

# 2016 Metamaterials Program Review

**Drs. Marshall, Nachman, Pomrenke; Weinstock | November 9, 2016 | Arlington, VA**

## **Abstracts**

### **ORAL PRESENTATIONS**

#### **Anisotropic Impedance Surfaces for Control of Surface Wave Propagation and Scattering**

(Daniel Sievenpiper, UC San Diego)

This talk will focus on methods for controlling propagation of surface waves using anisotropic metasurfaces. We have developed a wide range of useful patterns such as impedance surface waveguides, and metasurfaces for controlling scattering by both surface waves and plane waves. With these coatings, we have shown that we can manipulate the scattering properties of metallic objects, independently of their shape, and for either polarization. We have also developed ways to generate arbitrary patterns for anisotropic surfaces, with verifiable impedance functions even with complicated unit cell shapes. Current work is focused on end-to-end pattern generation to create custom non-uniform metasurfaces for any application. In addition, we have developed active surfaces based on non-Foster circuits that have dramatically increased bandwidth, e.g. a full octave at UHF with a 5 mm thick surface. This talk will also cover our work on a range of related topics such as nonlinear surfaces for protection from high power microwave sources, and new results in optical frequency metasurfaces for high performance photocathodes and plasmonically enhanced vacuum electronic devices.

#### **Reflective Photonic Limiters for Sensor Protection from High Power Laser Radiation**

(Nicholaos Limberopoulos and Ilya Vitebskiy, AFRL/RYPD)

Optical limiters are essential for protection of the human eye, optical sensors, antennas, and other sensitive devices from high-power laser or microwave radiation. Optical limiters transmit low intensity light, while blocking the laser or microwave radiation with dangerously high intensity. A typical passive optical limiter involves a nonlinear optical material which is transparent at low light intensity and becomes opaque when the light intensity exceeds certain level. Most of the high-level radiation is absorbed by the nonlinear material causing overheating, electrical breakdown, or some other irreversible damage (sacrificial limiters). This fundamental problem could be solved if the state of the nonlinear material changed from transparent to highly reflective (not absorptive) when the intensity becomes too high. None of the known nonlinear optical materials display such a property. A solution can be provided by a nonlinear photonic structure. We discuss different possible realizations of reflective optical limiters that do not absorb the high power electromagnetic radiation, but rather reflect it back to

space within a broad frequency range and arbitrary direction of incidence. The practical objectives include: (a) protection of the limiter and the device behind it from overheating and destruction by high power laser or microwave radiation, (b) dramatic increase in the limiter dynamic range. We also discuss some specific experimental realizations of reflective photonic limiters.

### **Extreme Platforms for Extreme Manipulation of Fields and Waves**

(Nader Engheta, Penn)

In this talk, I will give a progress report on our ongoing research projects supported under the Vannevar Bush Faculty Fellow (VBFF) award. We are exploring various “extreme” platforms in which fields and waves can be sculpted and manipulated in extreme ways, with goals towards unprecedented controls in photonic, phononic and thermal scenarios. The field/wave-platform interaction in such paradigms can lead us to exciting possibilities in wave-based and field-based devices and components.

Some of our ongoing research projects in this VBFF program include (a) introduction and development of the notion of photonic “doping” in extreme-parameter platforms, in which insertion of a single photonic impurity can significantly affect the global and local scattering; (b) manipulation and engineering thermal radiation and its spatial coherence using extreme-parameter structures in which spectral contents and spatial coherence can be tailored with properly selected platforms; (c) multiband detection based on extreme parameters, (d) planar structures for information storage and coding, (e) informatic structures for wave-based informatic devices for mathematical manipulations and information processing using waves, (f) nonreciprocal platforms with extreme parameters, (g) quantum phenomena in selected extreme platforms, (h) phononic scenarios, and more.

I will discuss our findings on the above projects, will present physical insights into the results, and will give the plans for the next steps in each project.

