

METAMATERIALS SCIENCE & TECHNOLOGY WORKSHOP

Celebrating
first 15 years of metamaterials

20 - 22 July 2015
San Diego, California

metamaterials.duke.edu/mstw

Dear workshop participant,

Welcome to the Metamaterials Science and Technology Workshop!

Fifteen years ago, around March of 2000, a metamaterial with negative refractive index was reported by researchers in the Department of Physics at the University of California, San Diego. At that time, the term metamaterial had just been created to describe materials with properties beyond what can be found in naturally occurring material. The negative index material—which had been theoretically analyzed by Victor Veselago in 1968, but never demonstrated—immediately garnered attention as embodying the definition of a metamaterial.

Over the past fifteen years, both negative index as well as metamaterials grew into major research topics, spreading across disciplines, into nearly every branch of science. Even further, the suggestion that metamaterials could be used to create invisibility cloaks caught people's imagination, making the metamaterials concept now a fixture in the popular media, with references appearing in such mainstream shows as Jeopardy! and The Big Bang Theory.

Though we have seen true surprises and remarkable scientific results from metamaterial research, the journey is far from over! Recent years have seen activity grow rapidly in the area of commercialization, with metamaterial products being matched to large market opportunities. In the coming years, these commercialization attempts will play out. Will we see metamaterials become as ubiquitous as lasers or semiconductors? Stay tuned!

As we now find ourselves at the junction of between basic metamaterials research and application development, we invite you to celebrate the extraordinary metamaterial achievements that have been realized, with many of the pioneers in the field. It is thus with great pleasure we welcome you to the campus of the University of California, San Diego, for the Metamaterials Science and Technology Workshop! This workshop has been organized and sponsored by Duke University's Center for Metamaterials and Integrated Plasmonics (CMIP), and jointly hosted by CMIP and UCSD.

We hope that you enjoy the program!

Professor David R. Smith

James B. Duke Professor of Electrical and Computer Engineering
Duke University



A negative index metamaterial—demonstrated at UCSD in 2000 and reported in Physical Review Letters (photo by Willie J. Padilla).

Workshop Schedule

SUNDAY, JULY 19, 2015

5-7 P.M.	Welcome Reception in the Olive Lawn (meet and greet)	Estancia Hotel 9700 N Torrey Pines Rd La Jolla, CA 92037
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MONDAY, JULY 20, 2015

7:30 A.M.	Buses depart La Jolla Shores Hotel and Estancia Hotel to Scripps (second run departs at 8:00 a.m.)	Hotel Lobby
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8:00 A.M.	MSTW Registration Opens and breakfast available	Scripps Courtyard 8610 Kennel Way La Jolla, CA 92037
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8:30 A.M.	Welcoming remarks: David Smith, Director of the Center for Metamaterials and Integrated Plasmonics (CMIP), Dimitri Basov and Willie Padilla	Scripps Auditorium
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9:00 A.M.	Keynote: "Not everything was negative" Sir John Pendry, Imperial College	Scripps Auditorium
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10:00 A.M.	"Nonlinear high-field response of terahertz metamaterials" Richard Averitt, University of California San Diego	Scripps Auditorium
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10:30 A.M.	CST Sponsored Break	Scripps Courtyard
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11:00 A.M.	"Tunable and Nonlinear Metasurfaces: Metamaterials Meet Optoelectronics" Igal Brener, Sandia	Scripps Auditorium
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11:30 A.M.	"Applied Acoustic Metamaterials" Steve Cummer, Duke University	Scripps Auditorium
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12:00 P.M.	LUNCH	Scripps Ocean View Patio
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WORKSHOP SCHEDULE

1:30 P.M.	Plenary: "Electronically Tunable Metamaterials" Harry Atwater, Caltech	Scripps Auditorium
2:15 P.M.	"Informatic Metastructures" Nader Engheta, University of Pennsylvania	Scripps Auditorium
2:45 P.M.	"Nanophotonics Technology" Shaya Fainman, University of California San Diego	Scripps Auditorium
3:15 P.M.	"Tunable Light-matter Interaction With Quantum Spillover and 2D materials" Nicholas Fang, Massachusetts Institute of Technology	Scripps Auditorium
3:45 P.M.	Closing remarks before poster session	Scripps Auditorium
4:00 P.M.	Poster Session (poster numbers 1-17) refreshments provided	Rooms 155 & 160
5:00 P.M.	Buses depart to La Jolla Shores and Estancia Hotel (second run 5:45 p.m.)	Scripps Courtyard

TUESDAY, JULY 21, 2015

7:30 A.M.	Buses depart La Jolla Shores Hotel and Estancia Hotel to Scripps (second bus at 8:00 a.m.)	Hotel Lobby
8:00 A.M.	PhD poster presenters breakfast with John Pendry, Nathan Kundtz and conference organizers	Room 165
9:00 A.M.	Morning welcome and introduction to commercialization efforts of metamaterials: David Smith	Scripps Auditorium
9:15 A.M.	Keynote: "Kymeta and the mass-market commercialization of metamaterials" Nathan Kundtz, President and CEO of Kymeta	Scripps Auditorium
10:15 A.M.	"Echodyne's challenge: Establishing a fast design cycle for productization of metamaterial-based imaging radar systems" Tom Driscoll, Echodyne	Scripps Auditorium
10:45 A.M.	CST Sponsored Break	Scripps Courtyard
11:00 A.M.	"Metamaterials: An Investor's Story How to invest in a technology when you're not sure what it's good for" Casey Tegreene, Intellectual Ventures	Scripps Auditorium
11:30 A.M.	"Development of Metamaterial for Military Applications" Anthony Starr, Sensormetrix	Scripps Auditorium

WORKSHOP SCHEDULE

12:00 P.M.	“Modular and metamaterial approaches to physical security” Alec Rose, Evolv Technologies	Scripps Auditorium
12:30 P.M.	LUNCH	Scripps Ocean View Patio
1:30 P.M.	Plenary: “All-dielectric nanophotonics and metadevices: From Fano resonance to functional metasurfaces” Yuri Kivshar, Australian National University	Scripps Auditorium
2:15 P.M.	“Optical Metamaterials Resonances with Large Quality Factors” Costas Soukoulis, AMES Lab / Iowa State University	Scripps Auditorium
2:45 P.M.	“2D and 3D Metamaterials: Physical Realization and Heterogeneous Integration” Nan Jokerst, Duke University	Scripps Auditorium
3:15 P.M.	“Quantum Plasmonic Metamaterials” Zhaowei Liu, University of California San Diego	Scripps Auditorium
3:45 P.M.	“Singular Optics in the Meta-World” Natalia Litchinster, University of Buffalo	Scripps Auditorium
4:15 P.M.	Closing remarks before poster session	Scripps Auditorium
4:30 P.M.	Poster Session (poster numbers 18-34) refreshments provided	Rooms 155 & 160
5:30 P.M.	Buses depart to La Jolla Shores and Estancia Hotel	Scripps Courtyard
6:30 P.M.	Buses depart La Jolla Shores and Estancia Hotel to Banquet Dinner	Hotel Lobby
7:00 P.M.	Banquet Dinner for registered attendees only	Birch Aquarium
9:00 P.M.	Buses depart to La Jolla Shores and Estancia Hotel	

WEDNESDAY, JULY 22, 2015

8:15 A.M.	Buses depart La Jolla Shores Hotel and Estancia Hotel to Scripps (second run 8:45 a.m.)	Hotel Lobby
9:15 A.M.	Morning welcome from organizers	Scripps Auditorium
9:30 A.M.	Plenary: “Recent progress on metamaterials in optics, thermodynamics, mechanics, and magneto-transport” Martin Wegener, Karlsruhe Institute of Technology	Scripps Auditorium
10:15 A.M.	“Control of Radiative Processes using Colloidally Synthesized Plasmonic Nanocavities” Maiken Mikkelsen, Duke University	Scripps Auditorium

WORKSHOP SCHEDULE

10:45 A.M.	“Metamaterials for Single Pixel Imaging at Long Wavelengths” Willie Padilla, Duke University	Scripps Auditorium
11:15 A.M.	CST Sponsored Break	Scripps Courtyard
11:30 A.M.	“Photonic Hypercrystals” Evgenii Narimanov, Purdue	Scripps Auditorium
12:00 P.M.	“Merging Metamaterials with Quantum Photonics” Vladimir Shalaev, Purdue	Scripps Auditorium
12:30 P.M.	LUNCH	Scripps Ocean View Patio
1:30 P.M.	Plenary: “Optical Antennas; Spontaneous Emission Faster Than Stimulated Emission” Eli Yablonovitch, Berkeley	Scripps Auditorium
2:15 P.M.	“Photonic Topological Insulators Based on Metamaterials: Molding the Flow of Light Around Corners and Obstacles” Gennady Shvets, University of Texas at Austin	Scripps Auditorium
2:45 P.M.	“Metamaterials for Defense Applications” Augustine Urbas, AFOSR	Scripps Auditorium
3:15 P.M.	“Metamaterials: In Pursuit Of Globally Optimal Designs” Yaroslav Urzhumov, Duke University/Intellectual Ventures	Scripps Auditorium
3:45 P.M.	“Metamaterials: Optical Properties on Demand” Nikolay Zheludev, Southampton University	Scripps Auditorium
4:15 P.M.	“Non-Hermitian Optics and Parity-time Symmetry in Metamaterials” Xiang Zhang, Berkeley	Scripps Auditorium
4:45 P.M.	Poster awards and closing remarks	Scripps Auditorium
5:15 P.M.	Buses depart to La Jolla Shores and Estancia Hotel (second run at 5:45 p.m.) -- workshop conclusion	Scripps Courtyard

Abstracts & Bios



SIR JOHN PENDRY, IMPERIAL COLLEGE NOT EVERYTHING WAS NEGATIVE

Abstract: Changing the sign of the refractive index has caused much controversy in the optics community. Veselago was the first to point out some of the remarkable counter-intuitive properties of negative refraction but it took the advent of metamaterials to realise the concept and to generate the fiercest arguments. I shall review some of the early history highlighting why ideas such as the perfect lens were controversial and how the controversy was resolved and concluding with the challenges remaining.

Bio: John Pendry has made seminal contributions to surface science, disordered systems and photonics. His most recent work has introduced a new class of materials, metamaterials, whose

electromagnetic properties depend on their internal structure rather than their chemical constitution. Pendry discovered that a *perfect lens* manufactured from negatively refracting material would circumvent Abbé's diffraction limit to spatial resolution, which has stood for more than a century. His most recent innovation of *transformation optics* gives the metamaterial specifications required to rearrange electromagnetic field configurations at will, by representing the field distortions as a warping of the space in which they exist. In its simplest form the theory shows how we can direct field lines around a given obstacle and thus provide a *cloak of invisibility*, which was first realized at Duke in 2006.



RICHARD AVERITT, UNIVERSITY OF CALIFORNIA SAN DIEGO NONLINEAR HIGH-FIELD RESPONSE OF TERAHERTZ METAMATERIALS

Abstract: The past decade has seen dramatic advances in creating active metamaterials (MM) with properties that can be dynamically modified and controlled with external stimuli, including optical excitation, electrical control, or mechanical actuation. A fair amount of this work has been at terahertz frequencies as this region of the electromagnetic spectrum is ripe for technological development while, from a fabrication point-of-view, providing rapid access to test new MM concepts and ideas. With the advent of pulsed terahertz sources capable of generating peak fields on the order of 1MV/cm, nonlinear THz "optics" is a new vista that, in concert with MM, offers

exciting and scientific and technological opportunities. In this work, I will present some of our recent efforts exploring nonlinear THz MM. This includes the nonlinear response of InAs plasmonic disks and electron field emission arising from strong field localization and enhancement within the capacitive regions of metamaterial resonators.

Bio: Richard Averitt received his PhD degree in Applied Physics from Rice University for work on the synthesis and optical characterization of gold nanoshells. Following this, Richard was a Los Alamos National Laboratory Director's Postdoctoral

Fellow where his work focused on time resolved far-infrared spectroscopy of strongly correlated electron materials. In 2001, Richard became a member of the technical staff at Los Alamos, and in 2005 a member of the Center for Integrated Nanotechnologies co-located at Los Alamos and Sandia National Laboratories. In 2007, Richard joined Boston University as a faculty member in the Department

of Physics and the Boston University Photonics Center. Since 2014, Richard has been with the Department of Physics at UC San Diego. Richard's research is primarily directed towards characterizing, creating, and controlling the optical and electronic properties of complex materials. This includes correlated transition metal oxides and metamaterials.



