ANNUAL PROGRESS SUMMARY – YEAR 4
29 September 2016

To: technicalreports@afosr.af.mil
Subject: Annual Progress Statement to Drs. Arje Nachman and Jason Marshall
Contract/Grant Title: "Innovative use of Metamaterials in Confining, Controlling, and Radiating Intense Microwave Pulses"
Contract/Grant #: FA9550-12-1-0489
Reporting Period: 30 September 2015 – 29 September 2016

Preamble

This report presents progress during year 4 on the FY12 AFOSR Transformational Electromagnetics MURI program. This MURI Consortium is led by the University of New Mexico (Edl Schamiloglu, PI) and includes MIT (Richard Temkin, PI), OSU (John Volakis, PI), UC-Irvine (Alex Figotin, PI), and LSU (Robert Lipton, PI). Two satellite efforts are also affiliated with this MURI consortium: The University of Huddersfield, UK (Rebecca Seviour, PI) and the University of Strathclyde, UK (Adrian Cross, PI). The annual accomplishments and listing of publications portion of this report are organized in sections corresponding to each consortium member's contributions. The remaining questions are then addressed by the MURI PI on behalf of the entire consortium.

MIT has experimentally hot tested their complementary split ring resonator structure. The experimental results are in partial agreement with the computational results obtained using CST Particle Studio. The University of New Mexico is using MAGIC to simulate the CST Particle Studio results. This is work in progress.

The University of New Mexico has designed and manufactured their split ring resonator structure and the structure is installed on the accelerator for hot testing.

A hallmark of this year's effort is the MURI team's response to a request by the Advisory Board following the Year 3 Annual Review that structures designed by other team members (Ohio State and UC Irvine) be hot-tested at MIT and/or UNM. Plans for this are discussed in detail in this report.

Finally, the MURI team has submitted proposals to Wiley/IEEE Press and CRC Press for an edited book entitled *High Power Microwave Sources and Technologies.* Both

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proposals were accepted and a decision moving forward will be made end early October 2016.

The third annual review of this MURI was held October 21, 2015 at an AFOSR facility in Arlington. In addition to the program managers, in attendance were each of the university PI's or their representatives, and many of the Advisory Board members.

University of New Mexico Year 4 Accomplishments:

The University of New Mexico (UNM) has continued hosting monthly graduate student teleseminars with all universities, advisory board members, and AFRL scientists participating. Table 1 summarizes which universities presented during Year 4 of this grant.

Table 1. Year 4 graduate student teleseminars.

October 02, 2015	University of California, Irvine
December 04, 2015	University of Strathclyde
February 05, 2016	University of New Mexico
March 04, 2016	Massachusetts Institute of Technology
April 01, 2016	Ohio State University
May 06, 2016	University of California, Irvine
June 06, 2016	Louisiana State University
July 01, 2016	University of Huddersfield
August 05, 2016	University of New Mexico
September 02, 2016	Massachusetts Institute of Technology
October 07, 2016	Ohio State University
November 04, 2016	University of California, Irvine

UNM has been coordinating and overseeing overall progress and interactions among the consortium members.

UNM's technical focus has remained the same and can be summarized in three broad areas: i) use of one of their two intense relativistic electron beam accelerators to experimentally test metamaterial (MTM) slow wave structures (SWSs) as they become realized; explore an alternate non-negative index "MTM-like" concept for a high power traveling wave tube amplifier (TWTA), and ii) study the properties of MTM SWSs (e.g., change in resonant frequency) as their physical characteristics change due to the intense electromagnetic environment; incorporating MTMs in High Power Microwave (HPM) components, and iii) develop plasma and optical diagnostic capabilities to perform *in situ* studies of MTM SWSs during operation.

Below is a detailed summary of the UNM accomplishments.

i) High Power SWS Design - UNM selected of broadside-coupled SRRs (BC-SRRs) as the basic building block of a prospective SWS. The BC-SRR has non-bianisotropic properties due to the fact that broadside coupling of ring and charge distribution does not result in a net electric dipole. This is in contrast to edge-coupled SRRs that are bianisotropic due to the asymmetry. The BC-SRR provides negative permeability and inserting these in a cut-off waveguide provides negative permittivity.