### **Photonics-Driven, Optically-Coherent Networks for Meta-Surface-Current Sheets as RF Array Antennas**

(Dennis W. Prather, Delaware)

We present our work on the direct integration of high power, high linearity photodiodes to feed an Ultra-Wide-Bandwidth (UWB) meta-surface-current phased array antenna to form a low profile, transmit aperture. The network design and device level integration leverages advantages of photonic techniques and design flexibility for UWB beam steering for Air Force applications in Communications, Radar, and Electronic Warfare. This work is motivated by the need for a paradigm shift within next generation avionic systems that need to incorporate frequency agility and multi-functional capability to address the challenges of modern operational environments. To this end, we leverage the development

of high power, high-linearity modified uni-traveling carrier (MUTC) photodiodes to enable an efficient a high fidelity optical-to-electrical conversion to enable high frequency, high gain, low noise figure, and high linearity meta-surface-current feed networks. Details of our design, fabrication, integration and recent demonstration at AFRL will be presented.

### **Wave Engineering with Metasurfaces Nanoantennas**

(Hossein Mosallaei, Northeastern)

In this talk, the concept of nanoantennas as building blocks for metasurfaces will be discussed. The designs in reflection mode, transmission, and tunable will be highlighted. It is demonstrated how unique building blocks can be engineered to manipulate the amplitude, phase, and polarization to the interest. Both plasmonic and all-dielectric nanoantennas will be investigated and presented in depth. Applications for beam steering, focusing, and beam shaping are demonstrated. We also investigate metasurfaces with multifunctional and tunable building blocks. The theory of the proposed systems is explained in detail. Also, considering the complexity of the proposed metasurfaces and having graded pattern array (of nanoantennas), large area and of billions of unknowns, we implement a unique computational paradigm for modeling such metasurfaces.

### **Chiral Nanophotonic Metadevices**

(Reza Khorasaninejad and Federico Capasso, Harvard)

The objective is to investigate physics and device applications of the interaction of light with chiral structures including nanoparticles, waveguides and surfaces. The project studies theoretically and experimentally the anomalous lateral scattering of surface plasmon waves by artificial chiral dipoles such as a metallic nano-helix. Concluding remarks will include information about the FY14 MURI project covering the Control of Light Propagation through Metasurfaces.

### **On-Chip Nanophotonics with CMOS-Compatible Plasmonic Materials**

(Alexandra Boltasseva, Purdue)

The high optical mode confinement offered by plasmonics holds a promise for compact, ultrafast data processing and transfer circuits. However, challenging integration and CMOS incompatibility of noble metals that are usual plasmonic materials, is a major roadblock in the integration of practical plasmonic devices with established silicon platform. Hence, dynamic plasmonic materials that are adjustable, tunable, robust, and CMOS compatible are required for practical on-chip plasmonics. Recently, our

group has demonstrated long-range surface plasmon polariton (LRSP) waveguides with titanium nitride that exhibit a performance similar to that of gold structures. Transition metal nitrides are CMOS-compatible materials used as a diffusion barrier in microelectronics. We have also realized zirconium nitride waveguides with a comparable performance. Solid-state waveguides using metal nitrides have also been designed and realized for on-chip interconnects. We have also studied transparent conducting oxides (TCOs) are CMOS compatible, tunable and have low optical losses at the telecommunication frequency range for ultrafast optical modulation. Ultrafast nonlinear response in the epsilon near zero region has recently been demonstrated for films of aluminium doped zinc oxide. Building upon these results we have designed CMOS-compatible TCO modulators on a transition metal nitride-based waveguiding platform.

### **Hybrid Molecular-Scale Materials: From Ultrafast Spontaneous Emission to Perfect Absorbers**

(Maiken H. Mikkelsen, Duke)

Department of Electrical and Computer Engineering, Department of Physics, Duke University

Hybrid materials structured on the molecular scale hold the promise to realize optical properties that are drastically different from their bulk counterparts. Here, I will describe our recent experiments utilizing a dynamically-tunable plasmonic platform where emitters are sandwiched in a sub-10-nm gap between colloidally synthesized silver nanocubes and a metal film. Incorporating colloidal semiconductor quantum dots into the nanocavities enables experimental demonstration of an ultrafast (<11 ps) yet efficient source of spontaneous emission, corresponding to emission rates exceeding 90 GHz [Nature Communications 6, 7788 (2015)]. By also utilizing the second order mode of the cavity, optical processes at multiple energies can be optimized simultaneously. We demonstrate this by enhancing both the absorption and the quantum yield in monolayer MoS<sub>2</sub> resulting in a 2,000-fold enhancement in the overall fluorescence [Nano Letters 15, 3578 (2015)]. Additionally, at a surface fill fraction of ~20%, these film-coupled nanocubes behave as spectrally selective perfect absorbers which can be tuned from the visible to the near-infrared utilizing inherently large-area solution-based deposition techniques [Advanced Materials 27, 8028 (2015)]. Combining this bottom-up fabrication technique with photolithography patterning enables demonstration of spectrally-narrow pixel arrays and a combinatorial pixel scheme exhibiting ~10,000 color combinations (Advanced Materials, in press, 2016, DOI: 10.1002/adma.201602971). Finally, the plasmon resonance can be tuned electrically over 100 nm in the visible by applying a bias across the nanoscale gap which causes changes in the gap thickness and dielectric environment [Applied Physics Letters 108, 183107 (2016)]. Our results provide an avenue to create ultrafast and reconfigurable integrated nanophotonic components.

