Generation of diffraction-free beams using resonant metasurfaces

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Abstract
Several metasurface diffraction-free beam generators are designed by using a set of resonant V-shaped nanoholes. Cosine beams, Bessel beams and cosine Bessel beams are generated through the corresponding metasurface structures with V-shaped nanoholes arranged in different ways. Theoretical analysis provides the design mechanism for these diffraction-free beam generators, numerical simulations and experiment measurement give the powerful verification for the generation of diffraction-free beams. The proposed diffraction-free beam generators have advantages of ultra-thin thickness, compact structure, ease to manufacture and flexibility to operate. The generated diffraction-free beams show high efficiency, polarization independence and validity for any visible wavelength. The compact design is benefit to the applications of diffraction-free beams in nanometer fabrication, optical integrated imaging and optical micromanipulation.

1. Introduction

Diffraction-free beams point to the beams with propagation invariant profiles and they are the solutions of Helmholtz equation in free space. In different coordinate systems, the solutions of Helmholtz equation have the different forms, and cosine beam [1], Bessel beam [2, 3], Mathieu beam [4] and parabolic beams [5] are the solutions of Helmholtz equation in Cartesian coordinates, cylindrical coordinates, elliptical coordinates and parabolic coordinates. These beams, especially Bessel beams, have been attracted much attention because of the interesting properties including the non-diffraction, self-reconstruction and even optical pulling forces [6]. Therefore, diffraction-free beams have been widely applied in optical micro drilling [7], atom guiding [8], optical micro-manipulation [9] and optical imaging [10, 11].

Traditionally, one well-designed optical element or the combination of several elements are used to generate diffraction-free beams, such as conical prism [12], double lenses [13], spatial light modulator [14, 15], optical fiber [16] and nonlinear medium [17]. Therefore, it is inevitable that the optical element or system has complex and bulk structure, low performance and wavelength dependence. As two-dimensional metamaterials, metasurfaces consisting of sub-wavelength spaced scatterers show the powerful ability of light manipulation [18–23]. Because of the advantage in dimension, metasurfaces have been utilized to design various compact optical components including beam splitter [24], lens [25, 26], hologram [27, 28], vortex generator [29] and vector beam generator [30].

Recently, metasurfaces consisting of different nanometer units have been used in the generation of Bessel beams. Aieta et al proposed a metasurface axicon using V-shaped nanoantennas and obtained zero order Bessel beam [31]. Liu et al designed a coding metasurface with the help of three layers of metallic split-rings with different orientations and realized the generation of zero-order Bessel beam [32]. Chen et al designed meta-axicon using nano-fins with different rotation angle and generated zero- and one-order Bessel...
beams [33]. Metasurfaces consisting of resonant transmission scatterers possess higher transmission efficiency and larger signal-to-noise ratio [19], and high efficiency diffraction-free beams including Bessel beam and its deformation like cosine Bessel beam are more important for the practical applications.

This work aims to design simple transmission metasurfaces based on resonant nanoholes and generates high efficiency and high signal-to-noise ratio diffraction-free beams including Bessel beams, cosine beams and cosine Bessel beams. Here, the proposed metasurfaces are designed by using eight V-shaped nanoholes with different parameters. These nanoholes provide eight independent phases covering from 0 to 2π, and they shape the wave front of light through the designated arrangements. The design principle elucidates elaborately the formation mechanisms of three kinds of diffraction-free beams of any order. Numerical simulations verify the theoretical predictions and the experimental results confirm the performance of the proposed diffraction-free beam generators. Moreover, our proposed diffraction-free beam generators behave the polarization independence and they can be applied conveniently in wide spectral region. All these advantages provide the brighter prospect for the applications of the proposed diffraction-free beams.

2. Design principle

As we know, an ideal diffraction-free beam can be approximated within a finite region by the superposition of multiple plane waves, and it is usually denoted by Whittaker integration [34, 35]. We may use a propagation factor with the spiral phase to form the integral expression in Whittaker integration and obtain the Bessel beam. Here, the spiral phase is formed with the help of eight V-shaped nanoholes etched in gold film, which introduce eight independent phase delays within the region of [0, 2π]. All these V-shaped nanoholes can be taken as two isometric rectangular holes with different cross angle. The former four nanoholes have independent length and different cross angle, and the latter four nanoholes are the results as the former four nanoholes rotate π/2. This design is akin to the one given by Ni et al [19].