IGAL BRENER, SANDIA **TUNABLE AND NONLINEAR METASURFACES: METAMATERIALS MEET OPTOELECTRONICS**

Abstract: After the initial flurry of activity in the theory and RF implementations of 3D metamaterials, it was quickly realized that the promise of metamaterials at optical wavelengths is hindered by the difficulty of fabricating three-dimensional composites with nanoscale inclusions. Metasurfaces, the two dimensional version of metamaterials, consist of planar arrays of metamaterial resonators. Despite their apparent simplicity, they can provide new functionality at optical wavelengths, especially when combined with other materials that change their optical properties in response to external stimuli. For example, when metasurfaces are integrated with semiconductor heterostructures, they can be voltage-tuned dynamically, or used to create nonlinear optical media with functionality that cannot be found in traditional nonlinear materials. By leveraging decades of development of semiconductor optoelectronics, metasurfaces coupled to semiconductors might enable new types of optical devices from the infrared to the visible spectral range.

Bio: Igal Brener is a Distinguished Member of Technical Staff at Sandia National Laboratories in Albuquerque, NM. He received the B.Sc. degree in Electrical Engineering, the B.A. degree in Physics, and the D.Sc. degree in Physics from the Technion- Israel Institute of Technology, Haifa, Israel, in 1983, 1983 and 1991, respectively. From 1983 to 1986 he worked for National Semiconductors in microprocessor VLSI design. He was with Bell Laboratories from 1991 until 2000, with Tellium Inc. from 2000 until 2002, and with Praelux/Amersham Biosciences/GE Healthcare from 2003 until 2004. He joined Sandia National Laboratories, Albuquerque, NM, in 2004 where he is active in nanophotonics, THz science, optoelectronics and metamaterials. He currently holds a dual appointment as thrust leader for nanophotonics at the DOE Center for Integrated Nanotechnologies. He has authored more than 200 refereed publications, and has received 15 patents. Dr. Brener is a fellow of the Optical Society of America and the IEEE, and has served in several conference committees (OSA, IEEE and SPIE), government panels and review boards.



STEVE CUMMER, DUKE UNIVERSITY **APPLIED ACOUSTIC METAMATERIALS**

Abstract: While acoustic wave propagation in periodic structures is an old topic, modern research in acoustic metamaterials began with efforts to mimic progress in electromagnetic metamaterials with a focus on exotic material parameters, such as negative modulus and negative effective mass. The field has since branched into a wide range of topics

including phononic bandgap materials, transformation acoustics, active materials, and thin metasurfaces. This presentation will focus on recent results from acoustic metamaterials research in my group, following two main paths. The first focus will be on transformation acoustics, focusing on the design and experimental demonstration of structures based on fluid-based anisotropic

acoustic metamaterials. Truly broadband devices have been demonstrated in air, for which the high contrast with solid materials makes it relatively easy to realize many useful effective parameters. We will also describe our initial work in developing the needed materials for the more challenging environment of water. The second focus will be on the development and use of labyrinthine metamaterials, a concept first described by Jensen Li in which the intra-cell coiling of propagation distance enables the control of transmission phase to create a wide range of properties and effects. This approach is proving particularly useful in the development of thin diffractive structures for manipulating acoustic wave transmission

and reflection.

Bio: Steven Cummer received his Ph.D. in Electrical Engineering from Stanford University in 1997 and prior to joining Duke University in 1999 he spent two years at NASA Goddard Space Flight Center as an NRC postdoctoral research associate. Awards he has received include a National Science Foundation CAREER award and a Presidential Early Career Award for Scientists and Engineers (PECASE) in 2001. His current work is in a variety of theoretical and experimental electromagnetic problems related to geophysical remote sensing and engineered electromagnetic materials.



HARRY ATWATER, CALTECH
ELECTRONICALLY TUNABLE METAMATERIALS

Abstract: Progress in understanding resonant subwavelength structures has fueled an explosion of interest in fundamental processes and nanophotonic devices. The carrier density and optical properties of photonic nanostructures are typically fixed at the time of fabrication, but field effect tuning of the potential and carrier density enables the photonic dispersion to be altered, yielding new approaches to energy conversion and tunable radiative emission. While the emissivity is normally a fixed material-dependent quantity, modulation of the carrier density enables tuning of the complex dielectric function and the emissivity of infrared emitter, enabling modulation of radiative emission at

constant temperature. We experimentally demonstrate tunable electronic control of blackbody emission frequency and intensity in graphene metasurfaces using field effect tuning of the graphene carrier density. We also describe designs for metasurfaces based on patch antenna arrays that allow field effect tunability of the reflection amplitude and phase of the incoming field.

Bio: Professor Atwater received his B. S., M. S. and Ph.D. degrees from the Massachusetts Institute of Technology respectively in 1981, 1983 and 1987. He held the IBM Postdoctoral Fellowship at Harvard University from 1987-88, and has been a member of the Caltech faculty since 1988.



NADER ENGHETA, UNIVERSITY OF PENNSYLVANIA
INFORMATIC METASTRUCTURES

Abstract: Materials manipulate waves, and therefore they can tailor, control, redirect, and scatter electromagnetic waves and photons at will. Recent development in metamaterials and nanomaterials has made it possible to sculpt fields and waves at the nanoscale, and thus has provided suitable platforms for innovation in information processing and computation at subwavelength domains. We have been exploring how metamaterials can facilitate data processing, image sensing, information handling, and mathematical operations and

computation with light. Starting from optical metatronic nanocircuits, we can design structures in which waves may undergo proper evolution, resulting in mathematical computation. In this talk, I will discuss some of the challenges and opportunities in such informatics metamaterials, and will present some of the results of our team's work.

Bio: Nader Engheta is the H. Nedwill Ramsey Professor at the University of Pennsylvania in Philadelphia, with affiliations in the Departments of Electrical and Systems

Plenary Speaker

Engineering, Physics and Astronomy, Bioengineering, and Materials Science and Engineering. He received his B.S. degree from the University of Tehran, and his M.S and Ph.D. degrees from Caltech. His current research activities span a broad range of areas including nanophotonics, metamaterials, nano-scale optics, graphene optics, imaging and sensing inspired by eyes of animal species, optical nanoengineering, microwave and optical antennas, and engineering and physics of fields and waves. He is the recipient of several awards for his research including 2015 SPIE Gold Medal, 2014 Balthasar van der Pol Gold Medal from the International Union of Radio Science (URSI), 2013 Benjamin Franklin Key Award, 2013 Inaugural SINA Award in Engineering, 2012 IEEE Electromagnetics Award, 2008

George H. Heilmeyer Award for Excellence in Research, the Fulbright Naples Chair Award, NSF Presidential Young Investigator award, the UPS Foundation Distinguished Educator term Chair, IEEE Third Millennium Medal, Guggenheim Fellowship, and Scientific American Magazine 50 Leaders in Science and Technology in 2006. He is Fellow of SPIE, IEEE, APS, OSA, MRS, and American Association for the Advancement of Science (AAAS). His current research activities span a broad range of areas including nanophotonics, metamaterials, nano-scale optics, graphene optics, imaging and sensing inspired by eyes of animal species, optical nanoengineering, microwave and optical antennas, and engineering and physics of fields and waves.

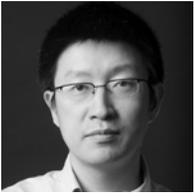


SHAYA FAINMAN, UNIVERSITY OF CALIFORNIA SAN DIEGO NANOPHOTONICS TECHNOLOGY

Abstract: Nanophotonics technology has the potential to revolutionize numerous future applications that rely on the ability to integrate it on a chip to augment and/or interact with other signals (e.g., electrical, chemical, biomedical, etc.). For example, future computing and communication systems will need integration of nanophotonic structures, devices and circuits with electronics and thus require miniaturization of photonic materials, devices and subsystems. Another example involves integration of microfluidics with nanophotonics for healthcare applications. We have advanced the nanophotonics technology by establishing design, fabrication and testing tools ranging from nanoscale engineered dielectric metamaterials, nanodevices, and circuits for various systems applications. Our most recent work emphasizes the construction of optical subsystems directly on-chip, with the same lithographic tools as the surrounding electronics. This has been made possible by the advances in lithographic tools, which can now create features significantly smaller than the optical wavelength and is predicted to reach as fine as 11 nm by 2020. Arranged in a regular pattern, subwavelength features act as a metamaterial whose optical properties are controlled by the density and geometry of the pattern and its constituents. As specific examples of our most recent work towards these goals, we will present nanoscale engineered second

order nonlinearities in silicon and various composite metal-dielectric-semiconductor gain geometries used to create new types of nanolasers for chip-scale integration of optical information systems.

Bio: Shaya Fainman is a Cymer Professor of Advanced Optical Technologies and Distinguished Professor in Electrical and Computer Engineering (ECE) at the University of California, San Diego (UCSD) where he is currently Chair of the ECE Department. He is directing research of the Ultrafast and Nanoscale Optics group at UCSD and made significant contributions to near field optical phenomena, inhomogeneous and meta-materials, nanophotonics and plasmonics, and non-conventional imaging. The research applications target information technologies and biomedical sensing. His current research interests are in near field optical science and technology. He contributed over 250 manuscripts in peer review journals and over 450 conference presentations and conference proceedings. He is a Fellow of the Optical Society of America, Fellow of the Institute of Electrical and Electronics Engineers, Fellow of the Society of Photo-Optical Instrumentation Engineers, and a recipient of the Miriam and Aharon Gutvirtz Prize, Lady Davis Fellowship, Brown Award, Gabor Award and Emmett N. Leith Medal.



NICHOLAS FANG, MASSACHUSETTS INSTITUTE OF TECHNOLOGY TUNABLE LIGHT-MATTER INTERACTION WITH QUANTUM SPILLOVER AND 2D MATERIALS

Abstract: Recently, exciting new physics of plasmonics has inspired a series of key explorations to manipulate, store and control the flow of information and energy at unprecedented dimensions. In this talk I will report our recent efforts on controlling light absorption and emission process through quantum effects in sub-20nm scale coatings. For example, we experimentally demonstrated strong absorption of 20nm thin oxides in the visible spectrum assisted by silver films. We found such a broadband light absorption below the bandgap of the oxide is a manifestation of quantum electron tunneling that penetrate into the thin oxide layer, and it is controlled by the static dielectric constant of the oxide instead of dopant. We also found quantum emitters on a graphene-hBN heterostructure can be switched on and off at mid infrared, by transferring energy into surface phonon polaritons, and this effect can be electrically tuned by biasing the graphene layer. I will also discuss application of these nanostructure for efficient light

harvesting and controllable emission, with potential impact in high resolution mid-IR spectroscopy and imaging.

Bio: Nicholas X. Fang received his BS and MS in physics from Nanjing University, and his PhD in mechanical engineering from University of California Los Angeles. He arrived at MIT in Jan 2011 as Associate Professor of Mechanical Engineering. Prior to MIT, he worked as an assistant professor at the University of Illinois Urbana-Champaign. Professor Fang's areas of research look at nanophotonics and nanofabrication. His recognitions include the ASME Chao and Trigger Young Manufacturing Engineer Award (2013); the ICO prize from the International Commission of Optics (2011); an invited participant of the Frontiers of Engineering Conference by National Academies in 2010; the NSF CAREER Award (2009) and MIT Technology Review Magazine's 35 Young Innovators Award (2008).



NATHAN KUNDTZ, PRESIDENT AND CEO OF KYMETA KYMETA AND THE MASS-MARKET COMMERCIALIZATION OF METAMATERIALS

Abstract: High gain antennas have been almost exclusively the domain of the parabolic reflector for the past 50 years. This fundamental tool at high frequencies (10GHz+) has constrained the use of these bands for mobile communications. Kymeta is addressing this challenge with metamaterials-based antenna designs which can be produced using liquid crystal display manufacturing lines. The confluence of disruptive new design tools with the \$250BB of invested infrastructure in the display industry is creating enormous opportunities and reflects a coming sea-change in wireless communications. In this talk I will cover Kymeta's technology and genesis from Duke to Intellectual Ventures to Kymeta's formation. I will also discuss the use of LCD technologies in microwave design with an emphasis on reconfigurable diffractive metamaterials. Finally I will describe some of the existing

and greenfield opportunities on the horizon for this technology.

Bio: Nathan Kundtz is an inventor and innovator in the field of metamaterials and microwave devices. Nathan's research and work at Duke University on metamaterials is highly cited as it focuses on the development of novel design techniques, such as transformation optics, to meet real-world needs. After conducting award-winning research at Duke, he was recruited by Bellevue, WA-based Intellectual Ventures where he pioneered the development and use of metamaterials technology in beam-forming applications. The success of his work at Intellectual Ventures ultimately led to the spin-out of Kymeta Corporation in 2012.



