

Review article

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The future and promise of flat optics: a personal perspective

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Abstract: Metasurfaces enable the redesign of optical components into thin, planar and multifunctional elements, promising a major reduction in footprint and system complexity as well as the introduction of new optical functions. The planarity of flat optics will lead to the unification of semiconductor manufacturing and lens-making, where the planar technology to manufacture computer chips will be adapted to make CMOS-compatible metasurface-based optical components, ranging from metalenses to novel polarization optics, areas where I foresee the greatest technological and scientific impact.

Keywords: flat optics; metalenses; metasurfaces; planar optics; wavefront engineering.

1 Introduction

I am very honored to have this special issue dedicated to me, and I am grateful to the distinguished colleagues who have contributed to this effort and, in particular, to Andrea Alù, Marko Lončar and Vlad Shalaev, who as editors have pulled it all together.

I would like to use this opportunity to focus on the potential of metasurfaces, one of the most rapidly expanding frontiers of nanophotonics [1] to revolutionize optics as we know it by displacing refractive optics (RO) in many large-scale applications and creating entirely altogether new functionalities. Metasurfaces, i.e. arrays of subwavelength-spaced and optically thin optical elements, enable new physics and phenomena that are distinctly different from those observed in three-dimensional (3D) bulk metamaterials, thus providing us with the unique capability to fully control the wavefront of

light with planar elements and thus realize “planar photonics” often dubbed “flat optics”. In the following, I will use these terms and “metaoptics” interchangeably. The fabrication complexity of 3D metamaterials has so far hindered technological applications at optical wavelengths. This situation has radically changed with the advent of metasurfaces. Of course, it is notoriously hard to make predictions on the future impact of a new technology! That is why I have titled this article a personal perspective; it concentrates on my group’s research, but recent review articles provide exhaustive coverage of the work of most groups in this rapidly expanding field [2–9].

2 Metasurfaces: a disruptive technology

RO, while very advanced, in many respects, considering its enormous industrial penetration, is nevertheless based on the centuries-old glass molding technology that requires very precise surface shaping and optical alignment of multiple elements, such as lenses, leading to bulky and often expensive components.

Metasurfaces can be fabricated instead with the standard processes of the semiconductor chip industry and can be designed to mold the diffracted wavefront in essentially arbitrary ways by locally controlling the phase shift, amplitude and polarization of scattered light, a process that can be intuitively understood in term of Huygens’ and Fermat’s principle. This has major implications for science and technology, on one end, by adding metasurfaces to the tool kit of structured light, and on the other, by enabling the redesign of essentially all conventional optical components and the invention of new ones. Our entry in this field started from the design of metasurfaces with constant phase gradient (gradient metasurfaces) that satisfies generalized Snell and reflections laws, where the deflection angle is controlled by the phase gradient [10].

One lithographic mask is sufficient to generate an arbitrary phase profile and can be used to integrate on the same surface multiple optical components. Essentially,

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one digitizes the desired phase with high fidelity using a library of optical elements (OEs) fabricated with well-established lithographic and deposition techniques. Although e-beam lithography has been widely used as laboratory tool, the future is in the use of deep UV lithography for near-infrared and visible optics and likely nano-imprint lithography to achieve the required nanoscale features over large areas using materials that can be reliably processed such as silicon, silica, titanium dioxide [11] and a variety of other insulators and semiconductors. The CMOS compatibility of metaoptics is technologically disruptive. Consider the omnipresent camera modules (in cell phones, laptops and in practically all cameras). By replacing in the future, the lens assembly by one composed of optically thin metalenses fabricated by lithography and other CMOS-compatible processes such as atomic layer deposition [11], the same company/foundry will be able to manufacture the whole camera module and sensor chip plus optics, disrupting the standard business model. The resulting module will be thinner than conventional ones, with additional advantages in assembly/packaging and optical alignment due to the planar nature of the optics. For an instructive video illustrating these points, based on Ref. [12], see https://www.youtube.com/watch?v=ETx_fjM5pms.

Flat or planar components hold promise in replacing refractive and diffractive optics in a large number of applications ranging from camera modules for cell phones and laptops to displays including wearable optics, virtual reality and many others. Given that metaoptics is a type of diffractive optics, it is important to point out some of its distinctive features compared with Fresnel optics.

