



Innovative use of Metamaterials in Confining, Controlling, and Radiating Intense Microwave Pulses

**Edl Schamiloglu
UNIVERSITY OF NEW MEXICO**

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Final Report**

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Submitted by:

Edl Schamiloglu — Principal Investigator and Distinguished Professor
Department of Electrical and Computer Engineering
Associate Dean for Research
School of Engineering
University of New Mexico
Albuquerque, NM 87131
Tel. (505) 277-6095
e-mail: edls@unm.edu

TABLE OF CONTENTS

TABLE OF CONTENTS	2
LIST OF FIGURES	3
I. ABSTRACT	4
II. INTRODUCTION	5
III. ADVANCES MADE	6
Chapter 2. Multi-Transmission Line Models	6
Chapter 3. Generalized Pierce Model from the Lagrangian	7
Chapter 4. Dispersion Engineering.....	9
Chapter 5. Perturbation Analysis of Maxwell's Equations.....	11
Chapter 6. Similarity of the Properties of Conventional Periodic Structures with Metamaterial Slow Wave Structures	14
Chapter 7. Group Theory Approach for Designing Metamaterial Structures for HPM Devices.....	15
Chapter 8. Time Domain Analysis of the Evolution of Electromagnetic Fields in Metamaterial Structures	16
Chapter 9. Metamaterial Survivability in the High Power Microwave Environment..	16
Chapter 10. Experimental Hot Test of Beam/Wave Interactions with Metamaterial Slow Wave Structures.....	17
IV. REFERENCES	18
V. PERSONNEL, PUBLICATIONS, INTERACTIONS, AWARDS FOR THE FINAL REPORTING PERIOD	20

LIST OF FIGURES

<p>Figure 1. Various SWSs. (a) Printed coupled microstrip lines that can realize the 3rd and 4th order dispersion curves. The field strength within the coupled transmission lines showing strong field intensities in the middle due to wave velocity slowdown. Wave amplitude representing field growth: (b) slow wave propagation within a helical wire structure placed in a waveguide, and (c) slow wave propagation within a curved ring-bar structure placed in a waveguide, the latter refer to traveling wave tube applications.</p>	6
<p>Figure 2. Periodic material structures to realize MPC and DBE modes. Top: Photonic crystals using simple dielectric stacking. Forward and backward waves are depicted using blue and green arrows, respectively. Bottom: Magnetic photonic crystals using volumetric stacks. Anisotropy is realized using metal strips printed on dielectric layers [8].</p>	7
<p>Figure 3. Section of infinitely long TWT consisting of electron beam surrounded by periodic, concentric, metallic rings embedded in a host material whose dielectric properties are those of a vacuum and a close-up view of the ε periodic interaction structure.</p>	11
<p>Figure 4. Cross-section of infinitely long TWT showing electron beam surrounded by periodic, concentric, metallic rings embedded in a host material whose dielectric properties are those of a vacuum.</p>	12
<p>Figure 5. Lozenge-shaped (above) and ellipsoidal (below) cross sections with different eccentricities corresponding to different aspect ratios $\Lambda = b/a$. Lengths with value a correspond to the z-direction.</p>	12
<p>Figure 6. Transmission coefficient as a function of frequency for an isotopic dielectric with dielectric constant 3.5 for an amplifier driven by a 1 kA beam.</p>	13
<p>Figure 7. The effect of aspect ratio Λ for lozenge-shaped inclusions with fixed filling fraction $\theta = 0.5508$.</p>	13
<p>Figure 8. The effect of filling fraction, symmetric lozenge-shaped inclusions.</p>	13

I. ABSTRACT

This final technical report describes our research over the past 5.5 years under the FY12 MURI award to investigate how metamaterials (MTMs) can be exploited as new means of high power microwave generation. We have concluded that MTMs have greatly expanded the parameter space for dispersion engineering for beam/wave interaction. We have demonstrated two operational high power MTM sources, one generating 5 MW at S-band and the other generating 100 MW in L-band. Considerable progress has been made in the theoretical understanding of these devices as well. This final report summarizes the discoveries made during this program and is written in a manner to provide a synopsis of the forthcoming *Advances in High Power Microwave Sources and Technologies using Metamaterials* (IEEE Press/Wiley, 2019).

II. INTRODUCTION

High power microwaves (HPMs), or directed energy RF, is an evolution of Vacuum Electron Devices (VEDs) that seeks to generate the highest peak power levels in the frequency range of 100s MHz through 10 GHz (and even higher frequencies) in short pulses (10s–100s ns in duration) that can be repetitively pulsed. They came onto the scene in the late 1960s following the advent of pulsed power drivers that not only provided high energy electron beams (on the order of a MeV and higher), but, concomitantly provided high currents as well (1–10's kA). Similar to VEDs, the electron beam is the power source from which the microwaves grow. Unlike VEDs, HPM sources have much less stringent vacuum and material requirements since their applications tend to be limited in scope with short mission times. The state-of-the-art in the practice of HPM sources has been led by intense beam-driven oscillators whose output scale as where is the peak output microwave power and is the operating frequency. This is the Figure-of-Merit (FOM) for HPM sources. Until recently, conventional wisdom suggested that, for emerging U.S. Air Force applications, the highest power on target (highest intensity field) was of greatest utility. However, recent advances in the understanding of the interaction of intense microwave fields with components and circuits argue that a tailored waveform synthesized at low power, and amplified to very high power, might provide even superior capabilities. This is termed waveform diversity.

Interest in metamaterials grew rapidly following the publication of Pendry in 2000 [1] and its implementation in practice by Smith afterwards [2]. The history of metamaterials dates back to the 19th century with numerous contributors, many of whom have only been recently rediscovered. This history has been reviewed in several books [3,4] and continues to be unraveled. While numerous books have been written on the electromagnetic properties of metamaterials, all of the applications that have been described to-date are at low power levels. In this research program, we brought together advances that have been made in studying metamaterials as slow wave structures (SWSs) for active electron beam-driven HPM devices. We discuss structures that satisfy Wasler's definition of a metamaterial, we also describe periodic SWSs with degenerate band edges (DBEs) that do not satisfy this definition, yet do offer novel engineered dispersion relations that are relevant to our overall goal seeking to discover novel beam/wave interactions that can be exploited for new HPM amplifiers.

This final report is organized as follows. Section III summarizes the advances made during this MURI program and each key contribution is summarized as a subsection. The advances are highlighted as Chapters 2-10 in the forthcoming *Advances in High Power Microwave Sources and Technologies using Metamaterials* (IEEE Press/Wiley, 2019). Section IV lists the references for this report and Section V summarizes personnel, publications, interactions, and awards during the final reporting period (this information for earlier reporting periods can be gleaned from the annual progress reports).

