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ABSTRACT

Rapid advancements in autonomous systems and the Internet of Things have necessitated the development of compact and low-power image sensors to bridge the gap between the digital and physical world. To that end, sub-wavelength diffractive optics, commonly known as meta-optics, have garnered significant interest from the optics and photonics community due to their ability to achieve multiple functionalities within a small form factor. Despite years of research, however, the performance of meta-optics has often remained inferior compared to that of traditional refractive optics. In parallel, computational imaging techniques have emerged as a promising path to miniaturize optical systems, albeit often at the expense of higher power and latency. The lack of desired performance from either meta-optical or computational solutions has motivated researchers to look into a jointly optimized meta-optical–digital solution. While the meta-optical front end can pre-process the scene to reduce the computational load on the digital back end, the computational back end can in turn relax requirements on the meta-optics. In this Perspective, we provide an overview of this up-and-coming field, termed here as "software-defined meta-optics." We highlight recent contributions that have advanced the current state of the art and point out directions toward which future research efforts should be directed to leverage the full potential of subwavelength photonic platforms in imaging and sensing applications. Synergistic technology transfer and commercialization of meta-optic technologies will pave the way for highly efficient, compact, and low-power imaging systems of the future.

INTRODUCTION

Visual data acquisition and processing form the backbone for a diverse range of technologies in all aspects of our lives, from biomedical imaging, to the Internet of Things, autonomous systems, and entertainment technology.[1] With rapid advancements in these technologies, there is an urgent need for compact and low-power imagers, capable of handling the ever-increasing data streams with minimal system latency. Current implementations, however, often entail sophisticated assemblies of bulky optical elements, which limit their deployment. Computational imaging offers a solution by transferring part of the imaging process to software, thus eliminating the need for such complex optical systems;[2] however, latency and power consumption often increase with the computational complexity. This is particularly detrimental for machine vision applications that require scene information beyond its simple 2D intensity distribution. Extracting such implicit properties of a scene, such as depth,[3] polarization,[4] or spectral information,[5] often entails significant computation.

A promising route to ease the computational burden on software is to perform computation directly in the optical domain, thereby taking advantage of the parallel nature of light.[6] Such optical image processing is passive and associated with short processing times, thus minimally affecting the system latency. Analog optical information processing, however, poses many challenges, including large size and stringent requirements on alignment.[7] In recent years, macroscopic freeform optics have emerged as an alternative to conventional bulk optics for constructing optical image processing systems.[8] While these offer the possibility of achieving multiple functionalities with a single optical element, their complicated geometries often make fabrication painstakingly difficult.

In recent years, rapid advancements in microfabrication and nanophotonics have led to the emergence of highly miniaturized optics, commonly known as meta-optics.[9,10] These typically consist of a planar distribution of sub-wavelength scatterers that can be configured to manipulate the incident electromagnetic radiation in the spatial and spectral domain.[11,12] While each of the individual scatterers can be thought of as introducing an additional phase to the incident light, their coordinated response generates the desired overall functionality. This allows the fabrication of freeform surfaces with desired phase profiles using a single-stage lithography process, that is scalable to wafer-size.[13–15] An appealing feature of meta-optics is the vast number of design degrees of freedom provided by such systems. In principle, the individual scatterers in a meta-optic as well as their global arrangement can be modified to tailor the amplitude, phase, spectrum, and polarization of optical waves. Several studies have demonstrated meta-optical analogs of conventional optical elements, such as lenses,[16] wave-plates,[17,18] spectral filters,[19] polarizers,[20] and holograms.[21] Despite impressive advancements, the performance of meta-optical systems often remains inferior to that of traditional refractive systems. For example, images captured with a single meta-optic have significantly more chromatic aberration compared to an image captured with a refractive lens. In fact, a single meta-optic faces a fundamental challenge for full-color imaging.[22] This brings forward an important question: what performance loss is acceptable to miniaturize a specific system in size and weight considering a specific application and is such a trade-off important for identifying the applications of meta-optics?

