Croucher Advanced Study Institute

New Materials and New Concepts for Controlling Light and Waves

3 – 7 October 2012

The Hong Kong University of Science and Technology

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Contents

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Kam Sing Wong	*The Hong Kong University of Science and Technology*
Zhaoqing Zhang	*The Hong Kong University of Science and Technology*

ASI Lecturers

Nader Engheta	*University of Pennsylvania* engheta@ee.upenn.edu
Javier García de Abajo	*Optics Institute – Spanish National Research Council (CSIC)* J.G.deAbajo@csic.es
Yuri Kivshar	*Australian National University* ysk124@physics.anu.edu.au
Sir John Pendry	*Imperial College London and* *HKUST Institute for Advanced Study* j.pendry@imperial.ac.uk
Vladimir Shalaev	*Purdue University* shalaev@purdue.edu
David R. Smith	*Duke University* drsmith@ee.duke.edu
Costas Soukoulis	*Iowa State University* soukoulis@ameslab.gov

Invited Speakers

Kok Wai Cheah	*Hong Kong Baptist University* kwcheah@hkbu.edu.hk
Hong Chen	*Tongji University* hongchen@tongji.edu.cn
Tie Jun Cui	*Southeast University* tjcui@seu.edu.cn
Eleftherios N. Economou	*Foundation for Research and Technology – Hellas (FORTH)* economou@admin.forth.gr
Shanhui Fan	*Stanford University* shanhui@stanford.edu
Nicholas Fang	*Massachusetts Institute of Technology* nicfang@mit.edu
Anthony Grbic	*University of Michigan* agrbic@umich.edu
Sebastien Guenneau	*French National Research Center (CNRS) and Liverpool University* sebastien.guenneau@fresnel.fr
Sailing He	*Zhejiang University* sailing@kth.se
Ortwin Hess	*Imperial College London* o.hess@imperial.ac.uk
Ulf Leonhardt	*University of St Andrews* ulf@st-andrews.ac.uk
Jensen Li	*City University of Hong Kong* jensen.li@cityu.edu.hk
Ross C. McPhedran	*University of Sydney* ross@physics.usyd.edu.au
Roberto Merlin	*University of Michigan* merlin@umich.edu

Graeme Milton	*University of Utah* milton@math.utah.edu
Raj Mittra	*Pennsylvania State University* rajmittra@ieee.org
Daniel H. C. Ong	*The Chinese University of Hong Kong* hcong@phy.cuhk.edu.hk
Ari Sihvola	*Aalto University* ari.sihvola@aalto.fi
Wing Yim Tam	*The Hong Kong University of Science and Technology* phtam@ust.hk
Din Ping Tsai	*Academia Sinica* dptsai@phys.ntu.edu.tw
Eli Yablonovitch	*University of California at Berkeley and* *HKUST Institute for Advanced Study* eliy@eecs.berkeley.edu
Zhiyu Yang	*The Hong Kong University of Science and Technology* phyang@ust.hk
Nikolay Zheludev	*University of Southampton* niz@orc.soton.ac.uk
Lei Zhou	*Fudan University* phzhou@fudan.edu.cn
Shining Zhu	*Nanjing University* zhusn@nju.edu.cn
Jian Zi	*Fudan University* jzi@fudan.edu.cn

Poster Presenters

Kristelle Bougot-Robin	*HKUST Institute for Advanced Study* bougot@ust.hk
Wen-Jie Chen	*Sun Yat-Sen University* wjchen_sysu@163.com
Wallace Choy	*The University of Hong Kong* chchoy@eee.hku.hk
Kun Ding	*Fudan University* datouding@fudan.edu.cn
Jian-Wen Dong	*Sun Yat-Sen University* dongjwen@mail.sysu.edu.cn
Renhao Fan	*Nanjing University* fanrenhao@gmail.com
Junxue Fu	*Hong Kong Baptist University* phyjxfu@hkbu.edu.hk
Dongshi Guan	*The Hong Kong University of Science and Technology* dsguan@ust.hk
Qiong He	*Fudan University* qionghe@fudan.edu.cn
Yusuke Horikoshi	*Ritsumeikan University* ro007083@ed.ritsumei.ac.jp
Bo Hou	*Soochow University* houbo@suda.edu.cn
Zhiwen Kang	*The Chinese University of Hong Kong* zwkang@ee.cuhk.edu.hk
Yun Lai	*Soochow University* laiyun@suda.edu.cn
Dangyuan Lei	*The Hong Kong Polytechnic University* dangyuan.lei08@imperial.ac.uk
Siu-Fung Leung	*The Hong Kong University of Science and Technology* siufleung@ust.hk

Guixin Li	*Hong Kong Baptist University* gxli@hkbu.edu.hk
Jensen Li	*City University of Hong Kong* jensen.li@cityu.edu.hk
Xin Li	*Fudan University* lx@fudan.edu.cn
Hui Liu	*Nanjing University* liuhui@nju.edu.cn
Haifei Lu	*The Chinese University of Hong Kong* hflu@ee.cuhk.edu.hk
Guancong Ma	*The Hong Kong University of Science and Technology* phmgc@ust.hk
Hui Feng Ma	*Southeast University* hfma@emfield.org
Lucia Petti	*Cybernetics Institute of CNR* luciapetti@hotmail.com
Dongxiang Qi	*Nanjing University* dongxiang87@gmail.com
Wujiong Sun	*Fudan University* sunwujiong@fudan.edu.cn
Jun Jun Xiao	*Shenzhen Graduate School, Harbin Institute of Technology* eiexiao@hitsz.edu.cn
Meng Xiao	*The Hong Kong University of Science and Technology* mengxiao@ust.hk
Min Yang	*The Hong Kong University of Science and Technology* erwinstu@ust.hk
Zhong-Jian Yang	*Beijing Computational Science Research Center* zjyang_opt@126.com
Haixi Zhang	*The Chinese University of Hong Kong* hxzhang@ee.cuhk.edu.hk
Furong Zhu	*Hong Kong Baptist University* frzhu@hkbu.edu.hk

Program Schedule

Venue: Tin Ka Ping Hall, Lo Ka Chung University Center *[except where indicated]*

3 October 2012 (Wednesday)		
Time	*Event*	*Presenter*
8:45 – 9:00	Registration	
9:00 – 9:15	Welcome Remarks	Wei Shyy *[The Hong Kong University of Science and Technology]*
9:15 – 10:45	Tutorial #1: "Non Locality and the Limits to Sub Wavelength Focussing"	Sir John Pendry *[Imperial College London, and HKUST Institute for Advanced Study]*
10:45 – 11:00	Refreshments	
11:00 – 11:35	Talk #1: "Perfect Imaging with Positive Refraction"	Ulf Leonhardt *[University of St Andrews]*
11:35 – 12:10	Talk #2: "Discrete Transformation Elastodynamics and Active Exterior Acoustic Cloaking"	Graeme Milton *[University of Utah]*
12:10 – 12:30	Talk #3: "Acoustic and Electromagnetic Double Negativity through Coiling up Space"	Jensen Li *[City University of Hong Kong]*
12:30 – 14:00	Lunch	
14:00 – 14:35	Talk #4: "From Metamaterials to Metadevices and Metasystems"	Nikolay Zheludev *[University of Southampton]*
14:35 – 15:10	Talk #5: "Ferroelectric Domain Engineering: Controlling Light and Photon at Desire"	Shining Zhu *[Nanjing University]*
15:10 – 15:45	Talk #6: "Dynamically Induced Non-reciprocity and Gauge Fields for Photons"	Shanhui Fan *[Stanford University]*
15:45 – 16:00	Discussion	
16:00 – 16:15	Refreshments	
16:15 – 16:50	Talk #7: "From Control of Lamb Waves in Plates to Seismic Metamaterials"	Sebastien Guenneau *[French National Research Center (CNRS), and Liverpool University]*
16:50 – 17:25	Talk #8: "Coupling between Forward and Backward Modes and the Truth about 'Trapped Rainbow' Storage of Light in Metamaterials"	Sailing He *[Zhejiang University]*
17:25 – 18:00	Talk #9: "Transparent Metal Slabs Based on Light-Tunneling Mechanism in Metamaterials"	Hong Chen *[Tongji University]*
18:00 – 18:15	Discussion	

4 October 2012 (Thursday)		
Time	*Event*	*Presenter*
9:15 – 10:45	Tutorial #2: “Metamaterials and Metasurfaces”	Vladimir Shalaev *[Purdue University]*
10:45 – 11:00	Refreshments	
11:00 – 11:35	Talk #10: “Metamaterial Surfaces”	Anthony Grbic *[University of Michigan]*
11:35 – 12:10	Talk #11 : “Metamaterials to Bridge Propagating Waves with Surface Waves and Control Electromagnetic Waves”	Lei Zhou *[Fudan University]*
12:10 – 12:30	Talk #12: “Chiral Metamaterials by Shadowing Deposition”	Wing Yim Tam *[The Hong Kong University of Science and Technology]*
12:30 – 14:00	Lunch	
14:00 – 14:35	Talk #13 : “Spontaneous Emission Rate is Enhanced by an Optical Antenna”	Eli Yablonovitch *[University of California at Berkeley, and HKUST Institute for Advanced Study]*
14:35 – 15:10	Talk #14: “Pinholes Meet Fabry-Pérot: Perfect and Imperfect Transmission of Waves through Small Apertures”	Roberto Merlin *[University of Michigan]*
15:10 – 15:45	Talk #15: “Microwave Metamaterial Antennas”	Tie Jun Cui *[Southeast University]*
15:45 – 16:20	Talk #16: “Structural-Color Production in Amorphous Photonic Structures”	Jian Zi *[Fudan University]*
16:20 – 16:35	Discussion	
16:35 – 19:30	Poster Presentations	

5 October 2012 (Friday)		
Time	*Event*	*Presenter*
9:15 – 10:45	Tutorial #3: "Leveraging Nonlocal and Nonlinear Effects in Metallic Nanoparticles for Optical Metamaterials"	David R. Smith *[Duke University]*
10:45 – 11:00	Refreshments	
11:00 – 12:30	Tutorial #4: "Light Control with Metamaterials and Plasmonic Structures"	Yuri Kivshar *[Australian National University]*
12:30 – 14:00	Lunch	
14:00 – 14:35	Talk #17: "Transformation Acoustics: Virtual Pinholes and Collimators"	Nicholas Fang *[Massachusetts Institute of Technology]*
14:35 – 15:10	Talk #18: "A Look at Transformation Optics—The Holy Grail for Designing Cloaks, Superlenses and Directive Antennas for Microwaves and Millimeter Waves Using Metamaterials"	Raj Mittra *[Pennsylvania State University]*
15:10 – 15:25	Discussion	
15:25 – 15:40	Refreshments	
18:30 – 21:30	Dinner Banquet (by invitation only) *Venue: Peking Garden, 3/F, Star House, Tsim Sha Tsui*	

6 October 2012 (Saturday)		
Time	*Event*	*Presenter*
9:15 – 10:45	Tutorial #5: "Bringing Gain to Metamaterials"	Costas Soukoulis *[Iowa State University]*
10:45 – 11:00	Refreshments	
11:00 – 12:30	Tutorial #6: "Metamaterials and Metasystems: Mixing Simplicity with Complexity"	Nader Engheta *[University of Pennsylvania]*
12:30 – 14:00	Lunch	
14:00 – 14:35	Talk #19: "Active Nanoplasmonic Metamaterials"	Ortwin Hess *[Imperial College London]*
14:35 – 15:10	Talk #20: "Branch Cuts and Resonances for Metamaterials and Plasmonics"	Ross C. McPhedran *[University of Sydney]*
15:10 – 15:45	Talk #21: "Emergent Phenomena in Optical and Electromagnetic Wave Interaction with Metastructures"	Ari Sihvola *[Aalto University]*
15:45 – 16:00	Discussion	
16:00 – 16:15	Refreshments	
16:15 – 16:35	Talk #22: "Coupled Membrane System with Doubly Negative Mass Density and Bulk Modulus"	Zhiyu Yang *[The Hong Kong University of Science and Technology]*
16:35 – 16:55	Talk #23: "Nonlinear Optics in Plasmonic Nanostructures"	Kok Wai Cheah *[Hong Kong Baptist University]*
16:55 – 17:40	Editors' Session #1	
17:40 – 17:55	Discussion	

7 October 2012 (Sunday)		
Time	*Event*	*Presenter*
9:15 – 10:45	Tutorial #7: "Graphene Plasmonics"	Javier García de Abajo *[Optics Institute – Spanish National Research Council (CSIC)]*
10:45 – 11:00	Refreshments	
11:00 – 11:35	Talk #24: "Possible Bottom-up Molecular Metamaterials Operating at the Near Infrared and/or Visible Range"	Eleftherios N. Economou *[Foundation for Research and Technology – Hellas (FORTH)]*
11:35 – 12:10	Talk #25: "Light Manipulation in Plasmonic Metamaterials"	Din Ping Tsai *[Academia Sinica]*
12:10 – 12:30	Talk #26: "Study of Surface Plasmon Polaritons from Periodic Metallic Arrays by Coupled Mode Theory"	Daniel H. C. Ong *[The Chinese University of Hong Kong]*
12:30 – 13:15	Editors' Session #2	
13:15 – 14:30	Lunch	

Tutorials

Non Locality and the Limits to Sub Wavelength Focussing

(Tutorial #1)

John B. Pendry[1]*, A. I. Fernández-Domínguez[1], A. Wiener[1], F. J. García-Vidal[2], S. A. Maier[1]

[1] The Blackett Laboratory, Department of Physics, Imperial College London, UK

**[2] Departamento de Física Teórica de la Materia Condensada,
Universidad Autónoma de Madrid, Spain**

***Email of Presenting Author: j.pendry@imperial.ac.uk**

We describe a general class of plasmonic systems designed to collect incident light over a broad spectrum and concentrate the energy into a very small volume. The resulting density of radiation can be exploited for enhanced molecular sensing and realising non-linear effects at low power levels. However the degree of enhancement is limited by the delocalisation of surface charge implied by the quantum nature of the electron liquid inside a metal.

First we construct a broad band absorber whose geometry is sufficiently simple for the spectrum to be calculated analytically. The spectrum is continuous and energy captured from a dipole source escapes to infinity. Next we apply a transformation that inverts the structure [1] so that in the new structure light from a uniform electric field, e.g. an incident plane wave, is harvested to the origin. The new structure inherits the spectral properties of the original. Because energy never reaches the origin (light moves more and more slowly as the origin approaches), the energy density increases as the light wave is compressed. In an ideal system infinite energy density would be found at the origin but in a real system other effects intervene: absorption removes some of the energy, but non-local effects also interfere with the harvesting process so that the radiation cannot be infinitely compressed. A calculation of the enhancement for silver cylinders including the effects of absorption using the Palik data, but excluding non-local effects can be found in reference [2].

When non-locality is included in the calculation quantum effects prevent the charge from crowding into the touching point, and enhancement is reduced. To maximise enhancement we must compromise between choosing large diameter cylinders to minimise the effect of charge delocalisation, and avoiding cylinders so big that radiative losses dissipate the energy. For silver the optimum cylinder radius lies in the range 35nm < R < 80nm.

References:

[1] A. Aubry et al., Nano Lett., 10, 2574 (2010); A. I. Fernández-Domínguez et al., Phys. Rev. Lett., 105, 266807 (2010).

