
BREAKTHROUGHS IN LOW-PROFILE LEAKY-WAVE HPM ANTENNAS

Prepared by: Robert A. Koslover (PI) and Sammuel M. Jalali



**Scientific Applications & Research Associates, Inc.
6300 Gateway Drive
Cypress, CA 90630-4844**

21 Jun 2016

Data Item: A002 - Progress, Status, & Management Quarterly Report #11

Prepared for:

**Program Officer: Lee Mastroianni
ONR Code 30**



**OFFICE OF NAVAL RESEARCH
875 North Randolph Street
Suite 1425
Arlington, VA 22203-1995**

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 21-06-2016		2. REPORT TYPE Quarterly		3. DATES COVERED (From - To) 20 Mar 2016 - 21 Jun 2016	
4. TITLE AND SUBTITLE Breakthroughs in Low-Profile Leaky-Wave HPM Antennas Progress, Status, & Management Report (Quarterly Report #11)				5a. CONTRACT NUMBER N00014-13-C-0352	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Koslover, Robert A.; Jalali, Sammuell M.				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Scientific Applications & Research Associates, Inc. 6300 Gateway Drive Cypress, CA 90630-4844				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 875 North Randolph Street Suite 1425 Arlington, VA 22203-1995				10. SPONSOR/MONITOR'S ACRONYM(S) Code 30	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Distribution Statement A. Approved for public release; distribution is unlimited. Other requests for this document shall be referred to the Program Officer listed in the contract.					
13. SUPPLEMENTARY NOTES ..					
14. ABSTRACT This report describes progress during the 11th quarter of this program and highlights the current status of the research. Some of the more notable activities this period included: (1) more development, analyses, and initial recommended/suggested designs for the AAWSEA, (2) identification, design, and analyses of a novel leaky-wave high-gain HPM-capable antenna that can be directly-connected, without requiring mode-conversion, to any cylindrical-type HPM-source having a TM ₀₁ -circular mode output, and (3) demonstrating (via 3D models) a method to incorporate HPM-capable leaky-waveguides into an extended but still fairly-compact package, in which the inherent frequency-based beam-scanning is effectively compensated, yielding a significantly broader-bandwidth antenna with a fixed-beam direction.					
15. SUBJECT TERMS Leaky-wave Antennas. High Power Microwaves (HPM) Antennas. Low-profile Conformal Antennas.					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES —	19a. NAME OF RESPONSIBLE PERSON (Monitor) Lee Mastroianni
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER(incl. area code) (703) 696-3073

Table of Contents

1. INTRODUCTION	1
1.1. Overview of Previous Activities (1 st thru 10 th Quarter).....	1
1.2. Overview of Recent Activities (11 th Quarter).....	2
2. STATUS OF THE PLAN/SCHEDULE AND FUNDING.....	3
3. RESEARCH AND ACTIVITIES PERFORMED THIS PERIOD.....	5
3.1. Status of AAWSEA designs and recipe development.....	5
3.2. A Circular TM ₀₁ -driven Leaky-wave HPM-capable Antenna.....	10
3.3. Beam Stabilization: Compensation/suppression of Scanning with Frequency	12
4. DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS	15

List of Figures

Figure 1. Updated Program Plan.....	4
Figure 2. Single-channel AAWSEA (design building block) designed for $f_0 = 1.0$ GHz.....	5
Figure 3. Grill wire diameters and location along leaky grill.	5
Figure 4. Four-channel AAWSEA based on the single-channel building block.	6
Figure 5. Predicted performance plots of the 4-channel AAWSEA, along with those from our other suggested designs.	7
Figure 6. Example 3D Antenna patterns for the <i>single-channel</i> AAWSEA at three frequencies. The orientation of the antenna is shown at the right.....	8
Figure 7. Example 3D Antenna patterns for the <i>four-channel</i> AAWSEA at three frequencies. The orientation of the antenna is shown at the right.....	8
Figure 8. Comparison of predicted gain vs. frequency for the 4-chan vs. 1-chan AAWSEA.	9
Figure 9. Model-predicted beam tilt (relative to normal at feed end of antenna) for the AAWSEA, vs. the expected curve for a FAWSEA.	9
Figure 10. Example physics-level design (preliminary) of an HPM-capable TM_{01} -circular mode driven leaky-wave antenna. (Note: This design is for $f_0 \sim 1.35$ GHz)	11
Figure 11. Predicted behavior of the antenna in Figure 10.	11
Figure 12. Some computed 3D radiation patterns for the antenna in Figure 10.	12
Figure 13. Motivation, problems, and solutions found on the research path that led to this broad-banding concept.	12
Figure 14. A novel antenna combining leaky-wave channels with compensating-path waveguides to drive an array. (L-band, 8x8 array. Other sizes and arrays are possible.)	13
Figure 15. Detail of the coupled paths, which use inductive irises and stubs instead of a wire grill, to leak/couple the traveling-wave's power into eight separate waveguides.....	13
Figure 16. Predicted behavior of this fixed-beam wide-bandwidth antenna is encouraging.	14

1. INTRODUCTION

This is SARA's 11th Quarterly Report for "Breakthroughs in Low-profile Leaky-Wave HPM Antennas," a 37-month Basic Research effort sponsored by the US Office of Naval Research (ONR). This work includes fundamental theoretical analyses, numerical modeling, and related basic research. Objectives include to discover, identify, investigate, characterize, quantify, and document the performance, behavior, and design of innovative High Power Microwave (HPM, GW-class) antennas of the *forward-traveling, fast-wave, leaky-wave* class.

1.1. Overview of Previous Activities (1st thru 10th Quarter)

During the *first* quarter, we prepared and established useful equations and algorithms for predicting reflections and transmission of incident TE waves from parallel-wire grills, dielectric windows, and combinations of wire grills with dielectric windows, in problems reducible to purely H-plane (2D) representations. We then applied this theory to guide the design of high-gain configurations (again, limited to 2D, H-plane representations) for linear, forward traveling-wave, leaky-wave antennas. The theory built upon equivalent circuit methods and wave matrix theory, which provided useful formalisms upon which we continue to build.

During the *second* quarter, we pursued initial extensions of the previous work into three dimensions, in order to include phenomena with E-plane dependencies. We succeeded in adding into the wave-matrix formalism the reflection/transmission properties associated with the transition to free space from a *finite-width* leaky-wave channel, including the edge-tapering essential to HPM applications. These geometric aspects do not arise in analyses confined to the H-plane alone. Our 3D analyses were somewhat more reliant on numerical models than in the 2D analyses, due to the greater complexity of identifying and/or building practical analytic approaches capable of addressing true 3D geometries of interest.

During the *third* quarter, we explored channel-to-channel coupling (aka, mutual coupling) which (as we have noted earlier) is an important design concern, since it can impact antenna performance significantly in terms of gain, peak power-handling, and impedance matching. Our approach leveraged mostly numerical methods, along with some intuitive arguments, as we explored designs exhibiting different degrees of mutual coupling between adjacent channels. As past and current antenna literature attest, mutual coupling analyses are non-trivial; suffice to say, there is still much work to be done in this area.

During the *fourth* quarter, we continued to study and employ wave-matrix based methods, but with less success than before in applying this approach to *improve* or *optimize* the initial designs. The formalism itself is still valid, but offers reduced practical rewards once an *initial* (i.e., not fully-optimized) geometry (e.g., grill, window, channel depth, etc.) is derived from the more basic-level principles. At that stage, we are finding that further optimization is currently best proceeding via numerical means. Additional work in the fourth quarter led us to identify *new aperture geometries* of potentially-significant practical value, which included the "BAWSEA" and "GAWSEA". These configurations may significantly extend the utility of leaky-wave antenna technology to support integration on more challenging platforms.

During the *fifth* quarter, we designed, analyzed, and documented representative high-performance FAWSEA and CAWSEA antennas suitable for designation as "standard" or "recommended." The configurations we described were scalable with wavelength. These are the initial entries in a library of antennas that will continue to be built throughout this program.

During the *sixth* quarter, we performed additional investigation of designs to support the newer curved apertures, especially the "Bent Aperture Waveguide Sidewall-emitting Antenna" (BAWSEA). We presented this work at the 17th Annual Directed Energy Professional Society (DEPS) Symposium in Anaheim, CA, on March 4th, 2015. Our full slide presentation, entitled "Advances in Low-Profile Leaky-Wave Conformable Antennas for HPM Applications," was included in the unclassified proceedings CD that was recently distributed by DEPS to all the conference attendees.

During the *seventh* quarter, we investigated RAWSEA design considerations and showed that the angle of rotation between the leaky wave channels and the aperture can be understood in terms of an equivalent linear (non-rotated) displacement, an interpretation which helps to guide application of the wave-matrix formalism. However, more work is still needed to speed-up the RAWSEA design process.

During the *eighth* quarter, we identified, investigated, and applied a seemingly-simple but clarifying wave-mapping methodology, which provided improved guidance in making optimal use of generally curved platform surfaces. Following this process helps guide the designer toward a solution that provides both higher gain and greater peak power handling. Via this approach we identified and reported a notable success with the design of an improved CAWSEA that can deliver superior gain, yet still conform to the same radius cylinder as our earlier-suggested “standard/recommended” design.

