COMMENTARY

PHOTONICS INSIGHTS

Electrifying the field of metasurface optics

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The field of optics has developed sophisticated ways to manipulate the flow of light by polishing pieces of glass or molding shapes from plastic. Many emerging applications, including displays, sensors, imaging systems, and communication devices, are now demanding a more favorable size, weight, power, and cost (SWaP-C) for the optical components to create ultra-compact optoelectronic systems. This is especially true when such systems are incorporated in wearables, drones, the internet of things (IoT), and point-of-care diagnostics where weight and size come at a premium. The need to miniaturize optical elements has propelled the field of metasurfaces[1–5], which has taught us how to create essentially planar optical elements by judiciously nanostructuring thin films of metal and semiconductor materials. Metasurfaces provide major advantages over conventional optics (e.g., a lens or prism) through their ability to decouple shape from function. For metasurfaces, it is the nanopattern that controls the optical function. This brings tremendous design flexibility in arranging the myriad light-scattering nanostructures in a metasurface, opening valuable new ways to manipulate optical wavefronts and mitigate aberrations. Fortunately, a developing intuition about the operation of metasurfaces and the widespread availability of powerful rapid-design software tools based on topological optimization, inverse design, and deep-learning principles has facilitated rapid progress in their development[6–8]. As a result, we have been able to create a wide range of high-performance small-form-factor optics components, realizing very high numerical apertures and minimal aberrations, which enable us to focus or redirect light, control the state-of-polarization, produce holograms, perform nonlinear optical functions, deliver multi-functionality, and enable complex light-field imaging. However, despite the notable progress, most metasurfaces have remained passive, merely converting one wavefront into another.

Writing in *Photonics Insights*, Ding *et al*.[9] review one of the most recent frontiers in the metasurface field, which is aimed at electrifying metasurfaces. Here, the goal is to endow them with a variety of dynamic functions and facilitate reconfiguration through external electrical stimuli. If this can be achieved with high optical efficiencies, high speed, and low electrical power consumption, it will unlock a plethora of advanced capabilities in modern optics. One can imagine flat optical imaging systems that can dynamically reshape light fields to, e.g., tune the focus of a lens, tailor a polarization state, steer light beams, adjust wavefronts in real-time to mitigate aberrations, or alter resonant filtering functions. The review describes how such dynamic functions can impact a broad spectrum of technologies including medical and computational imaging, augmented and virtual reality (AR and VR), light detection and ranging (LIDAR), displays, adaptive optics, and (quantum) optical communication and processing. Current research is also opening up entirely new directions for explorative science as dynamic metasurfaces are not bound by the fundamental limits of static elements[10] and can, e.g., break Lorentz reciprocity or achieve Doppler-like wavelength shifts. This opens the door to new types of devices capable of providing optical isolation without the presence of magnetic fields and shows the way to realize topologically protected systems.

The review provides a comprehensive overview of the key fundamental mechanisms by which metasurfaces can be tuned electrically. These mechanisms are intimately linked to materials and structures whose optical properties can display dramatic changes upon an electrical stimulus. As the interaction times/lengths for light waves that are traversing metasurfaces are very short, materials are needed that can display unity-order changes in their refractive index. An impressive amount of creative research is discussed on electronic and structural phase change materials, 2D materials with strong excitonic material resonances, microelectromechanical devices, semiconductor nanostructures that display Stark or free-carrier dispersion effects, electrochemical materials, transparent conductive oxides, and electro-optic materials. Even when metasurfaces are made from materials whose optical properties are hard to tune (e.g., noble metals), it is still possible to dynamically change their behavior by altering the dielectric environment[11–13]. Here, we can take advantage of the fact that metasurfaces have an open structure with many voids between the scattering nanostructures, which allows easy infiltration with liquids and soft materials. This has made it possible to, e.g., create tunable metasurfaces using mature liquid crystal technology[14–17] and microfluidics[18].

The review also illustrates how to benefit from plasmon[19–21], Mie[16,22], materials[23,24], and guided-mode resonances[25–27] to boost light–matter interaction and achieve larger tunability by exploiting resonant behaviors. In general, the enhanced light–matter interaction allows metasurfaces to do more with less, reducing materials and fabrication costs. Resonances also bring the valuable opportunity to selectively interact with light waves at a desired frequency, polarization, or angle of incidence. It is worth noting that the optical properties of resonant metasurface building blocks are as much determined by their geometric shape as by their material properties. This often brings

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flexibility in material choices and frequently makes it possible to select earth-abundant and environmentally friendly ones. This is why metasurface science is making it possible to move towards more sustainable fabrication and recycling pathways than those available for conventional optics.

