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Perspective

Metasurfaces: Shaping the future of photonics

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A metasurface, often abbreviated as MS, represents a thin, artificially crafted surface consisting of an assembly of subwavelength structures that interact with light in distinct manners. Typically, smaller than the wavelength of the light they engage with, these structures empower precise management of light properties such as polarization, phase, and amplitude. The operational mechanism of MSs hinges upon the precise arrangement and design of these subwavelength structures [1]. Upon encountering an MS, light undergoes diverse transformations dictated by the attributes of the nanostructures, encompassing factors like their size, shape, and spacing. Through careful manipulation of these parameters, scientists can customize the optical response of the MS to achieve specific functionalities. For instance, by engineering an MS with varying nanostructure dimensions, it becomes possible to manipulate the direction of light propagation, concentrate light into desired configurations, or even generate intricate wavefronts for applications such as holography. MS-based holographic displays promise immersive visual experiences, bringing virtual objects to life with vivid colors, sharp details, and wide viewing angles. Moreover, the compact form factor and scalability of MS designs open doors to applications in augmented reality, 3D visualization, and head-up displays, revolutionizing how we interact with digital content in various contexts. In essence, the working principle of MSs revolves around harnessing nanoscale structures to exert unparalleled control over light, paving the way for a broad spectrum of innovative photonic devices and applications

MSs possess an extraordinary ability to finely manipulate light on the nanoscale, offering immense potential for revolutionizing photonics. By customizing MS designs, researchers can fabricate flat, lightweight components like lenses, waveplates, and holograms, supplanting traditional bulky optics with thin, planar structures. This miniaturization not only streamlines existing technologies but also paves the way for diverse applications spanning telecommunications, imaging, sensing, and quantum technologies. In the realm of imaging, MSs show great potential for improving resolution, contrast, and depth perception. They possess the capability to rectify aberrations, enable super-resolution imaging, and streamline the creation of compact, lightweight lens systems tailored for cameras and microscopes [2]. Additionally, MSs are adaptable across a spectrum of wavelengths, spanning from visible light to THz radiation, rendering them suitable for diverse imaging techniques such as medical imaging, remote sensing, and industrial inspection. As advancements in MS design and fabrication persist, we stand on the cusp of a transformative era in photonics, where the manipulation of light is constrained only by the boundaries of human imagination.

MSs offer a broad array of practical uses across various domains thanks to their capacity to manipulate light in innovative manners [3]. Fig. 1 showcases the material platforms and functionalities that MSs can incorporate. One variety of MS termed flat lenses has attracted considerable attention for its potential in imaging and sensing applications [4]. These lenses sidestep the constraints of traditional bulky optics by presenting ultra-slim, lightweight designs while upholding top-notch performance. Wide field-of-view (FOV) optics play crucial roles in various optical systems used for imaging, display, sensing, and beam steering. Traditional refractive wide FOV optics typically consist of multiple stacked lenses, which can lead to bulky, heavy, and expensive setups. Metalenses offer a promising alternative for achieving wide FOV optics without the need for complex lens assemblies.

However, metalenses encounter substantial compromises concerning achromaticity, signal-to-noise ratio (SNR), numerical aperture, and aperture size. Consequently, achromatic metalenses have been confined to NIR wavelengths, small diameters (typically 10–40 μm), low numerical apertures (<0.3), or diminished focusing efficiencies. Overcoming these compromises necessitates the fabrication of nanopillars that are significantly taller, possess higher aspect ratios, and are more geometrically intricate than those reported using materials visibly transparent. Hybrid achromatic imaging systems combine diffractive and refractive optics, leveraging their opposing dispersion properties to correct chromatic focusing errors effectively. This approach strikes a favorable balance between lens size and achromaticity, outperforming diffractive lenses in chromatic correction and conventional refractive doublets in terms of thinner geometries. Richards et al. [5] demonstrated densely integrated aligned refractive and diffractive elements using subsurface 3D printing inside mesoporous hosts, resulting in thin high-performance hybrid achromatic imaging micro-optics.

