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Optical metasurfaces: fundamentals and applications

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Optical metasurfaces are currently an important research area all around the world because of their wide application opportunities in imaging, wavefront engineering, nonlinear optics, quantum information processing, just to name a few. The feature issue "Optical Metasurfaces: Fundamentals and Applications" in *Photonics Research* allows for archival publication of the most recent works in optical metasurface and provides for broad dissemination in the photonics community.

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Optical metasurfaces, consisting of a two-dimensional (2D) or quasi 2D arrays of dielectric or metallic meta-atoms, represent a compact and novel platform for controlling the polarization, phase, and amplitude of light. In the last decade, the concept of metasurface has been explored to design various functional optical devices such as metasurface lenses, metasurface holograms, metasurface nonlinear sources. Compared with conventional techniques, optical metasurfaces provide much more flexibilities to simultaneously control the polarization, phase, and dispersion of light, thus making the metasurface more attractive for various applications. The feature issue aims to showcase the wide variety of topics, towards which metasurfaces have diversified. The targeted scope ranges from advanced scientific topics, which have entered the stage just recently, e.g., nonlinear metasurfaces, topological metasurfaces, and control of light emission from metasurfaces, to topics being already close to commercialization, e.g., flat imaging systems. This should allow the reader to comprehend the connections between the different fields and to draw conclusions on further breakthrough developments. This feature issue includes two review papers and nine research articles.

The combination of nonlinear light-matter interaction and topological effects with the concept of controlling light by metasurfaces bears many new opportunities in fundamental and applied science. The first session of the feature issue includes two review papers in the field of optical metasurfaces. In the first review, Vabishchevich and Kivshar discuss systematically the new opportunities arising from concentrating the nonlinear processes in the ultrathin metasurfaces in contrast to traditional bulk nonlinear optics [1]. In their review, they therefore emphasize multi-frequency and cascaded effects and even touch on nonperturbative and quantum regimes, which are supported by the metasurfaces' resonant excitations, e.g., Mie resonances or bound states in the continuum. In addition, the recent developments in topological photonics have greatly broadened the horizon in designing metasurfaces for novel functional applications. In the second review, You and coauthors introduce the recent developments of topological metasurface from passive to active and then to quantum [2]. First, passive topological metasurfaces based on different physics and phenomena are surveyed, and then they discuss the nonlinear topological metasurfaces and reconfigurable topological metasurfaces. For nonlinear topological metasurfaces, they discuss the nonlinear frequency conversion as well as topological lasers. For the reconfigurable topological metasurfaces, different ways to realize the reconfigurability, such as electrical, optical, mechanical, and thermal, are examined. In addition to classical electrodynamic regime, they also analyze how topological metasurfaces can advance the study of quantum optics, e.g., topological metasurfaces can not only protect single or multi-photon states, but also integrate with quantum emitters to create strongly interacting topological quantum metasurfaces.

Advances in optical metasurfaces are manifested not only in fundamental aspects but also in practical applications, due to their capability of manipulating light at the subwavelength scale, allowing the creation of ultra-thin and integrated optical devices. The second session of this feature issue is on nanofabrication and advanced imaging. One of the most important issues in the field is the large-scale and cost-efficient fabrication of metasurface with high resolution. Tan *et al.* report on a new strategy for high throughput fabrication of large-scale metasurface in the visible light regime by using the chemically amplified resist SU-8 with electron beam lithography (EBL) [3]. The large-scale printing of optical metasurface can speed up the prototyping of metasurface designs. Based on the promising fabrication, practical applications of metasurface become in reach. Moreover, this feature issue includes three research articles on advanced imaging. Lei *et al.* report the concept of multi-dimensional computational imaging (MCI) by combining the principles of both lensless computational imaging and metasurface optics [4]. The metasurface diffuser can simultaneously gather intensity, depth, polarimetric, and spectral information, enabling numerous applications in e.g., medical sciences, robotics, and surveillance. Wang *et al.* report that empowering metasurface by lithium niobate, which is one of the most promising material platforms for multi-functional optical components and photonic circuits, can provide optical phase arrays with an enlarged field of view up to $41.04° \times 7.06°$ [5]. In addition, chromatic dispersion is also a major concern in optical system design for high numerical aperture (NA) optics. The engineerable strong dispersion of metasurfaces is hence a new design degree of freedom, which can be exploited to solve this problem. Baek and coauthors report on an achromatic metalens operating at three different wavelengths spanning the visible spectrum [6]. Combining both theoretical and experimental work, they demonstrate high NAs by simple integration of metalens components with a spatial interleaving method. Their experimental demonstration is based on low-loss hydrogenated amorphous silicon, which despite its limited transmission in the visible spectrum paves the way to realistic applications.

The third session of this feature issue focuses on the manipulation of the multiple degrees of freedom of light fields with artificial structures. Photonic spin-dependent splitting, as a transport phenomenon of photon spin, provides a prominent pathway for manipulating photon spin and developing marvelous photonic devices. Li and coauthors design a metasurface according to the canonic Aharonov-Bohm interferometer, whereby the Pancharatnam-Berry phases arising from opposite spin states transition within pathways introduce path-dependent oscillatory focusing and defocusing behaviors depending on the chiral PB phase shifts, giving rise to oscillatory spin splitting of light along the optical path [7]. A metasurface-type structure is used to realize high-performance solid-state quantum sources as reported by Xu *et al.* [8]. When the In(Ga)As/GaAs quantum dots (QDs) are deterministically coupled to metasurface resonators by using a wide-field fluorescence imaging technique, high purity single-photon emissions under both continuous wave (CW) and pulsed operation modes are demonstrated. Yang and coauthors employ cascaded phase matching by introducing traveling wave modulation to relax the restriction on modulation frequency for parametric amplification [9]. They demonstrate that the signal can be efficiently amplified by a low-frequency pump and show that the proposed mechanism provides a promising opportunity for the practical implementation of intense amplification and coherent radiation based on dynamic modulations.

The fourth session of the feature issue discusses the realization of novel optical functionalities with advanced materials. Most of the so-far demonstrated realizations of optical metasurfaces encode a fixed function in the geometry, distribution and alignment of the underlying meta-atoms. While this allows to address already a wide range of applications, even more would become possible if the metasurfaces' functionality could be dynamically changed or tuned. Phase-transition materials are expected to offer the practical realization of this concept. Li and coauthors examine the fundamental limits of transmission modulation, which could be achieved by using VO_2 as a promising candidate of such materials offering an insulator-metal transition [10]. While considerable material loss limits the transmission modulation of planar VO_2 thin films, the authors are able to considerably enhance the modulation by appropriate nano-structuring of the VO_2 metasurface, bringing many applications into reach. Moreover, transformation optics enables flexible designs of optical materials via coordinate transformations. However, the application of transformation optics in control of hyperbolic waves remains elusive due to the spatial metric signature transition. Tao and coauthors propose a distinct Pythagorean theorem, which leads to establishing an anisotropic Fermat's principle [11]. It provides guidelines for polaritons and nanoscale extreme light manipulation via reshaping the space geometry to hyperbolic. Taking advantage of the natural in-plane hyperbolic polaritons in van der Waals α–MoO_3 layers, they show that by simply modulating the thickness of the α–MoO_3, excellent collimating and focusing behaviors of hyperbolic polaritons can be achieved, opening up a new way for polaritons manipulation.

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