

Highlights from Session KK: Resonant Optics 2014 Materials Research Society Spring Meeting

Recent advances in the fields of plasmonics, metamaterials and nanophotonics, whereby enhancements and sub-wavelength confinement of optical electromagnetic fields are realized, have led to a wide-array of potential applications such as enhanced molecular sensing, flat optics, negative index metamaterials, hyperbolic metamaterials, quantum nanophotonics and optical antennas. Session KK at the Spring MRS meeting, entitled “Resonant Optics – Fundamentals and Applications”, provided the forum for an exciting, highly interactive symposium focused on recent advances in these various disciplines. In addition, a joint session was held on Wednesday, April 23rd focusing on the “Optics of Graphene and 2D Materials” that was very well attended and had several novel and stimulating presentations.

The symposium was focused on several key research areas within resonant optics, including optical magnetism, exotic plasmonic materials, surface phonon polaritons, optical antennas for energy and catalysis, fundamentals of dielectric optical resonances, sub-wavelength focusing and imaging, metasurfaces for beam control, aperiodic media, hybrid photonic/plasmonic optoelectronic devices and non-linear metamaterials. Invited and contributed talks in each of these areas were presented and were very well received. Below find a brief summary of a few presentations that the organizers of Symposium KK found especially exciting.

KK1.02 – Mr. Edward Sachet, North Carolina State Univ. – Tues. 9:00AM

Mr. Sachet, a student of Prof. Jon-Paul Maria, presented an extremely exciting presentation discussing the potential of a novel, highly doped, plasmonic semiconductor material in cadmium oxide. Recently, it has been widely reported that plasmonic metals exhibit optical losses that preclude their use in many potential applications. This has led to a focus on identifying alternative plasmonic materials, with doped semiconductors receiving a wide degree of interest. However, similar to plasmonic metals, the high free carrier concentrations required in order to support a surface plasmon typically result in only modest reductions in the optical losses. In this talk, not only was the growth of a novel semiconductor material discussed, but it was demonstrated that contrary to other plasmonic materials, the optical losses were *reduced* with increasing carrier density, while also offering operation within the mid-infrared spectral region. This work could provide the basis for novel low-loss plasmonic materials for mid-infrared metamaterials and nanophotonics.

KK4.04/II5.04 – Prof. Rainer Hillenbrand, CIC nanoGUNE – Wed. 9:30AM

Prof. Hillenbrand provided an exciting discussion of his group’s prior efforts in near-field imaging of surface phonon polariton modes within silicon carbide, a low-loss, mid-infrared analog to the surface plasmon polariton and then followed this with his more recent efforts in such imaging of graphene. In his talk he discussed the

methodology of mid-infrared scanning near-field optical microscopy (SNOM) and its use in characterizing the localized near-fields of nanophotonic materials. He demonstrated the focusing of surface plasmon polaritons within graphene by incorporating gold nanoantennas on the surface, illustrating the role of the antenna tip curvature. Furthermore, he reported on bilayer graphene 'prisms' whereby the propagation of the surface plasmon is modified by the sub-nm thick prism. This can have exciting implications for the future of flat optics and nanophotonic circuitry.

KK4.05/II5.05 – Prof. Gennady Shvets, Univ. Texas at Austin – Wed. 10:30AM

In this talk, the speaker presented recent research from his group on dielectric metasurfaces. He demonstrated the realization of ultra-sharp Fano resonances in silicon-based infrared metamaterials, with these resonance linewidths, and thus quality factors well exceeding what is observed from standard plasmonic materials. Furthermore, he demonstrated that silicon-based metamaterials can be used to control the chirality of light. This work indicates that dielectric metamaterials could provide comparable or even better functionality than the more commonly studied metallic metamaterials.

KK 6.01-Prof. Shanhui Fan, Stanford Univ. – Thurs. 8:30 AM

The speaker presented an interesting strategy on the dynamic modulation of optical structures. He demonstrated theoretically that by rationally engineering the optical coupling in optical resonator array structures that non-reciprocal behaviors can be induced and thus enables the ability to achieve gauge potentials and gauge fields for photons. The research opens up a new avenue for the development of non-reciprocal photonic devices, such as optical isolators.

KK7.04 – Prof. Andrea Alu, Univ. Texas at Austin – Thurs. 2:30 PM

On Thursday, Andrea Alu provided an overview of his group's recent work on tailoring the radiation response of materials with plasmonic nanoantennas and metasurfaces. The talk covered many disciplines, highlighting his research group's high degree of productivity and the large impact they have had on the field of nanophotonics. He discussed nanostructures designed for radiofrequency and optical response as well as nonreciprocal circulators for acoustic waves. Novel concepts such as parity-time symmetric nanoantenna arrays and new non-linear optical structures were highlighted.

KK8.01 – Prof. Alexandra Boltasseva, Purdue Univ. – Fri. 8:45 AM

To kick off the final day of the Spring 2014 MRS meeting, Alexandra Boltasseva, gave an exciting presentation about her recent work using transition metal nitrides for plasmonics and metamaterials. Traditional plasmonic materials such as silver and gold have the drawbacks that they are expensive, not compatible with CMOS processing, and have significant optical losses. Boltasseva showed how titanium nitride and zirconium nitride can be used for plasmonic and metamaterial applications and are compatible with

biological environments and semiconductor processing. Further, these materials have high temperature durability, chemical stability, and corrosion resistance – potentially at a low cost. Several examples of plasmonic structures and metamaterial devices were shown including plasmonic waveguides and hyperbolic metamaterials.

Based on the success of this program, it has been accepted for inclusion in the Spring 2015 MRS Meeting, with two of the current organizers, Dr. Joshua Caldwell and Dr. Stephane Larouche, being joined by Prof. Gennady Shvets of the University of Texas at Austin as the organizing committee.

The funding provided, as dictated in our original proposal, was used to run a student poster award session, whereby the top three posters were determined by the collective judgment of the symposium organizers. In addition, we were able to provide travel support to 11 students, including 3 foreign students, allowing them to participate in the meeting.



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Program—Symposium KK: Resonant Optics—Fundamentals and Applications



2014 MRS Spring Meeting & Exhibit

April 21-25, 2014

San Francisco, California

2014-04-22

Symposium KK

[Hide All Abstracts](#)

Symposium Organizers

- Linyou Cao, North Carolina State University
- Joshua Caldwell, Naval Research Laboratory
- Jeremy Munday, University of Maryland
- Stephane Larouche, Duke University

Support

- Department of Energy

KK1: Emerging Plasmonic Materials and Devices

- Chair: Linyou Cao
- Chair: Jeremy Munday
- Tuesday AM, April 22, 2014
- Moscone West, Level 3, Room 3008

8:30 AM - *KK1.01

Quantum Plasmonic Materials and Devices

Harry A. Atwater1.

1, Applied Physics and Materials Science, California Institute of Technology, Pasadena, California, USA.

Hide Abstract

Nanoscale fabrication methods as well as single photon excitation and detection methods have made it possible to design and carry out experiments probing the properties of single plasmons. In this paper, I describe results of two plasmon quantum interference measurements that demonstrate entanglement of surface plasmons in 50-50 directional couplers. These results indicate plasmons can retain complete quantum coherence, which has important implications for characterization of plasmonic dissipation processes and also for nonclassical measurements using plasmons. Also, nanoscale graphene resonators have enable plasmon localization in ultrasmall modes enabling conditions for plasmon coupling to single emitters and scattering centers. Results of graphene nano resonator experiments and models will be discussed.

9:00 AM - KK1.02

Degeneratively Doped Cadmium Oxide: A Material for Plasmonic Applications in the Mid-IR

Edward Sachet1, Misun Kang2, Josh Harris1, Christopher Shelton1, Douglas Irving1, Stefan Franzen2, Jon-Paul Maria1.

1, MSE, North Carolina State University, Raleigh, North Carolina, USA; 2, Chemistry, North Carolina State University, Raleigh, North Carolina, USA.

Hide Abstract

CdO is a prototypical transparent conducting oxide with excellent n-type conductivity and high charge carrier mobility. We will present a plasma assisted molecular beam epitaxy (MBE) growth technique that employs dysprosium as an n-type dopant. This approach allows for tuning of the carrier concentration from -1×10^{19} up to $-5 \times 10^{20} \text{ cm}^{-3}$, which corresponds to plasma frequencies covering the entire mid-IR range ($2\text{-}10 \mu\text{m}$, $1000\text{-}5000 \text{ cm}^{-1}$). Thin heteroepitaxial films grown by this method routinely exceed mobilities of $450 \text{ cm}^2/(\text{V s})$, making them an ideal basis for the next generation of plasmonic applications where low loss and high optical confinement are needed. We will discuss optical properties of CdO:Dy and describe the doping mechanisms and donor states in the CdO:Dy system. Results will be compared to density functional theory (DFT) calculations to further describe the origin of conductivity and the high charge carrier mobility in CdO. In contrast to metals, degeneratively doped semiconductors do not suffer from loss caused by intra-band transitions or electron-electron interactions due to high charge carrier concentration. Additionally, doping techniques allow for precisely controlled tuning of the plasma frequency and the resulting plasmonic effects. The outstanding properties of CdO allow us to study numerous prospective plasmonic applications in the mid-IR.

Many traditional dielectrics, such as gases or organic compounds become absorbing in the mid-IR, with optical properties distinctively different compared to those at optical frequencies. A material (CdO) that supports low loss surface plasmon propagation at those energies allows us to study the interaction of surface plasmon polaritons with mid-IR absorption bands in the surrounding medium. These interactions could lead to advances in mid-IR spectroscopy and open up possibilities for the exploration of new resonant phenomena. Furthermore, we will present our efforts towards designing a monolithically integrated plasmonic platform that combines a solid-state light source with CdO thin films. We will demonstrate the sensing capabilities of CdO thin films for bio-applications, translating the well-understood measurements for protein binding events onto functionalized surfaces into the mid-IR. A combination of an integrated plasmonic platform with functionalized surfaces could lead to the next generation of miniaturized sensors and lab-on-a-chip applications.

We will present experimental data demonstrating the feasibility of both applications mentioned above and will compare the results to FDTD simulations as well as reflectivity calculations based on a free electron Drude model.

9:15 AM - KK1.03

Plasmon-Mediated Large Enhancement of the Verdet Constant in Colloidal Magnetic Metals

Ondrej Vlasin¹, Oana Pascu¹, Anna Roig¹, Gervasi Herranz¹.

¹, ICMAB-CSIC, Bellaterra, Spain.

Hide Abstract

By combining magnetic materials with metals at the nanoscale, magnetoplasmonic effects can arise. One particularly effect of this magnetoplasmonic coupling is the large increase of the magneto-optical activity associated with plasmon resonances, whereby the rotation of the polarization of light is largely enhanced. This phenomenon has a significance that goes beyond its fundamental interest, with obvious relevance for applications in sensing and optical communications. Yet, the lack of a general theoretical framework able to anticipate over the whole visible spectrum and with high accuracy the rotation/ellipticity of light after interacting with a magnetoplasmonic medium is a serious hindrance towards an efficient development of new materials. Here we have addressed this paucity of knowledge by formulating an innovative theoretical approach that endows our model with a powerful predictive character [2]. Based on measurements of the magneto-optic activity in nickel nanoparticle colloids, we have found a striking quantitative agreement between experiment and theory. Even more, large enhancements of the Verdet constant are found at high fields, again in very good accordance to the expected values from our model. The essence of our successful approach is that our effective medium theory does not only consider the plasmon polarizability of the metal clusters in the dielectric solvent host, but also takes into account the non-diagonal coefficients of the solvent permittivity induced by the magnetic fields [2]. The latter point is crucial, as traditionally it has been ignored in the description of the magneto-optics of magnetic/metal systems, but here we demonstrate that it is an indispensable element for any comprehensive and predictive theory. Note that the applicability of our model goes well beyond the particular case of colloidal metals, as other systems such as metal inclusions in polymers or glasses can be as well considered. In addition, the observed large Verdet constant enhancements allow envisioning the exploitation of light polarization, instead as the commonly used reflectance, as a probe for plasmon-sensing devices. Our results provide new routes for plasmon-based biological and chemical detection, as well as new avenues for largely transparent tunable isolators for optical communications.

[1] G. Armelles et al., *Adv. Optical Mater.* 2013, 1, 10

[2] O. Vlasin et al., submitted.

9:30 AM - *KK1.04

Aperiodic Resonant Structures for Light Manipulation

Mark Brongersma¹.

¹, Materials Science and Engineering Department, Stanford University, Stanford, California, USA.

Hide Abstract

The ever-increasing power of computers and the development of new optimization methodologies have enabled the design of complex aperiodic devices, which can outperform periodic ones and offer new functionalities. In this presentation, I will describe the realization and optical properties of ultra-compact, aperiodic groove-arrays in a metal film. These arrays are capable of performing a variety of valuable optical functions, including unidirectional launching of surface plasmon polaritons (SPP) and spectral splitting of optical signals. The high performance of these structures are in part derived from the strong (light and SPP) scattering properties of the building blocks making up the arrays: subwavelength resonant grooves. They also rely on the unique properties that aperiodic photonic structures have to offer. I will show how a transfer matrix model can be used to facilitate the rapid optimization of complex aperiodic structures. I will also illustrate that the general design principles behind this study may readily be extended to a great diversity of more sophisticated aperiodic nanophotonic devices.

10:00 AM -

BREAK

Hide Abstract

10:30 AM - *KK1.05

Nonlinear Upconversion Enhancement from a Single Semiconductor Nanoparticle Coupled to a Plasmonic Antenna

Heykel Aouani¹, Mohsen Rahmani¹, Miguel Navarro-Cia², Stefan A. Maier¹.

¹, Department of Physics, Imperial College London, London, United Kingdom; ², Department of Electrical and Electronic Engineering, Imperial College London, London, United Kingdom.

Hide Abstract

Frequency upconversion of low energy quanta into a quantum of higher energy is of great interest for a variety of applications such as bioimaging and photovoltaic light harvesting. Although phase matching processes enable achieving high nonlinear conversion efficiency rates within macroscopic nonlinear crystals, the characteristic dimensions of subwavelength materials prevent exploiting such coherent enhancement processes. Achieving strong nonlinear effects from nanoscale devices is essential for the future development of on-chip frequency conversion, as well as for ultrafast switching and modulations of optical signals. Here, via utilizing a combined procedure of etch-down and lift-off nanofabrication approaches with high alignment precision, we demonstrate that the third harmonic generation from a single indium tin oxide (ITO) nanoparticle decorated with a plasmonic gold dimer can be extracted from the nonlinear intrinsic metallic signal and used as an efficient nanoscale upconversion system. Such a hybrid nanodevice provides visible third harmonic upconversion enhancements up to 10⁶ fold compared to an isolated ITO nanoparticle, which leads to effective third order susceptibilities up to 3543 nm²/V² and conversion efficiencies of 0.0007%. Furthermore, exploiting the non-absorbing nature of harmonic generation processes, we accurately quantify the intensity enhancement at the gap of various plasmonic dimers when coupled to single localized emitters by using an ITO nanoparticle as a near-field nanoprobe.

11:00 AM -

Discussion Time

Hide Abstract

11:15 AM - KK1.07

Experimental Demonstration of Plasmonic 4-Way Power Splitters and 2×2 Resonant Guided Wave Network Color Routers

Stanley Burgos¹, Howard Lee¹, Eyal Feigenbaum¹, Ryan Briggs¹, Harry Atwater¹.

¹, Caltech, Pasadena, California, USA.

Hide Abstract

Resonant guided wave networks (RGWNs) have been theoretically proposed to function as topological optical networks that can be engineered to have optical functionality such as serving as resonators and color routers. The RGWN concept is quite general, consisting of optically isolated waveguides in a network layout, whereby the isolated waveguides serve to transport energy and information within the network and the waveguide crossings serve to redistribute that information within the network. In this work, we experimentally demonstrate a plasmonic implementation of the RGWN concept by demonstrating that a properly excited 90-degree waveguide crossing of two v-groove channel plasmon polariton (CPP) waveguides operates as an ultra-compact power-splitting element, the key component for the realization of the RGWN concept. By combining these plasmonic power splitters together with the CPP waveguides that comprise them in a network layout, we demonstrate a prototype plasmonic nanocircuit composed of four v-groove waveguides in an evenly spaced 2×2 configuration, which functions as a compact optical logic device at telecommunication wavelengths, routing different wavelengths via different on/off combinations to separate transmission ports. The reported

logic device exhibits expanded 8-port functionality compared to other photonic crystal/plasmonic add/drop filters, in which only two on/off states are accessible. This work illustrates how ultra-compact plasmonic components can form the platform for next-generation integrated plasmonic circuits, and paves the way for the integration of Si-photonics with sub-wavelength mode volume plasmonic waveguides.

11:30 AM - *KK1.08

Nonlocal Optical Response Dramatically Enhances Third-Order Nonlinear Electrodynamics of Plasmonic Nanostructures

Cristian Ciraci¹, David R. Smith¹, Christos Argyropoulos¹.

¹, Duke University, Durham, North Carolina, USA.

Hide Abstract

Large optical nonlinearities are critical to photonic technologies. The exploitation of nonlinear processes at low power levels, and in highly integrated formats, requires materials with large nonlinear susceptibilities in configurations that offer efficient nonlinear conversion.

Metals have long been recognized as compelling candidates for nonlinear materials, as they possess nonlinear susceptibilities that are orders of magnitude larger than dielectric materials, and support surface plasmon modes that allow the light to become strongly confined and enhanced in deeply sub-wavelength volumes. Classical nonlocality in conducting nanostructures has been shown to dramatically alter the linear optical response, for example placing a fundamental limit on the maximum field enhancement that can be achieved. This limit directly extends to all nonlinear processes, which depend on field amplitudes.