### **Tuning Chiroptical Response in Optical Metamaterials**

(Vivian Ferry, Minnesota)

The objective of this project is to create tunable chiral metamaterials, and to understand coupling between chiral metamaterials and nanoscale light emitters. This presentation will discuss our approach to designing switchable and tunable chiral metamaterials based on analogous chemical systems, designed so that nanoscale displacements result in an inversion of the circular dichroism response. A second important consideration is that coupling together different materials systems requires control over both the resonant and off-resonant interactions. By studying different combinations of materials systems, we have developed principles that control both the sign and the spectral position of the circular dichroism response.

### **Parity-Time Symmetric Nanophotonic Materials and Metamaterials**

(Brian Baum and Jennifer Dionne, Stanford)

This PECASE project investigates a new class of optical media, PT (parity-time) -symmetric nanophotonic metamaterials. These materials will combine concepts from both metamaterials and PT-symmetric materials to enable nanoscale optical components and devices capable of lossless, asymmetric, and ultimately nonreciprocal light propagation across wavelength and sub-wavelength scales.

### **Dispersion Engineering using Metamaterials for Transformational Electromagnetics**

(Edi Schamiloglu, UNM)

This FY12 AFOSR MURI on Transformational Electromagnetics has been exploring novel beam-wave interaction structures using metamaterials and other periodic structures. Dispersion engineering has been used to design double negative slow wave structures that would not be possible using conventional materials. As we are entering the final year of this effort we have already performed hot tests with one planar complementary split ring resonator slow wave structure in an oscillator configuration. A hot test of a cylindrical broadside-coupled split ring resonator structure is about to commence. Hot tests of two more structures, one structure based on a degenerate band edge and another based on a slow wave structure with a mode controlling metallic inclusion are planned for later in 2017. Advances on our theoretical understanding of beam-wave interactions with metamaterials and other periodic structures will also be presented.

### **Tailoring Magnetic Nanomaterials for Electromagnetic Wave Absorption**

(Chao Wang, Johns Hopkins)

This project explores the application of magnetic nanomaterials for electromagnetic wave absorption. We present organic solution synthesis routes towards preparation of a wide range of rare earth-free magnetic nanoparticles, including soft ( $\text{Fe}_3\text{O}_4$ ,  $\text{CoFe}_2\text{O}_4$ , Co) and hard ( $\text{Fe}_{2.3}\text{Cr}_{0.7}\text{Se}_4$ ) magnetic materials. We have been able to manipulate the synthetic conditions to tune the particle size, shape and composition to tailor the magnetic properties in terms of coercivity ( $H_c$ ) and magnetization ( $M_0$ ). We have also evaluated the dependence of the permittivity ( $\epsilon$ ) and permeability ( $\mu$ ) of the nanoparticle assemblies on these material parameters, based on which we have further derived the correlation between the electromagnetic wave absorption characteristics and the nanoscale architectures of the materials. Our research will substantially advance the fundamental understanding of the interactions between electromagnetic waves and magnetic materials, in particular when the materials are with features tailored at the sub-wavelength nanoscales.

