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Efficient bending and focusing of light beam with all-dielectric subwavelength structures

Yue Shen [a], Xiangang Luo [b,*]

[a] Department of Electronic Engineering, Tsinghua University, Beijing 100084, China
[b] State Key Laboratory of Optical Technologies on Nano-Fabrication and Micro-Engineering, Institute of Optics and Electronics, Chinese Academy of Science, P. O. Box 350, Chengdu 610209, China

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ABSTRACT

In this paper, all-dielectric subwavelength structures are proposed to construct beam deflectors and lenses that modulate the light fields efficiently. These devices are composed of planar array of silicon pyramids with spatially varying geometric shapes, thereby introducing arbitrary phase shift to the propagating light. Meanwhile, owing to the intrinsic low-reflection property, average reflectance as low as 10% is accomplished. The lenses were rigorously designed in both one-dimensional (1D) and two-dimensional (2D) cases. Due to the symmetry of the unit cell, there is no limitation on the polarization state of the incident light. Since no plasmonic loss is incorporated, this design could meet the requirement of wavefront manipulation for laser beams.

1. Introduction

In recent years, metamaterials have been intensively studied and used to control electromagnetic waves in exotic manners. Applications such as invisibility cloaking, perfect imaging have been demonstrated by taking advantage of the light–matter interaction in complex subwavelength structures [1,2]. Nevertheless, huge challenges still exist for the practical application of metamaterials in the optical regime, since three dimensional (3D) metamaterials are highly lossy and difficult to fabricate in this particular frequency region [3,4]. As an alternative, two dimensional (2D) metasurfaces were proposed to replace metamaterials to provide complete control of the light wave via a thin structured layer [5,6]. Up to date, a lot of metasurface-based optical devices have been demonstrated, including flat lenses [7–13], mantle cloaks [14,15], perfect absorbers [16–18], ultrathin polarizers [19–21], anti-reflection coatings [22,23], and spin-optical devices [24–26].

One of the simplest (and maybe one of the most important) applications of metasurfaces is about the control of phase of electromagnetic wave. In principle, there are three kinds of phase-manipulating mechanisms: one is based on phase accumulation along optical path [27–33], and the other two rely on the impedance-induced delay [34–36] and polarization-depending scattering [11,12,26,37], respectively. By utilizing the localized phase shift, traditional optical devices such as bulk lens [11,13,28], prisms [11,37], axicons [11,38], and spiral phase plates [11,37] were successfully compressed into one single layer. More recently, Capasso et al. proposed a metasurface with gradient V-shaped antennas to achieve similar effects. The introduction of phase gradient in the metasurface can be regarded as a generalization of the Snell's law, similar with the discussion about nonlinear slab reported several decades ago [39].

Although metallic metasurfaces provide the compact and light-weight properties required by integrated systems, there are also some intrinsic drawbacks in these designs [11]. Firstly, the ohmic losses in metallic structures in optical frequency regions are much larger than that in low frequency regions, which limited the energy efficiency to be typically less than 20% in such systems. Secondly, almost all plasmonic metal would melt at high temperature, thus not suitable for applications with high-power laser and high temperature [17]. In order to overcome these issues, many efforts have been paid to construct all-dielectric metasurface devices based on material with high dielectric constant [10,11]. Nevertheless, the high dielectric-constant means that a considerable portion of incident light would be reflected if no other antireflection techniques are utilized [23,40]. It should be noted that although the efficiency of spin-optical lens can be optimized by using high-index material, such devices could only work for one particular polarization [11], thus have a maximal efficiency of 50% for naturally polarized light. As a result, it is advantageous if one can combine the phase-shifting and anti-reflection properties together in a polarization-independent structure.

In this paper, we report the design and analysis of a planar lens

* Corresponding author.
E-mail address: lxg@ioe.ac.cn (X. Luo).

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which performs at a wavelength of $\lambda = 1.064$ µm. The lens consists of an array of pyramidal-like subwavelength unit cells, which can be fabricated by techniques such as laser direct writing and two-photon photopolymerization [23]. Abrupt phase changes were introduced to light beams by locally changing the apex angles of these pyramids, with average transmittances larger than 95%. As a proof of the principle, deflection of light to an arbitrary angle was accomplished by spatially periodic arrangement of the structures. Subsequently, both one and two dimensional (1D and 2D) dielectric lenses were designed to focus incident light into a linear and a circular spot, with spot sizes closing to the diffraction limit. Owing to the high degree of symmetry, this lens is completely independent on the polarization states of incident light. These outstanding properties render these all-dielectric flat optical devices applicable in integrated optics.

