UNM SCHOOL of ENGINEERING

Department of Electrical & Computer Engineering

AFRL AFOSR

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

Edl Schamiloglu, PI (IEEE Fellow)

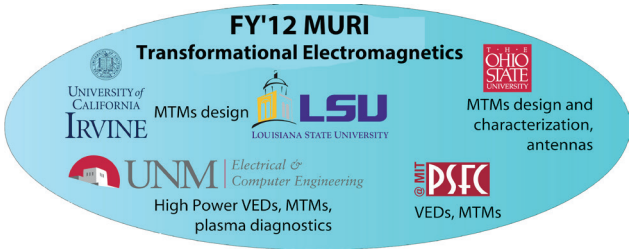
Distinguished Professor, University of New Mexico

FY'12 AFOSR Transformational Electromagnetics MURI

Presented at the MURI Program Review

Tuesday, July 29, 2014

Arlington, VA USA



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OUTLINE

- Scientific Objective/Technical Approach
- Why is this an Important Area of Research?
- Budget Overview
- Who We Are
- Progress To-Date
- Challenges We Have Identified
- Productivity Data
- Accolades
- Future Plans

Scientific Objective

The evolution of High Power Microwave (HPM) sources has entered the third era:

- **First era** – power derby between researchers in US and USSR/ Russia (1960's – early 1990's)
- **Second era** – pulse shortening, emergence of virtual prototyping (early 1990's – early 2010's)
- **Third era** – effects-based source development, interest in HPM amplifiers (*viz.*, dispersion engineering using metamaterials) (2010's – present)

Who We Are

- University of New Mexico (UNM) – Lead Institution - **Schamiloglu**
- Massachusetts Institute of Technology (MIT) – Temkin
- Ohio State University (OSU) – Volakis
- University of California, Irvine (UCI) – Figotin
- Louisiana State University (LSU) – Lipton
- University of Strathclyde, UK (US) – Cross
- University of Huddersfield, UK (UH) - Seviour

*satellite efforts in blue

Technical Approach

- **Analytical Theory** (UCI using first principle Lagrangian and multi-transmission line derviations of Pierce model for traveling wave tube (TWT); LSU developing multiscale representation of solutions of Maxwell's equations inside structured metals; UNM using group theory to design metallic metamaterials)
- **Particle-in-cell and Electromagnetic Simulations for Virtual Prototyping** (UNM, MIT, OSU for interaction structure design)
- **Experiments** (UNM and MIT for study of beam/wave interaction in metamaterial SWSs; UNM for metamaterial survivability studies using optical and plasma diagnostics)

Why is this an Important Area of Research?

- Effects-based high power microwave amplifiers offer a paradigm shift as to how to employ directed energy microwaves for electronic attack
- Dispersion-engineered metamaterial slow wave structures offer potential beam/wave interactions that do not exist for slow wave structures made using standard materials
- This opens the parameter space to study new device concepts and explore new interactions to achieve new capabilities across a wider range of the electromagnetic spectrum

Budget Overview

University	Year 1	Year 2	Year 3	Year 4	Year 5	Total/Univ.
UNM	395k	395k	395k	395k	395k	1.975M
MIT	375k	375k	375k	375k	375k	1.875M
OSU	175k	175k	175k	175k	175k	0.875M
UCI	350k	350k	350k	350k	350k	1.750M
LSU	205k	205k	205k	205k	205k	1.025M
Total/Year	1.500M	1.500M	1.500M	1.500M	1.500M	7.500M

We are here (Year 2 anniversary date 30 September 2014)

Who We Are - Continued

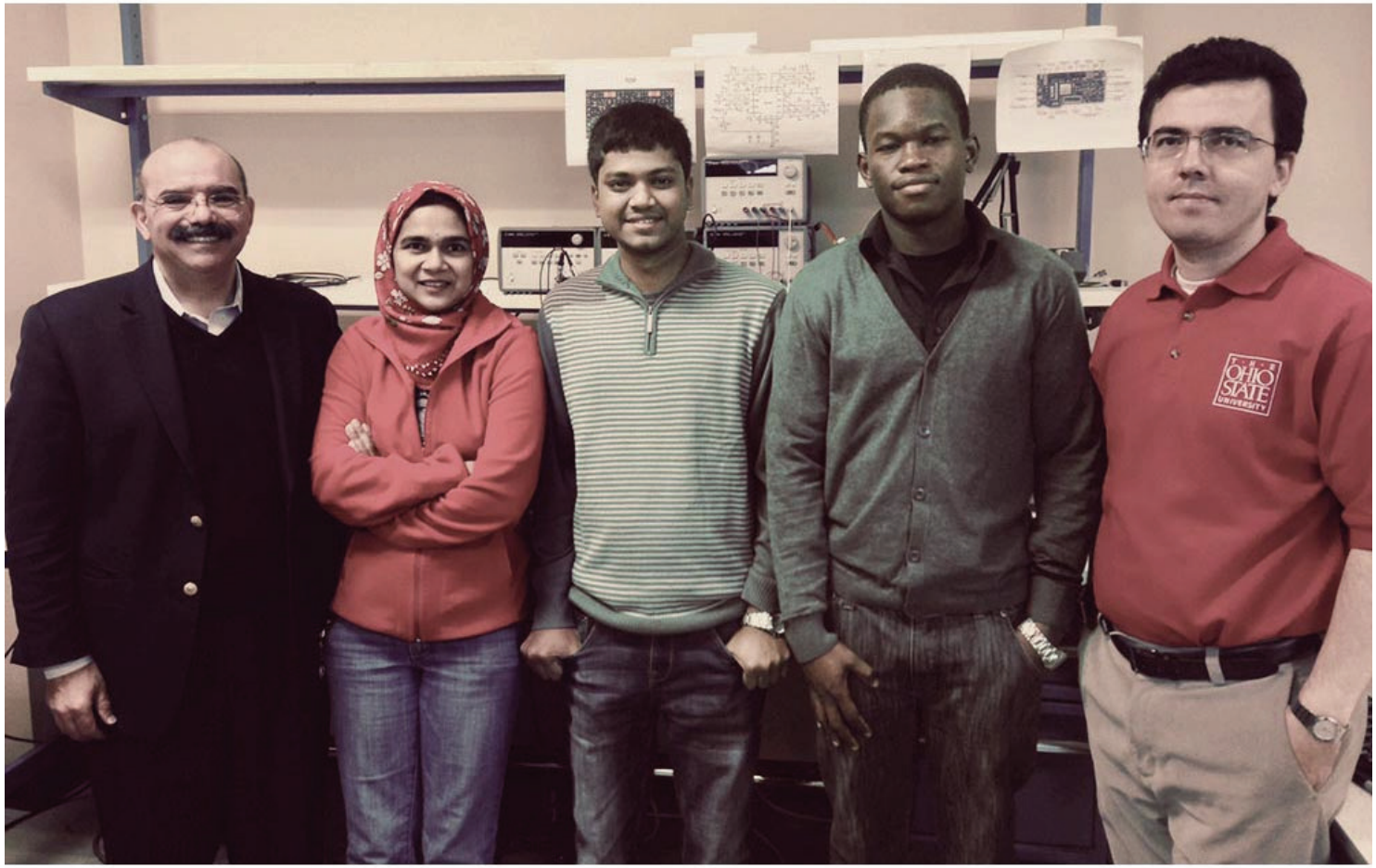
Our MURI Consortium – The University of New Mexico Research Team

(Left to right) Tyler Wynkoop, Georgios Atmatzakis, Kimberley Nichols, Sabahattin Cihad Yurt, Mehmet Su, Kost' Ilyenko, Sarita Prasad, Mikhail Fuks, Christos Christodoulou, Edl Schamiloglu, Mark Gilmore, Hamide Seidfaraji, Salvador Portillo

Our MURI Consortium – The MIT Research Team

(Left to right) Samuel Schaub, Jiexi Zhang, Xueying Lu, David Tax, Alexander Soane, Elizabeth Kowalski, Sudheer Jawla, Ivan Mastovsky, Brian Munroe, Paul Woskov, Michael Shapiro, William Guss, Zhaoyun Duan