III. ADVANCES MADE

Chapter 2. Multi-Transmission Line Models

To understand the physics of engineered SWSs, it is necessary to analyze Coupled Transmission Lines (CTLs), as shown in Fig. 1. These CTLs, inherently periodic in nature, are loaded with coupled inductive and capacitive (L_M, C_M) elements in a periodic manner. As is well-known, any periodic loading supports Bloch waves [5] and exhibits passband and stopbands. The corresponding $\omega - \beta$ dispersion curves are of second order and even show supported waves with nearly zero group velocity at the band edge. By changing the material properties or loading of the CTLs as in the Fig. 1(a), the order of the dispersion curve can be altered, a process called dispersion engineering. Specifically, higher order dispersion curves (third or fourth) can be attained. Indeed, use of anisotropic material in periodic stacks, instead of isotropic ones, can lead to third or fourth order dispersion relation [6] (Fig. 2). The fourth order dispersion relation leads to maximally flat curves, and is associated with Degenerate Band Edge (DBE) modes that are inherently narrowband in nature [5,7-9]. Nevertheless, DBE modes provide the means for large field enhancement as the group velocity drops to nearly zero [5,7]. This reduction in group velocity also implies device miniaturization [10] and increased antenna directivity [8,11-13].

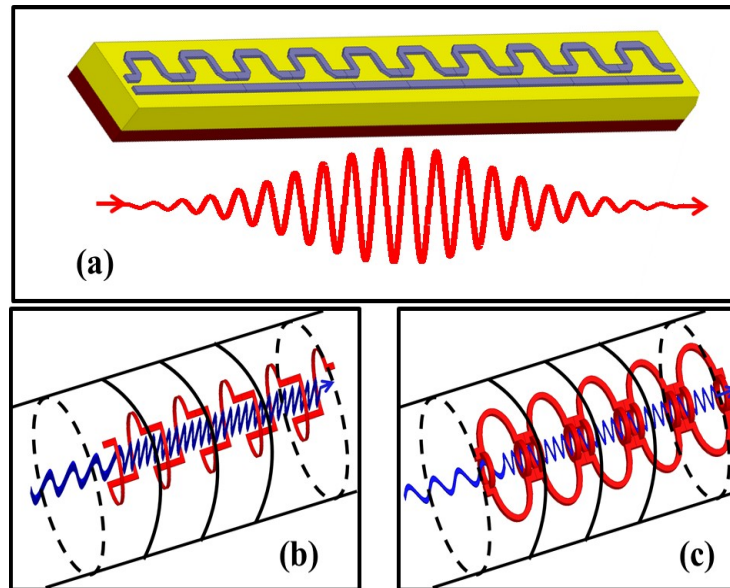


Figure 1. Various SWSs. (a) Printed coupled microstrip lines that can realize the 3rd and 4th order dispersion curves. The field strength within the coupled transmission lines showing strong field intensities in the middle due to wave velocity slowdown. Wave amplitude representing field growth: (b) slow wave propagation within a helical wire structure placed in a waveguide, and (c) slow wave propagation within a curved ring-bar structure placed in a waveguide, the latter refer to traveling wave tube applications.

Chapter 2 of *Advances in High Power Microwave Sources and Technologies using Metamaterials* summarizes advances made at Ohio State University and UC Irvine on multi-transmission line models. The relevant publications that form Chapter 2 are:

- A. Figotin and G. Reyes, “Multi-Transmission-Line-Beam Interactive System,” *J. Math Phys.*, vol. 54, 111901 (2013).

- V.A. Tamm and F. Capolino, “Extension of the Pierce Model to Multiple Transmission Lines Interacting with an Electron Beam,” *IEEE Trans. Plasma Sci.*, vol. 42, 899 (2014).
- M. Zuboraj, K. Sertel, and J.L. Volakis, “Novel Propagation Model of Degenerate Band Edge Modes Using Dual Non-Identical Pair of Coupled Transmission Lines” (arXiv:1612.00844, 2016).
- M.D. Zuboraj, *Coupled Transmission Line Based Slow Wave Structures for Traveling Wave Tubes Applications* (Ph.D. Dissertation, Ohio State University, Columbus, OH, 2016).

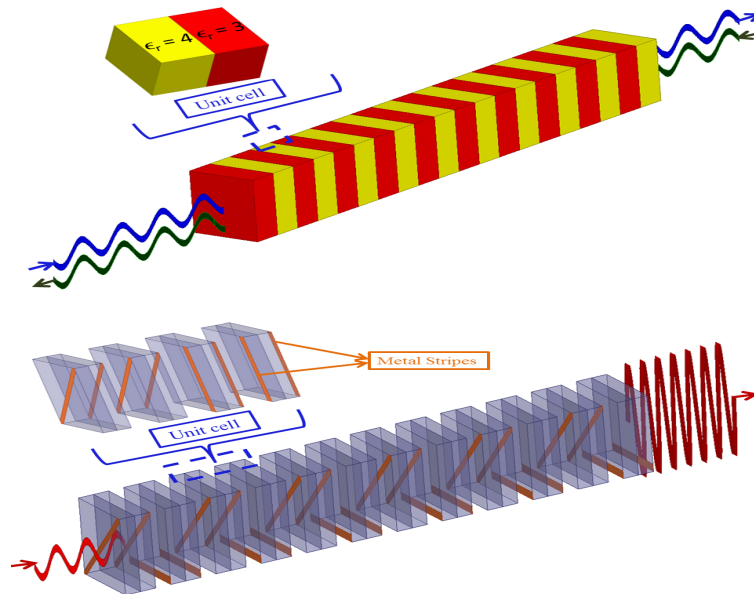


Figure 2. Periodic material structures to realize MPC and DBE modes. Top: Photonic crystals using simple dielectric stacking. Forward and backward waves are depicted using blue and green arrows, respectively. Bottom: Magnetic photonic crystals using volumetric stacks. Anisotropy is realized using metal strips printed on dielectric layers [8].

Chapter 3. Generalized Pierce Model from the Lagrangian

The subject of our studies in Chapter 3 of *Advances in High Power Microwave Sources and Technologies using Metamaterials* is the theoretical aspects of generation and amplification of microwave radiation by traveling wave tubes (TWTs). Generation and amplification of electromagnetic radiation can be produced by an enormous variety of devices of different designs depending on the frequency of the radiation and its power. A list of well-known microwave amplifying devices includes masers, magnetrons, klystrons, TWTs, crossed-field amplifiers, and gyrotrons. However different they are, they have one feature in common: an electron beam. Microwave radiation is commonly produced by microwave vacuum electronic devices, known formerly as microwave tubes. These devices use free electrons in a vacuum to convert energy from a DC power source to an RF (radio frequency) signal. In other words, as a result of the interaction between the electron beam and a properly designed structure, the kinetic energy of the electrons is converted into electromagnetic energy stored in the field, [14-17]. The key operational principle of any microwave device is a positive feedback interaction between coherent radiation by electrons radiating in-phase on the one hand and on the other hand electron

bunching caused by radiation on the stream of electrons. The electron bunching associated with acceleration and deceleration of groups of electrons along the beam constitutes the physical mechanism of radiation generation and its amplification.

