2. S. Anlage, "When Waves Meet Chaos: A Clash of Paradigms," Physics Colloquium, Wesleyan University, Middletown, CT, USA, 29 November 2018.
3. S. Anlage, "Long Range Wireless Power Transfer – Some New Ideas," NASA Goddard

Spaceflight Center Engineering Colloquium (Greenbelt, MD, 16 April 2018).

Awards/Honors

Min Zhou: **Best Student Paper Award** (BSPA) at the AMEREM Conference, Santa Barbara, CA, Aug 27-31, 2018.



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Annual Report on AFOSR/AFRL COE: Science of Electronics in Extreme Electromagnetic Environments

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Period of Performance: 01 April 2019 – 31 March 2020

Program Managers: Arje Nachman (AFOSR), Timothy Clarke (AFRL)

Principal Investigator: Edl Schamiloglu

ABSTRACT

This AFOSR/AFRL-funded Center of Excellence is led by the University of New Mexico with the University of Maryland a partner. This report summarizes progress in Year 5. Dr. Pat Roach is organizing a virtual review for AFOSR in June.

University of New Mexico

The research tasks that are being investigated are listed below and brief updates are provided for each of them.

1. Microcontroller Investigations – Over the past reporting period, we have continued our research effort into understanding the impact of EEMI pulses on the software execution of instructions on an elementary microcontroller. In the last year we demonstrated a relationship between the onset and width of the incident EEMI pulse with respect to the natural clock-cycle timing of the microcontroller and developed a probabilistic model using conditional probabilities to show the probability that a software script, comprising a series of different instruction cycles, will successfully execute/be affected due to EEMI injection. Building up on this research accomplishments, this year, we have demonstrated the impact of machine pipelining architectures and augmented our probabilistic model to include pipelined architectures, which is more relevant to microcontroller architectures today. In addition, we showed a correlation in the susceptibility response of different types of instructions that belong to specific class of instruction cycles (memory, ALU, data operations) and its impact on creating reproducible and predictable outcomes in register contents.

For future work, leveraging our results in reproducibly and predictably altering register contents, we are now studying how EEMI glitching can affect random number generators with its implication for predictably changing the “randomness” of random generators, thereby promising exciting avenues in leveraging EEMI to affect/compromise cyber security software routines.

2. CMOS Injection Experiments – The focus of our research activity in the past year was to develop a predictive model for RF injection in data transmission digital systems. The new model predicts and characterizes the impact of Electromagnetic Interference (EMI) on the quality of data transmission, namely eye-diagram parameters. We found that the impact of RF injection on eye height depends primarily on the level of injected noise and its frequency, whereas the width of the eye depends not only on the level of injected noise and its frequency, but it also depends heavily on the bit rate of the data transmission. We also developed a preliminary model for bit-error-rate (BER) as a function of the eye-diagram parameters.

In support of our CMOS injection investigations we have developed an analytical model for the probability of occurrence of out-of-bounds input voltage—and consequent output voltage error—in a CMOS inverter making an output transition at some random instant during the presence of n greater than or equal to 1 complete cycles of a sinusoidal additional voltage induced on the inverter input (nMOSFET and pMOSFET gates) by an external sinusoidal electromagnetic disturbance. This represents well the practical case of such an EMI disturbance occurring randomly in time with respect to a digital circuit performing software execution.

Future Work: Unfortunately, our experimental measurements to verify our predictive models for data transmission (eye diagram) was interrupted due to CoVID-19 pandemic outbreak. Our immediate next step is to continue our experiments to validate our newly developed predictive models for the eye-diagram and BER.

3. First-Principles Mathematical Model for the Statistical Wave Analysis of Antennas and Electronics in Complicated Enclosures – The research work by UNM CEM group Year 5 is centralized around first-principles mathematical and statistical model for information transmission in complex multipath environments. The work extends our stochastic Green's function theory and algorithms from confined systems to complex scattering environments. In this work, we exploit scientific advances in chaotic dynamics and chaos theory for the statistical analysis of information transmission. The emphasis is placed on spatial/spectral variance and correlation in the ray-chaotic propagation. The results lay down the theoretical foundation for analyzing channel capacity, coherence bandwidth, and power delay spread in indoor wireless communication. The theoretical research is validated through representative experiments.

We also investigated a space-time building block methodology for efficient time-domain analysis of multi-scale, locally periodic structures. By leveraging the principles of linear superposition and space-time causality in wave physics, the 4D simulation domain is represented by a few space-time building blocks, which are constructed upon 3D spatial unit cell and 1D time unit. The work results in novel time-evolution schemes, which exhibit high-order accuracy and achieve concurrency and parallelism in both spatial and temporal dimensions. The outcomes lead to significantly reduced computational resources. The capability and benefit of proposed algorithms are illustrated through representative applications.

4. Investigate EEMI Effects on Optoelectronics through Multi-Physics Analysis – Redirect Effort

Note: With the departure of Yang Shao to the University of Illinois, this task has been taken over by Drs. Sameer Hemmady and Payman Zarkesh-Ha.

Project description: Although optical devices seem to be resilient to electromagnetic interference (EMI), electro-optical devices that are the interface between electrical and optical systems (e.g. optical modulators) can be vulnerable to EMI. The focus of this research work is to analyze the impact of EMI on a commercial optical modulator and then develop an extended predictive model to characterize the impact of EMI on the behavior of any generic optical modulator. The model will be verified by experimental setup and measured data in an electro-optical link under RF

injection. This project has just started and is expected to produce the predictive model verified by experimental data in the next reporting period.

5. Photonic Interconnects and Future Devices – Effects of EEMI on single photon emitters (collaboration between Professor Balakrishnan's group and Professor Waks' group at UMD).

The focus of the effort this year was to develop quantum dots at specific wavelengths that would suit the characterization equipment at the University of Maryland. Specifically, the effort was focused on achieving quantum dots that emitted in the detector and laser specific wavelength and to do this an offset in the emission wavelength had to be achieved at room temperature since the measurements are done at cryogenic temperatures. An attempt was made achieving both short wavelength quantum dots which emitted below one $1\ \mu\text{m}$ and long wavelength quantum dots which emitted about 1300 nm. These are both non-trivial issues since InAs quantum dots typically emit in the 1100-1300 nm wavelength range and to achieve emission outside of this range requires significant epitaxial optimization. While achieving the shorter wavelength quantum dot was more challenging, the longer wavelength dots were successfully demonstrated, and samples were sent to the University of Maryland for processing and device demonstration. In the coming year we expect to grow a whole ensemble of such quantum samples with additional complexity added to the epitaxial process including features such as distributed drag reflectors.