Figure 1(a) shows the schematic diagram of one V-shaped nanohole etched in gold film with the thickness of h, and its structure parameters include the arm length of l, the arm width of w, and the cross angle of α. These parameters are optimized using the simulation calculations so as to output eight independent resonant phases with the same phase separation within the region of [0–2π] and equivalent transmission amplitudes. For the incident wavelength of λ = 633 nm, the optimized parameters of four independent nanoholes are h = 150 nm and w = 40 nm, l = 158 nm and α = π/3 for the first nanohole, 148 nm and α = π/2 for the second nanohole, 110 nm and α = 2π/3 for the third one, and 113 nm and α = 0 for the fourth one. Figure 1(b) gives V-shaped nanoholes with different parameters and their transmission phase distributions under the x-linear polarization light illumination. One can see the phases through these nanoholes change uniformly, and the wave front changes 2π from left to right. This indicates these V-shaped nanoholes satisfy our designated phase control. The further verification for the light modulation of V-shaped nanoholes among the wavefront deflection is given in supplementary 1 (https://stacks.iop/NJP/00/000000/mmedia).

When these eight kinds of V-shaped nanoholes are arranged orderly in fan-shaped regions along anti-clockwise or clockwise direction, like the case of figure 1(c). For convenience, we can denote eight nanoholes by the numbers of 1–8. The transmission phase through this metasurface increases 2π along
anti-clockwise or clockwise direction and an optical vortex of order 1 or −1 forms, which can be denoted by the spiral term of $\exp(i\theta)$ or $\exp(-i\theta)$ with $\theta$ representing the azimuthal angle. The generated spiral phase distributions are inserted in the lower right corners of the structure diagrams. Combine these two metasurfaces together, and we can easily obtain the cosine beam of $\cos\theta$ through the superposition of two vortex fields. We call this metasurface as a cosine beam generator. The intensity distribution of the generated cosine beam, which is composed of two bright spots, is inserted at the lower right corner of the structure diagrams. Figure 1(d) gives one- (top) and two-order (down) cosine beams with the initial angle taking $0$, $\pi/4$ and $\pi/2$. One can see clearly the bright spots in the intensity distributions rotate with the initial angle changing. The detailed explanation can be seen from supplementary 2, where more metasurface structures and the generated cosine beams are also provided.

Then, we imitate the working principle of axicon and design the metasurface based on these eight V-shaped nanoholes to generate Bessel beam. The transmission phase of the metasurface should be superposed by a spiral phase and a conical phase and it can be written as $\varphi(r) = 2\pi \sin \beta/\lambda + n\theta$, where $r$ and $\theta$ denote the radial and azimuthal coordinates of nanohole, $n$ is an integer representing the order of Bessel beam and $\beta$ is a constant with respect to the conical angle of the equivalent axicon. Thus, the light field through this metasurface is refracted by the angle of $\beta$ and the $n$-order Bessel beam of $\exp(\imath n\theta) J_n(k r r)$ generates, where $J_n(x)$ denotes the $n$-order Bessel function of the first kind and $k$ is the in-plane component of the incident wave number. Here, the spiral phase of $\exp(\imath n\theta)$ appears simultaneously.

Figure 2(a) shows the working principle of the proposed Bessel beam generator (top) and the variation of the transmission phase of zero-order Bessel beam generator with the radial coordination of nanohole (down). In practical design of $n$-order Bessel beam generator, we should definite the phase distribution in space with the given conical angle of $\beta$, and then arrange the different nanoholes at the corresponding radial and azimuthal positions. Figure 2(b) gives the schematic diagram for the structure of one-order Bessel beam generator and the longitude intensity distribution of the generated Bessel beam. One can see that the different nanoholes are arranged on the concentric rings, not like the sector structure of the cosine beam generator. The diffraction-free characteristic of the longitude intensity distribution with the zero intensity at the propagation axis lasts over $7 \mu$m. The transverse intensity and phase distributions at $z = 5 \mu$m are inserted in the lower corners of the longitude intensity pattern, and the annular shaped intensity and the spiral phase verify the generation of 1-order Bessel beam. The propagation distance of the generated Bessel beam along the transmission direction increases with decrease of the value $\beta$ and increase of device size, like the case of the traditional axicon. The spatial positions of different V-shaped nanoholes for the Bessel beam generator are detailed in supplementary 3. Similarly, we can design the high order Bessel beam generators and generate any order Bessel beams.