This 18-20 period BC-SRR SWS generates a TE-like RF mode at a frequency of 1.1 GHz that is evanescent in the waveguide and gets transformed into a hybrid mode due to reflections from the non-uniformities introduced by the BC-SRR SWS, which, in turn, provides the E_z component for interaction with the electron beam. Output powers of over 100 MW have been observed in particle-in-cell simulations with good extraction. A rough MTM SWS was constructed for cold tests and has been completely characterized and the results are in agreement with HFSS calculations. A complete MTM SWS assembly has been manufactured and is now installed on the SINUS-6 accelerator and is ready for hot tests, which will commence October 2016.

UNM also studied all-metallic corrugated waveguide SWSs and their dispersive characteristics as a function of corrugation depth. They found that negative dispersion appears after a certain corrugation depth, after which the lowest order modes in the structure are hybrid modes. This has been published in the IEEE Transactions on Plasma Science Special Issue on High Power Microwave Generation, August 2016. This portion of the UNM work has also fostered a collaboration with Rob Lipton's group at LSU, which is ongoing.

This portion of the UNM work has also elements in collaboration with UC Irvine. UCI has been modeling the UNM structure using their multi-transmission line theory and UNM has been modeling the UCI DBE structure.

ii) Metamaterials for Passive and Active HPM Components – During this year, UNM focused on applying the proposed group theory in designing a two dimensional metamaterial structure using a formalized method with desired electromagnetic properties. Group theory has been used in chemistry to classify molecules based on their symmetry; it has been shown that group theory can be used to determine the electromagnetic properties of metamaterials. The metamaterial is all-metallic, feasible to be fabricated and mounted which is suitable HPM environments.

We focused on designing a metamaterial that exhibits DNG properties when the E field is parallel to its plane and the H field is perpendicular to it, to be used as a load in a waveguide and to interact with TM modes for one of our experiments.

Using group theory, we showed that it is to possible to have a metamaterial structure, constructed by unit cells of variable dimensions, that exhibits negative permittivity and permeability at the same frequency. The proposed metamaterial dispersion diagram has been simulated and confirms that the designed metamaterial ($\vec{E}, \vec{H}$ and $\vec{k}$) forms a left-handed (LH) behavior.

We have also worked on designing high power microwave antennas using split ring resonators along the narrow wall of a rectangular waveguide. We have demonstrated that this design can decrease the overall size of the antenna compared to conventional slot waveguide antennas by almost 50%.

iii) Metamaterial Survivability - Our work has continued in two areas. The first is the investigation of the time response of metamaterials (MTMs) suitable for microwave applications. We have continued to study the temporal response of SRR arrays placed inside cutoff waveguide exhibiting double negative (DN) constitutive parameters. This year, refined experiments and numerical modeling have investigated, in detail, the three response time scales observed previously. It appears that these responses are determined by 1) the waveguide itself, 2) the ring-ring axial spacing, and 3) the position of the first set of rings (at the input end of the waveguide). The behavior is complex and nonmonotonic (e.g. larger axial ring-ring spacing does not necessarily lead to increased time delay). Experimentally, we have observed directly – for the first time we believe – backward wave propagation where DN behavior is observed. Additionally, we are developing a linear circuit network model aimed at capturing the time response of a SRR-loaded cutoff waveguide. Initial comparisons with fully numerical CST simulations are encouraging.

Secondly, we are working closely with Prof. Schamiloglu's group on preparing for high power experiments utilizing an MTM structure in a TWT configuration. In particular, we are taking the lead on breakdown diagnostics, as discussed in previous reports.

