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Polarization multiplexed all-dielectric metasurfaces for wavefront manipulation in a transmission mode

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Abstract

All-dielectric metasurfaces are planar structures completely consisting of dielectric materials, which enable the control of phase, amplitude and polarization of light. Due to the good process compatibility and high transmittivity, they have drawn considerable attention in diverse applications for polarization conversion and wavefront manipulation in a transmission mode. Although several kinds of all-dielectric metasurfaces have been reported in literature to achieve wavefront manipulation, they either have only one fixed wavefront output or have susceptible efficiency to the side-wall-angle (SWA) error, which is extremely difficult to be minimized with current top-down fabrication processes. In this work, we propose an elliptical silicon nanopillar array, which possesses a polarization multiplexed response and high transmittivity, and more importantly, it is less sensitive to the SWA error. Two metasurfaces, namely a beam deflector and a vortex convertor, are exemplified to examine the performance of the proposed elliptical nanopillar array at a visible wavelength of 600 nm. We achieve high transmittivity of 76.7% and 81.4% for the beam deflector and the vortex convertor, respectively. Moreover, both the deflecting direction of the beam deflector and the chirality of the generated beam from the vortex convertor can be controlled by the incident polarization. The proposed all-dielectric metasurfaces demonstrate great potential for practical and polarization multiplexed optical elements.

Keywords: all-dielectric metasurfaces, polarization multiplex, wavefront manipulation, optical vortex

(Some figures may appear in colour only in the online journal)

1. Introduction

In the field of optics, a wavefront describes the propagation of an imaginary surface defined by the locus of points that have the same phase [1], while wavefront manipulation enables the control of the flow and propagation of light [2]. Generally, the desired requirements of the device for wavefront manipulation include that firstly the device should possess high transmittivity or reflectivity, and secondly should provide 360° phase control in the transmitted or reflected light with respect to the incident light. In addition, the device should provide 180° control in the phase difference between the two orthogonal polarization components of the transmitted or reflected light, if polarization multiplex is desired [3]. Among the above three requirements, the polarization multiplex is an easily overlooked but significant indicator in the field of optical networks [4] and data storage [5] to achieve high throughput and storage capacity, respectively.

Traditionally, wavefront manipulation is realized by optical elements, such as lens and spatial phase modulators, which arises from a shaped phase accumulated along the light path. Accordingly, the key in traditional wavefront manipulation lies in changing the profile and thickness of bulk materials to acquire the ideally shaped phase, which is usually independent on the polarization of incident light [6, 7]. Moreover, due to the limitation of existing materials and
fabrication processes, the length of propagating path in these optical elements is usually much longer than the wavelength of interest. In contrast, metasurfaces, the surface version of metamaterials, enable control of phase, amplitude and polarization of light in a sub-wavelength propagating path [8–12]. Metasurfaces realize wavefront manipulation by spatially arranging the scatters with a sub-wavelength center-to-center distance and different structural dimensions [13]. Compared with traditional wavefront manipulation approaches, the metasurface-based approach is more powerful and more suitable for integration in miniaturized optical systems. However, it is also worth pointing out that, since the dimensions of metasurfaces are typically small especially at optical frequencies, a minor fabrication error in the metasurfaces will lead to a remarkable degradation in their performances.