Our MURI Consortium – The Ohio State University Research Team

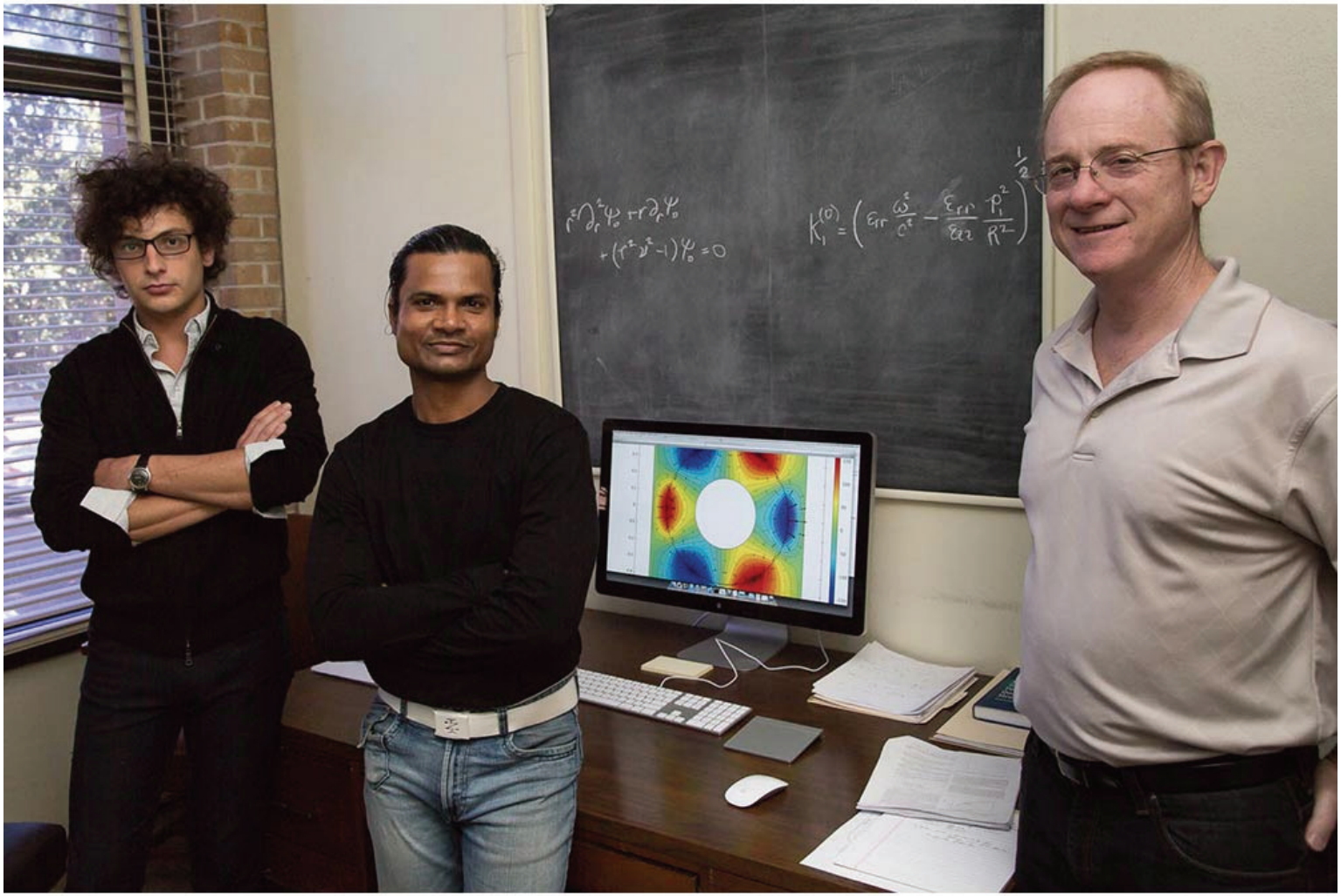


John L. Volakis Niru Nahar Md. Zuboraj Ushe Chipengo Kubilay Sertel

Our MURI Consortium – The University of California - Irvine Research Team

Ananth Tamma Filippo Capolino Alex Figotin Guillermo Reyes Mohamed Othman

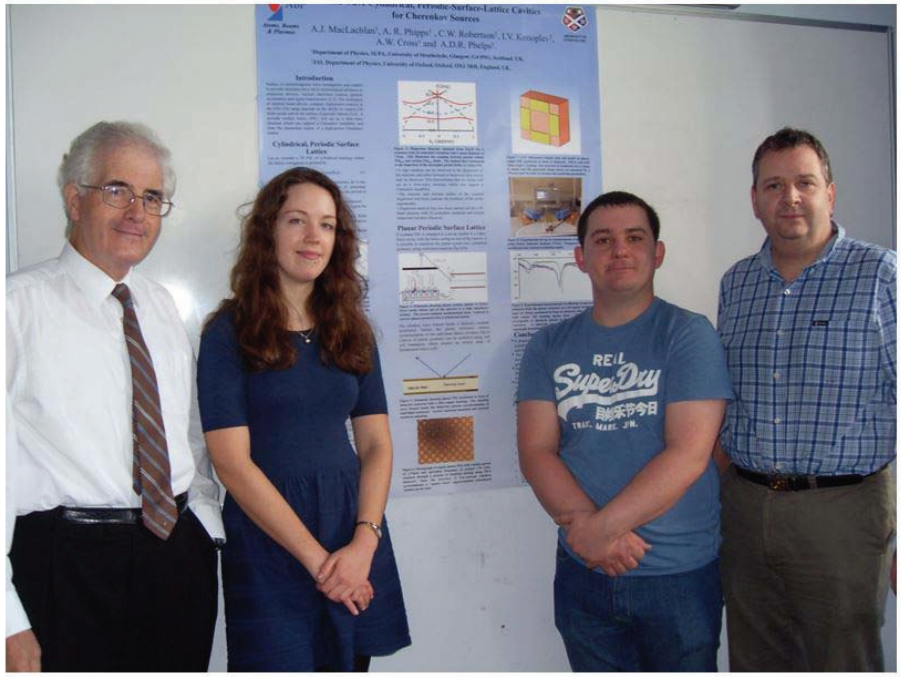
Our MURI Consortium – The Louisiana State University Research Team