University of New Mexico Publications:

Archival Publications:

- S.C. Yurt, A. Elfrgani, M.I. Fuks, K. Ilyenko, and E. Schamiloglu, "Similarity of Properties of Metamaterial Slow-Wave Structures and Metallic Periodic

Structures," IEEE Trans. Plasma Sci. Special Issue on High Power Microwave Generation, vol. 44, 1280-1286 (2016).

Conference Publications:

- S.C. Yurt, S. Prasad, M. Fuks, and E. Schamiloglu, "Designing of an O-Type BWO with a Metamaterial Slow-Wave Structure," Proc. IVEC 2016 (Monterey, CA, April 19-21, 2016), DOI: 10.1109/IVEC.2016.7561791.
- E. Schamiloglu, M. Fuks, S. Prasad, S. Yurt, A. Elfrgani, H. Seidfaraji, and J. McConaha, "Recent Advances in the University of New Mexico High Power Microwave Program," (Plenary) Proc. ICMRE 2016 (Chengdu, China, May 9-11, 2016), PS2-1-9.
- E Schamiloglu, S.C. Yurt, S.D. Prasad, and M I Fuks, "Advances in All-Metal Metamaterial Slow Wave Structure Design for High Power Microwave Generation, Proc. EUROEM 2016 (London, UK, July, 2016), paper 11.C.1.
- X. Pan, C.G. Christodoulou, and J. Lawrance, "Design of High Power Microwave Antennas Using 3D Printing Technology," *IEEE APS/URSI 2016*, Puerto Rico, pp. 821-822.
- H.S. Faraji, G. Atmatzakis, and C.G. Christodoulou, "High Power Microwave Polarization Rotator," International Union of Radio Science (URSI), Boulder, January, 2016.

MIT Year 4 Accomplishments:

Summary of Experimental Results from the First Experimental Runs:
MIT graduate student Jason Hummelt conducted experimental research using an intense electron beam passing through a metamaterial loaded waveguide. Power levels of up to 5 MW were observed in backward wave modes at a frequency of 2.40 GHz using a one microsecond pulsed electron beam of 490 keV, 84 A in a 400 G guide magnetic field. Contrary to expectations, the output power was not generated in the Cherenkov mode. Instead, the presence of the magnetic field, which is required to transport the electron beam, induced a Cherenkov-cyclotron (or "anomalous Doppler") instability at a frequency equal to the Cherenkov frequency minus the cyclotron frequency. Nonlinear simulations indicate that the Cherenkov-cyclotron mode should dominate over the Cherenkov instability at lower magnetic field where the highest output power was obtained. At higher values of magnetic field, from 750 to 1500 G, a symmetric metamaterial mode was excited but only at power levels in the tens of Watts to hundreds of Watts level. The low power results at higher magnetic field do not agree with theory and cannot be easily explained at this time. Future research will concentrate on

explaining these results. This research was part of the thesis research of Jason Hummelt, who received a Ph. D. degree at MIT in April, 2016.

Summary of Experimental Results from the Second Experimental Runs:
A second set of experiments is underway designed and conducted by graduate student Xueying Lu. The metamaterial waveguide consists of two identical plates. In the first runs, these plates were aligned in parallel and in the same orientation. In the second set of runs, the plates are parallel but one plate is reversed with respect to the other plate. This required a complete new fabrication of the metamaterial structure. First runs of the new structure have shown output powers at the megawatt power level when operated at low magnetic field. However, the power level in the two output arms is no longer equal. This inequality is in agreement with theory. The map of the operating space in terms of output power and frequency vs. voltage, current and magnetic field is currently being measured.

Collaboration with Ohio State University and UC Irvine
A detailed plan for testing the Ohio State structure at MIT has been developed in collaboration with graduate student Ushemadzoro Chipengo and Prof. John Volakis. The operating frequency of the Ohio State structure is expected to be near 5 GHz and some new equipment will be needed to make accurate power measurements at this frequency in the WR284 waveguides used at MIT. Discussions have also been carried out with Prof. Capolino of UC Irvine on possible tests of the UC Irvine structure at MIT. The UC Irvine structure is also predicted to operate near 5 GHz.

