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Polarization independent high transmission large numerical aperture laser beam focusing and deflection by dielectric Huygens' metasurfaces

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ABSTRACT

In this letter, we propose all-dielectric Huygens' metasurface structures to construct high numerical aperture flat lenses and beam deflecting devices. The designed metasurface consists of two-dimensional array of all-dielectric nanodisk resonators with spatially varying radii, thereby introducing judiciously designed phase shift to the propagating light. Owing to the overlap of Mie-type magnetic and electric resonances, high transmission was achieved with rigorous design analysis. The designed flat lenses have numerical aperture value of 0.85 and transmission values around 80%. It also offers easy fabrication and compatibility with available semiconductor technology. This spectrally and physically scalable, versatile design could implement efficient wavefront manipulation or beam shaping for high power laser beams, as well as various optical microscopy applications without requiring plasmonic structures that are susceptible to ohmic loss of metals and sensitive to the polarization of light.

1. Introduction

Recently, metamaterials and metasurfaces have attracted significant attention in the optics community [1,2]. Metamaterials are artificial materials which are constituted by nanostructures, and optical resonant effects of these nanostructures allow metamaterials to have unique optical properties due to negative dielectric permittivity, ε and magnetic permeability, μ. Metasurfaces are two-dimensional (2D) counterparts of metamaterials with thicknesses much smaller than the wavelength of the incident light, enabling complete manipulation of the basic properties of light beams, such as phase, amplitude and polarization [3,4]. Compared to metamaterials, metasurfaces do not require complex fabrication methods and can be fabricated with single step lithographical techniques. Thus, they are well suited for mass production and can be integrated onto a photonic chip. In addition, metamaterials have high loss in the optical regime; this also limits their practical applications at this particular frequency regime [5]. Even if metasurfaces are ultra-thin, they still effectively manipulate the phase, amplitude, and polarization of light in transmission or reflection mode. Many planar analogs of the traditional bulky optical components, such as lenses [6–13], anti-reflection coatings [14], axicons [8,15], polarization converters [16], optical vortex generators [17], and absorbers [18] have been demonstrated by using metasurfaces.

Electromagnetic phase control is one of the simplest and probably one of the most unique applications of metasurfaces. Full 2π phase control is the key for implementing various applications, such as beam steering, structured light generation, or lensing. Remarkably, metasurfaces can conveniently modulate the phase of electromagnetic waves in various ways, such as dynamical phase control, and geometrical phase control. Dynamical phase control relates to the change in the optical path to acquire the required optical path difference. Metasurfaces introduce interfacial phase discontinuities along the optical path as an alternative approach to realize very compact and flat dynamical phase elements. However, dynamical phase metasurfaces are circular polarization insensitive. The other types of metasurfaces, which are called geometrical phase metasurfaces, have also been proposed and demonstrated experimentally [19,20]. Geometrical phase metasurfaces utilize space-variant polarization manipulation of the incident field in order to induce local phase retardation. This type of phase retardation is actually a Pancharatnam–Berry (PB) phase shift which in some cases is an undesired effect but can be utilized for spin filter and beam shaping applications. By designing two-layer metasurfaces (one of them is polarization or spin-insensitive and the other one is polarization or spin-controlled), geometric phase and dynamic phase metasurface elements can be integrated to implement ultra-compact polarization

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beam-splitters and spin filters [21,22]. Majority of initial studies on metasurfaces focused on metal–dielectric structures, which have low efficiency due to nonradiative Ohmic losses at optical frequencies especially operating in transmission mode [23,24]. Many plasmonic-based metasurfaces and flat lenses were recently designed using V-shaped antennas and rotationally asymmetric nanostructures [8,25–27]. Such systems typically had energy efficiency less than 20% due to increased Ohmic losses in optical frequency regions. On the other hand, almost all metals melt at high temperatures and, thus, they are not well suited for high-power laser applications.

Due to the abovementioned drawbacks of metals, significant work has been done in developing dielectric analogs of metasurfaces in visible and near-infrared range, since many dielectric materials have very low absorption loss in these optical frequencies. Most of the previous designs relied on high contrast grating approaches with nano-pillar structures of higher aspect ratio [11]. High refractive index materials like silicon were studied to show strong Mie-type scattering mechanism [28]. The well-known "Huygens' principle" states that the new wavefront is determined by the sum of secondary wavelets generated by all points on the previous wavefront. Low-loss dielectric nanoresonators are designed to emulate the behavior of the forward-propagating elementary wavelets known from the Huygens' principle [3]. In other words, Huygens' sources can be achieved by using polarizable subwavelength particles that sustain both magnetic and electric dipolar resonances. The arrangement of many of such particles in a plane creates special reflectionless sheets or metasurfaces that are called Huygens' metasurfaces [29]. Silicon nanodisk structures were especially demonstrated to support the simultaneous excitations of electric and magnetic dipole resonances [30–34]. By varying the geometric parameters or the aspect ratio of silicon nanodisks, electric and magnetic dipole resonances can be overlapped at the same frequency. This also suppresses the backward scattering since electric and magnetic resonances will cancel each other in backscattering while interfering constructively in forward direction by realizing Kerker's condition [35]. Thus, these two dipole resonance mechanisms allow us to tailor the phase shift over 0-2π while having a high transmission and almost zero reflection. Also, silicon is a common material used mostly in semiconductor industry, which may benefit from mature semiconductor fabrication technology. Due to CMOS compatibility and the relative ease of fabrication, silicon-based structures continue to be an important element of the recent state-of-the-art nanophotonic device studies [36]. As a result, it is advantageous to use these silicon nanodisk metasurface structures to implement high-power laser beam manipulation with low-reflection losses and polarization-independence property.