[2] E. D. Palik, Handbook of optical constants of solids (Academic Press, New York, 1985).

Metamaterials and Metasurfaces

(Tutorial #2)

Vladimir Shalaev*

Birck Nanotechnology Center and School of Electrical and Computer Engineering, Purdue University, USA

***Email of Presenting Author: shalaev@purdue.edu**

Recent progress in the development of optical metamaterials allows unprecedented control over the flow of light at both the nano- and macroscopic scales. Metamaterials (MMs) are rationally designed artificial materials with versatile properties that can be tailored to fit almost any practical need and thus go well beyond what can be obtained with “natural” materials. We review the exciting field of optical metamaterials and discuss the recent progress in developing tunable and active MMs, nanolasers, artificial optical magnetism, semiconductor-based and loss-free negative-index MMs, and a new means for engineering the photonic density of states with MMs. A powerful paradigm of shaping space for light with transformation optics, which can enable a family of new applications ranging from a flat magnifying hyperlens to an invisibility cloak, will be also discussed. Finally, we review a new approach for controlling light by using meta-surfaces. Similar to the surface science that in the past revolutionized physics and open up a family of new phenomena and applications unattainable with 3D systems, we envision that *metasurfaces* can make a difference for the fields of metamaterials and transformation optics as well as for the science of light in general.

Leveraging Nonlocal and Nonlinear Effects in Metallic Nanoparticles for Optical Metamaterials

(Tutorial #3)

David R. Smith*, C. Ciracì, Y. Urzhumov

Center for Metamaterials and Integrated Plasmonics and Department of Electrical and Computer Engineering, Duke University, USA

***Email of Presenting Author: drsmith@ee.duke.edu**

The structured metal inclusions that have been so successful in forming metamaterials at microwave frequencies have proven much less attractive as those structures are scaled towards optical metamaterials. At frequencies above a few terahertzes, metals evolve from being good conductors to lossy insulators. Fortunately, some of the important features of low frequency metamaterials are retained into the optical, including the large field enhancement that occurs within the nanoscale gaps between nanoparticles or at sharp tips and other asperities. Thus, metal nanoparticles and metamaterials can still be used for enhancing photodynamical and nonlinear processes. As such, optical metamaterials are better suited for light generation applications.

Interesting composites can be formed by integrating nonlinear, active or tunable elements into the metallic metamaterial inclusions, such that their properties are enhanced by the large local fields. However, the inherent response of the conduction electrons in metallic and semiconducting nanoparticles can be leveraged to obtain large nonlinearity and other effects, potentially without the need for additional materials. For example, non-centrosymmetric metals such as silver and gold possess large third order nonlinear susceptibilities, which can be strongly enhanced in engineered nanostructured materials. Perhaps even more surprisingly, nanostructured composites formed from these same metals can exhibit large second order susceptibilities that can be optimized by controlling the geometry of the nanoparticle surfaces. Moving beyond the simple Drude model for the carriers in a metal or semiconductor, towards a hydrodynamic model that inherently includes nonlinear and nonlocal effects, much of the light-matter interaction observed can be explained.

The hydrodynamic model of the conduction electron response includes a pressure term that renders the effective permittivity nonlocal. Thus, to simulate the effects of nonlinearity, the nonlocal model—and the associated additional boundary conditions that ensue—must be treated properly. As a first step in clarifying the more complex response, we describe a set of experiments that allows us to correlate the nonlocality of the electron response with measurable optical shifts in the plasmon resonance of film-coupled nanoparticles. The results of the experiment, compared with theory, allow us to infer a value for the Thomas-Fermi screening length that is consistent with previously reported values. This first result is key, in that the nonlocality of the electron response factors into the second-harmonic generation that can be expected. Accurate predictions of advanced phenomena in metals require that the nonlocality be accounted for.

Light Control with Metamaterials and Plasmonic Structures

(Tutorial #4)

Yuri Kivshar*

Nonlinear Physics Center, Australian National University, Australia

***Email of Presenting Author: ysk124@physics.anu.edu.au**

We discuss our recent advances in the control of light propagation in metamaterials and plasmonic structures. First, we suggest and demonstrate experimentally the functional metamaterials in which microwaves interact with externally imposed patterns of light. We fabricate a light-tunable microwave metamaterial structure and prove its unique functionalities for reflection, shaping, and focusing of electromagnetic waves. For optical metamaterials, we demonstrate an efficient polarisation-dependent control of spontaneous emission of quantum dots through their coupling to magnetic metamaterials, and a sharp difference in the interaction of quantum dots with magnetic and electric resonances of the split-ring optical metamaterial. We also discuss novel effects in plasmonic core-shell nanoparticles that support both electric and artificial magnetic dipolar modes; when such modes are engineered to coincide spectrally with the same strength, the interferences of these two resonances result in azimuthally symmetric unidirectional scattering, which can be further improved by arranging the nanoparticles in a chain, with both azimuthal symmetry and vanishing backward scattering preserved over a wide spectral range. In particular, this property can lead to a number of new physical effects such as the polarization independent plasmonic Fano resonances.

Bringing Gain in Metamaterials

(Tutorial #5)

Costas M. Soukoulis[1,2]*

[1]**Institute of Electronic Structure and Laser, Foundation for Research and Technology – Hellas (FORTH), Greece**

[2]**Ames Laboratory and Department of Physics and Astronomy, Iowa State University, USA**

***Email of Presenting Author: soukoulis@ameslab.gov**

Most metamaterials (MMs) are metal-based nanostructure and eventually suffering from the dissipative losses at optical frequencies, which are still orders of magnitude too large for the realistic applications. In addition, MMs losses become an increasingly important issue when moving from metal-based MM made of only a few layers to the bulk case. Thus, the need for reducing or even compensating the losses is a key challenge for MMs technologies. One promising way of overcoming the losses is based on incorporating a gain material into the MM structure. We establish a new approach for pump-probe simulations of metallic metamaterials coupled to the gain materials. It is of vital importance to understand the mechanism of the coupling of metamaterials with the gain medium [1-5]. Using a four-level gain system, we have studied light amplification of arrays of metallic split-ring resonators (SRRs) with a gain layer underneath. We find that that the differential transmittance $\Delta T/T$ can be negative for SRRs on the top of the gain substrate, which is not expected, and $\Delta T/T$ is positive for the gain substrate alone. These simulations agree with pump-probe experiments and can help to design new experiments to compensate the losses of metamaterials. We numerically investigate loss compensation and transmission in pump- probe experiments in resonant metamaterials with gain using an FDTD algorithm coupled to semiclassical rate equations. We explain experimentally observed negative differential transmission by gain-dependent impedance [5]. Recent developments in the field of metamaterials and plasmonics have promised a number of exciting applications, in particular at terahertz and optical frequencies. Most metamaterials consist of carefully designed metallic structures that replace atoms in their role as the basic unit of interaction with electromagnetic radiation. Unfortunately, the noble metals are not particularly good conductors at optical frequencies, resulting in significant dissipative loss in metamaterials [6]. In this talk, we address the question of what is a good conductor for use in metamaterials and in plasmonics.

Summary:

The need for reducing or even compensating of the losses is a key challenge for metamaterial technologies. One promising way of overcoming the losses is based on incorporating a gain material into the metamaterial structure. Therefore, it is of vital importance to understand the mechanism of the coupling between metamaterials and the gain medium. In addition, these ideas can be used in plasmonics to incorporate gain to obtain new nano-plasmonic lasers. We will present our FDTD numerical new results with

gain in metamaterials. In this talk, we address the question of what is a good conductor for use in metamaterials and in plasmonics.

References:

[1] A. Fang, Th. Koschny, M. Wegener and C. M. Soukoulis, Phys. Rev. B. 79, 241104(R) (2009).

[2] A. Fang, Th. Koschny, and C. M. Soukoulis, J. Opt. 12, 024013 (2010).

[3] A. Fang, Th. Koschny, and C. M. Soukoulis, Phys. Rev. B 82, 121102 (R) (2010).

[4] A. Fang, Z. Huang Th. Koschny, and C. M. Soukoulis, Photonics and Nanostructures 10, 276 (2012).

[5] Z. Huang Th. Koschny, and C. M. Soukoulis, Phys. Rev. Lett. 108, 187402 (2012).

[6] P. Tassin, Th. Koschny, M. Kafesaki and C. M. Soukoulis, Nat. Phot. 6, 259 (2012).

Metamaterials and Metasystems: Mixing Simplicity with Complexity

(Tutorial #6)

Nader Engheta*

Department of Electrical and Systems Engineering, University of Pennsylvania, USA

***Email of Presenting Author: Engheta@ee.upenn.edu**

The field of metamaterials (and its predecessors such as complex media and artificial dielectrics) has witnessed unprecedented growth in recent years. As in any field of science and engineering, when a field reaches a certain level of maturity and development, new avenues and novel directions (both in the fundamental as well as the applied aspects of the field) appear in the horizon. In metamaterials, the possibility of expanding the material parameter space does not stop at engineering only the values of permittivity and permeability at will. There are many other features of such material parameters that can be designed to provide new electromagnetic properties for such metamaterials. Features such as nonreciprocity, nonlinearity, anisotropy, chirality, and non-locality can be manipulated in the material parameters by design. While these additional features may add to the complexity of the metamaterial, making the design of such metamaterials more challenging, one needs to explore other concepts that may lead to more simplicity in the materials when exploring future directions in metamaterials. Concepts such as modularization and parameterization, which in some other fields of science and engineering have accelerated development of those fields, must be exploited in order to expedite and quicken the pace of development in the next generation of metamaterials. This can provide metamaterials with new functionalities and possibilities.

In my group, we are exploring some of these issues in metamaterials and plasmonic optics in order to investigate new directions for the next generation of metamaterials. To that end, we are currently investigating topics such as phase-change nanostructures, merging nonreciprocity with metamaterials to achieve exciting features unattainable with each part individually, nonlinear metatronics for optical information processing at the nanoscale, extreme-parameter metamaterials for phase coherence in light-matter interaction particularly in quantum metamaterials, one-atom-thick metamaterials, digital metamaterials, and meta-machines for information processing and functionality.

In this talk, I will discuss some of our work on these topics and present a sample of our most recent results.

Graphene Plasmonics

(Tutorial #7)

Javier García de Abajo*, C.D. Wang

IQFR - CSIC, Spain

***Email of Presenting Author: J.G.deAbajo@csic.es**

We will discuss the extraordinary optical properties of highly doped graphene, along with new classical and quantum phenomena involving plasmons in this material. Doped graphene can host low-energy collective plasmon oscillations with unprecedented levels of spatial confinement, large near-field enhancement, and long lifetimes, which facilitate their application to enhanced light-matter interaction, optical detection, sensing, and nonlinear optics. Graphene plasmons only exist when the carbon sheet is electrically charged, as they involve collective motion of the doping charge carriers, and their frequencies, which scale up with the doping density, can be readily controlled through electrostatic gates, thus opening a realistic avenue towards electrical modulation of plasmon-related phenomena. We will start with a tutorial description of graphene plasmons and a critical comparison with conventional noble-metal plasmons. A summary of recent experimental observations will be presented, including spatial mapping of confined graphene plasmons and spectroscopic evidence of plasmon-mediated resonant absorption [1]. Theoretical descriptions of graphene plasmons will be examined, ranging from classical electromagnetic theory to first-principles quantum-mechanical approaches. We will elucidate the conditions under which quantum nonlocality shows up in the optical response of this material. The interaction with quantum emitters (e.g., quantum dots) placed in the vicinity of the carbon sheet will be shown to reach the strong-coupling regime and potentially serve as a robust platform for quantum-optics devices that can achieve temporal control of plasmon blockade, Rabi splitting, super-radiance, and other quantum phenomena via electrostatic doping [2]. Classical devices for infrared spectroscopy, sensing, and light modulation will be also discussed [3]. Prospects to extend these phenomena to the visible and near-infrared regimes will be examined. These advances in graphene constitute a viable realization of strong light-matter interaction, temporal control of quantum phenomena, and ultrafast electro-optical tunability in solid-state environments, thus bringing the expectations raised within the field of plasmonics closer to reality.

References:

[1] Chen et al., Nature 487, 77 (2012); Fei et al., Nature 487, 82 (2012).

[2] Manjavacas et al., ACS Nano 6, 1724 (2012).

[3] Thongrattanasiri et al., Phys. Phys. Lett. 108, 047401 (2012).

Invited Talks

Perfect Imaging with Positive Refraction

(Talk #1)

Ulf Leonhardt[1,2]*

[1]School of Physics and Astronomy, University of St Andrews, UK

[2]Centre for Optical and Electromagnetic Research, South China Normal University, China

***Email of Presenting Author: ulf@st-andrews.ac.uk**

Perfect imaging with Maxwell's fish eye opens the exciting prospect of passive imaging systems with a resolution no longer limited by the wave nature of light. But it also challenges some of the accepted wisdom of super-resolution imaging and therefore has been subject to controversy and discussion. Here we describe an idea for even simpler perfect-imaging systems based on geometrical optics and prove by experiment that it works [1].

Reference:

[1] Y. G. Ma, S. Sahebdivan, C. K. Ong, T. Tyc, and U. Leonhardt, New. J. Phys. 14, 025001 (2012).

Discrete Transformation Elastodynamics and Active Exterior Acoustic Cloaking

(Talk #2)

F. Guevara Vasquez[1], G.W. Milton[1]*, D. Onofrei[2], P. Seppecher[3]

[1]Department of Mathematics, University of Utah, USA

[2]Department of Mathematics, University of Houston, USA

[3]Institut de Mathématiques de Toulon, Université de Toulon et du Var, France

***Email of Presenting Author: milton@math.utah.edu**

We recall the transformation of elastodynamic equations under coordinate changes. The idea is to use coordinate transformations to manipulate waves propagating in an elastic material. Then we study the effect of transformations on a mass-spring network model. The transformed networks can be realized with "torque springs", which are introduced here and are springs with a force proportional to the displacement in a direction other than the direction of the spring terminals. Possible homogenizations of the transformed networks are presented, with potential applications to cloaking. Then we present cloaking methods that are based on cancelling an incident field using active devices which are exterior to the cloaked region and that do not generate significant fields far away from the devices. The exterior cloaking problem for the Laplace equation is reformulated as the problem of polynomial approximation of a function which takes the value one inside a disk and zero inside a disjoint disk. We also consider the active exterior cloaking problem for the Helmholtz equation in 2D and 3D. Our method uses Green's formula and an addition theorem for outgoing waves to design devices that mimic the effect of the single and double layer potentials in Green's formula. The advantage of the method is that it is broadband and leaves "throats" connecting the cloaked region with the outside.

Acoustic and Electromagnetic Double Negativity through Coiling up Space

(Talk #3)

Jensen Li[1], T. Feng[1], Z. Liang[1], Chi-Hou Chan[2], Seunghoon Han[3], Sangyoon Lee[3]

[1]Department of Physics and Materials Science, City University of Hong Kong, Hong Kong

[2]State Key Laboratory of Millimeter Waves, City University of Hong Kong, Hong Kong

[3]Samsung Advanced Institute of Technology, Samsung Electronics, Korea

***Email of Presenting Author: jensen.li@cityu.edu.hk**

Acoustic metamaterials are analog to their electromagnetic counterpart. They often employ local resonating elements given by subwavelength resonators. Inspired by the cut-off free waveguiding modes in acoustics, here we experimentally demonstrate an alternative route in achieving acoustic double negativity in the effective medium regime by coiling up space using curled perforations in a solid. These curled perforations delay the phase propagation to mimick one-dimensional elements with large refractive indices. By joining these high-index elements in different directions, a metamaterial with double negative density and bulk modulus can be fabricated. Moreover, we demonstrate a microwave metamaterial with double negative permittivity and permeability can be designed and fabricated using the similar principle.