During the *ninth* quarter, we developed/extended the ray-based analyses to the AAWSEA configuration, employing an analytic parameterization of the inner-curve (channel back-wall) and outer-curve (vicinity of the leaky-grill wall) ogives, while tracking the varying angles of reflection sequentially along the perspective leaky guide, and ultimately adjusting these curves to yield the desired output beam. The approach offered insight, but did not lead us to design recipes with a practical utility comparable to those for the FAWSEA or CAWSEA.

During the *tenth* quarter, we continued to investigate design methods for the AAWSEA and explored new and novel applications/extensions to HPM leaky-wave antenna technology. We presented our work at the DEPS 18th Annual Directed Energy Symposium. Our presentation also included concepts for the use of GW-capable FAWSEA or CAWSEA-type *feeds* to drive larger *conical* dish reflectors. Combining such a FAWSEA/CAWSEA feed with a *conical* trans-reflector and a flat twist-reflector (a configuration which is now patent pending) yields, to the best of our knowledge, *the world’s first and only GW-class, fully-steerable, high-gain antenna*. Also during the tenth quarter, we began to explore ways to *suppress beam-scanning* with frequency, to see if broader-bandwidth HPM-capable antennas leveraging leaky-wave structures could be realized.

For more information, we encourage the reader to refer to our earlier *Quarterly Reports #1 thru #10*.

1.2. Overview of Recent Activities (11th Quarter)

We have continued our investigations into improved designs and design/methods for the AAWSEA. An initial suggested/recommended AAWSEA design appears in this report, along with performance predictions. In other work this quarter, we identified, designed, and analyzed a novel leaky-wave high-gain HPM-capable antenna that can be directly-connected, without requiring mode-conversion, to any cylindrical-type HPM-source having a TM₀₁-circular mode output. (This is not of mere academic interest, since several kinds of relativistic electron-beam based HPM sources feature TM₀₁-circ outputs.) An example geometry, along with performance predictions from 3D models, is included in this report. This concept expands the applicability of HPM-capable leaky-wave antennas to HPM source/platform combinations that might not otherwise be practical. Finally, as we noted last quarter, unwanted beam-scanning vs. frequency can preclude using these antennas with *broader-band* HPRF sources. Although the frequency-scanning behavior of the beam is *fundamental* to all continuous-aperture, fast traveling-wave, leaky-wave antennas, we can compensate and redirect/stabilize the beam-direction by adding special structures following the leaky-wave interface. In this regard, we reported previously a proof-of-principle (2D model only) of a compensation concept and set a goal of identifying a *practical* 3D configuration that would not sacrifice all the compactness advantages that make leaky-wave antennas so appealing. We are pleased to report some success toward this goal. In particular, this report presents an example 3D model of a new geometry that is compact enough for many applications while offering greater usable bandwidth and a *fixed beam* as the frequency is varied, just as we wanted.

Further information about the aforementioned new and recent activities is provided in Section 3.

2. STATUS OF THE PLAN/SCHEDULE AND FUNDING

Figure 1 (next page) maps out the updated program plan, for quick reference. The subject contract was awarded on 9/18/2013 and has an end date of 10/17/2016. The total contract value is \$868,350, all of which was authorized per P00006, dated 6/23/2015. According to SARA's accounting system, as of June 17, 2016, expenses and commitments (including fee) totaled \$819,492, thus leaving \$48,858 in available funds. If one simply compares the calendar and spending on this project, we have now consumed ~90% of the calendar and ~94% of the total contract value.

Again, we wish to thank ONR for the past and continued support of this project. There are no significant technical, schedule, or funding-related program problems to report at this time.

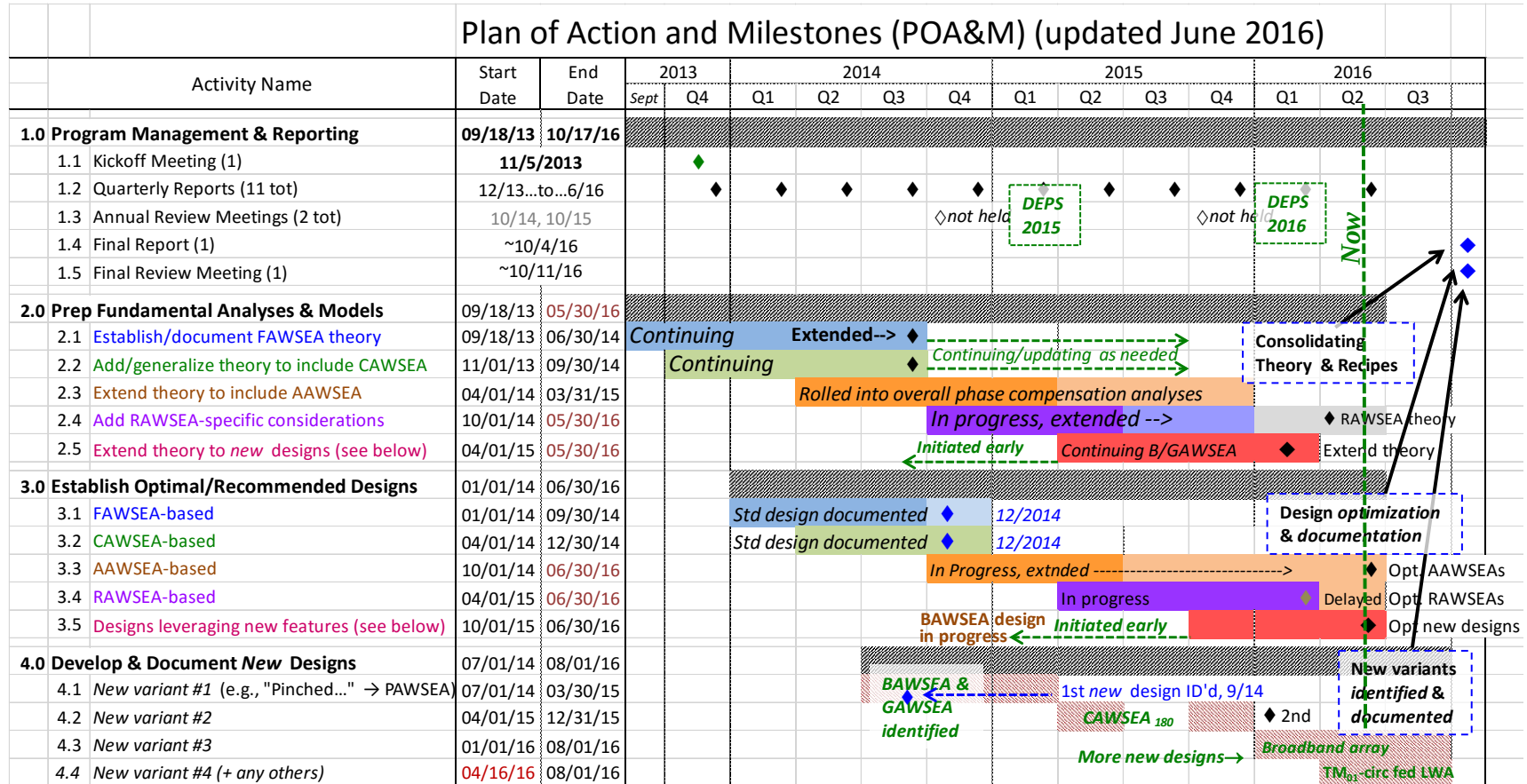


Figure 1. Updated Program Plan

3. RESEARCH AND ACTIVITIES PERFORMED THIS PERIOD

3.1. Status of AAWSEA designs and recipe development

We made significant progress this quarter in establishing suggested standard/example AAWSEA designs, and also in developing design recipes to guide engineers in the design of these antennas. As we noted in our 9th Quarterly Report¹ under this program, the H-plane aperture curvature of the AAWSEA is more complicated to manage (in terms of the mathematics) than the E-plane curvature of the CAWSEA. We have recently formulated a more detailed approach to the AAWSEA design process and will include it in the Final Report. For now, we will focus primarily on a *successful* AAWSEA design example that we developed with the aid of the new analyses. We are pleased to report that aperture-efficient configurations can now be considered as *demonstrated* (via full-wave 3D numerical models) to be realizable.

Figure 2 shows a *single-channel* AAWSEA just over 2m long, with its input cross-section very similar to that of our standard/recommended FAWSEA design documented in previous reports.