We numerically demonstrate a regime in which nonlocality can, in contrast, dramatically enhance the nonlinear optical response by several order of magnitude.

As an illustration, we numerically investigate the process of third-harmonic generation in metal film-coupled nanowires, showing that the impact of nonlocality is to enhance the effective nonlinear susceptibility up to 400 times over that obtained assuming a purely local response.

We show that the effective χ_{33} depends on the spacing between the nanowire and the metal substrate, making the film-coupled nanowire a flexible platform for experimental confirmation.

Our findings show a route to obtain efficient nonlinear processes that exceed other approaches by several orders of magnitude.

KK2: Nonreciprocal and Other Exotic Metamaterials

- Chair: Linyou Cao
- Chair: Stephane Larouche
- Tuesday PM, April 22, 2014
- Moscone West, Level 3, Room 3008

1:30 PM - *KK2.01

Nonreciprocal Metastructures

Nader Engheta¹, Uday Chettiar¹, Artur Davoyan¹, Ahmed Mahmoud¹, Fereshteh Abbasi¹, Cristian Della Giovampaola¹, David Di Ruscio¹.

¹, Department of Electrical and Systems Engineering, University of Pennsylvania, Philadelphia, Pennsylvania, USA.

Hide Abstract

In this talk, we present an overview of some of our ongoing efforts in exploring the various phenomena resulting from mixing the concept of time-reversal symmetry breaking with the notion of metamaterials: microwave, terahertz and optical metamaterials. Three general themes are explored: (1) Interaction of light with magnetized metastructures, in which phenomena such as symmetry breaking and nonreciprocal rotation

of electromagnetic power flow may occur within plasmonic nano-structures, providing potentials for subwavelength nonreciprocal devices such as plasmonic circulators; (2) the notion of electromagnetic isolation and symmetry breaking in wave scattering from metasurfaces, elaborating the concept of non-magnetic all-passive nonlinear-based metamaterials (e.g., electromagnetic diodes, passive non-biased Faraday rotators, etc); and (3) the roles of time-reversal symmetry breaking on the surface states and investigating the possibility of metastructures with one-way flow of surface waves, with potential for one-way loads, one-way antennas, and nonreciprocal wave-cavity interaction. In all these directions, we also explore how structural dispersion (such as waveguides with non-zero-cut-off modes), in addition to the material dispersion, can be utilized to enhance time-reversal symmetry breaking, leading to the possibilities for novel designs of functional devices and components in integrated photonics.

2:00 PM - KK2.02

Selective Self-Assembly of Symmetry-Breaking Optical Metamaterials

Sui Yang^{1,2}, Xiaobo Yin¹, Boubacar Kante¹, Peng Zhang¹, Jia Zhu¹, Yuan Wang¹, Xiang Zhang^{1,2}.

¹, NSF Nano-scale Science and Engineering Center, UC Berkeley, Berkeley, California, USA; ², Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA.

Hide Abstract

Optical metamaterials, as can be designed to achieve unprecedented topologies, introduce a new dimension to materials science and engineering. The symmetry of metamaterials is the key to their optical properties. Traditional top-down approaches such as e-beam lithography can only lead to strongly anisotropic and small-scale metamaterials. On the other hand, conventional self-assembly approaches offer advantages such as low cost and scalability. However, there are significant challenges in achieving rationally designed complex materials with non-trivial broken symmetries that are often not thermodynamically favorable. Here we demonstrate a novel self-assembly route with self-correction feedback mechanisms for scalable synthesis of a new class of symmetry-breaking metamaterials with superior optical properties. Through judicious optical design together with unique nanoscale chemical control, we achieved symmetry breaking assemblies of two side-by-side gold nanorod dimer with a longitudinal offset, which defines the degree of symmetry-breaking that gives rise of possible magnetic and electric resonances at same frequency. More importantly, synthetic feedback strategy based on electromagnetic properties of gold nanodimers is demonstrated to reshape the magnitude of symmetry interplays and structure homogeneity that led to realization of desired magnetic resonances. In conclusion, our research provides a novel self-assembly route to engineer symmetry-breaking optical material with unique functions.

2:15 PM - KK2.03

Parity-Time Symmetric Plasmonic Coaxial Resonators

Brian Baum¹, Hadiseh Alaeian¹, Jennifer Dionne¹.

¹, Materials Science, Stanford, Stanford, California, USA.

Hide Abstract

Parity-time (PT) symmetric structures have brought new importance to the imaginary component of the refractive index, k'' , in photonic and plasmonic systems. Coupled waveguides with asymmetric gain/loss profiles and single waveguides with Bragg-like gain/loss striations have formed the basis of a new class of metamaterials with unique electromagnetic properties including unidirectional invisibility, lossless Talbot revivals, perfect coherent absorber-lasers, and the potential for non-reciprocal photonic devices. These properties are contingent on k'' , in that if additional gain and loss are added to the system an 'exceptional point' or 'phase change' is reached, beyond which the electromagnetic properties of a system significantly shift. In this presentation, we discuss coaxial resonators as new PT-symmetric plasmonic architectures. We consider a plasmonic coaxial structure consisting of a 60-nm-diameter Ag core surrounded by a 25-nm-thick silica ring, embedded in a semi-infinite Ag cladding. The dielectric ring is bisected through the coaxial mid-point to

include loss on one side (positive k'') and gain on the other (negative k''). First, we develop an analytic model to determine the dispersion and field-distribution of the first three guided modes of these 'bilateral' coaxes as the magnitude of k'' is increased from 0 to 0.05 to 0.1. Our results predict a coalescence of the zero- and first-order modes at an exceptional point, above which light is either confined to the loss half or gain half of the waveguide. Then, we extend these results to finite-length resonators that could serve a nanoscale coherent perfect absorber-lasers. Using both finite difference time domain (FDTD) simulations and a variational analytic model, we investigate the transmission and absorption spectra of 150-nm-long bilateral coaxial resonators. For $k''=0$, the resonators exhibit a resonance at a wavelength of 674nm. As the magnitude of k'' is increased, the resonator exhibits enhanced emission and line-width narrowing, indicating a transition to lasing. Interestingly, if the coaxial resonator is pumped coherently from both sides, the resonator's transmission is reduced by greater than an order of magnitude even when k'' is below the lasing threshold. This effect is reduced if the phase of one input is varied independently. The combination of phase sensitivity and pump intensity dependence renders these coaxial resonators as nanoscale optical modulators, characterized by tunable emission intensities and spatial field profiles.

2:30 PM - KK2.04

Electrically-Controlled Photonic Isolation

Artur Davoyan¹, Nader Engheta¹.

¹, , University of Pennsylvania, Philadelphia, Pennsylvania, USA.

Hide Abstract

Design of an optical isolator that transmits electromagnetic waves in one direction only is a problem of a practical importance: such device would allow building high-speed all-optical integrated circuits similar to their electronic counterparts. Recent progress with magneto-photonics has shown a promise for building compact and monolithically integrated optical isolators [1,2]. However, a number of fundamental and technological challenges exist. In particular, for the purpose of miniaturization and nanoscale integration it is important to create optical isolators smaller than the wavelength. Furthermore, functionality of optical signal handling critically depends on the ability to dynamically tune the optical signal transmission and on the possibility for electrically controlling optical signal propagation.

In this work we propose a concept for merging electronics with photonics at the nanoscale and suggest a subwavelength-cross-sectioned electrically-controlled optical isolator. In particular, we study a plasmonic nanowire, in which a direct electric current (DC current) flows. We demonstrate, analytically and numerically, that the magnetic field inside and outside the plasmonic nanowire, generated by this DC current, induces a magneto-optical activity in the wire and in the material surrounding the wire, and consequently directly affects the optical surface wave propagating along this wire. As we show the electric current and the corresponding magneto-optical activity break the symmetry in the plasmon propagation, and at certain frequencies one-way regimes of plasmon propagation emerge. We also find that the plasmon propagation can be tuned and controlled with the electric current.

We solve the problem both analytically and numerically, and classify possible regimes of wave propagation in such a geometry. Our analysis predicts that optical isolation is possible for realistic values of the direct electric current in the wire. Our work opens up new possibilities for the optical components and electro-optical devices.

[1] Z. Yu, G. Veronis, Z. Wang, and S. Fan, Phys. Rev. Lett. 100, 023902 (2008).

[2] L. Bi, J. Hu, P. Jiang, D.H. Kim, G.F. Dionne, L.C. Kimerling, and C.A. Ross, Nature Photon. 5, 758-762 (2011).

2:45 PM - KK2.05

Parity-Time Symmetric Plasmonic Metamaterials and Superlenses

Hadiseh Alaeian^{1,2}, Jennifer Dionne².

1, Electrical Engineering, Stanford University, Stanford, California, USA; 2, Material Science and Engineering, Stanford University, Stanford, California, USA.

Hide Abstract

Textbook conceptions of light-matter interactions have been redefined by two recent material advances - metamaterials and parity-time (PT) -symmetric materials. On the one hand, metamaterials have enabled control over both the electric and magnetic fields of light. This control allows the permittivity and permeability to be precisely tuned throughout positive, negative, and near-zero values. Metamaterials have enabled negative refraction, optical lensing below the diffraction limit of light and invisibility cloaking. On the other hand, PT-symmetric potentials have emerged as a new technique to control field distributions in loss and gain media, so that light propagation can be asymmetric and even unidirectional. In wavelength-scale optical devices, PT-symmetric potentials have enabled loss-induced optical transparency, lossless Talbot revivals and unidirectional invisibility. Combined with non-linear media, they have also been suggested for optical diodes, insulators, circulators, and perfect cavity absorber-lasers.

In this presentation, we introduce a new class of optical media - PT symmetric plasmonic metamaterials. These materials combine concepts from both metamaterials and PT-symmetric materials to enable nanoscale optical devices capable of both lossless and asymmetric light propagation. As a case study, we consider a prototype metamaterial composed of a periodically-stacked planar plasmonic waveguide, composed of alternating, nanoscale layers of silver (Ag) and titanium dioxide (TiO₂). This metamaterial is designed to behave as an isotropic, three-dimensional negative refractive index material at optical frequencies, with $n=-1$ at free-space wavelengths of 450nm. By subjecting the plasmonic modes to PT-symmetric optical potentials, we demonstrate the broad tunability of the band curvatures, band gaps and effective refractive indices of the material. Small but non-zero PT-symmetric potentials increase the transmission of the isotropic negative index metamaterial to unity. Larger potentials morph the material from isotropic to anisotropic and directional. In particular, double negative refraction, Bloch power oscillations, unidirectional invisibility, and reflection and transmission coefficients that are simultaneously equal to or greater than unity can all be achieved with increasing PT-symmetric potentials. We then use a dyadic Green's function formulation to calculate the generated image of a radiating dipole in the vicinity of the proposed PT-plasmonic slab. Our results indicate that PT-symmetric plasmonic metamaterials are a powerful foundation for designing isotropic, lossless and reflectionless sub-diffraction-limited Veselago lenses at ultraviolet and visible frequencies.

3:00 PM -

BREAK

Hide Abstract**3:30 PM - *KK2.06**

Plasmonic Mode Amplification Using Organic Semiconductor Gain Media in Nano-Confined Geometries

Deirdre O'Carroll¹, Sarah Goodman¹, Jesse Kohl¹.

¹, Rutgers University, Piscataway, New Jersey, USA.

Hide Abstract

Coupling of gain materials to metallic nanostructures and thin films offers an avenue for amplification of plasmonic modes in both confined and extended geometries. In the past decade, a deeply sub-wavelength analogue to the laser, using surface plasmons instead of photons, i.e., the SPASER, has been proposed and demonstrated. Additionally, propagating surface plasmon polaritons on extended metallic films have been amplified using gain media to achieve chip-scale propagation lengths. Here, we investigate amplification of resonant and propagating surface plasmon modes using organic conjugated polymer semiconductor gain media. These gain media are of interest because: (1) unlike laser dye molecules, they do not undergo concentration quenching in the solid-state and a very high chromophore density can be packed into the optical near-field of the metal structure; (2) they exhibit large gain cross-sections at blue and green wavelengths; (3) the oscillator strength and transition dipole orientation of the polymer gain medium can be manipulated by

controlling polymer chain orientation offering selective coupling or excitation of particular plasmonic modes. For resonant surface plasmon amplification we have fabricated gold nanorod-conjugated polymer core-shell nanoparticles through a miniemulsion synthesis process. Pulsed laser-induced photoluminescence from the core-shell nanoparticle dispersions shows a more distinct threshold in emitted intensity compared to polymer nanoparticles and dissolved polymer molecules. This is attributed to a resonant exchange of energy between in the polymer gain material and surface plasmons supported by the gold nanorods resulting in amplified emission from the hybrid nanostructure. Demonstrations of amplified surface plasmon polariton modes supported by conjugated polymer semiconductor-metal-insulator asymmetric planar waveguides at blue and green wavelengths will also be reported. Theoretical work has predicted increased surface plasmon polariton mode leakage by factors of up to 88 when the polymer undergoes stimulated emission and both gain and loss measurements on fabricated structures will be reported to support these findings.

4:00 PM - KK2.07

Mid-Infrared, Naturally Hyperbolic Metamaterials Based on Hexagonal Boron Nitride Nanostructures

Joshua D Caldwell¹, Andrey Kretinin², Yiguo Chen³, Vincenzo Giannini³, Yan Francescato³, Stefan A. Maier³, Konstantin Novoselov².

¹, Naval Research Laboratory, Washington, District of Columbia, USA; ², School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom; ³, The Blackett Laboratory, Imperial College - London, London, United Kingdom.

Hide Abstract

The term hyperbolic media pertains to a series of materials or layered structures that exhibit anisotropic optical constants, whereby at the same frequency the material exhibits negative and positive permittivities in orthogonal crystallographic orientations. Typical materials exhibit a closed spheroidal or ellipsoidal three-dimensional dispersion curve that naturally leads to a reduction in the photonic density of states at large wavevectors. However, in the case of hyperbolic materials, the three dimensional dispersion curve exists as a hyperboloid, which in principle leads to an infinite optical density of states as the wavevector is increased. Practically speaking, this means that the wavelength of light within such a material could be arbitrarily small, well beyond the Abbe diffraction limit and can lead to potential applications such as extremely efficient nanoscale absorbers and resonators, diffraction free-focusing (e.g. hyperlens), flat optics, and broadband, multifunctional nanophotonic devices.

In the visible and near-infrared spectral ranges, natural hyperbolic media do not exist, thus results such as the first hyperlens was achieved through the creation of alternating, sub-wavelength, multilayer stacks of plasmonic metals and dielectrics. However, in the mid-infrared and THz spectral ranges, some naturally occurring hyperbolic materials exist. One highly promising material is hexagonal boron nitride (hBN), a two-dimensional layered material (similar to graphite) that exhibits plasmonic-like optical response in one crystallographic axis, while in the other it responds like a high refractive index dielectric. Further, while metal-based plasmonic metamaterials are in many cases limited in their functionality due to the high optical losses they exhibit, hBN achieves the necessary negative permittivity through the stimulation of surface phonon polariton (SPhP) modes within the highly reflective Retherald band. In addition, as such SPhP modes can be supported in both the ordinary (6.2-7.3 μm) and extraordinary (12.1-12.8 μm) optical axes, two such bands exist, enabling the realization of low-loss, hyperbolic metamaterials that can be operational at two different frequencies depending on the incident angle of light.

Here we report on the demonstration of hBN-based, deeply sub-diffraction limit nanoscale resonator arrays. The nanostructure arrays consist of 100-1000 nm diameter cylindrical nanoparticles, fabricated from 60-350 nm thick hBN flakes. The nanostructures exhibit several resonances and the diameter, thickness and angular dependences of these modes will be discussed. Finite elements modeling of the electromagnetic near-fields and localized modes within these structures and the anisotropic optical response will also be discussed.

4:15 PM - KK2.08

Touching Gold Nanoparticle Chain Based Plasmonic Antenna Arrays and Optical Metamaterials

Zhongyang Li¹, Serkan Butun¹, Koray Aydin¹.

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Hide Abstract

The control of light-material interactions at the nanoscale requires optical elements with sizes much smaller than the wavelength of light. In recent years, tremendous amount of efforts have been devoted to the research of plasmonic nanostructures and optical metamaterials that enable drastic control and manipulation of light at such small scales. However, it is quite challenging to further reduce the size of resonant elements using conventional plasmonic nanostructures particularly at optical wavelengths. Here, we will describe novel plasmonic resonators that rely on the conducting plasmon mode of touching nanoparticle chains. We demonstrate that one can enable significant size reduction in the optical resonator design using nanoparticle chains when compared with widely used nanostripe antennas and U-shaped split-ring resonators. We employ full-field electromagnetic simulations to study the resonance behaviors of nanoparticle chain arrays. In comparison with the nanobar plasmonic antennas, nanoparticle chain based antenna with similar physical sizes operates at larger wavelengths opening route for deep subwavelength plasmonic resonators. Moreover, using nanoshell chain arrays, we demonstrate an optical resonator that is 10 times smaller than the resonance wavelength ($\lambda/10$). Similarly, nanoparticle based split-ring resonators provide significant size reduction that could be used for smaller metamaterial and metasurface building blocks. Designing nanoparticle based resonant elements is a promising route for achieving optical metamaterials with broader bandwidths, smoother resonance dispersion and lower optical losses.

4:30 PM - *KK2.09

Plasmonic-Waveguide Metamaterials at Visible and Ultraviolet Frequencies

Henri Lezec¹, Ting Xu^{1,2}, John M. Koutek^{1,2}, Kenneth J. Chau⁴, Amit K. Agrawal³.

