Focused discussion meeting on

Metamaterials and Photonic Nanostructures

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Indian Institute of Technology Kanpur

Abstracts of Invited talks

Surface multiplasmonics and Dyakonov–Tamm waves

Akhlesh Lakhtakia

NanoMM—Nanoengineered Metamaterials Group
Department of Engineering Science and Mechanics
Pennsylvania State University, University Park, PA 16802, USA

Electromagnetic surface waves travel along the interface of two dissimilar materials. Periodic nonhomogeneity normal to the interface in at least one of the partnering materials gives rise dramatic changes. This talk will focus on multiple surface plasmon polariton waves and Dyakonov - Tamm waves when a periodically nonhomogeneous sculptured thin film is a partnering material.

Nanophotonic Structures for Control of Light-matter Interaction

Ganapathi Subramania
Sandia National Laboratories, Albuquerque, NM 87175, USA

Controlling light-matter interaction at the nanoscale is key to next generation of photonic devices that are extremely energy efficient operating at high speeds with small foot prints. One such area of importance is solid state lighting. Photonic crystals, metamaterials and other photonic nanostructures are vital ingredients for achieving such control. In this talk, I will review some of the nanophotonics research activities at Sandia. I will discuss two and three dimensional photonic crystal work at optical frequencies including one of the first logpile photonic crystals with broad photonic bandgap in the visible and near-ultraviolet. These were fabricated from titanium dioxide1 and gallium nitride2 materials using advanced lithographic techniques enabling 100-150nm minimum feature sizes. More recently, utilizing the slow group velocity modes in III-nitride nanowire two dimensional photonic crystals we have demonstrated lasing at very low thresholds with broad range of color tunability.

On the metamaterials front I will discuss nansoscale silver/dielectric based epsilon near zero)(ENZ) structures3 at visible frequencies. Finally, I will discuss 'double-grooved' metallic nanostructures4 that can confine electromagnetic waves to an area (lambda/500)^2 across a broad wavelength band (several microns in the midinfrared) with large transmission. The operation is based on quasistatic response of the metallic structures rather than any plasmonic resonance enabling this broadband behavior.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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Fourier plane imaging of propagation characteristics of surface plasmons, localized surface plasmons and demonstration of plasmon stimulated emission in dye coated metal

A. Arora and A. Krishnan
Department of Electrical Engineering, Indian Institute of Technology Madras
Chennai-600 036, India

We describe experimentally the propagation characteristics of dye coated planar thin metal layers on glass substrate using a non-scanning high speed Fourier plane imaging technique. The momentum images obtained from these structures reveal the propagation length and effective index of fundamental surface plasmon modes in visible region. The effect of thickness of dye coating on the emission characteristics reveal the existence of fundamental surface plasmon mode of high momentum and higher order asymmetrical hybrid modes with lower momenta. It was found that the polarization states of successive modes are orthogonal to each other. The emission characteristics of sub-10 nm thick metal layers coated with dye reveal the existence of localized surface plasmon resonances due to islandic morphology. We further image the coherence properties of the emission by imaging metallic gratings coated with dye and the analysis reveal plasmon stimulated emission in these structures.

Active Plasmonics: Merging metals with semiconductors

Parinda Vasa
Departments of Physics, Indian Institute of Technology Bombay

Future nano-plasmonic devices will most likely be based on active plasmonics, relying on the interplay between the strong intrinsic optical nonlinearities of excitonic nanostructures and the ability of metallic nano-objects to concentrate electromagnetic fields locally. Consequently, the optical properties of hybrid nanostructures comprising active materials, e.g., semiconductors or J-aggregated molecules, and metals are currently attracting considerable attention. In favorable geometries, their properties are governed by a new class of short-lived quasiparticles, exciton - surface plasmon polaritons with hitherto unexplored nonequilibrium dynamics. In this talk, the optical properties of prototypical hybrid nanostructures probed using ultrafast spectroscopy will be discussed. These hybrid structures are progressively becoming important for developing high efficiency optical devices.