Anthony Polizzi Lakendra Thakur Robert Lipton

… and Two UK Satellite Efforts

Our MURI Consortium – The University of Strathclyde Satellite Effort



Alan Phelps Amy MacLachlan Alan Phipps Adrian Cross

Our MURI Consortium – Huddersfield University Satellite Effort

Rebecca Seviour Aimee Hopper David Sangcheol Lee Simon Albright

Collaborations To-Date

Advisory Board Members

Dr. Dave Abe, Naval Research Laboratory, Washington, DC

Dr. Richard Albanese, ADED Co., San Antonio, TX

Dr. Carter Armstrong, L-3 Communications EDD, San Carlos, CA

Dr. Bruce Carlsten, Los Alamos National Laboratory, Los Alamos, NM

Mr. Charles Chase, Lockheed Martin, Palmdale, CA

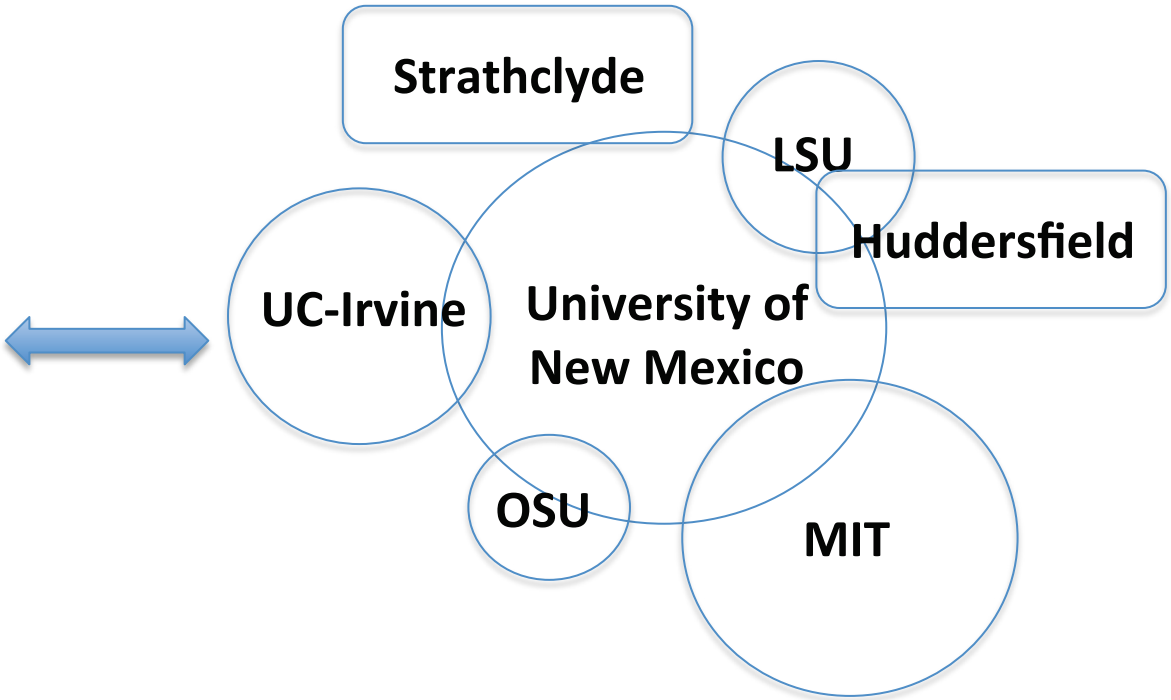
Mr. Chuck Gilman, SAIC (retired) Albuquerque, NM

Dr. John Petillo, SAIC Boston, MA

Dr. Don Shiffler, AFRL/RD, Kirtland AFB, NM

Dr. Don Sullivan, Raytheon-Ktech, Albuquerque, NM

Dr. Pravit Tulyathan, Boeing, Huntington Beach, CA



Progress To-Date

Our philosophy is to explore novel metamaterial slow wave structures (SWSs) and explore new SWS concepts based on traditional materials – dispersion engineering!

- Revisit beam/structure interactions in theory and reconsider Pierce Theory for metamaterial-based SWSs (UCI) – this is important because recent studies at MIT suggest behavior of metamaterial-based backward wave oscillator very different from traditional one (*viz.,* dependence on I_{beam}/I_{start})
- Explore novel metamaterial-based SWSs (MIT, UNM, LSU, UH) – in this manner dispersion relations to be engineered that cannot be made using traditional materials

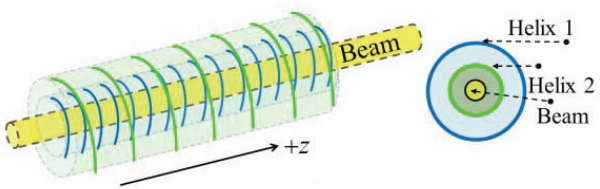
Progress To-Date

- Explore new SWSs based on traditional materials and sub-wavelength periods (UNM, OSU, US) – this is important because there is no guarantee that a metamaterial-based SWS will necessarily lead to a better device
- Explore metamaterial SWSs in the HPM environment (UNM, UH) – this is important in order to engineer metamaterial SWSs that can survive in the HPM environment
- Include nonlinear elements in metamaterial SWSs (UNM) – this adds agility and reconfigurability to future devices

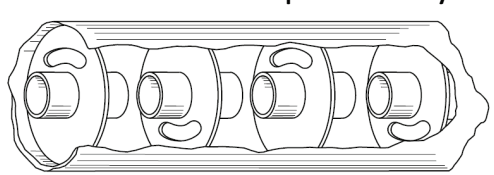
Breaking Boundaries

Analytical Theory - UCI

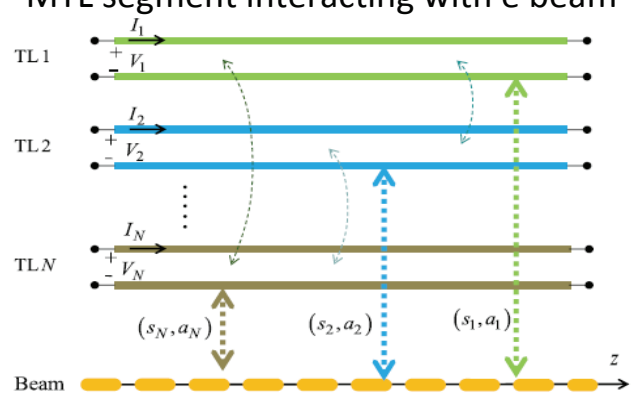
- ✓ New amplification regimes in waveguides with at least two EM modes interacting with a space-charge wave (SCW). Both EM modes are synchronous with the SCW velocity.
- ✓ Enhanced gains in TWTs based on periodic multiple transmission lines, especially when using two EM modes both synchronous with the SCW.
- ✓ "Frozen modes" based on the degenerate band edge (DBE) yield gigantic TWT gains.
- ✓ Two interacting EM modes with e-beam provide for more flexibility to engineer dispersion diagrams and wide band TWT amplifiers.
- ✓ Extension and advancement of the Pierce theory to periodic multiple transmission lines interacting with a SCW.



Coupled cavity TWT

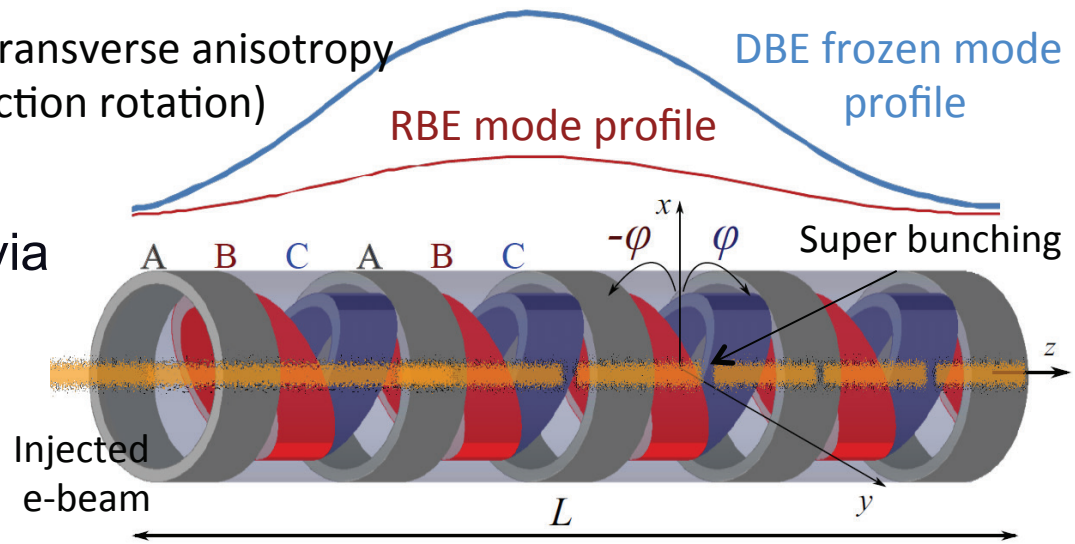


MTL segment interacting with e beam



Analytical Theory - UCI

A, B, C : transverse anisotropy (cross-section rotation)

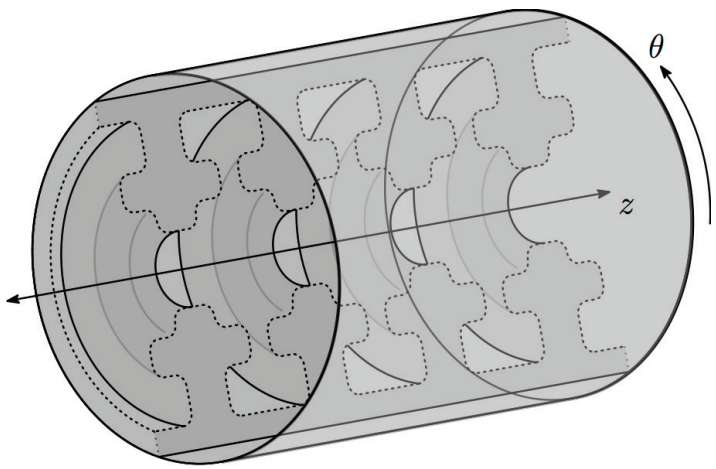


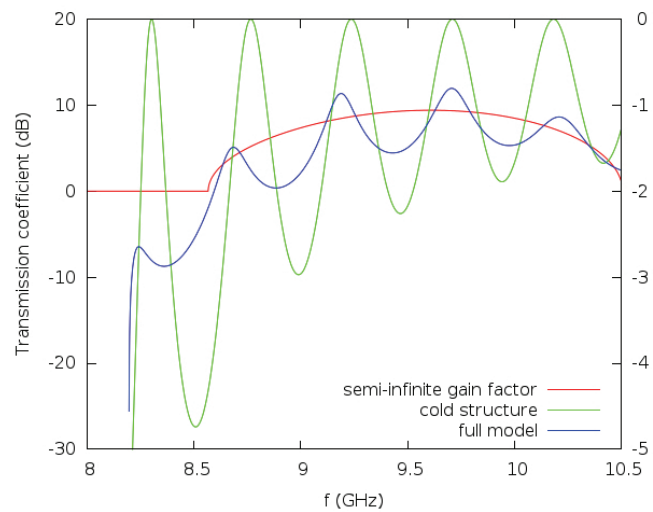
Frozen mode amplifiers:

