Metasurface waves in digital optics

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Abstract
Digital optics is a new discipline that aims to replace traditional curved and bulky optical elements with flat and thin ones that can be intelligently designed by a computer and be compatible with the mature semiconductor fabrication industry. Metasurface-based digital optics is characterized by enhanced or multifunctional performances, a compact footprint, and most importantly the ability to break the limitations of conventional refractive, reflective and diffractive optics. The structural inclusions on the subwavelength scale can tremendously change the light fields and give rise to novel electromagnetic modes. In particular, the coupled evanescent fields within the subwavelength structures form a special kind of wave, termed a metasurface wave (M-wave), possessing many interesting properties. This article provides a short perspective of M-waves in digital optics, with particular emphasis on the representative applications in metalenses, photolithography, and optical phased array, etc. Finally, an outlook on the generalized diffraction limit and intelligent digital optics is presented.

1. Introduction

It is often stated that the 21st century is the century of optics. However, restricted by Fermat’s principle, refractive and reflective optics have to rely on curved surfaces to control light propagation [1]. With the development of microelectronics and computer technologies, some advances in the planarization of optical devices have occurred since the 1970s [2], including computer-generated holography, optical discs, diffractive optical elements, charge-coupled devices, liquid crystal displays and digital micromirror devices. These flat optical devices enable the digitalization of optics. Nevertheless, the pixel size of these devices is generally about tens of light wavelengths, leading to limited optical performances.

Recently, the emergence of the optical metasurface, a kind of digitally structured material composed of subwavelength-spaced thin elements, greatly advances the developments of ‘digital optics’ by downscaling the pixel sizes of the structural inclusions to the subwavelength scale, which enables us to overcome the bottlenecks of conventional optics (e.g. the Abbe–Rayleigh diffraction limit, classical refractive and reflective laws, as well as the limitations on absorption and radiation) [3]. Besides, metasurfaces enable planar optics or flat optics that can be easily accessed by the standard processes of the semiconductor industry, i.e. digital (binary) microlithography fabrication techniques [4]. Since the structural inclusions can implement independent phase, amplitude, and polarization modulation, enhanced, multifunctional or even totally new functionalities can be realized by designing digital meta-atoms and optimizing their layout [5–13]. These efforts push engineering optics into a new era: Engineering Optics 2.0 [3, 14, 15]. Related concepts such as ‘digital metamaterials’ in the optical band [16] and ‘coding metamaterials’ in the microwave and terahertz bands [17] have been proposed over the past few years.

Considering the rapid development of optical metasurfaces and flat optics, we envision that digital optics will gain more power in the future. In this perspective, we would like to focus on a special surface wave in digital optics: the metasurface wave (M-wave) [18–20]. In principle, M-waves may be simply defined as slow waves in metasurfaces, which can be considered as a generalization of surface waves [18–20]. In the optical band, one of the simplest M-waves is the coupled surface plasmon polariton (SPP) in a thin metallic slit [21] or nanofilm [22, 23]. Unlike SPPs, however, M-waves can be excited at lower frequency bands by using
Structured subwavelength metallic structures [18, 24]. M-waves also provide a microscopic view of the complex wave interactions in metasurfaces. Combining the catenary field distribution and dispersion model, one can obtain more accurate numerical results [18, 25, 26]. These unique properties allow M-waves to find widespread applications in digital optics.

2. Principle and applications of digital M-waves

2.1. Digital M-waves for gradient phase modulation

In the optical band, the M-wave was first observed in the extraordinary Young’s double slits interference (EYI) at the surface of the penetrated metallic film [21]. The period of the interference fringes through the thin metallic film was smaller than one-quarter of the incidence wavelength, half than the classical prediction of one-half. This EYI phenomenon fundamentally unveils the extremely short wavelength property of M-waves. In the far field, when the widths of double metallic slits are unequal, the original bright stripe appeared at the center of the interference pattern counter-intuitively became a dark stripe [27]. This exotic phenomenon indicates that M-waves transmitted through unequal metallic slits pick different phase shifts, which is fundamentally attributed to the width-independent propagation constant $\beta$. For a subwavelength slit width, $\beta$ may be several times large than $k_0$. By changing the slit width $w$ on the subwavelength scale, an arbitrary phase shift within the full range of $2\pi$ can be realized.