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Hide Abstract

Predictions of exotic and potentially useful properties, such as a negative refractive index [1], have propelled the creation of materials with tailored electromagnetic responses under the form of metamaterials, artificial media structured on a deep-subwavelength scale [2]. Here, we focus on a novel class of three-dimensional (3D) metamaterials, based not on lithographically-patterned resonators, but on stacked, thin metal-dielectric plasmonic waveguides with smooth interfaces. Using this approach [3], we demonstrate a bulk metamaterial, based on Ag/TiO₂ waveguides, having a negative-index electromagnetic response in the ultraviolet [4]. A flat slab of this metamaterial, designed with an isotropic refractive index $n = -1$, can act as a 3D Veselago flat lens [1] capable of projecting into free-space, beyond the near field, the image of arbitrary two-dimensional objects. We also show that unidirectional transmission of visible light can be provided by an ultra-thin structure incorporating subwavelength diffraction gratings and a pseudo-hyperbolic metamaterial incorporating Ag/SiO₂ plasmonic waveguides engineered to display a sharp transmission window for incident electromagnetic waves having specific transverse spatial frequencies. Fabricated devices designed for operation at central wavelengths of 532nm and 633nm, respectively, display broadband, efficient asymmetric optical transmission with maximum contrast ratios exceeding 14dB. Finally, we report recent progress towards elucidating the anomalous radiation pressure response of plasmonic waveguide metamaterials.

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KK3: Poster Session

- Chair: Joshua Caldwell
- Chair: Linyou Cao
- Chair: Jeremy Munday
- Chair: Stephane Larouche
- Tuesday PM, April 22, 2014
- Marriott Marquis, Yerba Buena Level, Salons 8-9

8:00 PM - KK3.01

Broadband Terahertz Sensing on Spoof Plasmon Surface

Binghao Ng¹, Stephen Hanham², Norbert Klein², Minghui Hong³, Stefan Maier¹.

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Hide Abstract

Corrugated metallic surfaces which support strongly confined electromagnetic surface modes, called Spoof Plasmon Surfaces (SPSs), have been shown to be a viable platform for narrowband refractive index sensing at terahertz (THz) frequencies [1]. In this work, we extend the SPS to broadband sensing by implementing a broadband coupling scheme [2]. This scheme utilises the scattering of THz radiation off a sharp razor blade placed in the vicinity of the SPS to achieve the appropriate phase matching conditions to excite spoof plasmons on the SPS over a broad range of frequencies. The spoof plasmons can then be converted back into free-space propagating light by scattering off a second razor blade and collected by a detector. The use of a THz time-domain spectrometer in combination with the razor-blade coupling method allows us to extract the broadband spoof plasmon dispersion characteristics in a single measurement.

Owing to the highly confined nature of the spoof plasmons, the SPS is very sensitive to refractive index changes in its vicinity and any interaction between the spoof plasmon and its environment is reflected as a change in the spoof plasmon dispersion relation. We demonstrate the utility of this approach for sensing by measuring the changes in the spoof plasmon dispersion caused by a number of liquids placed on the SPS over the bandwidth 0.1 - 1.7 THz.

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[2] Williams, C. R., Andrews, S. R., Maier, S. A., Fernández-Domínguez, A. I., Martín-Moreno, L., & García-Vidal, F. J. (2008). Highly confined guiding of terahertz surface plasmon polaritons on structured metal surfaces. *Nat. Photonics*, 2, 175.

8:00 PM - KK3.02

Selective Excitation and Enhancement of Multipolar Resonances in Dielectric Nanoparticles

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Hide Abstract

At optical frequencies, magnetic dipole and higher order multipole transitions (e.g. electric quadrupole) are generally considered to be “forbidden” due to their vanishingly small matrix elements. As a result, the optical response of conventional materials is dominated by the electric dipole moment. However, the ability to engineer subwavelength elements with large multipolar resonances has enabled researchers to construct optical metamaterials which exhibit qualitatively new optical phenomena. The recent discovery of multipolar luminescent transitions in rare earth ions and inorganic quantum dots raises intriguing possibilities for exploiting atomic multipolar phenomena in nanomaterials. Methods to directly quantify and probe the

multipolar nature of both engineered and atomic optical resonances are critical to furthering our understanding of metamaterials. Here, we propose and theoretically demonstrate a method to selectively excite and enhance coupling to multipolar resonances using novel light sources.

Every multipole resonance exhibits a unique electromagnetic field distribution and associated radiation pattern. By measuring the radiation patterns of scattered or emitted light, researchers have quantified multipolar phenomena in metamaterial constituents and quantum emitters. Here, we apply these principles in reverse: by illuminating materials with an appropriately engineered light source, we show that one can selectively excite and enhance coupling to any desired multipole resonance. We illustrate this effect for a single dielectric nanoparticle (NP). Using Mie theory, we show that the NP exhibits a sequence of multipole resonances under plane wave illumination. We construct solutions for the response of a NP under arbitrary illumination conditions by superimposing the response of many plane waves. By studying the absorption profile of a NP under differing illumination conditions, we demonstrate the ability to select which multipole resonances are excited and to significantly enhance the power coupled into a desired resonance. We show how these illumination conditions can be mapped onto specific quantum mechanical selection rules. Finally, we describe ongoing efforts to experimentally construct multipole light sources using a variety of different techniques. This work enables a better fundamental understanding of light-matter interactions in metamaterials and lays the foundation for researchers to identify, quantify, and manipulate “forbidden” optical transitions in unconventional nanomaterials.

8:00 PM - KK3.03

Tunable Plasmonic Nanofocusing Using Template-Stripped Asymmetric Metallic Pyramids

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Hide Abstract

Subwavelength nanofocusing of light using sharp metallic nanostructures has gained a lot of interest owing to its potential applications in tip-enhanced spectroscopy and super-resolution imaging. Nanometer sized metallic tips can concentrate and enhance the local electric field by several orders of magnitude when coupled with their plasmonic resonances. However, reproducible cost-efficient and high throughput fabrication of such metallic tips has been a challenge. Furthermore, symmetrically-shaped tips require radially polarized or oblique-angled illumination for optimum field enhancement, demanding nanometric alignment tolerances. In this work we demonstrate a simple scheme for plasmonic nanofocusing of light with internally illuminated asymmetric template-stripped metallic pyramidal tips using linearly polarized light. Pyramids fabricated with asymmetric thickness on opposite faces facilitate the propagation of plasmons on one side using Kretschmann -like coupling while limiting it on the opposite thicker side. Plasmons traveling towards the tip converge at the apex of the pyramid, forming a very confined nanolight source. The asymmetry is necessary for these focusing effects since symmetric pyramids display destructive plasmon interference at the tip. Computer simulations confirm that internal illumination with linearly polarized light at normal incidence on these asymmetric pyramids will focus optical energy into nanoscale volumes. Far-field optical experiments demonstrate large field enhancements as well as angle-dependent spectral tuning of any reradiated light. Owing to low background light, high-throughput fabrication and facile excitation scheme, this method is expected to find applications in near-field probe microscopy and tip-enhanced spectroscopy.

8:00 PM -

KK3.04 TRANSFERRED TO KK8.10

Hide Abstract

8:00 PM - KK3.05

Plasmon-Enhanced Photoluminescence in Ag-Decorated ZnO/MgO Core-Shell Nanowires

Claire Elizabeth Marvinney¹, Daniel C Mayo¹, Ephraim S Bililign², James R McBride³, Richard R Mu⁴, Richard F Haglund^{1,5}.

¹, Interdisciplinary Materials Science Program, Vanderbilt University, Nashville, Tennessee, USA; ², Department of Physics, North Carolina State University, Raleigh, North Carolina, USA; ³, Department of Chemistry, Vanderbilt University, Nashville, Tennessee, USA; ⁴, Department of Physics, Fisk University, Nashville, Tennessee, USA; ⁵, Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee, USA.

Hide Abstract

With a direct band gap of 3.37 eV and exciton binding energy of 60 meV, zinc oxide (ZnO) is a promising material for optoelectronic devices. Room temperature photoluminescence (PL) spectra for ZnO show two primary emission bands: a sharply defined band-edge peak centered at 3.37 eV that is a result of exciton recombination, and a broad visible emission peak centered around 2.3 eV that is due to a superposition of donor-acceptor-pair recombinations of near conduction band electrons with deep holes in oxygen vacancies and interstitials. Although different growth, annealing, and doping conditions have been used to control the ZnO emission, one of the most effective methods for PL enhancement is the Purcell mechanism initiated through changes in the local environment.

We have demonstrated dramatic band-edge PL enhancement in ZnO nanowires coated with varying thicknesses of MgO. This enhancement is due to resonant Fabry-Perot cavity modes in the nanowires, and is much larger than can be accounted for from surface passivation of shallow ZnO defects. The opposing faces of the hexagonal nanowire form a three-fold symmetric resonant cavity, in which the resonant modes can be calculated using a standing-wave analysis that agrees closely with experimental results. Contrariwise, the visible luminescence is not significantly enhanced and does not follow the trend of enhanced PL observed for the band-edge decay.

Further enhancement of the band-edge PL occurs when the core-shell nanowires are decorated with Ag nanoparticles. Plasmon-exciton coupling results in a two-fold enhancement of the band-edge emission compared to the resonant cavity effects alone. An additional differential enhancement of the band-edge emission is observed for the first higher-order mode compared to the lowest-order mode, due to the asymmetrical nanowire geometries that support higher-order modes. The combination of the optical cavity effects and plasmonic enhancement establishes the nanoparticle-decorated core-shell architecture as an attractive approach to selectively enhance the band-edge emission of ZnO for near-UV optoelectronics.

8:00 PM - KK3.06

Synthesis of AlN by Reactive Ultraviolet Plasmonic Oxidation of Hydrazine

Siving Peng¹, Matthew T. Sheldon¹, Harry A. Atwater¹.

¹, Applied Physics, California Institute of Technology, Pasadena, California, USA.

Hide Abstract

We have observed ultraviolet surface plasmon-mediated oxidation of hydrazine on aluminum surfaces and the resulting growth of aluminum nitride films at ambient temperature. Conventional methods for growing aluminum nitride films use magnetron sputtering to generate reactive nitrogen ions with high kinetic energy via plasma ionization, which limits the crystalline quality of aluminum nitride films. For growing high quality aluminum nitride films, chemical vapor deposition is the commonly adopted method. But this method requires high temperatures greater than 900 K to dissociate strong nitrogen-containing chemical bonds in precursor molecules such as ammonia. To grow high quality aluminum nitride films at ambient temperature, we use ultraviolet surface plasmons to generate neutral atomic nitrogen from enhanced oxidation of hydrazine adsorbed on Al surfaces.

In order to resonantly excite ultraviolet surface plasmons, we fabricated a 1 cm x 1 cm aluminum grating using a combination of electron-beam and nano-imprint lithography. We designed the grating geometry to produce a 25x increase in the near-field intensity at 248 nm incident wavelength, using iterative FDTD simulations. We

experimentally characterized the UV and optical properties of the grating. We used a pulsed 10 W m^{-2} KrF laser operating at 248 nm to excite surface plasmons on the aluminum grating after a layer of hydrazine was cryogenically adsorbed to the Al surface at 77K. We used gas phase mass spectrometry to characterize the products from athermally decomposed hydrazine in low pressure vacuum at 10-6Torr. Our results indicate a >10 enhancement of the hydrazine oxidation rate on Al plasmonic nanostructures compared with control substrates. Atomic nitrogen generated by the ultraviolet plasmonic source can be combined with shuttered aluminum deposition from an effusion cell, enabling an atomic layer deposition process to grow aluminum nitride at low temperatures ($< 100 \text{ C}$). We will also report on investigation of epitaxial growth of GaN and InGaN films via this method and compositional and structural characterization of the films by XPS, X-ray diffraction and transmission electron microscopy will be discussed.

8:00 PM - KK3.07

Low-Stress SiNx Platform for Mid-Infrared Microphotonics

Pao Lin 1,2, Vivek Singh1, Lionel Kimerling1, Dawn Tan2 1, Anu Agarwal1.

1, , MIT, Cambridge, Massachusetts, USA; 2, , Singapore University of Technology and Design, Singapore, Singapore.

Hide Abstract

Implementation of mid-infrared (mid-IR) chip-scale microphotonic circuits is critical to advancing the science for applications such as (i) ultra-fast telecommunications that require wider bandwidth and (ii) integrated biochemical sensors which can finger-print using infrared absorption signatures. We experimentally demonstrate a sophisticated mid-IR microphotonics platform adopting engineered Si-rich and low-stress SiNx thin films where an extensive infrared transparency up to $\lambda = 8.5 \mu\text{m}$ is achieved. Because of the designed low-stress property, the SiNx deposition is able to reach a thickness $> 2 \mu\text{m}$ that significantly reduces mid-IR waveguide loss to less than 0.2 dB/cm. We show directional couplers functioning over a broad infrared spectrum, thus enabling monolithic mid-IR multiplexing schemes for integrated linear and nonlinear photonics leading to sophisticated label-free sensing technologies.

8:00 PM - KK3.08

Plasmonic-Electrical Effects of Metal Nanoparticles for Highly Efficient Organic Solar Cells

Wallace C.H. Choy1, Fengxian Xie1, Di Zhang1, Wei E.I. Sha1, Xinchen Li1, B. F. Ding1.

1, Department of Electrical & Electronic Engineering, the University of Hong Kong, Hong Kong, Hong Kong.

Hide Abstract

Optical effects of the plasmonic structures and materials effects of the metal nanomaterials have recently been individually studied for enhancing performances of organic solar cells (OSCs). In this work, differently, the effects of plasmonically induced carrier generation and enhanced carrier extraction of the carrier transport layer (i.e. plasmonic-electrical effects) in OSCs are investigated. We propose and demonstrate enhanced charge extraction in TiO₂ as a highly efficient electron transport layer by the incorporation of metal nanoparticles (NPs). While OSCs using pristine TiO₂ can only operate by UV activation ($< 400 \text{ nm}$, otherwise poor S-shape J-V characteristics are exhibited), efficient device performance is demonstrated by using Au NPs incorporated TiO₂, at a plasmonic wavelength (560-600 nm) far longer than the originally necessary UV light. By optimizing the amount of Au NPs doped into TiO₂, the performances of OSCs with various polymer active layers are enhanced and efficiency of 8.74% is reached [1]. In order to understand the fundamental physics, an integrated optical and electrical model (i.e. a multiphysics model), which takes into account hot carrier tunneling probability and extraction barrier between TiO₂ and active layers, is introduced here. From experimental and theoretical studies, we attribute the enhanced charge extraction under plasmonic wavelength illumination to the strong charge injection of plasmonically excited electrons from NPs into TiO₂. The mechanism favors better energy alignment at the TiO₂ interface which facilitates carrier transport in OSCs. Recently, we also find that the TiO₂-metal NPs composite can enhance the carrier accumulation which

can fill the trap states in TiO₂ and thus improve the electrical conduction of TiO₂ and thus improve the device performances of OSCs [2]. The work can contribute to new approaches and knowledge to utilize plasmonically electrical nanostructures in organic optoelectronic devices for enhancing device performances.

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8:00 PM - KK3.09

Photocurrent Enhancements of Organic Solar Cells by Thermally Evaporated Silver Nanoparticles

Inho Kim¹, Tyler Fleetham², Jian Li², Hyung Woo Choi², Terry Alfrod², Jea-Young Choi², Doo Seok Jeong¹, Taek Sung Lee¹, Wook Seong Lee¹, Kyeong-Seok Lee¹.

1, , Korea Institute of Science and Technology, Seoul, Republic of Korea; 2, , Arizona State University, Tempe, Arizona, USA.

Hide Abstract

Incorporation of metal nanoparticles such as Au and Ag into active layers of organic solar cells is one of promising light trapping approaches for enhancing optical absorptions and in turn, photocurrents. Localized surface plasmon resonance (LSPR) plays a key role in enhanced optical absorptions. The size of metal nanoparticles is one of key factors to strong light trapping. We demonstrate by numerical calculations that larger metal nanoparticles are more desirable for enhancing optical absorptions in active layers owing to stronger scattering in broad spectral ranges and less absorption losses. The size of thermally evaporated metal nanoparticles at room temperature can be enlarged by post heat treatment and surface modification of substrates. We deposited silver nanoparticles on ITO by varying nominal thicknesses from 1 nm to 4 nm. Post annealing was carried out to increase their size, and the average size in radius was found to 5 nm to 10 nm with increasing the nominal thicknesses. In efforts to increase the size of silver nanoparticles further, conductive polymer of low surface energy, PEDOT:PSS was introduced on ITO. Silver nanoparticles on PEDOT:PSS after annealing were dramatically increased by more than three times compared to those on ITO. Planar heterojunction solar cells based on ZnPc and fullerene were fabricated on PEDOT:PSS and ITO with incorporation of those metal nanoparticles, and photocurrents were measured under a standard condition. The photocurrents of the cells with the active layers on PEDOT:PSS were enhanced by 30 % when the annealed silver nanoparticles were introduced. In contrast, the silver nanoparticles on ITO without PEDOT:PSS did not lead to the photocurrent enhancements, and the slight decreases in the photocurrents were observed. The origin of the photocurrent enhancements with introducing the silver nanoparticles on PEDOT:PSS are discussed.

8:00 PM - KK3.10

Substrate Effect on the Near-Field Distribution and Scattering Spectra of a Single Crystalline Zinc Oxide Microsphere on Metallic Thin Film Over a Substrate

Huai-Yi Xie¹, Yia-Chung Chang¹.