Since the generated Bessel beam always carries a spiral phase factor of $\exp(\imath n\theta)$, we utilize two similar metasurfaces to generate two Bessel beams carrying respectively the spiral phase factors with opposite topological charges. Then, combining these two metasurfaces, we can obtain one cosine Bessel beam
Figure 3. (a),(b) SEM images of two samples for diffraction-free beam generation, (c) experiment setup with QWP denoting the quarter wave plate, P denoting the polarizer, S representing the sample, BS denoting the beam splitter, M denoting the mirror, DF meaning the dense filter and MO pointing to the microscopy objective, (d),(e) the simulated and measured intensity and phase distributions of two samples, where the illumination wavelength is 632 nm and the incident polarization is along the horizontal direction.

generator and the generated cosine Bessel beam can be expressed by \( \cos(n\theta)J_n(kr) \) with \( n \) taking an even number or \( \sin(n\theta)J_n(kr) \) with \( n \) taking an odd number because of \( J_{-n}(kr) = (-1)^n J_n(kr) \). Figure 2(c) shows the structure diagram for two-order cosine Bessel beam generator and its longitude intensity distribution. The nanoholes with two colors among the structure are for two Bessel beam generators. The inserted patterns in the below are the transverse intensity and phase distributions at \( z = 5 \mu m \). One can see that the longitude intensity distribution takes on the diffraction-free characteristic. Four bright spots appear in the transverse intensity pattern and the phase distribution near center indicates that the phases at up and down or left and right regions are in-phase, and the phases at adjacent regions are out of phase. These intensity and phase distribution characteristics accord with the distribution rules of two-order cosine Bessel beam. The spatial positions of different V-shaped nanoholes for the cosine Bessel beam generator are also detailed in supplementary 3. On this basis, we can easily design any cosine Bessel beam generator and generate any order cosine Bessel beam.

3. Experiment measurement

Based on the above design principle, we manufacture practically the metasurfaces to generate Bessel beam and cosine Bessel beam. Figures 3(a) and (b) show the scanning electron microscopy (SEM) images for two metasurface samples and parts of their magnified pictures. The former is used to generate one-order Bessel beam and the latter is used to generate two-order cosine Bessel beam. The nanoholes are etched in gold film with the thickness of 100 nm deposited on the glass with Ti film of 5 nm serving as the transition layer. The other parameters of the nanoholes are chosen as the theoretical optimized ones. The sample manufacture process is described in the section of sample preparation.

Put one sample into the experimental light path like figure 3(c), and measure its transmission intensity distribution of the sample. In the experiment setup, the light beam from the He–Ne laser passes through the combination of a quarter wave plate (QWP) and polarizer \( P_1 \) and changes into the needed linear polarization. Then, it illuminates the fabricated sample (S) to generate the diffraction-free beam. A microscopy objective (MO) is used to magnify and image the intensity distribution of the sample and the polarizer \( P_2 \) is applied to select and analyze the polarization component of the diffraction-free beam. The magnified intensity distribution is received by a charge-coupled device with No. DU-888U3. The reference light path is used to realize the interference of one plane wave and the diffraction-free beam, where the dense filter (DF) controls the intensity of light in the reference light path.

Figures 3(d) and (e) give the measured transverse intensity distributions of two samples and the interference results. The interference fringes are highlighted by some red dash lines. For convenient comparison, we also give the simulated results for the intensity and phase distributions of two samples. Where the gray patterns are for the experimental results and the color patterns are for the simulated results. From figure 3(d), one can see that the measured and simulated intensity distributions are the same and they take on the annular shape. The interference result takes on a fork fringe, which is with respect to the spiral phase of the simulated result. This is just the one-order Bessel beam as the theory predicted. The measured intensity in figure 3(e) shows that four bright spots distribute symmetrically, which is the same as the
Figure 4. Simulated and measured diffraction intensity distributions of two-order cosine Bessel beam generator illuminated by the light with different polarization states and different wavelengths, where the patterns in (a)–(c) correspond to the results for wavelengths of 633 nm, 532 nm and 450 nm and the inserted arrows on the left denote the incident polarization states.

simulated result. The interference result show that parallel fringes take on at different characteristic regions. Comparing the fringes at the top and right, we can see the bright fringes displace a half period, and comparing the fringes at the top and down, we can see the bright fringes do not displace. These fringe distribution properties correspond to the simulated phase distribution rule, namely, the phases at the top and down are in phase and the phases at two adjacent regions are out of phase. The intensity distribution and the interference fringes of figure 3(e) coincide with the characteristic of two-order cosine Bessel beam.