In this Perspective article, we provide an outlook on the emerging field of software-defined meta-optics. Instead of relying on a pure optics-based solution or computational reconstruction, this approach provides a hybrid co-optimized optical–digital solution (Fig. 1). On the one hand, the meta-optical front end can relax the power consumption and latency of the digital back end. On the other hand, the digital back end can relax the constraints on fabrication and fundamental limitations of the meta-optic. Such simplification of a hardware system using software is akin to the field of "software-defined radio," which has revolutionized the field of wireless communication prototyping.[23] We envision a much larger role played by software-defined meta-optics in the field of imaging and sensing. This is especially true, because almost all imaging systems today come with a computing system, and a large amount of image signal processing, such as noise reduction and high dynamic range correction, are already performed in smartphone cameras.[24] We highlight the recent progress in this emerging field and outline several challenges and opportunities. We note that this Perspective article primarily focuses on the visible and near-infrared part of the electromagnetic spectrum, as we believe the challenges and opportunities here are distinct from those of the microwave regime, where similar research is also growing in interest.[25]

CURRENT STATE OF THE ART

In this section, we provide a brief overview of the current state of the art for systems that utilize meta-optics in tandem with a computational back end for full-color image reconstruction or sensing. We note that most of these works do not utilize a full end-to-end co-optimization of the optical front end and computational back end. However, they demonstrate how a software can be used for extracting additional information from a scene captured by a meta-optic.

A major roadblock associated with visible imaging under broadband illumination using meta-optics is the presence of strong chromatic aberrations. These manifest as wavelength-dependent blur in images captured by such systems.[26] Physically, this effect can be understood by considering a given meta-optic's point spread function (PSF), which represents the image of a point source produced by it. The three-dimensional PSF of conventional meta-optics, such as a hyperboloid metalens, is a spot with a wavelength-dependent location along the optic axis. As a result, a scene imaged through such meta-optics using a fixed sensor plane appears focused with respect to one wavelength/color while having significant blur for the other colors. This constrains metasurface-based imaging to discrete wavelengths or very narrow bandwidths.[27]

One way to mitigate this wavelength-dependent blur is to engineer the phase profile of the meta-optic to have a wavelength-independent PSF. This can be achieved by exploiting extended depth of focus (EDOF) lenses, which produce a depth-independent PSF, although with increased blur. For a fixed sensor plane, this blur is spectrally invariant over a broad range of wavelengths and can be corrected by using a single, wavelength-independent filter. This insight led to