6. Research Framework for Uncertainty Quantification and Investigate the Origin of "Randomness" in EEMI Interaction with Electronic Devices and Software Processes –

We have continued to develop and refine an analytic model to compute the stochastic drain-source current through a single MOSFET as a consequence of (possibly) simultaneously stochastic gate-source and drain-source voltages, and to compute as well for that MOSFET the probability of its functional failure as a consequence of such stochastic gate and drain voltages.

7. Effects on Software Execution – During the last year we have made advances in two areas: i) Developing a Hamilton-Jacobi equation for evaluating the effects of EEMI – in this work, we developed a theoretical framework for modeling the empirically observed cascading of software failures on a complicated computing system exposed to EEMI. Our approach is to treat the temporal evolution of the electromagnetic coupling and the resultant cascading series of electromagnetic-induced faults as the "flow" in a dynamic fluid-mechanical system and thereby utilize aspects of the Navier Stokes and Hamilton-Jacobi equations to predict the rate of this flow. Therefore, inspired by the concepts of fluid dynamics, we include a diffusion term in the Hamilton-Jacobi-Isaacs (HJI) equation. We have considered two approaches. In one we apply a Taylor expansion to the optimality principle and consider additional terms; in the other scenario, we simply add a diffusion term in the form of a Laplacian applied to the cost function $H(x, \dots)$ and some constant c , as it is present in the Navier-Stokes equation for incompressible flow. We found numerical comparisons for both approaches with respect to the original HJI equation where the dynamical vector field corresponds to analytical models of a NOR logic gate. This model is a second-order differential equation that describes the behavior of the gate that incorporates a new term accounting for EEMI injection. ii) Developing a simplified flip-flop gate model for EEMI injection – we developed a second order dynamical system to represent the behavior of a D flip-flop. We employed windowing functions and vector fields to replicate a characteristic found in earlier work, which resorts to switching. The model also takes into account metastable behavior, which can be exploited when studying software execution faults due to an undefined logical state. We conceived the noise injection to be additive noise targeting the transition between the stable equilibrium points. However, the model is flexible, and many parameters can be changed to alter its behavior. We are in the process of acquiring empirical data to validate this work.

Personnel Supported

Faculty: Balakrishnan, Dietz, Heileman (U. Arizona), Hemmady, Peng (U. Illinois), Schamiloglu, Shao, and Zarkesh-Ha

PostDocs: S. Addamane

Students: S. Lin, E. Dohme, J. Chen, M. Vitovsky, L. Valbuena, N. Sule, Z. Abidi, S. Wang

UNM Publications – Journals

1. S. Lin, Z. Peng and T. Antonsen, “A Stochastic Green’s Function for Solution of Wave Propagation in Wave-Chaotic Environments,” IEEE Trans. Antennas Propag., early access, DOI: 10.1109/TAP.2019.2963568.
2. S. Wang, Y. Shao and Z. Peng, “A Parallel-in-Space-and-Time Method for Transient Electromagnetic Problems,” IEEE Trans. Antennas Propag., vol. 67, no. 6, pp. 3961-3973, June 2019.
3. N.H. Sule, Z. Abedi, E. Schamiloglu, Fellow, S. Hemmady, and P. Zarkesh-Ha, “Predictive Modeling of Non-Persistent Effects in MOSFET Response under Large Signal Gate Noise Injection,” IEEE Trans. Electromag. Compat. (accepted and to appear 2020).
4. R. Bilalic, D. Guillet, M. Landavazo, M. Martinez-Ramon, S. Hemmady, and E. Schamiloglu, “A Novel Application of Machine Learning Methods to Model Microcontroller Upset due to Intentional Electromagnetic Interference (IEMI),” submitted to IEEE Trans. Electromag. Compat. (2020).
5. J.M. Chen, S. Portillo, G. Heileman, G. Hadi, R. Bilalic, M. Martinez-Ramon, S. Hemmady, and E. Schamiloglu, “Time-Varying Radiation Impedance of Microcontrollers and its Dependence on Software Instruction,” submitted to IEEE Trans. Electromag. Compat. (2020).
6. D. Dietz, “Stochastic Drain Current Through a MOSFET as a Consequence of Simultaneously Stochastic Gate and Drain Voltages—Part I: Model Formulation,” submitted to IEEE Trans. Electromag. Compat. (2020).
7. D. Dietz, “Probability of Output Voltage Error in a CMOS Inverter Undergoing Stochastic State Transition During the Presence of an Extraneous Input Voltage,” submitted to IEEE Trans. Electromag. Compat. (2020).
8. H. Ahmed and V. Babicheva, “Nanostructured Tungsten Disulfide WS₂ as Mie Scatterers and Nanoantennas,” MRS Advances, 1-8. doi:10.1557/adv.2020.173.

UNM Publications – Conference Papers

1. S. Wang and Z. Peng, “A Novel Space-Time Building Block Methodology for Transient Electromagnetic Analysis,” 28th Conference on Electrical Performance of Electronic Packaging and Systems, Montreal, Canada, October 2019 (*Best Paper Award*).
2. S. Lin, Z. Peng, E. Schamiloglu, Z.B. Drikas, and T. Antonsen, “A Novel Statistical Model for the Electromagnetic Coupling to Electronics inside Enclosures,” 2019 IEEE International Symposium on Electromagnetic Compatibility, Signal & Power Integrity, New Orleans, Louisiana, USA, July 2019 (*IEEE EMC Symposium Best Paper Award*).
3. S. Lin and Z. Peng, “Physics-Oriented Statistical Analysis of Information Transmission in Wave-Chaotic Environments,” IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting (2019 IEEE AP-S/USNC-URSI), Atlanta, Georgia, USA, July 2019 (*Honorable Mention Award in Student Paper Competition*).
4. O. Noakoasteen, S. Wang, and Z. Peng, “Physics-Informed Deep Neural Networks for

Transient Electromagnetic Analysis,” 2019 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization, Boston, USA, May 2019 (*3rd place in Best Student Paper Competition*).

