Collective phenomena in photonic, plasmonic and hybrid structures

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Abstract: Preface to a focus issue of invited articles that review recent progress in studying the fundamental physics of collective phenomena associated with coupling of confined photonic, plasmonic, electronic and phononic states and in exploiting these phenomena to engineer novel devices for light generation, optical sensing, and information processing.

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1. Introduction

Photonic and plasmonic nanostructures open up fascinating opportunities for controlling and harvesting light-matter interactions on the nanoscale. In particular, a capability of optical microcavities and plasmonic nanostructures to manipulate the local density of electromagnetic states has already been harnessed for a variety of practical applications in optical communications and biomedical research. Properly-designed photonic and plasmonic nanostructures also provide a useful testbed for the exploration of novel physical regimes in atomic physics and quantum optics.

The next generation of challenges in the design and applications of nanophotonic circuits, fueled by the continuing development of powerful and flexible top-down and bottom-up nanofabrication techniques, lies in understanding and manipulating collective phenomena — phenomena that emerge from the interactions of the individual photonic, plasmonic, electronic and mechanical components. The scattering, radiative and mechanical properties of structures and materials dominated by collective phenomena can differ significantly from those of individual components. Additional degrees of freedom offered by complex heterogeneous nanostructures can be used to obtain new device functionality through coupling-induced tailored control of fundamental physical processes.

The recent trends in the exploration and exploitation of collective phenomena in nanophotonics and plasmonics include (but are not limited to) (i) classical and quantum information processing based on collective phenomena (e.g., optically-induced transparency and Fano-resonance engineering, coupling-mediated light routing and transport, coupling-induced switching architectures); (ii) development of sensors and detectors based on collective modes excitation, such as plasmonic nanorulers, high-efficiency SERS platforms, ultra-sensitive and self-referenced refractive-index, stress and rotation sensors; (iii) development of hybrid optomechanical devices that allow optical control of mechanical motion or can be optomechanically tunable; (iv) collective radiative engineering through manipulation of photon-exciton hybridization and control of collective spontaneous radiation – superradiance; (v) development of novel light sources including entangled photon sources as well as single- and multi-mode lasers; (vi) engineering of novel nano-structured metamaterials with custom-designed optical and mechanical characteristics.

2. Key findings

This focus issue highlights recent progress in this burgeoning research field with 24 invited articles from the leading theoretical and experimental groups around the globe spanning nearly the whole spectrum of research activities mentioned above.

2.1 Collective phenomena in plasmonic structures and metamaterials

The overview of the collective phenomena in plasmonics starts with a comprehensive review article by Mark Stockman [1], which summarizes recent advances in nanoplasmonics and provides a special emphasis on ultrafast, active and gain plasmonics. In particular, the author discusses possible ways to bypass, mitigate, or overcome dissipative losses inherent to nanoplasmonic networks, with the main focus on the Ohmic loss compensation by gain in photonic-plasmonic metamaterials. Next, the contribution from Li *et al*. [2] presents an experimental demonstration of the propagation of the long- and short-range surface plasmon polaritons assisted by stimulated amplification in electrically-pumped quantum wells gain medium.

Collective non-local and long-range coupling effects in plasmonic nanoparticle arrays can be exploited to tailor their spectral and spatial characteristics in both, far-field and near-field zones. For example, Blanchard and collaborators [3] propose a hybrid photonic-plasmonic antenna that exploits coupling between a localized surface plasmon (SP) resonance of a bow-tie antenna and a delocalized photonic mode of a nanoparticle array to provide high electric field enhancement at multiple mid-infrared wavelengths in a single sub-wavelength nano-focus for applications in broadband high-spatial resolution imaging and biosensing. Cheng and colleagues [4] report on the design and fabrication of inverted-pyramidal-nanostructure SERS platforms, which simultaneously achieve high field enhancement and directional far field radiation pattern. However, cooperative coupling phenomena in plasmonic metamaterials may be very sensitive to the array uniformity as well as to the spectral, polarization, and directional properties of the excitation fields. To address these issues, Mousavi and associates [5] investigate suppression of non-local and long-range interactions in periodic arrays of plasmonic double-antenna meta-molecules, which results in the disappearance of the Wood's anomalies and offers new approaches to weakening the metamaterial spatial dispersion and dependence of the optical response on the light incidence angle.

