Metasurface-Based Wide-Angle Beam Steering for Optical Trapping

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ABSTRACT Metasurfaces become increasingly important for wavefront shaping and beam steering with high efficiency. We propose a wide-angle beam steering device based on all-dielectric metasurfaces consisting of two symmetrical blazed gratings for optical trapping of particles, which can convert the input Gaussian beam to a special beam with intensity gradient along the propagation direction. Two major types of metasurfaces (Pancharatnam-Berry phase and nanoposts) are compared, and dramatic difference is found between them, especially at oblique incidence. We show that the Pancharatnam-Berry phase-based metasurface is more tolerant to the incident angle and that significant optical gradient force can be generated over a large angle range of $-50^\circ$ to $50^\circ$, and the maximum attractive force is up to tens of pN/W, with a trapping range of $14 \mu m$ for particles of $2.5 \mu m$ in diameter. The proposed scheme exhibits great potential to trap a large fraction of particles floating in a microfluidic channel when the beam is dynamically steered.

INDEX TERMS Metasurface, gradient force, optical trapping, wide-angle beam steering.

I. INTRODUCTION

In recent years, optical field manipulation using metasurfaces has gained increasingly more interest. One can use an array of antennas with a high index contrast and subwavelength separation to control amplitude and phase responses and manipulate optical wavefronts for various applications [1]–[3]. Metasurfaces exhibit light weight, small thickness, subwavelength resolution, flexible material choice, and CMOS compatibility [4]–[6] and become promising in the field of beam shaping and steering. Subwavelength resolution can eliminate higher diffraction orders, which is the fundamental limitation of diffractive optical components [2]. Many kinds of metasurfaces have been proposed, featured by V-shape antennas [7], H-shape antennas [8], elliptical nanoposts [9], square nanoposts [10], and topology-optimized unit cells [11]. By changing the geometric parameters of the unit cells, phase changes can be tailored from 0 to $2\pi$. These nanostructures are adopted to build, e.g., blazed gratings [12], plane focusing lenses [13], [14], flat optical vortex plates [15] and holograms [16] and so on. Pancharatnam-Berry (PB) phase-based metasurfaces have also been proposed [17], [18].

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modulator [27] or an axicon [28] can potentially be used to realize a large trapping range, they are bulky and hard to achieve wide-angle steering. Thus, ultrathin metasurfaces are very attractive. Before a tractor beam was formed for trapping [21], [29], [30], without wide-angle steering. In fact, a microfluidic channel, particles are randomly floating in the whole channel, and it would be highly desirable to achieve dynamic beam steering in a large angle range so that a large fraction of particles in a microfluidic channel are attracted and trapped.

In this work, we proposed beam steering for optical trapping based on blazed gratings formed with metasurfaces, which have the advantages of high transmittance, flexible design and high integration. Two types of metasurfaces are compared, and it is revealed for the first time to the best of our knowledge that PB phase metasurface exhibits good tolerance to oblique incidence. We analyze the optical force exerted on particles and show that the particles can effectively be trapped as the beam is steered over a large angle range, from $-50^\circ$ to $50^\circ$.

II. PRINCIPLE AND STRUCTURE DESIGN

The proposed configuration of metasurface-based beam steering and trapping is shown in Fig. 1(a), in which two metasurface blazed gratings are placed in the $xy$ plane in order to deflect input Gaussian beam towards the $yz$ plane. This way, the gradient of Gaussian optical field in $x$ direction is converted to $z$ direction so that an optical gradient force can be formed along $z$ direction. As the incidence angle is changed by $\pm \varphi$ in the $yz$ plane by moving an optical fiber below the metasurface, the formed beam is steered accordingly above the metasurface. The beam can sweep a large area in the $yz$ plane, as long as the blazed gratings still work well at a large incidence angle, $\varphi$.

