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Photonic Nanomaterials are Lighting the Way

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Photonic nanomaterials have come of age. When Yablonovitch first proposed photonic crystals in the mid 1980′s there seemed no possibility of structuring materials on the micrometer-scale, still less on the nanoscale and, as so often in electromagnetism, proof of concept had to look to the microwave regime. How things have changed. Here, in this Special Issue, we see many techniques demonstrated for sub-wavelength structuring, including shadow growth, in article number 2107917, where Jang-Hwan Han et al. present a comprehensive review on engineering plasmonic nanostructures using this vacuum deposition method that permits a wide variety of 3D-shaped nanoparticles and structures to be fabricated from a large library of materials.

Whereas the first nanomaterials consisted of simple shapes, such as spheres and rods, the progress of fabrication technology (both bottom-up and top-down) opened the way to more intricate patterns, epitomized by chirality, a physical property that is often expressed as a lack of mirror-symmetry in 3D nanomaterials. Several papers in this issue focus on chirality. Shuang Jiang and Nick A. Kotov (article number 2108431) survey the topic of emitting circularly polarized light from chiral inorganic nanoparticles. They discuss nanoclusters, nanoparticles, nanoassemblies, and nanocomposites from metals, chalcogenides, perovskite, and other nanostructures. Andrew Lininger et al. (article number 2107325) present a review on chirality in light–matter interaction. They cover chiral properties of structural light and the role of machine learning in chiral metasurface design. Robin R. Jones et al. (article number 2209282) reveal the potential of plasmonic nanohelices (less than 100 nm in length) for surface-enhanced Raman spectroscopy, showing two ways of probing near-field enhancement generated with circular polarization at chiral metasurfaces. First, they use the Raman spectra of achiral molecules (crystal violet); then they use a single, element-specific, achiral molecular vibrational mode (i.e., a single Raman peak). Chirality is not only expressed in the geometry of matter but also in the shape of propagating light. Haoran Ren and Stefan A. Maier (article number 2106692) review photonic nanomaterials that are useful for twisted light manipulation. They present design principles and exemplary devices for orbital angular momentum generation with metasurfaces. Chirality can also be observed in the energy structure of materials. Accordingly, Liheng Zheng et al. (article number 2204908) show electron-induced chirality-selective routing of valley photons in a WS_2 monolayer with Au nanostructures.

Much of this structural ingenuity is motivated by plasmonic systems that enable nanoscale resonances: nanostructures in a passive dielectric excite displacement currents but the overall interaction with light is weak, whereas plasmonics systems give rise to rich spectra that can be exploited in the variety of fashions that we see in this issue. Yi-Yu Cai et al. (article number 2108104) address photonic noble-metal nanomaterials and examine their chemical and physical properties. Starting from colloidal nanospheres and nanorods, they discuss individual and collective properties of network assemblies and metamaterial imprints.

Particularly significant is the ability to achieve "epsilon near-zero" conditions, which are known to greatly enhance nonlinear phenomena and are candidates for enabling femtosecond switching, leading on to whole new fields of optical research, combining spatial nanostructures with temporal femtosecond structures. In this issue, Soham Saha et al. (article number 2109546) explore epsilon-near-zero-enhanced photonic applications by tailoring the thickness of polycrystalline titanium nitride (TiN) and aluminum-doped zinc oxide (AZO). Their AZO film operates in the telecom wavelength range, extending from 1470 to 1750 nm. Also, Tomasz Stefaniuk et al. (article number 2107023) temporally shape optical pulses using an epsilon-near-zero metamaterial. Upon varying the angle of illumination, they switch the pulse propagation from sub- to superluminal and also to "backward" propagation.