From Metamaterials to Metadevices and Metasystems

(Talk #4)

Nikolay I. Zheludev*

**Optoelectronics Research Centre and Centre for Photonic Metamaterials,
University of Southampton, UK**

***Email of Presenting Author: niz@orc.soton.ac.uk**

Metamaterials, artificial electromagnetic media achieved by structuring on the subwavelength scale, were initially suggested for the negative index “superlens”. Later metamaterials became a paradigm for engineering electromagnetic space and controlling propagation of waves: the field of transformation optics was born. The research agenda is now shifting to achieving tunable, switchable, nonlinear and sensing functionalities. We therefore believe that the time has come to talk about the emerging research field of metadevices that we define as devices with unique and useful functionalities achieved by structuring of functional matter on the subwavelength scale. Here we envisage that the future platform for highly integrated electromagnetic signal processing and distribution will emerge that will combine nonlinear, memory and switchable functionalities with transformation optics’ ability to guide light via the engineered electromagnetic space using metamaterials with spatially variable parameters, the metasystems. Here we overview our recent progress in this area.

Ferroelectric Domain Engineering: Controlling Light and Photon at Desire

(Talk #5)

Shining Zhu*

**College of Physics and National Laboratory of Solid State Microstructures,
Nanjing University, China**

***Email of Presenting Author: zhusn@nju.edu.cn**

The nonlinear crystals with modulated quadratic nonlinear coefficients $\chi^{(2)}$ are called quasi-phase-matching (QPM) materials, or optical superlattices. The concepts were first referred to by Armstrong et al and Ming et al several decades ago. Berger later extended the QPM from one dimension (1D) to 2D, and proposed the concept of $\chi^{(2)}$ photonic crystal in order to contrast and compare it with a regular photonic crystal having a periodic linear susceptibility. Since then, such a nonlinear photon crystal has become a very important artificial microstructure material applied to nonlinear optics and laser, in particular, recently in quantum optics. The $\chi^{(2)}$ photonic crystal is routinely fabricated by pattern-poling a ferroelectric crystal. The sign of $\chi^{(2)}$ in such a crystal is modulated by reversing the orientation of ferroelectric domain according to some sequence. The motivation for such a modulation is in order to realize a goal that is for either a significant enhancement of nonlinear frequency conversion efficiency by QPM, or a required wavefront of the parametric wave by nonlinear Huggens- Fresnel principle, or for both. In history, the study for the domain modulation in a ferroelectric crystal was extended from 1D to 2D, from periodic to quasi-periodic, aperiodic, even more complicated structure. Many novel nonlinear phenomena, such as third harmonic generation, nonlinear light scattering, nonlinear Cherenkov radiation, nonlinear Talbot effect etc were discovered from such artificially micro- structured materials. Nowadays, ferroelectric domain engineering enters a new regime, quantum optics. The bright entangled photon pairs have been generated from 1D optical superlattice by spontaneously parametric down-conversion. Moreover, the generated entanglement photons could been controlled with full freedom offered by redesigned domain structures in crystals, demonstrating focusing, beam-splitting and other novel effects, which cannot be realized usually in an uniform nonlinear crystal at all. This would bring revolutionary impacts on quantum optics and quantum information in future.

Dynamically Induced Non-reciprocity and Gauge Fields for Photons

(Talk #6)

Shanhui Fan*, Kejie Fang, Zongfu Yu

Department of Electrical Engineering, Ginzton Laboratory, Stanford University, USA

***Email of Presenting Author: Shanhui@stanford.edu**

We show that inter-band photonic transition, as induced by dynamic modulation, can be used to achieve linear optical isolators that completely reproduce the functionality of magneto-optical devices [1,2]. We further show that the phase of the modulation induces an effective gauge transformation for photon wavefunctions [3]. By controlling the phase distribution, one can then achieve an effective magnetic field for photons. As an evidence of such effective magnetic field, we show an effective Lorentz force for photons, as well as a dynamically-induced one-way edge mode in dynamically modulated photonic resonator lattice [4].

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From Control of Lamb Waves in Plates to Seismic Metamaterials

(Talk #7)

Sebastien Guenneau[1,2]*

[1]Institut Fresnel, French National Research Center (CNRS), France

[2]Department of Mathematical Sciences, Liverpool University, UK

***Email of Presenting Author: sebastien.guenneau@fresnel.fr**

This talk addresses mathematical models for the propagation of elastic waves in structured plates and their application to the focussing of (a) Lamb waves in a 8.5cm thick Duraluminium plate with an array circular holes (diameter: 12mm, array pitch 15mm) around frequency 20 KHz and (b) Rayleigh waves in a soil with an array of air columns (diameter: 32cm, array pitch 2m) around frequency 50 Hz. The first experiment was performed at the Institut Langevin in Paris, while the second experiment was carried out near the alpine city of Grenoble (France). A third experiment for cloaking of Lamb waves around 400 Hz in a PVC plate with about 100 perforations is also discussed.

After a brief introduction on analogies between Pendry's perfect lens [1] and electromagnetic cloaks [2,3], and their counterparts in elastic plates [4-7], I shall describe two multi-scale models of structured plates for lensing via all-angle-negative refraction (AANR) [4] and cloaking via artificial anisotropy [5,7].

The former model, known as thin beam (or lattice) approximation [4], led to an experiment by the group of Patrick Sebbah at the Institut Langevin in Paris, which I shall discuss in light of numerical solutions for the full Navier-system (whereas [4] was based upon an approximate bi-harmonic scalar equation). I shall then present the description of a preliminary large-scale seismic test held on a soil metamaterial using vibrocompaction probes, bearing in mind that the most simplistic way to interact with seismic wave is to modify the global properties of the medium, acting on the soil density and then on the wave velocity. The usual concept is to reduce the amplification of seismic waves at the free surface, called « site effects » in earthquake engineering. However, I shall develop in this talk another way to counteract the seismic signal by modifying the distribution of the seismic energy thanks to a "metamaterial" made of a grid of vertical, cylindrical and empty "inclusions" bored in the initial soil. Experiments were led by the group of Stéphane Brûlé (MENARD Company) in the Alpine city of Grenoble in August.

The latter model known as homogenization or asymptotic analysis of periodic structures allows for artificial anisotropy which is the essential ingredient for cloaking in thin structured plates [5,7]. The effectiveness of such models has been confirmed experimentally by the group of Martin Wegener in Karlsruhe [6]. I shall discuss another experiment led by the group of Nicolas Vandenberghe in Marseille, where cloaking of Lamb waves was achieved by perforating a thin PVC plate. I shall finally discuss some possible further extensions of these results.

Acknowledgments:

This is a joint work with A.B. Movchan (Liverpool University, United Kingdom), S. Enoch and M. Farhat (Institut Fresnel, Aix-Marseille Université, France), N. Vandenberghe (Institut IRPHE, Aix-Marseille Université, France), S. Brulé and E. Javelaud (MENARD Company, France: http://www.menard-web.com), P. Sebbah and M. Dubois (Institut Langevin, Ecole Supérieure Physique Chimie Industrielle, Paris, France).

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Coupling between Forward and Backward Modes and the Truth about 'Trapped Rainbow' Storage of Light in Metamaterials

(Talk #8)

Sailing He[1,2]*, Yingran He[1], and Yi Jin[1]

[1]Centre for Optical and Electromagnetic Research, Zhejiang University; Sino-Swedish Joint Research Center of Photonics, China

[2]Department of Electromagnetic Engineering, Royal Institute of Technology, Sweden

***Email of Presenting Author: sailing@kth.se**

It has been predicted that a metamaterial slab waveguide can slow down light propagation significantly (even to zero velocity) as the thickness of the core layer approaches a critical thickness. Tsakmakidis et al. claimed in [Nature 450, 397-401, 2007] that a tapered metamaterial waveguide could lead to a complete standstill of light at the critical core thickness, and such a 'trapped rainbow' waveguide could be used for storage of light. Their theoretical conclusion was based on the application of the adiabatic approximation method, which, in fact, is not applicable near the critical thickness, where degenerated forward and backward modes coexist. Here we show that coupling between the forward and backward modes becomes significant near the critical thickness and consequently, even if the metamaterial is lossless the energy incident from the input port of such a tapered metamaterial waveguide will be totally reflected (instead of being trapped at the position of critical thickness). We explain the underlying physical mechanism for this strong intermodal-coupling, and prove the energy reflection using several independent methods, namely, (1) the semi-analytical mode matching technique, (2) the numerical finite element simulation, (3) the requirement of energy and momentum conservation, and (4) an experimental verification at microwave frequency.

Transparent Metal Slabs Based on Light-Tunneling Mechanism in Metamaterials

(Talk #9)

Hong Chen*

Department of Physics, Tongji University, China

***Email of Presenting Author: hongchen@tongji.edu.cn**

Metals have much larger third-order nonlinear susceptibility than those of typical dielectrics. However, when the thickness is much larger than the skin depth, the metal is nearly opaque due to high reflectance and such nonlinear effect is inaccessible. In this talk, we will discuss our recent studies on zero-reflection or transparent phenomenon in an optical thick metal (M) slab based light-tunneling mechanism in a pairing structure made of a permittivity (ε)-negative (ENG) and a permeability (μ)-negative (MNG) metamaterial, as proposed first by Alu and Engheta. We show theoretically and experimentally, that a one-dimensional dielectric photonic crystal (PC) $(CD)_n$ may mimic a lossless optical ENG or MNG metamaterial in the band-gap region. Then a visible-light tunneling mode can be realized by pairing a MNG-like PC with a metal slab behaving as an optical ENG metamaterial, leading to the transparent phenomenon in an optical thick metal. Moreover, transmittance as high as T = 33% and T =38% are observed at visible light λ = 589 nm for M=Ag, with thickness d = 60.2 nm in a heterostructure $M(CD)_n$ and d = 83.1 nm in a sandwich structure $(CD)_nM(DC)_n$, respectively. The transmittance is more than 200 times larger than that of same thickness of Ag without tunneling in the late case. Possible applications based on transparent metal or magnetic metal slabs, e.g., enhancing optical properties such as absorption, nonlinearity and Faraday effects; realizing all-optical diode action and nonlinear excitation of surface plasmon polaritons are also discussed.

Metamaterial Surfaces

(Talk #10)

Anthony Grbic*

Department of Electrical Engineering and Computer Science, University of Michigan, USA

***Email of Presenting Author: agrbic@umich.edu**

The talk will begin with a brief overview of electromagnetic metamaterials. These are subwavelength-structured materials that exhibit tailored electromagnetic properties. They can be designed to possess a wide range of properties, even those not found in natural materials. For this reason, metamaterials have received widespread attention in recent years and have been the subject of an intense research effort in the engineering and physics communities. This presentation will describe directions we are pursuing in this emerging field of research.

The talk will primarily focus on metamaterial surfaces (metasurfaces). Metamaterial surfaces are textured at a subwavelength scale, in the same way that bulk metamaterials exhibit subwavelength granularity. They can be described macroscopically in terms of effective impedances/admittances just as bulk metamaterials are described in terms of effective material parameters: permittivity and permeability. The presentation will cover non-periodic metasurfaces for near-field electromagnetic manipulation, planar metamaterials with tensor impedance properties for the design of microwave devices and antennas based on transformation electromagnetics, and contoured subwavelength-textured surfaces for electrically-small antenna development. Throughout the talk, metamaterial-based devices will be shown and application areas identified for the proposed structures.

Metamaterials to Bridge Propagating Waves with Surface Waves and Control Electromagnetic Waves

(Talk #11)

Lei Zhou*

Department of Physics, Fudan University, China

***Email of Presenting Author: phzhou@fudan.edu.cn**

Controlling electromagnetic (EM) waves freely is a dream for researchers. While manipulating propagating waves (PWs) or surface waves (SWs) has separately become possible using transformation optics, a bridge that can link PWs with SWs at will has not yet been found and is highly desired to make the full control over EM waves possible. Recently, graded structures were widely used to control EM waves, leading to trapped rainbows, lensing, beam bending and deflection, but none of them was focused on bridging a PW with an SW. Here, we demonstrate that a specific gradient-index meta-surface can convert a PW to an SW with theoretically 100% efficiency [1]. Distinct from conventional devices such as prism or grating couplers, here the momentum mismatch between PW and SW is compensated by the reflection-phase gradient of the meta-surface, and perfect PW-SW conversion can happen for any incidence angle larger than a critical value. Experiments, including both far-field and near-field characterizations, are performed to verify this idea in the microwave regime, which are in excellent agreement with full-wave simulations. In addition, we demonstrated that such SWs bounded on the meta-surfaces, which are driven by incident PWs, can be guided out to flow as surface plasmons on another system supporting eigen surface EM modes. Our findings may pave the road for many applications, including high-efficiency surface plasmon couplers, anti-reflection surfaces, light absorbers, and so on. Finally, I will also present our latest efforts in realizing the noted phenomena in optical frequency regime [2].

We also present our recent efforts in designing appropriate metamaterials to control EM waves, leading to several fascinating physical effects. Based on theoretical analyses and full-wave simulations, we proposed a non-resonant scheme to make a *continuous* metal film transparent in optical regime, with light scattered from the metal film cancelled by those from two composite layers consisting of metallic and dielectric stripes. Such a transparency fully retains the conductivity of the targeted metal and is robust against incidence angle as well as structural disorders. As a proof of concept, we performed microwave experiments to verify all theoretical predictions [3]. We also designed an anisotropic ultrathin metamaterial to allow perfect transmissions of EM waves for two incident polarizations within a common frequency interval. The transparencies are governed by different mechanisms, resulting in significant differences in transmission phase changes for two polarizations. The system can thus manipulate EM wave polarizations efficiently in transmission geometry, including polarization conversion and rotation. Microwave experiments performed on realistic samples are in excellent agreement with numerical simulations [4].

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Chiral Metamaterials by Shadowing Deposition

(Talk #12)

Chunrui Han, Ho Ming Leung, and Wing Yim Tam*

Department of Physics, The Hong Kong University of Science and Technology, Hong Kong

***Email of Presenting Author: phtam@ust.hk**

We report the fabrication of chiral metamaterials using a simple shadowing vapor deposition technique. A template consisting of columnar arrays is used as the substrate for the deposition such that only unshielded/exposed areas are coated. The degree of shielding/shadowing among the arrays, and hence the chirality, can be controlled by adjusting the deposition angle with respective to the arrays. Using this technique we have fabricated 3D metallic chiral metamaterials in the optical range exhibiting very large circular dichroism for circularly polarized incidence light. The shadowing technique is very promising because it is simple, inexpensive, and more importantly, can be applied to the production of large sample size chiral metamaterials.

Spontaneous Emission Rate is Enhanced by an Optical Antenna

(Talk #13)

Eli Yablonovitch*, Ming C. Wu, Nikhil Kumar, Michael Eggleston, Kevin Messer

Department of Electrical Engineering and Computer Sciences,
University of California at Berkeley, USA

***Email of Presenting Author: eliy@eecs.berkeley.edu**

For over 50 years, stimulated emission has been stronger and far more important than spontaneous emission. Indeed spontaneous emission has been looked down upon, as a weak effect.