A blazed grating consists of periodically arranged super cells, and each super cell contains five units cells to cover the phase change from 0 to $2\pi$ linearly [31]. As shown in Fig. 1(b), two kinds of unit cells are investigated. Based on PB phase principle [32], every unit cell is formed by a silicon nanofin placed on a silicon dioxide substrate. When a light beam normally passes through a birefringent “waveplate”, an additional phase that is dependent only on the optical axis direction of the “waveplate” is introduced. The phase change is $\Phi = 2\alpha$, where $\alpha$ is the orientation angle of the unit cell. The factor 2 arises because the anisotropic medium reverses the handedness of the circular polarization and applies an additional geometric phase factor $2\alpha$ to the output light [19], [20]. High transmissivity can be obtained by choosing proper structure parameters. Nanoposts change phase by adjusting the side length, $a$. Figure 1(c) shows that five unit cells are combined to form a super cell. We choose left-handed circularly polarized light as the incident polarization for PB phase-based metasurface and $x$-polarization for nanopost-based metasurface.

The proposed geometric metasurface was designed using CST software based on finite integration technique (FIT), and for PB phase-based unit cells, we set $w = 150$ nm, $d = 450$ nm, $h = 1200$ nm, $p = 600$ nm, while for nanopost-based unit cells, we set five different lengths, $a$, as 220, 278, 320, 378, 456 nm, and other parameters are fixed as $h = 1000$ nm, and $p = 600$ nm. The Blazed grating is $30 \mu$m wide in $x$ direction and $20 \mu$m long in $y$ direction. At $1550$ nm, we choose a Gaussian beam pointing to the origin of coordinates as the incident beam. The beam size is set according to the fundamental mode in a single-mode fiber. From the structural symmetry, the results are the same when the light is incident at $\varphi$ or $-\varphi$, so we can only examine the incident angle of $0-\varphi$.

The linear phase shift and high transmissivity of the five unit cells in Fig. 1(c) are found in Fig. 2. For PB phase-based unit cells, their transmissivities are almost all around $94.5\%$. A nanofin has a varied phase shift by its rotation but has stable amplitude response, which is beneficial to wavefront control. For nanopost-based unit cells, their transmissivities change greatly with the sizes.

Figure 3(a) shows the transmitted electric field distributions of the proposed blazed grating. According to the generalized Snell’s law [1], the deflection angle is given by

$$n_1 \sin(\varphi) - n_2 \sin(\theta) = \frac{\lambda_0}{2\pi} \frac{d\Phi}{dx}$$

(1)

where $n_1$ and $n_2$ are the refractive indices of materials in the incident and transmitted regions, respectively, $\lambda_0$ is the wavelength in vacuum, $\varphi$ is the incident angle, $\theta$ is the deflection angle, and $d\Phi/dx$ is the gradient of phase discontinuity along the interface. Here, the $\theta$ is $31^\circ$ according to Eq. (1). It can be clearly seen that the blazed grating deflects the beam at
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FIGURE 2. The phase shifts and transmissivities of the five cells in one super cell.

FIGURE 3. Electrical field distribution near the blazed grating with normal incidence. (b) The normalized far-field intensity profile of the deflected beam. the angle of 31° as shown in Fig. 3(b), in good agreement with Eq. (1).

III. WIDE-ANGLE OPTICAL TRAPPING

For beam steering, incident angle needs to be swept. Figure 4(a) shows the optical field profile in the yz plane at the incident angle from 0 to 50°. The angle of the transmitted beam is aligned to the incident direction. Figure 4(b) shows the normalized electrical field along the z-axis starting from the origin in the case of normal incidence. There exists intensity gradient to induce an optical gradient force. Similarly, there is an intensity gradient along the beam axis \( z = \tan(\phi)y \) at oblique incidence. We note in Fig. 4(c) that the efficiency decreases with the incident angle in the case of using PB phase at the large angle. In the case of normal incidence, the efficiency is as high as 91%, but at an incident angle of 50°, the efficiency is reduced to about 60%. In contrast, using the nanoposts causes a quickly decreasing efficiency at oblique incidence. This is because, in device design, the response of each unit cell is optimized only at normal incidence, and the transmissivity of each unit cell on metasurfaces changes at oblique incidence. Figure 5 shows the transmissivity and phase shift of each unit cell at different incident angles. For the PB-based unit cells, the relative phase shifts are almost constant, and the transmissivities slightly increases, as the incident angle varies between 0 and

FIGURE 4. (a) Electrical field distributions in the yz plane generated by symmetric blazed gratings at different incidence angles from 0° to 50°. (b) The distribution of the normalized electrical field along the z axis at normal incidence. (c) The efficiency of the structures at different incidence angles.
FIGURE 5. (a) The transmissivity of each unit cell at different incidence angles from 0° to 50°. (b) The phase shift of each unit cell at different incidence angles from 0° to 50°, where “P” represents PB-based unit cell and “N” represents nanopost-based unit cell.