### **Toward Active Circuits and Metamaterials Utilizing Bandgap-Less Hydrodynamic Gain from Ultra-Slow 2D Plasmons** (Donhee Ham, Harvard)

Plasmonic waves excited in two-dimensional (2D) conductors behave vastly differently from plasmons excited in three-dimensional (3D) bulk conductors. Notably, while surface plasmons in 3D bulk metals exhibit a propagation velocity down to  $\sim c/10$  ( $c$ : light speed), the velocity of 2D plasmons can be reduced down to  $\sim c/700$  or more, as we have amply demonstrated in the series of our recent works with various forms of 2D conductors such as graphene as well as semiconductor quantum wells. Such extreme velocity reduction and proportionally reduced wavelength of 2D plasmons bring a number of exciting possibilities in the science and technology of metamaterials, such as extreme device miniaturization, greatly enhanced light-matter interaction, and near-field operation. Another significant possibility with such extremely slow 2D plasmons, which will be the focus of my presentation, is that they can be harnessed to produce gain (amplification). Specifically, due to the slow 2D plasmonic velocity that can be reduced towards the velocity of the electron drift associated with a DC current, 2D plasmonic waves excited in a drifting 2D electron gas (set up by the DC current) can extract energy from the DC current via hydrodynamic wave-current interaction, thus producing gain. In fact, in a recent set of our experiments, by setting up a DC current in a 2D conductor (quantum well) with a proper boundary condition and exciting 2D plasmonic waves on top, we have measured strong evidences of such gain originating from the hydrodynamic wave-current interaction. This gain mechanism is not based on bandgap, and does not suffer from the traditional frequency scaling limitation of transistors; the gain mechanism is possible up to until interband transition occurs (up to near infrared frequencies typical with 2D semiconducting and semi-metallic systems). This gain mechanism thus can be harnessed for obtaining THz and infrared coherent radiation, or self-sustained oscillation (e.g., in connection with bilayer graphene where room-temperature plasmonic excitation is possible) as well as for making various metamaterials based on 2D conductors such as graphene active. In this talk, I will present the physical concept, the device engineering and measurement, and the future prospects of this hydrodynamic gain from ultra-slow 2D plasmons.

## **Compressive Sensing and Enhanced Detectors with Plasmonics and Photonic Nanojets.**

(Augustine Urbas, AFRL/RXAN)

Detecting optical signals in the mid and long wave infrared are significant to a range of Air Force technologies and drive the research to increase performance and functionality. Both spectral and spatial information is obtained in images with hyperspectral. New challenges arise as detector pixel counts increase and the information desired from image data is more widely used. Limitations on data communication rates provide a bottle neck for acquiring and processing the increasingly large data sets. Compressive sensing may allow for more efficient acquisition data with higher information content, while preserving mission utility. Our research develops a combined method to integrate plasmonic and micro-optical elements onto detector structures which can both improve the performance of detector systems and provide a means to introduce compressive sensing and computational imaging methods. By coupling a variety of simulation environments which cover the optical, plasmonic, and electronic domains, we can efficiently comprehensively model detector function and performance for a wide range of designs and incorporate compressive sensing into the design loop. We will present the results of several design studies and experimental verification of modeled device performance for several device configurations.

## **Film-Coupled NanoPatch Platform for Novel Apertures at Infrared and Visible Wavelengths**

(David R. Smith, Duke)

We present the latest results on both disordered and periodic arrays of film-coupled nanopatch antennas. The film-coupled nanopatch is a planar nanoparticle that strongly couples to its electromagnetic image formed in a nearby metallic plane. Leveraging planar fabrication and deposition techniques, the gap between nanopatch and image can be controlled to sub-nanometer distances, allowing the electromagnetic enhancement region to be tightly controlled. In recent work, we have applied this system to demonstrate such optical phenomena as fluorescence enhancement and controlled reflectance surfaces. Currently, we have additional predictions for many other phenomena, including enhanced nonlinear processes and optical bistability. The ability to control the gap precisely, and the nature of the field scattered from the film-coupled nanopatch impart particularly advantageous properties to the system as a whole, such that optimizing enhancement-dependent phenomena can be efficiently accomplished. Using a combination of basic transmission line theory combined with coupled mode theory, the properties of the film-coupled nanopatch can be determined from quasi-analytical formulas with excellent accuracy (compared with experiments and numerical simulations). Moreover, since the nanopatches radiate to good approximation as magnetic dipoles, a coupled-dipole formulation enables entirely quasi-analytic predictions of both periodic and random systems. We have shown, for example, that in periodic arrays of nanopatches, a variety of spectral features relate to the nature of both the coupling of the radiating magnetic dipoles both to free space modes as well as surface plasmon modes, and have obtained exact agreement between the extended theory and simulations. As part of our long term objective, we are also interested in the potential of the film-coupled nanopatch system

for novel imaging architectures. The development of new physical architectures motivates the development of accompanying algorithms that will best leverage the advantages of the physical layer. Motivated by work on metasurfaces at lower frequencies, we have begun the exploration of a variety of computational imaging techniques, including phaseless imaging and several variants of MIMO (Multiple-Input, Multiple Output) imaging that may eventually be a good match for the nanopatch system.