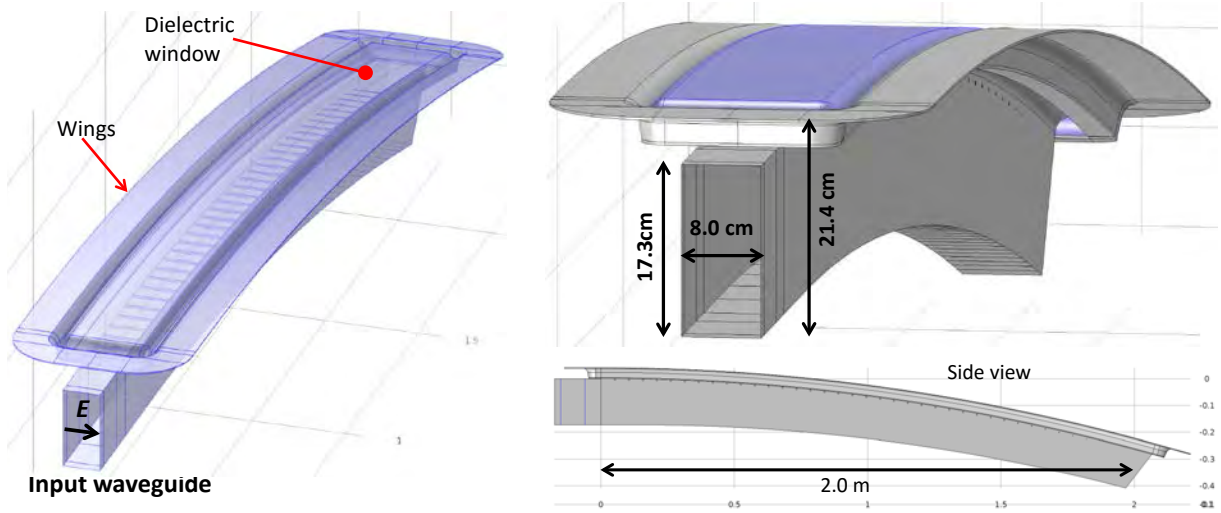


Figure 2. Single-channel AAWSEA (design building block) designed for $f_0 = 1.0$ GHz

The shape of the curved wall opposite the leaky grill is represented by a polygon approximation. Scripts for its computation will be given in our Final Report, along with algorithms for computing AAWSEA grill wire diameters. Figure 3 provides a table of diameters vs. placement for the 35 wires composing the grill used in the AAWSEA in Figure 2.

Grill wire index	Distance along the arc (cm)	Grill wire dia (mm)	...continued:			...continued:		
			Grill wire index	Distance along the arc (cm)	Grill wire dia (mm)	Grill wire index	Distance along the arc (cm)	Grill wire dia (mm)
1	5.25	6.007	14	73.50	5.644	25	131.25	4.656
2	10.50	5.995	15	78.75	5.591	26	136.50	4.496
3	15.75	5.980	16	84.00	5.533	27	141.75	4.316
4	21.00	5.964	17	89.25	5.469	28	147.00	4.112
5	26.25	5.945	18	94.50	5.399	29	152.25	3.879
6	31.50	5.924	19	99.75	5.322	30	157.50	3.612
7	36.75	5.900	20	105.00	5.238	31	162.75	3.301
8	42.00	5.873	21	110.25	5.144	32	168.00	2.937
9	47.25	5.844	22	115.50	5.041	33	173.25	2.504
10	52.50	5.811	23	120.75	4.926	34	178.50	1.987
11	57.75	5.775	24	126.00	4.798	35	183.75	1.365
12	63.00	5.735						
13	68.25	5.692						

Figure 3. Grill wire diameters and location along leaky grill.

¹ For our earlier but incomplete AAWSEA analyses, see: Jalali, S.M., and R.A. Koslover, "Breakthroughs in Low-Profile Leaky-Wave HPM Antennas: Progress, Status, & Management Report" Quarterly Report #9, 12/21/2015, this contract.

Figure 4 shows a four-channel AAWSEA based on the above building block, and employing a channel-to-channel spacing the same (i.e., 19 cm) as we used in our standard/recommended 4-channel FAWSEA (also for $f_0 = 1.0$ GHz, which provides for convenient design scaling to other frequencies).

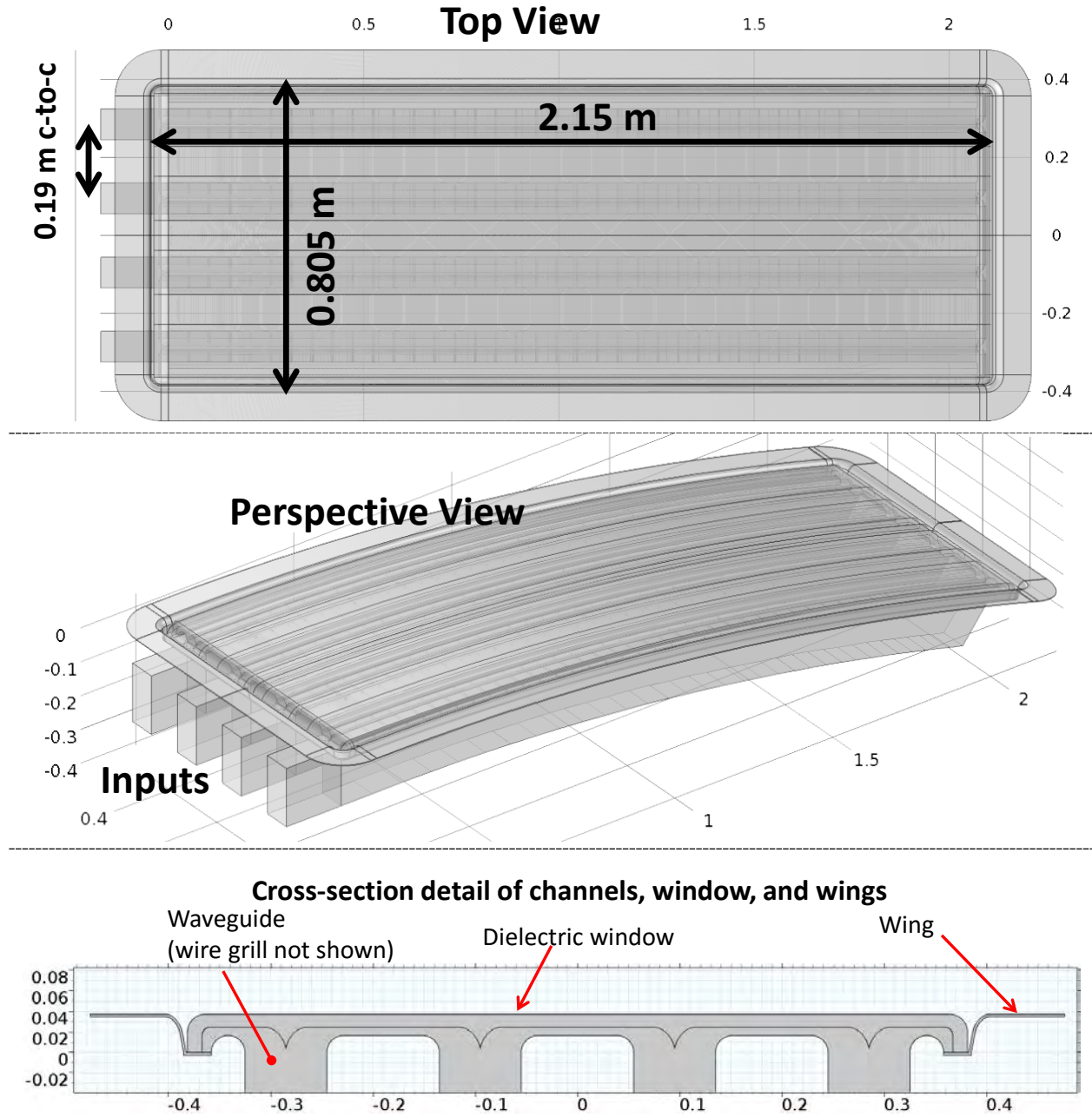


Figure 4. Four-channel AAWSEA based on the single-channel building block.

Figure 5 (next page) compares the predicted performance of the 4-channel AAWSEA with that of three other 4-channel designs (specifically FAWSEA, CAWSEA, and BAWSEA) presented in our earlier reports. The relatively high gain of the AAWSEA is partly due to our use of a slightly larger aperture; a more apples-to-apples comparison is revealed in the aperture efficiency plot. The effective VSWR of the AAWSEA is higher than the other designs at the low-frequency end, which is partly a consequence of the termination section becoming close to cut-off. The surface-field magnitude for a given input power is encouragingly low. This means that AAWSEAs are well-suited to extremely high peak power operation.