30 degrees and then begins to decrease. In contrast, for the nanopost-based unit cells, the transmissivities and phase shifts change irregularly as the incident angle increases. We believe that for nanoposts oblique incidence may excite undesired resonance effect [33] with significantly lower transmissivity, and the nanoposts in a different size have varied transmissivities, which reduces the overall efficiency of nanopost metasurface. Although the PB phase-based metasurface exhibits higher transmittance and relatively higher tolerance to incident angle than its nanopost-based counterpart, it is important to note that the former requires the incident light to be circularly polarized, while the latter is insensitive to polarization. To complete a larger range of optical trapping in the following we select the blazed gratings based on PB phase.

The proposed structure can produce a gradient of the field along the incident direction, so it can be used to trap particles. The Maxwell-Stress Tensor is adopted to calculate the optical force exerted on the particles [34], which is expressed as

\[
\langle T_M \rangle = DE^* + HB^* - \frac{1}{2} (D \times E^* + H \times B^*) I \tag{2}
\]

where \( T_M \) represents the Maxwell stress tensor, \( E \) is the electric field intensity, \( D \) is the electric displacement, \( H \) is the magnetic field intensity, \( B \) is the magnetic induction intensity and \( I \) is an isotropic tensor. We calculate the integral of Maxwell tensor on a closed surface near a spherical particle to obtain the optical force on it. The force is expressed as

\[
F_{opt} = \oint ((T_M) \cdot n) \, dS \tag{3}
\]

FIGURE 6. (a) Fz and (b) Fy as a function of distance to the origin along the beam. (c) Electrical field distribution in the presence of a particle at oblique incidence. (d) Fy as a function of particle location.
We calculate the force for a particle in water with the refractive index of 1.44, and it is 2.5 μm in diameter. We place the particle along the beam to calculate the optical force. The structure is symmetric in the x direction, and we change the incident angle in the yz plane. Therefore, when a particle moves in the yz plane, it feels no force along the x direction, so we only consider the components along the y and z directions. In particular, Fy is also zero at normal incidence.

Figure 6(a) shows Fz as a function of the distance of a particle to the origin of coordinates at different incident angles. When the distance is >7 μm, the negative Fz means an attractive force exerted on the particle. However, when the distance is <6 μm, Fz is switched to the repulsive force. Therefore, the particle can be trapped at a trapping potential about 6–7 pN/m away from the center of the device. Note that they may not move along a straight trajectory, and instead it could move back and forth around the beam. It is important to note that Fz at the same distance becomes stronger with the incident angle, as an attractive force, which is up to 18 pN/W. This can be explained as follows. One can see in Fig. 6(c) that the presence of the particle changes the field distribution such that the field is locally enhanced above the particle due to diffraction. This causes a local gradient force to drag the particle upwards, which partially cancels the main attractive force by the beam. The local force decreases with the incident angle, and then the attractive force becomes stronger. Figure 6(b) shows that Fy is always positive with the incident angle of 0–φ, which means that the particle is pushed along the y direction. It is believed that it results from the slight distortion of the beam as shown in Fig. 4(a) and 6(c). To show that floating particles can be effectively attracted and trapped by the proposed beam steering, in Fig. 6(d) we plot the horizontal force, Fy, as a function of particle’s offset to the beam axis, i.e., along the dash line in Fig. 6(c). Within a small range of ±2 μm around the beam, a particle feels a strong force up to 50 pN/W to drag it into the beam. Thus, as the beam is dynamically steered, particles can be attracted toward the beam and moved along it.

IV. CONCLUSION
We have shown the use of the blazed gratings based on metasurface for optical trapping of small particles floating in a microfluidic channel. Wide-angle beam steering based on two types of metasurfaces (PB phase and nanoposts) is analyzed. It has been shown that large optical gradient force can be generated over a large angle range of −50° to 50°, and the maximum attractive force is up to tens of pN/W, with a trapping range of 14 μm for particles. This work exhibits great potential to trap a large fraction of particles floating in a microfluidic channel when the beam is dynamically steered.

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