- ✓ TWT with super amplification via the DBE mode. $\text{Gain} \propto L^5$
- ✓ We have conceived a novel approach for pulse compression based on DBE.
- ✓ Develop designs of novel backward wave oscillators (BWO) based on frozen mode regimes (a weak e-beam can produce a strong output signal).

Analytical Theory - LSU

The LSU team develops mathematical methods enabling systematic design of metamaterial structure for controlling beam wave interaction inside High Power Traveling Wave Tube Amplifiers





Analytical Theory - LSU

Applied mathematics approach:

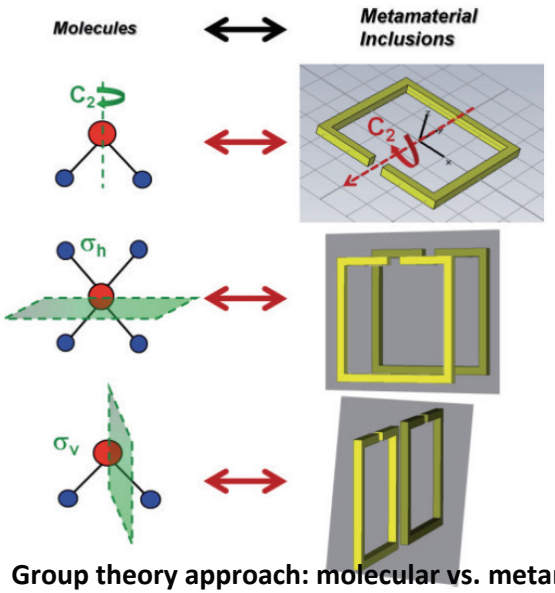
- Multiscale representation of solutions of Maxwell's equations inside structured metals
- Providing a quantitative way to link metmaterial structure to performance of TWT amplifiers
- Enabling the systematic design of high power microwave amplifiers

Stage I. Multiscale representation for solutions of Maxwell system inside TWT amplifiers. Provides a design method for metamaterial loaded TWT amplifiers in microwave regime. Current designs provide floating all metallic interaction structures for control of gain and bandwidth. Forms a theoretical foundation for multiscale representations of waves in TWTs.

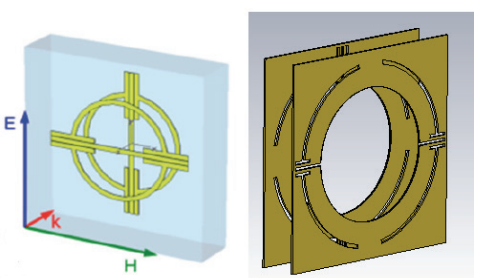
Stage II. Current work successfully extends representation of solutions of Maxwell system in TWT amplifiers for design of all metal anchored interaction structures. This method now being coded to be used as a computational simulation tool for prototyping and testing all metal interaction structures.

Analytical Theory - UNM

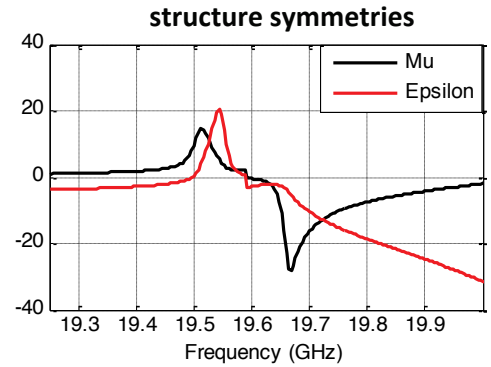
- A metamaterial structure for HPM applications
  - All-metallic design, no dielectric substrate
  - Complementary form amenable to stand-alone mounting
  - Negative index (ε<0, μ<0) without ancillary structures (cutoff-mode waveguide, rods or wires)
- Group theory based design approach
  - No more random guessing
  - Systematic design for desired features (biaxial, bianistropic, chiral)



Group theory approach: molecular vs. metamaterial structure symmetries



Zia metamaterial **Complementary form**

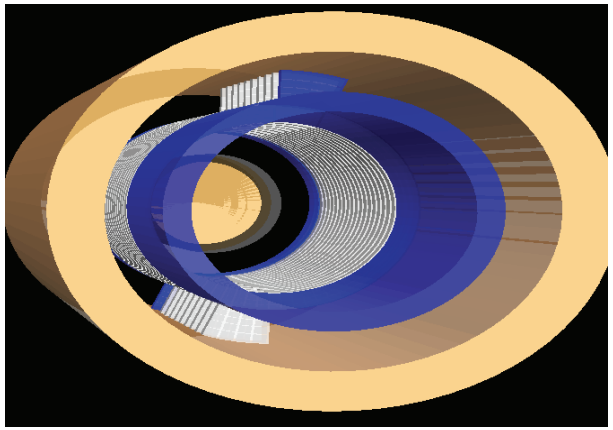


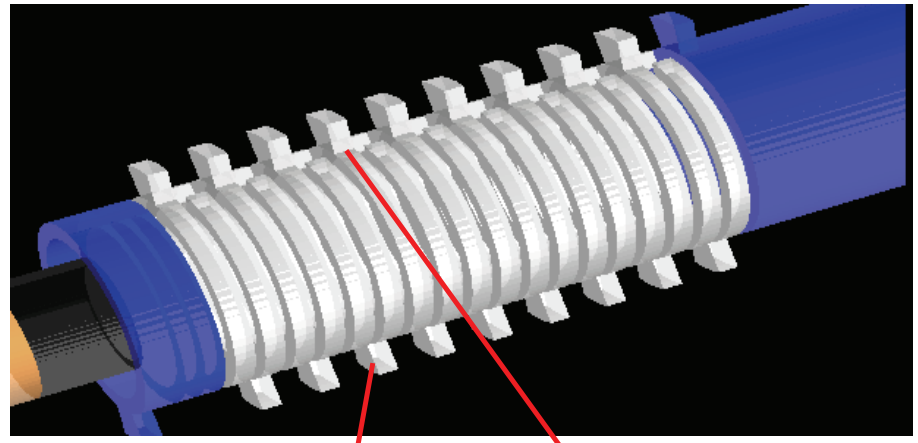
ε<0, μ<0 resonances (unpublished results)

Virtual Prototyping/Exp't – UNM Broadside Coupled SRR

The SWS consists of split rings where the adjacent rings are 180° out of phase. Each split ring is electrically connected to the output waveguide by means of a conducting tab.