Optical response of complex nano-structured systems is typically obtained via the numerical solution of the full Maxwell equations, however, this process is often time-consuming, and the resulting spectra need careful interpretation. In the search for new tools to design novel plasmonic devices, Langguth and Giessen [6] propose a simple and efficient multiple dipole approximation model, which utilizes the current distributions at the resonances in single objects and can account for the coupling behavior of complex plasmonic nanostructures. In turn, Gallinet and Martin [7] present a simple fitting approach to interpret Fano-like spectral features in the far-field spectra of nanostructures and to relate them to the corresponding near-field intensity profiles, which provides a useful tool to interpret experimentally-observed spectra and to design photonic and plasmonic elements that exploit the Fano effect. On the other hand, the work of Natarov *et al.* [8] demonstrates the importance of rigorous analytical techniques in studying and interpreting collective phenomena in complex plasmonic arrays. By revisiting the problem of scattering and absorption of light by periodic gratings of plasmonic nanowires, they provide deep insight into mechanisms of electromagnetic coupling between SP-type and the grating-type array resonances.

2.2 Collective phenomena in photonic structures

Long-range collective effects in photonic structures and metamaterials, in combination with non-linear properties of the media, play an important role in tailoring their scattering response as well as spatial and spectral distribution of the local density of optical states (LDOS). Extended and local perturbations of the long-range order in photonic structures results in strong light localization, which can be used for enhancing nonlinear material properties or tailoring interactions of light with localized quantum emitters.

As demonstrated by Quan *et al*. [9], collective long-range effects can be used to overcome the difficulties associated with efficient light confinement in low-index-contrast photonic structures. The resulting high-Q photonic crystal nanobeam cavities in polymer material platform with an ultra-low index contrast feature extended evanescent field and small mode volumes and thus provide an ideal platform for ultra-sensitive biochemical sensing. By combining two nanobeam cavities with different resonant wavelengths, Rivoire and colleagues [10] demonstrate a nanocavity with multiple spatially overlapping resonances that can serve as a platform for nonlinear frequency conversion. Shinkawa *et al*. [11] report on realization of low-dispersion slow light and its nonlinear enhancement in photonic crystal (PhC) waveguides fabricated using Si CMOS-compatible process, which enables integration of spotsize converters and simplifies optical coupling from fibers. Tomljenovic-Hanic and colleagues [12] demonstrate that a high-Q PhC cavity can be induced by the presence of a nanodiamond on the air-hole side wall in an otherwise defect-free photonic crystal, making the nanodiamond naturally self-aligned with the cavity mode.

Tailored coupling between confined photonic states in micro- and nanocavities can be used to create bio(chemical) sensors with new sensing modalities. Lei and Poon [13] propose coupled-resonator optical waveguide based refractive index sensors, which realize pixelized spatial detection at a single wavelength. Zhang and co-authors [14] report an ultrahigh sensitivity achieved in a new active sensor structure consisting of a ring laser coupled to an optofluidic tube, which uses the optofluidic tube as the sensing element and monitors the envelope shift of the modulated lasing spectrum.

Resonator-based optical devices and materials are fundamentally bandwidth-limited by the quality factors of individual elements. To address this issue, Qui and colleagues [15] propose a new type of optical circulator based on directional coupling between one-way photonic chiral edge states and conventional two-way waveguides, which has the potential for simultaneous broadband operation and small device footprint. Mitsui and associates [16] demonstrate a way of controlling broadband long-range propagation through chains of microsphere resonators via the mechanism of coupled photonic nanojets by tuning the diameters of micro-joints between neighboring spheres, which serve as optical analogs of nanojet throttle valves.

