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Design of beam deflector, splitters, wave plates and metalens using photonic elements with dielectric metasurface

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ABSTRACT

Under the trend of miniaturization and reduction of system complexity, conventional bulky photonic elements are expected to be replaced by new compact and ultrathin dielectric metasurface elements. In this letter, we propose an αTiO_2 dielectric metasurface (DM) platform that could be exploited to design high efficiency wave-front control devices at visible wavelength. Combining with fundamental principles and full wave simulations (Lumerical FDTD 3D solver®), we successfully realize four DM devices, such as anomalous beam deflectors, polarization insensitive metalens, wave plates and polarization beam splitters. All these devices can achieve high transmission efficiencies (larger than 80%). Among them, the anomalous refraction beam deflectors can bend light propagation to any desired directions; the polarization insensitive metalens maintains diffraction limited focus (focal spot as small as 0.67λ); the quarter-wave and half-wave plates have broadband working wavelengths from 550 to 1000 nm; and the polarization beam splitter can split an arbitrarily polarized incident beam into two orthogonally polarized beams, the TM components is deflected to the right side, and the TE components is deflected to the left side. These devices may find applications in the areas of imaging, polarization control, spectroscopy, and on-chip optoelectronic systems etc., and our studies may richen the design of all-dielectric optical elements at visible wavelength.

1. Introduction

The wave-front of an electromagnetic wave can be well expressed by its polarization, phase and amplitude. Independently controlling the three parameters of wave-front with the same device is hardly feasible several years ago. For example, in free-space optical systems, the polarization can be controlled with wave-plates or polarization beam-splitters; the phase can be shaped using lenses, curved mirrors or spatial phase modulators; while the amplitude can be controlled via absorptive or reflective filters. Also, free-space optical components suffer from the Abbe's diffraction limit imposed by diffraction. These aspects make the optical system huge and being hard to realize integration and miniaturization. Furthermore, the functionality that realized with these components have propagation length several times larger than wavelength, and thus, tunability is limited if these devices are working at optical wavelengths.

Over the last few years, the advent of metamaterials seems to have partial solutions to above mentioned queries. The "metamaterials" are man-made nano-devices, can control the wave-front of light through their smartly engineered artificial structures. This control over light at the nanoscale has not only unveiled a plethora of new phenomena but also has led to a variety of relevant applications, including negative refractive index materials [1–3], zero-index [4–6], invisibility cloaking [7–9], and sub-diffraction imaging [10–12]. All of which would be impossible to achieve with the naturally occurring materials. However, regardless of the fascinating and novel physical phenomena provided by such three-dimensional (3D) metamaterials, the bulky volumetric arrangement has many fabrication difficulties and the absorption loss of metamaterials already prevents them from making useful devices. In order to overcome losses and pursue miniaturized on-chip integration and large area fabrication, one has to turn to 2D optical metasurfaces

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from 3D metamaterials. Metasurfaces [13] are planarized, ultrathin, patterned artificial surfaces that are designed to mimic the functionalities of conventional optics and metamaterials in two dimensions, can avoid absorption losses by light propagation in the third dimension. Due to the resonant features, each unit plasmonic component can alter the phase and amplitude of the light field. This enables the realization of beam shaping [14–19], polarizers [20,21] and flat lenses [22–24] etc. It should be noted that, most of these plasmonic metasurfaces exhibit low efficiencies in transmission due to metallic energy dissipation and the maximum efficiency reported so far does not exceed 25%. In contrast, resonant all-dielectric metasurfaces (DMs) [21,25–28] have negligible absorption losses, and then the overall efficiency, especially in the transmission regime, can be drastically enhanced.

To realize a highly-efficient dielectric metasurface, finding suitable constituent materials at specific spectra ranges are usually indispensable. The complex refractive index ($\tilde{n} = n + ik$) of DM materials must satisfy two conditions [29]: high refractive index and low loss, i.e., $n > 2$ and $k \sim 0$ are the ideal case for a dielectric metasurface operating at optical frequencies. A negligible absorption could ensure high transmission efficiency, while the high refractive index would allow full control over the phase of the exiting wave-front due to strong confinement of the light. The common used high index materials for DMs are silicon, germanium and tellurium at infrared frequencies. For example, there may excite a series of waveguide modes when light passing through high contrast silicon gratings. Tuning the thickness and width of the grating would result in an arbitrary control over the phase of the reflected and transmitted light, being appropriate for a wide range of applications, such as anomalous reflection, [30] achromatic metalens [28,31], hollow-core waveguides [32], and broadband high-reflectivity mirrors [33]. Besides, deep-subwavelength silicon gratings are effectively anisotropic structures that producing different phase shifts, φ, for transverse electric (TE) and transverse magnetic (TM) polarized light, can be used to design ultrathin half-wave plate [34], and unconventional azimuthal polarizer [26]. Recent demonstrations also show that, by employing the Mie resonance in all-dielectric antennas, one can realize perfect magnetic mirrors [35–37]. Such perfect magnetic mirrors do not reverse the phase ($\varphi = 0$) of the reflected electric field, and the formed standing wave that reflected from magnetic mirror has a maxima of electric field strength near the surface. Therefore, stronger light–matter interactions can be expected with the planar optoelectronic devices. However, these original dielectric metasurfaces are limited to transparent windows at infrared and terahertz regimes, due to that such dielectric materials also suffer from significant optical absorption and losses at visible wavelength. It is then critical to find new materials to extend dielectric metasurfaces design across the scientific and technological important visible spectrum band. Unfortunately, most dielectric materials are not included in the category of DM materials due to their lower refractive index. More recently, Capasso et al. reported that amorphous titanium dioxide (αTiO_2) has those two features of negligible loss and high refractive index ($n \approx 2.5$) at optical frequencies [38]. Based on the αTiO_2 material, they have successfully realized high-efficiency metalenses [39–41], by using a bottom-up nanofabrication via atomic layer deposition, functioning in forward transmission direction.