5. S. Wang, B. Mackie-Mason, and Z. Peng, “Platform-Aware In-Situ Antenna and Metamaterial Analysis and Design,” 2019 International Applied Computational Electromagnetics Society (ACES) Symposium, Miami, Florida, USA, April 2019 (*Best Student Paper Award*).

6. Z. Abedi, S. Hemmady, T. Antonsen, E. Schamiloglu, and P. Zarkesh-Ha, “Electromagnetic Compatibility in Leakage Current of CMOS Integrated Circuits,” Proceedings 2019 International Symposium on Electromagnetic Compatibility (EMC Europe 2019) (Barcelona, Spain, September 2-6, 2019), 765- 768.

7. L. Valbuena, G.L. Heileman, S. Hemmady, and E. Schamiloglu, “Simplified Flip-Flop Gate Model for EEMI Injection,” Proceedings ICEAA 2019 (Granada, Spain, September 09-13, 2019), 845-850.

8. L. Valbuena, G.L. Heileman, S. Hemmady, and E. Schamiloglu, “Diffusion Term in a Hamilton-Jacobi Equation to Evaluate EEMI Propagation in a Computing System,” Proceedings ICEAA 2019 (Granada, Spain, September 09-13, 2019), 851-856.

9. M. Vitkovsky, T.M. Antonsen, Jr., E. Schamiloglu, and S. Hemmady, “Predictive Modeling of Erroneous Software Behavior in Embedded Digital Systems Due to Extreme Electromagnetic Interference,” Proceedings ICEAA 2019 (Granada, Spain, September 09-13, 2019), 1304-1307.

10. H. Ahmed and V.E. Babicheva, “Resonant and Scattering Properties of Tungsten Disulfide WS₂ Nanoantennas,” Proc. SPIE 11289, Photonic and Phononic Properties of Engineered Nanostructures X, 112891R (26 February 2020).

Awards and Recognition

- 2019 “Physics-Oriented Statistical Analysis of Information Transmission in Wave-Chaotic Environments” received honorable mention award at 2019 IEEE AP-S Student Paper Competition (Shen Lin and Zhen Peng).
- 2019 3rd place in the student paper competition, “Physics-Informed Deep Neural Networks for Transient Electromagnetic Analysis,” 2019 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization, Boston, USA, May 29-31, 2019 (Oameed Noakoasteen, Shu Wang, and Zhen Peng).
- 2019 1st place in the student paper competition – “Platform-Aware In-situ Antenna and Material Analysis and Design,” 2019 International Applied Computational Electromagnetics Society (ACES) Symposium, Miami, Florida, USA, April 14-18, 2019 (Shu Wang, Brian MacKie-Mason, and Zhen Peng).
- 2019 Best paper award at IEEE 28th Conference on Electrical Performance of Electronic Packaging Systems (EPEPS) – “A Novel Space-Time Building Block Methodology for Transient Electromagnetic Analysis” (S. Wang and Z. Peng).
- 2019 IEEE EMC Symposium Best Paper Award – “A Novel Statistical Model for the Electromagnetic Coupling to Electronics Inside Enclosures” (Shen Lin, Zhen Peng, Edl Schamiloglu, Zachary B. Drikas, and Thomas Antonsen).
- 2020: Sameer Hemmady, awarded Albuquerque’s Forty under 40 award, for his contributions to shaping Albuquerque’s STEM community.
- Payman Zarkesh-Ha 2019: Outstanding Teacher Award, Department of Electrical & Computer Engineering, University of New Mexico
- Payman Zarkesh-Ha 2019: STC.UNM Creativity Award
- Edl Schamiloglu 2019: STC.UNM Creativity Award
- Edl Schamiloglu 2019: IEEE Nuclear and Plasma Sciences Society’s 2019 Magne “Kris”

UNM Students Who Graduated

- None

University of Maryland

8. Photonic Interconnects and Future Devices – Our group has been working on integration of photonics and efficient light sources for robust optical interconnects that are insensitive to EM interference. In this phase of the project we have been exploring two approaches. The first is based hybrid integration of III-V semiconductors with Si, which combines the most promising material for light emission with the most scalable optical platform. This project is a collaboration with Dr. Ganesh Balakrishnan, who is providing MBE growth of materials using his state-of-the-art MBE capabilities. In this phase of the project we have successfully integrated quantum dots with a silicon photonic on-chip filter based on a ring resonator. The filter is compact and requires only 10 μm footprint, making ideally suited for compact and scalable integration. We showed that the filter could efficiently route light with narrow bandwidth, and further improvements could fast switchable filters that are suitable for high efficiency wavelength and time-division multiplexing. In the second approach, we worked with another promising material platform, thin-film lithium niobate. This emerging material combines the high electro-optic coefficient of lithium niobate with the efficient optical emission of rare-earth ions, which serve as the core technology for fiber amplifiers, the primary workhorses of the internet. This combination enables compact on-chip light emitters that can serve as sources for optical interconnects and transmit data at high bandwidths. This year, for the first time, we have demonstrated integration of rare-earth ions with thin-film lithium niobate. We showed that implanting RE ions in to thin-film LN does not degrade their properties, making them suitable for on-chip light emission.

9. Efficient Statistical Model for Predicting Electromagnetic Wave Distribution in Coupled Enclosures – The Random Coupling Model (RCM) has been successfully applied to predicting the statistics of currents and voltages at ports in complex electromagnetic (EM) enclosures operating in the short wavelength limit. Recent studies have extended the RCM to systems of multi-mode aperture- coupled enclosures. However, as the size (as measured in wavelengths) of a coupling aperture grows, the coupling matrix used in the RCM increases as well, and the computation becomes more complex and time consuming. A simple Power Balance Model (PWB) can provide fast predictions for the averaged power density of waves inside electrically-large systems for a wide range of cavity and coupling scenarios. However, the important interference induced fluctuations of the wave field retained in the RCM are absent in PWB. We have combined the best aspects of each model to create a hybrid treatment and studied the EM fields in coupled enclosure systems. The proposed hybrid approach provides both mean and fluctuation information of the EM fields without the full computational complexity of coupled-cavity RCM. We compared the hybrid model predictions with experiments on linear cascades of over-moded cavities. We found good agreement over a set of different loss parameters and for different coupling strengths between cavities. The range of validity and applicability of the hybrid method was tested and discussed.