An important class of microwave devices uses as its operation principle the Cherenkov radiation generated by charged particles propagating in or near a medium supporting slow waves with phase velocity comparable with the particle velocity. TWTs, the main subject of study here, belong to this class. TWTs are used widely in many areas including satellite communication and radar systems. A typical TWT consists of an elongated vacuum tube containing an electron beam which passes down the middle of an RF circuit (a slow-wave structure). The operation principle of a TWT is as follows. At one end of the TWT structure, the RF circuit is fed with a low-power radio signal to be amplified. As the RF signal travels along the tube at near the same speed as the electron beam, the electromagnetic field acts upon the beam and causes electron bunching with consequent formation of the so-called *space-charge wave*. The electromagnetic field associated with the space-charge wave induces more current back into the RF circuit, thus enhancing the bunching, and so on. The electromagnetic field thus builds up and is amplified as it passes down the structure until a saturation regime is reached and a large RF signal is collected at the output. The role of the slow-wave structure is to slow down the electromagnetic wave to match up with the velocity of the electrons in the beam, usually a small fraction of the speed of light. Such a synchronism is required for effective in-phase interaction between the structure and the beam with optimal extraction of the kinetic energy of the electrons. A typical slow-wave structure is the helix, which reduces the speed of propagation according to its pitch. Further details on the design and operation of TWT can be found in [14-18].

An effective mathematical model for a TWT interacting with an electron beam was introduced by J. R. Pierce, [19,20]. This model is the simplest one that accounts for wave amplification along the structure, energy extraction from the electron beam and its conversion into microwave radiation in the TWT. In Section 3.3 of Chapter 3 we provide a precise description of the model as presented in [19,20]. The mentioned presentation is done in the time domain, in contrast to other presentations dealing with the frequency domain counterpart. Though simple, Pierce's model allows for adequate estimates of the gain and it was used effectively in designing working TWTs in the 1950s. This model captures remarkably well significant features of wave amplification and the beam-wave energy transfer, and is still in use for basic design estimates.

The model presented by Pierce is one-dimensional and consists of: (i) An ideal linear representation of the electron beam and (ii) a lossless transmission line (TL) representing the waveguide structure. The transmission line is assumed to be homogeneous, that is, with uniformly distributed capacitance and inductance. To overcome Pierce's theory's limitations far more sophisticated nonlinear theories have been developed to model very involved physics of the electron beam and slow-wave structures [16,17,20]. Those are far more complex and their implementation often requires massive computer work.

In this Chapter we advance Pierce's theory to a theory that, while keeping its simplicity and constructiveness, allows for more complex slow-wave structures. We start by developing a Lagrangian field framework for the original model. Such a framework allows for extension of the model in two directions: (a) We can replace the transmission line with a multi-transmission line (MTL) and (b) we can dispense with the homogeneity assumption, thus considering general inhomogeneous systems consisting of a multi-transmission line (MTL) coupled to an electron beam. We refer to such a system as a MTLB system. Extension to multiple transmission lines is motivated by the fact that general MTLs can approximate with desired accuracy real waveguide structures which can be homogeneous (uniform) as well as inhomogeneous (nonuniform) [21-23].

Chapter 3 of *Advances in High Power Microwave Sources and Technologies using Metamaterials* summarizes advances made at UC Irvine on the Lagrangian variational framework for boundary value problems. The relevant publication that forms Chapter 3 is:

- A. Figotin and G. Reyes, “Lagrangian Variational Framework for Boundary Value Problems,” *J. Math. Phys.*, vol. 56, 093506-1-35 (2015).

Chapter 4. Dispersion Engineering

Vacuum electronic devices (VEDs) generate high power electromagnetic radiation using various designs and interaction principles. However, all these devices in one way or another involve a high power electron beam interacting with an electromagnetic mode inside a SWS. The need for SWSs in vacuum electronic devices is a direct consequence of the beam-mode synchronism condition that is required for Cherenkov radiation. That is, in order for the electron beam to lose energy to the electromagnetic mode, the phase velocity of the electromagnetic wave must be approximately equal to the velocity of electrons in the beam. While waveguides are usually the energy transfer medium of choice, normal electromagnetic mode propagation in a waveguide does not allow this beam-mode synchronism condition. Specifically, the phase velocity of electromagnetic waves propagating in an empty smooth-walled waveguide is always greater than the speed of light, that is $v_{ph} > c$. Since the electrons cannot be accelerated to velocities greater than c , synchronism can only be achieved by slowing down the electromagnetic wave. Such critical wave slow down occurs in a SWS. Therefore, the SWS is a critical component of VEDs as it slows down electromagnetic waves while also providing the medium for beam-mode energy transfer.

Wave slow down is achieved in two primary ways. The first technique involves the use of effective media by exploiting metamaterials. Specifically, it will be shown how fully metallic metamaterial structures can be used to mimic regular dielectrics in order to achieve wave slow down. In addition, it will also be shown how metamaterial structures with double negative constitutive parameters ($\epsilon_r, \mu_r < 0$) can support backward waves which can be exploited in backward wave oscillators. The second wave slowdown mechanism involves the use of periodic structures and the resulting space harmonics. Such SWSs will also be shown to exhibit backward wave propagation properties via their backward wave space harmonics. To achieve adequate wave slow down and facilitate Cherenkov interaction at a specific frequency, it is necessary to carefully engineer the dispersion properties of the SWS. In this Chapter, we present various SWS designs and multiple novel dispersion engineering techniques for SWS design.