The latter requires multilevel lithography, and the ability to achieve multi-wavelength/broadband operation is very limited due to strong chromatic aberrations that are hard to compensate. The subwavelength arrangement of OEs in metaoptics circumvents the formation of spurious diffraction orders, which generally prevails in conventional diffractive components such as gratings, where the constitutive elements are spaced on a wavelength scale. These spurious orders not only degrade the efficiency of diffractive components but also give rise to undesired effects such as virtual focal spots, halos and ghost images. For all the above reasons and fabrication tolerances related to the ridges and grooves, Fresnel lenses are not good for imaging and are not diffraction limited, preventing high resolution.

In addition to enabling much thinner and less bulky optical components, metasurfaces offer the possibility of realizing complex optical components/instruments with greatly reduced complexity (often just a single

metasurface) and of integrating in the same phase profile multiple functions.

3 Metalenses

A refractive lens requires a non-spherical shape to correct for spherical aberration (aplanatic lens) and achieve diffraction-limited focusing (which in turn requires complex fabrication equipment to achieve the required precision of phase control) or a planar cylindrical configuration with compositionally varying material to provide the graded refractive index needed for focusing (GRIN lens). Correction of other monochromatic aberrations such as coma, distortion, astigmatism and field-curvature requires multiple lenses, increasing footprint and complexity. A dielectric metalens can be instead designed to achieve high-efficiency diffraction-limited focusing [9, 12] and a simple doublet can lead to a large field of view ($\sim 50^\circ$) and near-diffraction-limited imaging in the visible region [13]. Applications of single-wavelength metalenses are numerous, including security, machine vision, laser lithography and confocal microscopy.

Achromatic focusing is essential for broadband operation, which is technologically challenging to achieve across the visible region, again leading to very thick objectives. Through appropriate nanostructuring of metalens OE, typically pillars or fins that can be treated as subwavelength-long waveguides characterized by an effective mode index, dispersion (frequency-dependent phase) can be designed so that group delay is independent of wavelength and group-delay dispersion is negligible across the desired bandwidth. Broadband achromatic focusing across visible and white-light imaging has recently been achieved by my group using a single metalens [14]. Most importantly, the metalens' focal length can be also designed to increase or decrease with increasing wavelength, mimicking the behavior of refractive lenses and Fresnel lenses, respectively, or as a matter of fact, exhibiting a dispersive behavior that can be designed and controlled with a particular function in mind.

The extremely high data density over large areas required by metalenses at near IR and visible wavelengths generates unmanageably large total file sizes, limiting their fabrication to sizes no larger than a few millimeters. For example, a 5 cm diameter device may be comprised of over 6 billion meta-elements, each of which must be described by nanometer-precision definitions of position and radius, resulting in a size >200 GB. Since these design files must subsequently undergo computationally

intensive processes such as data conversion (often known as “fracturing”) for use with mask-writing equipment, it is critical that these file sizes be minimized so that they can be handled by chip foundries.

Using a new scalable metasurface layout compression algorithm (METAC, for “metasurface compression”) that exponentially reduces design file sizes (by three orders of magnitude for a 1-cm-diameter lens) and stepper photolithography, recently, my group designed and fabricated metalenses with large areas. Using a single 2-cm-diameter near-infrared metalens less than 1- μm -thick fabricated in this way, we experimentally implemented the ideal thin lens equation, while demonstrating high-quality imaging and diffraction-limited focusing [15].

The next challenge is to achieve achromatic broadband focusing across the visible region over a \sim 1-cm-diameter metalens, with additional correction of monochromatic aberrations such as coma. Here, recent advances in topological optimization using subwavelength-thick multi-layer metasurfaces could help [16].

Focal adjustment and zooming are widely used in cameras and advanced optical systems. It is typically performed along the optical axis by mechanical or electrical means. Metalenses, which might lead to future major miniaturization of cell phones and wearable displays, will require tuning based on lateral rather than longitudinal motion. Recently, my group, in collaboration with David Clarke’s group at Harvard, demonstrated experimentally electrically tunable large-area metalenses controlled by elastomers, with simultaneous larger focal length tuning ($>100\%$) and real-time astigmatism and image shift corrections, which, until now, were only possible in electron optics [17].

The device’s thickness is only 30 μm . These results demonstrate the possibility of future optical microscopes, which operate fully electronically, as well as compact optical systems that employ the principles of adaptive optics to correct many orders of aberrations simultaneously.

4 Multifunctional components: polarization optics

Notably, multiple optical functions can be encoded in a metasurface-phase profile, leading not only to reduced footprint and complexity and enhanced performance but also to new optical components and instruments. Recent examples from my group are metalenses that enable circular dichroism spectroscopy by creating two spatially

separated images of a chiral object when illuminated with light of opposite circular polarization [9]. This simple setup replaces multiple phase plates and two parallel optical paths.