10. Wireless Power Distributions in Multi-Cavity Systems at High Frequencies – A possible way to incorporate site-specific information in EM propagation analyses without reverting back to full-wave solvers, which are far too costly given that typical distances are orders of magnitudes smaller than the wavelength, is using full ray-tracing computations. Ray tracing is efficient as long as the number of possible reflections taken into account is small, but may become inefficient in reverberant environments. Recently, a mesh-based ray-tracing solver called *Dynamical Energy*

Analysis (DEA) has been developed. It approximates wave energy transport using energy flow equations written in terms of so-called linear transfer operators, formulated as a boundary integral equation computing power fluxes through interfaces. DEA provides an efficient numerical approximation of these operators in matrix form and can be formulated on computational meshes, such as provided by Finite Element (FE) meshes in two and three dimensions. The advantages compared with standard ray-tracing are that the complexity of the environment (due to complex boundaries) is fully modeled as part of the mesh and multiple reflections can be accounted for by iterations of the linear operator. The size of the DEA mesh is independent of frequency and allows for large variations in cell size.

We analyzed the usefulness of the DEA methodology compared with standard ray tracing methods, but also compared to full FE methods and simplified power balance relations, offering an example of multiply connected and open indoor environments.

11. Coherent Perfect Absorption on a Network – We have experimentally demonstrated coherent perfect absorption (CPA) in the complex network system with and without time-reversal symmetry. Importantly, the proposed platform, based on a complex network design, is reconfigurable, allows one to directly harvest the output signal, and demonstrates 99.99+% absorbance efficiency. On the fundamental level, based on a standard model of wave chaos, our platform can inspire studies of CPAs in complex/chaotic systems where traditional tools from semi-classics and Random Matrix Theory can be utilized for the design of efficient CPA traps. We expect that this work will motivate practical applications, including designing extremely efficient absorbers/detectors, enabling practical long-range wireless power transfer, developing secure communication links, and associated high-efficiency energy conversion systems. Our work creates a new paradigm for CPA and opens many new opportunities to exploit this concept for both fundamental and practical directions.

12. Nanoscale Device Level Modeling of EMI Induced Vulnerability – We are investigating the vulnerability of electronics to EMI at the small circuit, device (transistor) and sub-device level. These vulnerabilities can lead to both Soft Errors and Hard Failures. The Soft Error is due to bit flips and system latch-ups that can be corrected by re-booting. The Hard Failure is a permanent damage to the individual devices (transistors), which are mainly Metal-Oxide Semiconductor Field Effect Transistors (MOSFETs); the EMI-related Hard Failures can degrade or even destroy the operability of the circuit. For Soft Errors, we study the internal mechanisms within a MOSFET that can be activated by transient high-level EMI disruptions, including impact ionization and the Snapback phenomenon. For Hard Failures, we focus our investigation on MOSFET gate oxide damage and rupture, due to high voltages and thermal effects.

Soft Error: Our earlier works on Soft Errors included device-level simulation and analysis of the impact ionization effect, which is significantly enhanced/worsened by high terminal voltages and high internal fields caused by transient EMI disruptions; as well as the parasitic bipolar-junction transistor (BJT) structure, which is occurring by the MOSFET design, but only activated under extreme conditions together with the impact ionization effect. These device-level phenomena can drastically change the affected transistor's input-output relations, e.g. abnormal, exponential current amplification and even locking the device into erroneous states, and that eventually cause circuit-level abnormal events that may need rebooting to remove.

In the past year, we studied several aspects of the issue. We conducted experimental tests using MOSFET devices to verify the underlying theories, and realistic data for further analysis and modeling. The experiments confirmed our expectation that depending on specific device geometrical and electrical structures, Soft Error may occur under high-voltage disruptions, while the physical MOSFET structure is unharmed or only minimally degraded. We established the theoretical foundations and a workflow for compact modeling. The compact model covers the structural information from device designs (e.g. oxide thickness, doping profile, gate length), and

reduces the underlying physical mechanisms into simplified input-output relations, which are ideal for higher-level simulations involving multiple transistors. We devised a model extraction technique that is suitable for our analytical, circuit-level Soft Error model, which can be incorporated with both experimental and computational data. The extraction technique is based on a heuristic-search algorithm which is suitable, for not only the proposed Soft Error model, but also various extraction tasks involving closed-form equations that are not easily differentiable or optimizable. In the upcoming year, we will demonstrate a working example of extracting a compact circuit-level model from device-level data. The supposed model can be applied in SPICE simulations by circuit designers to evaluate the EMI-related Soft Error vulnerabilities.

Hard Failure from Dielectric Breakdown: The gate terminal dielectric is a key structure in MOSFET devices, which insulates the carrier flow from the source to drain by applying the gate terminal voltage. They are extremely thin (in modern, advanced devices, they can be only a few nanometers thick) and vulnerable to EMI, as they can easily be ruptured by EMI-induced voltages between the electrodes. The damage to the gate dielectric is usually unrecoverable, and hence can cause Hard Failures in circuits.

One way to describe and model the damage to the dielectric, or oxide breakdown (BD), is by using the bond breaking process, which is treated as a chemical reaction that requires the presence of electrons in the gate dielectric, which is normally an insulator, and can further be accelerated by the oxide field (from the applied gate voltages and enhanced by EMI disruptions) and the lattice (or electronic device) temperature (which can be affected by Joule heating from the EMI disruptions). In the past year, we have developed a computer program that takes the device structure (gate dielectric properties, thickness, doping profile, etc.) as well as applied terminal voltage as inputs, and simulates the penetration of electron wavefunctions into the insulating dielectric, indicating the presence of conduction electrons in the gate oxide, which should ideally be a pure dielectric. The simulation also showed that depending on the applied gate voltage, the amount of electron penetration could vary from minimal to significant, which could determine the speed of the device degradation, or equivalently, the lifetime before a permanent BD event. The existence and change of wavefunctions is believed to be instant, so transient EMI disruptions may lead to different consequences than constant stress. We will continue to collect more simulation data while improving the methodologies. Together with the chemical reaction-based theory, we will derive a modeling technique to describe the BD progress in a circuit simulation environment and under transient EMI conditions.