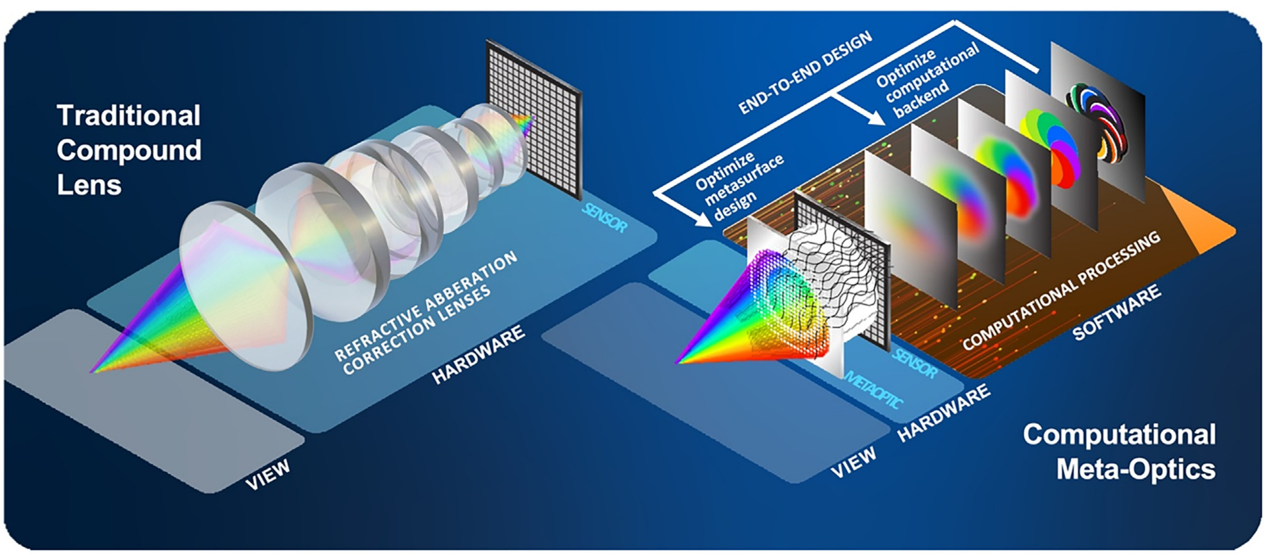

FIG. 1. Schematic comparing the imaging modalities of traditional optics and computational meta-optics. In contrast to conventional lens-based imaging systems (left), meta-optics (right) can achieve multiple functionalities within a small form factor when used in conjunction with computational post-processing. The system performance can be further improved by using an end-to-end design approach to co-optimize the computational back end and the meta-optic design based on a pre-defined figure of merit.

our first work on full-color computational imaging using an EDOF meta-optic based on a cubic phase profile and Wiener deconvolution.[28] In a later work, we inverse designed these lenses instead of utilizing a predefined phase profile, to obtain better quality imaging.[29] Such inverse design techniques rely on defining a figure of merit (FOM) in terms of the structural parameters of the meta-optic.[30] Starting with an initial set of values, these parameters are updated over multiple iterations to either maximize or minimize the FOM until an optimal solution is reached. We later demonstrated that a sharp improvement in image quality can be obtained by employing an "end-to-end" approach to co-optimize the meta-optics with the computational back end.[31] Here, we used a neural network based computational back end to drastically improve the image quality. We emphasize that we were achievable full-color images beyond the perceived fundamental limit, thanks to the use of a computational back end, thereby demonstrating the power of software-defined meta-optics. Recently, we also reported full-color imaging with a large-aperture refractive/meta-optics ($\sim$6 mm) in conjunction with a computational back end.[32]

To further illustrate the widespread utility of meta-optics for sensing applications, we demonstrated a miniature dual-aperture camera for 3D imaging.[33] The device consisted of two, spatially separated metasurfaces. One of these was an EDOF meta-optic, with which a mono-chrome image of the scene was captured and reconstructed using a total variation-regularized deconvolution algorithm. The reconstructed image was segmented, and different objects were labeled for depth sensing. The second metasurface was designed to produce a double-helix PSF (DH-PSF) that rotates depending on the distance of the light source from the metasurface. After deconvolving each subregion of the segmented image with a Wiener filter, the DH-PSF metasurface was used to determine their corresponding PSFs. The rotation angle of these PSFs was subsequently used to obtain an estimate of the depths of different objects in the scene. Several other works have also explored 3D imaging using such meta-optical computational imaging systems.[34,35] In a recent work, we used the strong chromaticity of the DH-PSF to design a compact metasurface-based, computational spectrometer in the near-infrared.[36] Going beyond the visible range, foveated thermal imaging has been reported using polarization-dependent meta-optics.[37] Here, two different meta-optics capture two views of the scene in a single sensor, and the resulting images are decoupled computationally.