Controlling Emission of Quantum Dots in Hybrid Photonic-Plasmonic Metamaterial templates

SRK Chaitanya Indukuri, Haridas M and J. K. Basu
Department of Physics, Indian Institute of Science Bangalore
Banglore, India

Hybrid Plasmonic-Photonic templates have recently attracted intense attention due to the possibility of enhanced LDOS modifications at different length to control the optical properties of emitters like quantum dots. In the first part of the presentation we will discuss how embedding plasmonic nano-antenna in photonic templates leads to control of the photoluminescence (PL) intensity of the quantum dots varying monotonically with increasing fraction of added gold nanoparticles, while the corresponding variation in lifetime of photoluminescence decay shows a unique, non-monotonic variation with gold nanoparticle doping indicative of subtle interplay of LDOS to control the Purcell factor for quantum dot emission. In the second part we will discuss how these photonic template can be converted to plasmonic metamaterial templates and used to control the emission properties of quantum dots including PL anisotropy.

Study of Modal Guidance in Plasmonic Multi-layered Waveguides and Photonic Crystal Fibers

Shyamal K. Bhadra*
Fiber Optics and Photonics Division, CSIR-Central Glass and Ceramic Research Institute, Jadavpur, Kolkata-700032
** skbhadra@cgcri.res.in*

Plasmonic metamaterials and nanophotonics are the most highly rated research topics in optics for the last two decades. At CSIR-CGCRI we have initiated research work in developing metallic-dielectric composite-loaded plasmonic waveguides mostly for sensing applications, and metal embedded single mode and photonic crystal fibers for future need [1].

We tried to study the effect of plasmonic nanostructures on propagation of modal field in multi-layered waveguides and also in hollow-core photonic crystal fibers. It is observed that the light guidance in a metal embedded slab waveguide can be manipulated if we introduce a periodically perturbed surface at the metal-dielectric interface or replace the bulk metal with metal-dielectric stratified composite. Particularly the presence of stratified layers shows optical anisotropy, which can be utilized to realize a plasmonic waveguide with low absorption loss [1].

Recently we have shown the effect of metallic nanostructures in specialty optical fiber. The nonlinearity and zero dispersion wavelength of a conventional step index silica fiber can suitably be tailored in such structures. Cumulative effect of localized plasmon resonance leads to large field enhancement in the near field of nanoparticles doped into the core glass of the optical fiber [2]. Waveguding phenomena in a band gap hollow core photonic crystal fiber can be manipulated if the air holes are replaced by metallic nanowires selectively. We have initiated the work on introducing typical metallic nanostructure in optical fiber to get negative index effect, but fabrication of these kind of structures especially in photonic crystal structure is still a major challenge. Some of these results will be presented.

Acknowledgement: Director, CSIR-CGCRI, CSIR-12th Plan Project and Research students in my group

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Sensors based on optical micro-nano fibers

Rajan Jha
Nanophotonics and Plasmonics Laboratory
School of Basics Sciences, Indian Institute of Technology Bhubaneswar
Toshali Bhawan, Bhubaneswar, India

Diffferent types of optical fiber (Microstructured Fiber, Single Mode fiber and Multimode Fiber) have been used to design and develop sensors based on optical techniques like Surface Enhanced Raman Scattering (SERS), evanescent field and modal interference. Based on these techniques, different types of volatile organic compounds, medicinal dyes and biochemical's have been detected and sensed thereby opening a new window for refractometery, environmental monitoring and food degradation analysis. Also, single mode fiber has been tapered into sub-wavelength regime to design photonic nanowire for sensing applications thereby paving a way for design of ring resonator and ultrasensitive biosensors.

