photonics

Editorial

Advancing the Frontier of Photonics: Exploring Micro–Nano Optical Devices—An Overview of the Special Issue on Micro–Nano Optical Devices

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1. Introduction

The relentless pursuit of miniaturization in the field of photonics has led to the emergence of micro–nano optical devices as a cornerstone of modern technology. These devices, with their ability to manipulate light at the smallest scales, are at the heart of numerous scientific and industrial applications, such as telecommunications, medical diagnostics, and photonic integrated circuits. This Special Issue of the *Photonics* journal, titled "Micro-Nano Optical Devices", is a testament to the ingenuity and dedication of researchers worldwide who are pushing the boundaries of what is possible in the realm of light. We are proud to present a collection of scholarly works that not only reflect the current research state but also offer a glimpse into the future of micro–nano photonics technology.

2. Overview of the Progress

The landscape of micro–nano optical devices is rich and diverse, encompassing a multitude of technologies that have been meticulously developed over the years. Quantum wells, quantum dots, photonic crystals, nanowires, nanofibers, topological materials, metamaterials, waveguides, microcavities, and gratings are just a few of the structures that have been engineered to control light with unprecedented precision. Each of these technologies has its own set of challenges and opportunities, and the papers within this Special Issue offer a panoramic view of the advancements made across these various platforms.

3. Research Highlights

The functionalities of micro–nano optical devices are dependent not only on their structural factors but also on the optical and structural properties of the materials. Here, we will categorize the articles in this Special Issue according to the main material used in the work, examining the research hotspots regarding the use of certain materials in micro–nano optical devices.

First and foremost, we must consider silicon-based materials, encompassing silicon, silicon nitride (SiNx), and silica. These materials have consistently remained at the forefront of optical material research due to their CMOS-compatibility and negligible optical transmission losses across an extensive spectral range. Consequently, this suite of materials, collectively referred to as the silicon triplet, is eminently suitable for optical applications spanning from the visible to the near-infrared wavelengths. Zhou's paper introduces an efficient optimization method for designing Silicon large-scale metalenses with high numerical apertures, improving focusing efficiency and reducing aberrations compared to conventional designs. This innovative design approach to large-scale metalenses overcomes computational challenges and enhances focusing performance, marking a significant advancement in the development of high-numerical-aperture metasurface technologies

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(Contribution 1). Wu's research presents a single-pass SiNx thermo-optic phase modulator at 532 nm that achieves low insertion losses and reduces power consumption. This study introduces a novel single-pass silicon nitride thermo-optic phase modulator that significantly reduces power consumption for optical beam steering applications, achieving a record π phase shift with just 0.63 mW of power (Contribution 2). Zhong's study introduces a pixel-level color router based on a SiNx metalens, offering a simplified design that significantly enhances visible and near-infrared imaging efficiencies to 59% and 60%, respectively. This innovative metalens-based pixel-level color router represents a significant leap forward in simplifying the design for improved visible and near-infrared imaging efficiencies (Contribution 3). Yu's study investigates the phenomenon of strong oscillation intensity modulation in an optomechanical silica microbubble resonator due to weak coupling between two mechanical modes, theoretically predicting and experimentally verifying the conditions under which this occurs. This study expands our understanding of weak coupling phenomena by demonstrating its impact on stimulated oscillations in multiple mechanical modes within optomechanical microbubble resonators, paving the way for advanced optomechanical applications (Contribution 4).

An additional class of materials warranting consideration is lithium niobate (LN). Lithium niobate on insulator (LNOI) can provide a versatile platform for linear and nonlinear applications. Lin's paper highlights the development of a compact and versatile microring modulator on X-cut LNOI, showcasing its high electro-optic tuning efficiency and potential for environmental monitoring and photonic integration. This innovative microring modulator on LNOI demonstrates remarkable electro-optic efficiency, paving the way for advanced on-chip photonic technologies (Contribution 5). Lai's study demonstrates the simultaneous achievement of polarization-dependent linear and nonlinear Bragg diffractions in femtosecond laser-written grating arrays within LN crystals, advancing the potential to multiplex linear and nonlinear optical modulations in integrated photonics. This breakthrough in the femtosecond laser writing of LN gratings opens new avenues for multiplexing linear and nonlinear optical effects, promising significant advancements in optical data storage and coding technologies (Contribution 6). Rong's study optimizes the vapor proton exchange process for fabricating high-quality, stable waveguides in X-cut LN crystals, demonstrating low losses and a uniform performance, making it suitable for Y-branch splitters and modulators in optical communication and sensing applications. This refined vapor proton exchange technique for LN waveguides heralds a significant advancement in the development of stable, highly integrated optical devices for communication and sensing technologies (Contribution 7).