In recent years, multi-aperture meta-optics have attracted considerable attention from the scientific community due to their ability to overcome the challenges posed by conventional optics and provide additional functionalities. In their pioneering work on light field imaging using meta-optics, Holsteen and co-workers demonstrated a device consisting of three interleaved metasurfaces for single particle tracking in an aqueous medium.[38] The device was based on the concept of light-field imaging in which multiple views of a given scene are used to extract the full complex vector field. In this work, the authors used three laterally separated views of a bead fluorescing at a wavelength of 532 nm generated by the metasurfaces to retrieve its spatial location. Later work demonstrated broadband light field imaging in the visible range by using 60×60 arrays of achromatic GaN metalenses.[39] Here, an image rendering algorithm was used on the different perspectives of the scene captured by the metalens array to retrieve depth information of different objects. Going beyond light field imaging, synthetic aperture metalenses in conjunction with computational postprocessing have also been used to achieve image resolution comparable to conventional lenses within a compact form factor.[40]

Thus far, we have limited our discussion to meta-optics capable of imaging on a fixed focal plane. Several applications, on the other hand, require optical elements with varifocal imaging capabilities. Integrated optical systems often rely on active control mechanisms, such as high-precision actuators and active feedback, to adjust the focal plane. These mechanisms have several drawbacks resulting from extra electrical circuitry and temperature sensitivity. To overcome these challenges, we recently demonstrated a software-defined EDOF meta-optic for varifocal imaging in the visible wavelength range.[41] We utilized a cubic phase profile to design a varifocal meta-lens with a high numerical aperture of 0.28 and large of depth of focus extending from 3.5 to 14.5 mm. A computational backend based on total variation regularization was used to denoise the raw images obtained from the meta-lens. We further demonstrated the integration of the meta-optic into an off-the-shelf camera module for varifocal imaging at a wavelength of 530 nm. We believe that using an end-to-end design approach could potentially enable the realization of broadband varifocal imaging using meta-optics.

The above-mentioned applications illustrate the true potential of software-defined meta-optics in realizing advanced functionalities within a small form factor, thereby providing avenues for the development of next-generation sensing and imaging systems.

FUTURE DIRECTIONS

While the past decade has witnessed huge strides in software-defined meta-optics, the field is far from realizing its full potential. Most notably, the quality of images captured by state-of-the-art meta-optics followed by computational reconstruction is still inferior compared to that of images captured by bulky refractive lenses. While this limitation can potentially be addressed by using a hybrid refractive—meta optic,[32] below we highlight several other directions for software-defined meta-optics (Fig. 2).

Advanced computational imaging

Rapid progress in software-defined meta-optics has the potential of advancing the state of the art in computational imaging. Here, we discuss three application areas that could benefit immensely from the numerous degrees of freedom provided by meta-optical systems. Synthetic aperture imaging techniques have received considerable success in the radio and mm-wave due to their ability to overcome several constraints imposed by single-aperture imaging systems.[42] However, such techniques have not been widely adopted in optical and thermal imaging due to challenges associated with aligning multiple, off-axis refractive elements. This limitation can be overcome by utilizing meta-optics, co-optimized with image reconstruction algorithms, allowing us to access previously unexplored parts of the size-resolution-light throughput phase space.[40,43] Additionally, the ability of meta-optics to structure the wavefront of incident light can be exploited for phase retrieval techniques, such as Fourier ptychography (FP).[44] FP exploits phase diversity from light coming from different angles via structured illumination or multi-aperture imaging to reconstruct wavefronts. Sequences of illumination patterns or object-target motion are most commonly used to capture phase-coded images. Recent preliminary