Sub-wavelength, Long-range, Unconventional-polarized Optical Beams

Nirmal Viswanathan and Geo Philip
Beam Optics and Applications Lab, School of Physics, University of Hyderabad
Hyderabad 500046, India
Email: nirmalsp@uohyd.ernet.in

Polarization, coherence and phase characteristics significantly influence the focusing properties of a light beam. For example, high-numerical aperture focusing of radially-polarized light beam results in longitudinally-polarized ‘needle’ beam with small spot size. But the spot size reduction happens by compromising the depth-of-focus (DOF) of the beam. Many applications such as super-resolution microscopy, laser focusing and acceleration of electrons need the DOF to be high and different techniques were employed to increase the efficiency and DOF of longitudinally polarized fields.

We present an axicon based method to generate sub-wavelength spot-size (0.43λ) ultra-long (80λ) longitudinally-polarized beam, purely transversely-polarized beam and polarization singular beams with ‘tailorable’ field structure by appropriately selecting the phase and polarization characteristics of the input beam. The electric field distribution at any point after the axicon is calculated using Rayleigh diffraction integrals. Using the calculated field components the Poynting vector density and three-dimensional degree of polarization are also calculated.

Coupled and Isolated: Plasmonic and Excitonic Nano-Architectures

G.V. Pavan Kumar
Photonics and Optical Nanoscopy Laboratory, Departments of Physics and Chemistry,
Indian Institute of Science Education and Research, Pune – 411008, India

Propagation, confinement and enhancement of optical fields at sub-wavelength scales are important issues pertaining to nano-optics and -spectroscopy. Surface-polaritons based on plasmons and excitons are excellent candidates to study the above-mentioned issues. In this talk, I will: 1) introduce photonic nano-architectures facilitating plasmons and/or excitons which are physically coupled and spatially isolated; 2) emphasize how such geometries can be harnessed for on-chip, polariton-mediated remote-excitation of optical processes such as molecular-Raman-scattering and whispering gallery modes of microsphere; 3) conclude with a discussion on bi-metallic plasmonic-nanosphere architectures, and how they can be utilized for spectroscopic detection of single molecules.

Mode-symmetry requirement for creating photonic Dirac cones in the Brillouin-zone center

Kazuaki Sakoda
National Institute for Materials Science & Tsukuba University

We formulate a degenerate perturbation theory for the vector electromagnetic field of periodic structures and apply it to the problem of the creation of Dirac cones in the Brillouin-zone center by accidental degeneracy of two modes. We derive a necessary condition by which we can easily select candidates of mode combinations that enable the creation of the Dirac cone. We can obtain the analytical solution of dispersion curves and can judge the presence of the Dirac cone. These findings clearly show that the presence of the Dirac cone in the zone center is solely determined by the spatial symmetry of the two modes.

Metamaterials for optical and THz regions

Achanta Venu Gopal
DCMPMS, Tata Institute of Fundamental Research, Homi Bhabha Road
Mumbai 400005, India

In this talk I will present our results on making arrays of asymmetric structures like H and U. Fabrication involving e-beam lithography and dry etching requires optimizing the dose as well as base pattern. While in H type structures the polarization dependent switching was demonstrated at optical and near infrared wavelengths, U-type structures could be useful for light localization. I will present designing metamaterial with arrays of U-type structures for localizing THz fields.

Ultrafast Active Terahertz Metamaterials

Dibakar Roy Chowdhury*, Ranjan Singh, Antoinette J. Taylor, Hou-Tong Chen, and Abul K. Azad
Center for Integrated Nanotechnologies, Materials Physics and Applications Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
Email:dibakarrc@gmail.com

We demonstrate ultrafast and active control of near field coupling between bright and dark resonance modes in terahertz metamaterials. The metamaterial unit cell consists of two orthogonally twisted resonators tightly coupled through near fields. We place ion implanted silicon patch with ultrafast carrier lifetime inside dark resonator split gap to achieve active control of its fundamental resonance that determines the near field coupling within the unit cell. We observed ultrafast dynamical transition of near field coupling between bright and dark resonators allowing the metamaterial unit cell to change its state from coupled to decoupled, and eventually back to the coupled state.

