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Editorial

Editorial for the Special Issue "Optical Metasurfaces: Applications and Trends"

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1. Introduction

Optical metasurfaces enable control of light using subwavelength structures. By tailoring their geometry and arrangement, researchers can design optical components with specified phase, amplitude, polarization, and spectral responses. Over the past decade, this approach has advanced metalenses, beam shaping, polarization optics, and optical sensing [1].

As the field has developed, attention has shifted from demonstrating individual optical functions to integrating metasurfaces into practical systems. Imaging systems may require high efficiency together with a wide field of view, broad spectral bandwidth, and aberration correction. Sensing applications also depend on sample preparation, optical readout, calibration, and environmental stability. Fabrication tolerances and design scalability become increasingly important as devices move from small prototypes toward larger apertures and integrated platforms. The Special Issue Optical Metasurfaces: Applications and Trends brings together contributions addressing several of these challenges. The studies cover optical system design, beam shaping, resonant and reconfigurable structures, polarization control, data-driven design, and biosensing. Collectively, they illustrate the versatility of metasurfaces and the need to assess their performance in complete optical systems.

2. Contributions to the Special Issue

A recurring challenge in meta-optical imaging is the simultaneous control of dispersion and off-axis aberrations. Liu et al. [2] addressed this problem by designing a hybrid mid-infrared imaging system that combines refractive lenses with a dispersion-engineered metasurface. Operating over the 3–5 μm band, the proposed system provides a wide field of view within a compact layout. The study illustrates the additional design freedom that metasurfaces can provide alongside conventional optical elements. The importance of system-level evaluation is also reflected in the work of Lu et al. [3], who developed an integrated optomechanical method for analyzing the line-of-sight stability of an off-axis three-mirror space camera. The treatment of structural deformation and alignment sensitivity is relevant to the future integration of meta-optical components into spaceborne instruments.

For deep-ultraviolet beam shaping, Li et al. [4] compared a metalens-based microlens array with a chromium thin-film attenuator at 193 nm. Both approaches produced a uniform beam under static conditions, whereas the phase-dependent microlens array was more sensitive to incident-beam fluctuations. The work highlights the need to assess robustness under realistic conditions alongside nominal optical performance.

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Polarization control and resonant structures are addressed in two complementary studies. Ghimire and Boreman [5] designed and experimentally characterized a reflective meanderline quarter-wave plate for the mid-wave infrared, demonstrating broadband polarization conversion over a range of incidence angles. Chen and Zhang [6] proposed a chiral metasurface based on guided-mode resonance in which a geometric scaling parameter tunes the quality factor while maintaining strong circular dichroism. Their design provides an approach to controlling resonance linewidth and chiral response for polarization-sensitive applications.

The Special Issue also includes studies of tunable optical responses. Lin et al. [7] investigated infrared devices incorporating the phase-change material In_3SbTe_2, including a silicon metasurface configuration that switches between broadband transparency and narrowband thermal emission. Ko and Magnusson [8] studied singular spectral states in asymmetric one-dimensional photonic lattices and showed how changes in air-slit positions can modify guided-mode resonances and filtering responses. These studies explore spectral control through material transitions and structural asymmetry.

As metasurface designs become more complex, data-driven methods can accelerate the search for suitable structures. Bian et al. [9] proposed a transformer-based model for predicting the spectral responses of metasurface unit cells and incorporated it into an inverse-design framework for metalenses. The study demonstrates how predictive models can support the design of devices operating across multiple wavelengths.

Metasurfaces also offer opportunities to enhance light–matter interactions for biosensing. Kumar et al. [10] reviewed the operating principles, design approaches, performance metrics, and applications of metasurface-based optical biosensors. Geng et al. [11] investigated a photonic-metamaterial-based approach intended for cancer biomarker sensing and experimentally characterized wavelength-selective thermal emission from the fabricated structure. Together, these contributions illustrate the potential of metamaterials for bio-sensing and the importance of validating the complete measurement procedure.

3. Future Research Directions

The studies in this Special Issue suggest several directions for future work. First, meta-optical components should be assessed as parts of complete optical systems. Hybrid systems combining metasurfaces with refractive or diffractive components provide additional design freedom. Comparisons should use application-relevant measures such as modulation transfer function, signal-to-noise ratio, usable field of view, and overall optical efficiency.

Second, optical design and computational reconstruction should be developed jointly for computational imaging. A metasurface can encode spatial, spectral, or polarization information in a form suited to a particular reconstruction task. End-to-end design provides a framework for jointly optimizing the optical front end and the reconstruction algorithm [12]. Future studies should account for photon noise, detector sampling, fabrication errors, and calibration drift.

Third, reconfigurable and resonant metasurfaces require closer attention to practical control and stability. Phase-change materials, structural tuning, and other modulation mechanisms can provide multiple optical states, but each involves trade-offs in switching speed, optical loss, power consumption, and endurance [13,14]. For high-Q resonances, fabrication imperfections, material absorption, and environmental changes can substantially affect the response. Future work should therefore consider device performance alongside the requirements of driving circuitry, packaging, and readout systems.

Fourth, biosensing research should emphasize the complete measurement chain. Improvements in resonance sensitivity or field enhancement alone do not establish the performance of a diagnostic test. Surface functionalization, analyte transport, nonspecific binding,

reproducibility, and readout stability can all influence the measured signal. Integration with microfluidics and compact detection systems may address some of these challenges. Comparisons using clinically relevant samples and established analytical methods will be essential for evaluating proposed sensors.

Finally, fabrication and reliability remain central to metasurface development. Large-area patterning, dimensional tolerances, material absorption, packaging, and long-term stability can determine whether a design is practically feasible. Data-driven and inverse-design tools can help address these constraints if manufacturing variations are incorporated into the design process and predictions are validated against fabricated devices. Clearly reported measurement conditions and shared datasets would also support comparison and reproducibility.

The contributions to this Special Issue span resonant structures, optical design, sensing, and system integration. Continued progress will depend on close connections among electromagnetic design, manufacturing, instrumentation, and application-specific validation.

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