## **POSTERS**

### **Fabrication of Graphene-Based Metasurfaces for Terahertz Modulators**

Thomas A. Searles (Howard)

Recently, electro-optic modulators featuring atomic-layered two dimensional materials, specifically graphene and MoS<sub>2</sub>, have shown great promise as ultrafast optical interconnects with transfer rates up to ~20 GBit/s. The increase in demand for higher speed communications applications have many predicting that TBit/s speeds will be available within the next 10 years, and due to operation at terahertz (THz) frequencies, new formats are predicted, such as a 5G cellular network. However, THz photonic devices such as sources, detectors and modulators are still in the design and development stages. Here, we present simulations for a novel graphene hybrid metasurface device with amplitude modulation at 40% and frequency modulation up to 50 GHz. Furthermore, we present the fabrication process for our metasurface and advances in the transfer of graphene to our substrates. We will characterize our proposed devices with a turnkey terahertz time domain spectroscopy system which features a have large bandwidth (>6 THz), high spectral resolution (1 GHz) and flexibility to add on other instrumentation to explore future materials, systems and other experimental methodologies such as optical pump-THz probe phenomena.

### **Design and Fabrication of Metasurface Lenses in Midwave Infrared**

(Bryan Adomanis, AFIT; D. Bruce Burckel, Sandia; Michael Marciniak, AFIT)

Flat lenses require precise control of a phase gradient across an interface, which is enabled through the application of engineered surfaces, such as metasurfaces. Periodic arrays of plasmonic antennas have been utilized to generate this desired phase gradient, which dictates the angle of “anomalous” refraction of the cross-polarized field scattered from a normal-incidence beam. However, the designs utilized to-date have been simple geometries, due to the challenges of numerical modeling more complex forms, and as a result, scattering efficiencies have been unacceptable for real-world application. Therefore, an optimization effort is necessary to improve the performance. In order to establish confidence before proceeding with complex designs, the finite element analysis (FEA) software COMSOL Multiphysics® was used to simulate the response of parametrized gold V-antennas on a silicon substrate, which served as a basis for the design of several plasmonics-based metasurface lenses. The simulated phase and amplitude of the scattered, cross-polarized far-field of the scatterer were

parametrized over the dipole length ( $h/2$ ) and vertex angle ( $\Delta$ ) to determine the optimal geometries needed to access the full  $2\pi$  phase space. These elements were then arrayed linearly according to Fresnel lens phase calculations and formed the basis of a cylindrical focusing optic. Nineteen lenses and eight metasurfaces were fabricated with varying wavelengths, focal lengths, diameters, number of unique elements and packing densities. By validating the lens design using a non-optimized scatterer made of a simple geometry, this effort provided confidence in the future use of FEA solvers for a comprehensive investigation of lens design optimization using more complex structures and architectures.

### **Metasurface Absorbers for Multispectral Pixel Arrays**

Jon W. Stewart, Gleb M. Akselrod, David R. Smith & Maiken H. Mikkelsen Duke)

Multispectral imaging is an extremely powerful technique in a wide variety of fields including chemical analysis, surveillance, remote sensing, and geospatial analysis. Current approaches for multispectral imaging require complex, bulky, and expensive optical systems. One approach to overcome these limitations is by constructing multispectral photodetectors with spectrally selective pixels to simultaneously achieve spatial and spectral resolution. However to date, plasmonic pixels have been unable to simultaneously achieve spectral selectivity, strong absorption, and scalable fabrication. Here we demonstrate high-performance plasmonic multispectral pixel arrays based on gap-plasmon resonators that exhibit absorptions upwards of 85 percent with spectral widths near 100 nm. The key to our approach is a multiscale fabrication method, which combines bottom-up colloidal fabrication to form the plasmonic elements and top-down fabrication to define the pixels. By tuning the size of the plasmonic resonators, the sub-pixels can span resonances from 580 to 1125 nm. We demonstrate the power of our approach by reconstructing an RGB image using the plasmonic pixels which show ~10,000 different color combinations. Integrating the passive plasmonic metasurfaces with an electrically active material is promising for future on-chip multispectral photodetectors in the infrared.