The emergence of metasurfaces attracts much research for wavefront manipulation, and much of these research has focused on the metal-dielectric structure (plasmonic metasurface), which have relatively low efficiencies at optical frequencies, due to inherent ohmic dissipation [14–17]. Metal-insulator-metal structures [18–21] and gain materials [22, 23] can be used to implement a high efficiency for manipulating the wavefront, while they are usually operating in a reflection mode and may not be compatible with contemporary semiconductor industry technologies, which restricts the miniaturized integration of optical systems working in the transmission mode. This limitation of plasmonic metasurfaces, a low efficiency in the transmission mode, can be overcome by all-dielectric structures (all-dielectric metasurfaces) [16, 24–34]. In 2014, it was demonstrated numerically by Cheng et al. that an all-dielectric metasurface platform based on low-aspect-ratio silicon disks has high transmittivity and enables 360° phase control for wavefront manipulation at a near-infrared wavelength [27]. This capability is obtained by overlapping scattering contributions of magnetic and electric dipoles [25]. Based on the same principle, in 2015, Shalaev et al. experimentally implemented wavefront manipulation with high transmittivity at a near-infrared wavelength [30]. However, the reported device based on this principle either is polarization-independent or only responds to one polarization state, and thus lacks the function of polarization multiplex. Arbabi et al. realized complete control of phase and polarization with high-aspect-ratio silicon nanoposts using a top-down fabrication approach, and experimentally demonstrated the great potential in wavefront manipulation [32]. Employing a bottom-up fabrication process, F Capasso’s group obtained a ∼90° vertical side wall, and achieved a 360° phase control for arbitrary polarization based on high-aspect-ratio titanium dioxide nanofins [34]. Although two fabrication approaches (top-down and bottom-up) have been used to realize polarization multiplex for wavefront manipulation, it is quite challenging for the top-down fabrication processes to fabricate a high-aspect-ratio structure with vertical side wall [35]. Moreover, the SWA error induced in the fabrication will have a noticeable influence on the transmission properties of metasurfaces. Even so, considering the widespread usage of the top-down fabrication approach, here we focus on metasurfaces fabricated with this approach. To the best of our knowledge, although the metasurfaces for wavefront manipulation with high transmittivity have been reported in [27, 30–32], the metasurfaces that have high transmittivity, a polarization multiplex and are process-friendly have not been reported yet.

In this paper, we propose a process-friendly metasurface platform based on an elliptical nanopillar array to realize wavefront manipulation at a visible wavelength of 600 nm. The proposed metasurface platform has high transmittivity and is capable of achieving entire phase control and polarization multiplex. Inspired by a structural configuration in [3], we also alleviate the influence of the structural SWA error on the performance of the designed metasurfaces. Differing from the reported polarization multiplexed metasurfaces that work in circularly polarized light [14, 15, 24, 36, 37], the wavefront transmitted from our metasurfaces is controlled by a linear polarization state. The approximation in the design process of metasurfaces for wavefront manipulation, namely the local transmission properties of a nonuniform array approximated by those of a uniform array, is discussed. Two kinds of all-dielectric metasurfaces, including a beam deflector and a vortex convertor, which are realized by the proposed metasurface platform, are finally taken as examples to demonstrate the capability of wavefront manipulation with high efficiency and polarization multiplex.

2. Design

2.1. Transmission properties of the nanopillar array

Figure 1 presents a schematic of the designed metasurface, which consists of a single-layer infinite and uniform array of high refractive index poly-silicon elliptical nanopillars on the top of a fused silica substrate. The pitches of the pillar array along the x and y directions are identical and denoted as P. The height of pillars is H. The diameters of pillars along the x and y directions are D_{x} and D_{y}, respectively. We assume that
the incident plane wave is propagating oppositely along the z axis with a linear polarization state along the x or y axis. Due to the overlap of elliptical axes of pillars and polarization direction of incident light, the pillar array does not change the polarization of light as it passes through the array; however it imparts different phases to the transmitted light polarized along the x and y axes, respectively. Therefore, the designed metasurface could be regarded as a waveplate whose principal axes are along the x and y axes, and thus possesses a polarization response [32].

The modeling results in this work were performed via a commercial software, FDTD Solutions (Lumerical Solutions, Inc.). In the numerical calculation, the refractive indices of the poly-silicon and fused silica at the wavelength of 600 nm are 3.94 – 0.018i and 1.46, respectively. For the given pitch of 257 nm and height of 294 nm, we first calculated the transmission coefficients $t_x$ and $t_y$ of uniform pillar array as functions of the elliptical pillars diameters $D_x$ and $D_y$ ranging from 60 to 200 nm. For the convenience of subsequent design, the diameter and transmittivity were recovered as a function of the phase shift by minimizing the following equation

$$MSE = \frac{1}{2} [|t_x - \exp(i\phi_x)|^2 + |t_y - \exp(i\phi_y)|^2 ],$$

(1)