As shown in figure 1, an efficient method to construct a gradient metasurface is by arranging variable-width metallic slits in an array [28, 29]. When a continuous plane wave is projected on such a metasurface, it is discretized by the subwavelength-spaced slits as M-waves and each isolated component can be squeezed into the metallic slits. By engineering the widths of the slits, the phase shifts of the M-waves are quantized into several discrete values, forming a digital near field. When M-waves emanate from the metasurfaces, the digital near field restores to the continuous field in the far field. According to the Huygens’ principle, the output wavefront is fundamentally determined by the gradient phase of the digital near fields. It should be noted that one-dimensional (1D) metallic slits are polarization selective. Alternatively, rectangular or circular metallic holes should be adopted in polarization-independent optical metasurfaces [30–33].

Inspired by the unique properties of coupled SPPs in the optical band, it is highly desirable to obtain similar characteristics in the lower frequency band, e.g. microwave and terahertz bands. Instead of adopting the concept of spoof SPP [34], we found that when the thickness of the metallic layer decreases to an extent that is much smaller than the wavelength M-waves with rather large effective propagation constants would occur at the edges. The electric field within the metallic slit can be described by a hyperbolic cosine function due to the evanescent coupling between the two edges of the metallic slits [18], as shown in the inset of figure 1.
For ultrathin metallic layers, one may take them as effective impedance sheets [18, 26, 35]. According to the conformal transformation theory, the dispersion of the effective impedance follows a catenary of equal strength [25]. In conjunction with the generalized Fresnel’s equations [19], the complex transmittance and reflectance coefficient can be easily calculated. Considering a single layer of metallic slits, the metasurface is not sufficient to generate a considerable phase shift, so multi-layered metallic slits are usually utilized in practice [18, 24, 25, 36]. With the catenary dispersion theory, the design efficiency of digital M-waves can be greatly improved since time-consuming full-wave simulations and parameter sweeps can be avoided.

The digital M-waves with abrupt phase shift levels can be utilized to realize flat lenses, which have greatly reduced device thickness and minimized spherical aberration compared with their traditional counterparts [37], albeit that the chromatic and off-axis aberration still exists. Although some innovative methods have already been devoted to broadband achromatic metasurfaces [38–40], they still suffer from a low numerical aperture (NA, generally smaller than 0.2) or limited bandwidth. Considering that the digital M-waves supported by structured metallic metasurfaces possess large $\beta$ and tunable dispersion, the above limitation can be alleviated to a certain extent. For instance, Li et al. proposed a high NA ($\sim$0.74) achromatic metalens and beam deflector (figures 2(a)–(d)) composed of gradient metallic slits, where the structural dispersions of M-waves are utilized to compensate for the chromatic dispersion in a broadband wavelength range of 1–2 $\mu$m [41].

By replacing 1D metallic slits with two-dimensional (2D) counterparts, polarization-independent devices are possible. With the help of a particle swarm optimization algorithm, a polarization-independent achromatic lens across the X band and Ku band has been reported [36] with focal shift deviation ratios less than 2%. The low profile and broadband achromatic performance may find promising applications in satellite communications. Similar achromatic metalenses have also been reported in the visible band [11, 42, 43].

Besides the chromatic aberration, the field-of-view (FOV) of a metalens is limited due to the off-axis aberration. In order to correct the off-axis aberration, metalens doublets were widely adopted, with a FOV beyond 50° [7, 44]. It was also found that a quadratic phase modulation could lead to wide-angle lenses with only a single metalens [45], owing to the perfect symmetry transformation from rotational symmetry to a transversal one. With an elaborately designed catenary ordered metasurface, the FOV was extended to $\pm 80^\circ$ in the visible band [45] and thus enabled a wide-angle Fourier lens [46]. Based on the same principle, a wide-angle metalens with a 170° FOV was built at around 30GHz based on spoof M-waves confined at 2D variable-width metallic slits [24]. Differing from conventional spoof plasmon waveguides with a high metal filling ratio (typically>90%) [47, 48], the metallic layer was quite thin (~3.4%) to excite M-waves. By exploiting a multilayer configuration with a subwavelength thickness (0.15λ), high transmittance and an arbitrary phase shift within the full range of $2\pi$ could be obtained. More interestingly, the spoof M-waves exhibit an angle-insensitive phase shift property, which is helpful in constructing wide-angle metalenses.

In accordance with the reciprocity of the symmetry transformation principle, if a microwave feeding source is located in the focal plane and transversally moved, the radiated beam through the metalens will be highly directional and the far-field steering angle is determined by the transversal shift. With this method, a wide-angle beam-steering antenna beyond $\pm 60^\circ$ was demonstrated [49].