Personnel Supported

Faculty: Antonsen, Ott, Anlage, Waks, Goldsman

Students: T. Cai, S. Aghaeimeibodi, Z. Luo, F. Adnan, C. Darmody, Z. Cui, S. Ma, S. Chandra, T. Ghutishvili, S. Banik, M. Rahaman, S. Dutta, L. Chen

Publications

1. S. Dutta, E.A. Goldschmidt, S. Barik, U. Saha, and E. Waks, "Integrated Photonic Platform for Rare-Earth Ions in Thin Film Lithium Niobate," *Nano Letters*, vol. 20, 741-747 (2020).
2. J-H. Kim, S. Aghaeimeibodi, J. Carolan, D. Englund, and E. Waks, "Hybrid Integration Methods for On-Chip Quantum Photonics," *Optica*, vol. (2020) .
3. S. Aghaeimeibodi, C-M. Lee, M. Atabey Buyukkaya, C.J.K. Richardson, and E. Waks, "Large Stark Tuning of InAs/InP Quantum Dots," *Appl. Phys. Lett.*, vol. 114, 071105 (2019) .
4. S. Aghaeimeibodi, J-H. Kim, C-M. Lee, M. Atabey Buyukkaya, C. Richardson, and E. Waks, "Silicon Photonic Add-Drop Filter for Quantum Emitters," *Optics Express*, vol. 27, 16882–16889 (2019).

5. B. Addissie, J. Rodgers, and T. Antonsen, "Extraction of the Coupling Impedance in Overmoded Cavities," *Wave Motion*, vol. 87, 123-131, (2019).
6. M. Zhou, E. Ott, T.M Antonsen Jr., and S.M Anlage, "Scattering Statistics in Nonlinear Wave Chaotic Systems," *Chaos*, vol. 29, 033113 (2019).
7. S. Ma, B. Xiao, Z. Drikas, B. Addissie, R. Hong, T.M Antonsen, E. Ott, and S.M Anlage, "Wave Scattering Properties of Multiple Weakly Coupled Complex Systems," *Phys. Rev. E*, vol. 101, 22201 (2019).
8. S. Lin, Z. Peng and T. Antonsen, "A Stochastic Green's Function for Solution of Wave Propagation in Wave-Chaotic Environments," *IEEE Trans. Antennas Propag.*, early access, DOI: 10.1109/TAP.2019.2963568.
9. S. Ma, S. Phang, Z. Drikas, B. Addissie, R. Hong, V. Blakaj, G. Tanner, T.M. Antonsen, E. Ott, and S.M. Anlage, "Efficient Statistical Model for Predicting Electromagnetic Wave Distribution in Coupled Enclosures" arXiv preprint arXiv:2003.07942.
10. S. Ma, B. Xiao, R. Hong, B. Addissie, Z. Drikas, T. Antonsen, E. Ott, and S. Anlage, "Classification and Prediction of Wave Chaotic Systems with Machine Learning Techniques," arXiv preprint arXiv:1908.04716
11. F. Adnan, V. Blakaj, S. Phang, T.M. Antonsen, S.C. Creagh, G. Gradoni, and G. Tanner, "Wireless Power Distributions in Multi-Cavity Systems at High Frequencies, submitted to *Proc. R. Soc. A* (2020).

Conference Papers

1. S. Anlage, S. Ma, S. Phang, Z. Drikas, B. Addisie, R. Hong, V. Blakaj, G. Gradoni, G. Tanner, T. Antonsen, and E. Ott, "Efficient Hybrid Model of Field and Energy Flow in Interconnected Wave Chaotic Systems," *Bull. Amer. Phys. Soc.*, W25.00004 (2020).
2. S. Ma, T. Antonsen, E. Ott, S. Chandra, and S. Anlage, "Experimental Realization of Reservoir Computing with Wave Chaotic Systems," *Bull. Amer. Phys. Soc.*, M34.00009 (2020).
3. M. Vitkovsky, T.M. Antonsen, Jr., E. Schamiloglu, and S. Hemmady, "Predictive Modeling of Erroneous Software Behavior in Embedded Digital Systems Due to Extreme Electromagnetic Interference," *Proceedings ICEAA 2019 (Granada, Spain, September 09-13, 2019)*, 1304-1307.
4. G. Gradoni, T.M. Antonsen, and E. Ott, "Influence of Multi-Path Fading on MIMO/OAM Communications," *Proceedings ICEAA 2019 (Granada, Spain, September 09-13, 2019)*, 1230-1230.
5. S. Lin, Z. Peng, E. Schamiloglu, Z.B. Drikas, and T. Antonsen, "A Novel Statistical Model for the Electromagnetic Coupling to Electronics inside Enclosures," *2019 IEEE International Symposium on Electromagnetic Compatibility, Signal & Power Integrity, New Orleans, Louisiana, USA, July 2019 (IEEE EMC Symposium Best Paper Award)*.
6. S. Phang, S. Ma, S.C. Creagh, G. Gradoni, S.M. Anlage, D.W.P. Thomas, T. Antonsen, and G. Tanner, "High-Frequency Electromagnetic Coupling Calculation Using the Dynamical Energy Analysis by Discrete Flow Method," *2019 ESA Workshop on Aerospace EMC (Aerospace EMC, Budapest, Hungary, May 20-22, 2019)* 1-6.
7. S. Aghaeimeibodi, C. Lee, M. Buyukkaya, A. Karasahin, J. Kim, C. Richardson, and E. Waks, "Integrated Quantum Photonic Circuits with Quantum Dots," *IEEE Photonics Conference (San Antonio, TX, October 2019)*.
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September 27, 2021

Year 6 Report on AFOSR/AFRL COE: Science of Electronics in Extreme Electromagnetic Environments

AFOSR Grant FA9550-15-1-0171

Period of Performance: 01 April 2019 – 31 March 2021

Program Managers: Arje Nachman (AFOSR), Timothy Clarke (AFRL)

Principal Investigator: Edl Schamiloglu

NOTE: We requested and received a no-cost extension of three months and I did not realize that this forced the requirement of an annual report for Year 6. This, and confusion regarding funding and changeover(s) in Program Officers resulted in the delay of this annual report. The final report will be submitted by September 30, 2021.