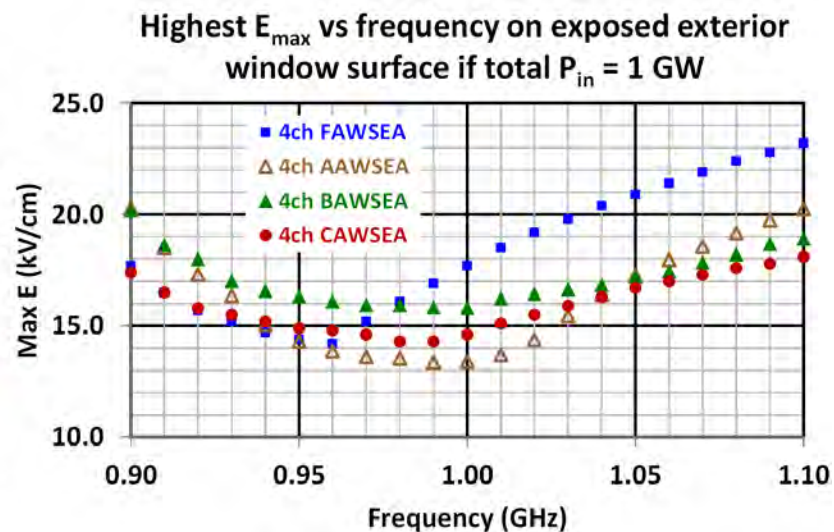
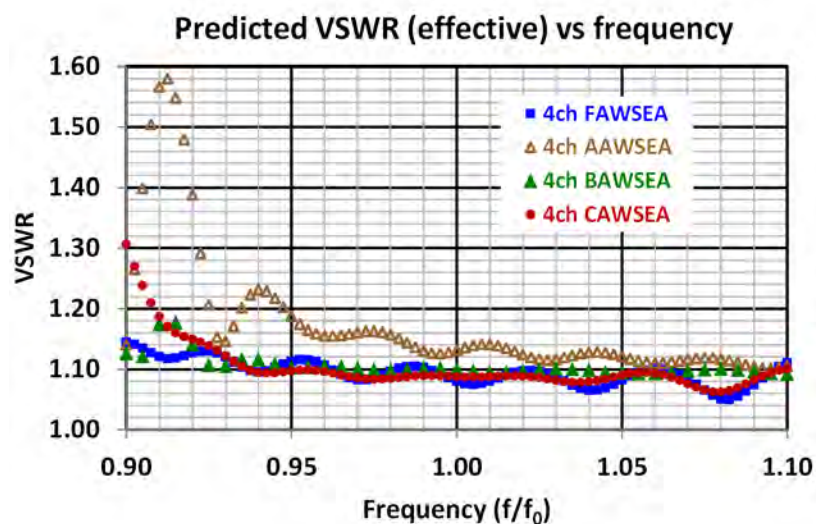
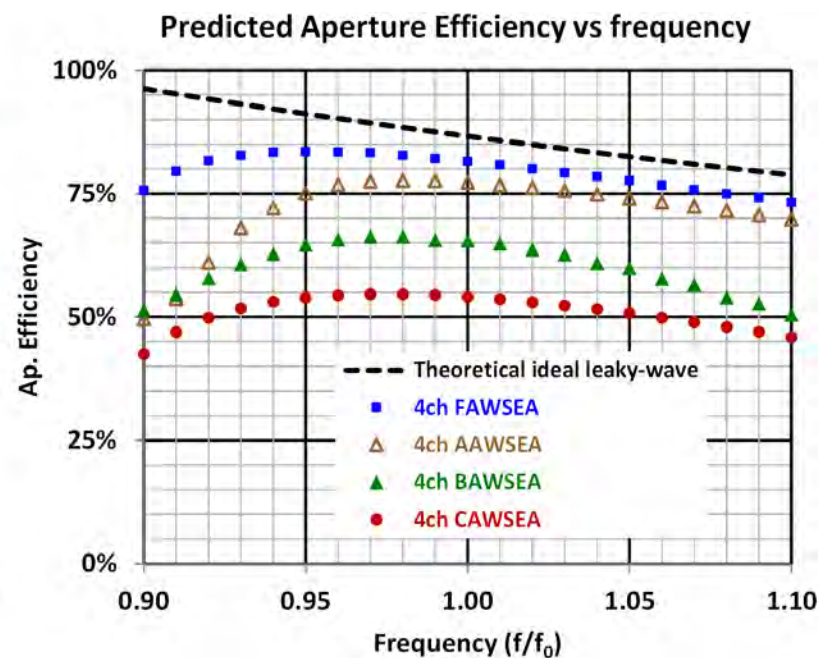
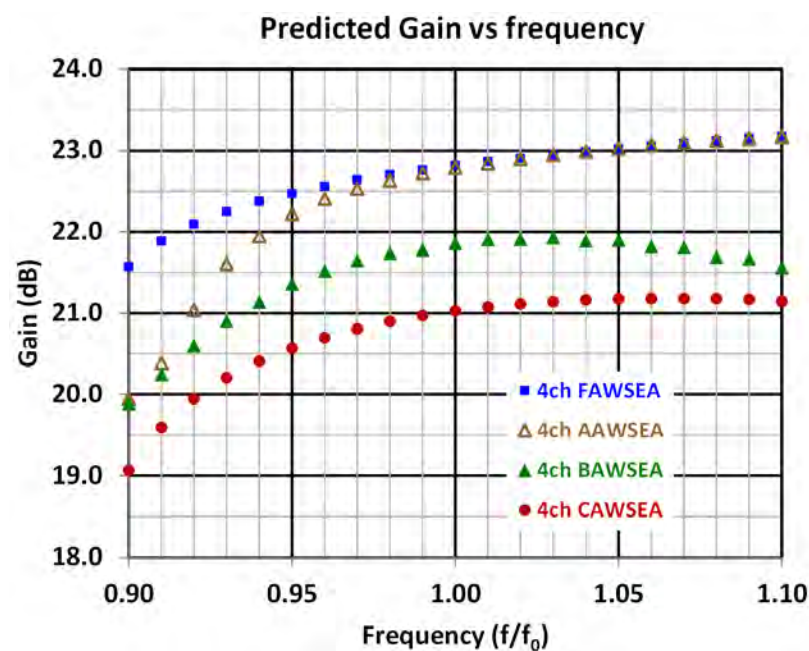


Figure 5. Predicted performance plots of the 4-channel AAWSEA, along with those from our other suggested designs.

Sample 3D antenna patterns are shown for three frequencies ($0.95f_0$, f_0 , and $1.05f_0$) for the single-channel and four-channel AAWSEA in Figure 6 and Figure 8, respectively. Notice how the beam pattern narrows in the E-plane as channels are added, while the H-plane is not noticeably affected. This is as it should be.

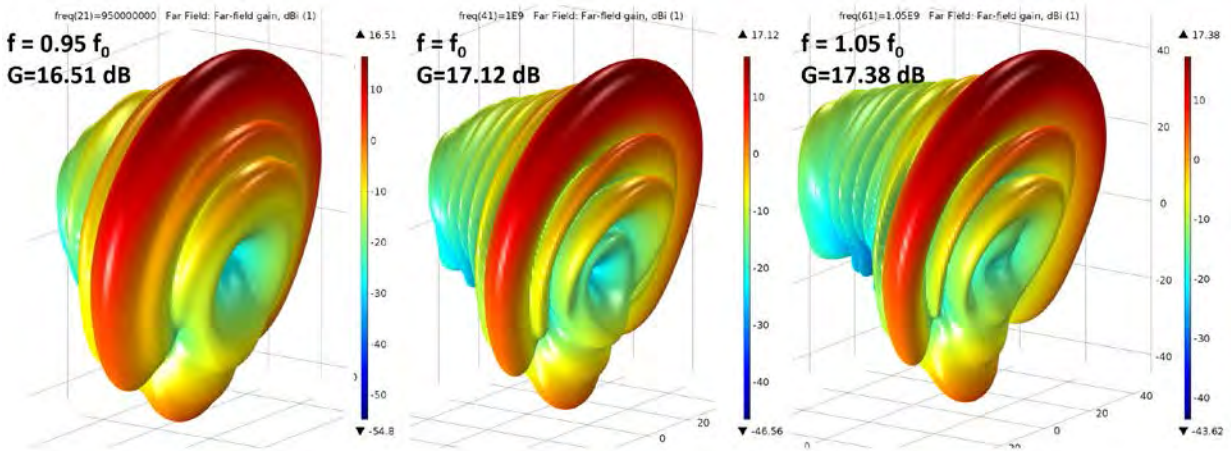


Figure 6. Example 3D Antenna patterns for the *single-channel* AAWSEA at three frequencies. The orientation of the antenna is shown at the right.

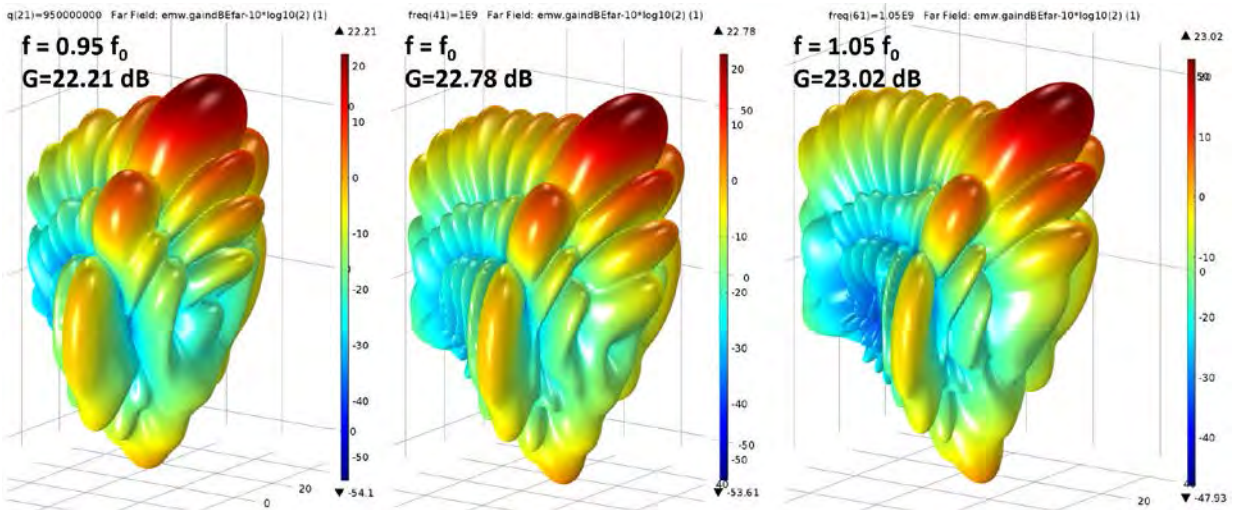


Figure 7. Example 3D Antenna patterns for the *four-channel* AAWSEA at three frequencies. The orientation of the antenna is shown at the right.