Another interesting application of digital M-waves is the optical cloak, where the gradient phase levels generated by a geometric metasurface are utilized to compensate for the phase retardation caused by the physical profile of the object. Recently, all-metallic reflective gratings with strong anisotropy were utilized as the building blocks of geometric metasurfaces to excite digital M-waves at the groove edge of gratings [50]. By optimizing the inherent catenary dispersion induced by an all-metallic grating, broadband and high-efficiency spin–orbit interaction was obtained. In addition, the all-metallic materials lead to two extra benefits: high temperature operation and microwave-infrared-compatible invisibility due to the intrinsic low thermal emittance.

### 2.2. Digital M-waves for near-field and far-field super-resolution imaging

The extremely short wavelength property of the M-wave in the near field may be utilized in super-resolution imaging, which offers a low-cost alternative to current expensive and complex ultraviolet lithography, electronic beam lithography (EBL), and focused ion beam (FIB) [21, 51–53]. Recently, many complex meta-holograms composed of spatially rotating nano-apertures or nano-antennas have been fabricated by recording the digital M-waves generated in rotating slit arrays [54], as indicated in figures 2(a) and (b). Also, a kind of maskless fabrication method was proposed based on homogenously structured metal-photoresist-metal cavities [22]. As depicted in figure 2(c), the top metallic film was patterned as periodic metallic disks, which coupled with the bottom metallic film to localize M-waves within the cavities. Owing to the polarization-dependent property, M-waves can record the space-variant linear polarizations generated by the interference of inclined, circularly polarized lights with opposite spins. Benefiting from the
Figure 2. (a) Light field distributions at the photoresist (PR) layer in a metal-insulator-metal cavity lens. (b) A zoom view of the green dashed line region in (a) and corresponding light intensity distributions in x–z plane. Reproduced from [54] with permission, © 2017 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (c) Electric field map in the x-z plane as well as along the white dashed line. (d) Intensity patterns in the PR layer. Adapted with permission from [22], © 2018 American Chemical Society.

short-wavelength property of M-waves, the resolution of this nanolithography is much smaller than the diffraction limit. As a result, geometric metasurfaces composed of rotating elements for orbit angular momentum generation [55, 56] and colorful holography [57–59] can be fabricated with ease.

M-waves may also be utilized for far-field super-resolution telescopic imaging [60–62]. By elaborately engineering the phase levels on a phase mask, some local Fourier components beyond the cut-off frequency of the telescope can be restored in the farfield, resulting in a sub-diffraction focusing spot accompanied by high sidelobes. Such a phenomenon provides evidence counter to the common knowledge that the primary diffraction-limited images of an objective lens would not be observed in more detail by the following relayoptics, as stated in the Principles of Optics [63]. Benefiting from the dispersionless geometric phases of rotating metallic slits, super-resolution imaging with a resolving ability of about 0.64 times that of the Rayleigh criterion was obtained in the whole visible band [64].

2.3. Dynamic digital M-waves
All the digital M-waves mentioned above are fixed once the structures are fabricated and the wavefront cannot be flexibly tuned. An effective method to realize tunable digital M-waves is to fill the variable-width metallic slits with nonlinear media [65]. Each slit supports an M-wave with specific phase retardation, controlled by both the slit width and the intensity of incident light. Owing to the nonlinear response of digital M-waves localized in the nonlinear media, the deflection angle and the focal length of the output beam will be tunable. In particular, this dynamic beam-steering property may find potential applications in the optical phased array (OPA). Thanks to the subwavelength pixel size of digital M-waves, the side lobes of far-field radiation can be effectively reduced and a rather large FOV may be obtained [66–68].

Besides the light-pumped, nonlinear metasurfaces, gate-tunable metasurfaces based on conducting oxide, graphene, and transition metal dichalcogenides have also been proposed for dynamic M-wave modulation [69–73]. As shown in figures 3(a) and (b), the upper metallic patterns were simultaneously used for M-wave excitation and as electrodes to create electrical gates. Tunability arises from field-effect modulation of the complex refractive index of conducting oxide layers incorporated into metasurface antenna elements (figure 3(c)) [69]. Since only a 180° phase change was realized, a 2-bit OPA was demonstrated. By electrical control over subgroups of metasurface elements, the equivalent period of the radiation antenna varies between 3.2µm, 2.4µm, and 1.6µm, resulting in three different steering angles, as indicated in figure 3(d). In order to further extend the phase shift range, a dual-gated reflectarray metasurface architecture that enables much wider (>300°) phase tunability was subsequently proposed [71].