As an accident of Nature, atoms and quantum dots emit radiation wavelengths that are much larger than the atoms themselves. Molecular sized structures are simply too small to act as efficient antennas. Nonetheless, a molecule is forced to be its own antenna. Thus we live in a world in which spontaneous emission is relatively slow. Therefore the key requirement for speeding up spontaneous emission is to provide the radiating molecule with a proper optical antenna.

Size makes a huge difference in antennas. An efficient optical frequency antenna would preferably be $\lambda/2$, a half-wavelength in size. To the degree that the antenna is smaller, the radiation rate falls as $(a/\lambda)^{3,}$ slowing down spontaneous emission by many orders of magnitude. On the other hand, with the proper optical antenna, the increase in spontaneous emission rate can be up to 8 orders of magnitude, continuing to improve provided radiation loss dominates Ohmic loss.

In practice the maximum spontaneous emission speedup requires the molecule to be very close to the metal surfaces. This leads to optical current crowding, which at lower frequencies is often called “spreading resistance”. In addition, the optical resistivity, that is related to the imaginary part of the dielectric constant, ε'', can become more lossy. As molecules approach the surface the skin depth becomes thinner, leading to more frequent surface collisions, (called the “anomalous skin effect”),further adding to Ohmic loss.

Thus both “spreading resistance” and the “anomalous skin effect” become more severe as molecules approach the nearby antenna surfaces. There will eventually come a point of diminishing returns from a nanoscale optical antenna. Nonetheless, it appears that a 10^4 x spontaneous emission rate enhancement should still be possible.

In a light emitting diode,(LED), even a200x speedup would be sufficient that the LED would become faster than the fastest semiconductor laser.

Pinholes Meet Fabry-Pérot: Perfect and Imperfect Transmission of Waves through Small Apertures

(Talk #14)

Roberto Merlin*

C-PHOM and Department of Physics, University of Michigan, USA

***Email of Presenting Author: merlin@umich.edu**

It has been known for a long time that small holes, of dimensions ℓ, are ill suited for transmitting electromagnetic, acoustic or other disturbances of wavelength λ. The normalized transmittance, T_N, i.e., the ratio between the power transmitted and that incident upon the hole, is $\sim (\ell/\lambda)^4$. More recently, Ebbesen *et al.* [*Nature* 391, 667 (1998)] showed that periodic arrays of small apertures in a metallic film can lead to an extraordinary enhancement of the optical transmission. This important discovery has led to numerous ideas for applications in areas such as sensing, near-field microscopy and light harvesting, that can benefit from the concurrent enhancement of the electric field in the vicinity of the apertures.

The mechanisms underlying extraordinary transmission for hole arrays are fairly well understood. In particular, the distinct and cooperative roles played by surface modes (plasmon polaritons) and waveguide or Fabry-Pérot-type resonances are now well established; see: F. J. García-Vidal *et al.*, *Rev. Mod. Phys.* 82, 729 (2010). The same cannot be said for single apertures. While the utilization of geometric and plasmon resonances to enhance the transmission of small, isolated openings has been considered before, a unified physical picture has not yet emerged. Here, we introduce a simple yet comprehensive model of a closed-curve aperture coupled to an oscillator that gives perfect transmission, that is, $T_N \sim (\ell/\lambda)^2$, in the absence of all but radiative losses. The model draws from ideas that have been hinted at but not fully treated in the engineering literature. It applies to openings in resonant cavities as well as to approaches involving *LC* and other geometric resonances for which the resonant wavelength decreases with the size of the aperture. We also give an example of resonant transmission through apertures with open-curve boundaries, which relies on the interaction with a localized state bound to a pair of pinholes in a two-dimensional waveguide. This problem is related to the so-called single-slit funneling [Pardo et al., *Phys. Rev. Lett.* 107, 093902 (2011)] in that the key resonance is of the Fabry-Pérot type but, unlike funneling, the transmittance does not decrease with decreasing slit width and exactly matches the incident power for arbitrarily small hole sizes. In funneling and related cases, we find that resonant coupling to waveguide modes gives imperfect transmission, with transmitted powers that are on the order of those for single slits off-resonance.

Microwave Metamaterial Antennas

(Talk #15)

Tie Jun Cui*

State Key Laboratory of Millimeter Waves, Southeast University, China

***Email of Presenting Author: tjcui@seu.edu.cn**

Metamaterials have attracted great attentions due to their ability to control electromagnetic waves and the unusual properties. This presentation will be focused on the application of metamaterials in microwave antennas, exploring better performance and/or new features of antennas. Three types of metamaterial antennas are presented: zero-index material antennas, small patch antennas for wireless communications, and metamaterial lens antennas.

We propose and experimentally demonstrate two kinds of anisotropic zero-index materials (AZIMs) in the Cartesian and cylindrical coordinates, respectively. The Cartesian AZIMs (such as z component of permittivity or permeability tensor equals zero) are shown to generate perfectly plane waves in the z direction, resulting in high-directivity antennas. We make two-dimensional (2D) and three-dimensional (3D) experiments to verify such new features. On the contrary, the radially AZIMs (radial component of permittivity or permeability tensor in the cylindrical coordinate equals zero) will always produce omnidirectional radiations regardless the numbers and positions of sources inside AZIM. We also show experimentally the powerful ability of AZIM to reach high-efficiency spatial power combination for the omnidirectional radiations.

We experimentally demonstrate efficient methods to improve the bandwidth and radiation efficiency of patch antennas and reduce the coupling among patch antenna array using metamaterials, which are important to the wireless communications (e.g., MIMO systems).

We present two kinds of metamaterial lens antennas. First, we demonstrate a series of 3D broadband, low loss, dual polarization, and high-directivity planar lens antennas which are realized using gradient-index metamaterials, which have excellent features and superior performance than traditional antennas (horns or Rotman lenses). Second, we propose and realize a 3D Luneburg lens with flattened focal surface using the transformation optics. The novel 3D lens has great advantages to the conventional uniform-material lens and spherical Luneburg lens with no aberration, zero focal distance, a flattened focal surface, and the ability to form images at extremely large angles. It can be directly used as a high-gain antenna to radiate or receive narrow beams in large scanning angles for dual polarizations.

Structural-Color Production in Amorphous Photonic Structures

(Talk #16)

Jian Zi[1]*, Biqin Dong[1], Tianrong Zhan[1], Xiaohan Liu[1], Eli Yablonovitch[2]

[1]Department of Physics, Fudan University, China

**[2]Department of Electrical Engineering and Computer Sciences,
University of California at Berkeley, USA**

***Email of Presenting Author: jzi@fudan.edu.cn**

In addition to pigmentation, structural coloration is another major way of color production in the biological world, produced by the interactions of light with photonic structures via optical effects. Natural photonic structures can be classified into three categories. The first one is ordered photonic structures possessing both short- and long-range order, such as thin films, multilayers, gratings, and photonic crystals. The resulting structural colors are iridescent, in other words, varying with viewing angles. The second category is amorphous photonic structures with only short-range order, leading to non-iridescent structural coloration. The third category is random photonic structures with neither short-range nor long-range order, giving rise to white colors.

For ordered photonic structures like photonic crystals, the origin of structural colors is well understood, produced by the partial photonic bandgaps. Iridescence stems from the directional dependence of the partial photonic bandgaps. For amorphous photonic structures, their non-iridescent structural coloration can be conceptually understood by coherent scattering. Nevertheless, some fundamental questions, such as the ultimate physical mechanisms of non-iridescent structural coloration, remain to be answered.

In this talk, we present our recent results of structural characterizations, optical measurements, and numerical simulations on three kinds of amorphous photonic structures: i) amorphous diamond-like photonic crystal in the feather barbs of the scarlet macaw, ii) random-close-packing of sub-micron spheres in the longhorn beetle *Anoplophora graafi*, and iii) disordered bicontinuous macroporous structure in the longhorn beetle *Sphingnotus mirabilis*. Our results show that the three kinds of amorphous photonic structures possess direction-independent photonic pseudogaps, which are ultimately responsible for the non-iridescent structural coloration.

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Transformation Acoustics: Virtual Pinholes and Collimators

(Talk #17)

Nicholas X. Fang*

Department of Mechanical Engineering, Massachusetts Institute of Technology, USA

***Email of Presenting Author: nicfang@mit.edu**

The remarkable success of electromagnetic metamaterials stimulated exploration of controlling and manipulation of other form of waves in materials. For example, it is theoretically predicted that acoustic wave in fluids could be bent artificially by providing a desired spatial distribution of anisotropic acoustic elements. However, experimental studies of these exciting ideas based on coordinate transformation have been hindered due to the difficulty in creating suitable materials with proper anisotropic mass density or bulk modulus. To overcome such challenges, we take the analogy between lumped acoustic elements (pipes and chambers) and electronic circuit elements to construct a new class of metamaterials. When the dimensions of the region in which the sound propagates are much smaller than the wavelength, the phase is roughly constant throughout the element, a lumped-parameter model is appropriate. This transmission line approach enabled ultrasound focusing through a metamaterial network and low-loss and broadband cloaks with the use of non-resonant constituent elements.

In this talk, I will present our preliminary study of a virtual hole and a broadband acoustic collimator, by combination of the concept of complimentary media with transformational acoustics. Such effect is exemplified by a segmental defect in the original cloak, which appears as if a dipole scatterer was under the acoustic imager. We also derived a set of spatially varying effective parameter from coordinate transformation. These parameters can be readily implemented using non-resonant acoustic elements. Our numerical study confirmed the collimation of acoustic beam from a small hydrophone behind the metamaterial device. The potential application of such novel device concept in underwater communication and medical ultrasound will be also discussed.

A Look at Transformation Optics—The Holy Grail for Designing Cloaks, Superlenses and Directive Antennas for Microwaves and Millimeter Waves Using Metamaterials

(Talk #18)

Raj Mittra*

Pennsylvania State University, USA and
King Fahd University of Petroleum and Minerals, Saudi Arabia

*** Email of Presenting Author: rajmittra@ieee.org**

Transformation Optics (TO), aka Transformation EM, is a relatively new field, which has engendered a tremendous level of interest and curiosity among researches in Optics and Microwaves, because it offers a novel approach to designing cloaks, superlenses and directive antennas. The backbone of the TO algorithm is coordinate transformation from one system to another, say from virtual to real or vice versa, implemented to morph an object of a certain shape and size into another, modifying the surrounding media of the objects in the two systems in the process, in a way such that the behaviors of the scattered fields are preserved when going from one system to another. For instance, to design a cloak for a cylindrical structure that renders it invisible, one might first transform the cylinder of radius a—located in real space—into a much smaller one, say b, which resides in the virtual space. Of course, to make this happen, the original cylinder (radius a) must be shrouded by a cloak, such that when the combination (cylinder+cloak) residing in real space is transformed into the desired geometry in the virtual space, it becomes a smaller cylinder (radius b) entirely embedded only in free-space. The TO is used to systematically relate the two system geometries, as well as the material parameters of the media surrounding the objects in these geometries. Similar comments also apply to the design of carpet cloaks, using the TO.

Turning now to the lens problem, typically the objective here is to design flat lenses which provide performances comparable to those of hyperbolic or spherical lenses. The TO does this, once again, by transforming the geometry of the original “conventional” lens, with curved interfaces, into a flat one. Here, too, the TO algorithm is useful for prescribing precisely what the material parameters of the flat lens must be in order to maintain the field equivalence between the two systems, namely the conventional and flat lenses.

The paper will begin by posing some questions which we typically run across when applying the TO to design cloaks and lenses. They are:

a) Does the TO require both ε and μ, or could a TO-designed cloak be ε-only or μ-only type?

b) Can we design TO-based cloaks with naturally available materials, or must we use Metamaterials?

c) Are the TO-designed cloaks and lenses necessarily dispersive and narrowband, and do they only work for a single polarization, e.g., E-field polarized parallel to the axis of the cylinder, but not when the polarization is arbitrary?

d) Is the thickness of the TO-cloak typically comparable to the wavelength (or even larger) and how can we reduce it?

e) How do we circumvent the problems we encounter them in the process of applying the TO algorithm, and what avenues do we have for mitigating them?

In an attempt to answer these questions we introduce a slightly different and relatively simple interpretation of the TO paradigm for relating the material parameters when one system is transformed into another by “stretching.” We also introduce the concepts of Field Transformation (FT), which shows good potential for mitigating some of the problems, alluded to above, encountered in the process of applying the TO algorithm to lens and cloak designs.

Active Nanoplasmonic Metamaterials

(Talk #19)

Ortwin Hess*

The Blackett Laboratory, Department of Physics, Imperial College London, UK

***Email of Presenting Author: o.hess@imperial.ac.uk**

Nanoplasmonics and optical metamaterials have in the last 10-15 yeas emerged as a new paradigm in condensed matter optics and nanoscience, offering a fresh perspective to the optical world. They enable the efficient coupling of light fields to the nanoscale, the world of biological or other inorganic molecules [1]. This tight light localisation on truly nanoscopic dimensions (well below the diffraction limit of light) enhances its interaction with mater, paving the way for a multitude of classical and quantum nano-optics applications. However, metal optics suffers from inherent dissipative losses and only recently theoretical [2,3] and experimental [4] advancements have shown that it is realistically possible to overcome dissipative losses of nanoplasmonic metamaterials, even in the exotic negative-index regime. If the gain supplied by the active medium is sufficient to overcome dissipative and radiative losses, the structure can eve function as a coherent emitter of surface plasmons over the whole ultrathin 2D area, well below the diffraction limit for visible light [5,6]. The talk will give an overview of recent advances in the field of gain-enhanced plasmonics and optical metamaterias and show that these constitute an exciting new frontier in nanophotonics and nanoscience, and are precursors towards active, intergrated quantum nano-optics. Bringing gain on the nanoscale is anticipated to improve the performance of a host of active nanocomponents, such as electro-optic modulators and light sources, but also passive ones, such as plasmonic waveguides or sensors featuring intensified plasmonic hotspots for single-emitter spectroscopy.

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Branch Cuts and Resonances for Metamaterials and Plasmonics

(Talk #20)

Ross C. McPhedran*

School of Physics, University of Sydney, Australia

***Email of Presenting Author: ross@physics.usyd.edu.au**

Resonances in physics correspond to poles of a response function, and are of interest because they give rise to large responses to an input signal, and rapid changes in output as a parameter such as frequency is varied. There are however circumstances under which a system response function can exhibit branch cut characteristics rather than isolated resonances. This may be of interest in applications where heightened response is desired over a continuous band of frequencies, rather than at well-separated values.

I will discuss situations which give rise to poles in the response function, using the example of localized plasmons and formulae of the Maxwell-Garnett type. I will also discuss effective media formulae, which typically give rise to formulae involving branch cuts of the square root function. I will contrast these with the behaviour of solutions associated with inclusions of negative permeability or permittivity, and having sharp corners. These have branch cuts which depend on the corner angle, and may provide a type of strong broadband resonance useful in applications of plasmonics, and in new designs for metamaterials.