MIT Publications:

Archival Publications:

- J.S. Hummelt, X. Lu, H. Xu, I. Mastovsky, M.A. Shapiro, and R.J. Temkin, "Coherent Cherenkov-Cyclotron Radiation Excited by an Electron Beam in a Metamaterial Waveguide" (submitted for publication, 2016)

Conference Publications:

- J. Hummelt, X. Lu, H. Xu, M. Shapiro, and R. Temkin "High Power Microwave Generation from a Metamaterial Waveguide," Proc. IVEC 2016 (Monterey, CA, April 19-21, 2016), DOI: 10.1109/IVEC.2016.7561790.

Ohio State University Year 4 Accomplishments:
In the past year, Ohio State (OSU) fabricated and tested a 3-section inhomogeneous Slow Wave Structure (SWS) for high efficiency BWO applications. This experiment is, to the

best of our knowledge, the first demonstration of multiple secondary inflection points (*MSIPs*) in the dispersion curve of a BWO SWS. PIC simulations validated the measurements. This SWS design delivered 8.25 MW output power at 2.64 GHz corresponding to a 70% efficiency. We also conducted a first-of-its-kind study on inhomogeneous SWSs to provide optimum profiles for BWO operation. This study provided insights on the frequency response and output power levels of various SWS profiles when the beam voltage is varied. As part of an ongoing collaboration with MIT, OSU designed a complete SWS for an upcoming hot test experiment at MIT's Plasma Science and Fusion Center. The SWS design featured a mode converter, output coupler and a modified power measurement coupler. Power generation was achieved using a novel 2-stage beam-mode interaction concept. For the OSU-MIT experiment entire SWS was redesigned to fit into MIT solenoid and mate to existing WR284 output and measurement system. For the proposed BWO experiment, PIC simulations predict an electron beam interaction with a hybrid TE_{11} mode yielding over 16 MW at 5 GHz in a TE_{01} mode. This corresponds to an efficiency of 40%.

Ohio State also made key innovations in developing novel coupled transmission line concepts that can support high order dispersion modes. Key aspect in realizing the novel dispersion curves is the choice of non-identical transmission lines that are as many as 4 in number. These transmission lines can be free standing (as is the case inside the TWT or BWOs), printed or embedded in dielectrics. By controlling the coupling parameters among the transmission lines a variety and nearly arbitrary dispersion characteristics can be generated. These include Degenerate Band Edge and Magnetic Photonic Crystal mode as well as other higher order modes that can feature novel propagation phenomena. In effect, the proposed coupled multi-transmission line concept replaces the need for constructing complex material crystals and multilayered configurations. That is, the multi-transmission line concept provides a means for generating novel modes without resorting to expensive material fabrication.

As an example of the multi-transmission line concept, a 'butterfly' structure was designed. This butterfly structure is composed of four coupled transmission lines. Each pair of the lines is composed of pair of curved ring-bars (CRBs), each independently designed from the other to allow for more parameter control. This butterfly SWS demonstrated Degenerate Band Edge (DBE) mode, and can be used to design Backward Wave Oscillators inside circular waveguides for high power output.

Ohio State also fabricated and tested a simpler CRB slow wave structure for wideband high power TWTs. This CRB considered of a single pair of transmission lines. Simulations predicted that the TWT output power will be more than 1 MW with 20% bandwidth centered at 2.1 GHz. Previously, the structure was modeled and optimized using a coupled transmission line model to predict the slow wave formation with TM_{01}

mode dominance. This year, a section of 6 period SWS was fabricated and tested for experimental demonstration of the slow wave formation. A novel synthetic technique was also used to determine the $\omega - \beta$ relation using the six-period fabricated CRB structure. Measurement results exhibited a phase velocity of $0.7c - 0.75c$ across $2 - 2.5$ GHz with a maximum error of less than 5%. The on-axis interaction impedance (K_0) was > 43Ω across the entire band, and a satisfactory agreement with theoretical predictions.