The gain exhibited by the 4-channel design is about half a dB less than the ideal +6dB above that of the single channel. This is due to the proximity of the channels and is necessary to maintain a compact package (and high aperture efficiency). Figure 8 provides a more detailed comparison from $0.9f_0$ to $1.1f_0$.

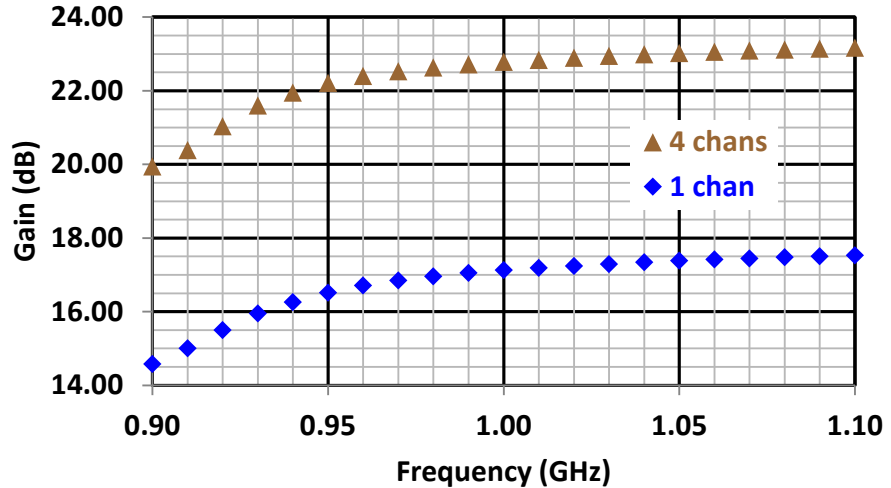


Figure 8. Comparison of predicted gain vs. frequency for the 4-chan vs. 1-chan AAWSEA.

To predict the desired direction of the AAWSEA beam without resort to a full-wave 3D model appears to require some iteration in the design process. It is more complicated than with the other types. For the example design here, the realized beam direction departed from our planned design value (30°) at f_0 by roughly 3° . But perhaps even more interesting is that its behavior vs. frequency is not just a simple offset from the customary (for other leaky-wave antennas) curve. Figure 9 compares the observed (in the numerical model) beam angle vs. frequency of what one would expect (and which we do see) in a FAWSEA vs. that observed in our 3D numerical model of the AAWSEA.

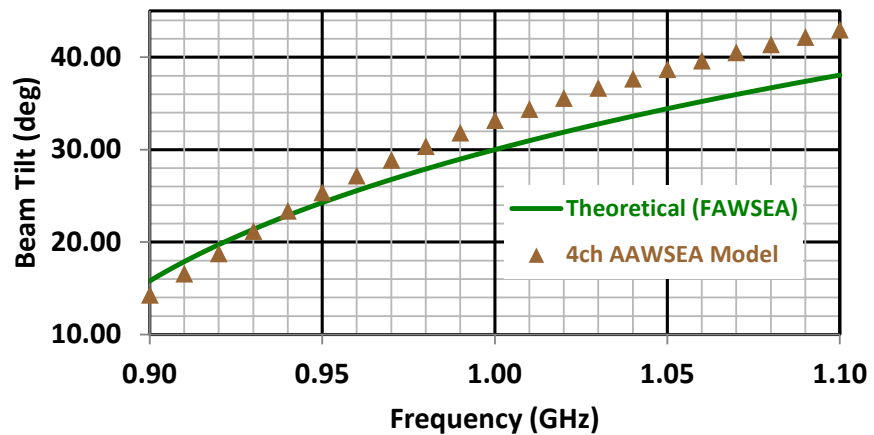


Figure 9. Model-predicted beam tilt (relative to normal at feed end of antenna) for the AAWSEA, vs. the expected curve for a FAWSEA.

3.2. A Circular TM_{01} -driven Leaky-wave HPM-capable Antenna

A number of important cylindrically-shaped HPM sources generate outputs directed along their axes of symmetry, in the circular-waveguide TM_{01} mode. Direct radiation (such as by a conical horn antenna, as was commonly done in the 1980s) yields a low-gain pattern with a null on the axis. This is inconvenient for both effects testing and weaponization. A single-peak beam is much preferred. Fortunately, there exist means for converting from the TM_{01} circular mode to fundamental mode of either circular² (TE_{11}) or rectangular³ (TE_{10}) waveguide, either of which becomes much more convenient for driving an antenna to yield a high-gain beam. Nevertheless, such mode-converting components increase bulk, while potentially also reducing bandwidth and/or efficiency. Some alternative options for managing HPM sources with circular TM_{01} outputs are to employ asymmetric apertures (e.g., the “Vlasov” antenna^{4,5}) or asymmetric reflectors⁶ to compensate for the circularly-symmetric TM_{01} mode, yielding an acceptable moderate- or high-gain beam. There also exists some discussion in the literature of leaky-wave antennas driven by *non-fundamental* waveguide modes, including⁷ circular TM_{01} modes, but of course there has been little if any analyses of the suitability of these kinds of antennas for high peak power (e.g., GW-class) operation. We decided to explore this possibility.

Our investigations using numerical models have convinced us that there is indeed value in using circular-waveguide TM_{01} -based forward-traveling leaky-wave HPM-capable antennas with TM_{01} -output HPM sources. Like SARA’s FAWSEA-family of antennas, the subject antenna is of the continuous-aperture, forward traveling-wave type. However, the leaky “wire grill,” to the extent it can be said to exist at all, is now aligned with the antenna axis and is far simpler. The resulting antenna appears to be especially well-suited to long, narrow-diameter, cylindrical packages. Its leaky aperture(s) can be made to span various fractions of the full azimuthal-angle around the guide. The example shown in Figure 10 has apertures spanning less than 180° around the guide. The curved dielectric window (polyethylene, in this example) provides the vacuum-to-air interface. This interface is similar in geometry to a window suitable for one of our CAWSEA designs. As such, its curvature provides structural support without needing to be excessively thick. We have also found that the addition of modest-extension fins, as a sort of back-plane, help to increase the gain. The aperture length is, of course, customizable, but relatively-long lengths appear to work better, allowing for a more gradual leakage of the radiation. The output beam direction depends on frequency, just as with other types of forward traveling-wave, leaky-wave antennas. Predicted performance (see Figure 11 and Figure 12) in regard to VSWR and gain vs. frequency, while ensuring that $|E|$ does not exceed breakdown, are all very respectable. We conclude that this antenna deserves both attention and consideration by anyone interested in integrating TM_{01} -circular output HPM sources into DEW systems.

²R.A. Koslover, C.D. Cremer, W.P. Geren, D.E. Voss, and L.M. Miner, “Compact, Broadband, High Power Circular TM_{01} to TE_{11} Waveguide Mode Converter,” US Patent No. 4,999,591, March 12, 1991.

³R.F. Harrington and J.R. Mautz, “A High Power TM_{01} Circular to TE_{10} Rectangular Waveguide Mode Converter,” *Seventh International Conference on Antennas and Propagation, (IEE)*, York, 1991, pp. 125-128 vol.1.

⁴S.N. Vlasov and I.M. Orlova, “Quasioptical Transformer which Transforms the Waves in a Waveguide Having Circular Cross-Section into a Highly Directional Wave Beam,” *Radiophys. Quantum Electron.*, vol. 17, pp. 115–119, 1975.

⁵M.D. Haworth, et. al, “Significant Pulse-lengthening in a Multigigawatt Magnetically Insulated Transmission Line Oscillator,” *IEEE Trans. Plasma Sci.*, vol. 26, no. 3, pp. 312-319, Jun 1998.

⁶C.C. Courtney and C.E. Baum, “The Coaxial Beam-rotating Antenna (COBRA): Theory of Operation and Measured Performance,” *IEEE Trans. Antennas Propag.*, vol. 48, no. 2, pp. 299–309, Feb. 2000.

⁷L.O. Goldstone and A.A. Oliner, “Leaky-Wave Antennas II: Circular Waveguides,” *IRE Trans. Ant. and Propagat.*, May, 1961, pp. 280-290.