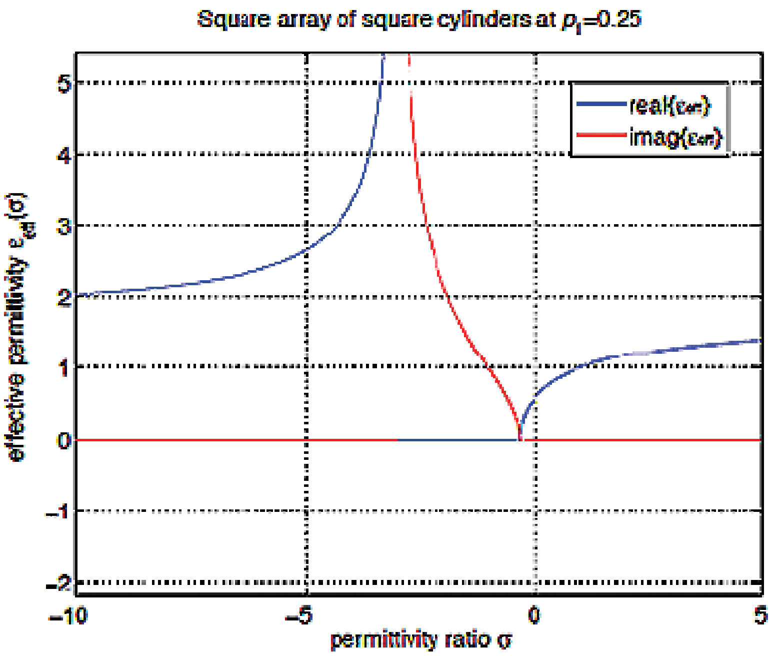


Figure 1. Effective permittivity of a square array of square cylinders (area fraction 25 %) as a function of the permittivity of the cylinders (blue: real part; red: imaginary part).

Emergent Phenomena in Optical and Electromagnetic Wave Interaction with Metastructures

(Talk #21)

Ari Sihvola*

Department of Radio Science and Engineering, Aalto University, Finland

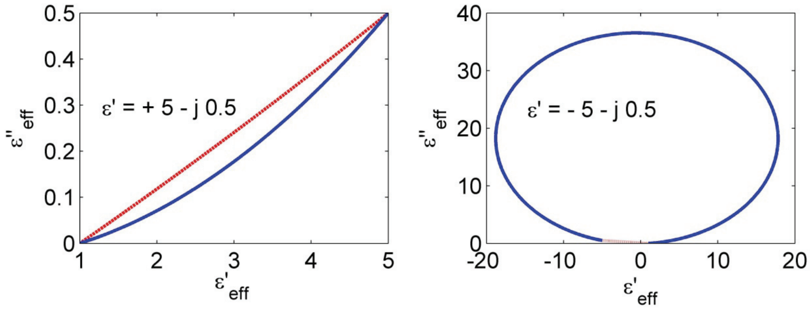
***Email of Presenting Author: ari.sihvola@aalto.fi**

In this presentation, I will concentrate on the emergence of complex behaviors from simpler building blocks and constellations. Such artificial creation of new functionalities has been the ultimate motivator of metamaterials studies.

In parallel to metamaterials, in today's discourse, the "meta" concept has spread into a more broad range, and it is not uncommon to hear use of terms like metagadgets, metamachines, metadevices, metasystems, metafunctions, or other kind of metastructures. Since in the original metamaterial ethos, the idea of emergence is important and essential, also in the present climate where the meta-word has conquered additional domains one needs to pay attention to the repercussions of idea of emergence on higher system levels.

In the presentation, I will focus on examples of this path of reasoning. One exemplary case of metastructure in this respect is the appearance of electromagnetic boundary conditions from the interface between an "ordinary" medium and a metamaterial (here understood as a medium with extreme or otherwise very special material parameters). Then the metamaterial in all its three-dimensional extent and structure behind its surface becomes sacrificed and replaced by an electromagnetic boundary condition.

The figure below illustrates another example of the extremely wide palette of available building blocks for metastructures. It charts the allowed range of achievable complex permittivities of a two-phase mixture where the permittivity ratio between the two phases is +5–j0.5 (left) and –5–j0.5 (right). The allowed area of the composite reduced permittivity is bounded by the solid blue and dotted red curves. Note the dramatic increase (pay attention to the scales!) of freedom when allowing the components have different sign in the real parts (right-hand figure).



Coupled Membrane System with Doubly Negative Mass Density and Bulk Modulus

(Talk #22)

Min Yang[1], Guancong Ma[1], Zhiyu Yang[1]*, and Ping Sheng[1,2]

[1]Department of Physics, The Hong Kong University of Science and Technology, Hong Kong

[2]Institute for Advanced Study, The Hong Kong University of Science and Technology, Hong Kong

***Email of Presenting Author: phyang@ust.hk**

We present an acoustically doubly negative metamaterial using two coupled membranes. Due to its symmetry, the system can generate both monopolar and dipolar resonances, which are separately tunable in the frequency spectrum. To characterize the material, we developed an eigen-function-based exact homogenization scheme that directly utilizes the experimental displacement fields on the sample's surfaces to extract the effective mass density and bulk modulus. It is found that double negativity is achieved in a finite frequency regime. Excellent agreement between experiment and theory is seen.

Nonlinear Optics in Plasmonic Nanostructures

(Talk #23)

G. X. Li, K. F. Li, S. M. Chen, K. W. Cheah*

Department of Physics and Institute of Advanced Materials,
Hong Kong Baptist University, Hong Kong

***Email of Presenting Author: kwcheah@hkbu.edu.hk**

Non-linear optical response can be greatly enhanced from having strong localized electric or magnetic resonance. This can be achieved by designing plasmonic nanostructures that have strong localized plasmonic excitations. This was demonstrated by several research groups [1-5]; these include plasmon enhanced harmonic generation in second and third orders. In this talk, some of our investigation on nonlinear optical properties such as plasmon enhanced third harmonic generation by optical excitation of Au hole-array, nonlinear Fano resonance and giant Rabi splitting will be presented [5-7].

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Possible Bottom-up Molecular Metamaterials Operating at the Near Infrared and/or Visible Range

(Talk #24)

Eleftherios N. Economou*

Foundation for Research and Technology-Hellas, Greece

***Email of Presenting Author: economou@admin.forth.gr**

Benzene based ring molecules, carbon nanotubes, and hexagonal graphene pieces have been considered as possible components of electromagnetic metamaterials operating in the near infrared or visible-frequency-regime. In all cases the dangling bonds at the edges have been passivated by hydrogen incorporation. Using DFT and LCAO techniques the structure and the stability of the undoped and the doped molecules were studied. The adsorption coefficient of these molecules was calculated under the assumption of almost negligible $e\ell - ph$ scattering. The capacitance component in the SRR-like operation may be incorporated by doping the molecule with a cluster of pentavalent or trivalent atoms such as nitrogen, boron, or iron.

Light Manipulation in Plasmonic Metamaterials

(Talk #25)

W. T. Chen[1,2], M. L. Tseng[1,2], P. C. Wu[1,2], C. M. Chang[3], B. H. Cheng[4], Y.-W. Huang[1,2], Y. Z. Ho[2], C. T. Hsiao[2], K.-Y. Yang[1], C. Y. Liao[2], K. S. Chung[2], H.-K. Tsai[5], S. Sun[2,6], L. Zhou[7], G. Y. Guo[2,6], V. Fedotov[8], N. I. Zheludev[8], and D. P. Tsai[1,2,9]*

[1]Graduate Institute of Applied Physics, National Taiwan University, Taiwan

[2]Department of Physics, National Taiwan University, Taiwan

[3]Graduate Institute of Photonics and Optoelectronics, National Taiwan University, Taiwan

[4]Department of Photonics, National Cheng Kung University, Taiwan

[5]Institute of Electro-Optical Science and Technology, National Taiwan Normal University, Taiwan

**[6]National Center of Theoretical Sciences at Taipei, Physics Division,
National Taiwan University, Taiwan**

**[7]State Key Laboratory of Surface Physics and Key Laboratory of Micro and
Nano Photonic Structures (Ministry of Education), Fudan University, China**

**[8]Optoelectronics Research Centre and Centre for Photonic Metamaterials,
University of Southampton, UK**

[9]Research Center for Applied Sciences, Academia Sinica, Taiwan

***Email of Presenting Author: dptsai@phys.ntu.edu.tw**

Plasmonic metamaterials are composite of artificial, subwavelength structures with extraordinary properties which cannot be found in nature. The development of plasmonic metamaterials has potentials for new frontier of science including engineering, physics, biology and chemistry. During the past decade, a number of unique phenomena and applications associated with plasmonic metamaterials are investigated, such as negative refractive index and transformation optics, sub-diffraction-limited imaging and chirality and bionics in plasmonic metamaterials. Here, we design, fabricate and integrate both of planar and three dimensional plasmonic metamaterials for more realization on coupling effects between plasmonic metamaterials and practical applications, such as electromagnetically induced transparency (EIT) through magnetic interaction, toroidal metamaterials, light manipulation via nanostructures and meta-surface, optical hybrid-superlens-hyperlens for super resolution imaging. For breaking the diffraction limit, the device involving two anisotropic metamaterial components, an upper planar-superlens and a lower cylindrical-hyperlens with opposite signs permittivity tensors has been theoretically proposed. Moreover, high throughput of multilayer structures by laser direct writing (LDW) technology also has been discussed and reported. LDW technique is a useful method for fabricating plasmonic devices. Until now, fabricating multilayer metamaterial by the LDW technique has not yet been well developed. Using the femtosecond laser-induced forward transfer technique, as a kind of LDW, the multilayer structures can be made with high throughput and efficiency.

Study of Surface Plasmon Polaritons from Periodic Metallic Arrays by Coupled Mode Theory

(Talk #26)

H.C. Ong*, Z.L. Cao, H.Y. Lo, S.L. Wong, L. Zhang

Department of Physics, The Chinese University of Hong Kong, Hong Kong

***Email of Presenting Author: hcong@phy.cuhk.edu.hk**

We find the optical properties of periodic metallic arrays can be understood by using coupled mode theory. By using this simple analytical formalism, we attempt to maximize field enhancement, sharpening the p-s polarization phase difference, and image the radiative decay of surface plasmon polaritons (SPPs) from periodic arrays. We verify these experimentally and find they are applicable in surface plasmon mediated fluorescence, surface plasmon resonance phase sensing, and understanding some fundamentals of SPPs.

Poster Presentations

Analyzing Fano Line Shapes Using Correlation Techniques

Kristelle Bougot-Robin[1]*, Shunbo Li[2], Yinghua Zhang[3], I-Ming Hsing[3], Henri Benisty[4], Weijia Wen[2]

[1]Institute for Advanced Study, The Hong Kong University of Science and Technology, Hong Kong

[2]Department of Physics, The Hong Kong University of Science and Technology, Hong Kong

[3]Department of Chemical and Biomolecular Engineering, The Hong Kong University of Science and Technology, Hong Kong

[4]Institut Optique Graduate School, CNRS, Université Paris Sud, France

*Email of Presenting Author: bougot@ust.hk

Fano resonance results from interference between a background and a resonant scattering. Its response has an asymmetric line shape. Due to discreteness, extraction of Fano profile peak position might be necessary to gain in sensitivity over the step-wise experimental profiles. Increase in sensitivity may be obtained by fitting data to known models or using a correlation approach, by correlating the signal image (whose shift we want to determine) with a reference image. We will demonstrate the superiority of a correlation approach against Gaussian and Lorentzian shape fitting, and see that this approach also achieves a high immunity to parasitic contributions (noise, distortion from various origins). This will be illustrated through simulation and experiments with profiles from dielectric resonant waveguide gratings (RWGs). Spatial profiles of tracks composed of RWGs micropads with slowly varying geometry (i.e. slowly varying resonance condition) measured in monochromatic imaging in (λ=547nm, θ=17°, polarization=TM) configuration will be analyzed with this approach. Tracking of maximum position of these Fano profiles will serve for multiplex refractive index based sensing. An improvement over the step-wise maximum position tracking by more than 2 orders of magnitude allows to obtain down to 2×10^{-5} RIU sensitivity. Together with highly accurate fitting demonstration through correlation analysis, this "Peak-tracking chip" based scheme demonstrates a new technique for bioarray imaging with simple set-up. Although this illustration is based on dielectric resonant structures, we will present a general approach of Fano line shapes analysis with large relevance for plasmonic or other Fano resonance signals.

Observation of Backscattering-immune Tunneling States in Nonmagnetic Dielectric Photonic Crystals

Wen-Jie Chen[1]*, Zhi Hong Hang[2], Jian-Wen Dong[1,2], X. Xiao[2], C. T. Chan[2], He-Zhou Wang[1]

[1]State Key Laboratory of Optoelectronic Materials and Technologies, Sun Yat-Sen (Zhongshan) University, China

[2]Department of Physics, The Hong Kong University of Science and Technology, Hong Kong

*Email of Presenting Author: wjchen_sysu@163.com

A general strategy is proposed to realize robust transportation in time reversal (TR) invariant photonic system [Phys. Rev. Lett. 107, 023901 (2011)]. By both numerical simulation and microwave experiment, we demonstrate that a chiral photonic mode in a 3D dielectric photonic crystal is immune to scattering of impurities, which is similar to robust transportation of electrons in topological insulator. In particular, our strategy is no need external magnetic fields, which is obviously distinct from the previous findings in the field of magnetic electromagnetic system. The most advantage is that it could possibly be realized in optical and telecom region with nonmagnetic dielectric materials that not relying on a huge external magnetic field. Our findings may promisingly lead to the production of new classes of electromagnetic devices and experiments that rely on chirality of photonic modes.

The chiral structure we studied is built up in 3D woodpile photonic crystal made of non-magnetic dielectric material. The robustness of transportation is demonstrated by comparing the transmitted spectra of such a chiral structure with/without a PEC scatterer, whose size is larger than that of waveguide. We emphasize that such a backscattering-immune tunneling states can emerge in photonic system without external magnetic field, which makes sure TR invariant. This may be mapped to a similar problem that the topologically protected modes in topological insulator are TR invariant and do not require an applied field. Our findings are distinctly different from the topological electromagnetic states in a TR breaking photonic system, e.g. magneto-optical photonic crystals.

Single-Junction Organic Solar Cells with Efficiency of 8.79% Achieved by Using Dual Plasmonic Nanostructures

Wallace C.H. Choy*, Xuanhua Li, Fengxian Xie, Wei E.I. Sha

Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong

***Email: chchoy@eee.hku.hk**

Polymer-fullerene-based bulk heterojunction (BHJ) solar cells have many advantages including low-cost, low-temperature fabrication, semi-transparency, and mechanical flexibility. However, there is a mismatch between optical absorption length and charge transport scale. These factors lead to recombination losses, higher series resistances and lower fill factors. Attempts to optimize both the optical and electrical properties of the photoactive layer in organic solar cells (OSCs) inevitably result in a demand to develop a device architecture that can enable efficient optical absorption in films thinner than optical absorption length. Here, we report the use of dual metallic nanostructures to achieve the broad light absorption enhancement, increased short-circuit circuit (J_{sc}) and improved fill factor (FF) simultaneously based on a new small-bandgap polymer donor of poly{[4,8-bis-(2-ethyl-hexyl-thiophene-5-yl)-benzo[1,2-b:4,5-b']dithiophene-2,6-diyl]-alt-[2-(2'-ethyl-hexanoyl)-thieno[3,4-b]thiophen-4,6-diyl]} (PBDTTT-C-T) in BHJ cells. The dual metallic nanostructure consists of 2D arrays of metallic nanograting electrode as a back reflector and the metallic nanoparticles (NPs) embedded into the active layer. Apart from the waveguide modes and diffractions, we simultaneously introduce hybridized surface plasmonic resonances (from Ag nanograting) and localized plasmonic resonances (from Au NPs) to successfully achieve a broadband absorption enhancement. The detail understanding has been described with our theoretically studies. As a consequence, we improve PCE to reach 8.79% by improving both optical properties and electrical properties of OSCs through introducing dual plasmonic nanostructures which contribute to the practical application of OSCs for photovoltaics.