2.3 Hybrid optoplasmonic architectures

Hybrid resonant metallo-dielectric structures allow combining the best of two worlds: multiple-frequency and high-Q properties of photonic components with the nanoscale dimensions of plasmons, leading to a wealth of novel effects.

In particular, interaction of high-Q photonic modes with the localized SP resonances on noble-metal nanostructures results in giant cascaded field enhancements within sub-wavelength volumes in hybrid optoplasmonic devices. De Angelis and colleagues [17] discuss various approaches to realize adiabatic surface plasmon polaritons compression on metallic conical tips built-in on AFM cantilevers, and demonstrate the use of silicon based photonic crystal cavities to efficiently couple the incident linearly polarized laser beams to the localized SP fields on the tip apex. Melnikau *et al*. [18] report on a hybrid system consisting of cyanine dye J-aggregates and Ag nanoparticles attached to a spherical dielectric microcavity, and demonstrate the concerted action of the high-Q optical states, localized SP oscillations, and nonlinear properties of J-aggregates, which opens exciting possibilities for creating new structures with localized states in the optical spectrum and nonlinear optical response. Chamanzar and Adibi [19] present numerical analysis of a hybrid photonic-plasmonic structure composed of a noble-metal nanoantenna coupled to a microdisk resonator and demonstrates a feasibility of efficient resonant light coupling into SP oscillations on the nanoantenna in the device configurations amenable to planar fabrication by standard lithographic techniques, offering a way for on-chip integration of hybrid devices.

Boriskina and Reinhard [20] propose to go beyond cascaded light focusing and enhancement in optoplasmonic structures and introduce a new approach to realize active spatio-temporal control of light on the nanoscale by manipulating the flow of light through plasmonic nanocircuits via controllable activation of optical vortices around resonantly-excited high-Q microcavities, which paves the way to the development locally-addressable vortex-operated switching architectures for quantum information nanocircuits and bio(chemical) sensing platforms.

2.4 Photon-phonon coupling and manipulation of optical forces

Strong field gradient and scattering forces in the near-field of resonant photonic and plasmonic structures are widely used for trapping and manipulation of micro- and nano-objects and can also be harnessed to actuate optomechanical devices. Sun *et al*. [21] demonstrate wheel-shaped optomechanical resonators that are fabricated on a CMOS-compatible all-integrated Si photonics platform and operate at GHz frequency with high mechanical Q factor in ambient air, opening the way for developing high-speed systems for sensing and wavelength-selective signal routing. Wang and Rakich [22] introduce a generalized response theory of optical forces, which treats electromagnetic systems as multi-port systems with multiple mechanical degrees of freedom, and demonstrate a fundamental link between the scattering properties of an optical system to its ability to produce conservative or non-conservative optical forces. In turn, Rubin and Deych [23] extend the theory of optical forces exerted by the field of an optical cavity on a polarizable dipole to the case when the cavity modes are modified due to interaction with the dipole, which alters the properties of the force and makes all the vector force components non-conservative. Finally, Alexeyev and colleagues [24] propose a novel approach to recovering evanescent waves in the far field, which relies on shifting the frequency and the wave vector of near-field components via scattering on acoustic phonons and enables subwavelength-resolved imaging and spatial spectroscopy.

3. Conclusions, acknowledgments and outlook

The guest editors are very grateful to all invited authors for their effort in preparing high quality manuscripts that highlight the state-of-the-art in fundamental physics and applications of collective phenomena associated with coupling of confined photonic, plasmonic, electronic and phononic states. We hope that the publication of this focus issue will spur further research in this area to address the remaining fundamental and technical challenges, potentially enabling development of novel classes of high-performance devices for light generation, optical sensing, and information processing. We also would like to thank the Optics Express Editor-in-Chief Martijn de Sterke for his strong support of the idea of this Focus Issue and OSA staff and, in particular, Meghan Cook for the technical assistance with the Focus Issue preparation and publication.