TOM DRISCOLL, ECHODYNE **ECHODYNE'S CHALLENGE: ESTABLISHING A FAST DESIGN CYCLE FOR PRODUCTIZATION OF METAMATERIAL-BASED IMAGING RADAR SYSTEMS**

Abstract: The radar market is a fragmented space, with systems operating across the spectrum and using milliwatts to kilowatts. Addressing this market efficiently requires the ability to design, build, and verify in a fast cycle which leverages modeling and high-reliability manufacturing. Here, I present an overview of Echodyne's approach

and discuss some of the methods, tools, and manufacturing selections that underlie our design cycle. Chief among these is a method for calculating the realized gain pattern of an array from single unit-cell simulations, coupled with a custom approach for selecting final beam-patterns from a semi-degenerate set.



CASEY TEGREENE, INTELLECTUAL VENTURES **METAMATERIALS: AN INVESTOR'S STORY** **HOW TO INVEST IN A TECHNOLOGY WHEN YOU'RE NOT SURE WHAT IT'S GOOD FOR**

Abstract: We have started three metamaterials-based companies in the past 5 years, with a fourth arriving soon. However, the process actually began over a decade ago and much of it had to be invented along the way, because metamaterials was a new technology (or design approach) looking for applications, and the usual rules for spinning out companies did not really apply. The presentation will describe some of the steps and missteps along the way and will provide some of the lessons learned (and taught), some of the key considerations for future commercialization, and some thoughts the technologists' roles in helping to drive commercialization of metamaterials in the future.

Bio: Casey Tegreene is Executive Vice President and Chief Patent Counsel at Intellectual Ventures. In this role, he leads all Invention Science Fund efforts in invention development, licensing, startup and product development, and overall management.

Over the past decade, Tegreene's organization has founded several companies around ISF technologies in communications, imaging, medical, software, and radar technologies, and established a world-leading Metamaterials Commercialization Center at IV. Additionally, he has assisted several ISF inventors to become fixtures in the top-10 most-prolific inventor lists in the U.S., and partnered with several companies around the world to bolster their innovation.

Tegreene holds more than 600 patents relating to a wide variety of technologies. He is a co-founder of several ISF spinout companies, and serves as a member the board of directors of Kymeta Corporation, twice named to CNBC's annual list of most disruptive technologies.

Prior to joining Intellectual Ventures, Tegreene served as intellectual property counsel and Chief Technology Officer for Microvision, Inc., a publicly traded Seattle-based photonics company. In addition, he was a co-founder of Lumera Corporation, a pioneer in electro-active polymer materials and devices for optical communications applications, also a publicly traded company. Earlier in his career, Tegreene practiced intellectual property at a law firm in the Northwest, Seed & Berry, where he specialized in IP matters, and at Cravath Swaine & Moore, a New York general practice law firm, where he specialized in corporate transactional work. He has also been a research engineer at Motorola.

Tegreene holds a JD from NYU School of Law School (Law Review), an MSEE from Georgia Institute of Technology, and a BSEE (cum laude) from the University of South Florida. Tegreene is a member of the Washington State Bar and New York Bar and is registered to practice before the U.S. Patent and Trademark Office.



ANTHONY STARR, SENSORMETRIX DEVELOPMENT OF METAMATERIAL FOR MILITARY APPLICATIONS

Abstract: The emergence of metamaterials near the start of the new Millennium initiated a rapid growth of possibilities. Our views of electromagnetics, and later other types of wave propagation including mechanical waves, changed and grew. As scientists rushed to understand the ramification of these concepts, the commercial world looked at the potential economic impacts, and the military wondered how metamaterials would change the landscape for the warfighter. SensorMetrix was one the first companies to focus on transitioning metamaterials for Government and military applications. Transitioning a new technology requires understanding the science as well as the intended applications. This presentation provides insight into the challenges and successes of bridging metamaterial concepts to a range of possible military applications.

Bio: Anthony Starr received his Bachelor's in Physics from Cornell University and his Masters/PhD from UC San Diego. Dr. Starr has been actively involved in commercializing electromagnetic related technologies for over 20 years. Dr. Starr is the President of SensorMetrix, which he co-founded in 2003 with Prof. David Smith. SensorMetrix seeks to develop EM-related materials and technology for governmental and defense clients. Dr. Starr contributed to the first experimental demonstration of an electromagnetic cloak and the first IR perfect absorber, and he has spearheaded efforts to develop structural metamaterials and applications.



ALEC ROSE, EVOLV TECHNOLOGIES MODULAR AND METAMATERIAL APPROACHES TO PHYSICAL SECURITY

Abstract: At the same time that threats to physical security advance and modernize, the security process experienced by most individuals has become predictable and mundane. No single device better attests to this than the ubiquitous metal detector, whose state-of-the-art inception remains a recognizable relative of its 50 year old ancestors. Following the rise of the internet, the smart phone, and now crowd-sourced apps, what other vital industries can say the same? The recent advances in many other industries can be boiled down to the concept of functional modularity within a unified framework. The same could be said of metamaterials, it seems, in that a common toolbox and process can be deployed across a huge and varied swath of applications with minimal effort on the part of the engineer. How else could metamaterials come to encompass microwaves, optics, fluidics, acoustics, and seismology, and yet still be considered a device-oriented field? In this talk, I will discuss our latest modular and metamaterial conceptions of physical security, connecting our current progress in the area of antenna and sensor design for

millimeter wave detection to our vision of the industry's future as an interconnected web of inexpensive and distributed sensors. While metamaterials, in their strictest definition, may or may not reinvent each sensor, their modular framework can still prove to be a powerful driver towards the next generation of physical security devices.

Bio: Alec Rose received his PhD in Electrical and Computer Engineering from Duke University in 2013, under the guidance of Professor David R. Smith. As a member of the Smith research group, Rose made contributions to the theory and design of nonlinear electromagnetic metamaterials, working across the spectrum from microwaves to optics. Since graduating from Duke, he has worked as Principle Scientist at Evolv Technology, a Gates funded startup advancing physical security with breakthroughs in metamaterials, compressive sensing and object recognition algorithms. Rose's current research interests include the modeling and analysis of millimeter wave scattering in the radiative near-field.



YURI KIVSHAR, AUSTRALIAN NATIONAL UNIVERSITY
ALL-DIELECTRIC NANOPHOTONICS AND METADEVICES: FROM FANO RESONANCE TO FUNCTIONAL METASURFACES

Abstract: Rapid progress in the fields of plasmonics and metamaterials is driven by their ability to enhance near-field effects with subwavelength localization of light, and a majority of such effects is usually associated with metallic structures. Recently, we observe the emergence of a new branch of nanophotonics aiming at the manipulation of strong optically-induced electric and magnetic Mie-type resonances in dielectric and semiconductor nanostructures with high refractive index. Unique advantages of dielectric resonant nanostructures over their metallic counterparts are low dissipative losses and the enhancement of both electric and magnetic fields that provide competitive alternatives for metal-based plasmonic structures including nanoantennas, nanoparticle sensors, and metasurfaces. In this talk, we review the new emerging field of nanophotonics and metamaterials and demonstrate that the co-existence of strong electric and magnetic resonances and resonant enhancement of magnetic field in dielectric nanoparticles bring new physics and entirely novel functionalities to simple geometries not much explored in plasmonic structures especially in the nonlinear regime.

Bio: Yuri S. Kivshar received a PhD degree in theoretical physics in 1984 from the Institute for Low Temperature Physics and Engineering (Kharkov, Ukraine). From 1988 to 1993 he worked at different research centers in USA, France, Spain, and Germany, and in 1993 he moved to Australia where later he established Nonlinear Physics Center at the Australian National University being currently Head of the Center and Distinguished Professor. His research interests include nonlinear photonics, optical solitons, nanophotonics, and metamaterials. He is Fellow of the Australian Academy of Science, the Optical Society of America, the American Physical Society, the Institute of Physics (UK), as well as Deputy Director of the Center of Excellence for Ultrahigh-bandwidth Devices for Optical Systems CUDOS (Australia) and Research Director of Metamaterial Laboratory (Russia). He received many prestigious awards including the Lyle Medal (Australia), the State Prize in Science and Technology (Ukraine), and the Harrie Massey Medal of the Institute of Physics (UK).



COSTAS SOUKOULIS, AMES LAB / IOWA STATE UNIVERSITY
OPTICAL METAMATERIALS RESONANCES WITH LARGE QUALITY FACTORS

Abstract: Most metamaterials (MMs) to date are made with metallic constituents, resulting in significant dissipation loss in the optical domain. Therefore, we need to find other ways to create high-quality resonators with less dissipative loss for the meta-atoms. One innovative approach we plan is to reduce dissipative losses by making use of dielectrics rather than metals for building the EM resonators. This avoids resonant loss in the metals and we indeed demonstrate electric and magnetic dielectric metamaterial resonators with very large quality factors. The resulting structures can be straightforwardly scaled at optical frequencies to create low-loss MMs with a wide range of properties.

Bio: Costas Soukoulis received his B.S. in Physics (1974) U. of Athens, Greece; Ph.D. in Physics (1978) U. of Chicago. Visiting Assistant Professor (1978-1981) Physics, U. of Virginia. Staff (1981-1984) Exxon Research and Eng. Co. and since 1984 has been at Iowa State University (ISU) and Ames Laboratory. He is currently a Distinguished Professor of Physics since 2005. He has been an associate faculty member of FORTH since 1983. Soukoulis received the senior Humboldt Research Award; he shared the Descartes award for research on metamaterials. He received an honorary doctorate from Vrije University in Brussels, and shared the 2013 McGroddy Prize of the APS for new materials. He won the 2014 OSA Max Born Award. He is Fellow of the APS,

OSA, and AAAS. He has chaired numerous committees for international conferences, and served on committees for NSF, DOE, and the EU.

Prof. Soukoulis has made seminal contributions to the theory, design,

fabrication, and experimental realization of metamaterials (MMS) and photonic crystals (PCs). He was the prime initiator and mover for the development of metamaterials, which do not exist in natural materials.



NAN JOKERST, DUKE UNIVERSITY
2D AND 3D METAMATERIALS: PHYSICAL REALIZATION AND HETEROGENEOUS INTEGRATION

Abstract: The physical realization of metamaterials offers tremendous opportunities to create new materials with unprecedented functionality. However, the fabrication and integration issues that accompany practical implementation of metamaterials are challenging, and include controlling losses, shrinking feature size with decreasing wavelength of operation, planarization for 3D structures, and yield. This presentation will focus on the practical implementation of 2D metamaterials in a waveguide format, as well as metamaterials designed to be addressed in a surface normal format, including multilayer 3D metamaterials. Often, substrate losses interfere with the operation of metamaterials, and thus, the heterogeneous integration of thin film materials and structures onto lower loss host substrates can be key to low loss operation of metamaterials. Heterogeneous integration techniques, 2D and 3D fabrication techniques, and yield investigations for metamaterials will be presented.

Bio: Nan Marie Jokerst is the J. A. Jones Distinguished Professor of Electrical and Computer Engineering at Duke University. She received PhD in Electrical Engineering

from the University of Southern California in 1989. She was named a Fellow of the IEEE in 2003, a Fellow of the Optical Society of America in 2000, received an IEEE Third Millennium Medal in 2000, was a National Science Foundation Presidential Young Investigator in 1990, a DuPont Young Professor in 1989, a Newport Research Award winner in 1986, and a Hewlett Packard Fellow in 1983. She received the University of Southern California Alumni in Academia award from the Viterbi School of Engineering in their 100th anniversary year, 2006. She joined the Duke faculty in 2003 after 14 years on the faculty at Georgia Tech. She has also been recognized for her teaching accomplishments, which include the Harriet B. Rigas IEEE Education Society/Hewlett Packard Award in 2002. Her research work focuses on the fabrication, integration, and application of thin film semiconductor optoelectronic and high speed electronic devices for integrated nano and micro systems, optical interconnections, planar lightwave integrated circuits, chip scale integrated sensors and sensing systems, metamaterials, and plasmonics. She has 6 patents, and over 250 journal and conference publications.