Ohio State University Publications:

Archival Publications:

- U. Chipengo, M. Zuboraj, N.K. Nahar, J.L. Volakis, "A Novel Slow-Wave Structure for High-Power Ka-Band Backward Wave Oscillators with Mode Control," *IEEE Trans. Plasma Sci.*, vol. 43, 1879-1886 (2015).
- U. Chipengo, N. K. Nahar and J. L. Volakis, "Cold Test Validation of Novel Slow Wave Structure for High-Power Backward-Wave Oscillators," in *IEEE Trans. Plasma Sci.*, vol. 44, no. 6, pp. 911-917 (2016).
- M. Zuboraj and J.L. Volakis, "Curved Ring-Bar Slow Wave Structure for Wideband High Power Traveling Wave Tubes," *IEEE Trans. Plasma Sci.,* vol. 44, no. 6, pp. 903-910 (2016).
- M. Zuboraj, U. Chipengo, N.K. Nahar and J.L. Volakis, "Experimental Validation of Slow-Wave Phenomena in Curved Ring-Bar Slow-Wave Structure," *IEEE Trans. Plasma Sci.* (2016) (in press).
- U. Chipengo, N.K. Nahar and J.L. Volakis, "Design of an Efficient Hybrid TE_{11} Mode Based Backward Wave Oscillators Operating in Low Magnetic Fields" in *IEEE Trans. Plasma Sci.* (submitted).
- M. Zuboraj, K. Sertel, and J.L. Volakis "Novel Propagation Model of Degenerate Band Edge Modes Using Non-identical Coupled Transmission Lines," *IEEE Trans. Microw. Theory Techn.* (submitted).
- M. Zuboraj and J.L. Volakis, "Realization of Slow Wave Phenomena Using Coupled Transmission Lines and their Application to Antennas and Vacuum Electronics," Ch. in book *Broadband Metamaterials in Electromagnetics: Technology and Applications,* Ed. D.H. Werner, 2016. https://www.crcpress.com/Broadband-Metamaterials-in-Electromagnetics-Technology-and-Applications/Werner/p/book/9789814745680

Conference Publications:

- M. Zuboraj, K. Sertel and J.L. Volakis "Non-identical Coupled Transmission Lines and Higher-order Dispersion Engineering" *APS/URSI 2016 IEEE*

International Symposium on Antennas and Propagation, Fajardo, Puerto Rico, 2016

- M. Zuboraj, U. Chipengo, N.K. Nahar and J.L. Volakis "A Novel Slow Wave Structure for V-band Traveling Wave Tube" *APS/URSI 2016 IEEE International Symposium on Antennas and Propagation,* Fajardo, Puerto Rico, 2016
- U. Chipengo and J.L. Volakis, "A highly efficient X band BWO with an inhomogeneous slow wave structure," *2015 IEEE Pulsed Power Conference (PPC)*, Austin, TX, 2015.
- U. Chipengo, N.K. Nahar and J.L. Volakis "Cold Test of Homogeneous and Inhomogeneous Slow Wave Structures for High Power Backward Wave Oscillators" *APS/URSI 2016 IEEE International Symposium on Antennas and Propagation,* Fajardo, Puerto Rico, 2016
- U. Chipengo, N.K. Nahar and J.L. Volakis, "Experimental Demonstration of Multiple Secondary Inflection Points in a Novel Slow Wave Structure for Highly Efficient Backward Wave Oscillators*" IEEE National Aerospace and Electronics Conference,* Dayton, OH, 2016.
- U. Chipengo and J.L. Volakis, "Experimental Validation of Mode Dominance Reversal in Novel Slow Wave Structures for High Power Backward Wave Oscillators," National Radio Science Meeting, Jan 5-8, 2016, Boulder CO.