ABSTRACT

This AFOSR/AFRL-funded Center of Excellence is led by the University of New Mexico with the University of Maryland a partner. This report summarizes progress in Year 6 of this award.

University of New Mexico

The research tasks that are being investigated are listed below and brief updates are provided for each of them.

1. CMOS Injection Experiments – We developed a predictive model to estimate the impact of high-frequency Electromagnetic Interference (EMI) on the leakage current of CMOS inverters, which can be extended to complex logic gates as well. The developed analytical model was successfully validated using experimental results for devices fabricated using 180 nm, 130 nm, and 65 nm standard CMOS process through TSMC. This simple model can be utilized by EMI/EMC engineers to quickly ascertain the soft and hard error decision limits for their circuits under external RF interference.

2. E/O Injection Modeling and Experiments – We developed a predictive model to estimate the impact of high-frequency Electromagnetic Interference (EMI) on the E/O transfer characteristics of electro-optic modulators. We focused on time-domain eye diagram analysis to develop a predictive model for bit error rates induced into E/O systems due to RF/EMI interference. Experimental tests were performed to study the impact of EMI on the different parameters which define the digital “eye” diagram.

3. CMOS Inverter Response under Stochastic Supply Signals – During this reporting period we continued to develop rigorous analytical models for the stochastic behavior of MOSFET devices subject to stochastic voltage inputs, with this stochasticity arising from an only- stochastically-characterized external

electromagnetic disturbance inducing voltages on those inputs, and with stochastic “out-of-bounds” voltage values leading to probability of failure of any digital circuit employing such devices. In this period, we slightly changed our earlier focus on induced stochastic signal propagation time delays to (a) stochastic drain current for a single MOSFET and (b) stochastic output voltage for a [single] CMOS inverter. With respect to (a), we have completed development of an analytic model to compute the stochastic drain-source current through a single MOSFET as a consequence of (possibly) simultaneously stochastic gate and drain voltages, and to compute as well for that MOSFET the probability of its functional failure as a consequence of such stochastic “out-of-bounds” drain voltages; and we have completed a two-part manuscript detailing this work. With respect to (b), we have completed development of an analytic model that provides analytical expressions for the probability of occurrence of CMOS inverter out-of-bounds input voltage—and consequent probability of inverter output voltage error.

4. Source Reconstruction – Source reconstruction methods (SRM), sometimes referred to as inverse source methods, enables one to experimentally determine an equivalent distribution of surface currents that characterizes the emission from an emitter of arbitrary complexity. In this work we have explored the possibility of similar techniques that can be used to characterize the absorption of EEMI radiation by complex targets specifically considering the case of highly resonant overmoded cavities and the random coupling model (RCM). We began the research by modeling and developing SRM algorithms using models in CST of patch antennas: a single patch; and a series of modified two-element arrays.

5. Quantum Dot Collaboration with UMD – The quantum dot is a well-established source of single photon emission. The use of such quantum dot based single photon emitters allows for the realization of photonic qubits which would be the building blocks of quantum computers. The photonic qubits also allows for the use of silicon photonics platforms that are currently used in a variety of devices and adapt this technology for quantum computation. The use of photonic qubits also makes the quantum dot emitters susceptible to the same issues faced by traditional optoelectronics devices. Thus, quantum dot single photon emitters constitute a key technology in Photonic interconnects and devices that must be studied for EEMI effects.

6. Microcontroller Experiments – Our manuscript, “Time-Varying Radiation Impedance of Microcontroller GPIO Ports and their Dependence on Software Instructions,” was submitted to IEEE transactions on Electromagnetic Compatibility this past June 2021 for technical review and subsequent publication. The paper details our work to experimentally measure the radiation port impedance of a GPIO (General Purpose Input Output) port of an Atmel Microcontroller and measuring the port impedance as a function of the microcontroller’s instruction set. While previous work had measured a time invariant impedance solely dependent on the input frequency, however this is only valid for passive structures. Our novel work showed that time dependent radiation impedance fluctuations within the GPIO port are indeed a function of the instruction being run within the microcontroller and this time dependent impedance is a key attribute needed to model highly reverberant cavities utilizing the Random Coupling Model. As part of this work we employed clustering algorithms, such as K-means and PCA (Principal Component Analysis), to correlate radiation impedance as well as electromagnetic emissions with instructions being executed—ultimately this can lead to predictive models of microcontroller electromagnetic susceptibility highly reverberant enclosures, even without detailed a priori knowledge of the specific instruction being executed.

7. Photonic Interconnects and Future Devices – Room temperature optical limiters using Nano-Photonics – We have realized the first optical limiter with microwatt continuous wave power. The device works at room temperature and operates in the optical o-band which is critical for optical communications. Optical limiter is a nonlinear material platform that blocks incident light at high power while allowing only light at low power. Typically, material is transparent for low light intensity, but it becomes opaque/absorptive/reflective after a certain threshold of light intensity is exceeded. Optical limiters are used in various high power optical platforms in order to prevent damage to optical systems at high laser radiation.

Many such optical platforms operate at telecom wavelength at room temperature with high power laser irradiance. Here, we have realized a telecom o-band passive optical limiter that works at room temperature. Our device consists of an ensemble of quantum dots at telecom o-band coupled to a nanobeam photonic crystal cavity which behaves as an optical limiter at cavity resonance. The device also exhibits all-optical bistability for incident signals detuned from cavity resonance.

8. Efficient Statistical Model for Predicting Electromagnetic Wave Distribution in Coupled Enclosures – The Random Coupling Model (RCM) has been successfully applied to predicting the statistics of currents and voltages at ports in complex electromagnetic (EM) enclosures operating in the short wavelength limit. Recent studies have extended the RCM to systems of multi-mode aperture- coupled enclosures. However, as the size (as measured in wavelengths) of a coupling aperture grows, the coupling matrix used in the RCM increases as well, and the computation becomes more complex and time consuming. A simple Power Balance Model (PWB) can provide fast predictions for the averaged power density of waves inside electrically-large systems for a wide range of cavity and coupling scenarios. However, the important interference induced fluctuations of the wave field retained in the RCM are absent in PWB. We have combined the best aspects of each model to create a hybrid treatment and studied the EM fields in coupled enclosure systems. The proposed hybrid approach provides both mean and fluctuation information of the EM fields without the full computational complexity of coupled-cavity RCM. We compared the hybrid model predictions with experiments on linear cascades of over-moded cavities. We found good agreement over a set of different loss parameters and for different coupling strengths between cavities. The range of validity and applicability of the hybrid method was tested and discussed.