3-dimensional view

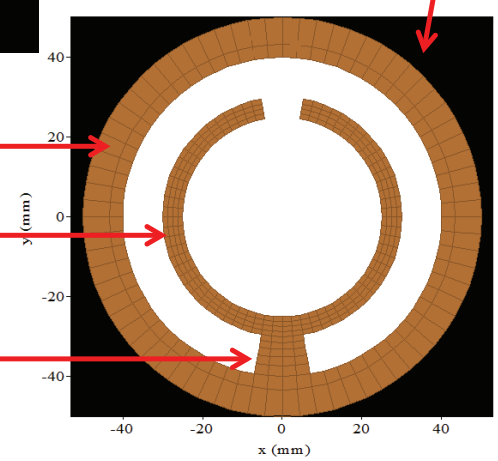


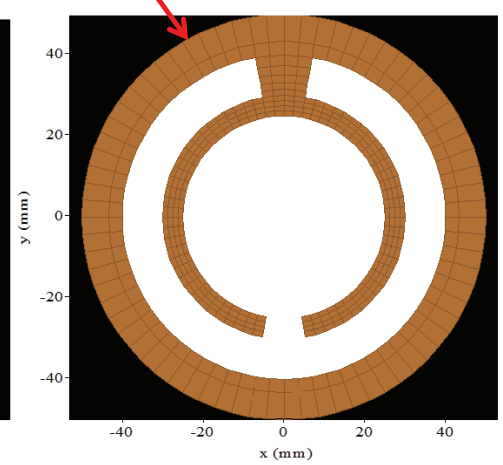


Output waveguide

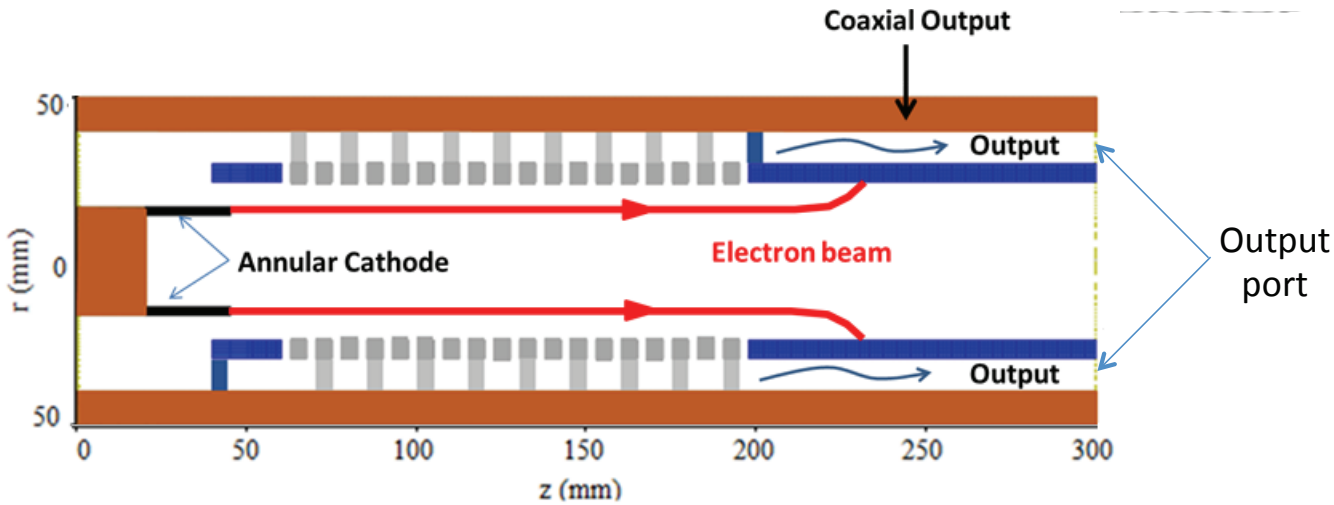
Split ring

Conducting tab





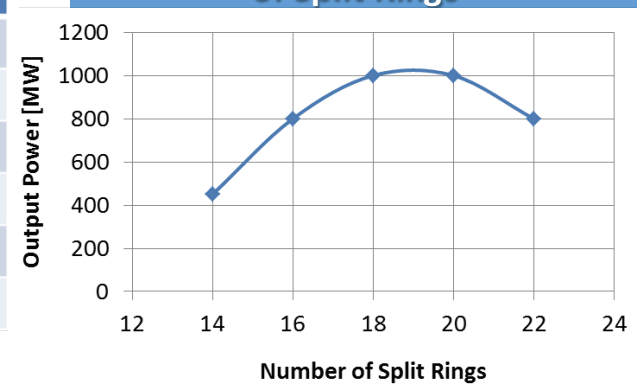
Virtual Prototyping/Exp't – UNM Broadside Coupled SRR



Split Ring Dimensions	
Ring Inner Radius, R_i	2.5 cm
Ring Outer Radius, R_o	3.0 cm
Ring Width, R_w	0.5 cm
Gap Between Rings, R_g	0.5 cm
Angular Width of Slit	20°
Angular Width of Tab	20°

Simulation Parameters	
Cathode Radius	1.75 cm
Anode Radius	4.0 cm
# of Rings	9
Applied Voltage	500 kV
Voltage Rise-time	1 ns
Magnetic Field	2 T

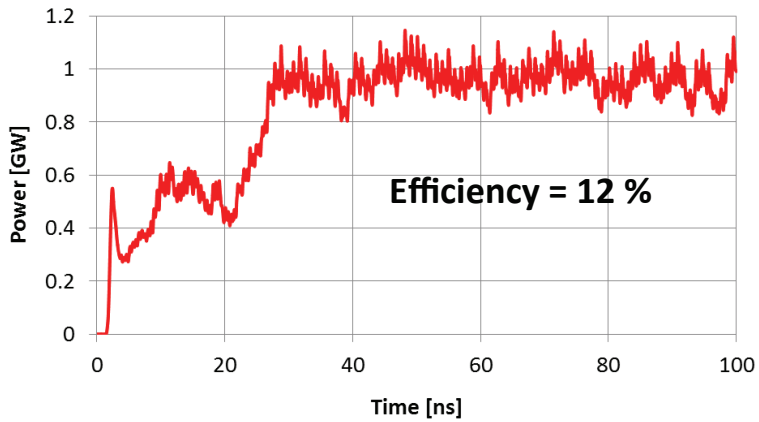
Power Dependence on Number of Split Rings



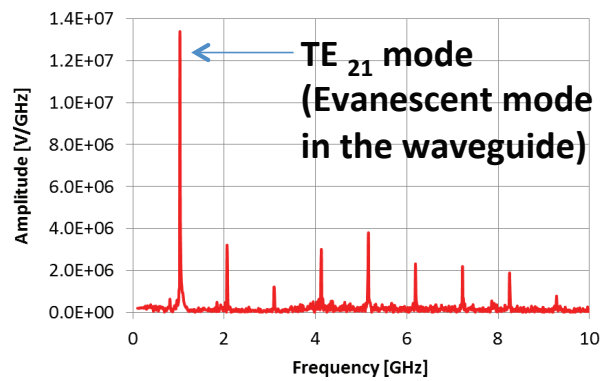
Virtual Prototyping/Exp't – UNM Broadside Coupled SRR

An example of the RF Signal obtained from the 3D MAGIC Simulation

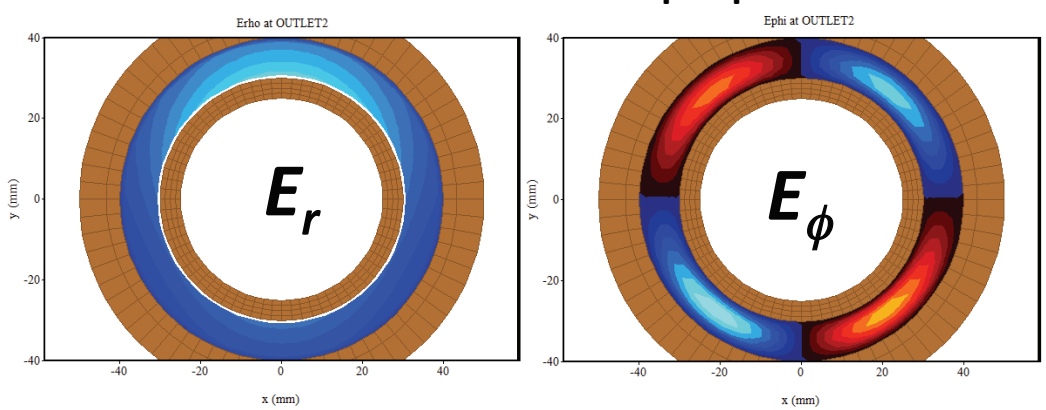
Output Power



FFT of the RF signal



RF Mode measured at the output port of the coaxial waveguide



To propagate the TE $_{21}$ mode at 1.1 GHz it would require a cylindrical waveguide 13.3 cm in radius. This design provides 3 times reduction in size.