UC Irvine Year 4 Accomplishments: In Year 4 of this MURI project the UCI group has been very active in developing new schemes for high power microwave generation utilizing the proposed new scheme based on the four mode interaction regime associated with the degenerate band edge (DBE). The four mode degeneracy has been verified to exist in all-metallic waveguides in a cold test, and in the high power regime with an electron beam, utilizing PIC (particle in cell) simulations as well. The UCI team reports the following milestones:

(i) The DBE has been experimentally demonstrated in all-metallic slow wave structures (SWSs) in collaboration with The University of New Mexico (cold test)

(ii) Low starting electron beam current in oscillators based on the DBE has been reported using the four mode interaction based on the coupled mode theory previously developed, and now also using PIC simulations

(iii) The operation of a DBE oscillator (DBEO) has been shown for the first time based on PIC simulations in collaboration with UNM; which operates for short pulses and high beam energy

(iv) The DBEO has been demonstrated to operate also with low beam current, and promising high efficiency from preliminary PIC simulations (up to 23% and optimization is currently ongoing)

(v) A new interaction scheme based on another degeneracy, the stationary inflection point (SIP), for wideband amplification is proposed for the first time.

(vi) Novel metamaterial-based SWSs with the four mode interaction regime are designed for potential a hot test experiment conducted in collaboration with UNM and/or MIT partners.

The UCI team approach is based on exploiting the degeneracy conditions (coalescence of eigenmodes) for achieving super synchronism (i.e., multimode with degeneracy) with the electron beam. The achievements are as follows:

1) The UCI team has demonstrated giant gain enhancement and low starting electron beam current using the four mode interaction regime. The UCI team has shown that the four mode synchronized with the electron beam enables a novel oscillation regime in which the starting oscillation beam current scales as L^{-5} where L is the length of the interaction region.

3) The UCI team has successfully demonstrated the degenerate band edge (DBE) in metallic circular waveguides with periodic metallic loading, experimentally in collaboration with the University of New Mexico, with Christos Christodoulou group. A giant scaling of the quality factor as L^5 where L is the length of the SWS is reported.

3) The UCI team has established a collaboration with UNM for utilization of the four-mode interaction concept in high power oscillators. An-all metallic, corrugated waveguide SWS has been proposed as a test bench for the four mode interaction scheme. We have shown preliminary PIC simulation proving that the structure is capable of producing ~100 MW at 4.5 GHz with an efficiency of ~10% (short pulse, ~10 ns). Moreover, the structure is able to provide for at least 23% efficiency with 34 MW of RF power (longer pulse, ~250 ns). These are first ever implementations and the team is working to boost the performance of the DBEO in order to perform a hot test in collaboration with UNM. The teams also collaborate in various aspects of numerical simulations of UCI and UNM structures using different PIC solvers, as well as using the coupled-mode theory.

4) The team has established collaboration with the MIT team. The UCI team proposed a metamaterial-based SWS compatible with the high power test setup at MIT. The structure combines the framework of metamaterials previously used by MIT with a new design based on the four mode interaction to produce a phenomenologically-novel scheme in the interaction and consequently boosting the oscillator efficiency. Moreover, the new proposed structure is smaller in size with less metallic inclusions than MIT's counterpart. The structure, which is still under optimization using PIC simulations, is capable of

producing at least 5 MW at 5 GHz with at least 10% efficiency. The team also exchanges ideas with the MIT group so the UCI design would be suitable for the experimental setup at MIT.

5) The UCI team is also working on a new scheme for amplifiers. This is based on three-mode interaction with the electron beam relying on the stationary inflection point (SIP) degeneracy in the dispersion of slow-wave structures. The SIP is more tolerant to high electron beam current for high power application compared to the DBE. Also it has a lenient dispersion relation that is shown to be very beneficial in achieving wideband interaction with the electron beam. The team is investigating potential use of SIP in wideband power amplifiers. They also propose a realistic implementation of the SIP in metallic SWS with application to high power TWT. This concept will be further developed by the UCI team in Year 5 of this project.