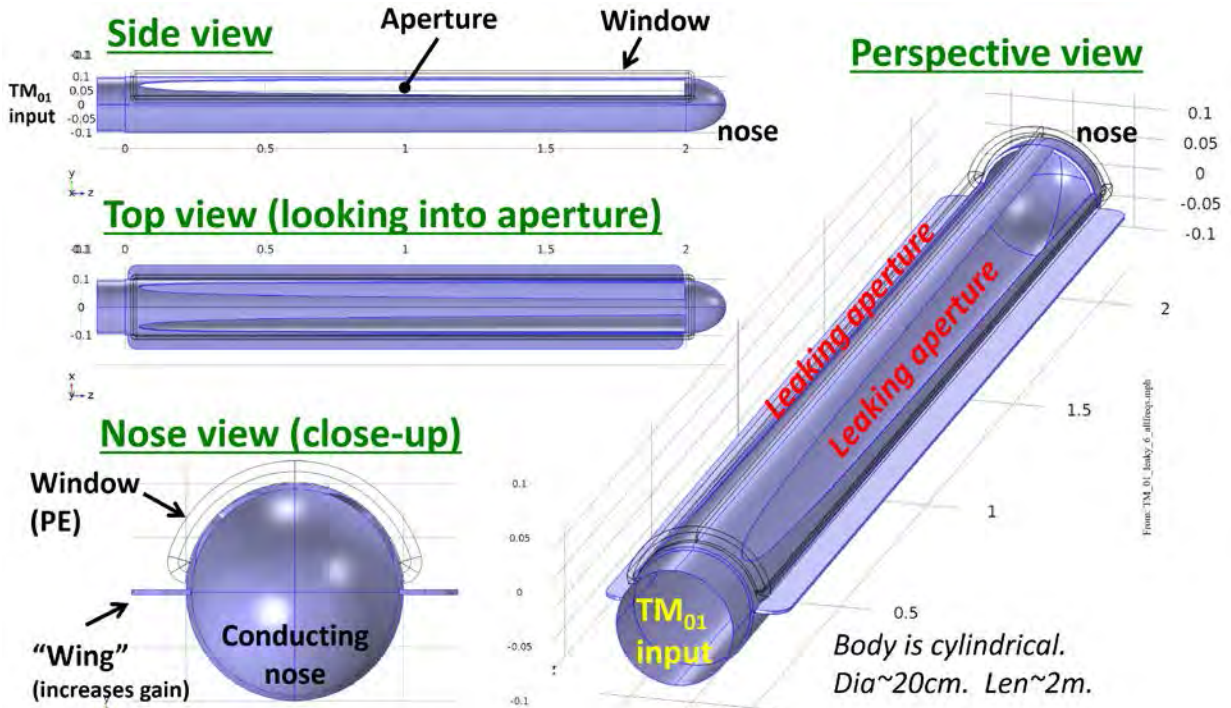


Figure 10. Example physics-level design (preliminary) of an HPM-capable TM₀₁-circular mode driven leaky-wave antenna. (Note: This design is for $f_0 \sim 1.35$ GHz)

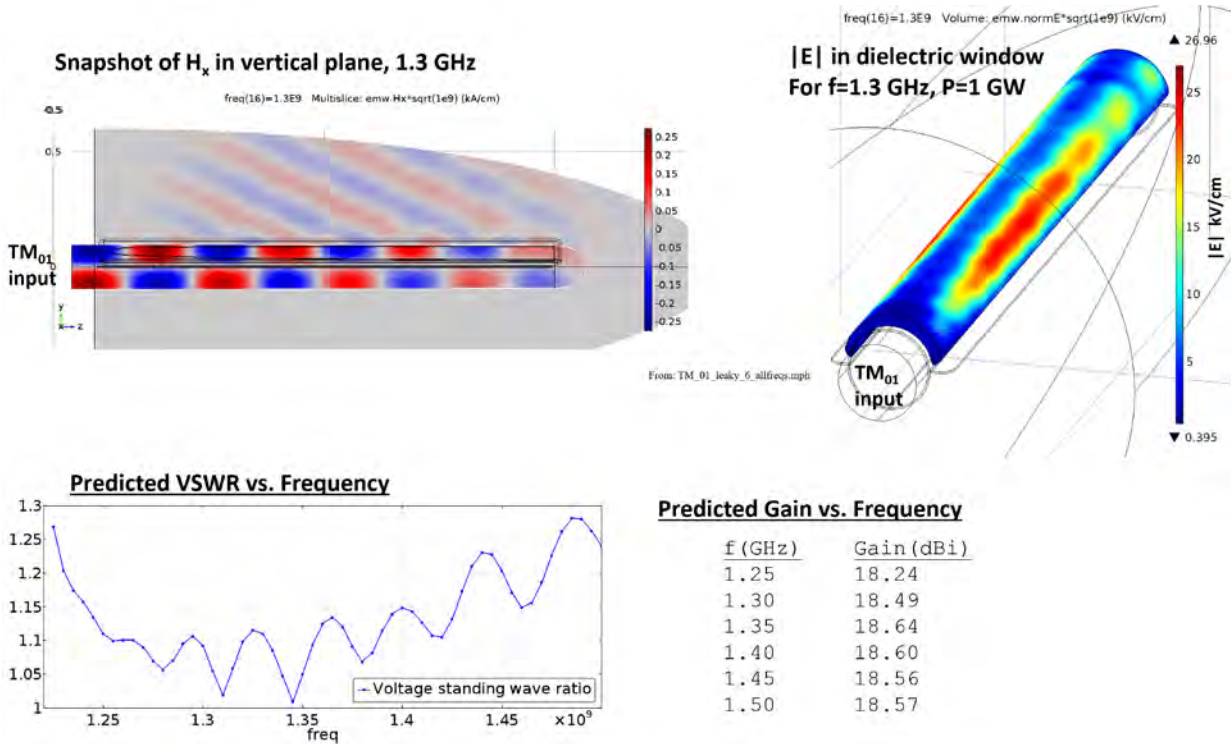


Figure 11. Predicted behavior of the antenna in Figure 10.

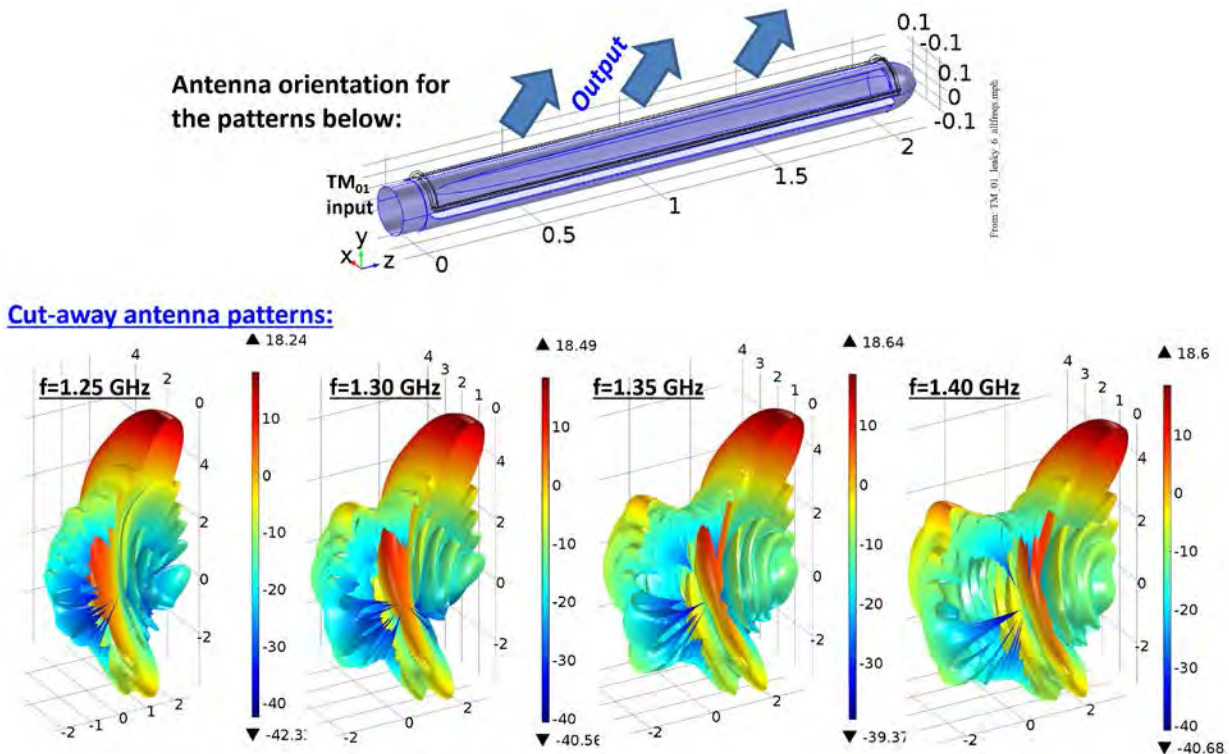


Figure 12. Some computed 3D radiation patterns for the antenna in Figure 10.

3.3. Beam Stabilization: Compensation/suppression of Scanning with Frequency

We are pleased to report that we have found a way (see notes in Figure 13) that combines leaky-waveguides (such as those used in our FAWSEA-type narrowband HPM antennas) with added waveguides to compensate for frequency-dependent beam scanning. Some results of a recent concept exploration (work done by SARA under separate support from AFRL⁸) are shown in Figures 14-16. Note how each “path compensating” waveguide is shorter in length than its predecessor, since the corresponding path to reach it along the leaky channel increases. Despite dielectric-filling, the overall antenna is not as shallow as the more-purely leaky-wave antennas studied under this ONR program. It remains to be seen if its narrow structures will limit peak-powers to sub-GW. However, this configuration does yield a *fixed-direction beam*, thereby expanding the applicability of this technology to broader bandwidth sources.

Motivation: Leaky-wave narrowband HPM antennas (e.g., FAWSEA, CAWSEA, RAWSEA, BAWSEA...) offer *superior* P_{pk} -handling in *compact* packages.