2. Structure and simulation

2.1. Design of the unit cell

In general, the unit cell of a phase shifter should have both high transmittance and full control of phase shift within [0, 2π]. As shown in Fig. 1a, the unit cell is a quadrangular pyramid, which could introduce phase shift by delaying the light beam while maintaining small reflection at the surface. The period, height and apex angle of the structure are set as p, h and α. In our design, the period p was kept invariant, while α was tuned to control the phase delay. Clearly, the height h is determined by α and p as $h = \tan\alpha \times p/2$. In order to reduce the height h, the pyramids are made of silicon with permittivity ε which equals to 12.67 at a wavelength of $\lambda = 1064$ nm. Based on the symmetry of these pyramids, the phase delay is independent on the polarization states of the incident light at normal incidence.

In the following numerical simulation, we set the period p to be 200 nm and operational wavelength to be 1064 nm. By using commercial software (CST microwave studio), the diagram representing the relationship between phase discontinuity $\Delta\varphi$ and variable α was obtained, as shown in the left axis of Fig. 1b. The overall thickness of the substrate is set as 2 µm, and light is incident from the bottom of the substrate. Since the port is attached to the substrate, there is no reflection at the entrance side. We noted that when fabrication errors are taken into account, the phase and amplitude may departure from the ideal values. Furthermore, since the device is designed for laser wavelength, no broadband operation requirement is needed.

To facilitate the design, a fitted third order polynomial was acquired as:

$$\Phi(\alpha) = 0.15904255\alpha^3 - 34.5215 \times \alpha^2 + 2511.52 \times \alpha - 61221.5. \quad (1)$$

Eq. (1) means that the phase shift can cover [0,2π] by changing α from 70° to 84°.

One of the advantages of the pyramids is the relatively high transmission efficiency compared to traditional structures. As shown in the right axis of Fig. 1b, the transmittance, defined by the squared ratio of the amplitude of the transmitted light to that of the incident light, is above 0.91 for all α ranging from 70° to 84°. The average transmittance is even larger than 95%. This high transmission property is essential to the application of the metasurface, as shown in the following design examples. It should also be noted that the proposed structure may have relatively strong chromatic dispersion. Nevertheless, such dispersion is not a significant problem since the discussion in this paper is focused on the manipulation of laser beam, which intrinsically operates in narrowband.

2.2. Design of 1D deflector and flat lens

The straightforward application of the pyramidal array is to act as a blazing grating and to realize deflection of the incident light. As shown in the inset of Fig. 2a, N gradient unit cells are treated as one super-cell ($\Lambda = Np$) and then duplicated 19 times along the x-axis. Meanwhile, the boundary conditions along the y-axis are set as periodic. According to the revised law of refraction [4,37], the formula about the angle of deflection θ can be written as:

$$\sin\theta = \frac{\lambda}{np} \quad (2)$$

Under transverse electric (TE, electric field polarized along the y-direction) polarized illumination, the angular spectra for $N = 8$, 10 and 12 were calculated by Fourier transform of the transmitted fields. As shown in Fig. 2a, the calculated deflecting angles are 41.29°, 31.92° and 26.4°, close to the theoretical evaluations (41.68°, 32.14° and 26.31°). We noted that the angular width of the transmitted light varies with the deflection angle, which can be attributed to the reduction of effective beam width.

Fig. 2b illustrates the distribution of electric field amplitude (E_y) in the x–z plane for $N = 8$. Obviously, the deflected wavefront is nearly perfect except some minor noise, which can be attributed to the scattering in these structures.

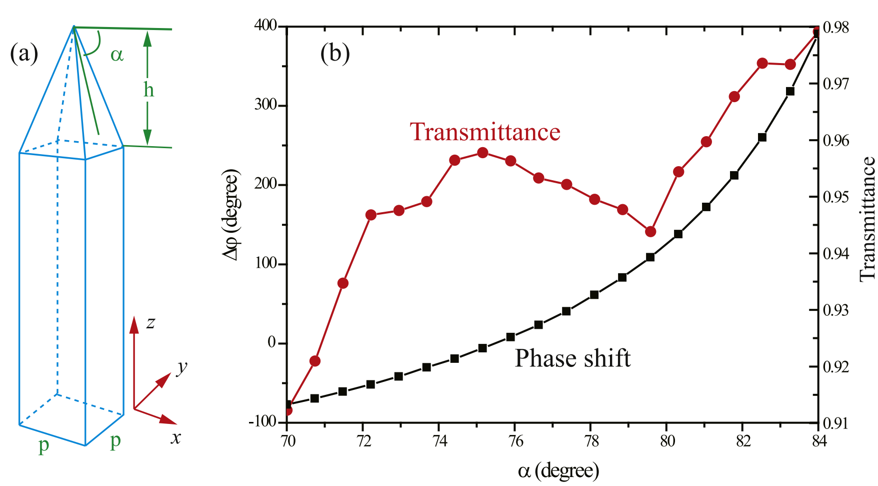

Fig. 1. (a) Schematic of the unit cell. (b) Simulated phase shift (left) and transmittance (right) versus the apex angle.