6) Besides these efforts, the UCI team has been exploring new concepts that would lead to an operation scheme based on degeneracy with very high electron beam energy. One of the efforts is based on a pulse compression scheme utilizing the electron beam as a switch. Another concept is based on the gain and loss balance which is a critical condition that guarantees the existent of point of degeneracy. Also, the concept of Parity-Time symmetry is invoked when gain and loss exhibit spatially symmetry in the structure. The team is actively exploring this unprecedented avenue for potential use in high power microwaves. This concept will be also further developed by the UCI team in Year 5 of this project.

- UCI Student (Mr. M. Othman) has visited the University of New Mexico twice, in summer of 2015 and spring of 2016 in order to establish collaboration. Verification of the DBE in all metallic waveguides in collaboration with Christos Christodoulou's group was one fruitful outcome of these visits. Moreover, several ideas were exchanged between the UCI and UNM teams during these visit in order to push forward the DBEO hot test experiment.
- Two articles published by the UCI group in 2016 have been selected in the editorial highlights in the *IEEE Trans. Plasma Sci*. in April and June issues.

UC Irvine Publications:

Archival Publications:

- M.A.K. Othman, F. Yazdi, A. Figotin, and F. Capolino, "Giant Gain Enhancement in Photonic Crystals with a Degenerate Band Edge," *Phys. Rev. B*, vol. 93, no. 2, p. 024301, Jan. 2016.

- V.A. Tamma, A. Figotin, and F. Capolino, "Concept for Pulse Compression Device Using Structured Spatial Energy Distribution," *IEEE Trans. Microw. Theory Tech.*, vol. 64, no. 3, pp. 742–755, Mar. 2016.
- M.A.K. Othman, M. Veysi, A. Figotin, and F. Capolino, "Giant Amplification in Degenerate Band Edge Slow-Wave Structures Interacting with an Electron Beam," *Phys. Plasmas 1994-Present*, vol. 23, no. 3, p. 033112, Mar. 2016.
- M.A.K. Othman, V.A. Tamma, and F. Capolino, "Theory and New Amplification Regime in Periodic Multi Modal Slow Wave Structures with Degeneracy Interacting with an Electron Beam," *IEEE Trans Plasma Sci.*, vol. 44, no. 4, pp. 594 – 611, April 2016. Article is highlighted by the Editor in April's Issue.
- M.A.K. Othman, M. Veysi, A. Figotin, and F. Capolino, "Low Starting Electron Beam Current in Degenerate Band Edge Oscillators," *IEEE Trans Plasma Sci.*, vol. 44, no. 6, pp. 918-929 June 2016. Article is highlighted by the Editor in June's Issue.
- J. Sloan, M. A. K. Othman, and F. Capolino. "Theory of Double Ladder Lumped Circuits with Degenerate Band Edge." arXiv preprint arXiv:1609.00044 (2016).
- M.A.K. Othman, X. Pan, Y. Atmatzakis, C. Christodoulou, and F. Capolino, "Experimental Demonstration of Band Edge Degeneracy in Metallic Periodically-Loaded Circular Waveguide," (in submission), 2016.

Conference Publications:

- M.A.K. Othman, and F. Capolino, "Theory of Coupled Waveguides with Modal Degeneracies and Gain," Metamaterials 2016. The 10th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics, Crete, September 17-22 2016.
- M.A.K. Othman and F. Capolino, "Coupled Waveguides with Exceptional Points of Degeneracies," SPIE NanoScience + Engineering (OP16N), San Diego, CA, August 28 – September 1, 2016.
- M.A.K. Othman, F. Yazdi, and F. Capolino, "Exceptional Points of Degeneracy in Coupled-Mode Periodic Structures," International Symposium on Electromagnetic Theory (EMTS), Espoo, Finland, August 14–18, 2016.
- M. Veysi, M.A.K. Othman, and F. Capolino, "Time Domain Analysis of Coupled-Waveguides with Modal Degeneracies and Gain", IEEE International Symposium on Antennas and Propagation/USNC-URSI National Radio Science meeting, Fajardo, Puerto Rico, June 26 - July 1, 2016.
- M.A.K. Othman, A. Figotin, and F. Capolino, "Super Synchronous Operation of Traveling Wave Tubes Based on Band Edge Degeneracy," IEEE International Symposium on Antennas and Propagation/USNC-URSI National Radio Science meeting, Fajardo, Puerto Rico, June 26 - July 1, 2016.