In electronics, the ability to tailor and manipulate the transport of charged carriers has led to the development of many functional devices and components over the past several decades. In photonics, this is achieved by controlling photons and optical waves. However, structuring and sculpting electromagnetic and optical fields in order to endow them with useful functionalities requires properly engineered and judiciously designed materials with feature sizes comparable with the light wavelength, or smaller. With recent extensive development and rapid growth in nanoscience and nanotechnology, numerous new opportunities arise in nanomaterials with sub-wavelength dimensions. These materials offer new light–matter interactions that are being explored by various groups worldwide. In this Special Issue, Emilija Petronijevic et al. (article number 2206005) examine the crystal orientation of ZnO with respect to the biaxiality of a $ZnWO_4$

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matrix, in zinc oxide–zinc tungstate (ZnO–$ZnWO_4$). They report polarized luminescence in the visible part of the spectrum and a metamaterial behavior in the mid-infrared spectral region. Moreover, Aurelian John-Herpin et al. (article number 2110163) map the materials and functionalities that are associated with metasurface-enhanced infrared spectroscopy. These enhancements are both spectral and spatial, improving the molecular-fingerprinting capability of the technique. Additionally, Nikita Nefedkin et al. (article number 2106902) report significantly improved frequency upconversion efficiencies compared to conventional approaches. They propose a counterintuitive pumping scheme, combined with tailored material and photonic engineering of the metasurface, to avoid saturation at practical levels of continuous-wave pump intensities. Furthermore, Parikshit Moitra et al. (article number 2205367) present a programmable all-dielectric Huygens' metasurface made of antimony sulfide (Sb_2S_3) phase-change materials. They create a programmable beam-steering device with $\approx 2\pi$ phase modulation and high transmittance.

This Special Issue would not have been complete without covering some of the many technological applications offered by photonic nanomaterials. Imaging, sensing, and light sources are among the main such applications. In article number 2103262, Jun Guan et al. demonstrate plasmonic nanoparticle lattice devices for white-light lasing. Specifically, they use combinations of dyes (as gain material) and aluminum nanoparticle square lattices of different periodicities to achieve red, green, and blue lasing, which can be combined for white-light emission. Mu Ku Chen et al. (article number 2107465) present a meta-device for applications in intelligent depth perception. Their compact and multifunction stereo vision system adopts an array with 3600 achromatic meta-lenses and a size of 1.2×1.2 mm^2 to measure the depth over a 30 cm range with deep-learning support. The meta-lens array can also work with a light source as an active optical device to project structured light. Zhen Wang et al. (article number 2207923) report on using thermal annealing to tune the colors of photonic glass pigments. They apply heat treatment to block copolymer microparticles with a photonic glass architecture, which tunes their coloration from blue to red. This concept can lead to the production of a thermochromic patterned hydrogel. Xinzhong Chen et al. (article number 2109171) suggest improvements of data acquisition and analysis for nanometer-scale optical imaging and spectroscopy, based on artificial-intelligence and machine-learning algorithms. In article number 2107986, Daria Semeniak and co-authors provide a review of recent technologies for medical diagnosis and for performing clinical test using plasmonic fluorescence enhancements. They highlight the fact that high near-field enhancements can improve the excitation rate, quantum yield, photostability, and radiation pattern of fluorophores.

In summary, photonic nanomaterials, forming 2D and 3D structures, have become essential platforms in various applications ranging from spectroscopy to sensing, imaging, signal processing, and data handling, to name a few. This special issue offers cutting-edge contributions from leading scientists in photonic nanomaterials and it does indeed point the way to the future.

Conflict of Interest

The authors declare no conflict of interest.

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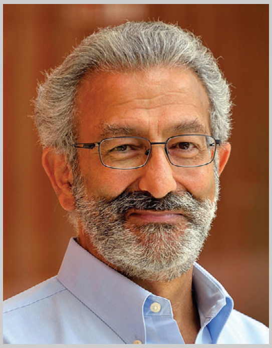

Nader Engheta is the H. Nedwill Ramsey Professor at the University of Pennsylvania in Philadelphia, where he has been since 1987. His interest in specialized materials dates back to the 1980s when he began his work on electromagnetics of novel chiral and complex materials. His current research activities span a broad range of areas including optics, metamaterials, near-zero-index photonics, wave-based analog computing, nano-optics, imaging and sensing, electrodynamics, and physics and engineering of fields and waves.

John B. Pendry has worked at Imperial College since 1981. In collaboration with scientists at Marconi he has designed a series of metamaterials, completely novel materials, with properties not found in nature. These designs were subsequently the basis for new concepts with radical consequences. More recently his interests have focused on time-dependent media where he and his collaborators have uncovered new conservation laws relating to lines of force in amplified fields and conservation of photon number.