Chapter 4 of *Advances in High Power Microwave Sources and Technologies using Metamaterials* summarizes advances made at Ohio State University, MIT, UC Irvine, and University of New Mexico. The relevant publications that form Chapter 4 are:

- M.A. Shapiro, S. Trendafilov, Y. Urzhumov, A. Alù, R.J. Temkin, and G. Shvets, “Active Negative-Index Metamaterial Powered by an Electron Beam, *Phys. Rev. B*, 86, 085 132 (2012).
- J.S. Hummelt, S.M. Lewis, M.A. Shapiro, and R.J. Temkin, “Design of a Metamaterial-Based Backward-Wave Oscillator, “*IEEE Trans. Plasma Sci.*, 42, 930-936 (2014).
- J. Hummelt, S. Lewis, H. Xu, M. Shapiro, I. Mastovsky, and R. Temkin, “Fabrication and Test of a High Power S-band Metamaterial Backward-Wave Oscillator, 2015 IEEE International Vacuum Electronics Conference (IVEC), pp. 1-2 (2015).
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 - M.A.K. Othman, V.A. Tamma, and F. Capolino, "Theory and New Amplification Regime in Periodic Multimodal Slow Wave Structures with Degeneracy Interacting with an Electron Beam," *IEEE Trans. Plasma Sci.*, 44, 594-611 (2016).
 - 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.*, 44, 918-929 (2016).
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 - 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*, 93, 024 301 (2016).
 - N. Apaydin, L. Zhang, K. Sertel, and J.L. Volakis, "Experimental Validation of Frozen Modes Guided on Printed Coupled Transmission Lines," *IEEE Trans. Microw. Theory Tech.*, 60, 1513-1519 (2012).
 - M.A.K. Othman and F. Capolino, "Demonstration of a Degenerate Band Edge in Periodically-Loaded Circular Waveguides," *IEEE Microw. Wireless Compon. Lett.*, 25, 700-702 (2015).
 - I.V. Konoplev, A.R. Phipps, A.D.R. Phelps, C.W. Robertson, K. Ronald, and A.W. Cross, "Surface Field Excitation by an Obliquely Incident Wave," *Appl. Phys. Lett.*, 102, 141 106 (2013).
 - I.V. Konoplev, A.J. MacLachlan, C.W. Robertson, A.W. Cross, and A.D.R. Phelps, "Cylindrical Periodic Surface Lattice as a Metadielectric: Concept of a Surface-Field Cherenkov Source of Coherent Radiation," *Phys. Rev. A*, 84, 013 826 (2011).
 - I.V. Konoplev, A.J. MacLachlan, C.W. Robertson, A.W. Cross, and A.D.R. Phelps, "Cylindrical, Periodic Surface Lattice-Theory, Dispersion Analysis, and Experiment," *Appl. Phys. Lett.*, 101, 121 111 (2012).
 - A.R. Phipps, A.J. MacLachlan, C.W. Robertson, I.V. Konoplev, A.D.R. Phelps, and A.W. Cross, "Numerical Analysis and Experimental Design of a 103 GHz Cherenkov Maser," 2014 39th International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz), pp. 1-2 (2014).
 - M. Zuboraj and J.L. Volakis, "Curved Ring-Bar Slow-Wave Structure for Wideband MW-Power Traveling Wave Tubes," *IEEE Trans. Plasma Sci.*, 44, 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.*, 44, 1794-1799 (2016).
 - U. Chipengo, M. Zuboraj, N.K. Nahar, and J.L. Volakis, "A Novel Slow-Wave Structure for High-Power Ka-band Backward Wave Oscillators with Mode Control," *IEEE Trans. Plasma Sci.*, 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," *IEEE Trans. Plasma Sci.*, 44, 911-917 (2016).
 - U. Chipengo and J.L. Volakis, J.L., "A Highly Efficient X-Band BWO with an Inhomogeneous Slow Wave Structure, in 2015 IEEE Pulsed Power Conference (PPC), pp. 1-4 (2015).

Chapter 5. Perturbation Analysis of Maxwell's Equations

From an operational viewpoint, a TWT amplifier can be thought of as a waveguide loaded with a dielectric shell and an electron beam running through its center. The electron motion is parallel to the waveguide and confined by a strong uniform magnetic field applied along the beam. To fix ideas the beam is cylindrical surrounded by vacuum and enclosed by a concentric cylindrical dielectric shell. When the dielectric constant is larger than unity it is a SWS and it is possible to get amplification from the TWT [16,24]. Unfortunately, most dielectric materials are insufficient for high power applications and break down after a few operational cycles. On the other hand, Shiffler, Luginsland, and Watrous [25] propose sub-wavelength all-metal interaction structures that effectively act as a dielectric medium with dielectric constant greater than unity. This provides the opportunity for a meta material paradigm for the design of TWTs with metal beam-wave interaction structures.

To begin we ignore finite length effects and carry out the dispersion analysis for an infinitely long TWT amplifier region loaded with a sub-wavelength metallic interaction structure. In a novel development we apply a two-scale perturbation analysis [26-29] to the Maxwell system used to model beam wave interaction inside the infinitely long amplifier. We address both TM and hybrid modes, and the asymptotic analysis delivers a leading order theory, from which we recover the leading order dispersion relation for the amplifier. We begin by considering periodic all metallic interaction structures that are not grounded to the outer wall of the wave guide, see Figs. 3 and 4. The analysis shows that these sub-wavelength structures can be modeled to leading order as a waveguide loaded by an effective dielectric material, see Fig. 3. On the other hand, if the structure is grounded to the outer wall of the wave guide as in a corrugated waveguide, see Fig. 4, then the structure can be modeled to leading order as a perfectly cylindrical waveguide with an effective anisotropic surface impedance. These phenomena have been reported in [30] and [31].

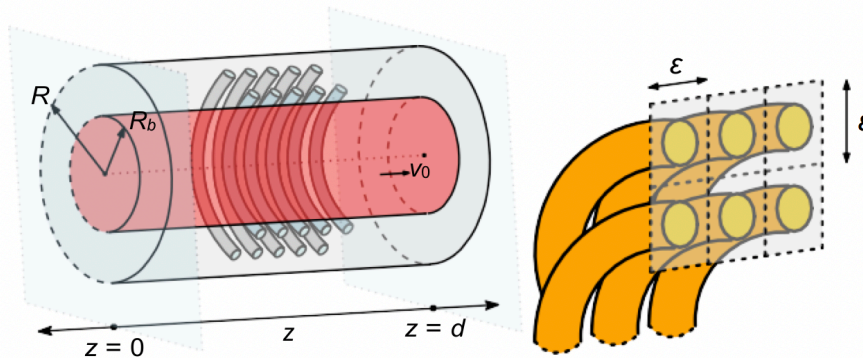


Figure 3. Section of infinitely long TWT consisting of electron beam surrounded by periodic, concentric, metallic rings embedded in a host material whose dielectric properties are those of a vacuum and a close-up view of the ϵ periodic interaction structure.

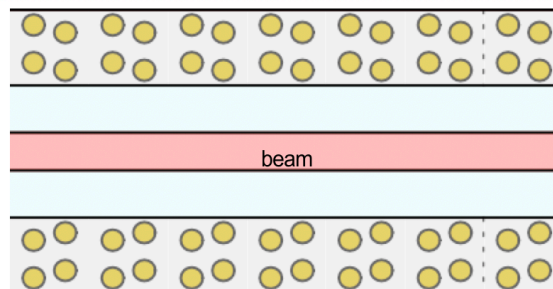


Figure 4. Cross-section of infinitely long TWT showing electron beam surrounded by periodic, concentric, metallic rings embedded in a host material whose dielectric properties are those of a vacuum.