- M.A.K. Othman and F. Capolino, "Parity-Time Symmetry in Chain of Scatterers," IEEE International Symposium on Antennas and Propagation/USNC-URSI National Radio Science meeting, Fajardo, Puerto Rico, June 26 - July 1, 2016.
- M.A.K. Othman, M. Veysi, A. Figotin, and F. Capolino, "Degenerate Band Edge Electron Beam Oscillators: Low Starting Current", IEEE International Vacuum Electronics Conference (IVEC), Monterey, CA, April 19-21, 2016.
- M.A.K. Othman, M. Veysi, and F. Capolino, "Theory of Gain Enhancement in Periodic Structures with a Degenerate Band Edge," National Radio Science Meeting (USNC-URSI NRSM), 2016 United States National Committee of URSI, Boulder, CO, Jan. 5-8 2016.

Louisiana State University Year 4 Accomplishments: This year in coordination with UNM the LSU group identified a fundamental link between slow wave metamaterial impedance layers and corrugated metallic wave guides. The outer walls of the waveguide are perfect conductors with periodic corrugations. Asymptotic analysis applied to corrugated waveguides for wavelengths longer than the corrugations shows that the waveguide can be modeled as a smooth cylindrical waveguide surrounded by an anisotropic metamaterial impedance layer. The surface impedance is given by an explicit formula for square corrugations. For corrugations of general shape it is computed by solving a two point ode boundary value problem with coefficients given explicitly in terms of a function describing the profile of the corrugation. The surface impedance formula formally derived and used by Clarricoates and Sobhy in the 1970's is rigorously shown to be that of a metamaterial associated with infinitely thin ribs.

The effective surface impedance is a purely subwavelength phenomenon. The theory unambiguously shows that the presence of negative group velocity hybrid modes is a multiscale phenomenon represented by an anisotropic effective surface impedance. It is shown that the negative group velocity arises from subwavelength resonances generated at the corrugated boundary for sufficiently deep corrugations. It is shown from first principles that the corrugated boundary functions as a true metamaterial influencing dispersion at wavelengths longer than the period of the corrugations. This reduced order model is fast and easy to compute relative to full numerical simulation and should be useful in design slow wave effective impedance structures. This is part of an ongoing collaboration with UNM and optimal corrugation geometries will be prototyped in collaboration with UNM.

Louisiana State University Publications:

Archival Publications:

- R. Lipton R. and R. Viator, "Bloch waves in crystals and periodic high contrast media," *ESAIM: Mathematical Modeling and Numerical Analysis*, June 2016, http://dx.doi.org/10.1051/m2an/2016046.
- R. Lipton, A. Polizzi, and L. Thakur, "Negative Group Velocity from Perfectly Conducting Subwavelength Corregations," *SIAM J. on Applied Math.*, submitted for publication.
- R. Lipton and R. Viator, "Creating Band Gaps in Periodic Media," SIAM Multiscale Modeling and Simulation, submitted for publication.

Conference Presentations:

- R. Lipton "Novel Dispersion from Metamaterials," Colloquium, Department of Mathematical Sciences, New Jersey Institute of Technology, September 25, 2015.
- R. Lipton, "The Mathematics of Dispersion in Electromagnetic Meta-Materials," Department of Mathematical Sciences, University of Delaware, March 19, 2015.
- R. Lipton and R. Viator, "Spectral Theory with Out Ellipticity: Bloch Waves and Separation of Frequency Spectra," SIAM Conference on Mathematical Aspects of Materials Science, May 8-12, 2016, Philadelphia, PA.
- R. Lipton and R. Viator, "High Contrast Periodic Media: Bloch waves and band gaps," AMS Joint Mathematics Meetings, January 6–9, 2016, Seattle, WA.