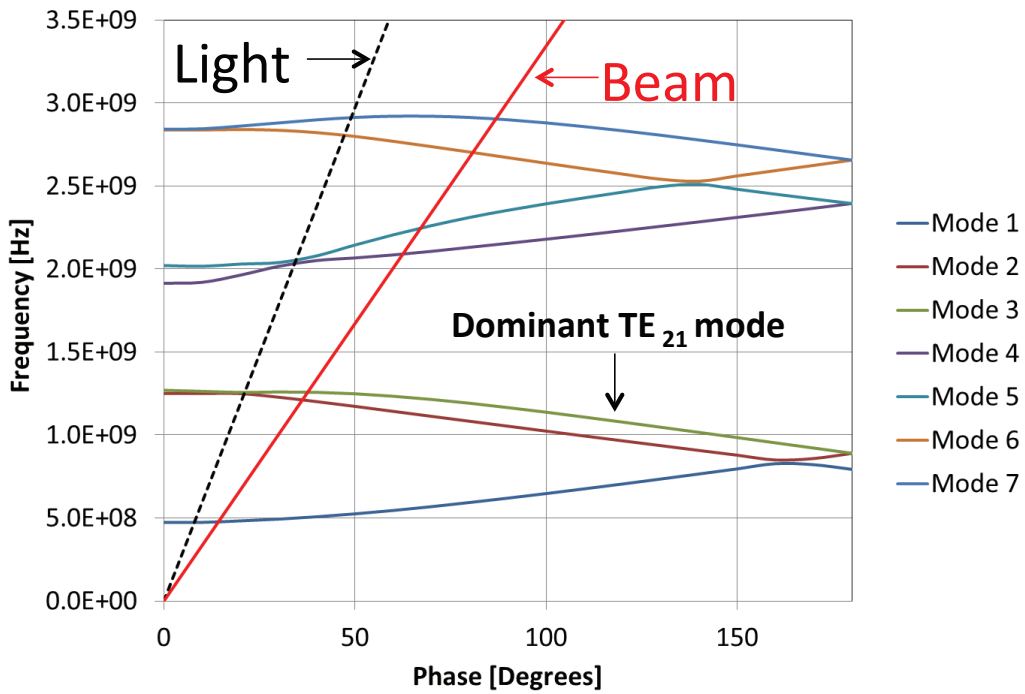
Virtual Prototyping/Exp't – UNM Broadside Coupled SRR

1. Dispersion diagram shows that the beam intersects with negative slope of the dominant mode suggesting a backward wave generation.
2. The RF signal being evanescent in the waveguide gets reflected from the upstream and downstream ends thereby providing feedback for RF generation.

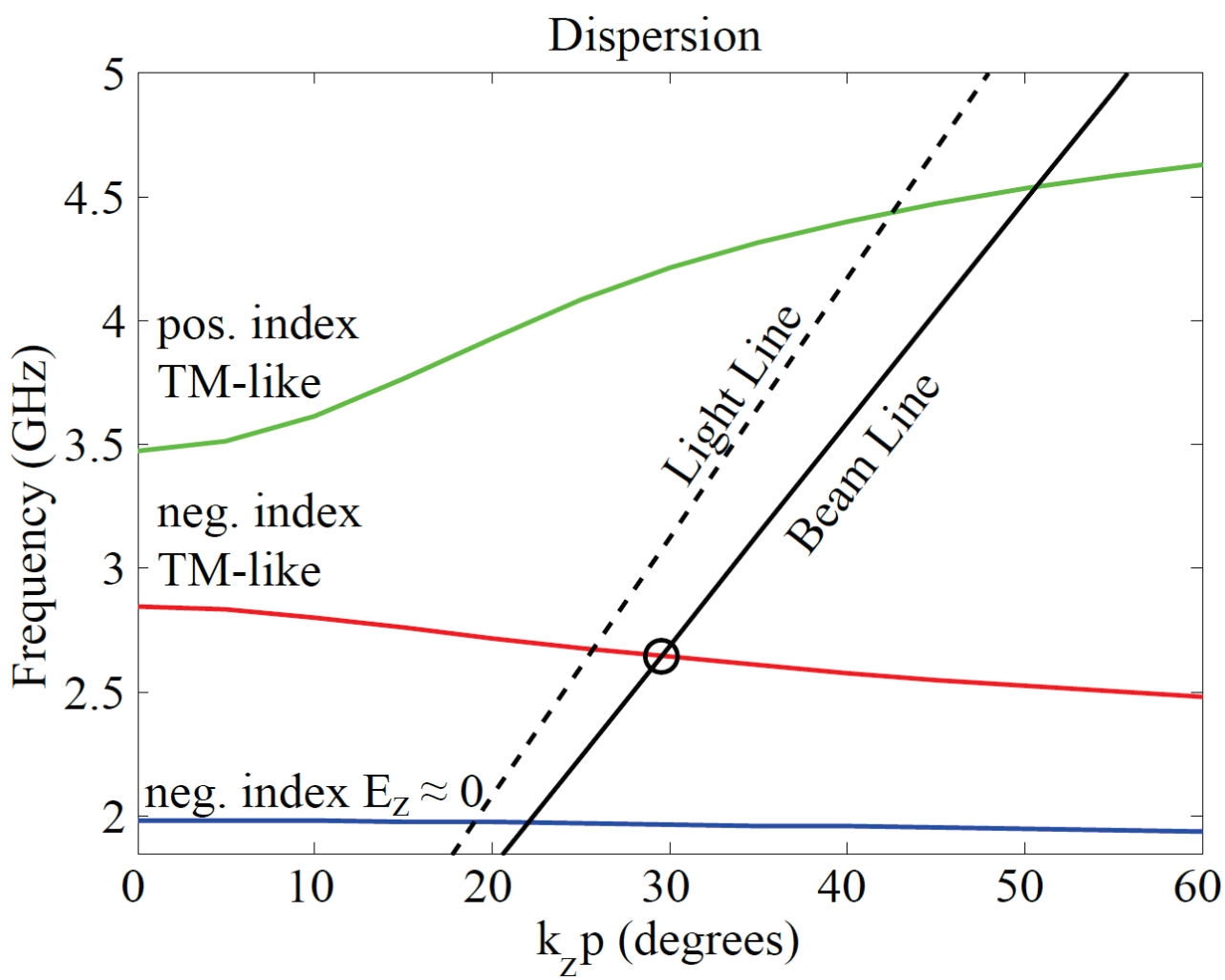
SRR provides negative μ

Below waveguide cutoff provides negative ε

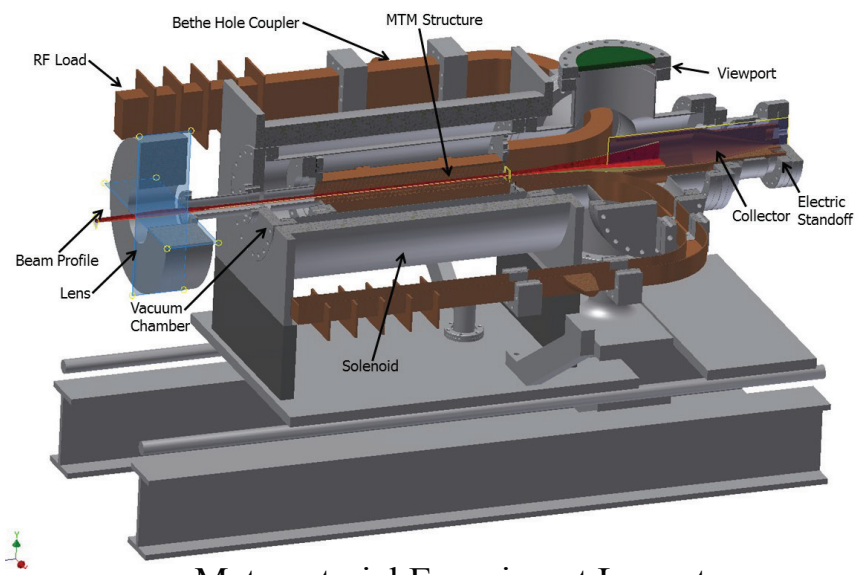
Experiments planned



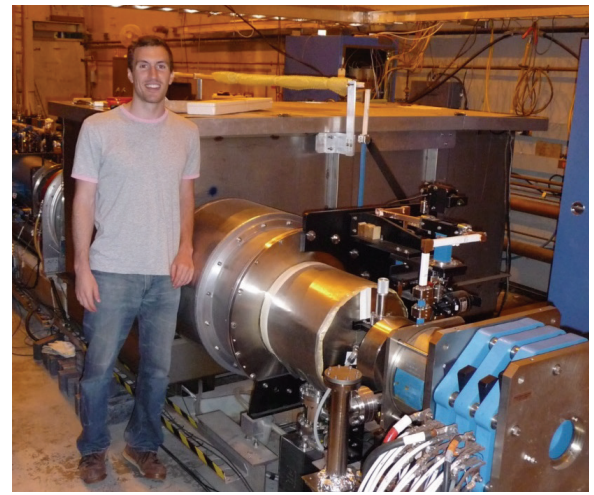
Virtual Prototyping/Exp't – MIT Double Negative SWS