For those working in metasurface design, materials with low losses and high refractive index are the preferred option. The advent of αTiO_2 would definitely ignite the hope in this community. Therefore, in this article, we present some optical device designs with metasurfaces based on αTiO_2, to achieve ultrathin and high efficient optical elements at visible wavelengths, without using metals. In comparison with plasmonic metasurface that using V-shape and split resonant ring (SRR) structures, our devices use the simplest dielectric structures (e.g. nano-grating, nano-pillar and nano-brick) that can relieve both the fabrication and design burdens. First, we employ the generalized Snell's law to demonstrate anomalous refraction by engineering the spatial dispersion of nano-pillar based metasurface, in which, the light can be bend to any desired directions. Second, we demonstrate a polarization insensitive metalens using a square nano-brick array, with high efficiency (84%) and a diffraction limited focus. Third, we realize a broadband quarter-wave plate and a half-wave plate, by taking advantage of the geometric anisotropy of αTiO_2 grating structure, which accumulate a phase shift ($\pi/2$ or π) between the two electric field components. Finally, by utilizing the different phase-shift for TM and TE polarized light in rectangle nano-brick array, we have successfully demonstrated a new design of a polarizing beam splitter. It shows a polarization-selective deflecting behavior, with one polarization (TM) deflected to right side and the orthogonal polarization (TE) deflected to left side. Since presently less materials meet the requirements in terms of low loss, high refractive-index, easy fabrication, and high optical transparency at visible spectrum band, we believe that our work may richen the design of all-dielectric optical elements with subwavelength thickness, high performance and potential tunability at visible band.

2. Anomalous refraction beam deflector

αTiO_2 metasurface elements can provide arbitrary phase control for an optical wave-front while can still maintain high transmission efficiency across the entire visible spectrum. As shown in Fig. 1(a), a cylinder nano-pillar structure on SiO_2 substrate, with the increase of diameter, the transmission phase (blue diamond line) varies across the whole 0–2π range, while the transmitted intensity (black circle line) stays very high (>90%) at a certain wavelength of 532 nm. The transmission spectrum inset Fig. 1(a) shown that the nanopillar for a given diameter $D = 150$ nm can maintain high transmission efficiency in the entire visible range (450–1000 nm). This excellent phase control capability gives us the possibility to realize anomalous refraction metasurface: (1) if one could design a interface covered with a collection of subwavelength nanostructures (nano-pillar) whose transmission coefficient is unity in the absolute value, and (2) the phase of the transmission coefficient changes in accordance with the generalized laws of refraction [42], and (3) it has discontinuous gradients at the interfaces [17,43,44]. In the following, we will try to design such a device with the assistant of Fermat principles.

Fermat's principle states that two (or any arbitrary number of) paths traversed by light, are infinitesimally close to the actual light path. Therefore, the generalized laws of reflection and refraction can be obtained from the Fermat's principle. As shown in Fig. 1(b), the metasurface is located at the xy-plane between two isotropic half-spaces with refractive indices of n_i and n_t, and $k_0 = 2\pi/\lambda_0$, where λ_0 is the vacuum wavelength. We assume that the metasurface is illuminated from medium 1 by a plane wave at an angle θ_i. After passing through the metasurface, the incident wave is transformed into a propagating refracted wave in medium 2 at an angle θ_t. Two paths are taken by light traveling from point A to point B. Here, metasurface elements allow us to arbitrarily tailor the phase accumulated by light as a function of position; φ and $\varphi + d\varphi$ are the phase discontinuities at the locations where the two paths cross the interface, respectively; dx is the distance between the crossing points. We see that Path 1 differs to Path 2 by the extra distances c and d traveled in media 1 and 2, respectively, where a and b correspond to a fixed distance traveled by the wave in media 1 and 2, respectively. Therefore, the total phase of two paths are respectively given by:

$$Path\,1: ak_0n_i + \varphi + k_0n_t\sin\theta_t dx + bk_0n_t \tag{1}$$

$$Path\,2: ak_0n_i + \varphi + d\varphi + k_0n_i\sin\theta_i dx + bk_0n_t \tag{2}$$

According to the constraints of Fermat's principle, the phase difference between two paths is zero, we then have:

$$[k_0n_i\sin\theta_i dx + d\varphi] - [k_0n_t\sin\theta_t dx] = 0 \tag{3}$$

The generalized Snell's Law of refraction is:

$$\sin\theta_t n_t - \sin\theta_i n_i = \frac{\lambda_0}{2\pi}\frac{d\varphi(x)}{dx} \tag{4}$$