where $\phi_x$ ($\phi_y$) indicates the abrupt phase shift imparted by the pillar array with x (y) polarized incident light [32]. In this paper, transmittivity is an energy ratio of output light to input light, phase is the position of a point on a waveform cycle, and phase shift is the difference of phase at bottom and top surfaces of the pillar. Equation (1) shows a relationship between the numerically calculated transmission coefficients and the ideal ones. The smaller the $MSE$ is, the better the transmission properties the pillar array has. In the phase shift range from $-180^\circ$ to $180^\circ$, the recovered results are shown in figure 2. As can be observed, all combination of phase shifts for wavefront control could be acquired, and the corresponding transmittivity and pillar diameters could thereby be readily figured out. Notice that the transmittivity is larger than 78% for the majority of combination of phase shifts, which makes the design of metasurfaces for wavefront manipulation flexible. In addition, the independence of imparted phase for x- and y-linearly polarized light makes the polarization multiplex available for wavefront manipulation.

2.2. Approximation of the local effect

As for wavefront manipulation, the top layer of metasurfaces consists of a nonuniform array of pillars with varied dimensions. In the design process of these metasurfaces, local transmission properties of a nonuniform array are typically approximated by those of a uniform periodic array to simplify the design process. Weak coupling among pillars makes this approximation valid, which attributes to the confinement of the optical energy inside the pillars [32]. A uniform array of pillars with diameters of $D_x = D_y = 120$ nm was used to verify this approximation of the local effect, and the results are illustrated in figure 3. As can be seen, the energy of incident light mostly converges into pillars from their top-surfaces, and radiates from their bottom-surfaces into the substrate. When propagating through the top layer of the metasurface, the energy of the incident light is mostly confined inside the pillars.

2.3. Influence of the SWA error

In the fabrication of metasurfaces, the top layer made of complex nanostructures is usually acquired by etching. Currently, it is difficult for the etching processes to rigorously guarantee a SWA of 90° for the nanostructure. A little SWA error will have a significant impact on the performance of metasurfaces, especially for those metasurfaces with high aspect ratios. Three groups of nanopillars with increasing aspect ratios are chosen to investigate the influence of SWA error on transmission properties. The diameters of the three groups of nanopillars along the x and y directions are $D_{x1} = 170$ nm, $D_{y1} = 170$ nm and $D_{x2} = 120$ nm, $D_{y2} = 120$ nm and $D_{x3} = 75$ nm, $D_{y3} = 200$ nm, respectively. We calculated the transmission properties of three uniform metasurfaces as a function of SWA, and the results are shown in figure 4.

In figure 4, the transmittivity and phase shift of the first two metasurfaces for TM and TE incident light are identical, due to the same diameters of the nanopillars along the x and y directions. As can be seen, the transmission properties of the first metasurface with a low aspect ratio are almost unchanged as SWA decreases, and the transmission properties of metasurfaces with a higher aspect ratio are more susceptible with SWA. Even so, the transmittivity for three metasurfaces are pretty high within the SWA range from 82° to 90°, and this SWA range could be realized by current top-down fabrication processes. In addition, the phase shifts of the second and third metasurfaces sharply decline as SWA decreases, but the difference between the two phases is almost constant. So when nanopillars with suitable diameters are selected, the constructed wavefront is less susceptible to SWA. This characteristic of our proposed metasurface reduces the requirement of a fabrication process, and thereby improves the manufacturability of the metasurface. The above merit of the proposed metasurface might be attributed to two reasons. Firstly, instead of an overlap between the magnetic and electric dipole resonances in previous reports [26, 27, 29–31, 33], the transmission properties of the proposed metasurface are associated with scattering contributions of dipoles and high-order multipoles. The effect of tailoring the side wall of the pillars will be compensated with a balance among these dipoles and multipoles [3]. Secondly, the aspect ratio of the proposed metasurface is relatively small, and a minor SWA error has little influence on the entire dimensions of the pillar. In addition, we also investigated the influence of the diameters and height of the pillars with SWA being 90° on the transmittivity of these metasurfaces. The simulation results indicated that both TE and TM transmittivity are more than 70% when the diameters and heights of all pillars uniformly deviated from their designed values within the range of 10%, respectively.
2.4. Designs of an optical beam deflector and a vortex convertor

The two degrees of freedom of the proposed metasurface platform, including the polarization and phase, allow for realizing a great variety of optical elements. Here, we will present two optical elements, namely the beam deflector and vortex convertor, to demonstrate the capacity of wavefront manipulation with high efficiency and polarization multiplex. Both of the two metasurfaces are composed of eight pillars selected from figure 2, which provide the linear phase variation from $-180^\circ$ to $+180^\circ$. The corresponding diameters, transmittivity and phase shifts are listed in table 1.