ZHAOWEI LIU, UNIVERSITY OF CALIFORNIA SAN DIEGO
QUANTUM PLASMONIC METAMATERIALS

Abstract: Plasmonic and metamaterials have introduced tremendous research interest within last decade and has become an increasingly important field in nanophotonics. We have been exploring how to utilize metamaterials for imaging at sub-10nm scales, enhancing the spontaneous light emission for ultrafast optical wireless communications, as well as tailoring the scattering cross-section

of an object. Recently, we experimentally confirmed that the quantum size effect has to be considered when the feature size of the metallic structure in metamaterials approaches a few nanometers scale. As a consequence, the quantum plasmonic metamaterials emerges with extremely high nonlinear effect and tunabilities. In this talk, I will present some of our recent results in the field and also discuss the new

opportunities when the metamaterials go into the realm of quantum world.

Bio: Zhaowei Liu is an Associate Professor in the Electrical and Computer Engineering Department at UCSD. He received his Ph.D. in Mechanical and Aerospace Engineering (MEMS/Nanotechnology) from UCLA in 2006, and was subsequently a postdoctoral researcher in NSF Nanoscale Science & Engineering Center (NSEC) and Mechanical Engineering at UC Berkeley. In 2008 he joined the faculty at UCSD. His previous work was selected as top 100 science stories of 2007 by Discovery Magazine, and top

10 scientific discoveries of 2008 by Time Magazine. He is a recipient of the 2010 Society of Manufacturing Engineers (SME) Outstanding Young Manufacturing Engineer Award, the UCSD 2010 Hellman Faculty Fellowship Award, the 2013 Office of Naval Research (ONR) Young Investigator Award, and the 2013 Defense Advanced Research Projects Agency (DARPA) Young Faculty Award. He is also the invited participant for the Frontiers of Science 2010 by National Academy of Science and the Frontiers of Engineering 2014 by National Academy of Engineering.



NATALIA LITCHINISTER, UNIVERSITY OF BUFFALO SINGULAR OPTICS IN THE META-WORLD

Abstract: We discuss fundamental optical phenomena at the interface of singular optics and metamaterials, including theoretical and experimental studies of linear and nonlinear light-matter interactions of vector and singular optical beams in optical metamaterials. Understanding the physics of the interaction of complex beams with nanostructured “engineered” media is likely to bring new dimensions to the science and applications of complex light, including novel regimes of spin-orbit interaction, extraordinary possibilities for dispersion engineering, and novel possibilities for nonlinear singular optics. We show that unique optical properties of metamaterials open unlimited prospects to “engineer” light itself. For example, we demonstrate a novel way of complex light manipulation in few-mode optical fibers using metamaterials highlighting how unique properties of metamaterials, namely the ability to manipulate both electric and magnetic field components, open new degrees of freedom in engineering complex polarization states of light. We discuss several approaches to ultra-compact structured light generation, including a nanoscale beam converter based on an ultra-compact array of nano-waveguides with a circular graded distribution of channel diameters that converts a conventional laser beam into a vortex with configurable orbital angular momentum. Such beam converters is likely to enable a new generation of on-chip or all-fiber structured light applications. We also present our initial theoretical studies predicting that vortex-based nonlinear optical processes, such as second harmonic generation or parametric amplification that rely on phase matching, will also be strongly

modified in negative index materials. Finally, we will discuss novel approaches to electromagnetic wave manipulation in free-space hyperbolic metamaterials originating from light filamentation in air.

Bio: Natalia Litchinister is a Professor of Electrical Engineering at University at Buffalo, The State University of New York. Her group research focuses on fundamental properties and applications structured light in metamaterials, biomedical imaging, optical communications and nonlinear optics. Natalia M. Litchinister earned her Ph.D. degree in Electrical Engineering from the Illinois Institute of Technology and a Master’s degree in Physics from Moscow State University in Russia. She completed postdoctoral training at the Institute of Optics, University of Rochester in 2000. Prof. Litchinister joined the faculty of the department of Electrical Engineering at the State University of New York at Buffalo as Assistant Professor in 2008. Natalia Litchinister previously held a position of a Member of Technical Staff at Bell Laboratories, Lucent Technologies and of a Senior Member of Technical Staff at Tyco Submarine Systems. Natalia Litchinister’s research interests include linear and nonlinear optics in metamaterials, photonic devices, and optical communications. She is a Fellow of the Optical Society of America, Fellow of the American Physical Society, and a Senior Member of the IEEE. She holds grants from US National Science Foundation and US Army Research Office. She is a recipient of The 2014 Exceptional Scholar Award for Sustained Achievement.



MARTIN WEGENER, KARLSRUHE INSTITUTE OF TECHNOLOGY RECENT PROGRESS ON METAMATERIALS IN OPTICS, THERMODYNAMICS, MECHANICS, AND MAGNETO-TRANSPORT

Abstract: To me, “negative” effective material parameters and invisibility cloaking are among the most exciting aspects that become possible by tailored artificial materials called metamaterials. I shall discuss four recent corresponding examples from my group. First, I speak about invisible metal contacts on solar cells to increase their overall efficiency. Second, I address three-dimensional macroscopic core-shell invisibility cloaks in the diffusive regime of light propagation that work for all directions, colors, and polarizations of visible light. Third, I describe static elasto-mechanical cloaks designed by a direct lattice-transformation approach (instead of by material-parameter transformations). Fourth, I discuss three-dimensional metamaterials exhibiting a sign inversion of the classical Hall effect. A simple cubic lattice of interlinked tori made of an electron conductor, such as n-doped silicon, effectively appears like a hole conductor.

Bio: After completing his PhD in physics in 1987 at Johann Wolfgang Goethe-Universität Frankfurt (Germany), he spent two years

as a postdoc at AT&T Bell Laboratories in Holmdel (U.S.A.). From 1990-1995 he was professor (C3) at Universität Dortmund (Germany), since 1995 he is professor (C4, later W3) at Institute of Applied Physics of Karlsruhe Institute of Technology (KIT). Since 2001 he has a joint appointment as department head at Institute of Nanotechnology of KIT. From 2001-2014 he was the coordinator of the DFG-Center for Functional Nanostructures (CFN) at KIT. His research interests comprise ultrafast optics, (extreme) nonlinear optics, near-field optics, optical laser lithography, photonic crystals, optical, mechanical, and thermodynamic metamaterials, as well as transformation physics. This research has led to various awards and honors, among which are the Alfried Krupp von Bohlen und Halbach Research Award 1993, the Baden-Württemberg Teaching Award 1998, the DFG Gottfried Wilhelm Leibniz Award 2000, the European Union René Descartes Prize 2005, the Baden-Württemberg Research Award 2005, the Carl Zeiss Research Award 2006, and the SPIE Prism Award 2014 for the start-up company Nanoscribe GmbH.



MAIKEN MIKKELSEN, DUKE UNIVERSITY CONTROL OF RADIATIVE PROCESSES USING COLLOIDALLY SYNTHESIZED PLASMONIC NANOCAVITIES

Abstract: Metal-dielectric nanocavities have the ability to tightly confine light in small mode volumes resulting in strongly increased local density of states. Placing fluorescing molecules or semiconductor materials in this region enables wide control of radiative processes including absorption and spontaneous emission rates, quantum efficiency, and emission directionality. In this talk, I will present an overview of our recent experiments utilizing a tunable plasmonic platform where emitters are sandwiched in a sub-10-nm gap between colloiddally synthesized silver nanocubes and a metal film. By varying the size of the nanocubes, we tune the plasmon resonance by ~200 nm throughout the excitation, absorption, and emission spectra of embedded fluorophores and, for nanocavities resonant with the excitation wavelength, observe a 30,000-fold

enhancement in fluorescence intensity [Rose et al. Nano Letters 14, 4797 (2014)]. Utilizing emitters with an intrinsic long lifetime, and cavities resonant with the emission, reveals spontaneous emission rate enhancements exceeding a factor of 1,000 while maintaining directional emission and high quantum efficiency [Akselrod et al. Nature Photonics 8, 835 (2014)]. Incorporating semiconductor quantum dots into the nanocavities enables ultrafast spontaneous emission and the demonstration of an efficient single photon source. Additionally, 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 MoS₂ resulting in a 2,000-fold enhancement in the overall fluorescence.

Finally, the large field enhancement in these types of nanocavities is well-suited for control of nonlinear processes, and we show an increase in the third-harmonic generation in Al₂O₃ by nearly five orders of magnitude [Lassiter et al., ACS Photonics 1, 1212 (2014)]. These artificially structured hybrid nanomaterials hold the promise to enable a new class of ultrafast optoelectronic devices such as LEDs, enhance the performance of photovoltaics and bio sensors, and impact quantum-based technologies.

Bio: Maiken H. Mikkelsen is an Assistant Professor in the Department of Electrical and Computer Engineering and in the Department of Physics at Duke University. Her research interests span ultrafast optical

experiments in nanophotonics, plasmonics, light-matter interactions in quantum confined structures, spin phenomena in the solid state, and quantum information science. She received her B.S. in Physics from the University of Copenhagen, Denmark in 2004, and her Ph.D. in Physics from the University of California, Santa Barbara in 2009 in the group of Prof. David Awschalom. Before joining Duke in 2012, she was a postdoctoral fellow with Prof. Xiang Zhang at the University of California, Berkeley. Her awards include the Ralph E. Powe Junior Faculty Award (2014), the Air Force Office of Scientific Research Young Investigator Award (2015), and the NSF CAREER award (2015).



WILLIE PADILLA, DUKE UNIVERSITY **METAMATERIALS FOR SINGLE PIXEL IMAGING AT LONG WAVELENGTHS**

Abstract: Focal plane arrays form the foundation for the vast majority of imaging systems. However, at wavelengths of 10 μ m and longer, it becomes difficult, expensive, and / or impractical to form focal plane arrays for imaging. Single pixel cameras are an alternative method for imaging where cost, size or efficiency rule out use of focal plane arrays. Metamaterial spatial light modulators provide advanced functionality thus enabling single pixel cameras through multiplexed techniques. A multiplexed image is sent to a detector and the measurement is repeated a number of times – usually equal to the desired resolution. Images are encoded as the coefficients of the Hadamard matrix which provides the best possible signal to noise single pixel imaging system possible. We also explore the related S-matrix for single pixel imaging and additionally utilizes compressive sensing techniques to increase imaging frame rate. Lastly we highlight the ability of metamaterials to realize hyperspectral, polarimetric, and phase sensitive imaging.

Bio: Padilla has been in the metamaterials field since 2000, when he co-authored the first paper on negative index materials with Smith. Padilla is particularly well known for his work at terahertz (THz) frequencies, as well as in the area of active and dynamically controlled metamaterials. While working under a Director's Postdoctoral Fellowship at Los Alamos National Laboratory, Padilla

led efforts to demonstrate dynamic tuning of a semiconductor hybrid metamaterial by photodoping and voltage control. Both of these key experiments are now widely recognized and cited. Padilla's lab specializes in the THz, infrared, optical and magneto-optic properties of novel materials utilizing various spectroscopic methods, including Fourier transform spectroscopy and ellipsometry. Padilla's recent interests include tailoring the emissivity of objects with metamaterial coatings, and the use of active metamaterial arrays as components in THz and infrared imaging systems.



EVGENII NARIMANOV, PURDUE PHOTONIC HYPERCRYSTALS

Abstract: Photonics hypercrystals represent a new class of artificial optical media. These hyperbolic metamaterials, with periodic spatial variation of dielectric permittivity on subwavelength scale, combine the features of optical metamaterials and photonic crystals.

Bio: Dr. Evgenii Narimanov received his Ph.D. from Moscow Institute of Physics and Technology. He has held postdoctoral

positions at Yale University and Bell Laboratories and a faculty position at Princeton University. Dr. Narimanov's general interests include teaching photonics, optics, and E&M theory at both the graduate and undergraduate levels. In addition, his background in condensed matter theory and nonlinear dynamics makes him comfortable teaching solid-state physics, electronic devices, and nonlinear dynamics and its engineering applications.



VLADIMIR SHALAEV, PURDUE MERGING METAMATERIALS WITH QUANTUM PHOTONICS

Abstract: Over the past decade, one of the major focuses for the area of nanophotonics has been on developing a new class of "plasmonic" structures and "metamaterials" as potential building blocks for advanced optical technologies, including data processing, exchange and storage; a new generation of cheap, enhanced-sensitivity sensors; nanoscale-resolution imaging techniques; new concepts for energy conversion including improved solar cells, as well as novel types of light sources. Designing plasmonic metamaterials with versatile properties that can be tailored to fit almost any practical need promises a range of potential breakthroughs. However, to enable these new technologies based on plasmonics, grand limitations associated with the use of metals as constituent materials must be overcome. In the structures demonstrated so far, too much light is absorbed in the metals (such as silver and gold) commonly used in plasmonic metamaterials. The fabrication and integration of metal nanostructures with existing semiconductor technology is challenging, and the materials need to be more precisely tuned so that they possess the proper optical properties to enable the required functionality. Our recent research aims at developing new designs and plasmonic materials (other than the metals used so far) that will form the basis for future low-loss, durable, CMOS-compatible devices that could enable full-scale development of the plasmonic and metamaterial technologies. Can these recently developed plasmonic structures and metamaterials based on new material

platforms help in unfolding the potential of quantum photonics? We report on our first efforts in that direction.