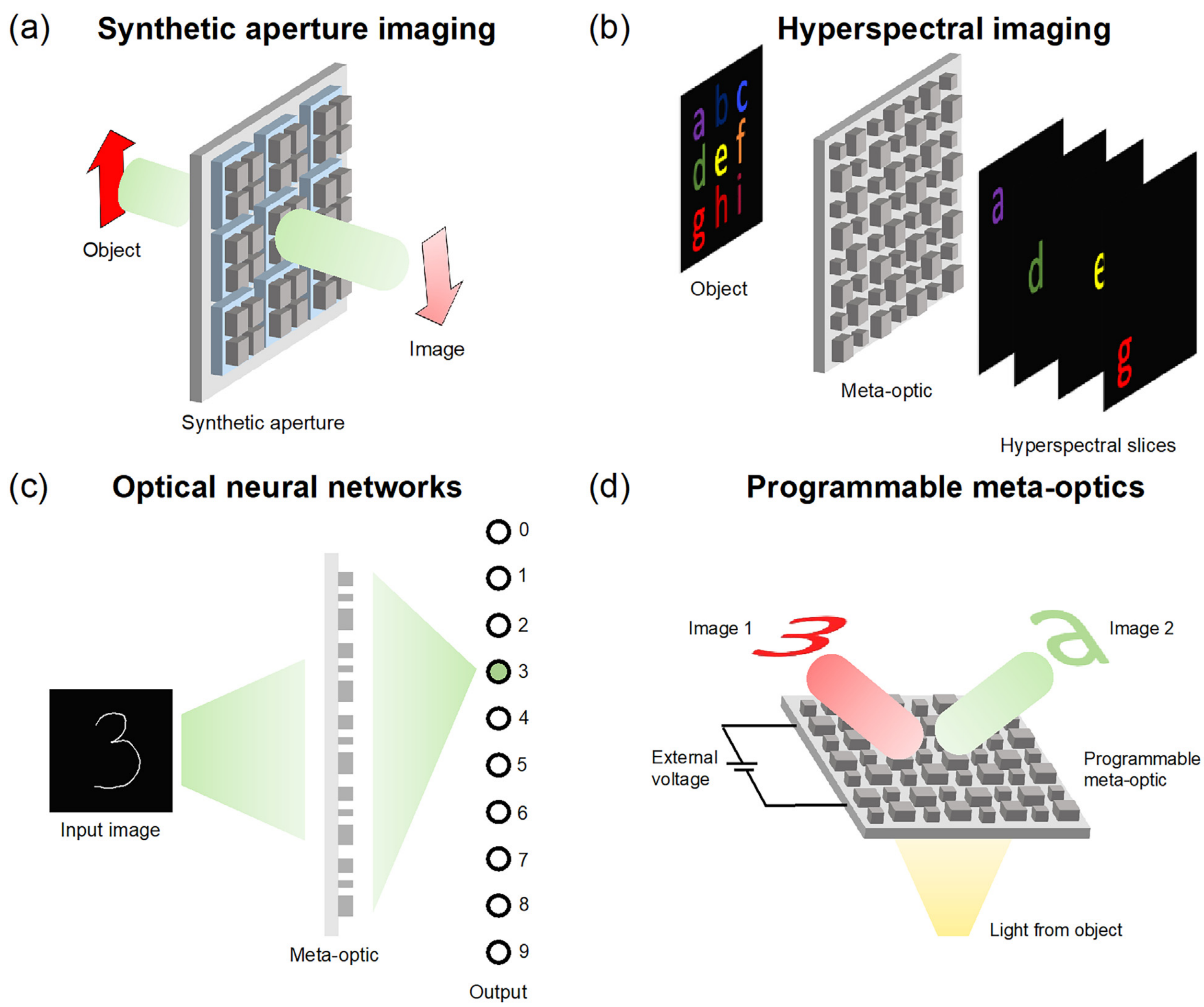

FIG. 2. Schematic showing examples of promising future directions for software-defined meta-optics: (a) synthetic aperture imaging, (b) hyperspectral imaging, (c) optical neural networks, and (d) programmable meta-optics.

studies have shown that diffractive elements may be used to code image patterns for single snapshot imaging. Owing to their large space-bandwidth product, meta-optics can increase the coding capacity and efficiency of such elements. However, designing such systems is challenging due to the requirement of matching the natural sampling period posed by the sensor pixel pitch. This can be overcome by designing composite meta-optical elements to map low numerical aperture fields from distant objects to high numerical aperture, oversampled images on the sensor plane. Furthermore, recent developments in reconfigurable metasurfaces have opened up avenues for the miniaturization of exotic computational imaging functionalities, such as high-dynamic range imaging. Co-designing the imaging sensor with the meta-optic can provide a way of distributing light in different parts of the sensor. This can help image higher luminance ranges than those possible with current state-of-the-art robotic and automotive image sensors.