9. Wavefront Shaping in Complex Cavities – We developed an efficient wavefront shaping scheme in a complex cavity by tuning a fully programable metasurface to explore the ability to control the scattering parameters of a complex system, inducing cold spots and coherent perfect absorption (CPA). A mechanical mode stirrer had been installed to collect cavity ensembles in a more traditional manner and fully characterize the response in relation to the Random Coupling Model (RCM). Using the metasurface, we have been able to successfully generate cold spots at arbitrary frequencies, with varying bandwidths, and when driving multiple input ports simultaneously. The CPA states have also been realized and verified through the input/output power responses, allowing for perfect absorption of the incoming electromagnetic power.

10. Statistics of Signals on Networks of Cables – The impedance matrix for an arbitrary passive network of transmission lines was developed mathematically and it was shown that it can be represented as a sum over modes of the isolated network with resonant denominators at complex frequencies corresponding to those normal modes. The statistics of the impedance matrix show significant deviations from those predicted for cavities. This is apparently due to the non-applicability of the random plane wave hypothesis. A replacement assumption of Gaussian-distributed voltages on the nodes is being developed based on representing the network in terms of signal paths. Results are being compared with measurements and the Random Coupling Model (RCM).

11. Nanoscale Device Level Modeling of EMI Induced Vulnerability – We studied the vulnerability of electronics to EMI at the small circuit, device (transistor) and sub-device level. These vulnerabilities can lead to both Soft Errors and Hard Failures. The Soft Error is due to bit flips and system latch-ups that can be corrected by re-booting. The Hard Failure is a permanent damage to the individual devices (transistors), which are mainly Metal-Oxide Semiconductor Field Effect Transistors (MOSFETs); the EMI-related Hard Failures can degrade or even destroy the operability of the circuit.

- **Soft Error:** Continuing our earlier work, we designed and conducted electrical experiments with off-the-shelf devices (MOSFETs). We validated the test data with underlying physical mechanisms and device-level simulations. We proposed a compact circuit model that represented the large-signal behaviors of the Soft Error-related vulnerability, including impact ionization-induced

avalanche current, parasitic bipolar current, and the snapback phenomenon in the worst case. This model contains only closed-form algebraic equations defining the device's voltage-current (I-V) relationship. It is compatible with common SPICE programs, and it works as an "add-on" module to a typical MOSFET model that calculates the "regular" or textbook-like I-V characteristics. We calibrated the model with our in-house parameter extraction program based on the genetic algorithm adapted to SPICE circuit model extraction. Finally, we demonstrated example EMI-induced circuit vulnerability evaluations using SPICE simulation and only compact models. By applying our extracted compact Soft Error model to the example circuits, additional vulnerabilities (change of behaviors) were observed and examined under the injection of power rail voltage-current disruptions, presumably induced by external EMI coupled to the circuit board. Our proposed model and calibration workflow serves as a convenient tool for circuit designers who need efficient circuit-level evaluation of EMI-induced vulnerabilities, and it relates the device's behaviors to the underlying physics.

- **Hard Failure from Dielectric Breakdown:** Under extreme EMI-induced voltage and current disruptions, a MOSFET's gate dielectric can rupture and lose its functionalities, rendering the circuit that contains the affected device either completely unusable or in a severely degraded state. Based on our earlier studies, we summarized the mechanism of permanent, rapid dielectric breakdown as a thermal event due to excessive leakage current under very large electric field in the gate dielectric layer. We have previously designed and conducted rapid gate oxide breakdown experiments, and we extracted the field-dependent breakdown criterion and post-breakdown behavioral changes. We adapted our in-house simulation program to fin-shaped MOSFET structures (FinFETs) which contain nano-scale structures such as ultra-thin gate oxide layers and very thin body regions protruding out of the wafer's plane. FinFETs are becoming more and more relevant nowadays since they provide higher device densities and better channel leakage current control, both beneficial to the increasing demands for smaller and more efficient electronic devices. Our simulations demonstrated the quantum-mechanical effects in a FinFET, and we extracted the gate dielectric field under various applied gate voltage. Based on our test data and simulation results, we proposed a compact model representing the hard gate dielectric breakdown in FinFETs. Similar to the Soft Error model, our Hard Failure model serves as an additional component in SPICE circuit simulations which calculates and monitors the internal state of the transistor's gate dielectric layer, and reports the gate layer as "broken" after the breakdown threshold has been met.

Personnel Supported – UNM

Faculty: Balakrishnan, Dietz, Hemmady, Schamiloglu, and Zarkesh-Ha

Students: E. Dohme, J. Chen, L. Valbuena, N. Sule, Z. Abedi, S. Wang

Personnel Supported – UMD

Faculty: Antonsen, Ott, Anlage, Waks, Goldsman

Students: F. Adnan, S. Ma, S. Chandra, T. Ghutishvili, L. Chen, B. Frazier, T. Cai, S. Aghaeimeibodi, Z. Luo, C. Darmody, Y. Cui, S., S. Dutta, Z. Fu

UNM Publications – Journals

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IEEE Trans. Electromag. Compat., vol. 62, 1763-1771 (2020).

2. Z. Abedi, S. Hemmady, T. Antonsen, E. Schamiloglu, and P. Zarkesh-Ha, "Application of High Frequency Leakage Current Model for Characterizing Failure Modes in Digital Logic Circuits," *Energies*, vol. 4, 2906-1-11 (2021).
3. D. Dietz, "A Mathematical Model for MOSFET Stochastic Drain Current as a Function of Simultaneously Stochastic Gate and Drain Voltages—Part I," preprint.
4. D. Dietz, "A Mathematical Model for MOSFET Stochastic Drain Current as a Function of Simultaneously Stochastic Gate and Drain Voltages—Part II," preprint.
5. D. Dietz, "Probability of Output Voltage Error in a CMOS Inverter Undergoing Stochastic State Transition During the Presence of a Stochastic Extraneous Input Voltage," preprint.
6. J.M. Chen, S. Portillo, G. Heileman, G. Hadi, R. Bilalic, M. Martinez-Ramon, S. Hemmady, and E. Schamiloglu, "Time-Varying Radiation Impedance of Microcontrollers and its Dependence on Software Instruction," submitted to *IEEE Trans. Electromag. Compat.* (2021) (in review).