1, Research Center for Applied Sciences, Academia Sinica, Taipei, Taiwan.

Hide Abstract

We have developed a spherical harmonics-based half-space Green's function (SHGF) approach for calculating light scattering from spherical objects on a multilayer substrate. We have applied this method to investigate the clustering effect on the ellipsometry spectra of glass substrates embedded with random distribution of Au nanoparticles and obtained useful structure information of these coupled nanoparticles.[1,2] Here, we use the SHGF approach to calculate near-field distribution of zinc oxide (ZnO) microsphere on a Au thin film over

glass substrate. For normal incidence, the axial symmetry allows us to reduce the number of spherical harmonics required for the calculation and saves computing time significantly. Our calculated results agree with Mie theory predictions for the case of an isolated sphere. Our approach allows us to examine the substrate effect, which can lead to a shift of whispering gallery mode (WGM) frequencies and significant change the near-field distribution for a ZnO microsphere. Furthermore, we investigate the dependence on the thickness of Au thin film over the SiO₂ substrate. Due to the strong coupling effect between the Au film and an isolated ZnO microsphere, we find that the near field distribution is very sensitive to the thickness of Au film when it is less than 50nm (while the diameter of ZnO microsphere is 1μm). The location of WGM modes have pronounced shifts in the long wavelength and strong near-field enhancement is observed. This useful information can help us investigate the biosensing capability of ZnO microsphere via microscopic imaging ellipsometry.

*Work Supported in part by the National Science Council of Taiwan under contract No. NSC101-2112-M-001-024-MY3.

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8:00 PM - KK3.11

Phase-Change Materials for Reversible Optical Tuning of Infrared Antenna Resonances

Ann-Katrin U Michel¹, Peter Zalden², Dmitry N Chigrin¹, Aaron Lindenberg², Thomas Taubner¹.

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Hide Abstract

The field of plasmonics is based on the capability of metallic nanoantennas to generate significantly enhanced and highly confined electromagnetic fields. The modification of nanoantenna material, geometry and substrate allows widely tuning their resonance frequency. We show a concept for reversible resonance tuning of aluminum nanorod arrays with defined geometry via variation of the refractive index n of an embedding medium based on phase-change materials (PCMs).

Recently, PCMs became very popular in the field of tunable plasmonics and metamaterials: transmission modulation of a planar gold metamaterial covered with gallium lanthanum sulphide [1], optical switching of asymmetric split ring slots in gold close to a Ge₂Sb₂Te₅ (GST-225) layer [2] and resonance tuning of gold nanodisks by slowly initiating the crystallization of GST-225 [3].

PCMs offer a huge contrast in n due to a phase transition from amorphous to crystalline state, which can be thermally triggered. Due to a negligibly small imaginary part of the dielectric function of both phases, resonance damping is avoided. Exemplary we used the two PCMs InSb and GST-326, which provide a huge contrast in ϵ_1 and a negligibly small ϵ_2 in the mid-infrared spectral range [4]. We present resonance tuning with a maximum shift of about 31% and a tuning figure of merit (FOM) of more than 3.6. Furthermore we will show reversible resonance tuning by applying single ultrafast optical pulses [5].

[1] Z. L. Sámsom, N. I. Zheludev, et al. Appl. Phys. Lett., 96, 143105 (2010).

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[5] A. U. Michel, P. Zalden, T. Taubner et al. to be submitted.

8:00 PM - KK3.12

Using Ink Nanodroplet Printing for Fabrication of Infrared Nanoantennas

Ann-Katrin U Michel¹, Patrick Galliker², Wilhelm Glaessner², Dimos Poulikakos², Thomas Taubner¹.

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Hide Abstract

Plasmonic nanoantennas allow the extreme enhancement of optical near-fields and the intense scattering of far-fields [1]. Due to this they can act e.g. as resonant structures for enhanced infrared absorption spectroscopy [2], as optical switches [3], for the manipulation of light [4] and as building block for metamaterial structures [5]. Due to their importance for the field of plasmonics and metamaterials, a fast, flexible and cost-efficient fabrication technique is crucial. Sophisticated fabrication methods like electron beam lithography or three dimensional direct laser writing allow the fabrication of a large variety of complex nanostructures, but also require multiple processing steps. Simpler fabrication techniques like nanosphere lithography or nanoimprint lithography underly restrictions regarding feasible geometries.

With direct printing of nanostructures by electrostatic autofocussing of ink nanodroplets a flexible, inexpensive, on-demand and scalable technique is realized [6]. Here, we show plasmonic nanoantennas, resonant in the infrared spectral range, fabricated with this technique. Their resonances are spectrally compared to nanoantennas fabricated with electron beam lithography.

Due to these results, NanoDrip printing based on the electrostatic nanodroplet autofocussing effect offers a great possibility for the fabrication of nanostructures with resonances in the infrared spectral range.

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- [5] C. M. Soukoulis, M. Wegener *Nat. Phot.* 5, 2011.
- [6] P. Galliker, D. Poulikakos et al. *Nat. Comm.* 3:890, 2012.

8:00 PM - KK3.13

Surface Plasmon Tsunami

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Hide Abstract

As surface plasmons (SPP) can be confined to small nanostructure sized areas - much smaller than the wavelength of the exciting free space photons - they are thought to combine the benefits of photonics and microelectronics, i.e. high speed and small dimensions, in future integrated devices. To take advantage of this feature it is necessary to control the propagation of SPPs. A recent approach is tailoring the SPPs effective refractive index using metamaterials or nanostructured dielectrics placed at the surface of the film carrying the SPPs [1, 2].

In this work we investigate the interaction of surface plasmons with a wedge shaped resist structure in the near field using phase resolved near field scanning optical microscopy. Gray-scale electron beam lithography is used to prepare a wedge to tailor the effective refractive index distribution for an incident surface plasmon wave propagating on a gold film. Within a distance of 10 μm the thickness of the wedge changes from 0 nm to 250 nm. This particular profile was chosen to create a continuously increasing refractive index ranging from $n = 1$ to $n = 1.7$ for a surface plasmon excited at 1.95 eV. The surface plasmon is excited via attenuated total reflection on the gold film using a prism. To isolate the propagating surface plasmon from the excitation area a chromium layer was prepared underneath the gold film at the position of the resist structure. The surface plasmon propagates along the gold surface towards the wedge, where it is exposed to the increasing effective refractive index. This increasing refractive index leads to a change in the surface plasmon's dispersion relation. Similar to Tsunami waves entering shallow water, the plasmon's wave vector increases, its group velocity decreases and the field amplitude rises. Our near field measurements show an increase in field amplitude at 2 μm from the beginning of the wedge. Electromagnetic simulations are in good agreement with our experimental results.

We gratefully acknowledge financial support of the Deutsche Forschungsgemeinschaft via the Graduiertenkolleg 1286.

- [1] P. A. Huidobro et al., *Nano Letters*, vol. 10, issue 6, pp. 1985-1990 (2010)
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8:00 PM - KK3.15

Freestanding Nanomembranes: From Surface-Engineered 3D Fabrication to Catalytic and Plasmonic Nanodevices

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Hide Abstract

Slender structures in nature, for example, from leaves, petals to proteins and DNA, usually tend to fold or roll into diverse three-dimensional configurations. Beyond changing the size and form, folding and rolling can transform relatively simple structures into complex shapes with new and distinct properties. Mimicking these naturally occurring assembly processes by thinning, shaping, and rolling artificial free sheets can be implemented to create novel 3D fine structures and devices at small scales. Facing the demand of deterministic self-assembly and precise control of driving forces and energy minimization at the nanoscale, we utilize a rapid thermal process for the manipulation of surface tension of metallic nanodroplets at high temperature. We demonstrate that the surface tension of self-assembled metallic nanodroplets can be applied to overcome the deformation barriers of freestanding inorganic nanomembranes and produce extremely nanoscale rolled-up tubes, which is consistent with our theoretical predication. Aggregated nanoparticles were subsequently integrated on the surface of rolled-up nanotubes. The generalization and versatility of this approach were demonstrated by a series of nanoparticle (Ag, Au, Pt) decorated oxide nanotubes (TiO₂, Al₂O₃, SiO, SiO₂) with tunable geometric parameters.

Such surface-engineered 3D nanofabrication technology spans across different scientific fields ranging from chemical powered nanomachines to plasmonic nanosensors. The small tubes embedded with Pt nanoparticles can work as self-propelled catalytic nanoengines and exhibit a dramatic acceleration in speed compared to those with smooth Pt surface due to enhanced mass transfer and larger catalytic surface area. Furthermore, such hybrid nanostructures were used as 3D plasmonic architecture that couples a dense plasmonic hot-spot array in a dielectric nanotube which exhibit high SERS enhancement. High-quality Raman spectra and mapping with enhanced intensity were obtained on Ag nanoparticles decorated SiO/TiO₂ nanotubes. Our methodology offers a great opportunity for mechanical deformation, such as folding, bending, buckling, and zipping, in nanoscale self-assembly, and may enable solid nanomembranes becoming an essential building blocks in flexible electronics, and lab-on-a-chip micro/nano-electromechanical systems (MEMS/NEMS).

8:00 PM - KK3.17

Engineering Plasmonic Nanostructures for Artificial Color Generation

Yanhui Zhao¹, Guangyuan Si², Tony Jun Huang¹.

¹, Engineering Science and Mechanics, Penn State University, State College, Pennsylvania, USA; ², College of Information Science and Engineering, Northeastern University, Shenyang, Liaoning, China.

Hide Abstract

Plasmonics, focusing on metal-light interactions at nanoscale, is benefiting from the advance of the nanotechnology and quickly becoming one of the most important research branches of optics. Its promising future has been well recognized through various plasmonic-based devices or elements that can achieve super resolution, invisible cloaking, plasmonic lasing, active plasmonic switch, and plasmonic computing, etc. Among those applications, the possibility of engineering artificial colors using various plasmonic nanostructures has drawn wide research interests. The significance of using plasmonic based color filters is that they can help to shrink down the size of single color pixel to micro or even sub-micro level, as compared with conventional pixel sizes that range from tens of microns to hundreds of microns. Those reductions at

single pixel size will allow more pixel numbers available within the same confined area, leading to significant improvement on display resolutions in accordance with the development of driving circuit. We demonstrated plasmonic color filter that works in transmission mode. The color filter is achieved through plasmonic resonance of engineered annular aperture arrays (AAA) and patterned nanorod arrays with certain wavelengths in a broadband incident light source. Through fine-tuning the size of unit cells in each array, plasmonic resonance can be adjusted in a continuous way, leading to different color generated visible to human eyes.

2014-04-23

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- Linyou Cao, North Carolina State University
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KK4/II5: Joint Session: Optics of Graphene and 2D Materials

- Chair: Koray Aydin
- Chair: Linyou Cao
- Chair: Frank Koppens
- Wednesday AM, April 23, 2014
- Moscone West, Level 3, Room 3006

8:30 AM - *KK4.01/II5.01

2D Materials for Active Control of Plasmons and Light-matter Interactions

Frank Koppens.

1, , ICFO - The Institute of Photonic Sciences, Castelldefels, Spain.

[Hide Abstract](#)

Optics and opto-electronics of graphene is one of most vibrant, rapidly developing and exciting areas which has already led to some commercial applications. Rather than being just another new photonic material, it combines a wide palette of unique aspects which promise breakthroughs in several outstanding problems of nanophotonics and optoelectronics, including broadband photodetection and sensing, on-chip manipulation of nanoscale optical fields and lasing.

In this talk, the most recent developments of graphene nano-photonics, plasmonics and photoconversion for near-infrared and infrared frequencies are being reviewed. Strong interactions between graphene and nanoscale light-emitters are actively controlled and detected by tuning graphene from an absorbing to plasmonic material. Graphene plasmons, which allow for strong confinement of optical fields are visualized in

real space and gate-tunability and long propagation lengths are demonstrated by employing high mobility graphene.

9:00 AM - KK4.02/II5.02

Phonon Polariton Coupling of Monolayer Boron Nitride and Graphene

Victor Brar^{1,3}, Min Seok Jang², Seyoon Kim¹, Michelle Sherrott¹, Laura Kim¹, Josue Lopez¹, Mansoo Choi⁴, Harry A Atwater^{1,3}.

¹, Caltech - Applied Physics, Pasadena, California, USA; ², Seol National University, Seol, Republic of Korea; ³, Kavli Nanoscience Institute, Caltech, Pasadena, California, USA; ⁴, Global Frontier Center for Multiscale Energy Systems, Seoul National University, Seoul, Republic of Korea.

Hide Abstract

The 2D nature of graphene, along with its novel electronic structure, makes it an intriguing platform to study propagating surface plasmons. Behaving as an extraordinarily thin waveguide, graphene has been recently shown to support electronically tunable, Mid-IR plasmons with optical mode volumes that are 10⁷ times smaller than freespace, and plasmon wavelengths more than 100 times shorter. In addition to these unique effects, the extreme thinness of a monolayer graphene sheet make the plasmonic properties strongly dependent on the dielectric properties of the surrounding media. In this talk we show that the large optical confinement properties of monolayer graphene allow for the plasmonic dispersion relations to be strongly altered by the nearby optically active excitations, such as phonons or excitons. We will demonstrate, experimentally, that the phonons of just a single, underlying boron nitride (BN) sheet can be used to create new surface phonon plasmon polariton modes (SPPPs) in graphene. By studying the wavelength and doping dependence of these modes, we map out their dispersion relation and observe anti-crossing behavior between the graphene plasmon and this new SPPP mode. We further show that the high quality factor of the BN optical phonon at 170 meV leads to epsilon near zero (ENZ) behavior in the SPPP mode as the wavelength varies from 160 to 600 nm. These experimental observations are compared to a theoretical model that has been developed to explain optically active graphene devices, and we find good agreement.

9:15 AM - KK4.03/II5.03

Resonant Enhancement of Optical Absorption in Graphene Nanoresonators

Michelle C. Sherrott¹, Victor W. Brar^{1,2}, Min Seok Jang^{1,3}, Mansoo Choi³, Harry A. Atwater^{1,2}.

¹, Thomas J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, California, USA; ², Kavli Nanoscience Institute, California Institute of Technology, Pasadena, California, USA; ³, Global Frontier Center for Multiscale Energy Systems, Seoul National University, Seoul, Republic of Korea.

Hide Abstract

We report here results of simulations and experiments demonstrating a resonant enhancement of optical absorption in graphene nanoresonators. Theoretical predictions for 'perfect' two-dimensional absorbers have shown that, in principle, by carefully tuning of the geometry of graphene ribbons on a $\lambda/4n$ thickness dielectric membrane with a metallic back reflector, the transmission and reflection coefficients may be nulled, resulting in 100% absorption of light in the graphene at its optical resonance^[1]. The plasmonic resonance of a graphene nanoribbon is determined by the ribbon width and its charge carrier density, wherein incident light is strongly localized in half wavelength resonant modes of the ribbon. At this resonant wavelength, we can tune the reflection coefficient to zero by selecting a membrane of thickness $\lambda/4n$ so that infrared radiation reflected from the top surface is perfectly out of phase with that reflected from the back metal surface. Transmission is blocked by using an opaque metal layer on the back of the structure. The combination of these three factors results in resonant infrared absorption enhancement in graphene nanoribbon resonators.

Using finite element electromagnetic calculations we optimized our design to achieve a theoretical 100% absorption. We also fabricated a resonant interference absorber structure with graphene nanoresonators of

varying width on a 1 μ m thick Si₃N₄ membrane with a 100nm thick gold back-reflector. Broadband reflectivity measurements were obtained using Fourier transform infrared spectroscopy. Our current results have demonstrated 17.6% light absorption at 1340cm⁻¹.

We extend this mechanism of enhanced light absorption to a broadband absorption by layering multiple $\lambda/4n$ dielectrics beneath the graphene resonators, analogous to a traditional antireflection coating. By selecting materials and layer thicknesses to tune the accumulated phase upon reflection and path length traveled by the light, we can achieve resonant interference at the multilayer stack top surface for a broad range of wavelengths [2]. As previously, an opaque metal layer on the back surface blocks transmission. Finally, patterned graphene nanoribbons of different widths tuned to their resonant frequency form the basis of achieving broadband perfect absorption. We will also discuss extensions of total optical absorption to light-trapping techniques in other 2D materials such as direct bandgap semiconductors MoSe₂ and MoS₂, which have potential as ultra-thin and lightweight optoelectronic devices and solar cells.

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9:30 AM - *KK4.04/II5.04

Nanophotonics with SiC Surface Phonon Polaritons and Graphene Plasmons

Rainer Hillenbrand 1, 2.

1, , CIC nanoGUNE, San Sebastian, Spain; 2, , Ikerbasque, Bilbao, Spain.

Hide Abstract

Losses in metal-based plasmonic systems currently trigger the search for novel materials supporting low-loss surface polaritons. Surface phonon polaritons (SPhPs) on SiC and plasmons in graphene are two promising candidates.

In this talk we will describe near-field microscopy studies of phonon-resonant near-field interactions [1] and real-space imaging of propagating SPhPs [2,3] and graphene plasmons [4,5]. We visualize and measure the most fundamental properties such as the polariton wavelength and propagation length, and most intriguingly, how near fields can be electrically controlled by gate-tuning of graphene plasmons.

We also apply near-field microscopy to study the reflection of graphene plasmons at grain boundaries in CVD graphene [6] and at nanoscale gaps in graphene [7], and how structuring of the sample surface can be used for excitation and wavefront engineering of SPhPs [3], graphene plasmons [8] and their hybrids.

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10:00 AM -

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10:30 AM - *KK4.05/II5.05

Active Low-Loss Metasurfaces and Their Applications

Gennady Shvets 1.

