Plasmonics

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Surface plasmon photonics ("plasmonics") is an expanding field at the frontiers of optical science and engineering, concerned with the interaction of light with metallic structures. Surface plasmons are coupled electromagnetic/charge-density waves propagating along metal-dielectric interfaces or localized at metal nanostructures. Light suitable for exciting surface plasmons is typically within or near the visible but may extend into the infrared and ultraviolet regions. Metallic structures that support surface plasmons are highly varied, including planar arrangements of metal films, stripes or grooves, metal gratings, and metal nanoparticles such as islands, spheres, rods, or antenna-inspired structures. Surface plasmons can be localized at subwavelength scales, and, for example, are involved in optical transmission through one or several subwavelength holes in a metal film, in what is now referred to as "extraordinary optical transmission." Surface plasmons are intimately involved in the response of "metamaterials" and "metasurfaces" constructed from deep subwavelength metallic features, producing esoteric macroscopic properties such as a negative refractive index, or a permittivity/permeability near zero.

Plasmonics is rapidly gaining importance within the scientific and engineering research communities. Strong interest is due to advances in nanofabrication enabling the realization of an increasingly diverse set of structures and experiments, the existence of many unanswered questions, and the peculiar physical attributes of surface plasmons, such as the existence of energy asymptotes in dispersion curves, complex resonance spectra, high electromagnetic field enhancement, confinement of light to deep subwavelength scales, and high surface sensitivity, which create opportunities for new or improved applications. The field is highly multidisciplinary, drawing broadly from several engineering disciplines (e.g., electrical, materials, chemical) and scientific fields (e.g., physics, chemistry), with results and advances disseminated across several scholarly societies, including the IEEE.

The papers in this special issue review the topical areas as well as promising applications in the rapidly growing field of plasmonics.

Digital Object Identifier: 10.1109/JPROC.2016.2624958

The attributes of surface plasmons and the wide variety of metallic structures that support them have stimulated the research and development of diverse applications within the fields of nanophotonics, biosensing, integrated optics, optoelectronics, and quantum optics, only to highlight a few. Specifically, applications such as biosensors for healthcare, light concentration for solar energy, optoelectronic devices for telecommunications, and near-field scanning instruments are emerging very quickly.

This special issue collects eight invited papers by leading authorities in the field, spanning these topics, providing a good snapshot of the field at this point in time. The issue is separated into two parts: The first collects three papers that review broadly topical areas within plasmonics, whereas the second gathers five papers that review application areas that appear particularly promising.

The first paper, by Shaltout *et al.*, titled "Development of optical metasurfaces: Emerging concepts and new materials," reviews the area of optical metasurfaces. Metasurfaces are 2-D metamaterials, constructed by defining subwavelength features on a plane. Metasurface applications seem within closer reach than applications involving 3-D metamaterials which are more complex and difficult to fabricate. Metasurfaces are very interesting because they enable "flat optics" through wavefront engineering at the subwavelength scale, and enhanced surface nonlinear effects. In their review, Shaltout *et al.* describe the basic operating principles of metasurfaces, materials typically used in their realization, and then survey applications. Specifically, the authors discuss phase-gradient and polarization-gradient linear metasurfaces, nonlinear metasurfaces for second- and third-harmonic generation, difference-frequency generation and four-wave mixing, along with active metasurfaces. They also make a case for using alternative materials such as transparent conductive oxides and metal transition nitrides which may render metasurface applications more appealing for applications.

The second paper, by Rodrigo *et al.*, titled "Extraordinary optical transmission: Fundamentals and applications," reviews the area of extraordinary optical transmission. Extraordinary optical transmission refers to the transmission of light through a subwavelength hole in an opaque metal film with an intensity far greater than expected from Bethe's theory, a phenomenon initially discovered by Ebbesen and co-workers. Rodrigo *et al.* review the basic principles underpinning this phenomenon including the enabling role played by surface plasmons. They subsequently survey the very wide and diverse range of applications that have emerged on the basis of this phenomenon, including (bio)chemical sensors and spectroscopic devices, single-molecule fluorescence, color filters, perfect absorbers, lenses, metamaterials, optical trapping, nonlinear effects, and strong coupling.

The third paper, by Fitzgerald *et al.*, titled "Quantum plasmonics," reviews this emerging area of the field. Quantum plasmonics is concerned with phenomena where the quantized nature of surface plasmons, or of matter with which surface plasmons interact, are of importance. The authors review the major theoretical frameworks relevant to this area, such as the quantum electron theory, nonlocality, and the hydrodynamic model, and some key quantum experiments conducted using surface plasmons, involving entanglement and the Hong–Ou–Mandel effect. Applications including sensing, lasing, and quantum computing are also discussed.