UNM Publications – Dissertation

1. N.H. Sule, "Device-Level Predictive Modeling of Extreme Electromagnetic Interference" (Ph.D. Dissertation, University of New Mexico, July 2020).

UNM Awards and Recognition

- Edl Schamiloglu elected Fellow of the American Physical Society

UNM Students Who Graduated

- Nischay Sule – he is with the Air Force Nuclear Weapons Center, Kirtland AFB, NM.
- Luis Valbuena – he is with Volansi, Concord, CA

UMD Publications

1. Benjamin W. Frazier, Thomas M. Antonsen, Jr., Steven M. Anlage, and Edward Ott, "Wavefront Shaping with a Tunable Metasurface: Creating Coldspots and Coherent Perfect Absorption at Arbitrary Frequencies," *Phys. Rev. Research* 2, 043422 (2020).
2. Farasatul Adnan, Valon Blakaj, Sendy Phang, Thomas M. Antonsen, Stephen C. Creagh, Gabriele Gradoni, and Gregor Tanner, "Wireless Power Distributions in Multi-Cavity Systems at High Frequencies," *Proceedings of the Royal Society A* (accepted), arxiv:2005.00411 (2020).
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5. Shukai Ma, Sendy Phang, Zachary Drikas, Bisrat Addissie, Ronald Hong, Valon Blakaj, Gabriele Gradoni, Gregor Tanner, Thomas M. Antonsen, Edward Ott, Steven M. Anlage, "Efficient Statistical Model for Predicting Electromagnetic Wave Distribution in Coupled Enclosures," *Phys. Rev. Applied* 14, 014022 (2020).

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11. BW Frazier, TM Antonsen, SM Anlage, E Ott, "Deep Wavefront Shaping: Intelligent Control of Complex Scattering Responses with a Programmable Metasurface", arXiv preprint arXiv:2103.13500.
12. Y. Cui, "Device and Circuit Level EMI Induced Vulnerability: Modeling and Experiment," Ph.D. Thesis, University of Maryland, 2021.
13. I. Baum, C. Darmody, Y. Cui and N. Goldsman, "Effects of Fermi Pinning and Quantum Mechanisms on Leakage Current of 4H-SiC Schottky Diodes," Submitted to *Journal of Applied Physics*, 2021.
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15. M. Buyukkaya, C. Lee, S. Harper, and E. Waks, "Optical bistability and saturable gain in a nanophonic cavity coupled to quantum dots", Manuscript in preparation.

UMD Conference Papers

1. Steven Anlage, Shukai Ma, Sendy Phang, Zachary Drikas, Bisrat Addissie, Ronald Hong, Valon Blakaj, Gabriele Gradoni, Gregor Tanner, Thomas Antonsen, Edward Ott, "Efficient Hybrid Model of Field and Energy Flow in Interconnected Wave Chaotic Systems," *Bulletin of the American Physical Society*, W25.00004.
2. Benjamin W. Frazier, Thomas M. Antonsen, Jr., Steven M. Anlage, Edward Ott, "Wavefront Shaping with a Tunable Metasurface," *METANANO 2020*, virtual conference, September 2020.
3. Lei Chen, Tsampikos Kottos, Steven Anlage, "Coherent Perfect Absorption in Chaotic Microwave Graphs," *Bulletin of the American Physical Society*. 2020.
4. Lei Chen, Tsampikos Kottos, Steven Anlage, "Perfect Absorption in Complex Scattering Systems with or without Hidden Symmetries," *METANANO 2020*, virtual conference, September 2020.
5. Shukai Ma, Thomas Antonsen, Edward Ott, Sarthak Chandra, Steven Anlage, "Experimental Realization of Reservoir Computing with Wave Chaotic Systems," *Bulletin of the American Physical Society*.
6. Shukai Ma, Steven Anlage, "Realization of Gaussian Symplectic Ensemble with Quantum Spin Hall Photonic Topological Insulator Graph," *Metamaterials 2020* (virtual session, 2020).
7. Shukai Ma, Steven Anlage, "Spin-resolved devices based on bi-anisotropic meta-waveguide photonic topological insulator," *METANANO 2020*, virtual conference, September 2020.
8. Shukai Ma, Thomas Antonsen, Edward Ott, Sarthak Chandra, Steven Anlage, "Wave Chaotic Reservoir Computer," *Dynamics Days 2020* (Hartford, CT, 2020).

9. Valon Blakaj, Shukai Ma, Steven Anlage, Gabriele Gradoni, Thomas Antonsen, Stephen C Creagh, Gregor Tanner, "Towards hybrid statistical-deterministic wireless channel modelling of multiroom environments," 2020 14th European Conference on Antennas and Propagation (EuCAP), Pages, 1-3, Publisher, IEEE.
10. TM Antonsen Jr., F. Adnan, L. Chen, B. Frazier, T. Ghutishvili, S. Ma, M. Zhou, S. Chandra, S. Anlage and E. Ott, S. Phang, V. Blakaj, G. Gradoni, S. Creagh, G. Tanner, "Understanding the Electromagnetic Response in Complex Topologies," Directed Energy Professionals Society, West Point, March 2020.
11. S Ma, T Antonsen, S Anlage, E Ott, "Short-wavelength Reverberant Wave Systems for Enhanced Reservoir Computing", - 2021 - europepmc.org.
12. B Frazier, T Antonsen, S Anlage, "Deep learning enabled wavefront shaping in complex cavities with a binary tunable metasurface", Bulletin of the American Physical Society
13. S Ma, T Antonsen, E Ott, S Anlage, "Experimental Realization of Reservoir Computing with Wave Chaotic Systems", Bulletin of the American Physical Society.
14. Y. Zhao, H. Chalabi, and E. Waks, "A computational design of cylindrically symmetric 2D dielectric grating meta-lens with optical limiting effect based on saturable absorption by FDTD simulation", APS March Meeting, 2020, Denver Co

UMD Students Who Graduated

Yumeng Cui