Alternatively, one can replace the active media by phase-change material, whose crystallization level can be actively varied by applying heat, photon, or electric energy to the phase-change material [73–75]. Owing to the dramatic difference in optical characteristics between its crystalline and amorphous states, abrupt phase shift levels are induced among different states. By filling a series of metallic slits with specific crystallization levels of Ge2Sb2Te5 (GST), tunable digital M-waves that enable various far-field focusing patterns have been demonstrated [76]. Also, an active OPA that could realize beam steering within ±60° was
Figure 3. (a) Schematic of dynamic M-waves in digital metasurfaces. (b) Steering diffracted beam angles via electrical gating of different numbers of antennas. (c) Spatial distribution of the z component of the electric field $E_z$. (d) The far-field intensity of the light beam reflected from the metasurface as a function of the diffraction angles for different periodicities. Reproduced from [69] with permission, © 2016 American Chemical Society.

Figure 4. Generalized diffraction limit in the focusing process: Resolution limit, Energy density limit, Achromatic bandwidth limit, and Depth of focus limit (READ).

3. Trends and challenges

Over the decades, M-waves have proven to be vital in the transformation of classical optics to digital optics. Many fundamental breakthroughs, such as the breaking of the diffraction limit and dynamic modulation, have been reported. However, it is realized that these achievements may be only the tip of the iceberg in digital optics. More efforts must be made to meet the following two challenges.

3.1. Generalized diffraction limit: READ

Traditionally speaking, the diffraction limit refers to the smallest resolution of imaging optics, which was discovered by Abbe and Rayleigh in the 1870s. But as this field, many other important parameters have been found that are fundamentally limited by the diffractive nature of light. Most importantly, there are four limits that are directly related to the future development and applications of Engineering Optics 2.0 [15]. These are the Resolution limit, Energy density, Achromatic bandwidth of the diffractive lens, and Depth of focus limits (here we refer to them as READ). As illustrated in figure 4, these values are termed the generalized diffraction limit, which is normally determined by parameters such as the wavelength, aperture size, and focal length. It is highly desirable to break these diffraction limits simultaneously. However, current technologies often fail to accomplish this objective. For instance, while the superoscillation focusing reduced the effective Airy disk radius, the energy density was actually reduced as a result of the strong side lobes.

In digital optics, it is possible to break these generalized diffraction limits, forming a potential road to super-READ. Nevertheless, more systematic investigations are required to realize it and lead us to the new world hidden by the 'diffraction limit'.

proposed [77]. Unlike a discrete beam-steering metadevice realizing three states at most [69, 74, 78], such an OPA can achieve continuous beam scanning due to the continuous permittivity change of GST.
3.2. Intelligent digital optics

Along with the development of dynamic M-wave devices, intelligent digital optics may be possible in the near future. To construct intelligent digital optical systems, the sensors, field-programmable gate array and artificial intelligence (AI) chips as well as active actuators must be integrated into a single platform. It is foreseeable that more exotic properties and flexible engineering of M-waves will be found with the emergence of 2D materials [79], van der Waals materials [80], and other active materials, resulting in greater performance enhancement and more promising applications.

As an important infrastructure, we must also build the data center for intelligent digital optics, which should encompass enormous digital optical designs and corresponding optical functionalities. Also, electronic design automation (EDA)-like optical design flow, termed photonic design automation (PDA), is highly desirable.

4. Conclusions

In this perspective, we summarized the recent advances of digital M-waves in subwavelength metallic slits or similar structures. Owing to their unique properties, a series of interesting applications have been found. Although this article mainly focuses on the M-waves in subwavelength metallic structures, it should be mentioned that M-waves can also be supported by dielectric counterparts. To eliminate the cross talk between adjacent elements, supercells consisting of several identical single resonators or high-index dielectric waveguiding modes are often adopted to realize isolated and local phase response [81–83].

We envision digital optics will continue to gain momentum in the upcoming years as technology evolves and new advancements will be introduced including fifth and sixth generation mobile communication systems (5G and 6G) [84, 85], digital optical phased array LIDAR [68, 77], integrated optical communication [86–89], highly dense optical storage [90], hybrid optical and electronic computation [91, 92], virtual reality, augmented reality, and naked eye three-dimensional display [9, 57, 93]. Also, the seamless integration between digital optics and digital electronics, enabled by compatible semiconductor manufacturing as well as the advances of AI, will form novel functionalities and architectures for digital optics.

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