Deep learning (DL) techniques hold significant promise in addressing key challenges associated with metalenses, including achromaticity, SNR, and numerical aperture (NA). One of the primary issues with metalenses is their inherent chromatic aberration due to the dispersion of different wavelengths of light. DL algorithms can be employed to design and optimize the nanostructures

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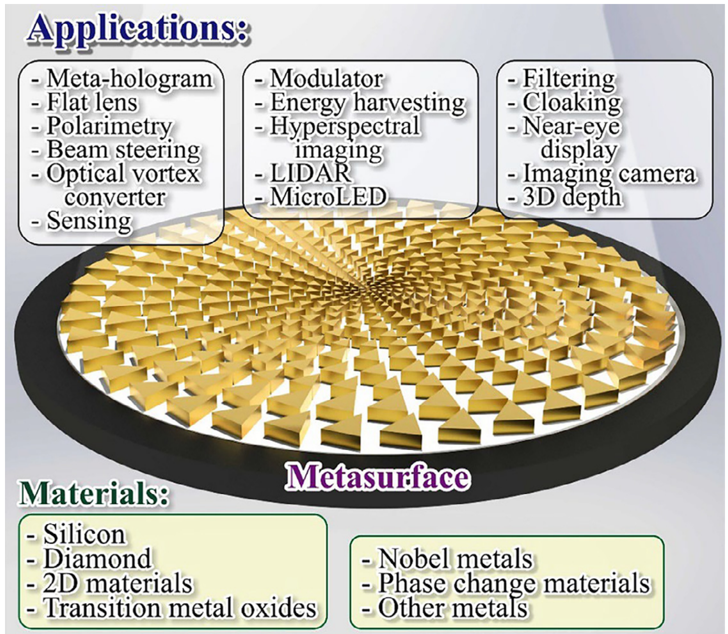

Fig. 1. (Color online) Material platforms and the potential applications of MSs.

of metalenses to achieve achromatic performance, ensuring consistent focusing across a broad spectrum of wavelengths. Additionally, DL models can enhance the SNR of metalenses by developing algorithms that effectively denoise captured images, compensating for any inherent noise in the imaging process. Furthermore, DL can optimize the NA of metalenses by fine-tuning the geometry and distribution of nanostructures, enabling better light collection efficiency and resolution. By leveraging the power of DL, metalenses can be enhanced to overcome these fundamental limitations, leading to improved performance and broader applications in advanced optical systems.

Another kind of MS, known as waveplates, serves in polarization management, facilitating advancements in optical communications and imaging setups. Through the strategic arrangement of subwavelength structures, MSs can manipulate the polarization properties of incoming light with unprecedented accuracy. This capability holds immense potential for enhancing polarimetric measurements in various applications, including remote sensing, material characterization, and optical communications [6]. MS-based polarimeters promise improved sensitivity, allowing for the detection of subtle changes in polarization that conventional techniques may overlook. Furthermore, the versatility of MSs enables the development of compact and lightweight polarimetric devices, facilitating their integration into portable and space-constrained systems. MSs also contribute to crafting holographic displays boasting unparalleled resolution and lifelike qualities, enriching entertainment, and visualization experiences. Moreover, MSs find utility in terahertz and infrared spectroscopy for chemical sensing and material analysis, alongside their role in quantum technologies for manipulating and detecting individual photons. The adaptability and versatility of MSs persist in propelling innovation across a spectrum of fields, heralding a future where precision and impact in light manipulation reach new heights. By precisely tailoring the geometry, material properties, and arrangement of meta-atoms, MS absorbers can achieve near-perfect absorption across a desired wavelength range. This ability makes them valuable in various applications, including solar energy harvesting, thermal imaging, and stealth technology [7].

Cloaking with MSs offers an innovative method to make objects invisible by manipulating light-matter interactions at the nanoscale. This groundbreaking technology has diverse applications, from military stealth to medical imaging and telecommunications. MSs can bend or redirect light waves around an object, creating a cloaked region where it becomes undetectable to certain wavelengths of light [8]. By controlling electromagnetic wave propagation, MS-based cloaking devices conceal objects from radar and infrared sensors. Despite facing challenges like limited bandwidth and viewing angles, ongoing research in MS design promises practical cloaking solutions in the future.

In our opinion, MSs hold great promise in revolutionizing neuromorphic computing by enabling efficient manipulation of electromagnetic waves at the nanoscale level. In this context, MSs can be utilized to design compact and versatile components for neuromorphic systems, such as tunable filters, beam steering elements, and phase shifters. By exploiting the unique properties of MSs, such as subwavelength confinement and tailored dispersion characteristics, novel devices capable of emulating synaptic connections and neuronal behavior can be engineered in a highly efficient way [9]. Moreover, the programmability and adaptability inherent to MS-based devices offer unprecedented flexibility in configuring neural networks and implementing complex computational tasks, paving the way for the development of ultrafast and energy-efficient neuromorphic computing platforms

MSs have rapidly emerged as key components in commercially available photonic devices, driving advancements in various industries [10]. While many companies are actively developing metalenses, Metalenz stands out as the pioneer in announcing the commercial implementation of its technology in consumer devices. In a significant move, Metalenz formed a strategic partnership with semiconductor giant STMicroelectronics (ST, based in Geneva, Switzerland) in June 2022, effectively replacing traditional multi-element optical systems with Metalenz's innovative optics solution [10]. Initially, Metalenz's technology will serve as a crucial component within ST's time-of-flight (ToF) module, known as Flight-Sense. This ToF module utilizes the speed of light to precisely measure proximity by calculating the time taken for a photon to travel to and from a surface. Key consumer devices integrating ST's ToF module include smartphones, drones, robots, and vehicles.