Figure 2. The recovered elliptical pillars diameters (a) $D_x$, (b) $D_y$ and transmittivity (c) $|t_x|^2$, (d) $|t_y|^2$ as functions of phase shifts for x and y polarized incident light.

Figure 3. The time-average energy density coded with colour and power flow vector indicated by white arrow at (a) upper surface, (b) lower surface and (c) cross-section of the pillar. Profile of the pillar is indicated with black lines.
As illustrated in figure 5(a), the metasurface for optical beam deflection consists of an infinite periodic array of super-units (shown in inset), composed of eight pillars from table 1. According to the linear variation of phase, the eight pillars are arranged in the x direction to acquire a phase change of $360^\circ$.

The thickness of the bulk substrate is assumed to be infinite, and the incident light is assumed to be a $x$- or $y$-polarized plane wave propagating along the $z$ axis in opposite directions. According to the general Snell’s law \[38], the theoretically deflecting angle can be expressed as

$$\theta_i = \sin^{-1}\left[\frac{1}{n_i} \sin \theta_i + \frac{\lambda_0}{\Lambda}\right], \quad (2)$$

where $n_i$ and $n_t$ are refractive indices for air and fused silica, respectively, $\theta_i$ is the incidence angle, $\lambda_0$ is the free-space wavelength of light, and $\Lambda$ is the period of super-unit in the $x$ direction.

To demonstrate the flexibility of the proposed metasurface platform for polarization multiplexed wavefront manipulation, we further design a metasurface that is able to convert a conventional Gaussian beam into a vortex beam with one topological charge (different topological charges are also realizable [37]). Figures 5(b) and (c) show the schematic diagram of the designed vortex convertor. It consists of eight sections, and each section is stuffed with the identical pillars from table 1. According to the linear variation of phase, the

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**Table 1.** Dimensions and transmission properties of the pillar array.

<table>
<thead>
<tr>
<th>Pillars</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>t_x</td>
<td>^2$</td>
<td>0.93</td>
<td>0.90</td>
<td>0.86</td>
<td>0.80</td>
<td>0.78</td>
<td>0.84</td>
</tr>
<tr>
<td>$</td>
<td>t_y</td>
<td>^2$</td>
<td>0.93</td>
<td>0.98</td>
<td>0.92</td>
<td>0.84</td>
<td>0.78</td>
<td>0.80</td>
</tr>
<tr>
<td>$\phi_x/\text{deg}$</td>
<td>$-179$</td>
<td>$-129$</td>
<td>$-87$</td>
<td>$-45$</td>
<td>$-5$</td>
<td>$46$</td>
<td>$85$</td>
<td>$137$</td>
</tr>
<tr>
<td>$\phi_y/\text{deg}$</td>
<td>$-179$</td>
<td>$137$</td>
<td>$85$</td>
<td>$46$</td>
<td>$-5$</td>
<td>$-45$</td>
<td>$-87$</td>
<td>$-129$</td>
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<tr>
<td>$D_x/\text{nm}$</td>
<td>170</td>
<td>200</td>
<td>145</td>
<td>130</td>
<td>120</td>
<td>110</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>$D_y/\text{nm}$</td>
<td>170</td>
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<td>100</td>
<td>110</td>
<td>120</td>
<td>130</td>
<td>145</td>
<td>200</td>
</tr>
</tbody>
</table>
Figure 6. The normalized phase of $x$- (a) and $y$- (b) polarized plane wave propagating through the metasurfaces illustrated with two parallel dash lines, $\alpha$ indicates the deflecting angle, the white arrows indicate the propagation direction of emerging light. (c) Transmittivity as a function of emergent angle. In the deflecting direction of $-11.5^\circ/11.5^\circ$, TM/TE transmittivity is indicated, others are amplified by 10 times for clarity. (d) Transmittivity for main light as a function of SWA.