1, Physics, The University of Texas at Austin, Austin, Texas, USA.

Hide Abstract

Metamaterials and their two-dimensional cousins, meta-surfaces, represent a remarkably versatile platform for light manipulation, biological and chemical sensing, and nonlinear optics. Mid-infrared part of the spectrum is particularly ripe for metamaterial applications because of its importance to molecular spectroscopy/fingerprinting, thermal imaging, and novel optical tools development. They can be easily functionalized with atomic and molecular monolayers, such as graphene or proteins. The resulting hybrid meta-surfaces can then be used to either develop agile optical structures (lenses, modulators, absorbers), or to perform ultra-sensitive spectroscopic characterization of the minute amounts of matter.

In the first half of my talk, I will provide a brief introduction to metamaterials and describe their applications to the development of active optical elements in the infrared based on graphene-functionalized metasurfaces and graphene spectroscopy. I will describe how electrically gated single-layer graphene can be used to inductively tune the infrared optical response of Fano-resonant meta-surfaces. Several implementations will be introduced: graphene of the meta-surface, graphene directly under the meta-surface, and graphene separated by a thin spacer from the meta-surface. Experimental realizations of infrared amplitude and phase modulators based on hybrid-functionalized meta-surfaces will be presented. We will demonstrate how the spectral shifts of metamaterials resonances introduced by the graphene can be utilized to extract graphene's electronic properties such as the complex-valued resistivity.

In the second half of the talk, I will describe how the most severe limitation of plasmonic metamaterials, their high Ohmic loss, can be overcome by using all-dielectric metamaterials. Experimentally-realized examples of Fano-resonant optical meta-surfaces supporting optical resonances with quality factors that are almost an order of magnitude sharper than those supported by their plasmonic counterparts will be presented. These silicon-based structures are shown to be planar chiral, opening exciting possibilities for efficient ultra-thin circular polarizers and narrow-band thermal emitters of circularly polarized radiation.

11:00 AM - KK4.06/II5.06

Graphene Based Tunable Nanoantenna Devices

Semih Cakmakyapan^{1,2}, Levent Sahin², Francesco Pierini², Ekmel Ozbay^{1,2,3}

¹, Physics, Bilkent University, Ankara, Turkey; ², Nanotechnology Research Center, Ankara, Turkey; ³, Electrical and Electronics Engineering, Bilkent University, Ankara, Turkey.

Hide Abstract

Graphene has been an attractive 2D material in recent years owing to its interesting electrical and mechanical properties. Strong light-matter interactions make graphene favorable for new plasmonic applications due to the field enhancement and confinement. Numerous applications based on metamaterials [1], photodetectors [2], photovoltaics [3], and nanoantennas [4], where electronics and plasmonics are combined in nanocircuitry, have been shown. The optical conductivity of graphene depends on the sheet carrier concentration of the graphene layer. Since high frequency interband transitions in graphene can be exploited through electrical gating [5], the plasmon resonance of graphene-hybrid structures such as nanoantennas can be modulated by applying a gate voltage [1, 4].

We report the modulation of the optical response for split ring resonator (SRR) arrays and bowtie nanoantennas fabricated on graphene. Strong localized fields on nanoantenna based structures couple to the incident field through a resonant process, causing a strong localization of electromagnetic waves. These antennas enhance the incident field, and therefore increase the interaction between light and graphene. We have shown the design, fabrication, and measurement of devices comprising a split ring resonator (SRR) arrays and bowtie nanoantennas on graphene. We obtained gate voltage dependent resonance broadening and tuning of these structures by utilizing a transistor-like graphene device. We obtained a frequency shift and electrical damping owing to the tunable carrier concentration of graphene, which consequently modulates its optical conductivity.

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11:15 AM - *KK4.07/II5.07

Graphene Enabled Hybrid Plasmonics and Sensors

Ertugrul Cubukcu¹, Jason C Reed¹, Alexander Y Zhu¹, Fei Yi¹.

¹, Material Science and Engineering, University of Pennsylvania, Philadelphia, Pennsylvania, USA; ², Electrical and Systems Engineering, University of Pennsylvania, Philadelphia, Pennsylvania, USA.

Hide Abstract

Graphene as a monolayer of carbon atoms in a honeycomb lattice has attracted significant interest for its unique optical, electrical, mechanical properties for a range of applications. Metal based plasmonic devices and sensors can capitalize on graphene for unprecedented new functionalities if synergistically integrated. One such intriguing property of graphene that plasmonics can benefit from is its impermeability to gas molecules even as small as a single He atom. Capitalizing on this we demonstrated that nanoantennas made of silver, the ideal plasmonic material that tends to oxidize due to sulfur containing ambient gases, can be effectively passivated with a monolayer graphene. Due to its atomic thickness, graphene also does not perturb nanoantenna near-fields significantly maintaining the full potential of silver nanoantennas in sensing applications.

Graphene is also a very promising material as a bioactive layer due to its ability to effectively adsorb biomolecules through pi-pi stacking interactions. If graphene is used a monolayer functionalization layer, lengthy sensor surface modifications steps will not be necessary. We studied the binding affinities between several different proteins and graphene and found that adsorption can be as strong as that of a specifically binding antigen-antibody pair.

We will also discuss a new multimodal opto-electro-mechanical device that synergistically combines a graphene field effect transistor based nanoelectronic sensor and a nanoantenna based photonic sensor on a mechanical resonator sensor. This hybrid approach combining electrochemical, refractive index, and mass sensing functions on the same device footprint opens up new directions in nano-bio-sensors with unprecedented features. This proof-of-concept nanosensor experimentally achieves sub-picomolar label-free detection limits across all three independent sensing modes, and possesses a dynamic range ~2-3 orders of magnitude larger than that of any single mode nanosensor.

11:45 AM - KK4.08/II5.08

Graphene-Antenna for Tunable Photodetector and Transistor

Zheyu Fang^{1,2}, Peter Nordlander¹, Naomi Halas¹, Javier Garcia de Abajo³, Ziwei Li².

¹, Rice University, Houston, Texas, USA; ², Peking University, Beijing, China; ³, ICFO, Barcelona, Spain.

Hide Abstract

Nanoscale antennas sandwiched between two graphene monolayers yield a photodetector that efficiently converts visible and near-infrared photons into electrons with an 800% enhancement of the photocurrent relative to the antennaless graphene device [1]. The antenna contributes to the photocurrent in two ways: by the transfer of hot electrons generated in the antenna structure upon plasmon decay [2], as well as by direct plasmon-enhanced excitation of intrinsic graphene electrons due to the antenna near field. This results in a graphene-based photodetector achieving up to 20% internal quantum efficiency in the visible and near-infrared regions of the spectrum. This device can serve as a model for merging the light-harvesting characteristics of optical frequency antennas with the highly attractive transport properties of graphene in new optoelectronic devices [3].

References

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- (3) Z. Fang, S. Thongrattanasiri, A. Schlather, et. al. *ACS Nano* 7, 2388, 2013.

KK5: Resonant Optics for Energy and Imaging

- Chair: Joshua Caldwell
- Chair: Stephane Larouche
- Wednesday PM, April 23, 2014
- Moscone West, Level 3, Room 3008

1:30 PM - KK5.01

Programmable Photoelectrochemical Water Splitting Based on CdS-Au Multi-Segmented Nanorod Arrays

Xiaotian Wang¹, Chi Hao Liow¹, Xiaodong Chen¹, Shuzhou Li¹.

¹, , Nanyang Technological University, Singaore, Singapore.

Hide Abstract

The technology of semiconductor-based photoelectrochemical water splitting to produce hydrogen using solar energy has been considered as one of the most important approaches to solving the world energy crisis. Introducing plasmonic-metal nanoparticles into a semiconductor photoanode has been explored to improve the photocatalytic activity for water splitting because they effectively enhance the light absorption and promote the separation of photo-generated electron-hole pairs in a semiconductor. However, the photocatalytic efficiencies by decorating metallic nanoparticles on semiconductor are not modulatable and programmable because of the complex and interrelated interactions in composite. We demonstrate the feasibility of using SPR-based CdS-Au multi-segmented NRAs as photoanodes for programmable PEC water splitting. The photocatalytic activity can be linearly modulated by the number of CdS-Au segments in a NR. The orderly arrangements of plasmonic-metal segments in the composite photocatalysts play a critical role in realizing the programmable PEC water splitting. Significantly, under the simulated AM 1.5G illumination, the CdS-Au multi-segmented NRAs exhibited excellent PEC properties with a photocurrent of 10.5 mA/cm² at 0 V (vs. Ag/AgCl), making them competent as photoanode for H₂ production using solar energy.

1:45 PM - KK5.02

Photothermal Induced Resonance: A New Method to Characterize Plasmonic Materials and the Surrounding Dielectric in the Near-Field

Andrea Centrone¹.

¹, , NIST, Gaithersburg, Maryland, USA.

Hide Abstract

PTIR is a new technique that combines the chemical specificity of IR spectroscopy with the lateral resolution of Atomic Force Microscopy (AFM). PTIR uses a tunable pulsed laser for sample illumination and an AFM tip in contact mode to measure the instantaneous sample thermal expansion induced by light absorption. The AFM tip acts as a spatial filter to extract the local spectral information (IR) with a lateral resolution several times smaller than the diffraction limit of IR wavelengths.

The recent development of plasmonic nanostructures with resonances in the mid-IR has generated considerable interest in Surface-Enhanced Infrared Absorption (SEIRA) Spectroscopy due to chemical detection limits in the zeptomolar range. SEIRA “hot spot” engineering is the subject of intense research mostly relying on theoretical modeling, but the diffraction of the long IR wavelengths (2-16 μm) has prevented direct quantification of SEIRA enhancement in the near field.

In this work we demonstrate the utility of the PTIR technique for characterizing and engineering plasmonic materials. For example, PTIR maps allow imaging near-field SEIRA hot-spots of asymmetric split ring

resonators (A-SRRs) coated with a polymer film and PTIR spectra allow quantifying, for the first time, SEIRA enhancement factors at the nanoscale. In addition to characterize the surrounding dielectric, PTIR maps allow visualizing bright and dark modes in the gold A-SRRs with nanoscale resolution. Furthermore, by correlating near-field SEIRA enhancement factors obtained from PTIR spectra with the quality factors measured in far-field FTIR spectra, we were able to engineer ASRR arrays with improved sensitivity. Finally, PTIR spectra and images on plasmonic materials revealed strong near-field asymmetries as a function of the excitation condition; something that could help engineering non-reciprocal plasmonic devices embedded in non-linear dielectrics.

2:00 PM - KK5.03

Reconciling Theory and Experiment in Monochromated Electron Energy-Loss Spectroscopy of Plasmon Modes in Individual Nanostructures

Andrew Herzing¹, Xiuli Zhou², Anton Hoerl³, Andreas Truegler³, Ulrich Hohenester³, Theodore Norris².

¹, Materials Measurement Science Division, National Institute of Standards and Technology, Gaithersburg, Maryland, USA; ², Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, Michigan, USA; ³, Institut für Physik, Karl-Franzens-Universität Graz, Graz, Austria.

Hide Abstract

The optical properties of nanostructures are often dominated by the surface plasmon response they exhibit in response to an external electromagnetic field. In turn, this response is highly dependent upon the composition and geometry of the material. To adequately control the resulting optical properties, a solid understanding of the relationships between structure, composition, and optical response is required. Monochromated electron energy-loss spectroscopy (EELS) in the scanning transmission electron microscope (STEM) offers a route to characterizing these resonance modes in individual nanostructures; combining spatial resolution on the order of a single nanometer and energy resolution near 150 meV.

Herein, we report our use of spatially-resolved, monochromated STEM-EELS to characterize the plasmonic response in silver nanowires that were 30 nm and 100 nm in diameter. Spectral shifts were observed in the plasmon excitation depending on the position of the beam with respect to the tip of the nanowire. In addition, hyperspectral EELS imaging was employed to map the resonant modes along the nanowire surface, within the bulk, and extending into the surrounding vacuum. This technique revealed periodic maxima in the loss probability near the side surface of the nanowires. The maxima were localized near the surface of the wire but extended a few nanometers into the surrounding vacuum. The intensity of these features was consistently asymmetric such that maxima on one side of the nanowire were more intense than those on the opposite side of the wire.

These experimental results were interpreted with the aid of three theoretical models: analytical models for energy-loss in infinite nano-cylinders and nanospheres, numerical simulations of optical excitation, and numerical calculation of electron energy-loss using a boundary element method. The models were found to faithfully reproduce many of our experimental observations. The strengths and weaknesses of each will be discussed along with aspects of the experimental work which cause the measured spectra to deviate from theory.

2:15 PM - KK5.04

Extending the Working Range of the Optical Transformer Probe

Aleksandr Polyakov¹, Mauro Melli¹, Giuseppe Cantarella¹, Adam Schwartzberg¹, Alexander Weber-Bargioni¹, P. James Schuck¹, Stefano Cabritini¹.

¹, LBNL, Berkeley, California, USA.

Hide Abstract

The introduction of adiabatic nanofocusing [1] in plasmonic sharp tips has generated a large interest in producing probes that can provide a superior spatial resolution and, furthermore, allow for a time-resolved

optical study [2]. A variation of this geometry has been successfully realized in an optical transformer (OT), a device that efficiently couples far field radiation to the Surface Plasmon Polariton (SPP) waves [3-4]. The OT geometry consists of a dielectric pyramid, with two opposite sides covered by a thin layer of a plasmonic material, such as a noble metal. This structure is illuminated from the base: as light is converted to the SPP waves, they undergo an adiabatic compression in the VIS and IR wavelength range producing a strong hot spot at the apex. By opening a small feed gap at the apex, this structure becomes an efficient coupler for locally delivering the radiation to the sample as well as collecting the resulting signal [3]. However, fabricating these structures has so far involved time-consuming and expensive processes. We now have successfully produced a high fidelity OT on an optical fiber tip via nanoimprint lithography. This new fabrication method has the advantage of fast production time and higher yield while maintaining a consistent spectral response.

The OT geometry provides a special type of SPP coupling mechanism - it contains both resonant as well as non-resonant high field enhancement spectral regions, making it especially useful for spectroscopy applications. However, the working distance is limited to within a few nm of the apex of the tip. In this work, we present a new concept for extending the working range of up to 100 nm by incorporating a specially designed nanoresonator into the sample (similar to injecting plasmonic nanoparticles in cells [5]). The OT extended range probe retains the sub-diffraction spatial resolution and strong field enhancement without the use of a complex optical system, and is of particular use for high resolution subsurface imaging applications.

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2:30 PM -

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3:00 PM - *KK5.05

Extreme Energy Concentration in Multi-Scale and Multi-Material Plasmon Resonant Systems

[Pieter G Kik](#).

1, CREOL, The College of Optics and Photonics, UCF-CREOL, Orlando, Florida, USA.

[Hide Abstract](#)

Several current applications in plasmonics make use of extreme energy concentration in order to achieve high temperatures in nanoscale volumes, high nonlinear optical response, or simply sufficiently high linear response. These include the use of surface plasmons for vapor generation, targeted tissue modification, and surface enhanced Raman scattering. In all these cases one needs to design structures that can provide large field enhancement factors while remaining thermally and optically stable. This talk discusses two general classes of plasmonic systems that meet these requirements by using structures composed of dissimilar metals in thermodynamically stable configurations. First it is shown that Au nanoparticle resonances on oxide coated metal substrates can provide extreme field concentration while experimentally withstanding irradiation at their plasmon resonance frequency under continuous wave irradiation with 100 W/mm². Second, a multi-material analog of what has been called the plasmonic nanolens is discussed. In such nanolens structures coupling of surface plasmons on adjacent metal nanospheres with significantly different diameter leads to effective multiplication of field enhancement factors. Thus far, research has focused on systems containing only a single material, and it is non-trivial to extend this to more materials. Here it is demonstrated that few-particle aggregates containing Au and Ag nanospheres of sizes in the 5 - 100 nm size range with well-chosen particle sizes and spacings can provide multiplicative electric field enhancement. These effects lead to an effective Au absorption efficiency that exceeds the single particle absorption efficiency by two orders of

magnitude, enabling extremely localized heat deposition or signal generation in a system that is composed of elements close to their equilibrium thermodynamic shape.

3:30 PM - KK5.06

Nanoscale Optical Tomography with Cathodoluminescence Spectroscopy

Ashwin C Atre1, Benjamin Brenny2, Toon Coenen2, Albert Polman2, Jennifer Dionne1.

1, , Stanford University, Stanford, California, USA; 2, , FOM Institute AMOLF, Amsterdam, Netherlands.

Hide Abstract

Visualizing light-matter interactions in three-dimensions with nanometer-scale spatial and spectral resolution is challenging, as most experimental techniques are limited to gathering two-dimensional (2D) information. Recently, the first experimental three-dimensional (3D) maps of optical modes were obtained by combining electron-energy loss spectroscopy (EELS), a 2D imaging technique, with tomographic reconstruction methods. Here, we introduce a complementary technique for nanoscale interrogation of optical properties in three dimensions: cathodoluminescence (CL) tomography. While both EELS and CL rely on electron-beam excitation of a sample, they are fundamentally distinct in their detection mechanisms and interpretation. In particular, CL spectroscopy detects photons emitted by a sample rather than the energy lost by electrons transmitted through the sample. It is therefore sensitive to all radiative mechanisms of the system, including radiative decay of plasmon modes as well as fluorescence from electron-hole pair recombination. To demonstrate this new tomographic technique, we consider a 3D metal-dielectric crescent, or nanocup, composed of a subwavelength dielectric core coated with a tapered metallic shell. We first experimentally obtain a series of CL maps of the nanostructure at various orientations. Next, the simple and established method of filtered backprojection is used to reconstruct the CL intensity. The result is the first 3D map of radiative optical properties with nanometer-scale spatial and spectral resolution. By plotting spectra of individual volumetric pixels, we are able to locate regions of efficient CL excitation in three-dimensions spanning the entire visible spectrum, with contributions from radiative decay of plasmons as well as incoherent material fluorescence. Furthermore, we correlate the experimental signal with the local density of optical states in particular regions of the reconstruction. While we have demonstrated CL tomography by reconstructing a metal-dielectric nanostructure, the technique can be applied to almost any inorganic or organic materials system to achieve high-resolution, three-dimensional visualization of light-matter interactions.