4. Discussions

Though our proposed metasurface diffraction-free beam generators are designed with respect to the given wavelength of 633 nm and the confirmed x-polarization illumination, the generated diffraction-free beams are wavelength independence and polarization independence. This means the generated diffraction-free beams can be obtained for the incident light with any wavelength and the diffraction-free performances of our proposed metasurface devices are valid for any linear or circular polarization expect x-polarization. The simulated and measured intensity distributions of two diffraction-free beam generators under the different polarization light illumination with different wavelength give the powerful verification. Figure 4 gives the results of two-order cosine Bessel beam illuminated by the light with two orthogonal linear polarization states and two orthogonal circular polarization states, where the illuminating wavelength takes 633 nm, 532 nm and 450 nm, respectively. The gray patterns are for the experimental results and the color patterns are for the simulated results. The arrows inserted on the left denote the incident polarization states. Here, for convenient comparison, we increase the intensity for the wavelength of 450 nm by about 20 times. This larger intensity difference results from the material.

From the results in figure 4(a), one can see that the measured diffraction intensity distribution is the same as the simulated result for any incident polarization and the results under the different polarization light illumination are almost the same. This indicates our proposed diffraction-free beam generator has good performance of polarization independence. The similar conclusion can be drawn from the results in figures 4(b) and (c). Moreover, comparing the results of figures 4(a)–(c), one can see that the intensity distributions for different wavelengths are close except for the intensity difference resulting from the material and the resonant effect of the nanofohles. This verifies our proposed diffraction-free beam generator can be used in wide waveband. The wavelength independence and the polarization independence of the generated diffraction-free beams provide the convenient condition for the practical applications of diffraction-free beams.

It needs to be pointed out that the determination for the parameters of the metasurfaces and the simulations for the transmission intensity distributions are completed by using the finite-difference time-domain technique. In practical simulation calculations, the perfectly matched layers are used to prevent non-physical scattering at the boundaries and the minimum mesh step is set at 2 nm. This method can simulate actually the light transmissions through the designed metasurfaces, and we also use this method to study the variation of optical vortex with the propagation distance [36] and design the compound metalens [37] and metasurface array illuminator [38]. The dielectric constants of gold, titanium and glass for three wavelengths are taken from the value given by Palik [39].

The diffraction-free beam generator samples are manufactured recurring to the design theory. First, the gold film with the thickness of 100 nm and the titanium film with the thickness of 5 nm are deposited onto
glass substrate with the help of the electron beam evaporation method. The ambient temperature of sample is 23 °C, the electric voltage is 9.8 KV and the current of electric beam is 22 mA. And the V-shaped nanohole arrays with the designated parameters and the desired arrangement are fabricated by the focused ion beam etching method, where the pressure is $2 \times 10^{-4}$ Pa, the voltage is 30 KV and the current is 48 PA. The high fabrication precision can be seen from SEM images for the provided samples in figure 3.

5. Conclusions

We demonstrate simple nanohole structures capable of generating diffraction-free beams with different types and different orders in a much more efficient and compact way. The utilization of resonant V-shaped nanoholes makes the generated diffraction-free beams take on high efficiency, high signal-to-noise ratio and polarization independence. The provided several examples for three kinds of diffraction-free beams give the powerful verification. Moreover, the generated diffraction-free beams are available for any visible light and the provided metasurfaces are effective for broad spectral band. These designs can be expanded to the manometer antenna structures with any materials, and the corresponding diffraction-free beam devices with large diameter can be mass-produced by using the advanced fabrication techniques. These properties of the proposed diffraction-free beam generators show great promise in potential applications ranging from laser lithography and micro manipulation to high resolution imaging.

Authors’ contributions

BR and MZ had the identical contribution. BR designed the metasurfaces and performed the numerical simulations. MZ prepared the experiment samples and perform the verification experiments. ZCD did parts of simulation calculations. HXB and HZH deposited the metal films. BQW and WSY explored the experiential condition. TSY proposed the physical idea and designed method and wrote the paper with BR. The authors declare no competing financial interest.

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