Meta-devices are pivotal in propelling ToF technology forward, augmenting its versatility across various applications [11]. Crafted with metamaterials or MSs, these devices harbor distinctive traits absent in naturally occurring materials. Within ToF applications, meta-devices are harnessed to manipulate electromagnetic waves, predominantly light or laser pulses, with meticulousness and efficacy. They are tailored to govern wave propagation, reflection, refraction, and scattering, thereby empowering superior sensing and imaging capabilities. Meta-devices within ToF technology foster the development of compact, high-performance sensors characterized by enhanced accuracy, range, and resolution. Leveraging the potency of metamaterials, ToF devices attain finer control over signal propagation, fostering advancements in realms such as 3D imaging, gesture recognition, robotics, and automotive safety systems.

In telecommunications, MS-based antennas enable compact and efficient signal transmission, enhancing the performance of wireless communication systems. Similarly, MS-based optical filters and modulators are integral to next-generation optical networks, offering precise control over the transmission and manipulation of light for data processing and routing. In consumer electronics, MS-enhanced displays and cameras deliver improved image resolution and color accuracy, enhancing the viewing experience for users. Additionally, MS-based sensors find applications in medical diagnostics, environmental monitoring, and industrial quality control, offering high sensitivity and specificity for detecting target molecules or materials [12]. The commercialization of MS-enabled photonic devices underscores their practical significance and underscores their potential to transform diverse sectors through innovative light manipulation techniques.

MSs offer transformative potential in free-space optics by providing a compact and versatile alternative to traditional bulky optical components. These ultrathin structures, composed of subwavelength meta-atoms, can manipulate light waves at will, enabling precise control over phase, amplitude, and polarization. In free-space optical systems, MSs can replace bulky elements such as lenses, mirrors, and beam splitters with ultrathin planar structures, drastically reducing size, weight, and complexity. By integrating MSs into optical systems, engineers can achieve unprecedented levels of miniaturization and integration, opening new possibilities for lightweight and portable optical devices for applications ranging from augmented reality headsets to LiDAR sensors. Moreover, the programmability and tunability of MSs allow for dynamic control of light propagation, enabling adaptive optics and advanced functionalities not achievable with conventional optical components. Overall, MSs represent a paradigm shift in free-space optics, offering compactness, flexibility, and performance enhancements that pave the way for next-generation optical systems in diverse fields [13].

We assert that contrary to conventional static MSs, reconfigurable MSs provide the capacity to modify their optical characteristics as needed, facilitating diverse functionalities and applications. This adaptability holds immense value in numerous situations where real-time manipulation of light is essential, such as in adaptive optics systems, beam steering devices, and optical communication networks [14]. Reconfigurable MSs can rapidly adjust their optical response to changing environmental conditions or user requirements, offering enhanced performance and functionality compared to fixed counterparts. Moreover, these MSs pave the way for the development of tunable lenses, phase shifters, and filters, facilitating advancements in imaging, sensing, and communication technologies. The importance of reconfigurable MSs lies in their ability to provide agile and adaptive solutions for manipulating light, driving innovation in photonics and beyond.

Two-dimensional (2D) materials play a pivotal role in advancing MS technology, offering unique properties that enable enhanced control over light-matter interactions. Graphene, for instance, stands out due to its exceptional conductivity and tunability, allowing for dynamic manipulation of electromagnetic waves across a broad spectrum. By integrating graphene into MS designs, researchers can achieve reconfigurable functionalities, such as phase modulation and beam steering, through electrical gating [15]. Other 2D materials like transition metal dichalcogenides (TMDs) exhibit intriguing optical properties, such as strong light-matter interactions and sizable bandgaps, making them suitable for various MS applications, including nonlinear optics and photodetection. The atomically thin nature of 2D materials also facilitates seamless integration with conventional MS fabrication techniques, offering versatility and scalability. Leveraging the unique properties of 2D materials in MS designs holds immense promise for developing next-generation optical devices with unprecedented performance and functionality.

As comprehension of the subject deepens, researchers pioneer another exceptional class of multifunctional MSs poised to serve a multitude of purposes. Multifunctional MSs present a myriad of opportunities spanning diverse fields, ranging from telecommunications to biomedical imaging. Notably, their ability to execute multiple functions concurrently within a compact space defies the bulkiness and constraints of traditional optical components. This feature not only simplifies device design but also boosts performance and efficiency. Whether directing light beams, altering polarization states, or molding spectral responses, multifunctional MSs showcase unmatched versatility, becoming indispensable in the pursuit of advanced technological solutions. Further exploration into their capabilities and refining fabrication methods promises to broaden their potential applications, catalyzing transformative impacts across various industries and domains. Nonetheless, challenges like fabrication scalability, material loss mitigation, and integration complexities persist, highlighting the imperative for ongoing research and innovation to fully unleash the capabilities of these extraordinary structures.