3:45 PM - KK5.07

Plasmoelectric Potentials: Tuning the Optical Absorption of Plasmonic Nanoparticles by Optical and Electrical Pumping

Ana Brown1, Matthew Sheldon1, Harry Atwater1.

1, , Caltech, Pasadena, California, USA.

Hide Abstract

We report modified optical absorption in plasmonic nanoparticles i)under electrical bias and ii)when optically excited by monochromatic radiation on the blue or red side of the plasmon resonance frequency. Specifically, we have performed optical pump-probe experiments to excite and probe 'plasmoelectric' potentials, quantitatively mapping the dependence on incident power and wavelength of illumination, consistent with this model.

While it is well known that the plasmon resonance frequency of metallic nanoparticles is dependent on particle charge density, it has only recently become apparent that metallic nanoparticle optical properties are tunable via optical and electrical excitation[1]. We have proposed theoretical models and experimentally demonstrated the 'plasmoelectric effect' in which optical excitation of metallic nanostructures can result in changes of charge density, producing electrochemical potentials (i.e. plasmoelectric potentials)[2]. When a plasmonic nanostructure is illuminated at frequencies higher than the plasmon frequency, a plasmoelectric response will

increase charge density and blue-shift the plasmon resonance to produce increased absorption. Increased heat absorption thermodynamically drives this response. At excitation frequencies lower than the plasmon frequency, a plasmonic potential will red-shift the plasmon resonance by decreasing charge density. To monitor the plasmonic-induced change in the optical response we measure the extinction of 60nm diameter Au colloids in an electrochemical cell using a lock-in detection scheme. First we performed experiments that mapped out changes in extinction as a function of applied voltages. We measured a clear dependence of the extinction profile on applied bias, with the peak wavelength shifting as a monotonic function of voltage. By comparison to simulations, we can estimate a ~3% change in charge density of the Au colloids at the most positive applied voltages. To characterize induced plasmonic potentials, instead of using an applied bias to charge the particles, we optically pump to the blue or to the red of the plasmon resonance, creating a driving force for plasmonic charging of the particles. When optically pumping to the blue of the resonance, our theory predicts that the particles will take on a higher charge density and a blue-shift of the extinction peak will result. Indeed, with a 3.5W/cm² pump at 514, we measured a blue shift of the extinction peak greater than 3nm. By comparing the changes in extinction as a function of pump intensity to the changes in extinction as a function of applied voltage, we estimate that changes in extinction at 3.5W/cm² power density corresponds to plasmonic charging equal to ~-1.75V on the particles. These results are strong evidence for an optically induced plasmonic potential in metal nanoparticles

[1] SK Dondapa, et al, *Nano Letters* 2012, 12(3)

[2] MT Sheldon, et al, 2012 in sub, arXiv1202.0301

4:00 PM - *KK5.08

Optical Nanospectroscopic Imaging at Length Scales that Matter

P. James Schuck¹, S. Cabrini¹, A. Weber-Bargioni¹, M. Mell¹, M. B. Salmeron¹, S. Aloni¹, D. F. Ogletree¹, P. D. Ashby¹.

¹, Molecular Foundry, LBNL, Berkeley, California, USA.

Hide Abstract

Near-field optical microscopies and spectroscopies seek to investigate materials by combining the best aspects of optical characterization and scan-probe microscopy techniques. In principle, this provides access to chemical, morphological, physical and dynamical information at nanometer length scales that is impossible to access by other means. But a number of challenges, particularly on the scan-probe front, have limited the widespread application of near-field investigations. This talk will describe the near-field advances developed at the Molecular Foundry that lay groundwork for generally-applicable nano-optical studies. The specific example of the “campanile” probe geometry will be discussed in detail, where it has recently been used for hyperspectral mapping of luminescence heterogeneity along InP nanowires, providing spectral information distinct from cathodoluminescence and micro-PL spectral imaging.

4:30 PM - *KK5.09

Resonant Dielectric and Plasmonic Nanocavities for High-Efficiency Solar Cells

Albert Polman¹.

¹, Center for Nanophotonics, FOM institute AMOLF, Amsterdam, Netherlands.

Hide Abstract

Resonant dielectric and plasmonic nanostructures can serve as efficient light coupling and trapping architectures for thin-film and wafer-based solar cells. We fabricate dielectric Mie scatterers made of Si, SiO₂, TiO₂, ZnO on ultra-thin silicon slabs, and demonstrate near-unity light coupling and light trapping well beyond the ray-optics $4n^2$ limit. We use cathodoluminescence imaging spectroscopy to obtain fundamental insight in the modal distribution of Mie resonances of individual Mie cavities, and determine their far-field radiation pattern. The orthogonality of dielectric and magnetic modes in dielectric nanocavities enables novel designs for spectral splitters and light directors as we will demonstrate.

Plasmonic nanostructures integrated on the surface of a solar cell combine efficient light coupling and trapping with electrical conduction. We show that nanopatterned Ag nanowire networks can serve as transparent electrodes, and have properties that make them excel beyond standard ITO layers as we will show. We use substrate-conformal soft-imprint technology to fabricate these structures over a large area. We apply our dielectric and plasmonic light management architectures on thin-film Si solar cells, wafer-based Si cells (both homo- and heterojunction designs), P3HT:PCBM polymer cells, CIGS cells and ultra-high efficiency GaAs cells.

2014-04-24

Symposium KK

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KK6: Dielectric Optic Resonances

- Chair: Joshua Caldwell
- Chair: Jeremy Munday
- Thursday AM, April 24, 2014
- Moscone West, Level 3, Room 3008

8:30 AM - *KK6.01

Modulating Optical Resonances to Create Photonic Gauge Field

Shanhui Fan1.

1, Electrical Engineering, Stanford University, Stanford, California, USA.

[Hide Abstract](#)

We explore the dynamic modulation of optical structures, including optical resonator array structures, as a mechanism to induce non-reciprocal behaviors, and to achieve gauge potential and gauge field for photons.

9:00 AM - KK6.02

Non-Equilibrium Thermal Super-Radiation of Real Materials

Yiling Yu2, Linyou Cao1.

1, Material science and engineering, North Carolina State University, Raleigh, North Carolina, USA; 2, physics, North Carolina State Univ., Raleigh, North Carolina, USA.

[Hide Abstract](#)

We elucidate the theoretically maximal thermal radiation power from real materials at a given temperature. Our results demonstrate that the thermal radiation from real materials may be larger than the blackbody

emission in free space, and indicate that this is rooted in the high refractive index of the materials. The refractive index contrast between the materials and environment dictates the radiation of real materials genetically not under thermodynamic equilibrium, but on the other hand can give rise to a larger density of photonic modes than that of the blackbody. One key to maximize the thermal radiation is to minimize the impedance mismatch of the materials with environment. By following this principle, we present a design of a carbon core coated by a four-layer transparent shell with gradually changed refractive indexes that can emit > 30 times more power than the blackbody, which reasonably approaches the predicted radiation maximum.

9:15 AM - *KK6.03

Fano Resonances in All-Dielectric Nanophotonic Structures

Andrey Miroshnichenko¹, Yuri Kivshar¹.

¹, Nonlinear Physics Center, Australian National University, Canberra, Australian Capital Territory, Australia.

Hide Abstract

We review the recent experimental and theoretical results from our groups in Canberra and Russia about the specific features of Fano resonances in nanophotonic structures. We demonstrate that, similar to numerous plasmonic structures composed of different types of metallic nanoparticles (the so-called plasmonic oligomers), light scattering by planar nanophotonic structures composed of all-dielectric nanoparticles demonstrate sharp Fano resonances with strong suppression of the scattering cross section at certain wavelengths [A. E. Miroshnichenko and Yu.S. Kivshar, *Nano Lett.* **12**, 6459 (2012)]. We reveal that this type of Fano resonances originates from the optically-induced magnetic dipole modes of individual high-refractive-index dielectric nanoparticles. By comparing to the plasmonic analogues, we observe that Fano resonances in all-dielectric nanoparticle oligomers are less sensitive to structural variations, which makes them promising for future applications in nanophotonics. Next, we present a robust and general approach for interpreting the physics of Fano resonances in planar oligomer structures with rotational symmetry made of both metallic and dielectric nanoparticles. We reveal a key mechanism for Fano resonances in such nanoparticle structures based on the interference of non-orthogonal bright collective eigenmodes, which are clearly identified based on the coupled-dipole approximation. Employing the group theory analysis, we determine a number of collective eigenmodes that can be excited in ring-type nanoparticle oligomers under the plane-wave excitation, and reveal that no dark-mode excitation is necessary for the existence of Fano resonances in symmetric oligomers [B. Hopkins et al, *Phys. Rev. A* **88**, 053819 (2013)]. As a result, we unify the physics of Fano resonances for both plasmonic and dielectric oligomers. In addition, we prove analytically that far-field optical properties (such as extinction, scattering, and absorption) of such nanoparticle structures with rotational symmetry are completely polarization independent [B. Hopkins et al, *Nanoscale* **5**, 6395 (2013)], despite the fact of dissimilar near-field field structures [M. Rahmani et al, *ACS Nano*, nn404869c (2013)]. Finally, we review several recent experimental observations of Fano resonances in the clusters of all-dielectric particles for both microwave and optical frequency ranges.

9:45 AM - KK6.04

Engineering Local Fields Surrounding Silicon Nanowire Resonators to Achieve Optimum Absorption in Single-Channel Resonant Optical Modes

Aaron Holsteen¹, Pengyu Fan¹, Mark Brongersma¹.

¹, MSE, Stanford University, Stanford, California, USA.

Hide Abstract

Dielectric optical antennas can support leaky mode resonances, which can confine light within subwavelength, high-refractive-index nanostructures. These resonances have been employed to enhance the volumetric absorption and scattering of light in various optical applications such as photodetectors and solar cells. Each resonant mode gives rise to a localized field distribution predicted by the Mie solution to the Maxwell's equations for cylindrical geometries which can be correlated to electric and magnetic monopoles, dipoles, and

other higher modes. Although there has been considerable research to enhance the volumetric absorption and scattering in dielectric optical antennas by tailoring the geometries of these antennas, the effect of the local field environment around the dielectric optical antennas has not been fully utilized to enhance optical mode coupling to an external driving field. We examine the volumetric absorption and scattering properties of single crystal and poly-silicon nanowires as a function of height above a metallic mirror. It is shown that the maxima in the standing electric and magnetic field profiles lead to selective coupling to the electric and magnetic dipole-like resonances respectively. Dependence of the coupling efficiency on the polarization state is also provided. In this work, we propose that one can engineer the local field environment surrounding a dielectric optical antenna to selectively excite optical modes and enhance single-channel absorption.

10:00 AM -

BREAK

Hide Abstract**10:30 AM - *KK6.05**

Semiconductor and Molecular Optical Antennas: Measuring and Manipulating Radiation Patterns

Jon A. Schuller¹.

1, , UC Santa Barbara, Santa Barbara, California, USA.

Hide Abstract

Optical antennas are at the heart of many transformative advancements in nanophotonics research. For instance, by engineering radiation patterns of plasmonic nanostructures researchers can construct novel optical metamaterials and directional light emitters. In this presentation, we describe myriad efforts to measure and manipulate antenna radiation patterns in two distinct materials systems: semiconductor nanostructures and self-assembled molecular materials. We will show how measurements of radiation patterns reveal new insight into the optical properties of these nanomaterials. We will subsequently describe various approaches for exploiting and manipulating antenna radiation patterns in novel optoelectronic devices.

11:00 AM - KK6.06

Optical Properties of Single Infrared Resonant Circular Microcavities for Surface Phonon Polaritons

Tao Wang¹, Peining Li¹, Benedikt Hauer¹, Dmitry N. Chigrin¹, Thomas Taubner¹.

1, 1st Institute of Physics (1A), RWTH Aachen University, Aachen, Germany.

Hide Abstract

Plasmonic antennas are crucial components for nano-optics and have been extensively used to enhance sensing, spectroscopy, light emission, photodetection, and others [1]. Recently, there is a trend to search for new plasmonic materials with low intrinsic loss at new plasmon frequencies [2]. As an alternative to metals, polar crystals have a negative real part of permittivity in the Reststrahlen band and support surface phonon polaritons (SPhPs) with weak damping. Here, we experimentally demonstrate the resonance of single circular microcavities in a thin gold film deposited on a silicon carbide (SiC) substrate in the mid-infrared range. Specifically, the negative permittivity of SiC leads to a well-defined, size-tunable SPhP resonance with a Q factor of around 60 which is much higher than those in surface plasmon polariton (SPP) resonators with similar structures. These infrared resonant microcavities provide new possibilities for widespread applications such as enhanced spectroscopy, sensing, coherent thermal emission, and infrared photodetectors among others throughout the infrared frequency range. [3]

1. L. Novotny, N. van Hulst, Antenna for light. Nat. Photonics 5, 83–90 (2011).
2. P. R. West, S. Ishii, G. V. Naik, N. K. Emani, V. M. Shalaev, A. Boltasseva. Searching for better plasmonic materials. Laser Photonics Rev. 4, 795–808 (2010).

3. T. Wang, P. Li, B. Hauer, D. N. Chigrin, T. Taubner. Optical Properties of Single Infrared Resonant Circular Microcavities for Surface Phonon Polaritons. *Nano Lett.*, ASAP. DOI: 10.1021/nl4020342

11:15 AM - KK6.07

Silicon Colloids Based Metamaterials in the Near Infrared Region

Francisco Meseguer¹, Roberto Fenollosa¹, Isabelle Rodriguez¹, Lei Shi¹, Xiaotang Lu³, Brian A. Korgel³.

¹, CTF UPV, CSIC Spain, Valencia, Spain; ², Instituto de Ciencia de Materiales de Madrid, CSIC, Valencia, Spain; ³, Department of Chemical Engineering, The University of Texas, Austin, Austin, Texas, USA.

Hide Abstract

It is generally accepted that the magnetic response of materials at optical frequency values is completely negligible. The recent discovery of Metamaterials (MMs) has broken this traditional understanding, since both the electric and the magnetic field are key ingredients in MMs [1]. The top-down technology used so far employs noble metals with large intrinsic losses. Here we report on a bottom-up approach for processing MMs based on polydisperse [2], and monodisperse [3] full dielectric silicon nanocavities with a large magnetic response in the near infrared region (NIR). Experimental results and theory show that silicon colloids (SCs) based liquid suspensions have strong magnetic response in the NIR region with small optical losses. Finally we have developed a two dimensional photonic crystal, which shows a perfect optical matching condition in the NIR region. Our findings have important implications in the bottom up processing of large area low loss MMs working in the NIR region.

[1] C. M. Soukoulis, M. Wegener, *Nat. Photon.* **5**, 523, (2011).

[2] L. Shi, J. T. Harris, R. Fenollosa, I. Rodriguez, X. Lu, B. A. Korgel, and F. Meseguer *Nature Communications*, **4**, 1904 (2013)

[3] L. Shi, T. U. Tuzer, R. Fenollosa, and F. Meseguer *Adv. Mat.*, **24**, 5934, (2012).

11:30 AM - *KK6.08

Increasing Device and Design Practicality in Transformation Optics

Douglas H. Werner¹, Jeremiah P Turpin¹, Donovan Brocker¹, Zhihao Jiang¹, Pingjuan L. Werner¹.

¹, Department of Electrical Engineering, The Pennsylvania State University, University Park, Pennsylvania, USA.

Hide Abstract

The initial excitement and hype surrounding the new capabilities made available by Transformation Optics (TO) has started to slowly solidify within the Electromagnetics and Optics communities as scientists and engineers clarify the advantages and limitations inherent to the new design technique. While interest in cloaks and other such esoteric devices appears to be waning, this simply demonstrates that efforts are being refocused into applications and implementations that show more practical promise. Ultimately, these efforts should be oriented towards the development of a TO component library based on specific fabrication techniques from which individual predesigned devices may be selected and integrated to perform a complex task, allowing for system-level designs such as optical integrated circuits.

Many research groups have been working to demonstrate useful and practically-realizable TO designs while refining their design techniques to avoid the undesirable implications of many of the original TO examples. Although simple enough to simulate, anisotropic and inhomogeneous material requirements, often with negative or zero-index properties, are difficult or impossible to fabricate with high enough fidelity at a reasonable cost, even when using metamaterials. Indeed, the use of metamaterials may be viewed as a liability in TO design due to the stringent bandwidth constraints inherent to resonant metamaterials; thus, there is a trend towards the design of all-dielectric TO-GRIN devices.

Our goal has been to demonstrate TO designs that perform as well as or better than conventional alternative

implementations for applications in RF antennas, optical waveguides and imaging, and energy concentration. This may be achieved by increasing the capability of individual transformations through greater experience with the TO techniques, and by reducing the complexity of the required material parameters necessary to achieve a given electromagnetic behavior by restricting and controlling the transformation itself.