Reducing power consumption in dynamic metasurfaces with nanoscale pixel arrays is shaping up as one of the major challenges moving forward, rivaling that of densely integrated electronic circuitry. Fortunately, the two-dimensional (2D) form factor of metasurfaces affords facile, dense integration with electronics. The ability to stack 2D metasurface optics directly on top of essentially planar electronic systems brings the benefit of ultrahigh operational speeds and enables minimized power consumption. However, in the identification of new metasurface tuning mechanisms, it is very important to identify ones that can benefit from low electrical switching powers and low optical losses. In this regard, nonvolatile structural phase change materials and certain microelectromechanical devices, which only consume power during switching events, can bring valuable benefits. For this reason, advances in device technology require a continuous search for better materials. The active search for structural phase change materials that display low electrical switching powers and low optical losses in the visible, such as antimony sulfide (Sb_2S_3), is one example[28,29].

Given the many amazing traits of dynamic metasurfaces and the promising prototypes, it is worth asking what is needed to commercialize them. One key roadblock is the accessibility of low-cost, large-area nanofabrication techniques. For some applications, we can benefit from the advances in the semiconductor chip industry where phase-shift lithography as well as deep and extreme ultraviolet (UV) lithography technologies have been developed to provide the required nanoscale spatial resolution. It should come as no surprise that early applications of metasurfaces[30] have emerged in consumer electronics[31] and automotive sectors[32], where the capabilities of semiconductor foundries can be leveraged. Certain large-area applications in aerospace, solar, medical, chemical, and civil engineering require the printing of nanostructures at large scales and very low costs. A variety of new printing technologies based on soft lithography[33,34], including nanoimprint lithography[35,36] and transfer printing, are currently demonstrating their potential to create metasurfaces for solar energy[37,38], photonic devices[39], and biosensor technologies[40,41]. Another challenge is the fabrication reproducibility and long-term stability of electrified devices under continuous operation. Here, each material system presents its own challenges, making research and development of encapsulation oxides, adhesion layers, and contact interfaces increasingly important.

As a closing point, it is worth noting that there are additional opportunities for electrified metasurfaces beyond the dynamic manipulation of light fields. Subwavelength structuring of metals and semiconductors can also enhance and manipulate light absorption[42–55] and emission[56–60] processes. For this reason, we have seen their successful introduction in solar cells[61–63], CMOS image sensors[51], solid-state light-emitters[60,64,65], and displays[66]. Nanopatterning of the continuous metal, semiconductor, and insulating layers in these devices has increased performance and enabled new optoelectronic functions. This area is ripe for commercialization, as the optoelectronic devices industry already makes extensive use of advanced nanostructuring techniques. For this reason, existing commercially-viable technologies may be re-envisioned by incorporating a series of strategic patterning steps into their fabrication process. Looking ahead, the capability to tune near-field light-matter interactions between individual emitters and a metasurface opens exciting possibilities for space-time quantum metasurfaces such as dynamically structuring light on the single-photon level[67–69]. There is also a broad range of opportunities for using metasurfaces to compact imaging systems and letting metasurfaces perform analog computing functions to extract more information from optical scenes[70–77].

We are at the start of a revolution in the development and commercialization of metasurface technologies. It is also clear that the fusion of semiconductor electronics and metasurface optics provides many new opportunities and application areas. It will be exciting to watch where the rapid electrification of metasurface technologies will take us in the coming years. The review by Ding *et al.*[9] in *Photonics Insights* will serve as an incredible valuable resource for those involved in pushing the boundaries in the field.

Acknowledgments

N. A. G. and M. L. B. acknowledge support from a US Department of Defense Multidisciplinary University Research Initiative (MURI) grant (No. FA9550-21-1-0312) and US Department of Energy grant (No. DE-FG07-ER46426). N.A.G is grateful to the German National Academy of Sciences Leopoldina for its support via the Leopoldina Postdoctoral Fellowship (No. LPDS2020-12).

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