Bio: Scientific Director for Nanophotonics in Birck Nanotechnology Center and Distinguished Professor of Electrical and Computer Engineering at Purdue University, specializes in nanophotonics, plasmonics, and optical metamaterials. Vlad Shalaev received several awards for his research in the field of nanophotonics and metamaterials, including the Max Born Award of the Optical Society of America for his pioneering contributions to the field of optical metamaterials, the Willis E. Lamb Award for Laser Science and Quantum Optics, Rolf Landauer medal of the ETOPIIM (Electrical, Transport and Optical Properties of Inhomogeneous Media) International Association, and the UNESCO Medal for the development of nanosciences and nanotechnologies. He is a Fellow of the IEEE, APS, SPIE, MRS and OSA. Prof. Shalaev authored three books, twenty-six invited book chapters and over 400 research publications.



ELI YABLONOVITCH, BERKELEY
OPTICAL ANTENNAS: SPONTANEOUS EMISSION FASTER THAN STIMULATED EMISSION

Abstract: Antennas emerged at the dawn of radio for concentrating electromagnetic energy into a small volume $\ll \lambda^3$, allowing for nonlinear radio detection. Such coherent detection is essential for radio receivers, and has been used since the time of Hertz. Conversely, an antenna can efficiently extract radiation from a sub-wavelength source, such as a small cellphone. Likewise, antennas can accelerate spontaneous emission from a small quantum dot or molecule, whose emission rate can become faster than stimulated emission. Antennas interact equally, with real electromagnetic fields, as well as the quantum zero point field fluctuations that are responsible for spontaneous emission. Regrettably, antenna physics is hardly addressed within the Physics curriculum. Whether from Jackson, the Feynman Lectures, or Yariv, it's hard to learn the true beauty of antenna science. This talk will commence with a pedagogic description of the three most important parts of antenna physics:

1. The Radiation Resistance;
2. The Electromagnetic Capture Cross-Section;
3. The Wheeler Limit on antenna Q.

These properties are encapsulated in an antenna equivalent circuit that provides us with physical understanding. Since antennas are intended to work at frequencies well below the plasma frequency, plasmonic effects are usually a minor perturbation to antenna physics, only contributing some

kinetic inductance to the underlying antenna properties.

Bio: Eli Yablonovitch is Director of the NSF Center for Energy Efficient Electronics Science (E3S), a multi-University Center based at Berkeley. After a career in industry and in Universities, he is now Professor of Electrical Engineering and Computer Sciences at UC Berkeley, where he holds the James & Katherine Lau Chair in Engineering. He contributed the 4n2 light-trapping factor to solar cells, which is used commercially in most solar panels world-wide. He introduced the benefit of strained lasers, an idea which is employed in almost all internet telecommunications. He is regarded as a Father of the Photonic BandGap concept, and he coined the term "Photonic Crystal". Prof. Yablonovitch is a Fellow of the OSA, the IEEE, and the American Physical Society. He was elected a Member of the National Academy of Engineering, the National Academy of Sciences, the American Academy of Arts & Sciences, and as Foreign Member of the Royal Society of London. He has been awarded the Adolf Lomb Medal, the W. Streifer Scientific Achievement Award, the R.W. Wood Prize, the Julius Springer Prize, the IET Mountbatten Medal (UK), the IEEE Photonics Award, the Harvey Prize (Israel), and the Rank Prize (UK). He also has an honorary Ph.d. from the Royal Inst. of Tech., Stockholm Sweden, and from the Hong Kong Univ. of Sci. & Technology.



GENNADY SHVETS, UNIVERSITY OF TEXAS AT AUSTIN
PHOTONIC TOPOLOGICAL INSULATORS BASED ON METAMATERIALS: MOLDING THE FLOW OF LIGHT AROUND CORNERS AND OBSTACLES

Abstract: Photonic crystals have been referred to as "semiconductors of light" because of the far-reaching analogies between electron propagation in a crystal lattice and light propagation in a periodically modulated photonic environment. However, this analogy was never completed because photonic crystals could not emulate the electron spin. I will demonstrate how the emulation of both the spin and the spin-orbit coupling (SOC) is enabled by bi-anisotropic metamaterials. The importance of the SOC is that it makes possible the

emergence of topologically nontrivial phases in condensed matter physics that give rise to topologically protected edge states immune to scattering. I will describe how the analogous photonic topological insulators (PTIs) emerge in metamaterials-based structures and enable topologically protected transport of electromagnetic waves. As the result, the fundamental limitation of light transport imposed by the wave equation, i.e. the inability of reflections-free light propagation along sharply bent pathway, can be circumvented.

Topologically protected electromagnetic states could be used for transporting photons without any scattering, potentially underpinning new revolutionary concepts in applied science and engineering. I will also describe a simple photonic structure, a periodic array of metallic cylinders attached to one of the two confining metal plates that behaves as a PTI: possesses a complete topological bandgap

and emulates spin-orbit interactions. An interface between two such structures supports topologically protected surface waves which can be guided without reflections along sharp bends of the interface as shown in Fig.1(d). Perspectives on how metamaterials can emulate condensed-matter phenomena such as valleytronics, quantum spin Hall effect, and quantum Hall effect, will be presented.



AUGUSTINE URBAS, AFOSR METAMATERIALS FOR DEFENSE APPLICATIONS

Abstract: Metamaterials provide the ability to design materials properties to meet the unique needs of applications beyond what is possible with conventional materials. From spatially tailored dielectrics to tunable, dynamic material properties and unique nonlinear behavior, these systems offer tremendous flexibility to application engineers. Applications across the electromagnetic spectrum have been proposed; from novel RF antennas to devices utilizing optical magnetism. Researchers have pursued optical, RF and acoustic materials and applications. The aim of this work is to gauge the readiness and maturity of metamaterials for the field. Within AFRL, applications spanning the electromagnetic spectrum have leveraged metamaterials. The work we have pursued utilizes the unique traits of meta systems to match broadly different wavelengths and to have dramatic changes in response as a function of wavelength to develop novel communication and sensing systems. Looking to the future, dynamic and tunable metamaterials will be pursued.

Bio: Augustine Urbas earned a B.A. in Physics from the University of Chicago in 1996 and a Ph.D. in Polymer Physics from the Massachusetts Institute of Technology in 2003. His thesis research was on the optical and morphological analysis of structured materials and nanostructures fabricated from ultra-high molecular weight block copolymers. As a post doctoral researcher at the Air Force Research Laboratory, Dr. Urbas expanded this work by investigating responsive patterned optical materials, holographic fabrication and HPDLCs with periodic and non-periodic structures. Dr. Urbas then moved on to study the nonlinearities and molecular photophysical properties of

high performance chromophores, and developed a comprehensive program to explore applications of metamaterial electromagnetic composites at the Air Force Research Lab, Materials Directorate. Dr. Urbas is currently the Optical Materials Research Lead for the Materials Directorate of AFRL. Research in this area encompasses; structured materials, self assembled optical composites, nanophotonics, adaptable/ responsive materials, nonlinear materials properties and enhancements, EM properties of composite and structured media and the design and characterization of structured electromagnetic materials. His expertise includes laser spectroscopy, nano-optics, photonic materials, self-assembly, holography and morphological characterization.



**YAROSLAV URZHUMOV, DUKE UNIVERSITY/INTELLECTUAL VENTURES
METAMATERIALS: IN PURSUIT OF GLOBALLY OPTIMAL DESIGNS**

Abstract: Metamaterials as effective media with engineered medium properties have opened the door to making materials with properties or property combinations well outside of the ranges found in naturally-formed structures. Yet their microscopic ingredients are the 90 naturally occurring chemical elements. The apparently “supernatural” effective medium properties of metamaterials derive from the wisely-crafted spatial distributions of those all-familiar ingredients. The more one wants to deviate from the properties occurring naturally, the cleverer one must be as the architect of those patterns. The architectural effort has two components: Design and Construction. While technology is making steady progress towards the ultimate – atomic – resolution in custom-built structures, we begin to wonder if we are in a position to solve the Design problem fully. One gram of regular matter contains some 10^{23} fundamental building blocks; consequently up to $10^2 \cdot 10^{23}$ structures that size are theoretically possible. While quantum computers might be able to solve design optimization problems of this scale in the future, today we are looking into the ultimate possibilities with classical computation. Metamaterials as a multiscale design methodology allow us to dramatically reduce the complexity of the problem, yielding rapid solutions to extremely challenging problems with a computational power of a single CPU. I

will talk about the various metamaterials solutions for acoustics, fluid dynamics, and RF electromagnetics.

Bio: Dr. Urzhumov has been in the fields of Metamaterials and Plasmonics since 2003. He is Adjunct Assistant Professor of ECE at Duke University, and also a Technologist at the Metamaterials Commercialization Center of Intellectual Ventures. Previously a research faculty at Duke, he works on applied and theoretical aspects of metamaterials, nanomaterials and microstructured media. His main focus at Duke is on engineering technologically-relevant electromagnetic and acoustic properties of such media across the spectrum, and designing device prototypes based on metamaterials. His demonstration of all-dielectric cloaking and metamaterial promise for wireless power and hydrodynamic wake suppression are recognized worldwide as novel industry-relevant metamaterial ideas. Dr. Urzhumov has interest in materials science aspects of metals, semiconductors and other plasmonic media, dielectrics and their micro/nanostructured forms, in particular their electromagnetic, electronic and phononic properties. Dr. Urzhumov’s industry expertise is in cross-disciplinary, multi-physics analysis of complex structures and systems, which require unprecedented computational efficiency.



**NIKOLAY ZHELUDEV, SOUTHAMPTON UNIVERSITY
METAMATERIALS: OPTICAL PROPERTIES ON DEMAND**

Abstract: Metamaterials were initially suggested as negative index media for the superlens and transformation optics devices. This started a major new research domain in modern science. Since then the research agenda has been significantly broadened and now includes tuneable, switchable, nonlinear, gain, sensing and quantum meta-devices and meta-systems. We overview Southampton contribution to this exciting field of research and offer our view on its future developments and technological drivers of this new enabling technology.

Bio: Professor Nikolay Zheludev’s research interests are in nanophotonics and metamaterials. He directs the Centre for Photonic Metamaterials at the ORC Southampton University, UK and Centre for Disruptive Photonic Technologies at Nanyang Technological University, Singapore. He is also founding co-Director of the Photonics Institute at NTU, Singapore.



XIANG ZHANG, BERKELEY
NON-HERMITIAN OPTICS AND PARITY-TIME SYMMETRY IN METAMATERIALS

Bio: Xiang Zhang is the inaugural Ernest S. Kuh Endowed Chaired Professor at UC Berkeley and the Director of NSF Nano-scale Science and Engineering Center (NSEC). He is the Director of Materials Science Division at Lawrence Berkeley National Laboratory (LBNL), as well as member of Kavli Energy Nano Science Institute. Professor Zhang is an elected member of US National Academy

of Engineering (NAE), Academia Sinica (National Academy of Republic of China), and Fellow of four scientific societies: APS (The American Physical Society), OSA (The Optical Society of America), AAAS (The American Association for the Advancement of Science), and SPIE (The International Society of Optical Engineering).

Poster Presentations

POSTER NUMBER: 1

Electromechanical Processes in Plasmonic Nanostructures

Authors: Yoonkyung E. Lee, Anshuman Kumar, Homer Reid, Owen Miller and Nicholas Fang
MIT

Abstract: Recently, exciting new physics of plasmonics has inspired a series of key explorations to manipulate, store and control the flow of information and energy at unprecedented dimensions. While the main efforts are primarily concerned of guided and propagating waves in these systems, the resulting transfer of field energy, momentum, and angular momentum on these nanostructures are of great importance as exemplified by the invention of optical tweezers. In this poster we will report our development of quantitative near field optical probes to measure the distinct local modes at spot size close to 10nm. Our quantitative measurement and electromechanical analysis in the nanostructures that promote photon momentum transfer and electron-photon interaction in the deep subwavelength regime, shows promise to application of these nanostructure for efficient light emission, optical assembly and energy conversion.