Virtual Prototyping/Exp't – MIT Double Negative SWS



Metamaterial Experiment Layout



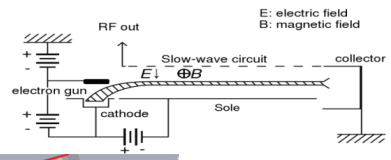
Lab setup showing electron gun and magnets; grad student Jason Hummelt

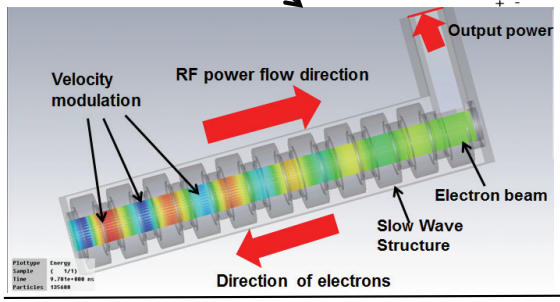
- Complete design of MTM Backward Wave Oscillator Experiment
  - 500 kV, 80 A electron gun operates in 2 microsecond pulses
  - Design for 6 MW of output power near 2.856 GHz
  - All parts for the MTM structure have been designed and are on order, many have been received
- First operation expected late Summer or early Fall

Virtual Prototyping – OSU Double Negative SWS

Backward Wave Oscillator (BWO's)

BWO schematic





Conventional slow wave structure unit cell

Available/Nominal BWOs

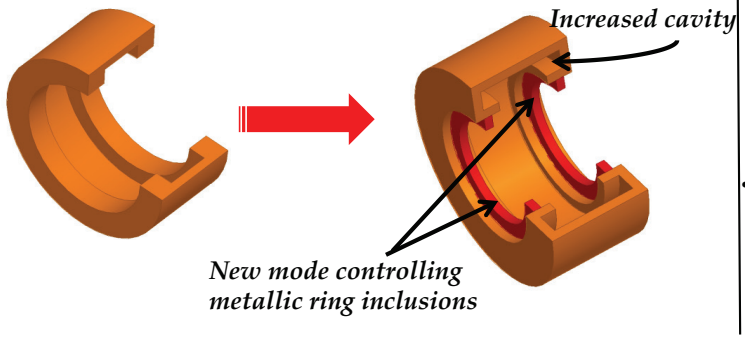
- Megawatt class device
- 20% power conversion efficiency
- Fully metallic design

New Slow Wave Structure

- Much more compact design
- Higher interaction impedance (larger power coupling)
- Much Improved spectral purity of output signal
- 50% to 100% better efficiency

New Slow Wave Structure (SWS) Design

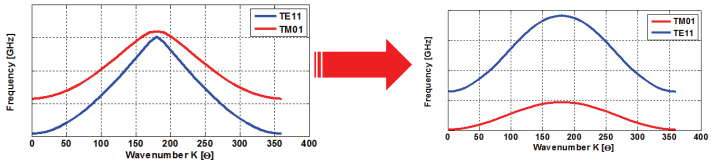
Conventional SWS | New SWS



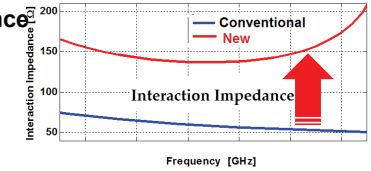
Results

- Mode dominance: Spectral Purity *(TE_{11} mode only)*

Conventional SWS | New SWS



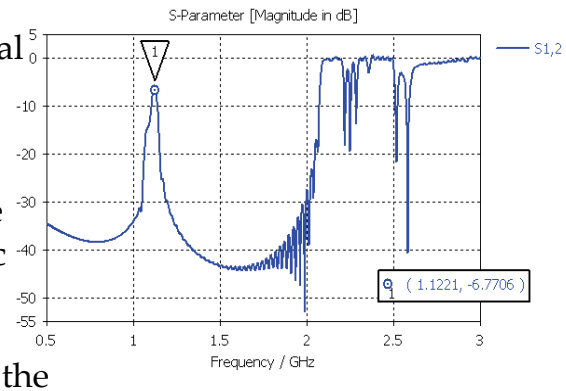
- Increased interaction impedance *(2X improvement)*
- Higher power coupling at least 50% higher efficiency



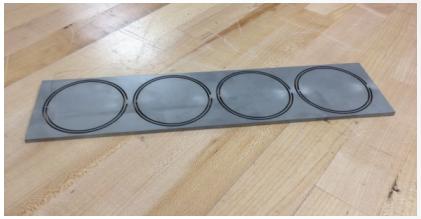
Virtual Prototyping/Exp't – UNM Metamaterial Survivability

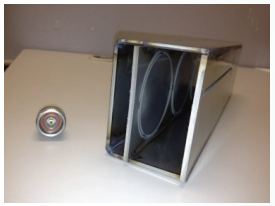
Compact HPM Antenna

- S-band waveguide with dual CSRR loading
- Operation in fundamental mode
- CSRR is placed on the wide wall to interact with electric field
- Operation at 1GHz
- Size reducton of 63.12% on the broad wall



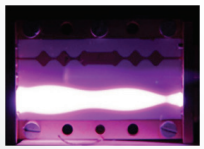
Fabricated Design

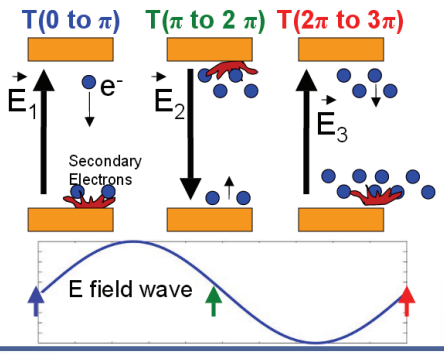




Breakdown in Vacuum

Multipactor manifests itself as an avalanchelike growth of the free electron density.





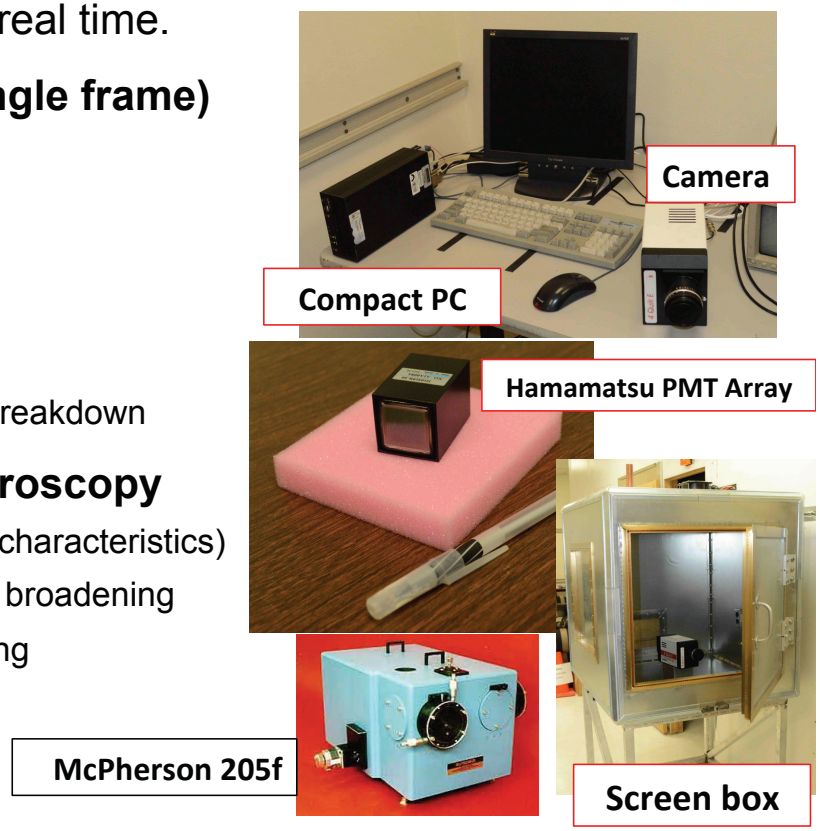
- Resonance phenomenon: Time that electron needs to travel the gap is T/2
- SEY >1