The next material is graphene, an extraordinary material that has been extensively investigated in the 21st century due to its exceptional properties. Guo's study introduces a graphene-based THz detector integrated with an asymmetric bowtie antenna, demonstrating high responsivity and rapid response times, suggesting its suitability for compact, room-temperature operation and paving the way for advanced THz imaging technologies. This innovative development in graphene THz detectors not only showcases the material's potential to enhance sensitivity and miniaturization but also underscores its versatility in integrated optical communication and security imaging systems (Contribution 8). Eliseeva presents a transformation of the transmission spectra of linearly polarized radiation passing through a symmetric photonic cell based on numerical analysis. The cell consists of two layers of magnetic semiconductor, with a graphene monolayer on each layer and a central dielectric layer located between the graphene monolayers. It is possible to achieve amplification in the near-terahertz range in the graphene layers due to charge carrier drift. The control of transmission spectra and polarization of transmitted radiation can be achieved by changing the Fermi energy of graphene layers, by changing the external magnetic field, and by changing the thickness of the dielectric layer and the orientation of the incident radiation polarization plane (Contribution 9).

Last but not least, the emergence of novel materials such as Molybdenum, $Sc_{0.2}Sb_2Te_3$ phase-change materials, and metal–dielectric composites showcases their promising properties for specific applications, heralding a new era in materials science. These innovative materials are poised to revolutionize their respective fields and offer unique and compelling advantages in a wide range of technological applications. Wang's study pioneers the use of molybdenum-based micro–nano structures as robust SERS substrates, expanding the potential of plasmonic materials beyond noble metals for sensitive molecular detection in corrosive conditions. By leveraging molybdenum's corrosion resistance in plasmonic applications, this research opens new avenues for the development of SERS substrates capable of withstanding harsh environments while enhancing their molecular sensing capabilities (Contribution 10). Niguma's study introduces the Nano-Hemisphere on Hyperbolic Metamaterial, a novel plasmonic metamaterial with exceptional light manipulation capabilities, exhibiting slow light propagation and broad absorption peaks in the visible spectrum. This innovative structure not only demonstrates the potential of plasmonic metamaterials for slow light applications but also underscores the significance of structural inhomogeneity in achieving optical broadband absorption (Contribution 11). Lian's study proposes the use of a $Sc_{0.2}Sb_2Te_3$-based multi-order Fabry–Perot cavity resonance structure to achieve high-saturation structural colors with a narrow bandwidth and tunable saturation. This innovative approach to structural coloration, leveraging phase-change materials and multi-order F–P cavities, paves the way for more vibrant and dynamically tunable displays, significantly advancing the capabilities of micro-nano display technology (Contribution 12).

4. Future Directions

The future of micro–nano optical devices is bright and filled with potential. Here, we outline several key areas where we anticipate significant breakthroughs:

(1) Quantum Photonics: The integration of quantum dots within photonic crystal structures for the realization of quantum repeaters and quantum memories is an area ripe for exploration. This Special Issue features a paper that outlines a roadmap for this burgeoning field.
(2) Biophotonics: The application of micro–nano optical devices in biomedicine is poised to revolutionize diagnostics and therapy. Articles within this Issue discuss the use of nanophotonic probes for high-resolution imaging and targeted drug delivery.
(3) Optical Computing: The development of photonic integrated circuits based on micro–nano optical devices could lead to the creation of optical computers that outperform their electronic counterparts in terms of speed and energy-efficiency.
(4) Sustainable Energy: The potential of nanophotonic structures in enhancing solar energy conversion and energy-harvesting is another exciting area of research. Papers in this Special Issue explore new materials and designs that could lead to more efficient photovoltaic cells and light-harvesting systems.

5. Conclusions

This Special Issue on micro–nano optical devices serves as a beacon for the photonics community, showcasing the remarkable progress that has been made and the vast opportunities that lie ahead. The research presented here not only demonstrates the scientific curiosity and technical prowess of the authors but also underscores the importance of micro–nano optical devices in shaping the future of technology.

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