Issue for broadband application: Dispersion in the waveguide steers the leaked beam vs. frequency, effectively limiting usable antenna bandwidth during a macro-pulse to much less than the waveguide operating range.

Idea: *Compensate* by attaching multiple waveguide channels of different lengths along the leaky-waveguide wall, then route them all to form a new aperture (e.g., array of horns) to yield direction ~independent of frequency.

Complications: (1) Could greatly-increase size and volume, (2) the discrete waveguides produce new reflections → grill-wires design algorithm *fails*, and (3) resulting array spacing is too-large → generates grating lobes.

Solutions: (1) Fold/arrange compensating waveguides judiciously and fill with dielectric to reduce size & volume, (2) use individually customized inductive irises instead of wire-grill to couple power into compensating channels, and (3) using dielectric-filled horns → tighter array spacing → avoids grating lobes.

Figure 13. Motivation, problems, and solutions found on the research path that led to this broad-banding concept.

⁸ SARA is a subcontractor under AFRL’s “HERA/HPM Technologies” Contract FA9451-13-D-0210, to Leidos, Inc.

Example geometry for a compact 3D realization of a high-gain 8x8 horn array:

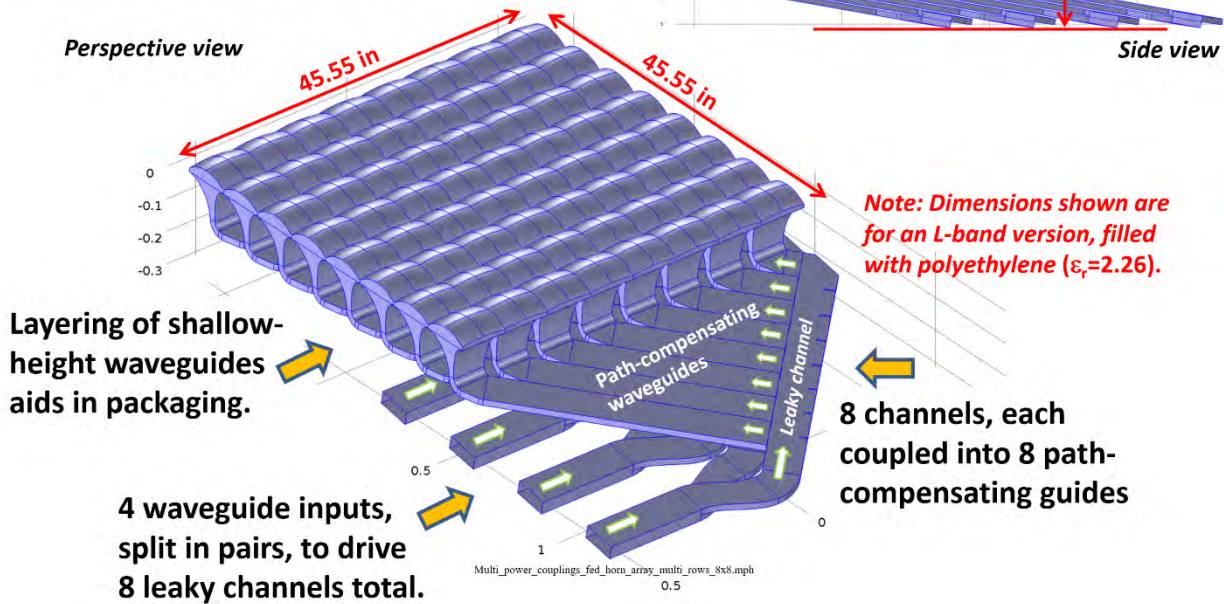


Figure 14. A novel antenna combining leaky-wave channels with compensating-path waveguides to drive an array. (L-band, 8x8 array. Other sizes and arrays are possible.)

Figure 15 shows how an approximately-balanced 1-to-8 power coupling geometry can be achieved.

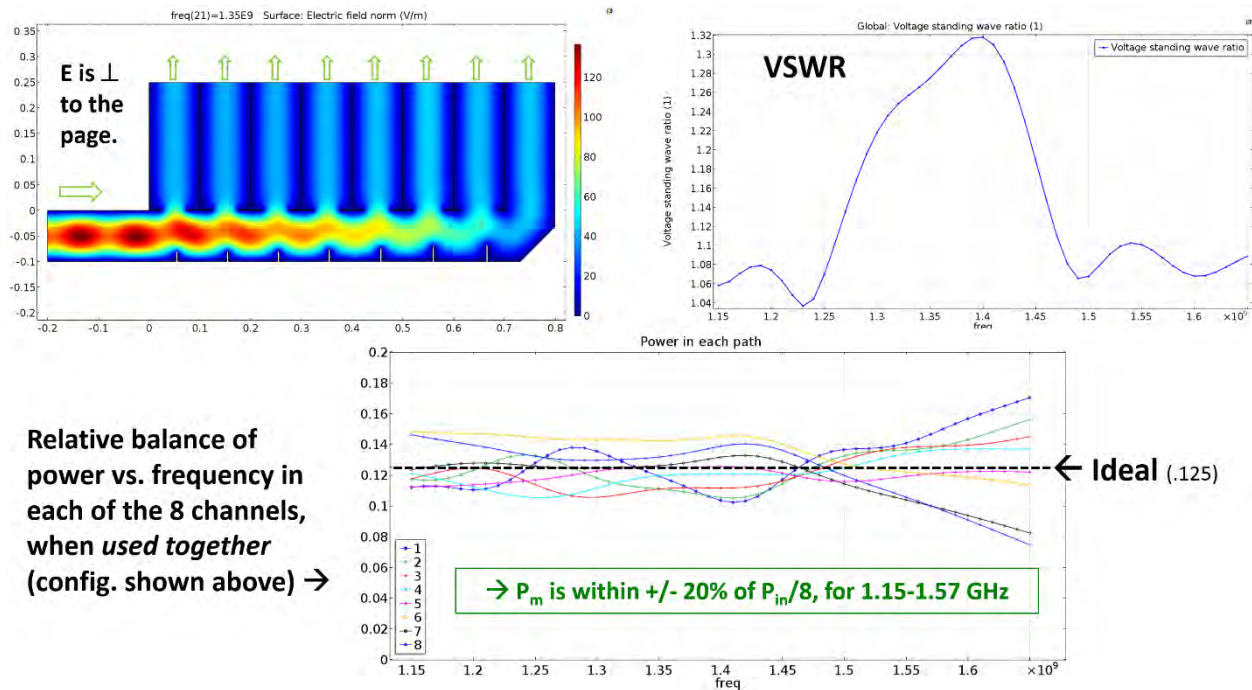


Figure 15. Detail of the coupled paths, which use inductive irises and stubs instead of a wire grill, to leak/couple the traveling-wave's power into eight separate waveguides.

Each output channel, as we step successively along the leaky-path from the input, must extract a greater fraction of the remaining power in the traveling wave. Ideally, the 1st channel couples exactly 1/8th of the input power, or $P_{in}/8$. For the 2nd channel to extract the same absolute power, it must couple 1/7th of the *remaining* power, i.e., $(1/7)*(P_{in} - P_{in}/8) = P_{in}/8$. The 3rd channel must couple 1/6th of the power remaining in the leaky channel, and so on, with the final (8th) channel extracting *all* of the remaining power in the guide. As noted in Figure 15, the achieved balance in our example here is imperfect, but it may be close enough to do the job (and can likely be improved with some additional effort).

Figure 16 shows predicted performance based on a 3D full-wave RF model of an L-band version. The predicted bandwidth and aperture efficiency are very encouraging.