Compactibility, Tunability and Nonlocality of Metamaterials Made by Different Electronic Materials

Kun Ding[1,2]*, Yuan Shen[1], Jack Ng[2], Lei Zhou[1]

[1]Surface Physics Laboratory (State Key Laboratory) and Physics Department, Fudan University, China

[2]Department of Physics, The Hong Kong University of Science and Technology, Hong Kong

*Email of Presenting Author: datouding@fudan.edu.cn

Despite of many exciting achievements, Metamaterials (MTM) made by conventional good metals suffer some limitations. For example, the functionalities of such MTMs are difficult to tune by external means, and the unit MTM element cannot be make very subwavelength. All these problems are related to the intrinsic electronic properties of materials, so finding new constitutional materials with extraordinary Electronic Band Structures EBS) are crucial. Graphene, the thinnest conducting material in the world, was shown to exhibit highly unusual EBS, and some graphene-based MTMs have been studied both experimentally and theoretically. However, the simple physics behind the dramatic differences between graphene and other metallic materials is obscured by the sophisticated theoretical treatments, and moreover the validity of Equivalent Medium Theory (EMT) for graphene has not been systematically discussed.

In viewing of these, we highlight the connections between photonic properties of MTMs and electronic properties of constitutional materials, and also discuss the EMT of graphene systematically in order to study graphene-based MTMs. We first derive a general formula to discuss the plasmonic performances of different materials, and show how photonic properties of these MTMs depend on their host materials' EBS. We then systematically study the EMT of graphene to calculate graphene-based MTMs with arbitrary microstructures. Applications of our theory on a particular system are in quantitative agreement with available experiments, and further applications on more complex cases are presented.

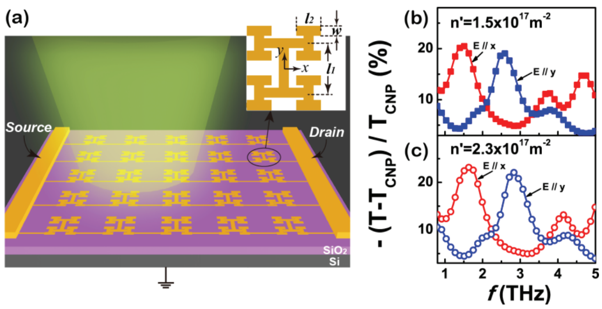

Figure 1. (a) Schematic picture of graphene-made four level fractal microstructures; (b,c) Relative transmission of fractal for x- polarization (red line) and y-polarization (blue line).

Engineering Group Delay and Energy Transmission in Active Plasmonic Waveguide with Slightly Detuned Resonators

Zi-Lan Deng[1,2], Jian-Wen Dong[1]*, Jensen Li[2]

[1]State Key Laboratory of Optoelectronic Materials and Technologies, Sun Yat-Sen (Zhongshan) University, China

[2]Department of Physics and Materials Science, City University of Hong Kong, Hong Kong

*Email of Presenting Author: dongjwen@mail.sysu.edu.cn

We investigate a sub-wavelength plasmonic waveguide with slightly detuned resonators in the window of electromagnetically induced transparency (EIT). Such phase-coupled structure is constructed by two metallic stripes and an asymmetric waveguide with gain-assisted dielectric core and metallic substrate. The stripes have same thickness but slightly different lengths to simulate detuning. We employ a phase map method to engineer energy transmission and group delay. All the results are demonstrated by both couple mode theory and COMSOL simulations. Several interesting characteristics have been found and summarized as follows.

One issue is that the lasing condition between the gain coefficient (α_0) and the detuning parameter (ΔL) is well-defined by the quadratic-like function with the form of $\exp(C\alpha_0) = A\,\Delta L^2 + B$, where A, B, and C are the fitting parameters. This quantitative function can also be predicted by couple mode theory after gain consideration. Another issue is that there is an exceptional region above the minimum value of the quadratic-like function in the phase map. In this region, the group delay and the transmittance of the SPP wave are positive correlation, which is contrast to the common sense that the negative relationship in the passive structure. It indicates that the SPP wave would highly transmit along the slow-light waveguide with large group delay (compared to the bare structure without metallic stripes). We also find that the lowest threshold for lasing will occur when the detuning parameter goes to zero, for example, two identical stripes above the plasmonic waveguide.

Transparent Metals for Ultrabroadband Electromagnetic Waves

R. H. Fan*, J. Li, D. X. Qi, Q. Hu, R. W. Peng, Mu Wang

National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, China

***Email of Presenting Author: fanrenhao@gmail.com**

In this work, we demonstrate for the first time with experiments that metallic gratings consisting of narrow slits can become non-dispersively transparent for terahertz (THz) waves. The broadband optical transmission is verified for the structured metals with significant thickness in the range of half a wavelength, and the high transmission efficiency is insensitive to the metal thickness. Furthermore, this approach can implement transparent metals nearly over the entire spectrum ranging from the radio frequency to the visible. The investigations provide a guideline to develop many novel devices, including transparent conducting panels, white-beam polarizers, broadband metamaterials, and antireflective solar cells. Particularly, broadband transparent metal panels may play important roles in THz regime. Our findings provide a novel design for transparent conducting panels with simultaneously desired electrical and optical performance, which may significantly benefit the information and communications technology.

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Integration of Plasmonic Nanorod Structures on Micro-patterned Substrates through Localized Oblique Angle Deposition (LOAD)

Junxue Fu[1]*, Zhen Cao[2], Mengying Zhang[2], Levent Yobas[2]

[1]Department of Physics, Hong Kong Baptist University, Hong Kong

[2]Department of Electronic and Computer Engineering, The Hong Kong University of Science and Technology, Hong Kong

***Email of Presenting Author: phyjxfu@hkbu.edu.hk**

By using localized oblique angle deposition (LOAD), we demonstrate a simple and convenient method of integrating Ag nanorods directly on microcavity or microchannel sidewalls. LOAD is a physical vapor deposition technique, in which the line of vapor incidence and substrate surface normal form a relatively large angle (>75°); and therefore thin-film columnar structures of nanorods are made due to shadowing effect and diffusion of adatoms. In this study, microcavities were lithographically etched in silicon and mounted horizontally in an electron beam evaporator. In return, a layer of Ag nanorods were aligned in the direction of deposition vapor on the sidewalls. Furthermore, the technique has been applied on the Polydimethylsiloxane (PDMS) substrates, having microchannels moulded from a patterned photoresist (SU8) template. The substrates were swung at an angle of 10° and a speed of 5°/second using a motor-controlled holder; and a layer of Ag nanorods grown on the either of the sidewalls of the PDMS microchannel. Thus, the integration of plasmonic nanostructures onto the microstructures having highly steep sidewalls or even those inclined at a negative angle can be conveniently realized. Plasmonic property of the Ag nanorods inside microcavities has been verified by unraveling their surface enhanced Raman spectroscopy (SERS). The enhancement factors calculated are higher than the order of 105. Our technique suggests the viability of decorating micro-patterned substrates with plasmonics-active nanostructures for integrated sample processing and more versatile plasmonic applications.

Optical Force Measurement in Plasmonic Resonant Cavities using Dynamic Mode AFM

Dongshi Guan[1]*, Zhi Hong Hang[1], Zsolt Marcet[2], Hui Liu[3], Che Ting Chan[1], Ho Bun Chan[1], Penger Tong[1]

[1]Department of Physics, The Hong Kong University of Science and Technology, Hong Kong

[2]Department of Physics, University of Florida, USA

[3]National Laboratory of Solid State Microstructures & Department of Physics,

Nanjing University, China

*** Email of Presenting Author: dsguan@ust.hk**

We have studied the optical force in plasmonic resonant cavities using the dynamic mode atomic force microscopy (AFM). The plasmonic cavity is made of a (upper) gold coated glass sphere and a (lower) quartz substrate patterned with an array of gold disks. The diameter d of the gold disks in the patterned substrate varies from 250 nm to 750 nm and the separation between the gold disks remains the same as 200 nm. An infrared laser of wavelength 1550 nm is vertically incident to the plasmonic cavity and its intensity is modulated at a frequency of 4 to 10 kHz. The gold coated glass sphere is glued onto an AFM cantilever, by which we measure the optical force on the sphere using AFM and phase-sensitive lock-in amplifier. The measured optical force is found to have a strong dependence to the cavity separation r between the sphere and the substrate and the size of nano disks d. The far-field ($r > 3$ μm) non- resonant force obtained for different patterns agrees well with the transmission measurement. In the near-field ($r < 0.5$ μm), a cavity resonance can be excited due to the mutual coupling between the sphere and gold nano disks, and the measured optical force can be enhanced in particular plasmonic resonant cavities. For $d = 625$ nm and $r = 30$ nm, we obtain the largest enhancement of the optical force. These results are in good agreement with the theoretical predictions.

Optic-Null Transformation Optical Media: Realizations and Applications

Qiong He*, Shiyi Xiao, Xin Li, Lei Zhou

State Key Laboratory of Surface Physics and Key Laboratory of Micro and Nano Photonic Structures (Ministry of Education), Fudan University, China

***Email of Presenting Author: qionghe@fudan.edu.cn**

Since its discovery in 2006, transformation optics (TO) theory has offered great versatility to design wave-manipulation devices, such as invisibility cloaks [1], superlenses [2], impedance-matched hyperlenses [3] and field rotator [4]. However, many TO ideas are very difficult to realize in practice, because of the extreme electromagnetic (EM) parameters required. It is highly desirable to design wave-functional devices for which real samples can be realized and with which the designed functionality can be demonstrated experimentally.

In this work, we designed and realized an optically non-existing medium, which we call an "optic-null medium" (ONM), based on a specific type of plasmonic metamaterial. An ONM is such a medium described by $\vec{\varepsilon} = \vec{\mu} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \infty \end{pmatrix}$, which is perfectly transparent for impinging EM waves at any incident angle under both transverse-electric (TE) and transverse-magnetic (TM) polarizations. In addition, waves transmitted through an ONM do not acquire phase accumulations. Such peculiar properties make an ONM transfer an image from one side to another side without causing any distortions. Based on the mode expansion theory under the single mode approximation, we found that a holey metallic plate with fractal-shaped apertures exhibits the desired effective $\vec{\varepsilon}$ and $\vec{\mu}$ as an ONM at a particular frequency. We fabricated a curved microwave sample based on the design, and experimentally demonstrated that such a device can work as a hyperlens, as expected Full-wave simulations are in excellent agreement with experimental results.

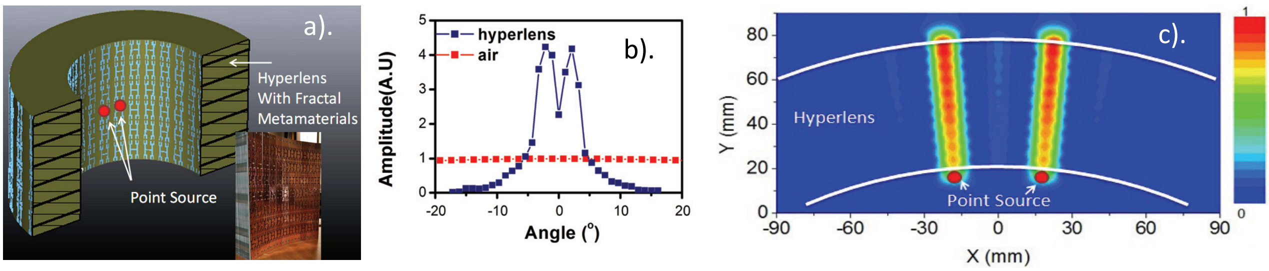

Figure 1. (a) Experimental set-up and picture of fabricated sample. (b) Experimental results of normalized amplitude of transmission wave through air and hyperlens (c) Distributions of electric fields obtained by full-wave simulations through hyperlens.

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Impact of Plasmon Excitation and Förster Energy Transfer to Light Emission in Organic Phosphors

Y. Horikoshi*, S. Kawasaki, A. Yamasaki, K. Kasahara

Graduate School of Science and Engineering, Ritsumeikan University, Japan

***Email of Presenting Author: ro007083@ed.ritsumei.ac.jp**

Energy absorbed to surface plasmon (SP) in organic light-emitting diodes (OLEDs) has been shown to be extracted by the metal surface roughness, thereby increasing the light extraction efficiency. On the other hand, the Förster energy mechanism has been known to arise in OLEDs. However, there have been few efforts to investigate the impact of the two processes at the same time. To understand the influence of the two competitive energy transfer mechanisms is important to optimize the OLED structure that has many organic layers for the realization of the white light source. We prepared an α-NPD film on a 200-nm Ag formed on a glass substrate by thermal evaporation. The thickness varied from 20, 40, to 60 nm. PL enhancement at its peak was 3.5, 4.5 and 4 for the 20, 40, and 60 nm thickness, respectively. Small enhancement seen in the 20-nm device was probably due to the influence of trap states generated in the vicinity of the interface between α-NPD and Ag. The peak enhancement started to decrease when increasing the thickness, as observed in 40 and 60-nm devices, which was reasonable. It was noteworthy that the spectrum in the long wavelength region became strong when the thickness became thicker. This is reproducible. The Förster mechanism occurs between molecules in proximity, typically less than 10 nm. The observed phenomena is presumably attributed to inhomogeneously broadened LUMO states and energy transfer from a neighboring organic molecule with a higher LUMO energy due to the Förster mechanism.

Reconstruction Deep Subwavelength Electromagnetic Transparency through Dual Metallic Gratings with Ultranarrow Slits

Chunyin Qiu[1], Sucheng Li[2], Ruirui Chen[2], Bo Hou[2]*, Feng Li[3], Zhengyou Liu[1]

[1]Key Laboratory of Artificial Micro- and Nano-structures of Ministry of Education and School of Physics and Technology, Wuhan University, China

[2]School of Physical Science and Technology, Soochow University, China

[3]Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, China

*Email of Presenting Author: houbo@suda.edu.cn

The extraordinary optical transmission through an opaque metallic plate perforated with subwavelength apertures has drawn tremendous attention because of many fascinating applications. The studies involve various grating geometries and span a broad range of frequency regimes (from microwaves to optic waves). Now it is widely accepted that the exotic transmission enhancement can be attributed to the resonances induced by the coupling of the external electromagnetic waves with apertures, either individually or collectively: the former stems from the Fabry-Pérot resonance of the fundamental waveguide mode inside the slit, in which the resonant wavelength is determined by the sample thickness; the latter is induced by lattice resonance and always accompanied with exciting bound states (either the intrinsic surface plasmons or the structure-induced spoof surface waves) on the metal surface, where the resonant wavelength is comparable with the structure period. In this study, we investigate the transmission response of microwaves through two identical metallic plates machined with ultranarrow slit arrays. The measured and calculated results consistently display a striking transmission peak at wavelength much larger than any characteristic length of the structure (~230-fold of slit width, ~16-fold of plate thickness, and ~20-fold of lattice period), which cannot be directly explained by the existing mechanisms. Both the LC-circuit-based microscopic picture and the effective-medium-based macroscopic model are established to capture the essential physics behind such unexpected resonance at the deep subwavelength scale. Prospective applications of this novel transmission property can be anticipated, considering the merits of compact and excellent immunity to structural imperfections.