Factors:

Gap length, Frequency, Power, SEY curve, Geometry

Virtual Prototyping/Exp't – UNM Metamaterial Survivability

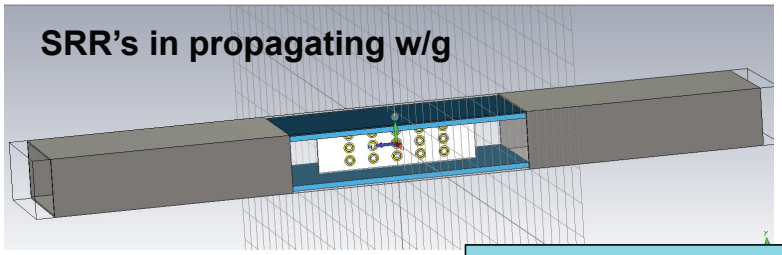
- A set of in situ optical diagnostics is being implemented to observe MTM breakdown performance in real time.
  - **Fast visible camera (1 ns, single frame)**
    - Breakdown initiation and localization
  - **Fast photomultiplier array**
    - Time history
  - **Visible survey spectroscopy**
    - Identification of species involved in breakdown
  - **Visible high resolution spectroscopy**
    - Ion/neutral temperature (breakdown characteristics)
    - Breakdown plasma density via Stark broadening
    - Electric field strength via Stark splitting

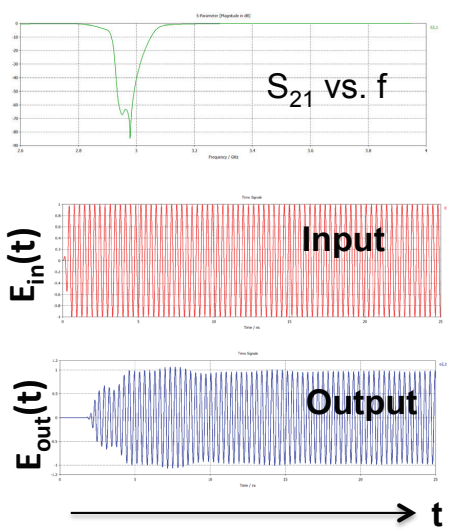


Virtual Prototyping/Exp't – Time Response of Metamaterials

I. Time Response of Metamaterials

CST Simulations

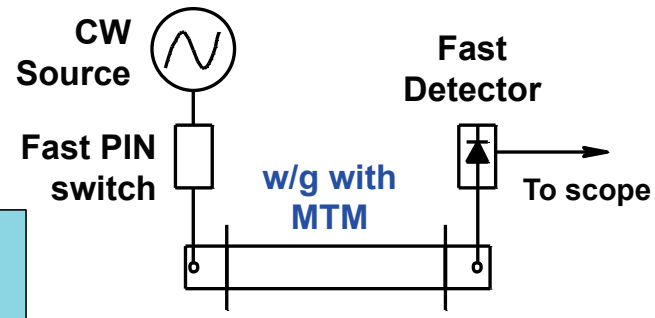




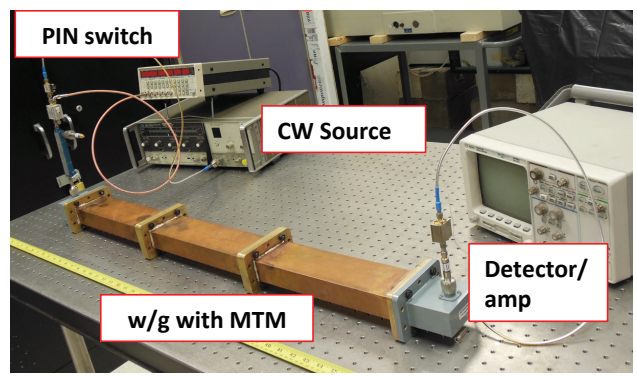
Investigate

1. Time response of standard MTM's (SRR's) and new MTM's for HPM → *how to optimize?*
2. Behavior in propagating and cutoff w/g, including DN MTM/waveguide
3. TE_{10} and other modes

Cold Test Stand



Simplified test crkt



Challenges We Have Identified

- The time response of metamaterials to electromagnetic fields is much longer than the time response of conductors
- The slow group velocity of metamaterial structures demands long pulse electron beams in order to achieve saturation
- There are preliminary indications that beam/wave interaction theory for metamaterial SWSs needs to be further developed and does not follow the established theory for traditional metallic SWSs

Productivity Data - Graduate Student Teleseminars To-Date

The inaugural MURI graduate student teleseminar took place March 1, 2013

Student teleseminars take place on the first Friday of each month at 11 AM Eastern Time US, 4 PM GMT

- March 01, 2013 University of New Mexico
- April 05, 2013 Massachusetts Institute of Technology
- May 03, 2013 Ohio State University
- June 07, 2013 Louisiana State University
- June 25, 2013 University of Strathclyde
- August 02, 2013 University of New Mexico
- September 06, 2013 Massachusetts Institute of Technology
- October 04, 2013 Ohio State University

Graduate Student Teleseminars To-Date

- December 06, 2013 Louisiana State University
- February 07, 2014 University of New Mexico
- March 07, 2014 University of Huddersfield
- April 04, 2014 Massachusetts Institute of Technology
- May 02, 2014 Ohio State University
- June 06, 2014 Louisiana State University
- August 01, 2014 UC Irvine

Productivity Data – To-Date

Team	# Journal Papers in Print	# Journal Papers in Review	# Conference Papers	# Post Docs	# Graduate Students	# Undergrad Students
UNM	2	1	22	2	5	2
MIT	3	1	4	0	4	1
OSU	0	1	5	1	2	0
UCI	2	1	0	2	2	0
LSU	2	1	0	1	1	0
TOTALS	**9**	**5**	**31**	**6**	**14**	**3**

Accolades To-Date

- Dr. Robert Lipton (LSU) elected Fellow of the American Association for the Advancement of Science in 2013
- Dr. Richard J. Temkin (MIT) received the 2013 IEEE NPSS PSAC Plasma Science and Applications Award
- Dr. Edl Schamiloglu (UNM) received the 2013 IEEE NPSS Richard F. Shea Distinguished Member Award
- Dr. Christos Christodoulou (UNM) promoted to Distinguished Professor in 2013
- Keynote Invited Talk at the Intl. Vacuum Electronics Conf. 2014, Monterey, CA: "Design of a High Power S-Band Metamaterial Backward-Wave Oscillator," J. Hummelt, S. Lewis, M. Shapiro, R. Temkin (MIT)
- Dr. Edl Schamiloglu (UNM) promoted to Distinguished Professor in 2014
- Dr. Edl Schamiloglu (UNM) received International Electrotechnical Commission (IEC) 1906 Award (for exceptional achievement)

Future Plans

- UNM to hot test its broadside-coupled SRR SWS and compare with virtual prototyping
- UNM to work with OSU, UCI, LSU to identify optimal SWS to construct and hot test
- MIT to optimize its DN SWS and suggest improvements
- Compare experimental data with virtual prototyping (UNM, MIT, OSU, UCI, LSU)
- Elaborate on the slow response time of metamaterial SWSs
- Refine beam/wave interaction theory to account for metamaterial SWS (UNM, MIT, UCI)
- Experimentally study metamaterial SWS survivability and propose failure model (UNM, UH)
- Study advanced SWSs made using traditional materials and compare with metamaterial SWS performance (OSU, US)

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Multidisciplinary Research Program of the University Research Initiative

MURI

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

http://www.ece.unm.edu/FY12MURI/