The fourth paper, by Smalley *et al.*, titled "Amplification and lasing of plasmonic modes," reviews the involvement of surface plasmons in optical amplification and lasing (oscillation) processes. The authors review the interaction of propagating and resonating surface plasmons with gain media, and the SPASER process (surface plasmon amplification by stimulated emission of radiation)—a term first introduced by Bergman and Stockman. Specifically, they review the amplification of surface plasmons propagating in planar metallo–dielectric structures and resonating in metallic cavities, ultimately surveying recent plasmonic laser achievements, including nanoparticle lasers, nanowire lasers, planar waveguide lasers, and cavity-free lasers.

The fifth paper, by Krasavin and Zayats, titled "Benchmarking system-level performance of passive and active plasmonic components: Integrated circuit approach," discusses various figures of merit rooted in energy consumption and bandwidth, to compare surface plasmon waveguides. The attenuation, propagation length, mode size (along with ratios of the latter), the bending radius, the coupling separation, and the bandwidth are used to benchmark (passive) waveguides. Several benchmarks involving the modulation bandwidth and the energy consumption per bit are introduced for plasmonic electro–optic, thermo–optic, and all-optical modulators.

The sixth paper, by Brongersma, titled "Plasmonic photodetectors, photovoltaics, and hot-electron devices," reviews this promising area of application. Such devices combine a metallic structure that supports surface plasmons with a photodetection region, operating via internal photoemission or electron–hole pair creation. The subwavelength confinement of surface plasmons and the ability of plasmonic metals to also operate as a device contact are exploited to convey useful characteristics to photodetectors and photovoltaic cells, which can take on highly varied architectures that challenge conventional bandwidth-responsivity tradeoffs. Here Brongersma begins by discussing the pros and cons of involving surface plasmons in such devices, followed by a review of the relevant detection mechanisms. Next, he reviews several plasmonic device concepts, including grating-, antenna-, waveguide-, and metamaterial-based photodetectors, closing with a discussion on plasmonic photovoltaic devices.

The seventh paper, by Haffner *et al.*, titled "Plasmonic organic hybrid modulators—Scaling highest speed photonics to the microscale," discusses a promising class of plasmonic modulators. Similar to photodetectors, the subwavelength confinement of surface plasmons and the ability of plasmonic metals to also function as device electrodes alters conventional energy-bandwidth tradeoffs. Haffner *et al.* describe electro–optic phase modulators based on the metal–dielectric–metal configuration using an organic electro–optic medium to effect the modulating action. Mach–Zehnder interferometers are then implemented and new results are given for IQ modulation, and advanced modulation formats are demonstrated (QPSK, 16 QAM).

The eighth and final paper, by Špačková *et al.*, titled "Optical biosensors based on plasmonic nanostructures: A review," reviews this important area of application. Biosensors were the first applications of surface plasmons to be commercially viable, with present products based primarily on prism-coupled structures, essentially in the Kretschmann–Raether configuration. Ongoing research in this area is carried out along several threads, including biosensing with nanostructured metal surfaces, which is of concern here. In their extensive review, Špačková *et al*. begin by discussing the properties of surface plasmons on various nanostructures along with the concepts underpinning affinity biosensing. They then review the various biosensor interrogation methods used, including wavelength, intensity, and phase, and then delve into various fluidic architectures and surface functionalization techniques. Finally, the authors discuss a variety of biodetection applications, such as the detection of cancer markers, bacteria and viruses, immuno-response biomarkers, drug residues, toxins, heavy metals, and applications in molecular biology.

The purpose of this special issue is to survey the broad landscape of applications enabled by plasmonics, with the aim of becoming a widely read issue for the field and for researchers wishing to enter the area. This project began over two years ago when prospective authors—leading researchers in the field—were first invited to contribute an article. This special issue would not have been possible without the significant time and effort invested by these authors. We would also like to recognize the efforts of the reviewers who contributed helpful suggestions for improvement and provided critical and constructive feedback to the authors, ultimately leading to improved articles. Finally, we would also like to thank the Managing Editor Vaishali Damle and the Senior Publications Editor Jo Sun for their patience, and invaluable support and assistance with this project. ■

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Pierre Berini (Fellow, IEEE) received the B.E.Sc. degree in electrical engineering and the B.Sc. degree in computer science from the University of Western Ontario, London, ON, Canada and the M.Sc.A. and Ph.D. degrees in electrical engineering from École Polytechnique de Montréal, Montréal, QC, Canada.

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Dr. Berini received an NSERC Steacie Fellowship, an NSERC Discovery Accelerator, a Premier of Ontario Research Excellence Award (PREA), the University of Ottawa Young Researcher of the Year Award, a URSI Young Scientist Award, a George S. Glinski Award for Excellence in Research, and is a Canada Foundation for Innovation researcher. He is a Fellow of the Canadian Academy of Engineering and a member of the Optical Society of America (OSA) and the International Society for Optics and Photonics (SPIE). He was an Associate Editor of *Optics Express* and is currently an Associate Editor of *Nanophotonics*.

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