A major impediment to constructing a general TO device is the strong anisotropy, which must be minimized to allow for a metamaterial design with reasonable complexity, or eliminated to allow for nonresonant all-dielectric implementations. In either case, anisotropic properties in a TO design may be managed through an appropriate choice of transformation. We have shown good results when working from conformal or quasi-conformal mappings, which can produce either uniaxial or isotropic GRIN profiles, and can generally be implemented in an all-dielectric GRIN structure. Numerically-computed transformations based on quasi-conformal mappings are limited in their behavior since they do not allow direct control over the interior of the mapped region, which increases the difficulty of performing a design to achieve a specific goal. This limitation has been countered, however, by the use of global optimizations to select the best transformation parameters.

KK7: Dielectric/Plasmonic Metasurfaces

- Chair: Joshua Caldwell
- Chair: Linyou Cao
- Thursday PM, April 24, 2014
- Moscone West, Level 3, Room 3008

1:30 PM - *KK7.01

Controlling Wave-Fronts of Light Using Plasmonic Metasurfaces

Shuang Zhang¹, Lingling Huang¹, Xianzhong Chen¹, Thomas Zentgraf².

¹, School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom; ², Department of Physics, University of Paderborn, Paderborn, Germany.

Hide Abstract

Benefiting from the flexibility in engineering their optical responses, metamaterials have been used to achieve control over the propagation of light to an unprecedented level, leading to highly unconventional and versatile optical functionalities in comparison to their natural counterparts. Recently the emerging field of meta-surfaces consisting of a monolayer of artificial atoms has offered attractive functionalities of shaping the wave front of light by introducing an interfacial abrupt phase discontinuity¹⁻¹⁰. In this talk, I will talk about our recent works on optical metasurfaces consisting of an array of plasmonic rods with spatially varying orientations, where the local phase profile is determined by the orientation of each rod³. In particular, I will focus on three examples of device applications: a dual polarity metasurface that can function either as a convex or a concave lens⁴, helicity switchable unidirectional excitation of surface plasmon polaritons⁶, and 3D computer generated hologram¹⁰. Lens is the most essential part of any imaging systems. Conventional lenses are made from dielectric materials, such as glass, with spatially varying topography. The polarity of any lens reported so far cannot be altered after fabrication, i.e., either positive (convex) or negative (concave), depending on the surface topography. We have experimentally demonstrated a counter-intuitive bipolar flat lens with switchable polarity at visible frequencies by controlling the phase discontinuities for the circularly polarized light. The positive and negative polarities are interchangeable in one identical flat lens under inversion of the helicity of the input light. Both focusing and imaging are observed for visible light. We also apply the concept of interfacial

phase discontinuity for circularly polarizations on a metasurface to the design of a novel type of helicity dependent SPP unidirectional excitation at normal incidence. Selective unidirectional excitation of SPPs along opposite directions is experimentally demonstrated at optical frequencies by simply switching the helicity of the incident light. This approach, in conjunction with dynamic polarization modulation techniques, opens gateway towards integrated nanoplasmonic circuits with electrically reconfigurable functionalities. Finally, I will talk about the realization of three dimensional (3D) holography by using metasurfaces. As the phase can be controlled locally at each subwavelength unit cell by the rod orientation, metasurfaces represent a new route towards high-resolution on-axis 3D holograms with wide field of view. In addition, the undesired effects of twin images and multiple diffraction orders usually accompanying holography are eliminated.

1. N. Yu et al, Light propagation with phase discontinuities: generalized laws of reflection and refraction. *Science* 334, 333-337 (2012).
2. X. Ni, N. K. Emani, A. V. Kildishev, A. Boltasseva, and V. M. Shalaev, Broadband light bending with plasmonic nanoantennas. *Science* 335, 427 (2012).

2:00 PM - KK7.02

Towards Efficient Nanoscale Wave Manipulation with Graded Plasmonic Metareflectors

Nasim Mohammadi Estakhri1, Andrea Alu1.

1, Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, Texas, USA.

Hide Abstract

Metasurfaces are a class of artificial materials with enhanced surface wave-matter interaction, which can provide an expedient platform for optical devices capable of extreme wave manipulation with promising applications for modern optical technology. As implied by their name, these structures are formed by a suitable distribution of electrically small inclusions over a surface. In general, the interaction between the impinging wave and the metasurface is controlled by the ordering and pattern of the individual elements composing the surface, as well as by the localized response of each individual inclusion. Owing to their reduced dimensions, metasurfaces offer low-loss functionality, which today represents the key challenge in applying metamaterials to practical optical devices.

In this presentation, we investigate a number of applications enabled by plasmonic nonperiodic metasurfaces. We begin by introducing a subwavelength phase element composed of two common optical materials: silver and silicon. The surface element, in spite of its deeply subwavelength dimensions, exhibits a wide range of tunability and the reflection phase from a periodic metasurface composed of such elements can be effectively controlled by only changing the filling ratio between the two constitutive materials. We utilize these subwavelength units in a variety of metasurfaces to build spatial phase modulators - generally nonperiodic - and impose arbitrary phase patterns to the impinging optical beam. The introduced metareflectors, with nanoscale resolution, enable point-by-point control of the scattering response of the system, and we outline their potential applications for light trapping solar cells, integrated optical couplers and conformal carpet cloaks. In this regard, we report broadband absorption enhancement in a 180 nm thick organic PV solarcell by adding a graded metareflector at the back. The metasurface is designed to provide a constant transverse momentum and enables multiple internal reflections in the active layer. In addition, an efficient (>80% at 500 nm) and broadband (460-610 nm) on-chip coupler is designed employing a nonperiodic gradient metasurface to effectively bridge between the waveguide mode profile and the free-space optical beam. We discuss the generality of the proposed method by demonstrating also the possibility of hiding arbitrary objects using metasurface carpet cloaks. With the object concealed under the metareflector, the whole system is designed point-by-point to mimic a flat reflector. Our results highlights the application of plasmonic gradient metasurfaces for unprecedented control of optical wave propagation and may open up a new route in designing compact wave manipulating integrated devices.

2:15 PM - KK7.03

Large-Area, Flexible, Wavelength-Selective Three-Dimensional Optical Metasurface

Ping-Chun Li, Edward T. Yu.

1, Electrical Engineering, University of Texas, Austin, Texas, USA.

Hide Abstract

Plasmonic metasurfaces are currently under intense investigation for a broad range of applications. In certain cases, wavelength-selective optical reflectance and transmittance arising from plasmonic resonances, combined with low absorption, are desired over large areas and on surfaces with curved or irregular shapes. We have designed, fabricated, characterized, and analyzed a variety of multilayer plasmonic metasurface structures that provide wavelength-dependent reflectance and transmittance insensitive to polarization and angle of incidence up to 45 degrees, with absorption loss of 1-20% at visible and near-infrared wavelengths. Using nanosphere lithography, we pattern multiple layers of metal nanostructure arrays quickly and reliably over 1-10cm² areas and on a variety of rigid and flexible substrates. In a representative structure containing two Ag nanostructure arrays separated by a 200nm dielectric layer, peak reflectance of ~95% at 650nm wavelength and a reflectance bandwidth of ~400nm FWHM are obtained. The reflectance and transmittance spectra are shown to be minimally sensitive to polarization and angle of incidence (up to 45 degrees) due to the origin of the reflectance in the dipolar resonance of each individual Ag nanostructure. Similarly high reflectance and correspondingly low loss can be achieved with different peak wavelengths and bandwidths by altering the nanostructure dimensions, array density, and array symmetry, or the dielectric-filled spacing between individual layers of plasmonic arrays. Detailed analysis reveals that the enhancement of peak reflectance and bandwidth and minimization of absorption are due to Bragg interference, enabling structures with minimal loss to be very readily designed. These characteristics are also shown to be highly tolerant of vertical misalignment between layers, and defects within individual layers. Finally, fabrication over large areas on flexible substrates enables the demonstration and characterization of wavelength-selective focusing of light at optical wavelengths.

2:30 PM - *KK7.04

Tailoring Scattering, Absorption and Radiation with Plasmonic Nanoantennas and Metasurfaces

Andrea Alu.

1, , The University of Texas at Austin, Austin, Texas, USA.

Hide Abstract

We discuss our recent efforts in exploring the ultimate potentials of composite nanoparticles and nanoantennas, as well as arrays of them, to tailor light scattering, absorption, polarization, transmission, reflection and radiation features at the nanoscale. Properly tailored nanoparticles can exploit the large field enhancement and localized light-matter interaction to realize novel optical nanodevices for optical communications, computing, energy harvesting, bio-sensing and polarization control. By translating some of the familiar radio-frequency concepts to optical antennas, we have proposed in recent years a variety of exciting possibilities for optical antennas in order to realize nanodevices with linear and nonlinear properties not available in conventional optical materials and systems. In our talk, we review our recent theoretical, numerical and experimental results involving individual nanoantennas and arrays of them, showing that these plasmonic nanoparticles may realize the true bridge between unconventional nanoscale optical processing and far-field propagation and radiation. We also introduce novel concepts for optical nanoantennas, such as parity-time symmetric nanoantenna arrays and 3D nanoresonators supporting open embedded eigen-states, which are applied to further enhance the scope and potential of optical nanoantennas in tailoring and controlling light.

3:00 PM -

BREAK

Hide Abstract**3:30 PM - *KK7.05**

Optic Spin Hall Effect at Metasurfaces

Xiaobo Yin1.

1, Mechanical Engineering, University of Colorado, Boulder, Colorado, USA.

Hide Abstract

The relativistic spin-orbit coupling of electrons results in intrinsic spin precessions and therefore spin-polarization-dependent transverse currents, leading to the observation of spin Hall effect (SHE) and the emerging field of spintronics. The coupling between charge's spin degree of freedom and its orbital movement is essentially identical to the coupling of the transverse electric and magnetic components of a propagating electromagnetic field. To conserve total angular momentum, an inhomogeneity of material's index of refraction can cause momentum transfer between the orbital and the spin angular momentum of light along its propagation trajectory, resulting in a transverse splitting in polarizations. Such a photonic spin Hall effect (PSHE) was recently proposed theoretically to describe the spin-orbit interaction, the geometric phase, and the precession of polarization in weakly inhomogeneous media as well as the interfaces between homogenous media.

The experimental observation of spin Hall effect of light, however, is fundamentally challenging since the amount of momentum that a photon carries is exceedingly small. The exploration of such a weak process relies on the accumulation of the effect through many multiple reflections or ultra-sensitive quantum weak measurements with pre- and post-selections of spin states. Here we demonstrate experimentally the strong interactions between the spin and the orbital momentum of light in a thin metasurface - a two-dimensional electromagnetic nano-structure with designed in-plane phase retardation over the wavelength scale. In such an optically thin material, the resonance-induced anomalous "skew-scattering" of light destroys the axial symmetry of the system and we observed PSHE even at the normal incidence. In stark contrast, for conventional interfaces between two homogeneous media, the spin-orbit coupling does not exist at the normal incidence.

4:00 PM - KK7.06

Ultrathin Semiconductor Metasurface Perfect Absorbers for Arbitrary Wavelength

Lujun Huang1, Yiling Yu2, Linyou Cao1 2.

1, Department of Material Science and Engineering, North Carolina State University, Raleigh, North Carolina, USA; 2, Department of Physics, North Carolina State University, Raleigh, North Carolina, USA.

Hide Abstract

We propose a general design principle of subwavelength perfect absorber for arbitrary wavelength by an ultra thin semiconductor metasurface. We found that the absorption spectrum of such a metasurface, which is made of single layer of semiconductor nanowire (NW) array, is dictated by the eigenmodes of the structure. In order to design a perfect absorber, three basic requirements are needed to be met and are listed as follows: (1) two degenerate modes; (2) critical coupling condition ($w=w_1=w_2$, $Q_{abs}=Q_{rad1}=Q_{rad2}$); (3) the coupling coefficient for both modes being unity. By tuning the size ratio of NW, we can first make sure that the resonant wavelengths of two eigenmodes are identical. After finding the critical size ratio, the radiative quality factors of two modes can be independently tuned to be the same as the intrinsic absorption quality factor by changing the period while the resonant wavelengths of two eigenmodes show the weak dependence on the period. Moreover, the resonant wavelength for these two degenerate modes should be larger than the period to obtain unity coupling coefficient. Besides, an alternative structure, which is composed of semiconductor NW array on the top, dielectric layer in the middle and mirror at the bottom, is also proposed to realize the perfect absorption. In the end, we also found that such a super absorber can work within a wide range of incident angle, and its performance is mildly dependent on the period, but sensitive to the size ratio of NW.

4:15 PM - KK7.07

Ultrathin Metasurface Absorber with Mie Resonance

Soo Jin Kim¹, Junghyun Park¹, Mark L Brongersma¹.¹, , STANFORD UNIVERSITY, Stanford, California, USA.**Hide Abstract**

As the size of optoelectronic devices scales down well below the wavelength of light, it is considered as promising techniques to design devices based on thin metamaterials with improved performance. Here we demonstrate ultrathin metasurface (<50nm) composed of pure dielectrics (e.g. Ge) and shows the absorption more than 90%. This material is constructed from dense arrangement of subwavelength optical resonant building blocks of dielectric materials. The resonances of such building blocks can be used to enhance light matter interaction and by engineering the resonances of building blocks, one can create the surface with designer absorption spectra. It is also noteworthy that there is no grating coupling / Bragg scattering effects (i.e. no diffracted orders of light) in such a dense arrangement at subwavelength scale and thereby the layer can serve as effective media whose optical property can be tailored through nanostructure design. The spectrum of strong coupling can be tuned based on the effective refractive index of Maxwell-Garnett theory resulting in the Fabry-Perot resonances to the new index of metamaterial derived by Mie resonances of each building block. Furthermore, by integrating two resonant structures, we obtained broadband absorption phenomena with separate resonant peaks. This new type of dielectric metasurfaces can be used as ultrathin photodetectors as well as the photoelectrodes for solar energy harvesting.

4:30 PM - KK7.08

Coherent Perfect Absorption in a Luminescent Slab: Redefining the Stokes' Shift

Giuseppe Pirruccio¹, Jaime Gomez Rivas¹ 2.¹, , FOM Institute - AMOLF, Amsterdam, Netherlands; ², COBRA Research Institute, Eindhoven University of Technology, Eindhoven, Netherlands.**Hide Abstract**

The Stokes' shift is a characteristic of any luminescent material firstly observed by Stokes in 1852 [1]. This shift is defined as the frequency difference between the maximum of the absorption spectrum of a light-emitting material and the frequency of maximum emission, which are given by the microscopic structure of the material. The Stokes' shift is thus an important parameter that represents an unavoidable energy loss in light down-conversion-based optical devices. Here we propose a new definition of the Stokes' shift which is not limited to the material properties, but it includes the illumination scheme and the photonic environment. The experiment is designed to satisfy the conditions for Coherent Perfect Absorption (CPA) in a 110 micron-thick slab of YAG:Ce [2]. CPA is realized by controlling the phase difference between multiple incident beams onto the slab. When a destructive interference pattern is built outside the YAG:Ce layer, the incident light is efficiently trapped and dissipated by the slab where it is converted into photoluminescence. Theoretically 100% absorption can be achieved at frequencies in which the absorption coefficient of the material is very low, therefore redefining the frequency of maximum absorption and the Stokes' shift. We will show how a remarkably large Stokes' shift reduction of 36% can be achieved in thin slabs of YAG:Ce.

[1] Stokes, G.G.; On the change of refrangibility of light, Phil. Trans. R. Soc. London, 1852, 142, 463-562.

[2] Chong, Y. D.; Ge, L.; Cao, H.; Stone, A. D.; Coherent Perfect Absorbers: Time- Reversed Lasers, Phys. Rev. Lett., 2010, 105, 053901.

4:45 PM - KK7.09

Dynamic Beam Steering Optical Antenna Using Dielectric Mie Resonators

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Hide Abstract

Dynamic control of light beams is of utmost importance in the photonic industry today. There have been many recent demonstrations of highly directive antenna structures. However, dynamically tunable directivities have been a missing link so far in many nanophotonic circuits. Here, we theoretically demonstrate a signal-pump design principle to control the scattered infrared radiation from low loss, high index dielectric spheres. We chose silicon to demonstrate the principle, due to its technological importance in the industry and to take advantage of the established CMOS fabrication processes. By controlling the intensity of a visible pump beam incident on a silicon sphere, we introduce charge carriers in the system, which enables us to tune the scattering response of an infrared signal beam. This allows for dynamic control of the phase and amplitude of scattered infrared radiation from a single sphere.

We first theoretically describe a simple two-sphere antenna system, where we dynamically tune the directivity of the antenna along two different directions by constructively interfering Mie scattering resonances. This 2 sphere system is then treated as a repeating element which is extended in a periodic linear array to dramatically increase the directivity of the antenna. We derive analytical expressions of the scattered field based on Mie Theory for a physically realizable array of spheres and show that the results match closely with numerical calculations done in COMSOL. We show that radiation lobes of infrared signal scattered from multi-sphere geometries of the repeating element, can be tuned using suitably designed visible frequency pump beams which induce the required phase shifts for constructive interference of scattered light. We have also shown that for carefully designed multi-sphere geometries, it is possible to individually enhance the magnetic or electric dipole resonance modes for the same signal by just varying the pumping intensity pattern. We believe this design principle can play a pivotal role in the control of infrared light beams, spurring new classes of optically controlled beam-steering technologies.

2014-04-25

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8:45 AM - *KK8.01

Plasmonics and Optical Metamaterials: Going Practical with Transition Metal Nitrides

Alexandra Boltasseva1.