Naturally self-assembled Inorganic-Organic Multiple Quantum Wells (IO-MQWs): Fabrication to photonic applications

Dr. G. Vijaya Prakash
Associate Professor,
NanoPhotonics Laboratory, Department of Physics,
Indian Institute of Technology Delhi, Hauzkhas, New Delhi 110016, India
http://nanophotonics.iitd.ac.in/

Natural self-assembly involves self-aggregation of one or more materials (organic and/or inorganic) into desired structures while templated self-assembly involves interstitial space filling of diverse nature entities into self-assembled ordered/disordered templates (both from molecular to macro levels). At molecular levels, one of the examples of self-assembly is the intercalation strategy wherein the organic/inorganic entities are space-filled within naturally self-assembled crystalline inorganic/organic semiconductor hosts, with an opportunity to produce a very special and tailor-made semiconductor, known as Inorganic-Organic (IO) hybrids. Among several low-dimensional hybrids, two-dimensional hybrids are of special interest. The 2-D (<100> oriented) hybrids are analogous to natural Multiple Quantum Wells (MQW), where inorganic and organic sheets (of molecular level sizes) are alternatively stacked. The carriers are confined within the inorganic layers by low dimensionality of inorganic layer (quantum confinement effect) combined with the large dielectric mismatch (dielectric confinement effect) between the inorganic and organic layers, enabling the formation of stable excitons with large binding energy even at room-temperatures, exhibiting narrow and strong exciton features within the visible region favourable for optoelectronics applications. This talk reviews and explores the advantages of such naturally self-assembled IO-MQWs, structural flexibility, low-cost device-oriented fabrication techniques, and wide range of photonic applications.

Photonic crystal ring resonators for communication and sensor applications

T.Srinivas
Department of Electrical Communication Engineering, Indian Institute of Science
Bangalore 560012

Photonic crystals promise compact integrated optic devices for optical communications and sensor applications. Using appropriate defects in photonic crystals we can form devices like waveguides, couplers and resonators, as an alternative to conventional integrated optic counterparts. One of the emerging devices is a resonator that can be formed by creating a line defect in photonic crystal in the form of a ring, supported by a bus waveguide. In this presentation after a brief review of recent developments, the work initiated on photonic crystal based hexagonal ring resonator affected by a cantilever beam placed below the coupling region will be described, along with modelling and simulation results and fabrication details using silicon photonics technology.

Silicon Photonics: Monolithic Integration of Micron to Sub-Micron Waveguide Devices

Bijoy K.Das
Department of Electrical Engineering, Indian Institute of Technology Madras
Chennai-600 036, India

It has been predicted that the on-chip server will become a reality by 2020 because of the recent advances of SOI based optical interconnect technology. However, optical devices with lower dimension waveguide cross-sections (< 1 micron) are polarization dependent and highly dispersive for broadband operations. This results into a temporary setback to CMOS optical interconnect technologies. Therefore, researchers have been engaged in developing interconnect devices using relatively larger waveguide cross-sections (2-3 micron). In this talk, we will be discussing about monolithic integration of photonics devices with various waveguide cross-sections (microns to submicron) in SOI platform.

Photonic Structured Materials Fabrication and Applications

Joby Joseph
Photonics Research Lab., Physics Department, Indian Institute of Technology Delhi
New Delhi, India.

Fabrication of photonic structures on relevant length scales can be achieved by means of various techniques such as electron or ion beam writing, deposition methods, self assembly, interference lithography etc. The prime advantage of interference lithography here is, to fabricate large area defect-free nano-photonic structures both rapidly and cheaply. The presentation gives an overview of the technique of interference lithography in combination with direct laser writing for photonic structure fabrication, and describes novel reconfigurable phase engineering based fabrication technique which is least complex and provide more flexibility compared to existing techniques, at the same time this technique is capable of fabrication of highly complex photonic structures. Fabrication of complex photonic structures has been achieved with potential for many applications such as, photonic circuits, photonic devices, light extraction, optical tweezers, biosensors, metamaterials etc.