Similarly, a few centimeter-size spectrometer with spectral resolution of 0.3 nm in the visible region was demonstrated by using highly dispersive off-axis metalenses as opposed to a grating and a collimating mirror with a meter-long propagation distance [18]. In addition, this spectrometer has the capability to resolve different helicities of light in a single measurement. This is an important example of how the chromatic dispersion of metalenses can be optimized for a particular function.

Metaoptics is poised to have a major impact in the area of polarization optics. The basic elements of polarization optics are polarizers and phase retarders (waveplates). Retarders most commonly take the form of bulk bi/uniaxial crystals whose birefringent properties allow for polarization conversion. These plates are, however, difficult to fabricate and process and are challenging to integrate. For example, current polarimeters use multiple optical components in sequence for polarization analysis and therefore often become bulky and expensive. The elements comprising a metasurface may possess tailored structural birefringence, making metasurfaces a fascinating platform for new polarization optics to circumvent the above problems.

In short, metasurfaces may replace complex cascades of polarization optics based on bulk birefringent crystals with a single, flat optical element. Consider, for example, in-line polarimeters, which perform nondestructive polarization measurements of optical signals and play a critical role in monitoring and controlling the polarization environment in, for example, optical networks. While current in-line polarimeters are constructed with multiple optical components, either fabricated into an optical fiber or using free-space optics, we recently demonstrated a novel architecture conducive to monolithic on-chip integration that enables the scalable fabrication of high-performance polarization sensors with exceptional stability, compactness and speed [19]. A metasurface consisting of a subwavelength antenna array was engineered to generate four scattered beams, related in intensity to different polarization components of the incident signal. Fast polarization measurements were performed by directly detecting those beams, resulting in an extremely compact polarimeter with a single, essentially two-dimensional, optical element and four photodetectors. It provided polarization state measurements matching those of a state-of-the-art commercial polarimeter. Recently, this work was extended to a fiber-coupled metasurface polarimeter capable of

measuring the polarization of four telecom wavelength channels [20].

Polarization can be used in a unique way to access two different functionalities built in a metasurface. Two completely independent phase profiles can be encoded in a metasurface and subsequently accessed with perpendicular polarizations (linear or more generally elliptical) to create corresponding unrelated images (holograms) in the far field [21]. Similarly, we demonstrated elliptical polarization beam splitters, a novel class of optical components [21]. Such a beam splitter can be designed by imposing two independent phase profiles corresponding to different deflection angles for two incident polarizations. This is possible for any set of two orthogonal, elliptical polarizations. More recent work has shown how incident polarization on suitably designed metasurfaces can control conversion of spin (SAM) to orbital angular momentum (OAM). We demonstrated a metasurface that converts left- and right-circular polarizations into states with independent values of OAM and another device that performs this operation for two elliptically polarized states, the only constraint being that they are orthogonal [22]. These results are likely to open new directions in structured light, singular optics and quantum optics.

Polarization can reveal details otherwise inaccessible in imaging. For example, automobile-mounted polarization cameras can easily distinguish water and mud puddles in a road environment; polarization can reveal stress birefringence in manufactured plastics and objects as large as tanks that are invisible to a traditional photographic image. A particularly fascinating application space of metasurfaces lies therefore in polarization imaging, because polarization cameras are not widely available and the devices that are available are expensive, bulky, and slow. Based on the unique polarization capabilities of metasurfaces, however, one can envision future compact and inexpensive polarization camera overcoming these limits that could have a transformative impact in a number of areas: autonomous vehicles, 3D depth vision, augmented reality, remote sensing and security, to mention just a few.

5 Conclusions

In summary, metasurfaces provide a new basis for recasting optical components into thin, planar elements. Their planarity allows for fabrication routes directly in line with conventional processes of the mature integrated circuit industry, allowing for opportunities to a scale unmet by 3D metamaterial designs. The technology required to

mass produce metasurfaces dates back to the early 1990s, when the feature sizes of semiconductor manufacturing became smaller than the wavelength of light advanced in stride with Moore's law. This provides the possibility of unifying two industries: semiconductor manufacturing and lens-making, whereby the same technology used to make computer chips is used to make metalenses and other optical components, based on metasurfaces. I therefore envision a future of digital optics based on metasurfaces with increased density of optical components and functionalities per metasurface; it is tempting to speculate which empirical law might govern its growth, akin to Moore's law for digital electronics.

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