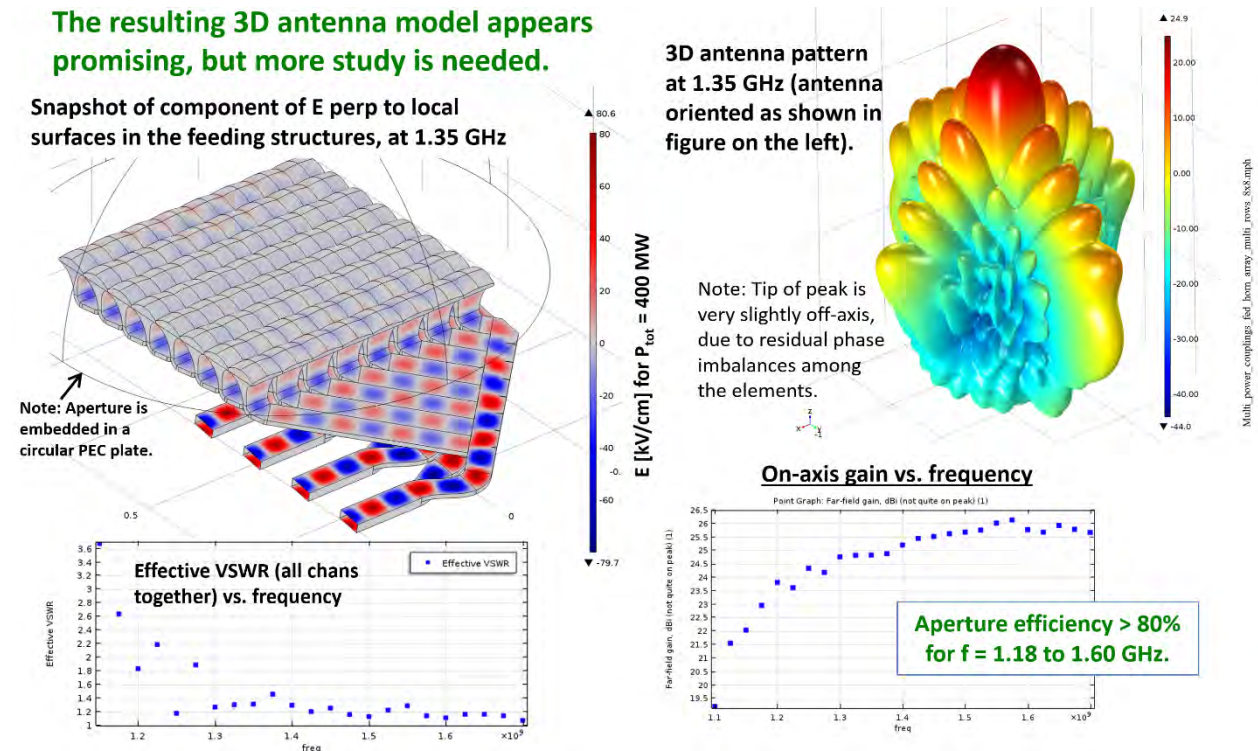


Figure 16. Predicted behavior of this fixed-beam wide-bandwidth antenna is encouraging.

4. DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

Work performed during this 11th quarter of the R&D program included continued investigation into improved designs and design methods/recipes for the AAWSEA (including suggested configurations), and the identification, design, and analyses of a novel leaky-wave high-gain HPM-capable antenna that can be directly-connected, without requiring any mode-conversion, to any cylindrical-type HPM-source having a TM_{01} -circular mode output. This report also notes our investigation (under a separately-funded program⁸) of an antenna concept that combines dielectric-filled forward-traveling leaky-wave structures with compensating-path waveguides, to drive arrays of small horns. The key feature of such a configuration is its *fixed-direction beam* as the frequency is varied. This effectively extends the applicability of leaky-wave structures to broader bandwidth HPM/HPRF sources.

With only 4 months and 6% of the funds left to go, this 37-month research program is closing-in on its schedule and funding limits. Overall, we are pleased with what we have accomplished so far, which has included the discovery, design, analyses, improvement, and documentation of a variety of HPM-capable, forward-traveling wave, leaky-wave antennas. We also conclude that, as an area of productive research, there still remain many interesting avenues to explore under the banner of “Low-Profile Leaky-Wave HPM Antennas.” Over the last several years, it seems that the DEW community (and its HPM/HPRF side in particular) has grown to appreciate, more than ever before, both the substantial present value and enormous future potential that these antennas bring toward realization of practical DEWs.

We appreciate ONR’s support for this R&D.

BIBLIOGRAPHY (alphabetical)

- Bodnar, D.G. and D.T. Paris, "New Variational Principle in Electromagnetics," *IEEE Trans. Antennas & Propagat.*, vol. AP-18, pp. 216-223, 1970
- Courtney, C.C. and C.E. Baum, "The Coaxial Beam-rotating Antenna (COBRA): Theory of Operation and Measured Performance," *IEEE Trans. Antennas Propag.*, vol. 48, no. 2, pp. 299-309, Feb. 2000.
- Goldstone, L.O. and Oliner, A.A., "Leaky-Wave Antennas I: Rectangular Waveguides," *IRE Trans. Ant. and Propagat.*, Oct., 1959, pp. 307-319.
- Goldstone, L.O. and Oliner, A.A., "Leaky-Wave Antennas II: Circular Waveguides," *IRE Trans. Ant. and Propagat.*, May., 1961, pp. 280-290.
- Harrington, R.F. and J.R. Mautz, "A High Power TM_{01} Circular to TE_{10} Rectangular Waveguide Mode Converter," Seventh International Conference on Antennas and Propagation, (IEE), York, 1991, pp. 125-128 vol.1.
- Haworth, M.D., et. al, "Significant Pulse-lengthening in a Multigigawatt Magnetically Insulated Transmission Line Oscillator," *IEEE Trans. Plasma Sci.*, vol. 26, no. 3, pp. 312-319, Jun 1998.
- Honey, R.C., "A Flush-Mounted Leaky-Wave Antenna with Predictable Patterns," *IRE Trans. Antennas and Propagat.*, 7, pp. 320-329, 1959.
- Ishimaru, A.K. and Beich, F.R., "Pattern Synthesis With a Flush-Mounted Leaky Wave Antenna on a Conducting Circular Cylinder," *J. of Res. of the Nat. Bureau of Standards-D. Radio Propagat* Vol. 66D, No.6, Nov- Dec. 1962, pp. 783-796.
- Jull, E.V., "Radiation from Apertures," Chap. 5 of *Antenna Handbook: Theory, Applications, and Design*, Ed. by Y.T. Lo and S.W. Lee, Van Nostrand Reinhold, NY, 1988.
- Koslover, R.A., C.D. Cremer, W.P. Geren, D.E. Voss, and L.M. Miner, "Compact, Broadband, High Power Circular TM_{01} to TE_{11} Waveguide Mode Converter," US Patent No. 4,999,591, March 12, 1991.
- Lewin, L., "Theoretical analysis of the junction discontinuity between a straight and a curved section of rectangular waveguide," *Proc. IEE*, Vol. 124, pp. 511-516, 1977.
- Lewin, L., "The E-plane Taper Junction in Rectangular Waveguide," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-27, pp. 560-563, 1979.
- Marcuvitz, N., *Waveguide Handbook*, McGraw-Hill, NY, 1951.
- Nishida, S., "Coupled Leaky Waveguides I: Two Parallel Slits in a Plane" *IRE Trans. Ant. and Propagat.*, May, 1960, pp. 323-330.
- Nishida, S., "Coupled Leaky Waveguides II: Two Parallel Slits in a Cylinder," *IRE Trans. Ant. and Propagat.*, July, 1960, pp. 354-360.
- Oliner, A.A. and R.G. Malech, "Radiating Elements and Mutual Coupling," "Mutual Coupling in Infinite Scanning Arrays," and "Mutual Coupling in Finite Scanning Arrays," -- Chaps. 2, 3, and 4 respectively of *Array Theory and Practice*, Vol. II of *Microwave Scanning Antennas*, Ed. by R.C. Hansen, Peninsula Publishing, Los Altos, CA, 1985.
- Oliner, A.A., and D.R. Jackson, "Leaky Wave Antennas," Chap. 11 of *Antenna Engineering Handbook*, 4th Ed., Edited by J.L. Volakis, McGraw-Hill, NY, 2007.
- Schwinger, J., and D.S. Saxon, *Discontinuities In Waveguides - Notes on Lectures by Julian Schwinger*, Gordon and Breach Science Publishers, NY, 1968.
- Silver, S., *Microwave Antenna Theory and Design*, 1st Ed, publ. by office of Scientific Research and Development, National Defense Research Committee, NY, 1949.
- Vlasov, S.N. and I.M. Orlova, "Quasioptical Transformer which Transforms the Waves in a Waveguide Having Circular Cross-Section into a Highly Directional Wave Beam," *Radiophys. Quantum Electron.*, vol. 17, pp. 115-119, 1975.

SUGGESTED DISTRIBUTION LIST

Official Record Copy

Mr. Lee Mastroianni
E-Mail: lee.mastroianni@navy.mil
Code 30
Office of Naval Research
875 North Randolph St.
Arlington, VA 22203-1995 1 cy

Dr. Joong H. Kim
E-Mail: joong.kim@navy.mil
Code 30
Office of Naval Research
875 North Randolph St.
Arlington, VA 22203-1995 1 cy

Director, Naval Research Lab
E-mail: reports@library.nrl.navy.mil
Attn: Code 5596
4555 Overlook Avenue, SW
Washington, D.C. 20375-5320 1 cy

Defense Technical Information Center
E-mail: tr@dtic.mil
8725 John J. Kingman Road
STE 0944
Ft. Belvoir, VA 22060-6218 1 cy

Dr. Donald Shiffler
AFRL/RDH
Kirtland AFB, NM 87117-5776 1 cy

Dr. Kyle Hendricks
AFRL/RDHP
Kirtland AFB, NM 87117-5776 1 cy

Dr. Andrew D. Greenwood
AFRL/RDHE
Kirtland AFB, NM 87117-5776 1 cy

Dr. Susan Heidger
AFRL/RDH
Kirtland AFB, NM 87117-5776 1 cy

Mr. Matthew McQuage
Naval Surface Warfare Center
Dahlgren Division, Q07
Dahlgren, VA 22448 1 cy

Michael Wagaman
Advanced Technology Directorate
PEO Strike Weapons and Unmanned Aviation
Patuxent River, MD. 1 cy

Dr. Frank E. Peterkin
Director
Directed Energy Technology Office
17320 Dahlgren Road
Naval Surface Warfare Center
Dahlgren, VA 22448 1 cy

LTC Charles Ormsby
Chief
Directed Energy Requirements
Langley AFB, VA 1 cy

Patrick Randeson
Science, Technology and Weapons Analyst
Central Intelligence Agency
Washington, D.C. 1 cy