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Hide Abstract

Interesting designs and various experimental realizations of devices with exotic optical properties in the fields of plasmonics and plasmonic metamaterials have attracted a great deal of attention over the past few decades. However, high expectations on emerging practical plasmonic devices have not been met so far. The main obstacle is the absence of robust, high performance, low cost plasmonic materials that can be easily fabricated using standard processing lines and integrated with established semiconductor technologies. In this talk alternative plasmonic materials (other than currently used silver and gold) for surface plasmon applications as well as plasmonic metamaterials will be discussed. This presentation will mainly focus on transition metal nitrides, in particular, titanium nitride and zirconium nitride, which are plasmonic materials having optical properties resembling gold. Titanium nitride is compatible with biological environments and semiconductor industry, and possesses superior properties compared to noble metals such as high temperature durability, chemical stability, and corrosion resistance, low cost and mechanical hardness. Additionally, titanium nitride can be grown in smooth, ultra-thin crystalline films, which are crucial in constructing high-performance, low loss plasmonic and metamaterial devices. Several examples of plasmonic structures and metamaterial devices using transition metal nitrides as the constituent plasmonic material will be shown including nanoparticles for localized surface plasmon applications, plasmonic waveguides as well as hyperbolic metamaterials. The prospects of using transition metal nitrides to enable the next generation of hybrid photonic devices based on low-loss optical metamaterials, CMOS-compatible plasmonic interconnects as well as novel devices for improved imaging, sensing, light harvesting and medical applications will be discussed.

9:15 AM - KK8.02

Investigation of the Purcell Effect in Rolled-Up Active Metamaterials by Means of Time-Resolved Photoluminescence Measurements

Hoan Vu1,3, Marvin Schulz1, Stephan Schwaiger1, Tobias Korn2, Christian Schueller2, David Sonnenberg1, Christian Heyn1, Tobias Kipp3, Stefan Mendach1.

1, , Institut für Angewandte Physik, Hamburg, Germany; 2, , Institut für Experimentelle und Angewandte Physik, Regensburg, Germany; 3, , Institut für Physikalische Chemie, Hamburg, Germany.

Hide Abstract

Metamaterials are artificial materials designed from subwavelength building blocks. Their electromagnetic properties are determined in particular by electromagnetic resonances of these building blocks and by the near-field coupling between them [1].

In metamaterials it is possible to deliberately tailor the iso-frequency surface, i.e., the surface of allowed wavevectors at constant frequency. The topology of this surface governs the wave dynamics inside a medium and, using Fermi's golden rule, this topology is linked to the electromagnetic density of states supported by the metamaterial. Accordingly, metamaterials with a hyperbolic iso-frequency surface exhibit a large number of electromagnetic states that can couple to quantum emitters. This leads to an enhancement of their lifetime, which is associated with a broadband Purcell effect [2].

Here, we investigate the Purcell effect of a GaAs quantum well embedded in rolled-up radial metamaterials, which we prepare exploiting the self-rolling mechanism of strained semiconductor layers [3,4].

In the experiments presented here, we varied the thickness ratio η of rolled-up Ag/GaAs layer systems to tune the effective permittivity of the metamaterial at the quantum well emission energy (1.63 eV) and thereby change the effective dispersions' iso-frequency surface from a closed spherical or ellipsoidal iso-frequency surface ($\eta < 0.53$) to an open hyperboloidal iso-frequency surface ($\eta > 0.53$). We show by means of highly time-resolved photoluminescence measurements that the lifetime of GaAs quantum wells is enhanced by a factor of 2.5 due to the surrounding hyperbolic metamaterial.

We acknowledge financial support by the Deutsche Forschungsgemeinschaft (DFG) via ME 3600/1.

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- [2] H. N. S. Krishnamoorthy et al., *Science* 336, 6078 (2012)
- [3] V. Ya. Prinz et al., *Physica E* 6, 828 (2000)
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9:30 AM -

KK8.03 ABSTRACT WITHDRAWN

Hide Abstract

9:30 AM - KK8.04

Collective Resonances and Lasing Induced by Photon Localization in Aperiodically Arranged Microresonators

Sushil Mujumdar¹, Anjani Kumar Tiwari¹.

¹, , Tata Institute of Fundamental Research, Mumbai, India.

Hide Abstract

We report on experimentally measured collective optical resonances in a quasi-one-dimensional array of aperiodically arranged microspherical resonators. The resonators are spherical microdroplets of a solution of Rhodamine dye in alcohol, excited by a 532 nm pulsed Nd:YAG laser. The large size parameter of the resonators enables collective modes sustained by the Fabry-Perot resonances of individual microspheres. The frequency distribution of the collective resonances indicate that they occur only within finite intervals of frequency[1]. Transfer matrix analysis shows that these modes originate from the gap states formed within the stopgaps of the band structure of a weakly perturbed periodic lattice. This periodicity originates from the monodisperse nature of the resonators. The quality factor of these gap states can be larger than the band-edge states, which are typically used for lasing. We obtain lasing from these gap-states[2] and show that the resonances are formed by an Anderson phenomenon[3], which is a result of interference of disorder-induced multiply reflected light. Angular profile of the emitted light shows a marked dip along the longitudinal direction, confirming the localized nature of the resonance. The study of the spatial profile of the modes reveals exponentially decaying tails, characteristic of localized modes. The measured localization length is in agreement with the sample size. We measure the spatial extent of the lasing modes using the Inverse Participation Ratio (IPR), and describe its distribution over a thousand aperiodic configurations. This is the first time measurement of the IPR distribution of localized lasing modes. We discuss the nature of the localized states under two different conditions of disorder, namely, monodisperse quasiperiodicity, and monodisperse aperiodicity. Current, ongoing studies of the spatial profile of the modes indicate that the origins of the modes in the two conditions are dissimilar.

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- 2] A. K. Tiwari and S. Mujumdar, “Random lasing over gap states from a quasi-one-dimensional, amplifying periodic-on-average random superlattice”, Under Review, *Phys. Rev. Lett.*
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9:45 AM - KK8.05

Spectral Phase Interferometry with Amplified Spontaneous Emission of Surface Plasmon Polariton: A Numerical Study

Chi-Man Lawrence Wu¹, Siu-Pang Ng¹.

¹, Physics and Materials Science, City University of Hong Kong, Hong Kong, Hong Kong.

Hide Abstract

Surface plasmon resonance (SPR) label-free sensor is an established technique detecting refractive index change induced by molecular interaction in the vicinity of metal/analyte interface. Detection of SPR phase

information by spectral interferometry has also been proved as a practical method for highly sensitive and wide dynamic range sensing. However, signal measurement at the SPR phase singularity with optimal resonance condition is always hampered by zero reflectivity thus detrimental to overall system resolution. In this paper, we propose to resolve the issue by amplified spontaneous emission of surface plasmon polariton (ASE-SPP) with the introduction of an optical gain layer to the conventional Kreschmann configuration. Upon sufficient optical pumping, the attenuated total reflection (ATR) due to SPR is inverted to ASE-SPP. The novel sensing scheme delivers remarkable advantages, namely, 1) extension of SPP propagation length for light-matter interaction, 2) reduction of SPR line width for sharper response, and 3) replacement of zero reflectivity by light emission, which are all positive for sensing performance. Thus, by means of simple Fresnel's formula, we calculate the reflectivity and phase response of the novel multilayer ASE-SPP sensor to minuscule refractive index change. With ASE-SPP and spectral phase interferometry, we also show numerically that the SPR phase singularity at optimal resonance condition may be monitored with unprecedented accuracy. Therefore, the refractive index resolution of the proposed system may be improved by two orders of magnitude, to 1E-10 refractive index unit (RIU). At the same time, the wide dynamic range of measurement to 1E-2 RIU is maintained. Consequently, it is expected that the proposed novel ASE-SPP will be a practical approach for detection of single biomolecule.

10:00 AM -

BREAK

Hide Abstract**10:30 AM - KK8.06**

Plasmonic Interferometers for Biochemical Sensing and Optical Coherence Measurements

Domenico Pacifici¹ 2 3, Drew Merrill¹.¹, School of Engineering, Brown University, Providence, Rhode Island, USA; ², Center for Biomedical Engineering, Brown University, Providence, Rhode Island, USA; ³, Institute for Molecular and Nanoscale Innovation, Brown University, Providence, Rhode Island, USA.**Hide Abstract**

Surface Plasmon Polaritons (SPPs) are fluctuations of the free electron density in metals coupled to electromagnetic waves. SPPs at optical frequencies show a significant momentum mismatch with respect to the light incident on a flat metal/dielectric interface, therefore coupling strategies generally rely on prisms (Kretschmann configuration) or metal gratings to excite them.

In this talk I will show alternative methods to generate SPPs at optical frequencies using light diffraction by individual nanocorrugations etched in metal films. In particular, I will show how nanometer scale slits, grooves and holes can be used as efficient, localized sources of SPPs.

Spatial localization of the source of SPPs allows for control of the SPP propagative phase, thus enabling researchers to perform "plasmonic interferometry," i.e. optical interferometry at the nano- and micro-scale using SPPs as the interfering waves.

By properly varying the nanoscatterer separation distance and in-plane distribution, the optical interference of SPPs can be spatially modulated and spectrally tuned. This property, together with the highly confined nature of SPPs, can be employed to enhance the optical absorption in thin film solar cells, and improve the sensitivity and selectivity of high-throughput, real-time biochemical sensors.

I will also discuss how Plasmonic Interferometry can be turned into a powerful tool to measure the coherence length of light sources, as well as determine the dispersion of optical constants of dielectric materials at the nanoscale.

10:45 AM - KK8.07

Quantitative Polarization Interferometry Phase Measurements for Real Time Spectroscopic Plasmonic Sensing

Lauren M Otto¹, Daniel A Mohr², Timothy W Johnson¹, Sang-Hyun Oh¹, Nathan C Lindquist².

1, Electrical Engineering, University of Minnesota, Minneapolis, Minnesota, USA; 2, Physics, Bethel University, St. Paul, Minnesota, USA.

Hide Abstract

With quantitative polarization interferometry phase measurements, we characterize novel buried grating structures and perform plasmonic sensing on an ultrasmooth surface. Our devices are produced via template stripping and offer backside optical illumination and collection with tunable plasmonic resonances. Unlike transmission-based plasmonic sensors, this reflection mode geometry allows the use of opaque or turbid liquids. The plasmonic nanostructures consist of a buried metallic grating while the flat upper sensing surface has a root mean square roughness of <0.5 nm. To fully characterize the sensing capability of these structures, real-time, quantitative interferometric phase information is obtained across the visible spectrum using a relatively simple setup that consists of an inverted microscope, a liquid crystal variable wave plate, linear polarizers, and a spectrometer. Our setup offers data collection at normal incidence in a reflection mode geometry using common path white light polarization interferometry that is insensitive to system vibration and alignment. This technique overcomes some drawbacks of previously demonstrated plasmonic phase detection techniques involving laser illumination, Michelson interferometry, Kretschmann prism coupling with oblique illumination angles, and beam splitting techniques with free space optics that require precise alignment and are extremely sensitive to vibrations. Furthermore, rather than tracking a spectral peak, dip, or angle of incidence, we track a sharp feature that is dependent on the real-time phase delay between orthogonal polarizations by scanning the liquid crystal variable wave plate and obtaining phase data at all wavelengths simultaneously. Experimentally obtained, real-time phase information for our buried grating sensor is compared to full-field COMSOL modeling results analyzed with Jones calculus.

11:00 AM - KK8.08

Ultraviolet Sensor Based on a Silica Optical Microresonator

Simin Mehrabani¹, Audrey Harker², Andrea Armani¹.

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Hide Abstract

It is well-known that exposure to ultraviolet (UV) light can result in various physical and psychological diseases. Therefore, there is a strong demand for a reliable UV sensor to monitor the level of exposure to UV in the physiologically relevant intensity ranges of mW/cm². Here, we demonstrate a UV sensor based on a silica whispering gallery mode microresonator.

The silica microtoroid resonator is fabricated on a silicon substrate using standard photolithography techniques. In such a device, light of a well-defined wavelength, known as the resonance wavelength, propagates in a circular orbit within the cavity. The resonance wavelength is sensitive to changes in the optical and geometrical properties of the device, including the refractive index and the diameter. A classic detection approach is the measurement of the resonant wavelength shift. Typically, this shift is induced by molecules binding to the surface of the cavity.

In contrast, the present approach leverages the intrinsic optical absorption of silica in the UV range. Specifically, as the UV light is absorbed by the silica the temperature of the device increases. As a result of the thermo-optic effect, the refractive index increases and a measurable resonant wavelength shift is observed. Because this approach does not rely on UV sensitive polymer coatings, it is robust and reusable. Therefore, it experiences minimal degradation over time and over multiple cycles. We have characterized the fundamental characteristics of the fabricated sensors such as signal-to-noise-ratio, linear response behavior and device hysteresis. In addition, we have developed a model based on thermodynamic principles which agrees well with the experimental results. This UV sensor works over physiologically relevant intensity ranges with linear performance both in forward and backward operating directions, with very high signal-to-noise ratio and can be utilized in monitoring the UV exposure in various applications.

11:15 AM - KK8.09

Tuning High-Q Surface Phonon Polariton Resonances of SiC Nanopillars

Ann-Katrin U Michel¹, Joshua D Caldwell², Francisco J Bezires², Richard Kasica³, Loretta Shirey², Thomas Taubner¹.

¹, I. Institute of Physics A, RWTH Aachen, Aachen, Germany; ², U.S. Naval Research Laboratory, Washington, District of Columbia, USA; ³, Center for Nanoscale Technology, National Institutes of Standards and Technology, Gaithersburg, Maryland, USA.

Hide Abstract

In plasmonics surface plasmon polaritons (SPPs) enable the subdiffraction confinement of light. As a result many fascinating topics emerged: e.g. metamaterials [1], surface-enhanced infrared absorption spectroscopy [2] and surface-enhanced Raman scattering. Another approach to confine the light below the Abbe diffraction limit are surface phonon polaritons (SPhPs). As a polar dielectric, SiC supports these localized SPhP resonant modes within the Restrahlen band [3]. For SiC, exceptionally low optical losses can be found, whereas in nanostructured SiC highly localized resonances, resulting in extraordinary quality (Q)-factors, occur.

Here, we demonstrate the active tuning of these narrow SPhP resonances of SiC nanopillars in the mid-infrared (10.3-12.5 μ m) spectral range. This can be realized by using so-called phase-change materials (PCMs) [4, 5], which offer a strong contrast in their dielectric function and electrical conductivity between the different stable - amorphous and crystalline - phases. Recently, they have also been used in the field of tunable plasmonics and metamaterials. For instance, the active tuning of the plasmonic resonances was realized in gold nanodisks by slowly initiating the crystallization of the Ge₂Sb₂Te₅ (GST-225) [6] and low-loss wide-range tuning of antenna resonances was also reported [7].

By using GST-326 with its widely tunable refractive index, the very narrow monopolar and dipolar resonances of the SiC nanopillar arrays can be shifted over a wide spectral range. Furthermore an extremely large tuning figure of merit (FOM) can be achieved.

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11:30 AM - KK8.10

Polymer Photonic Crystals by Self-Assembly

Raymond Andrew Weitekamp¹, Garret M Miyake¹, Victoria A Piunova¹, Benjamin R Sveinbjornsson¹, Harry A Atwater¹, Robert H Grubbs¹.

¹, Caltech, Pasadena, California, USA.

Hide Abstract

We recently reported that brush block copolymers can rapidly self-assemble to form photonic crystals, with tunable reflection spanning the entire visible spectrum. Due to the highly branched nature of this class of macromolecules, the energetic barrier due to chain entanglement is drastically lowered. In this recent work, we have achieved paintable photonic crystals that are chemically robust, and have not shown any signs of degradation for over 30 months. We have developed three unique systems that can achieve reflection peaks in the near infrared, through thermal annealing and direct solvent casting under ambient conditions. We have also demonstrated the ability to blend these copolymers to tune the wavelength of reflection, enabling an economically attractive approach to application-tailored photonic crystals. Our ongoing development of new polymer architectures and self-assembly methods for high fidelity photonic crystals will be discussed.

In our initial study, polystyrene/polylactide brush block copolymers were assembled by solvent casting and

thermal annealing to yield alternating lamellar morphologies with distinct visible reflections. For a given self-assembly method, the peak wavelength of reflection was found to be a linear function of molecular weight, unlike the analogous linear copolymer. Direct thermal annealing of the polymer melt yielded reflection from the ultraviolet (~300 nm) to the near infrared (~1300 nm), corresponding to lamellar periods between ~70 - 430 nm. Transfer matrix simulations were employed to justify the proposed mechanism of the observed reflection spectra. Good agreement with experiment was observed across the entire weight range (1.08×10^6 to 6.64×10^6 g/mol) of the polymers, and for each self-assembly method. The refractive indices of each block were measured by ellipsometry, which ranged from 1.45 - 1.65.

We next demonstrated the synthesis of isocyanate-based brush block copolymers, and their ability to form large lamellar nanostructures by simple solvent casting under ambient conditions (room temperature, from dichloromethane). We also showed that by blending two of these copolymers with different molecular weights, we could tune the peak of reflection across the entire visible spectrum, from 375 - 775 nm. The peak wavelength of reflection increased monotonically with the weight fraction of the blend, with an $R^2 = 0.989$. This work represents a significant step towards truly paintable photonic crystals.

Finally, we have developed a dendronized block copolymer system that exhibits superior nanostructure fidelity. As a result, the gap-midgap ratios of the resulting dielectric mirrors (9-18%) are significantly smaller than their brush block copolymer analogs (17-27%). In the course of this work, we have begun to elucidate the relationship between block copolymer chemical structure and the resonant optical properties of the resulting self-assembled nanostructures.

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