POSTER NUMBER: 2

Spinoptical Metasurface Route to Spin-Controlled Photonics

Authors: Nir Shitrit, Yuan Wang, and Xiang Zhang
University of California, Berkeley

Abstract: Spinoptics provides a route to control light, whereby the photon helicity (spin angular momentum) degeneracy is removed due to a geometric gradient onto a metasurface. The alliance of spinoptics and metamaterials offers the dispersion engineering of a structured matter in a polarization helicity-dependent manner. We show that polarization-controlled optical modes of metamaterials arise where the spatial inversion symmetry is violated. The emerged spin-split dispersion of spontaneous emission originates from the spin-orbit

interaction of light, generating a selection rule based on symmetry restrictions in a spinoptical metamaterial. The inversion asymmetric metasurface is obtained via anisotropic optical antenna patterns. This type of metamaterial provides a route for spin-controlled nanophotonic applications based on the design of the metasurface symmetry properties.

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POSTER NUMBER: 3

Acoustic focusing of metallic nanoparticles for plasmonic coupling

Authors: Daniela F. Cruz, Crystal E. Owens, C. Wyatt Shields IV, Maiken H. Mikkelsen, and Gabriel P. López
Duke University

Abstract: A simple technique is presented to induce the rapid concentration and confinement of 100-400nm gold nanoparticles (AuNPs) using bulk acoustic standing waves. The acoustic device was fabricated by placing two transducers on opposite walls of a square acrylic chamber fixed to a glass substrate, where one transducer served as an actuator and the other as a reflector. When AuNPs were added to a carrier fluid (e.g., hydrogel precursor) in the resonant chamber, they experienced a force due to the acoustic radiation potential. We used the acoustic device to propel the AuNPs toward the pressure nodes and maintained their confined arrangement by crosslinking the poly(ethylene glycol) diacrylate-containing carrier fluid by exposure to UV light. This allowed us to

keep the acoustically manipulated AuNP structures intact after the acoustic field was turned off and to observe the focused nanoparticles using an environmental scanning electron microscope. To our knowledge, this is the first time bulk acoustic standing waves have been used for the manipulation of metallic nanoparticles, providing a pathway for assembly of plasmonically active materials. By comparison of the experimental results described above with theoretical predictions and Brownian dynamics simulations, we are able to provide predictions as to the feasibility and limitations of this approach for the fabrication of plasmonic structures.

POSTER NUMBER: 4

Routing light with plasmonics

Authors: *Lin Li, Tao Li, Shining Zhu*
University of California, Berkeley

Abstract: Plasmonics has provided unprecedented optical designs in recent advances of optics and photonics. We demonstrated a serial beam engineering results with plasmonics to full control the phase and the polarization of light in a compact and integrated way. First, we realized a serial of optical beams with phase design by nanostructures in metal surface, such as Airy beam, collimated beam, as well as optical orbital angular momentum (OAM) beam. We proposed the phase modulation in the radial direction of the OAM beam simultaneous with the generation process, and realized non-diffraction, focusing, off-axis incident and even split OAM beams. The split OAM beams can have different topological numbers, which may have potential applications in optical communication. We also demonstrated a plasmonic polarization generator that can reconfigure an input polarization to all kinds of states simultaneously. It is based on the interference of the in-plane (longitudinal) field of surface plasmons that gives rise to versatile near-field polarization states on a metal surface, which was seldom considered in previous studies. With a well-designed nanohole array, the in-plane field of SPPs with proper polarization states and phases can be selectively scattered out to desired light beams. A manifestation of eight focusing beams with well routed polarizations were experimentally demonstrated. Our design offers a new route to achieve the full control of optical polarizations and possibly boost the development in photonic information processing.

POSTER NUMBER: 5

Metasurface-Enabled Remote Quantum Interference

Authors: *Xuexin Ren, Pankaj Jha, Xingjie Ni, Chihhui Wu, Taiki Hatakeyama, Yuan Wang, Xiang Zhang*
University of California, Berkeley

Abstract: Anisotropic quantum vacuum (AQV) opens novel pathways for controlling light-matter interaction in quantum optics, condensed matter physics, etc. Here, we theoretically demonstrate strong AQV over macroscopic distances enabled by judiciously designed array of sub-

wavelength-scale nano-antennas -a metasurface. We harness the phase-control ability and the polarization-dependent response of the metasurface to achieve strong anisotropy in the decay rate of a quantum emitter located over distances of hundreds of wavelengths. Such an AQV induces quantum interference among radiative decay channels in an atom with orthogonal transitions. Quantum vacuum engineering with metasurfaces holds promise for exploring new paradigms of long-range light-matter interaction for atom optics, solid-state quantum optics, etc.

POSTER NUMBER: 6

Parity-Time Symmetric Acoustics

Authors: *Chengzhi Shi, Marc Dubois, Yuan Wang, Xiang Zhang*
University of California, Berkeley

Abstract: The concept of acoustic parity-time (PT) symmetry is introduced and used for the study of extraordinary scattering behavior in acoustic PT-symmetric media consist of loss and gain units. The analytical study of acoustic PT-symmetric media shows that these media can be designed to achieve unidirectional transparency at specific frequencies named exceptional points (EPs). This unidirectional transparency occurs at the EPs is due to the asymmetrical arrangement of the periodic loss and gain units that results in different Bragg scatterings on the two sides of the PT-symmetric media. A close look at the phases of the reflections on both sides reveals a sudden jump of the reflection phase on one side at the EPs. This step-function like behavior causes an infinite delay time of the reflected wave on that side, and hence the media become reflectionless in that direction. Combining the concept of acoustic PT-symmetry with transformation acoustics, we design a two-dimensional acoustic cloak that is invisible in a prescribed direction. This kind of directional cloak is important especially for military use since a target object is hidden from the enemy in front can still be identified by friendly at the back. Other useful applications such as directional acoustic imaging, noise cancellation, architectural acoustics, acoustic amplification, etc can also be developed.

POSTER NUMBER: 7

Van der Waals Interactions at the Nanoscale Revealed by Transformation Optics

Authors: *Rongkuo Zhao, Yu Luo, and J. B. Pendry* The Blackett Laboratory, Department of Physics, Imperial College London, London SW7 2AZ, United Kingdom
University of California, Berkeley

Abstract: Through mapping nearly touching geometries into desired ones, powerful analytical approach can be developed to calculate the spectra of touching and nearly touching metallic structures. We have recently developed accurate and extremely efficient approaches for calculating the absorption and scattering spectra,

field enhancement performance, modal frequencies and spatial distribution for nanospherical dimers [Pendry et. al., Nat. Phys. 9, 518 (2013)]. This analytical approach enables us to shed physical insight into the sophisticated behavior of van der Waals forces in extremely small gaps [Zhao et. al., Phys. Rev. Lett. 111, 033602 (2013)]. The van der Waals interaction is a ubiquitous but subtle force between particles mediated by quantum fluctuations of charge. It is the most long-range force acting between neutral particles and influences a range of phenomena such as surface adhesion and colloid stability. Calculations of the force between parallel surfaces is a simple task, but when the geometry is more complex, e.g., a pair of nanospheres <5 nm apart, the task is more difficult. Furthermore a macroscopic description of the dielectric properties no longer suffices, and we must consider the diffuse nonlocal nature of the electron polarization cloud. We have proposed a simple analytic treatment of this problem [Luo et. al., PNAS 111, 18422 (2014)]. As an example, nonlocality in 3D spherical dimers plasmonic systems can be accurately analyzed using the transformation optics approach. The effects of nonlocality are found to dramatically weaken the field enhancement between the spheres and hence the van der Waals interaction.

POSTER NUMBER: 8

Effect of Purcell enhancement on spin-flip induced fluorescence contrast in diamond nitrogen-vacancy center ensembles

Authors: S. Bogdanov, M. Shalaginov, P. Kapitanova, J. Liu, M. Ferrera, A. Laguchev, P. Belov, J. Irudayaraj, A. Boltasseva and V. Shalaev
Purdue University

Abstract: Diamond nitrogen-vacancy (NV) centers are promising solid state systems for applications in nanoscale magnetometry and quantum information processing by virtue of possessing optically readable spins which retain coherence at room temperature. When coupled to nanophotonic structures such as optical metamaterials, metasurfaces or plasmonic waveguides the radiative transitions of NV centers experience a Purcell enhancement which affects the spin state readout. We have experimentally studied the correlation between the optical transition lifetime and spin-induced fluorescence contrast in nanodiamond NV ensembles and found good agreement with rate equations analysis. We have established optimal operating conditions of NV centers coupled to nanophotonic structures which promises to enable integrated quantum devices working at room temperature.

POSTER NUMBER: 9

Hyperbolic phonon polaritons in hexagonal boron nitride

Authors: S. Dai, Q. Ma, T. Andersen, Z. Fei, M. K. Liu, M. D. Goldflam, M. Wagner, S. -E. Zhu, A. McLeod, A. S. Rodin, W. Gannett, W. Regan, K. Watanabe, T. Taniguchi, M. Thiemens, A. H. Castro Neto, A. Zettl, F. Keilmann, G. C. A. M. Jassen, P. Jarillo-Herrero, M. M. Fogler, D. N. Basov
University of California, Berkeley

Abstract: Uniaxial materials whose axial and tangential permittivities have opposite signs are referred to as indefinite or hyperbolic media. While hyperbolic responses are normally achieved with metamaterials, hexagonal boron nitride (hBN) naturally possesses this property due to the anisotropic phonons in the mid-infrared. Using scattering-type scanning near-field optical microscopy, we studied polaritonic phenomena in hBN. We performed infrared nano-imaging of highly confined and low-loss hyperbolic phonon polaritons in hBN. The polariton wavelength was shown to be governed by the hBN thickness according to a linear law persisting down to few atomic layers [Science, 343, 1125–1129 (2014)]. Additionally, we carried out the modification of hyperbolic response in meta-structures comprised of a monolayer graphene deposited on hBN [arXiv: 1501.06956]. Electrostatic gating of the top graphene layer allows for the modification of wavelength and intensity of hyperbolic phonon polaritons in bulk hBN. The physics of the modification originates from the plasmon-phonon coupling in the hyperbolic medium. Furthermore, we demonstrated the “hyperlens” for subdiffractive focusing using a slab of hBN [Nature Communications, 6, 6963 (2015)].

POSTER NUMBER: 10

Voltage switching of a VO₂ memory metasurface using ionic gel

Authors: M.D. Goldflam, M. K. Liu, B. C. Chapler, H. T. Stinson, A. J. Sternbach, A.S. McLeod, J. D. Zhang, K. Geng, M. Royal, Bong-Jun Kim, R. D. Averitt, N. M. Jokerst, D. R. Smith, H-T. Kim, D. N. Basov
University of California, Berkeley

Abstract: We have demonstrated large area, low voltage, non-volatile tuning of an electrolyte-based vanadium dioxide (VO₂) THz memory metasurface. Using ionic gel gating, voltage is applied to drive the insulator-to-metal transition in an underlying VO₂ layer. Through application of positive and negative voltages, the metasurface resonance can be switched into the “off” or “on” state by driving VO₂ into a more conductive or insulating regime, respectively. As compared to our graphene-based control devices, the longer saturation time of resonance modification in VO₂-based devices suggests that this voltage-induced switching originates primarily from electrochemical effects resulting from oxygen migration across the electrolyte-VO₂ interface.

POSTER NUMBER: 11

Theoretical Analysis of Metamaterial Perfect Absorbers

Authors: Patrick Bowen, Alexandre Baron, David R. Smith
Duke University

Abstract: We present a fully analytical model that describes ideal absorbing metasurfaces composed of film-coupled optical nanoantennas. The model predicts the spectrum and the angular dependence of the absorption and is compared to full-wave numerical simulations.

POSTER NUMBER: 12

Sub-wavelength Hadamard Imaging with Metamaterials

Authors: Andrew Cardin, Kebin Fan, Willie Padilla
Duke University

Abstract: Metamaterial designs have been demonstrated over a broad spectrum of frequencies, from radio [1] to the near infrared [2, 3]. Furthermore it has been shown that with careful design, unit cell sizes on the order of $\lambda/1000$ are achievable [4]. Taking advantage of these remarkable properties we propose a design for an ultra-subwavelength imaging system using a metamaterial based spatial light modulator. We propose implementing a Hadamard single pixel imaging scheme, in which subwavelength details are encoded by rows of Hadamard coefficients. Such a system eliminates the need for large detector arrays and has been shown to be robust to noise compared to other encoding schemes [5]. In particular, this design shows strong potential for applications in medical imaging and security screening [6]. In the present work we focus on a subwavelength system centered in the X-band as an alternative to X-ray medical imaging, with higher contrast and without ionizing radiation. Low contrast in X-ray imaging leads to both false positives and false negatives at relatively high incidence [7]. Imaging in the X-band, one gains a contrast in excess of 2:1 [8] offering the potential to significantly reducing these false results.