Next, we model a finite size TWT amplifier loaded with an effective dielectric as a short Cherenkov system comprised of three components: a feeding waveguide, a finite length TWT amplifier region, and an output waveguide. The entire system is excited by a generator. Each of these components have different characteristic impedances, and reflections can occur at both input and output ends of the amplifier. The objective is to characterize the influence of the geometry of the interaction structure on the transmission pattern as well as its effect on the gain and bandwidth of transmission peaks. We follow Schäcter et. al. [24] and transmission patterns are calculated using the incident and reflected waves in the feeding waveguide, the dominant interacting modes inside the TWT amplifier region, and the space-charge waves in the output waveguide emitted from the amplifier region. The transmission coefficient is depicted as a function of frequency for a collection of different all-metal beam-wave interaction structures. To fix ideas, we study interaction structures made of metallic rings with lozenge-shaped cross sections. The inclusion geometries are indexed by their filling fraction relative to the period cell and their aspect ratio related to the eccentricity of their shape, see Fig. 5. For reference we calculate the transmission coefficient using the isotropic dielectric constant chosen in Schäcter et. al. [24] (see Fig. 6) and use it as a benchmark to demonstrate the effect of vary- ing the metal interaction structure on the performance of the TWT, see Figs. 7 and 8.

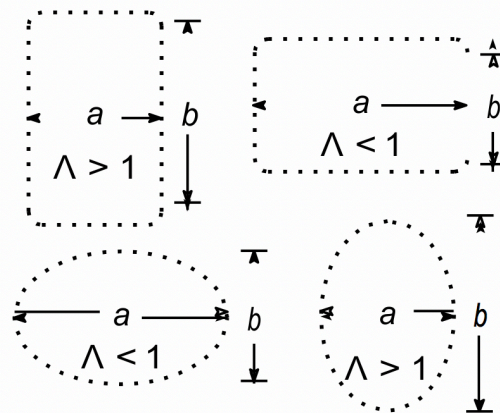


Figure 5. Lozenge-shaped (above) and ellipsoidal (below) cross sections with different eccentricities corresponding to different aspect ratios $\Lambda = b/a$. Lengths with value a correspond to the z -direction.

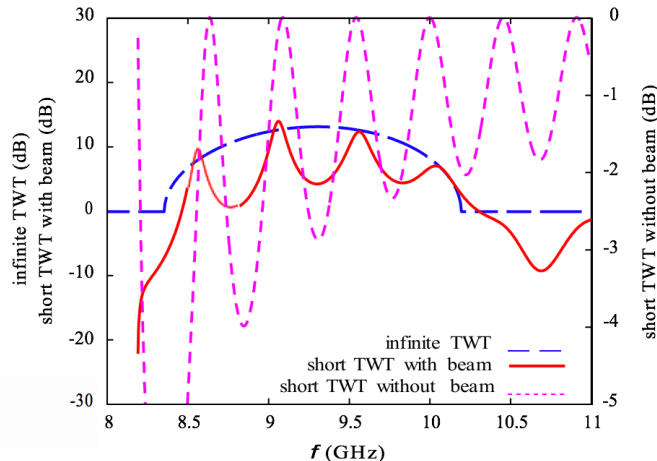


Figure 6. Transmission coefficient as a function of frequency for an isotropic dielectric with dielectric constant 3.5 for an amplifier driven by a 1 kA beam.

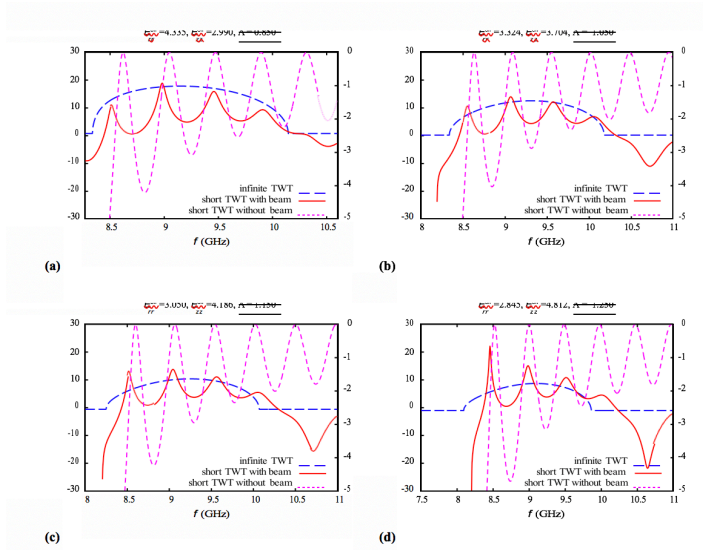


Figure 7. The effect of aspect ratio Λ for lozenge-shaped inclusions with fixed filling fraction $\theta = 0.5508$.

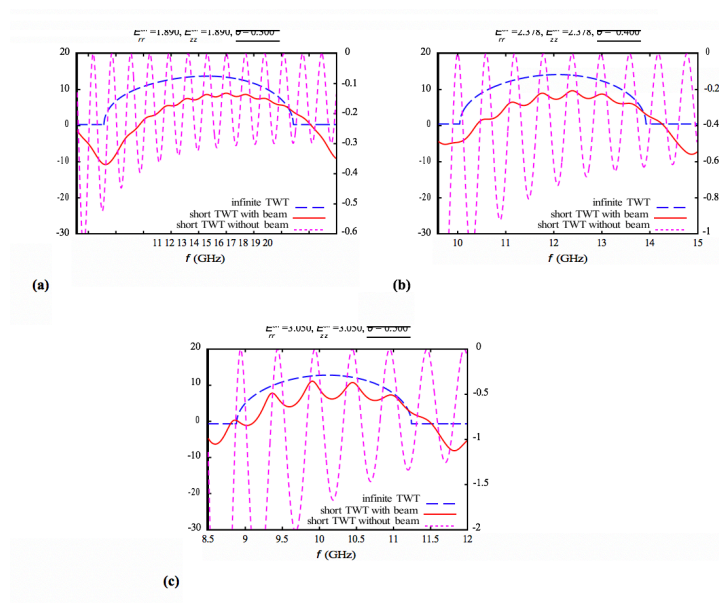


Figure 8. The effect of filling fraction, symmetric lozenge-shaped inclusions.