Developments in metamaterials, plasmonics and nanophotonics at IIT Kanpur

K. V. Srivastava[a], Harshawardhan Wanare[b], R. Vijaya[b] and S. A. Ramakrishna[b,]*
[a] *Department of Electrical Engineering, Indian Institute of Technology, Kanpur 208016*
[b] *Department of Physics, Indian Institute of Technology, Kanpur 208016*
*sar@iitk.ac.in

Ultra-Thin Metamaterial Absorbers for Microwave Applications: Metamaterials based absorbers come into picture because of their light-weight and ultra-thin structural properties. The major advantage of using metamaterial absorbers is to tailor the effective permeability and effective permittivity of the concerned effective medium, by designing the structure appropriately. Split ring resonator (SRR) based absorbers were first introduced as metamaterial absorber, but the incident electromagnetic wave had to travel a larger distance. They are successively replaced by Electric Field Driven LC (ELC) resonator structure, where the incident wave has to travel much lesser distance limited to thickness of printed structure. Different types of metallic patches can be proposed to achieve absorption at single or multiple frequencies using ELC resonators. Also, two ELC resonators can be combined to make a single ELC resonator to have dual band absorption. Similar approach has been used by us for designing of dual band, multi-band and wideband absorbers for C-band and X-band applications. Also, structures are designed to have high absorptivity over large range of angle of incidence and polarization. Further the proposed structures have been fabricated and measured for various incident angle as
well as polarization within the anechoic chamber.

Splitting, switching and steering of light beams in photonic structures: We study beam propagation in cross-waveguides made of photonic bandgap materials. It is well known that a single nanorod accompanied with an enclosing cavity can lead to nearly 100% throughput in such cross-waveguide structures. We show that an inclusion of a strategically placed nanorod can accomplish a host of versatile functions such as splitting, steering and switching of light beams within such structures. Simultaneous presence of multiple beams allows for near 100% light being steered into a desired port by controlling the relative phase of the light beams. Furthermore, we show near 95% steering of light into an orthogonally aligned output port, using a couple of nanorods inside the cross-waveguide structure. Essentially, we ask: Can a few strategically placed nanostructures act as light marshals that can split, steer and switch light beams? And indeed, it seems possible!

Lasing in Photonic Crystal Microcavities: The characteristics of band-edge lasing in three-dimensional photonic crystals (PhCs) with fcc structure is studied experimentally and theoretically analyzed by using the complex valued permittivity of the active medium. The possibility of low-threshold lasing as an effect of the reduced group velocity, which enhances the distributed feedback from the ordered layers of the PhC, is explained. The effect of the number of ordered layers on the wavelength of lasing and the lasing threshold are also analyzed. The angle-dependent tunability of the lasing frequency is theoretically demonstrated, thus adding a new thrust to PhC based laser research.

Surface plasmon excitations for enhanced radiation from surfaces: Structured plasmonic surfaces offer a variety of surface electromagnetic resonances of plasmonic origin that depend crucially on the geometric structure and dielectric surroundings. The enhancement of Raman scattering and fluorescence from molecules placed in the vicinity of the surface of corrugated gold gratings will be presented. These corrugated gold gratings of sub-micrometer periods and various symmetries were fabricated by laser interference lithography and subsequent gold deposition. Marker molecules consisting of Rhodamine 6G in PMMA were deposited in well known concentrations as thin films. Surface enhanced Raman scattering and the surface enhanced fluorescence were measured from the Rhodamine 6G molecules and showed large enhancements compared to the molecules deposited on unstructured substrates. Both localized and propagating surface plasmon resonances determine the enhancements and the surface plasmon resonances strongly depend on the periodicity of the gratings and the wavelength of the pump light.