POSTER NUMBER: 13

Tunable graphene-based hyperbolic metamaterial

Authors: Georgia T. Papadakis, Michelle Sherrott, Wei-Hsiang Lin, Philip W. Hon, Luke A. Sweatlock, Harry A. Atwater
California Institute of Technology

Abstract: Photonic metamaterials have revealed extraordinary physical phenomena like negative refraction for super-resolution imaging, extreme Purcell factors and near-zero response for slow light applications. Hyperbolic metamaterials (HMMs), a class of extremely anisotropic metamaterials leading to a hyperbolic dispersion surface, provide a platform for such effects to be demonstrated. They also support epsilon-near-

zero (ENZ) regions, allowing for topological transitions in photonic systems. Active tuning of their electromagnetic properties is fundamental for gaining control over those phenomena and enables dynamical study of topological transitions and band structure engineering in optical systems. Graphene is a 2D highly tunable material, upon carrier-induced Fermi-level tuning. In this work, we model graphene monolayers with a sheet-conductivity, separated by sub-wavelength SiO₂ layers to realize a planar HMM. Through a parameter retrieval method, we calculate the electric permittivity and magnetic permeability along all coordinate directions and demonstrate that they are highly tunable upon charge carrier injection onto the graphene layers. This leads to active control and tuning of the effective birefringence, dichroism, and figure of merit. Strong absorption of SiO₂ at 9 μ m also yields a broadband tunable ENZ region along the in-plane direction, while the out-of-plane permittivity remains dielectric-like. Thus, we are able to actively probe transitions of the dispersion surface between elliptical-hyperbolic and forbidden regions. We have fabricated the HMM unit cell and we are currently performing ellipsometric measurements while gating the graphene monolayers against each other. Using our retrieval model, we fit the ellipsometric data to reveal the tunability of both electric and magnetic parameters.

POSTER NUMBER: 14

Parallelization of THz Single Pixel Imaging Systems

Authors: Christian C. Nadell, Claire M. Watts, John M. Montoya, Sanjay Krishna, Willie J. Padilla
Duke University

Abstract: Owing to their scalability in the frequency domain, metamaterials have enabled the recent development of fast, efficient spatial light modulators in long wavelength regimes. Such developments have allowed single pixel THz systems to realize previously unseen degrees of success. However, traditional single pixel imaging schemes remain afflicted by a fundamental limitation, namely that they are serial in nature. Spatially multiplexing a scene requires the collection of a number of measurements proportional to image size, resulting in a slow and poorly-scaling acquisition times. Here we present two methods to solve this problem by parallelizing the single-pixel imaging process: frequency diverse multiplexing, and quadrature phase shift keying. These techniques take advantage of phase-sensitive detection and the speed of our spatial light modulator, reducing acquisition speed by a factor limited only by noise. Our methods are deterministic, highly scalable, and completely compatible, and thus we anticipate them playing an integral role in future photonics systems.

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POSTER NUMBER: 16

Artificial thermochromic infrared metamaterial

Authors: Xinyu Liu and Willie J. Padilla
Duke University

Abstract: The demand of thermochromic materials is urgently in solar energy, space exploration, and daily lives. However, the applications of conventional thermochromic materials are limited due to their narrow working temperature ranges and low flexibility for manual control. Here, we demonstrate an artificial thermochromic infrared metamaterial based on Microelectromechanical Systems (MEMS). The electromagnetic performance of our device was characterized by Fourier transform infrared spectroscopy (FTIR) and 62% modulation index from room temperature to 350 ° was presented at 5.2 μm . With blackbody as a reference, our device also has a good control on the emitted power density, so by carefully designed, it will have a broad application prospects as smart radiation device for spacecraft.

POSTER NUMBER: 17

Clarifying the Origin of Third-harmonic Generation from film-coupled nanostripes

Authors: Xiaojun Liu, Stéphane Larouche, Patrick Bowen, David R. Smith

Abstract: Due to their ability to strongly enhance local optical fields, plasmonic nanostructures have the potential to dramatically enhance the nonlinear response of the composite structure. Film-coupled plasmonic nanostructures are of particular interest, as extreme plasmonic enhancement can be achieved within precisely controlled dielectric gaps. However, when both metallic and dielectric components possess nonlinearities, the origin of the nonlinear signal generated from the film-coupled nanostructures can be ambiguous as the strongly enhanced fields interact with the metal as well as with any integrated dielectric materials. We propose a method that specifically identifies the origin of the third harmonic generation (THG) from film-coupled nanostripes, which consists of a metallic patch separated from a metallic film by a nanometer-scale dielectric spacer. By considering the THG from each nonlinear source separately, we show that the near- and far-field behaviors of the THG generated within the various constituents of the nanostructure are distinguishable due to fundamental differences in the THG radiation properties. While the THG from the spacer is enhanced significantly by the gap plasmon modes supported by the structure, the THG signal from the metal is suppressed by the structure itself. The total THG signal is found to be the sum of all nonlinear sources, with the far-field radiation pattern determined by the ratio between the third-order susceptibilities of the dielectric and the metal.

POSTER NUMBER: 18

Modeling of a Dynamic Metamaterial Aperture for Computational Imaging

Authors: Mike Boyarsky, Timothy Sleasman, Mohammadreza Imani, Jonah Gollub, David Smith
Duke University

Abstract: Metamaterial apertures have recently gained attention as novel physical hardware layers for computational imaging systems. By using metamaterial apertures' ability to generate frequency diverse radiation patterns, scene information is encoded into a few frequency measurements. While these apertures have shown encouraging results, their performance is limited by the quality factor of metamaterial resonators and require a large. To remedy this problem, a tunable metamaterial aperture has been sought after for its ability to modulate radiation patterns using switchable elements, thereby reducing dependence on frequency diversity. As the interest in metamaterial imaging devices grows, the need to model these electrically large apertures with subwavelength variations increases. In this poster, we present an approximate computational method for modeling such devices in a fast and efficient manner. Each metamaterial is modeled as a frequency-dependent dipole, while including the ability to tune each element. Comparisons between experimental data and simulation results are presented to confirm the fidelity of the proposed method. We further describe how using this method can streamline the design process for metamaterial imaging configurations while providing insight into the underlying physics of the aperture.

POSTER NUMBER: 19

Passive Lorentzian Holograms

Author: Guy Lipworth and Nicholas Caira
Duke University

Abstract: A frequency-diverse metamaterial (MM) aperture was realized recently in the form of a leaky-wave antenna with resonant MMs serving as irises. This antenna is able to generate radiation patterns suited for computational-imaging schemes by sweeping its operation frequency, obviating the need for moving parts or extraneous phase shifters which often plague conventional coherent imaging systems. We can think of this antenna as a holographic aperture in which the hologram pixels are implemented with MM resonators, and the reference mode is realized by the guided mode that excites these resonators. However, without holographic control of its radiation patterns, the fields radiating from such an aperture are pseudo-random and their diversity is limited by the resonators' quality-factor. Here we show how one can control the aperture's radiation pattern by modeling its pixels as Lorentzian dipoles excited by the local guided (reference) mode, and applying Lorentzian phase and amplitude constraints to the GS algorithm when designing the hologram's MM distribution.

POSTER NUMBER: 20

Millimeter-wave compressed active imaging system

Author: *Tomas Zvolensky*
Duke University

Abstract: Various imaging systems can utilize wide spectrum of frequencies to investigate the scene. Traditional active system, SAR, is employing microwave part of the spectrum, indirect holographic systems rely on millimeter waves, or infrared in the case of passive systems. Each part of the spectrum offers particular advantages with regard to application of the imager. Here we present an active imaging system operating in W-band frequencies taking advantage of frequency-diverse metamaterial-based antennas. Experimental verification is presented to verify the potential of the design.

POSTER NUMBER: 21

Ultrafast spontaneous emission from colloidal quantum dots using plasmonic nanoantennas

Authors: *Gleb M. Akselrod, Thang B. Hoang, Christos Argyropoulos, David R. Smith, Maiken H. Mikkelsen*
Duke University

Abstract: Control of the radiative properties of emitters such as molecules, quantum dots, and color centers is central to nanophotonic and quantum optical devices, including lasers and single photon sources. Plasmonic cavities and nanoantennas can strongly modify the excitation and decay rates of nearby emitters by altering the local density of states. In this poster, we will present our work on using plasmonic nanoantennas to control the spontaneous emission from colloidal quantum dots, a technologically important material. The nanoantennas resemble a microwave patch antenna and consist of colloidal silver nanocubes coupled to a metallic film, separated by a controlled sub-10 nm spacer layer embedded with emitters. The large electric field enhancements in this unique plasmonic platform allows for unprecedented control over spontaneous emission. By integrating colloidal quantum dots into these antennas, we show spontaneous emission with an ultrafast lifetime of <11 ps, corresponding to a rate enhancement of 880. At the same time, the emission intensity from these QDs is enhanced by a factor of 2,300, due to absorption enhancement and the antenna action of the structure. The nanopatch antenna geometry provides a promising platform for nanophotonic devices such as ultrafast light-emitting diodes and single photon sources, which require fast spontaneous emission.

POSTER NUMBER: 22

Directivity Enhancement of Slotted Waveguide Antennas using Parasitic Elements

Authors: *Laura Pulido-Mancera, Tomas Zvolensky, Mohammadreza Imani, Patrick Bowen*
Duke University

Abstract: For many satellite-based telecommunication applications, highly directive antennas are required. A conventional method for generating beams is to use a periodic array of dipoles with a narrow phase shift. Typical example of this type of structure are slotted waveguide antennas (SWAs), being attractive for their efficiency and high power handling capability. A branch of metamaterial research focused on enhancement of antennas has shown promise in improving their radiative properties by altering their near-field interactions rather than directly altering the geometry of the antenna. In this paper, we present a metamaterial structure based on parasitic elements placed on top of a SWA, which modifies the effective dipoles and improve the overall performance of the antenna. The discrete dipole approximation method (DDA) is used to rapidly model the SWA, as opposed to lengthy full-wave simulations. The results are compared with the theoretical limit for directivity improvement.

POSTER NUMBER: 23

Experimental Computational Imaging with a Dynamic Metamaterial Aperture

Authors: *Timothy Sleasman, Michael Boyarsky, Mohammadreza F. Imani, Jonah Gollub, David R. Smith*
Duke University

Abstract: Compressive sampling theory has made great strides in recent years and has been shown to improve imaging performance while reducing hardware burden. Compressive imaging can leverage the ability to sculpt electromagnetic waveforms to probe a scene and encode spatial information within the modulated signal. Metamaterial apertures, which grant the necessary control over the probing fields, have gained traction as a novel physical platform for computational imaging. For example, frequency-diverse apertures have been proposed that utilize the dispersive nature of metamaterials to generate spatially-variant fields at an imaging scene. In this poster, we advance this concept by employing tunable metamaterial elements, eliminating the reliance on large bandwidths and alleviating the limitations imposed by the inevitable losses of narrowband resonators. The dynamic aperture presented here consists of a transmission line loaded with metamaterial elements. Each element is switched by semiconductor components to provide flexibility in generating diverse radiation patterns. The design and operation of this device is detailed and its ability to achieve fast frame-rate, high-fidelity imaging is demonstrated experimentally. This device is designed to operate at K-band frequencies where most non-metallic objects are transparent and the radiation is

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non-ionizing. As a result, it offers great opportunity for security screening and biomedical imaging among other applications.

POSTER NUMBER: 24

Optical Bistability of Film-Coupled Nanocubes

Authors: Zhiqin Huang, Alexandre Baron, Stéphane Larouche, Christos Argyropoulos and David R. Smith
Duke University

Abstract: In this study, we present a novel method using full-wave numerical simulations based on the finite-element method to investigate the optical bistability of a metasurface composed of a periodic arrangement of silver nanocubes coupled to a metal film with an ultrathin nonlinear dielectric spacer. Using the commercial software COMSOL Multiphysics, we define an intensity dependent dielectric constant for the dielectric spacer. The simulated reflectance curve of the metasurface presents a hysteresis cycle as a function of the input intensity of a plane wave impinging on the metasurface under normal incidence. This numerical method is much more accurate than the traditional geometrical post-processing method, since it fully accounts for the inhomogeneity of the spatial profile of the dielectric constant. Our best optimized design exhibits an exceptionally low switching intensity of 0.06 MW/cm², which is much smaller than competing devices. We believe that our method is an efficient numerical tool for designing all-optical switches.