In this paper, we report the design and analysis of an efficient, ultra-thin planar metasurface lens and beam deflecting device which operates at a wavelength of λ = 1064 nm, by utilizing the recently developed Huygens' metasurfaces. Designed devices rely on silicon nanodisk structures which can support both Mie-type electric and magnetic dipole resonances to realize phase manipulation and completely suppress reflection losses. By locally changing the radius of the silicon nanodisk elements, abrupt phase changes were realized. A flat metasurface lens with a high numerical aperture value of 0.85 and with transmissivity as high as 80% and a metasurface beam deflecting device with beam deflecting angle of 6.9° with transmissivity of 75% have been demonstrated. With robust optimization algorithms, the design proposed here has great potential to be improved as a future study. Our design offers excellent polarization insensitive operation due to high degree of symmetry. Also, much higher transmission than the previous studies with the same wavelength of operation at 1064 nm was achieved [37] The proposed design is also easy to fabricate with standard single step electron beam lithography based conventional planar semiconductor fabrication methods due to ultrathin thickness and very small aspect ratio of the designed structures comparing to recent studies with longer pillars [7]. Based on these outstanding properties and spectral scalability, these devices can be utilized in applications where operation at distinct known wavelengths is needed such as high power laser beam systems and fluorescence microscopy techniques.

2. Design and results

2.1. Design of the unit cell

The proposed Huygens' metasurfaces are designed using high index silicon nanodisks, which have subwavelength periodicity and are embedded in a host low refractive index silica material. Other comparative design forms such as silicon free-standing in silica substrate may also be considered. Note that the spectral widths of the Mie-type resonances are determined by the proper choice of the dielectric environment. The refractive-index contrast between the nanodisk and surrounding media significantly affects the mode confinement of the electric and magnetic dipole resonances. Furthermore, by geometrical tuning of nanodisk dimensions, the spectral positions of the two resonances can be adjusted [30,32]. The schematic of 2D all-dielectric Huygens' metasurface lens is shown in Fig. 1(a) as an example. Silicon nanodisk array period (P), nanodisk height (H) and, nanodisk radius (R) are the three basic structural and geometric design parameters that control the transmission amplitude and phase of the Huygens' metasurfaces as shown in Fig. 1(b).

The metasurfaces considered here are designed for a wavelength of 1064 nm and optimized for operation in transmission under normal incident transverse-electric (TE) polarized plane wave. Design is polarization insensitive due to the symmetry of the structural nanodisk elements. In the analysis, the refractive index of Silicon (Si) and Silica (SiO_2) are 3.56 and 1.45, respectively as they are extracted from Palik's handbook [38]. Also, the imaginary part of the refractive index of silicon was taken as about 8×10^{-4} at 1064 nm from the data of Palik [38]. Using finite-difference time-domain (FDTD) method software, FDTD solutions from Lumerical Inc. the transmission and phase modulation of the nanodisk arrays with different geometric parameters are calculated. The nanodisks are assumed to be embedded in a host substrate of fused Silica (SiO_2) in the simulations. The periods of the arrays are optimized in order to get a broader overlap region of the electric and magnetic dipole resonances in the spectrum and, thus, a broader transmission region with respect to variation of nanodisk geometric parameters. It is estimated that a lattice period value of 620 nm is the best option to design a high NA (numerical aperture) flat lens with a numerical aperture value around 0.85 due to the Nyquist sampling criterion $\left(P < \frac{\lambda}{2NA}\right)$. Since periods of the arrays are fixed both in the x and y directions, and due to rotationally symmetric nanodisk elements, polarization independence is ensured. During unit cell analysis, the incident plane wave at 1064 nm is normal to the array plane with polarization along the x direction, and periodic boundary conditions are adopted in each boundary of the unit cell to decrease the amount of computation time.

Fig. 2(a) and (b) show the calculated contours of the transmissivity and transmission phase of the nanodisk arrays for different illumination wavelength and radii (R). By varying the nanodisk radius, relatively high transmission and full phase coverage (0–2π) can be achieved at the same time for the nanodisk height of 170 nm (nanodisk embedded in SiO_2), respectively. It is clear that this enables arbitrary wavefront control by precisely manipulating the spatial distribution of the radius variation of dielectric nanodisk resonators. A fixed lattice period of 620 nm both provides a broad area with high transmissivity and allows easy fabrication with high tolerance as well as less complex design. The more the lattice period reduces, the more coupling occurs between the adjacent unit cells and high transmission region significantly reduces.

Fig. 2(c) and (d) clearly show the transmission and the phase modulation for different nanodisk radii while the wavelength is fixed at 1064 nm as the operation wavelength. For convenience, here the phase modulation of 130 nm radius is set to be zero, and all negative phases are changed to positive by adding 2π to them. This result serves as look-up data for choosing the proper disk radius for the phase manipulation required In order to achieve any desired phase profile at each spatial location (x, y), an appropriate nanodisk diameter is chosen to minimize