Last, we pursue a different perturbation approach and consider a corrugated oscillator of length d . The beam is assumed to be a pencil beam modeled by a circular cylinder with generators parallel to the waveguide. The radius of the beam is smaller than the radius of the waveguide. We first find the standing wave modes supported by the oscillator in the absence of the beam. When the beam is turned on the oscillator is modeled under the assumption that the beam current is proportional to the axial component of the electric field. The proportionality constant α when multiplied by the free space dielectric permittivity ϵ_0 can be thought of as a dielectric constant that is both dispersive in space and time. The dielectric constant delivers a constitutive relation for the beam current in terms of the axial component of the electric field. This is precisely the hydrodynamic approximation of the beam given in the Pierce Theory adapted to fields as described in Chapter 4 of [16]. We apply a perturbation expansion and write the solution of the

Maxwell equations for the oscillator as a perturbation of the standing wave mode in the absence of the beam. For this case there are two perturbation parameters: the first is proportional to the frequency difference between the standing wave mode and oscillator frequency, $\delta\omega$. Here the oscillator frequency is ω , the standing wave frequency is ω_0 and $\delta\omega = \omega - \omega_0$. The second perturbation parameter is the coupling between beam current and electric field α . We carry out the perturbation theory in terms of the non-dimensional perturbation parameters $d\delta\omega/c$ and α . We find to leading order that the roots of a third order Pierce polynomial similar to that of Chapter 4 of [16] determines $\delta\omega$. We then run the numerical simulations for the leading order fields in perturbation theory to compute $\delta\omega$ and correlate the rise time to corrugation geometry. The simulations also confirm that non-dimensional perturbation parameters $d\delta\omega/c$ and α are small.

Chapter 5 of *Advances in High Power Microwave Sources and Technologies using Metamaterials* summarizes advances made at Louisiana State University. The relevant publications that form Chapter 5 are:

- R. Lipton, and A. Polizzi, "Tuning gain and bandwidth of traveling wave tubes using metamaterial beam-wave interaction structures," *J. App. Phys.*, 116, 144 504 (2014).
- R. Lipton, A. Polizzi, and L. Thakur, "Novel metamaterial surfaces from perfectly conducting subwavelength corrugations," *SIAM J. Appl. Math.*, 77, 1269-1291 (2017).
- 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.*, 44, 1280-1286 (2016).

Chapter 6. Similarity of the Properties of Conventional Periodic Structures with Metamaterial Slow Wave Structures

A study of the evolution of wave dispersion in systems of all-metallic periodic structures with increasing corrugation depth shows a similarity of the properties of waves in MSWSs and traditional metallic SWSs used in HPM sources. We show that the main properties of MSWSs, such as the existence of a lowest order negative dispersion wave below the cutoff, also appear in conventional metallic periodic systems with deep corrugations. Furthermore, we find that the appearance of negative dispersion in all-metallic periodic structures with increasing corrugation depth is accompanied by a hybrid mode being identified as the lowest order negative dispersion mode [32].

In this Chapter, our interest is to identify MSWSs with novel dispersion characteristics for use in HPM source concepts. To avoid problems with electron beam propagation, such as charging of dielectrics, and to increase the thresholds of DC and microwave breakdown, we restrict our considerations to all-metallic SWSs as is usually the case in vacuum electronic sources of microwaves.

It is also shown that using direct asymptotic analysis makes it possible to recover an effective surface impedance model directly from Maxwell's equations. Furthermore, without assuming infinitely thin corrugations, it is shown that effective impedance is a subwavelength phenomenon. Using numerical calculations, it is found that impedance sign change that is caused by a corrugation boundary has an effect on the sign change of the group velocity.

Chapter 6 of *Advances in High Power Microwave Sources and Technologies using Metamaterials* summarizes advances made at the University of New Mexico and Louisiana State University. The relevant publications that form Chapter 6 are:

- 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 [featured story of August 2016], vol. 44, 1280-1286 (2016).
- R. Lipton, A. Polizzi, L. and Thakur, “Novel Metamaterial Surfaces from Perfectly Conducting Subwavelength Corrugations,” SIAM J. Appl. Math., 77, 1269-1291 (2017).

Chapter 7. Group Theory Approach for Designing Metamaterial Structures for HPM Devices

In this Chapter, we outline the general description and symmetry concepts defined in group theory. First the general features of group theory are explained. Next, how symmetry properties of metamaterials can be used to identify their electromagnetic properties are explained. Several well-known metamaterial structures are analyzed using group theory. Moreover, how group theory can be utilized in synthesizing metamaterials with desired constitutive properties is demonstrated. Finally, the basic steps for designing HPM sources using metamaterials and group theory are presented and discussed.

Group theory has been used in chemistry to classify molecules based on their symmetry properties. Group theory explains how the symmetry properties of a molecule such as molecular orbital properties, its active vibrational modes, the active bands of infrared (IR), Raman spectrum, etc., are related to its symmetry properties.

Molecule behavior in chemistry can be seen as equivalent to metamaterial unit cells in electromagnetics. Using this analogy, molecular modes of vibrations are shown to correspond to the resonant modes of a metamaterial and hence group theory can be used to determine the electromagnetic properties of metamaterials. However, there are some limitations in using group theory for designing unit cells for periodic structures [33]. First, the group theory derivation is based upon the assumption of slowly varying external electromagnetic waves on a periodic structure, thus, incident fields need to be quasi-static along the unit cell. So, if a is the unit cell largest dimension and λ is the incident electromagnetic field wavelength, the condition $a/\lambda < 0.2$ needs to be satisfied, to use group theory for analyzing and designing metamaterial structures. Secondly, group theory can predict the general electromagnetic behavior of a metamaterial, but the exact value of permeability and permittivity and the exact resonance frequencies of the specific metamaterial structure need to be extracted through full wave electromagnetic simulations and through the retrieval of electromagnetic properties using scattering parameters [34].

In this Chapter, group theory is also shown how it can be applied specifically to complementary metallic metamaterial structures for high power microwave applications. In particular, we will demonstrate a double negative, multibeam high power BWO-like source.

Chapter 7 of *Advances in High Power Microwave Sources and Technologies using Metamaterials* summarizes advances made at the University of New Mexico. The relevant publication that forms Chapter 7 is:

- H. Seidfaraji, *High Power Microwave Metamaterial Based Passive and Active Devices* (Ph.D. Dissertation, University of New Mexico, Albuquerque, NM, 2017).

Chapter 8. Time Domain Analysis of the Evolution of Electromagnetic Fields in Metamaterial Structures

This Chapter details the work done on frequency and time-domain behavior of split-ring resonators (SRR) inside a cutoff waveguide structure. This research aims to explain and model more in depth the temporal behavior of the structure to get a better understanding of split-ring resonator structures and metamaterials on a general level. In particular, this research focuses on creating a model that maps the frequency and time behavior. The model seeks to draw the strength of linear distributed models.