MS fabrication encompasses a diverse array of techniques tailored to meet specific design requirements and material characteristics. One prevalent approach is electron-beam lithography (EBL), prized for its ability to achieve high resolution and precision in crafting nanostructures on substrates. Photolithography, employing masks and light exposure, facilitates the mass production of MSs featuring relatively simpler designs. Nanosphere lithography exploits self-assembled monolayers of microspheres to generate periodic patterns, well-suited for certain MS applications. Direct laser writing (DLW) utilizes focused laser beams to induce localized material modifications, shaping desired structures with precision. Nanoimprint lithography (NIL) enables large-scale replication of nanostructures by pressing a mold into a polymer resist. Fan et al. [16] have demonstrated a meta-II near-eye display (NED) that combines a commercial micro-display and a metalens array. The metalens array was fabricated using large-area NIL technology, and a novel real-time rendering algorithm was proposed to generate the elemental image array (EIA). The bottlenecks of video-rate meta-II displays were solved through hardware and software efforts. Additionally, a see-through prototype was built based on this meta-II NED, demonstrating the feasibility of augmented reality. In another instance, a meta-hologram was introduced, constructed from a nanoparticle-embedded resist (nano-PER) achieving a groundbreaking efficiency record of 96.9% [17]. This was achieved through fabrication using a high-throughput one-step NIL manufacturing process. It was confirmed that the optical properties of the nano-PER are adequate to generate high-efficiency meta-holograms, surpassing the performance of other low-loss dielectric materials. Furthermore, techniques like atomic layer deposition (ALD) and physical vapor deposition (PVD) are instrumental in depositing thin films with meticulous control over thickness and composition. Each of these fabrication methods has distinct advantages and constraints, driven by factors such as resolution, scalability, and material compatibility, thereby propelling ongoing research endeavors aimed at refining MS fabrication techniques.

MSs, though promising in their ability to manipulate electromagnetic waves with unprecedented precision and efficiency, face several challenges and limitations. Challenges such as fabrication imperfections, material losses, and sensitivity to incident angle or polarization can affect the efficiency of MSs [18]. These challenges may lead to reduced performance in certain scenarios. Despite notable advancements, the efficiency of technologically relevant silicon metalenses remains constrained by inherent material losses above the bandgap. Additionally, the proposed achromatic metalens, which uses transparent, high-index materials like titanium dioxide, faces limitations due to their small thickness and demonstrate relatively low focusing efficiency at longer wavelengths [19]. Consequently, metalens-based optical imaging within the biological transparency window has been significantly restricted thus far. Wang et al. [20] suggested a polarization-insensitive, broadband titanium dioxide achromatic metalens has been experimentally demonstrated for applications in near-infrared biological imaging. Large-scale fabrication technology has been developed to produce titanium dioxide nanopillars with record-high aspect ratios, featuring pillar heights of 1.5 μm and $\sim 90^\circ$ vertical sidewalls. The demonstrated metalens exhibit a dramatically increased group delay range, and the spectral range of achromatism has been substantially extended to the wavelength range of 650–1000 nm, with an average efficiency of 77.1%–88.5% and a numerical aperture of 0.24–0.1. This research represents a solid step towards practical applications of flat photonics.

Optimizing design and fabrication techniques emerges as a potential solution to mitigate losses and enhance the overall efficiency of MSs. Concurrently, progress in materials science facilitates the creation of new materials with diminished optical losses, poised to bolster MS performance upon integration. Furthermore, ongoing research delves into innovative methodologies like active tuning and dynamic control mechanisms, aiming to dynamically modify MS properties in real time, thereby tailoring their efficiency to suit specific applications.

Besides, achieving broadband functionality across a wide range of frequencies remains challenging due to inherent material constraints and design complexities. Moreover, MS designs often rely on intricate geometries and nanoscale features, demanding advanced fabrication techniques that may not be scalable or cost-effective for large-scale production. Another limitation lies in their narrow field of view, restricting their applicability in certain scenarios. Additionally, the integration of MSs with existing devices and systems presents compatibility and interfacing challenges. Therefore, we believe that addressing these issues requires interdisciplinary efforts spanning material science, nanotechnology, optics, and engineering to unlock the full potential of MSs in various applications.

Conflict of interest

The authors declare that they have no conflict of interest.

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