Multi-dimensional imaging

Several applications in medical research and defense require scene information beyond just two-dimensional spatial information. Extracting other information for a given scene, such as its spectral content, can unveil features that are otherwise hidden in the broad spectral response of image sensors. Rapid advancements in software-defined meta-optics have made it possible to perform such "multi-dimensional" imaging tasks within a compact form factor. Recent work has demonstrated three-dimensional meta-optics for classifying an incident light beam based on its spectral and polarization properties.[45] Here, the meta-optic is designed using topology optimization in which the refractive index distribution of the optical element is determined through an iterative process to optimize a predefined figure of merit. This is achieved by modeling the meta-optic as a three-dimensional grid of voxels, where each voxel can be assigned to one of the two materials chosen to fabricate the meta-optic. The optimization process updates the refractive index distribution of the meta-optic iteratively using a gradient descent process while taking into account any specified fabrication constraints. Such structures have been used to focus light with different wavelengths, polarizations, and angles of incidence at different spatial locations on a two-dimensional sensor array.[46]

We believe that such inverse-designed three-dimensional meta-optics could be used for more exotic imaging applications, such as hyperspectral imaging. Commercially available hyperspectral imaging systems are often bulky, inefficient, and involve scanning or moving elements, which limits their speed and prohibits integration into mobile devices. Meta-optics offers a promising alternative to conventional bulk refractive elements for hyperspectral imaging applications due to their compact size and strongly chromatic optical response. While previous studies have largely focused on eliminating these chromatic aberrations, we believe that this wavelength-dependent behavior can be exploited for efficiently extracting spectral information of captured image data. Further enhancements in spectral and spatial resolution of hyperspectral imaging systems can be achieved by using end-to-end design to co-optimize the meta-optic and computational backend.[47]

Optical accelerator

The last decade has witnessed a rapid increase in the use of machine learning and artificial intelligence-based approaches for a wide array of applications, from image sensing to autonomous systems. This has been facilitated by major breakthroughs in computational algorithms, availability of large amount of data, and digital hardware. While such deep learning approaches are highly versatile, their digital implementation using artificial neural networks (ANNs) are known to be associated with high power consumption and latency.[48,49] To this end, using light for deep learning applications could be advantageous, owing to its inherent parallelism, speed, and analog nature. This is particularly promising for applications where the data are already in the optical domain, such as the processing of images taken by cameras (e.g., on self-driving cars or fluorescence microscopes), for which the signal is in the light coming from the scene/object toward the camera. In recent years, several studies have investigated free-space optical neural networks for image classification and facial recognition.[50–52] These implementations exploit the ability of meta-optics to realize multiple optical functionalities within a small form factor. While most photonic implementations of deep learning have been limited to linear neural networks. Non-linearity was recently demonstrated using commercial image intensifiers[53] and thermal atoms.[54]

Despite the intriguing possibilities offered by ONNs, none of the reported works have shown a clear advantage of using optical neural networks over their digital counterparts. On the contrary, an analysis of the energy consumption in ONNs and digital ANNs suggests that using the optical implementation has an advantage only when the input has high dimensionality.[55] Moreover, a large portion of the literature on ONNs has focused on simple "toy" problems, for which no digital benchmark exists. We believe that using end-to-end design approaches to co-optimize the meta-optic and the data classification algorithm could be beneficial in realizing highly efficient ONNs capable of handling complex deep learning tasks.[55]