Chapter 8 of *Advances in High Power Microwave Sources and Technologies using Metamaterials* summarizes advances made at the University of New Mexico. The relevant publication that forms Chapter is:

- M.A. Hmaidi, *Split-Ring Resonator Waveguide Structure Characterization by Simulations, Measurements and Linear Time-Invariant Modeling* (M.S. Thesis, University of New Mexico, Albuquerque, NM, 2018).

Chapter 9. Metamaterial Survivability in the High Power Microwave Environment

Researchers first studying the use of metamaterials in high power microwave sources early on recognized that metallic structures on dielectric substrates were a bad idea [35]. The highly resonant nature of metamaterials meant that the dielectric substrates would heat up and even catch fire once exposed to even Watts of cw power in the microwave band. As a result, the community shifted to all-metallic metamaterial structures [25,32,36-40].

In anticipation of breakdown in the UNM metamaterial source that generated 100 MW in L-band [40], researchers at UNM prepared a diagnostic array of visible and optical detectors to monitor the inside of the SWS during high power testing. No breakdown was observed, likely due to the short pulse (~10 ns) nature of their SINUS-6-driven source. Nevertheless, the diagnostic suite developed will be fielded in higher power tests and breakdown will be studied [41].

Chapter 9 of *Advances in High Power Microwave Sources and Technologies using Metamaterials* summarizes advances made at the University of New Mexico. The relevant publication that forms Chapter 9 is:

- K.A. Shipman, *Experimental Testing of a Metamaterial Slow Wave Structure for High-Power Microwave Generation* (M.S. Thesis, University of New Mexico, Albuquerque, NM, 2018).

Chapter 10. Experimental Hot Test of Beam/Wave Interactions with Metamaterial Slow Wave Structures

This Chapter summarizes hot test results obtained to-date. Several of the results obtained have already been published with two series of tests outstanding (test of Ohio State structure at MIT and test of UC Irvine structure at UNM).

- Summary of MIT hot tests to-date of MIT structure
- Summary of UNM hot test to-date of UNM structure
- Summary of MIT hot tests to-date of OSU structure
- Summary of UNM hot test to-date of UCI structure
- Summary of Strathclyde hot tests to-date

The items in red are in progress, whereas the others have already been published.

Chapter 10 of *Advances in High Power Microwave Sources and Technologies using Metamaterials* summarizes advances made at MIT, the University of New Mexico, Ohio State University, UC Irvine, and the University of Strathclyde. The relevant publications that form Chapter 10 are:

- J.S. Hummelt, S.M. Lewis, M.A. Shapiro, and R.J. Temkin, "Design of a Metamaterial-Based Backward-Wave Oscillator," *IEEE Trans. Plasma Sci.*, 42, 930-936 (2014).
- J. Hummelt, S. Lewis, H. Xu, M. Shapiro, I. Mastovsky, and R. Temkin, "Fabrication and Test of a High Power S-band Metamaterial Backward-Wave Oscillator, 2015 IEEE International Vacuum Electronics Conference (IVEC), pp. 1-2 (2015).
- J. Hummelt, X. Lu, H. Xu, M. Shapiro, and R. Temkin, "High Power Microwave Generation from a Metamaterial Waveguide, 2016 IEEE International Vacuum Electronics Conference (IVEC), pp. 1-3 (2016).
- 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," *Phys. Rev. Lett.*, 117, 237 701 (2016).
- 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 [featured story of August 2016]*, vol. 44, 1280-1286 (2016).
- S. Prasad, S. Yurt, K. Shipman, D. Andreev, D. Reass, M. Fuks, and E. Schamiloglu, "A Compact Metamaterial High Power Microwave Slow Wave Structure - From Computational Design to Hot Test Validation," *Proc. Computing and Electromagnetics Workshop 2017 (Barcelona, Spain, June 21-23, 2017)*, 61-62.
- I.V. Konoplev, A.J. MacLachlan, C.W. Robertson, A.W. Cross, and A.D.R. Phelps, "Cylindrical, Periodic Surface Lattice-Theory, Dispersion Analysis, and Experiment," *Appl. Phys. Lett.*, 101, 121 111 (2012).

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V. PERSONNEL, PUBLICATIONS, INTERACTIONS, AWARDS FOR THE FINAL REPORTING PERIOD

Final Reporting Period Accomplishments:

Table 1. Final reporting period graduate student teleseminars.

November 3, 2017

University of California, Irvine

University of New Mexico Publications:

Archival Publications:

Z. Duan, M.A. Shapiro, E. Schamiloglu, N. Behdad, Y. Gong, J.H. Booske, B.N. Basu, and R.J. Temkin, "Metamaterial-Inspired Vacuum Electron Devices and Accelerators," submitted to IEEE Trans. Electron Dev. (2018).

Conference Publications:

E. Schamiloglu, S. Prasad, M. Fuks, S. Yurt, A. Elfrgani, K. Shipman, S. Hemmady, P. Zarkesh-Ha, Z. Peng, G. Balakrishnan, G. Heileman, Y. Shao, and D. Dietz, "Recent Advances in High Power Microwave Sources and the Science of Electronics in Extreme Electromagnetic Environments at the University of New Mexico," *Proc. ICEAA 2017* (Verona, Italy, September 11-15, 2017), 622-625.

Z. Duan, M.A. Shapiro, Y. Gong, E. Schamiloglu, N. Behdad, J.H. Booske, B.N. Basu, and R.J. Temkin, "Review of Metamaterial-Inspired Vacuum Electron Devices," to be published in Proc. IVEC 2018 (Monterey, CA, April 24-26, 2018).

Conference Presentations:

E. Schamiloglu, M. Fuks, A. Kuskov, D. Andreev, A. Sandoval, "HPM Sources: Magnetrons and Metamaterial Slow Wave Structures - More in Common Than Not," ICMRE 2018 (Qingdao, China, May 06-11, 2018).

University of New Mexico Awards:

Kelly Hahn, a physicist at Sandia National Laboratories and former Ph.D. student of Professor Schamiloglu (funded by AFOSR), has been recognized by the Society of Women Engineers for her support in the enrichment and advancement of women in engineering. She is a recipient of the 2018 Society of Women Engineers' Emerging Leader Award.

Inventions or Patents

None

MIT Publications:

Archival Publications:

X. Lu, J.C. Stephens, I. Mastovsky, M.A. Shapiro, and R.J. Temkin, "High Power Long Pulse Microwave Generation from a Metamaterial Structure with Reverse Symmetry," Phys. Plasmas, vol.

25, 023102 (2018).

Conference Publications:

X. Lu, J.C. Stephens, I. Mastovsky, M.A. Shapiro, and R.J. Temkin, "High Power Microwave Generation by Cherenkov-Cyclotron Instability in a Metamaterial Structure with Negative Group Velocity," 2018 Eighteenth International Vacuum Electronics Conference (IVEC 2018), Monterey, CA, pp. 1-2 (2018).