Real-time Nano-manipulation of Nanoparticles by Using Plasmonic Nano-optical Tweezers

Zhiwen Kang*, Aaron Ho-Pui Ho

Department of Electronic Engineering, The Chinese University of Hong Kong, Hong Kong

***Email of Presenting Author: zwkang@ee.cuhk.edu.hk**

Recently, plasmonic nano-optical tweezers (PNOTs) have attracted much attention due to their powerful capability for ultra-accurately immobilization of very small objects. By virtue of surface plasmons, the trapping force becomes much stronger and the confinement volume goes below the diffraction limit of light with lower working power used. Up to now, a variety of PNOTs based on nanostructures such as antennas, holes, disks, rings, strips, and etc., have been proposed and demonstrated to trap micro- or nano-sized particles and biologic specimen. These researches just emphasize on conducting effective optical trapping. However, less attention is paid to real-time manipulation of particles in nanoscale domain by using PNOTs. In this poster presentation, we will demonstrate a novel strategy to realize the nano-manipulation of particles by using a series of graded nano-disks. The nano-disks support different resonance respectively due to the graded property. The resonant wavelengths are well separated through careful design to avoid the cross-talk between the adjacent nano-disks. Under a certain resonant incidence, the corresponding nano-disk will act as a PNOT to trap particles efficiently. Rotating the polarization of incidence can move the particle around this nano-disk. Then switching the incidence to another resonant wavelength of the adjacent one, the particle can be moved correspondingly. Thus, by changing the incident wavelength one by one along with rotating the polarization, the particles can be real-time nano-manipulated step by step between the nano-disks.

Hiding Objects in Three-dimensional Index-near-zero Metamaterials

Jie Luo, Yun Lai*

School of Physical Science and Technology, Soochow University, China

***Email of Presenting Author: laiyun@suda.edu.cn**

We theoretically and numerically investigate transmission properties through three-dimensional index-near-zero materials with embedded defects. We find that contrarily to the two-dimensional cases where defects can control transmission rates, arbitrary three-dimensional defect objects of finite sizes embedded in index-near-zero metamaterials are invisible, irrespective of their sizes, shapes and material components. This robust invisibility effect is predicted by analytical derivation and verified by numerical simulations. The physical reason is the excitation of longitudinal fields that lead to energy flow in the transverse direction. It may find applications in cloaking and novel photonic devices.

Oblique Total Transmissions through Epsilon-near-zero Metamaterials with Hyperbolic Dispersion

Jie Luo, Yun Lai*

School of Physical Science and Technology, Soochow University, China

***Email of Presenting Author: laiyun@suda.edu.cn**

We study the anomalous transmission through an anisotropic epsilon-near-zero metamaterials with hyperbolic dispersions. Traditional isotropic zero-index metamaterials with nearly zero permittivity and/or permeability usually reflect oblique incident waves due to total reflection on the interfaces. In this work, we find that when one component of the nearly zero permittivity tensor turns from positive to negative under a tiny change of value, the dispersion changes dramatically from a tiny circle to a hyperbola, which makes oblique transmissions possible. A series of high order total transmission peaks at large incident angles are observed. Such transmission peaks attribute to the Fabry-Pérot interference effect, and are of very narrow angular bandwidths. Our work may have potential applications for angular filters, ultra-sensitive sensors and switches.

Revealing Plasmonic Gap Modes in Particle-on-film Systems Using Single-particle Dark-field Spectroscopy

D. Y. Lei[1, 2]*, A. I. Fernandez-Dominguez[1], Y. Sonnefraud[1], K. Appavoo[3], R. F. Haglund Jr.[3], J. B. Pendry[1], Stefan A. Maier[1]

[1]Department of Physics, Imperial College London, UK

[2]Department of Applied Physics, The Hong Kong Polytechnic University, Hong Kong

[3]Department of Physics and Astronomy, Vanderbilt University, USA

***Email of Presenting Author: dangyuan.lei08@imperial.ac.uk**

Polarization-controlled excitation of complex plasmonic modes in nanometric Au particle-on-film gaps is investigated experimentally using single-particle dark-field spectroscopy. Two distinct geometries are explored: nanospheres on top of and inserted in a thin gold film. The first geometry exhibits three discrete scattering peaks whose relative amplitude varies with incident polarization. In the contrast, the scattering spectrum becomes significantly broadening when the sphere intersects with the metal film. Numerical simulations are performed to reveal the physical origin of the observed scattering peaks measured from these two different configurations. More importantly, such complicated plasmonic responses can be well understood from a simple but intuitive transformation optics perspective.

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Single-Particle Plasmon-Resonance Spectroscopy of Nanoscale Phase-Transition in Vanadium Dioxide

D. Y. Lei[1, 2]*, K. Appavoo[3], Y. Sonnefraud[1], R. F. Haglund Jr.[3], S. A. Maier[1]

[1]Department of Physics, Imperial College London, UK

[2]Department of Applied Physics, The Hong Kong Polytechnic University, Hong Kong

[3]Department of Physics and Astronomy, Vanderbilt University, USA

***Email of Presenting Author: dangyuan.lei08@imperial.ac.uk**

A novel spectroscopic technique based on single-particle plasmon-resonance is developed and used to study the metal-to-insulator phase-transition of vanadium dioxide (VO_2) - a prototypical correlated electron material - on the nanoscale. On the one hand, by combining this plasmon resonance nanospectroscopy technique with first-principles density functional calculations, we correlate the decreased phase-transition energy observed in multi-domain VO_2 nanoparticles (NPs) with oxygen vacancies created by the strain at grain boundaries. On the other hand, two characteristics responsible for the Mott transition are observed indirectly by monitoring the plasmon response variation of individual Au nanoparticles deposited on a thin VO_2 film when thermally cycling through the metal-to-insulator transition of VO_2. This nanospectroscopy technique can thus be used for nanomaterials studies with simultaneous nanoscale spatial resolution and ultrasensitive spectroscopic characterization.

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[2] K. Appavoo[†], D. Y. Lei[†], Y. Sonnefraud et al, Nano Lett., 12, 780 (2012) ([†]Equal contribution).

Efficient Photon Capturing with Ordered Three-dimensional Nanowell Arrays

Siu-Fung Leung[1]*, Miao Yu[1], Qingfeng Lin[1], Kyungmook Kwon[2], Kwong-Lung Ching[1], Leilei Gu[1], Kyoungsik Yu[2], Zhiyong Fan[1]

[1]Department of Electronic and Computer Engineering, The Hong Kong University of Science and Technology, Hong Kong

[2]Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Korea

***Email of Presenting Author: siufleung@ust.hk**

Unique light-matter interaction at nanophotonic regime can be harnessed for designing efficient photonic and optoelectronic devices such as solar cells, lasers and photodetectors, *etc*. In this work, periodic photon nanowells are fabricated with a low-cost and scalable approach, followed by systematic investigations of their photon capturing properties combining experiments and simulations. Intriguingly, it is found that a proper periodicity greatly facilitates photon capturing efficiency of the nanowells, owing to the effect of diffraction. Meanwhile, the nanoengineered morphology renders the nanostructures with a broad-band efficient light absorption. The findings in this work can be utilized to implement a new type of nanostructure-based solar cells. And the methodology applied in this work can be generalized to rational design of other types of efficient photon harvesting devices.

Linear and Nonlinear Fano Resonance on Two-dimensional Magnetic Metamaterials

H. Liu[1, 2], G. X. Li[1]*, K. F. Li[1], S. M. Chen[1], S. N. Zhu[2], C. T. Chan[3], K. W. Cheah[1]

[1]Department of Physics, Hong Kong Baptist University, Hong Kong

[2]Department of Physics, National Laboratory of Solid State Microstructures, Nanjing University, China

[3]Department of Physics and Nano Science and Technology Program, The Hong Kong University of Science and Technology, Hong Kong

***Email of Presenting Author: gxli@hkbu.edu.hk**

We demonstrated that both linear and nonlinear Fano resonances can be realized on two dimensional magnetic metamaterials. The Fano resonance comes from the interference between localized magnetic plasmon resonance and propagating surface plasmon polaritons. When studying the linear optical response of the metamaterial structure, this interference phenomenon was observed in ellipsometric spectrum. By finely tailoring the geometrical parameters of the magnetic metamaterial device, nonlinear Fano response was tuned to near infrared wavelength (1.61-1.8 μm) of femtosecond pump laser, Fano-type modulation of third harmonic generation was found and agrees well with our theoretical model.

$\mathcal{PT}$-symmetry in Metamaterials

Jensen Li*, Ming Kang, Fu Liu

Department of Physics and Materials Science, City University of Hong Kong, Hong Kong

***Email of Presenting Author: jensen.li@cityu.edu.hk**

We theoretically investigate the analog of $\mathcal{PT}$-symmetric non-Hermitian quantum mechanical systems using metamaterials with dedicated balance between material gain and loss. Due to the flexible tuning in artificial atoms, metamaterials can provide a testing ground for various properties arising from $\mathcal{PT}$-symmetry. In particular, we investigate the optical properties within the transfer matrix formulation and numerically demonstrate the coherent perfect amplification associated to the symmetry.

Flat Meta-surfaces to Focus Electromagnetic Waves in Reflection Geometry

Xin Li[1]*, Shiyi Xiao[1], Bengeng Cai[2], Qiong He[1], Tie Jun Cui[2], Lei Zhou[1]

[1]State Key Laboratory of Surface Physics and Key Laboratory of Micro and Nano Photonic Structures (Ministry of Education), Fudan University, China

[2]State Key Laboratory of Millimeter Waves and Institute of Target Characteristics and Identification, Southeast University, China

***Email of Presenting Author: lx@fudan.edu.cn**

Metamaterials (MTMs) are man-made electromagnetic (EM) materials composed by local electric/magnetic resonant microstructures, which have strong capabilities to manipulate the propagations of EM waves, resulting in many fascinating physical phenomena such as subwavelength focusing [1] and invisibility cloaking [2]. Recently, many efforts were devoted to utilizing MTMs to focus a plane wave to a point image [3], which is quite different from Pendry's super lens that focuses a point source to a point image [1]. However, so far, all proposed lenses [3] were realized through optimizing the local transmission phase only, and therefore, there are significant energy losses due to reflections at the device surface. Here, we proposed a new structure that can focus a plane EM wave to a point source in reflection geometry. Compared to conventional devices with similar functionality, our device is much thinner than wavelength and makes full use of the incidence energy. We first employed the dyadic Green's function method [4] to identify the designing criterion of the proposed device, and then designed a realistic device based on full wave numerical simulations. Microwave experiments (Fig. 1(c)) performed on the fabricated samples (inset to Fig. 1(a)) are in excellent agreement with full wave numerical simulations (Fig. 1(b)) as well as analytical results based on dyadic Green's function method, showing the good functionalities of the proposed device.

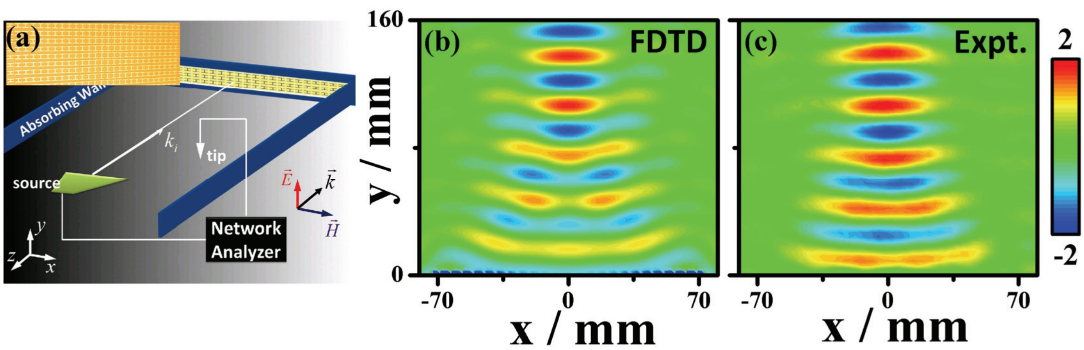

Figure 1: (a) Sketch map of the experiment. Distributions of electric fields of waves scattered by the planar MTM under illuminations of a plane-wave input, obtained by (b) full-wave simulations and (c) experimental measurements.

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Effective Refractive Index Controlling in Homogeneous Dielectric Waveguide and Transformation Optics of Violet Light

Hui Liu*, Y. Wang, C. Sheng, Y. J. Zheng, C. Zhu, S. M. Wang, S. N. Zhu

School of Physics, Nanjing University, China

***Email of Presenting Author: liuhui@nju.edu.cn**

In inhomogeneous medium, such as photonic crystals and metamaterials, we can control the propagation of light through manipulating the periodic refractive index or effective refractive index. In order to obtain photonic crystal or metamaterials, we introduce many inhomogeneous inclusions. Although such inhomogeneous inclusions bring us many novel interesting effects, they will simultaneously result in some things unwanted, such as scattering loss and ohmic loss. Such loss will decay the energy of light propagating in the medium. These loss are great disadvantageousness for practical applications. In this work, we will realize transformation optics of violet light in a graded homogeneous dielectric waveguide. Through changing the thickness of the waveguide, the effective index can be controlled. Some transformation effects can be experimentally obtained, such as 90 degree bending effect and luneburg lens focusing.

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Long Range Photothermal Trapping on the Metal Surface

Hui Liu*, Yajian Zheng, Yi Wang, Cong Zhu, Shuming Wang, Jingxiao Cao, Shining Zhu

School of Physics, Nanjing University, China

***Email of Presenting Author: liuhui@nju.edu.cn**

When a non-uniform light interacts with a particle, it will produce a gradient force on the particle. This can be used to realize optical trapping and manipulate the particles. However, such optical trapping can only work in the illumination region. For those particles outside of the region, the force is too weak. In one experiment, we use a laser to illuminate a silver film. Due to the absorption of light, the silver film is heated. This photothermal effect will caused convection of the water near the surface of silver film. The convective flow will catch particles to the laser spot. Such photothermal trapping is long range strong trapping which can attract the particles far away from the laser spot.

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Preparation of Silver Nanodecahedrons and their Application for Surface Enhanced Raman Scattering

H. F. Lu*, H. P. Ho

Department of Electronic Engineering, The Chinese University of Hong Kong, Hong Kong

***Email of Presenting Author: hflu@ee.cuhk.edu.hk**

Various sizes silver nanodecahedrons (NDs) with their localized surface Plasmon resonance ranged from 420 ~ 670 nm have been successfully prepared through a photochemical method. Because of their sharp tips and edges, silver nanodecahedrons perform relative strong scattering effect to the visible light and large electric field enhancement around them. In this poster, we would present our simulation result on the silver ND/silica spacer layer/gold film geometry. Through tuning the silica spacer thickness, the optical properties of the geometry can be greatly modified, and most of the light would be concentrated in the interface between silver ND and silica layer, which derives from the interaction between silver ND and its image in the gold film. Hence, we believe that this kind of geometry can be used for detection of the molecules on the silica surface through surface enhanced Raman scattering.