POSTER NUMBER: 25

Wireless Power Transfer in the Radiative Near-Field

Authors: Vinay Gowda, Okan Yurduseven
Duke University

Abstract: Wireless power transfer (WPT) using a patch array antenna in the radiative near field and beam steering using a pixel layer consisting of an array of subwavelength unit cells is studied. Most work demonstrated in the literature uses the inductive near-field region for WPT applications. Although considerably high transfer efficiencies can be obtained in the inductive near-field region, using this region limits the usability of WPT systems for applications where longer range power transfer is required. One way to overcome this challenge is to use the radiative near-field region, where beam-focusing can also be achieved.

In this work, we demonstrate a WPT system for the radiative near-field region. The system consists of highly efficient transmitter (Tx) and receiver (Rx) antennas, both of which are an 8 x 8 patch arrays while the receiver is connected to a half-wave rectifier to harvest the power (rectenna). Using this system, WPT is experimentally demonstrated by lighting an LED connected to the receiving block as a DC load. In this case, the beam for the transmitting and receiving antennas is in the broadside direction. While high WPT efficiencies in broadside

direction is currently focused in a region of Rx, when the Rx is moved from its position, this method fails. In order to address this problem, electronic beam steering (or dynamic beam steering) is required. In this work, we use a pixel layer approach for beam steering the power. The pixel layer consists of sub-wavelength square patch unit cells which are in the order of $\lambda g/7$. Depending on the way we can turn on and off these unit cells, we can steer the beam. Currently, the results for beam steering are in simulation stage and we have achieved a beam steering of 30o.

POSTER NUMBER: 26

Optical Properties of Transiently-Excited Semiconductor Hyperbolic Metamaterials

Authors: Salvatore Campione, Ting S. Luk, Sheng Liu, and Michael B. Sinclair
Sandia National Laboratories

Abstract: "Hyperbolic metamaterials (HMs) are usually formed by alternating subwavelength layers of positive and negative permittivity materials, and in the effective medium limit behave as uniaxial materials with hyperbolic isofrequency wavevector surfaces. These materials are characterized by extremely large (infinite in the effective medium limit) densities of states which can greatly enhance spontaneous emission, enhance near-field thermal energy transfer, and lead to enhanced absorption processes.

The degree to which these remarkable properties appear depends upon the range of photon momenta over which the isofrequency surface remains hyperbolic. We employ both the effective medium approximation (EMA) and Bloch theory to compare the dispersion properties of semiconductor hyperbolic metamaterials (SHMs) at mid-infrared frequencies and metallic hyperbolic metamaterials (MHMs) at visible frequencies. This analysis reveals the conditions under which the EMA can be safely applied for both MHMs and SHMs. We find that the combination of precise nanoscale layering and the longer infrared operating wavelengths puts the SHMs well within the effective medium limit and, in contrast to MHMs, allows the attainment of very high photon momentum states.

In addition, ultrafast optical excitation of photocarriers has the potential to transform undoped semiconductor superlattices into SHMs. In particular, we examine the possibility of achieving ultrafast topological transitions through optical pumping which can photo-dope appropriately designed quantum wells on the femtosecond time scale. Some of the attainable optical properties are here investigated under plane wave and Gaussian illuminations, giving rise to reflectionless features, perfect absorption and negative refraction in ultrafast timescales.

This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering and performed, in

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POSTER NUMBER: 27

Bound States in the Continuum in High-Index Dielectric Resonators: Resonance Trapping of Multipoles

*Authors: T. Lepetit and B. Kante
University of California San Diego*

Abstract: We report the first observation of "bound states in the continuum" in metamaterials, realizing ideal cavities with unbounded quality factors. Those mode pave the way to loss free metamaterials/metasurfaces.

POSTER NUMBER: 28

Influence of exciton dimensionality on spectral diffusion of single-walled carbon nanotubes

*Authors: Xuedan Ma, Oleksiy Roslyak, Feng Wang, Juan G. Duque, Andrei Piryatinski, Stephen K. Doorn, Han Htoon
Sandia National Laboratories*

Abstract: We study temporal evolution of photoluminescence (PL) spectra from individual single-walled carbon nanotubes (SWCNTs) at cryogenic and room temperatures. Sublinear and superlinear correlations between fluctuating PL spectral positions and linewidths are observed at cryogenic and room temperatures, respectively. We develop a simple model to explain these two different spectral diffusion behavior in the framework of quantum-confined Stark effect (QCSE) caused by surface charges trapped in the vicinity of SWCNTs. We show that the wave function properties of excitons, namely localization at cryogenic temperature and delocalization at room temperature, play a critical role in defining sub- and super-linear correlations. Room temperature PL spectral positions and linewidths of SWCNTs coupled to gold dimer nanoantennas on the other hand exhibit sublinear correlation, indicating that excitonic emission mainly originates from nanometer range regions and excitons appear to be localized. Our numerical simulations show that such apparent localization of excitons results from plasmonic confinement of excitation and enhancement of decay rates in the gap of the dimer nanoantennas.

POSTER NUMBER: 29

Optical Magnetic Mirrors without Metals and III-V Semiconductors based Dielectric Metamaterials

*Authors: S. Liu, M. B. Sinclair, S. Campione, J. Ginn, D. A. Bender, G. A Keeler, and I. Brener
Sandia National Laboratories*

Abstract: "Magnetic mirrors were first demonstrated at microwave frequencies to improve antennas radiation efficiency. In contrast to a normal mirror which exhibits a 180 degree phase shift of the reflected electric field, a magnetic mirror does not reverse the phase of the reflected electric field but reverts the phase of the reflected magnetic field. Therefore, while the emission from a transverse electric dipole placed close to a normal mirror will be largely canceled by its image, a transverse electric dipole emitter placed close to a magnetic mirror can radiate efficiently. Conversely, transverse dipole absorbers placed close to a magnetic mirror will be located at an anti-node of the total electric field and can absorb efficiently. These exceptional properties of magnetic mirror will lead to potential applications in the areas of sensors, photodetectors, and spectroscopy.

We used a special mid IR phase-locked time-domain system and directly observed that the electric field reflected from our dielectric optical magnetic mirror is in-phase with the incident wave, which directly demonstrates the magnetic mirror behavior. This behavior is further confirmed by observing ~180 degree phase difference between the electric and magnetic resonances. I will also discuss the radiative rate enhancement of a dipole close to our optical magnetic mirror. This is in contrast to the behavior for regular metallic surfaces where dipole emission is strongly quenched.

Finally I will show our recent results on realizing both 2D and 3D (multilayers) dielectric metamaterials using III-V semiconductors that enable metamaterials based active devices."

POSTER NUMBER: 30

Limits to Efficient Enhancement of Spontaneous Emission using Optical Antennas

*Authors: Kevin Messer, Michael Eggleston, Seth Fortuna, Ming C. Wu, Eli Yablonovitch
University of California, Berkeley*

Abstract: "The use of optical antennas to enhance the spontaneous emission rate of light emitters has become a field of growing interest. A 200x increase in the spontaneous emission rate of semiconductors could lead to a breakthrough in fast, efficient, low-power optical communications. However, demonstration of a large rate enhancement is only useful if accompanied with high optical efficiency.

Here we present a circuit model describing the tradeoffs between achieving high spontaneous emission rates

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and maintaining high efficiency. Using an antenna with a very narrow gap is a common strategy for achieving large enhancement. We show that good optical efficiency (>50%) can be maintained down to 10nm gaps. Smaller gaps result in large increases in loss due to severe current crowding of the optical currents in the metal. This loss can be interpreted as spreading resistance due to the optical emitter's close proximity to a metal surface. Increased electron collision rates in the metal also become important at gap distances below 10nm and increase the spreading resistance losses. We offer the spreading resistance description as an intuitive explanation for the commonly seen "quenching" of light emitters near metal surfaces."

POSTER NUMBER: 31

Effecting Time Reversal By Reciprocal Scattering

Authors: Morteza Karami, and Michael A. Fiddy
University of North Carolina, Charlotte

Abstract: We describe the use of complementary subwavelength-featured spatial codes to capture evanescent waves at a target and transfer the information to a remote site possessing a decoding complementary structure.

POSTER NUMBER: 32

Self-Action in Metal/Dielectric Plasmonic Waveguides

Authors: Alexandre Baron, Thang B. Hoang, Chao Fang, Stéphane Larouche, Daniel J. Gauthier, Maiken H. Mikkelsen, and David R. Smith
Duke University

Abstract: Plasmonic systems are viewed as important platforms for realizing nonlinear metamaterials and devices that operate at low control powers, thanks to subwavelength field confinement. Recent investigations of such systems have often considered dielectrics to be the primary source of the nonlinear optical response [1]. However, metals exhibit large nonlinear susceptibilities, though they are usually difficult to measure accurately due to small penetration depths. Here, we use surface plasmons polaritons (SPP) to probe the nonlinear optical response of metals. We analytically derive a model that describes the nonlinear propagation of SPPs, which enables us to introduce a metric predicting the scaling of the nonlinear response of a single metal/dielectric interface where both metal and dielectric present a third-order nonlinear susceptibility ($\chi(3)$) [2]. Our theory provides a formalism to relate experimentally measurable quantities to $\chi(3)$ of the metal, which we use to measure $\chi(3)$ of gold on an air/gold interface. The model, numerical simulations and experiments reveal that the SPP undergoes strong ultrafast self-action, consistently with a large third-order nonlinear susceptibility of gold [3]. These findings have important implications for plasmonics and metamaterials as they provide evidence that nonlinear absorption has a significant effect on the propagation of SPPs.

[1] H. Aouani et al., "Third-harmonic-upconversion enhancement from a single semiconductor nanoparticle coupled to a plasmonic antenna," *Nat. Nanotech.* 9, 290-294 (2014).

[2] A. Baron et al., "Scaling of the nonlinear response of the surface plasmon polariton at a metal/dielectric interface," *J. Opt. Soc. Am. B* 32, 9-14 (2015).

[3] A. Baron et al., "Ultrafast self-action of surface-plasmon polaritons at an air/metal interface," *Phys. Rev. B* 91, 195412 (2015).

POSTER NUMBER: 33

Stimulated Brillouin Scattering Simulation Methods for Metamaterials Applications

Abstract

Authors: Roberto Zecca, Stéphane Larouche, Patrick Bowen, and David R. Smith
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Abstract: Stimulated Brillouin scattering (SBS) is the stimulated nonlinear interaction between two photons and an acoustic phonon. Recently, there have been efforts to investigate metamaterial systems able to enhance SBS effects, e.g. amplification and slow light. Metamaterial devices are commonly designed through numerical simulations. However, since commercial software, such as COMSOL Multiphysics, cannot out of the box account for SBS effects, complementary methods must be developed to implement this functionality. In this work, we present a theoretical description of SBS in solids that allows its simulation in finite-element environments. In particular, we propose a transformation optics-based approach for the simulation of solid-state SBS in the frequency domain, and demonstrate its possibilities when applied to a film-coupled nanocube system.

POSTER NUMBER: 33

A Magnetic Wormhole

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Abstract: Wormholes are fascinating cosmological objects that can connect two distant regions of the universe. Because of their intriguing nature, constructing a wormhole in a lab seems a formidable task. A theoretical proposal by Greenleaf et al. presented a strategy to build a wormhole for electromagnetic waves. Based on metamaterials, it could allow electromagnetic wave propagation between two points in space through an invisible tunnel. However, an actual realization has not been possible until now. Here we construct and experimentally demonstrate a magnetostatic wormhole. Using magnetic metamaterials and metasurfaces, our wormhole transfers the magnetic field from one point in space to another through a path that is magnetically undetectable. We experimentally show that the magnetic field from a source at one end of the wormhole appears

at the other end as an isolated magnetic monopolar field, creating the illusion of a magnetic field propagating through a tunnel outside the 3D space. Practical applications of the results can be envisaged, including medical techniques based on magnetism.

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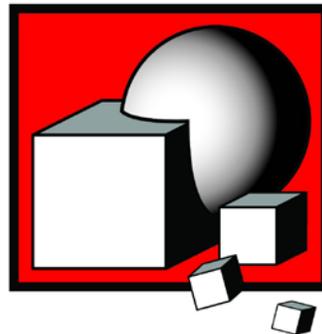


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