MIT Awards

Xueying Lu, Finalist for Best Student Paper Award, IVEC 2018.

Inventions or Patents

None

Ohio State/FIU Publications:

Archival Publications:

U. Chipengo, N. K. Nahar and J. L. Volakis, "A Study of Velocity Tapered Slow Wave Structures for High Efficiency Backward Wave Oscillators" IEEE Transactions on Electron Devices, 2018.

Conference Publications:

None

Ohio State/FIU Awards

None

Inventions or Patents

None

UC Irvine Publications:

Archival Publications:

M.A.K. Othman and F. Capolino, "Theory of Exceptional Points of Degeneracy in Uniform Coupled-Waveguides and Balance of Loss and Gain," IEEE Trans. Antennas Propag., vol. 65, no. 10, pp. 1–15, 2017.

M.A.K. Othman, V. Galdi, and F. Capolino, "Exceptional points of degeneracy and PT-symmetry in a photonic chain of paired scatterers," Phys. Rev. B 95, 104305, 2017.

M. Y. Nada, M. A. K. Othman, and F. Capolino, "Theory of coupled resonator optical waveguides exhibiting high-order exceptional points of degeneracy," *Phys. Rev. B*, vol. 96, no. 18, p. 184304, Nov. 2017.

J. Sloan, M. Othman, and F. Capolino, "Theory of Double Ladder Lumped Circuits with Degenerate Band Edge," *IEEE Trans. Circuits Syst. Regul. Pap.*, vol. 65, no. 1, pp. 3–13, 2018.

M. Veysi, M.A.K. Othman, A. Figotin, and F. Capolino, "Degenerate band edge laser," *Phys. Rev. B*, vol. 97, no. 19, p. 195107, May 2018.

M.Y. Nada, M.A.K. Othman, O. Boyraz, and F. Capolino, "Giant Resonance and Anomalous Quality Factor Scaling in Degenerate Band Edge Coupled Resonator Optical Waveguides," *J. Light. Technol.*, vol. 36, no. 14, pp. 3030-3039, 2018.

F. Yazdi, M.A.K. Othman, M. Veysi, A. Figotin, and F. Capolino, "A New Amplification Regime for Traveling Wave Tubes with Third Order Modal Degeneracy," *IEEE Trans. Plasma Sci.*, vol. 46, no.1, pp. 43-56, Jan. 2018.

Conference Presentations:

M.A.K. Othman, A.F. Abdelshafy, A. Figotin, and F. Capolino, "Exceptional points of degeneracy for enhanced interaction in multimode electron beam devices," *IEEE International Vacuum Electronics Conference Monterey, California, April 24-26, 2018.*

M.Y. Nada, M.A.K. Othman, and F. Capolino, "High order exceptional points of degeneracy in coupled resonators optical waveguides," *SPIE Photonics West 2018, San Francisco, CA, Jan. 27-Feb. 1, 2018.*

M.A.K. Othman and F. Capolino, "New Paradigm in Coherent Radiating Oscillators Based on Waveguides with Exceptional Points of Degeneracy," *URSI National Radio Science Meeting (NRSM), Boulder, CO, Jan. 4-7, 2018. [Invited Talk to a special session, Advanced Analysis, Design & Applications of Waveguiding Structures]*

UCI Awards

None

UCI Patents or Inventions

None

Louisiana State University Publications:

Archival Publications:

R. Lipton and B. Schweizer, “Effective Maxwell’s equations for perfectly conducting split ring resonators,” 2017. Archive for Rational Mechanics and Analysis. On line first, March 6, 2018. <https://doi.org/10.1007/s00205-018-1237-1>.

R. Lipton, A. Polizzi, and L. Thakur, “Novel metamaterial surfaces from perfectly conducting subwavelength corrugations,” SIAM J. on Applied Mathematics, 77 (2017), pp. 1269–1291.

R. Lipton and R. Viator, “Bloch waves in crystals and periodic high contrast media,” ESAIM: Mathematical Modeling and Numerical Analysis, 51, (2017), pp. 889–918.

Conference Publications:

None

LSU Awards

None

LSU Patents or Inventions

None

AFOSR Deliverables Submission Survey

Response ID:9987 Data

1.

Report Type

Final Report

Primary Contact Email

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505-277-6095

Organization / Institution name

University of New Mexico

Grant/Contract Title

The full title of the funded effort.

Innovative use of Metamaterials in Confining, Controlling, and Radiating Intense Microwave Pulses

Grant/Contract Number

AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-12-1-0489

Principal Investigator Name

The full name of the principal investigator on the grant or contract.

Edl Schamiloglu

Program Officer

The AFOSR Program Officer currently assigned to the award

Jason Marshall and Arje Nachman

Reporting Period Start Date

09/30/2012

Reporting Period End Date

03/31/2018

Abstract

This final technical report describes our research over the past 5.5 years under the FY12 MURI award to investigate how metamaterials (MTMs) can be exploited as new means of high power microwave generation. We have concluded that MTMs have greatly expanded the parameter space for dispersion engineering for beam/wave interaction. We have demonstrated two operational high power MTM sources, one generating 5 MW at S-band and the other generating 100 MW in L-band. Considerable progress has been made in the theoretical understanding of these devices as well. This final report summarizes the discoveries made during this program and is written in a manner to provide a synopsis of the forthcoming Advances in High Power Microwave Sources and Technologies using Metamaterials (IEEE Press/Wiley, 2019).

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Archival Publications (published) during reporting period:

X. Lu, J.C. Stephens, I. Mastovsky, M.A. Shapiro, and R.J. Temkin, "High Power Long Pulse Microwave Generation from a Metamaterial Structure with Reverse Symmetry," Phys. Plasmas, vol. 25, 023102 (2018).

U. Chipengo, N. K. Nahar and J. L. Volakis, "A Study of Velocity Tapered Slow Wave Structures for High Efficiency Backward Wave Oscillators" IEEE Transactions on Electron Devices, 2018.

M.A.K. Othman and F. Capolino, "Theory of Exceptional Points of Degeneracy in Uniform Coupled-Waveguides and Balance of Loss and Gain," IEEE Trans. Antennas Propag., vol. 65, no. 10, pp. 1–15, 2017.

M.A.K. Othman, V. Galdi, and F. Capolino, "Exceptional points of degeneracy and PT-symmetry in a photonic chain of paired scatterers," Phys. Rev. B 95, 104305, 2017.

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New discoveries, inventions, or patent disclosures:

Do you have any discoveries, inventions, or patent disclosures to report for this period?

No

Please describe and include any notable dates

Do you plan to pursue a claim for personal or organizational intellectual property?

Changes in research objectives (if any):

None

Change in AFOSR Program Officer, if any:

None

Extensions granted or milestones slipped, if any:

None

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, \$K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

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