Super-absorbing Dark Acoustic Metamaterials

Guancong Ma*, Jun Mei, Min Yang, Weijia Wen, Zhiyu Yang, Ping Sheng

Department of Physics, The Hong Kong University of Science and Technology, Hong Kong

***Email of Presenting Author: phmgc@ust.hk**

Absorption of low-frequency sound in linear systems is a difficult classical problem, since the Poynting's theorem states that loss is quadratic in frequency. However, it is possible to significantly enhance the dissipation of a system by designs that maximize local energy density. Here, we present a membrane-type acoustic metamaterial that can almost totally absorb airborne sound at a frequency as low as 170Hz, whose wavelength is ~104 times larger than the thickness of a single layer of the membrane. We show that at resonances, the asymmetric platelets on the membrane undergo flapping motion. Such motion generates minimal far-field radiation, while at the same time it generates very large elastic curvature energy density in the perimeter regions of the platelets. The resultant high energy density leads to significantly enhanced total dissipation.

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J. Mei, G. Ma, M. Yang, Z. Yang, W. Wen, P. Sheng, Nature Communications, 3, 756 (2012).

Three Microwave Devices Realized by Anisotropic Zero-index Metamaterials

Hui Feng Ma*, Tie Jun Cui

State Key Laboratory of Millimeter Waves, School of Information Science and Engineering, Southeast University, China

***Email of Presenting Author: hfma@emfield.org**

We demonstrate three microwave devices: cloak, super-reflector and bending waveguide, which are realized by using anisotropic zero-index metamaterials (AZIMs). The AZIMs we used have the property of $\mu_{rn}=0$ (in the normal direction to wavefronts) and $\mu_{rt}=\varepsilon_{rz}=1$ for transverse-electric polarized incident waves. The closed-form formula and full-wave simulation show nearly perfect effects of cloak, super reflection and wave bending. We show that a rectangular object coated with perfectly magnetic conductor (PMC) in a waveguide can be cloaked by using two AZIM slabs. However, when the object is coated with perfectly electric conductor (PEC), the incident waves will be totally reflected by the finite-size object in a way by an infinite PEC plane, generating a super reflector. We also show that when a bending waveguide is filled with AZIMs, then the incident waves will be perfectly bended and transmitted without any loss and reflection. Finally, experimental samples of AZIM and PMC are designed, fabricated and measured in the microwave frequency, which show good cloaking, super-reflecting and wave bending effects.

Active Planar Chiral Metamaterials for Light Extraction

L. Petti[1]*, M. Rippa[1], R. Capasso[1], P. Mormile[1], S. De Nicola[2], M. Zanella[3], L. Manna[3], J. Zhou[4], W. Song[5]

[1]Department of Materials and Devices, Cybernetics Institute of CNR, Italy

[2]Istituto Nazionale di Ottica-CNR, Italy

[3]Department of Nanochemistry, Istituto Italiano di Tecnologia, Italy

[4]Institute of Photonics, Faculty of Science, Ningbo University, China

[5]Institute of Material Technology and Engineering, Chinese Academy of Sciences, China

***Email of Presenting Author: Luciapetti@hotmail.com**

In this paper a two-dimensional (2D) active nanograting photonic crystal (PC) which consists of air rods with a gammadion shape in a nanocomposite prepared by incorporating CdSe/CdS core/shell nanorods (NR) in a polymer is proposed and experimentally demonstrated. Scanning electron microscopy and spectra measurements are used to characterize the experimental structure. The vertical extraction of the light, by the coupling of the modes guided by the PQC slab to the free radiation via Bragg scattering, consists of a very narrow orange emission band at 610 nm with a full width at half-maximum (FWHM) of 14 nm.

In this work the integration of CdSe/CdS core/shell nanorods in planar gammadion nanogratings is proposed as a new method to develop active devices based on organic photonics. The active nanocomposite containing colloidal semiconductor quantum rods of nanometer size scale is patterned to fabricate a 2D active PC. The 2D-PC pattern with gammadion rods with a side size of 550 nm and a depth of 350 nm has been uniformly formed by electron beam lithography in large areas of 900x900 μm^2. The active gammadion-PC has been designed to match the properties of the active photonic material by changing the geometrical parameters of the structure to obtain, eventually, enhanced performances of the PC device.

The possibility to pattern active materials open the route to the development of new high performing optical devices such as organic light-emitting diodes, ultra-low threshold lasers, sensors and non-linear devices.

Multiple-band Transmission of Acoustic Wave through Metallic Gratings

D. X. Qi[1]*, R. H. Fan[1], R. W. Peng[1], X. R. Huang[2], M. H. Lu[3], X. Ni[3], Q. Hu[1], M. Wang[1]

[1]National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, China

[2]Advanced Photon Source, Argonne National Laboratory, USA

[3]National Laboratory of Solid State Microstructures and College of Engineering and Applied Sciences, Nanjing University, China

***Email of Presenting Author: dongxiang87@gmail.com**

In this work, we demonstrate that acoustic waves can achieve extremely flat transmission through a metallic grating under oblique incidence within multiple frequency bands separated by Wood's anomalies. At the low-frequency band, the transmission of acoustic wave is independent of the frequency and presents a flat curve with the transmission efficiency reaching about 100%; while at high-frequency bands, the transmission decreases to be lower flat curves due to the diffraction effect. The transmission efficiency is insensitive to the thickness of the grating. This phenomenon is verified by experiments, numerical simulations and an analytical model. The broadband high transmission is attributed to the acoustic impedance matching between the air and the grating. This research may open up a field for various novel applications of acoustic gratings, including broadband sonic imaging and screening, grating interferometry, and antireflection cloaking.

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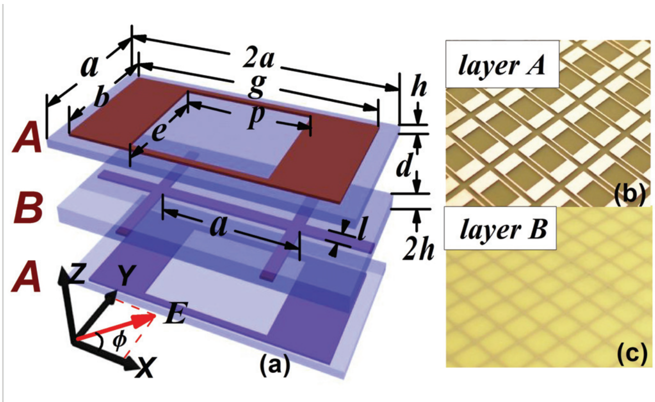
Reflectionless Ultra-thin Microwave Wave-plate Based on Metamaterials

Wujiong Sun*, Qiong He, Jiaming Hao, Lei Zhou

Surface Physics Laboratory and Physics Department, Fudan University, China

***Email: sunwujiong@fudan.edu.cn**

We have designed an anisotropic ultra-thin metamaterial to allow perfect transmissions of electromagnetic (EM) waves for two incident polarizations within a common frequency interval. This sample is composed of three thin artificial layers and combined as ABA sandwiched form. For single frequency, the sample is perfect transparent no matter what the polarization of incident wave is. Actually, the anisotropic transparencies are governed by two different mechanisms, resulting in significant differences in transmission phase changes for two polarizations after penetrate though this sample. The whole system works like a wave-plate, while the amazing phenomenon is the thickness is only 1/20 against to the wavelength. The two transparency mechanisms are ABA transparency and Extraordinary transparency respectively, which are independent structure properties of the sample, thus we can simply tune the working frequency to the desired one in microwave region. Finally, the system can freely manipulate EM wave polarizations efficiently in transmission geometry, including polarization conversion and rotation. Microwave experiments performed on realistic samples are in excellent agreement with numerical simulations.



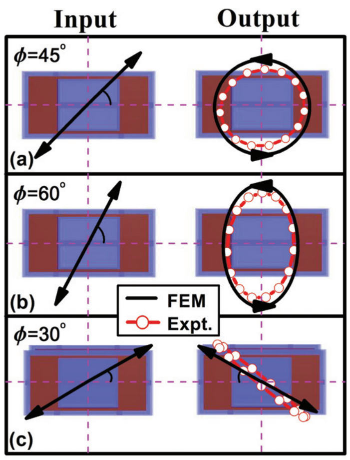


Figure 1. (a) Structure of the triple layer system; (b,c) Photos of layer A and layer B.

Figure 2. (a) Linear polarized converts to circular polarized; (b) Linear polarized converts to elliptical polarized; (c) Linear polarized rotate 60 degrees.

Reversal of Optical Binding Force Near a Dipole-quadrupole Fano Resonance in Plasmonic Heterodimers

J. J. Xiao*, Q. Zhang, X. M. Zhang

College of Electronic and Information Engineering, Shenzhen Graduate School, Harbin Institute of Technology, Xili, Nanshan, China

***Email of Presenting Author: eiexiao@hitsz.edu.cn**

By employing two different 3D full-wave EM computational methods—finite integral technique plus the Maxwell stress tensor integration (FIT-MST) and discrete dipole approximation plus Lorentz force (DDA-LF), we calculate the optical forces on a heterodimer of gold nanorods under plane wave illumination that is polarized along the dimer axis. In such systems, the short nanorod's dipole mode interacts with the long nanorod's quadrupole mode, resulting in a plasmonic Fano resonance. It is found that near this Fano resonance, the optical binding force between the nanorods reverses, indicating a transition from attractive to repulsive transition. Additionally, when the Fano resonance is spectrally tuned by varying the nanorods' length or their gap, the attractive force magnitude changes dramatically but the repulsive force magnitude keeps relatively constant. The various optical characteristics like the optical section, near field distribution, and the charge density are examined, which indicates that the unusual optical force spectrum is due to the strong phase delay between the dipole and quadrupole modes and the remarkably suppressed total dipole moment near the Fano resonance. These numerical results may be useful in studying plasmonic "optical matter".

On the Time Evolution of the Cloaking Effect of a Metamaterial Slab

Meng Xiao[1]*, Xueqin Huang[1], Jian-Wen Dong[1,2], C. T. Chan[1]

[1]Department of Physics, The Hong Kong University of Science and Technology, Hong Kong

[2]State Key Laboratory of Optoelectronic Materials and Technologies, Sun Yat-Sen (Zhongshan) University, China

*** Email of Presenting Author: mengxiao@ust.hk**

We investigated the time evolution of the cloaking behavior of a small particle placed in front of a meta-material slab with $\varepsilon = \mu = -1 + i\delta$. We found that the dipole excitation would be suppressed in the long time limit, while on the way to being cloaked; the excitation will exhibit oscillatory behavior as the result of the interference between particle-slab resonances and high density-of-states surface modes.

Full-Band Exact Homogenization of One-Dimensional Elastic Metamaterials

Min Yang*, Zhiyu Yang, Ping Sheng

Department of Physics, The Hong Kong University of Science and Technology, Hong Kong

***Email of Presenting Author: erwinstu@ust.hk**

Metamaterials extend the realm of materials' properties by carefully designed structural inclusions. By targeting the extraction of effective properties from composite materials, homogenization theory plays an important role for metamaterials in their design and characterization. However, conventional homogenization methods are limited to the long wavelength limit. Here, we introduce an exact homogenization scheme valid for one-dimensional metamaterials over the full frequency band. In this scheme, with the aid of eigenstates' characterization, a set of explicit formulas for effective mass density and effective elastic modulus are obtained by matching the surface responses properties of a metamaterial's single structural unit with a piece of effectively homogenized material. In the frequency regimes beyond the conventional homogenization theory, new features, such as the imaginary parts of the effective parameters, have been found. Applying this scheme on a layered structure, the predicted transport properties and displacement fields from the effective parameters show excellent agreement with numerical simulations.

Cooperative Effects of Two Optical Dipole Antennas Coupled to Plasmonic Fabry-Pérot Cavity

Zhong-Jian Yang[1,2]*, Qu-Quan Wang[1], Hai-Qing Lin[2]

[1]School of Physics and Technology, Wuhan University, China

[2]Beijing Computational Science Research Center, China

*Email of Presenting Author: zjyang_opt@126.com

We investigate the cooperative effects of two optical dipole antennas (OAs) that are coupled to a finite Au nanowire acting as plasmonic Fabry-Pérot (F-P) cavity. The coherent coupling between one single OA and the F-P cavity can result in Fano resonance, and the coupling strength is OA position dependent. At the standing wave antinodes the Fano resonance strength is the strongest, while at the standing wave nodes there is no Fano resonance. Two OAs show cooperative effects when they are coupled to the F-P cavity. For two OAs placed at two standing wave antinodes with distance equal to a plasmon wavelength, constructive interference between the two OAs occurs. As a result, Fano resonance is enhanced. While for two OAs placed at two standing wave antinodes with distance equal to half a plasmon wavelength, destructive interference between the two OAs occurs and the Fano resonance is weakened (or even destroyed). When one OA is placed at standing wave node, it is not coupled to the F-P cavity, so no cooperative effects. It was also found that changing one OA to the opposite side of the F-P cavity is equivalent to adding a π phase difference between the two OAs. These cooperative effects can provide a powerful way to efficiently engineer Fano resonance and complex nanophotonic devices.

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Optical Trapping and Sensing Based on Plasmonic Whispering-gallery Modes

H.X. Zhang*, Z.W. Kang, H.F. Lu, H.P. Ho

Department of Electronic Engineering, Center for Advanced Research in Photonics, The Chinese University of Hong Kong, Hong Kong

***Email of Presenting Author: hxzhang@ee.cuhk.edu.hk**

We propose a novel plasmonic optical tweezer based on a hybrid microstructure. The utilization of the metal split-ring configurations for optical trapping offers the following advantages: (1) The confined evanescent fields significantly reduce the trapping volume; (2) the preferable field gradients result in a large trapping force; and (3) the inherent Q value of whispering-gallery modes make the single nanoparticle trapping events much more readily (4) the integration allows many new opportunities for optical trapping for lab-on-chip.

Photocurrent Enhancement in OSC Using Grating Structured Electrode

Hoi Lam Tam, Qingyi Yang, Gui Xin Li, Furong Zhu*

**Department of Physics and Institute of Advanced Materials,
Hong Kong Baptist University, Hong Kong**

***Email of Presenting Author: frzhu@hkbu.edu.hk**

Organic solar cells (OSC) have attracted a lot of attention due to their potential of low-cost, lightweight, flexible and large area power sources. However, significant improvement in the performance of the devices is still required to make them competitive due to the low efficiency, which is limited by several factors such as low carrier mobility and poor light absorption. Light trapping is a promising approach to improve light absorption in organic solar cells by scattering the incident light to oblique angle and increase the optical path it traveled inside the device. In this work, a modified electrode having a 500nm periodic grating structure is used to enhance the absorption in organic solar cells via the light scattering effect. Photovoltaic properties such as incident photon to current efficiency (IPCE) and power conversion efficiency (PCE) of a set of structural identical cells made with planar and grating incorporated electrodes were analyzed. The OSC with grating electrode resulted in ~13% increase in short circuit current density (Jsc) compared to the planar devices. IPCE results reveal that over 60% of enhancement in Jsc can be obtained at wavelength ranges which coincide with the resonant wavelengths waveguide modes. Our IPCE results agree with FDTD simulations and showed that the enhanced photo-absorption in active layer is mainly due to part of light coupled into waveguide mode in the organic solar cells by the grated electrode.