Figure 7. (a), (c) The normalized near-field phase profiles and (b), (d) normalized far-field amplitude profiles for $x$- and $y$-polarized incident light, respectively.
eight sections are distributed in sequence around the center of the metasurface to acquire a phase change of 360°. On the basis of the approximation mentioned previously, every two adjacent sections impart a phase difference of about −45°/45° to the x-/y-polarized transmitted light. In order to reduce the calculation time and memory consumption, the metasurface with 30 × 30 units was used for the numerical simulations. The thickness of the bulk substrate is assumed to be infinite, and the incident light is assumed to be a x- or y-polarized Gaussian wave, propagating along the z axis in opposite directions.

### 3. Results and discussion

#### 3.1. Optical beam deflector

Figure 6 shows the results of the numerical simulations for the optical beam deflector. In order to observe the propagation of wave in near-field, the phase distributions of the transmitted wave are presented in figures 6(a) and (b). As can be seen, the wavefronts transmitted from the metasurface are nearly planar and dependent on the polarization state of incident light.

Figure 6(c) shows the energy distribution in far-field, and the energy of x-/y-polarized light is mainly deflected to the left/right direction with a deflecting angle of −11.5°/11.5°, while the emerging beams propagating along the other directions are almost completely suppressed. According to equation (2), the deflecting angles of the principal beams show excellent agreement with the theoretical angles of −11.53° and 11.53°. The transmittivity for the principal beams is 76.7% and 80.1% for the x- and y-polarized incident light, respectively. Taking into account the effect of SWA error, the transmittivity of the beam deflector as a function of SWA is calculated and shown in figure 6(d). As expected, the energies of the main light are generally declined when SWA error increases, but it is acceptable that the beam deflector has about 50% transmittivity within 5° SWA error. It is noteworthy that the declining transmittivity is mostly due to the nonlinear variation of phase, and we will focus on this problem in later works.

#### 3.2. Optical vortex convertor

The simulation results of the optical vortex convertor are presented in figure 7. As can be observed, the typical characteristics of the optical vortex, including far-field amplitude
profiles of donut shape and near-field phase profiles of spiral shape, are exhibited for both of x- and y-polarized incident light. The spiral phase profile is introduced by the azimuth distribution of nanopillars with different diameters, and the donut shape is due to the existence of phase singularity in the center of metasurface. The transmittivity of the vortex converter is 81.5% and 81.4% for the x- and y-polarized light, respectively. Due to the sharply increasing memory consumption when introducing SWA error, here we did not calculate the transmittivity of vortex converter as a function of SWA. However, it is expected that its transmittivity will be similar to that of the beam deflector, according to the approximation of the local effect.

To verify the function of polarization multiplex for this vortex converter, we investigated the evolution of the vortex beam along different propagation distances for x- and y-polarized incident light, respectively. The amplitude and phase profiles of the transmitted beam behind the interface are shown in figure 8. For the first and third rows of the simulation results, the amplitude profiles are gradually reaching their far-field amplitude profiles shown in figures 7(b) and (d), where all of the partial waves from eight sections have interfered [39]. Under the illumination of x-polarized light, the phase profiles shown in the second row rotate anticlockwise about 262.8° in every two adjacent distances. However, the handedness of phase profiles is inverted when the polarization state of light is y-polarized (shown in the fourth row). So this metasurface could spin chirality of the optical vortex through changing the polarization state of light.

4. Conclusions

In summary, we have demonstrated an all-dielectric metasurface platform with high-transmittivity and entire phase control for both x- and y-polarized light at a visible wavelength of 600 nm. The transmission properties of the proposed metasurface platform are less affected by the structural SWA error induced in actual fabrication with a top-down approach, which improves the manufacturability of the metasurfaces. Based on this platform, we designed an optical beam deflector with high transmittivity of 76.7%/80.1% and an optical vortex converter with high transmittivity of 81.5%/81.4% for x-/y-polarized incident light, respectively. Compared with most of the currently reported metasurfaces that have only one fixed output, our proposed metasurfaces possess the characteristic of polarization multiplex. In addition, the proposed metasurface consisting of silicon and quartz can be fabricated in one lithographical step and is compatible with the existing semiconductor process, which makes it promising in broad and practical applications. Considering the capabilities of high transmittivity, polarization multiplex and friendly process, the proposed metasurfaces are expected to gain applications with switchable functions in a variety of fields, such as optical network, data storage, information processing and nanoparticle manipulation.

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