Programmable meta-optics

The functionalities offered by static; software-defined meta-optics can be dramatically enhanced by introducing dynamic tunability. In recent years, a large body of work has been reported on tunable meta-optics.[56,57] High-speed free-space modulation has been reported using free-carrier effects in degenerately doped semiconductors[58,59] and organic electro-optic polymers.[60] Many of these works touted the possibility of creating a large space-bandwidth product (product of number of pixels and refresh rate of the phase-plate) over state-of-the-art spatial light modulators based on liquid crystal (LC) or micro-electro-mechanical systems (MEMS). While LC and MEMS systems are indeed slow, the current limitation of space-bandwidth product ($\sim 10^9$) primarily comes from electronic control, and as such it is unlikely to improve without significant progress in co-packaged electronics and photonics. We emphasize that, while large-scale electronic control is routine in display applications, to achieve ~MHz–GHz modulation per pixel will require fundamental innovations in co-packaging electronic integrated circuits and photonics. This problem is exacerbated by the need to modulate a large number of pixels, posing a serious problem for routing both electronic and photonic signals.[61] Additionally, feeding in a large amount of data, as is imperative for large space-bandwidth product, will be extremely power hungry. We believe that instead of a large space-bandwidth product, a large effective change in index is more desirable to tune the meta-optical front end in most emerging applications. To that end, in our opinion, the conventional techniques of LC and MEMS are still very powerful and combining them with meta-optics can provide added advantage of energy-efficiency due to small feature size. In fact, several groups have already reported tunable meta-optics using LC[62] and MEMS.[63–65] Another promising direction for programmable meta-optics is to employ chalcogenide-based phase-change materials (PCMs), which exhibit a large nonvolatile change in the refractive index ($\Delta n \sim 0.7$–1) under phase transition.[66–68] PCMs have also been integrated with meta-optics for free-space modulation of light.[69–71] One intriguing aspect of PCMs is their nonvolatile tuning, which has in-built memory in the reconfiguration process and, thus, can significantly reduce the control complexity for independent tuning of large number of pixels in a spatial light modulator.

CONCLUSION

In this article, we presented an overview of the rapidly advancing field of software-defined meta-optics. The last few decades have witnessed an upsurge in applications relying on visual data acquisition and processing, necessitating miniaturization of imaging technologies. To this end, artificially engineered materials known as metamaterials have attracted considerable attention from the scientific community owing to their compact size and enhanced optical functionalities. Consequently, mm-sized analogs to bulk refractive optics, i.e., meta-optics have been investigated for a wide array of applications, such as full-color imaging, spectroscopy, and depth sensing. While initial efforts in this field were aimed at designing meta-optics with predefined phase profiles, recent studies have employed inverse design techniques for realizing non-intuitive device geometries with enhanced functionalities. Further improvements in acquired image quality have been observed by utilizing a computational back end to process the raw image captured by the meta-optic. To leverage the full potential of such photonic platforms in imaging applications, end-to-end design approaches have also been used to co-optimize the meta-optic and the computational back end.

While research efforts in software-defined meta-optics have strong academic relevance, recent years have witnessed a growing interest in such technologies from industry. Several startups as well as large-scale companies are working toward commercializing meta-optics for mobile photography, sensing, and biomedical imaging. Owing to the increased demand, several foundries have started manufacturing meta-optics in large volumes using commercially viable fabrication techniques, such as immersion and nanoimprint lithography. Given the widespread demand and well-established research and development capabilities, this is an opportune time for rapid commercialization and deployment of meta-optics-based imaging systems.

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AUTHOR DECLARATIONS

Conflict of Interest

Yes, A.M., A.Z., S.C. are involved in a startup Tunoptix, which is commercializing the software-defined meta-optics.

Author Contributions

Romil Audhkhasi: Writing – original draft (equal); Writing – review & editing (equal). **Johannes E. Fröch:** Writing – review & editing (equal). **Alan Zhan:** Writing – review & editing (equal). **Shane Colburn:** Writing – review & editing (equal). **Arka Majumdar:** Conceptualization (equal); Funding acquisition (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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