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Realization of Terahertz Wavefront Manipulation Using Transmission-Type Dielectric Metasurfaces

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Metasurfaces, composed of an array of subwavelength artificial structures, have attracted great interest, owing to their high ability in locally manipulating the wavefront of electromagnetic waves. Here, we propose a dielectric metasurface based on a fused silica resonator, consisting of a rectangular-shaped bar placed in the center of a cross net-shaped structure, to manipulate the wavefront of terahertz waves. As proof of concept, several transmission-type devices for spatial modulation are designed at the target frequency of 0.14 THz, including on-axis and off-axis focusing, generation of a non-diffracting Bessel beam, and multi-focus lens. The simulated efficiencies range from 45 to 62%. This novel approach for manipulating THz wavefronts can be also used for information storage and other phase-related techniques in the rapid development of THz applications.

Keywords: metasurface, THz wave, spatial modulation, Bessel beam, multi-focus lens

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INTRODUCTION

The traditional electromagnetic (EM) devices are designed to realize the control functionalities by adjusting the physical geometrical shape and the component material [1]. Recently, metasurfaces, made of a large number of subwavelength structures, have performed very well to locally manipulate the wavefront of EM waves. Many EM controls have achieved by metasurfaces, including ultrathin planar lenses [2–4], multi-focal devices [5–9], vortex beam [10–12], and various holography [13, 14]. With the development of terahertz (THz) technology, highly efficient, compact functional devices are required, which can be provided by dielectric metasurfaces.

In this paper, we propose a transmission-type, fused silica metasurface to manipulate THz wavefront. Different from previous dielectric pillars on substrate [10, 11, 15] or cross shaped restorers [16–19], the metasurface unit cell consists of a cross net shaped structure with a rectangular pillar placed in the center. The weak coupling of each basic unit is formed by the high refractive index difference between the fused silica and the surrounding air, which concentrates the confined energy within the central structure. Compared with dielectric pillars, the proposed metasurface have more adjustable unit structural parameters. Moreover, the metasurface reduces the difficulty in fabricating because each of the basic unit is reciprocally freestanding by cross shaped restorers without substrates. Through this work, on-axis and off-axis focusing, generation of a non-diffracting Bessel beam, and multi-spot focusing are demonstrated. The total control efficiency could be as high as 62% in numerical simulation. These advantages of the proposed metasurface will enrich THz functional devices, and provide a novel way for the design of multifunctional miniaturized devices.

RESULTS AND DISCUSSION

Figure 1A schematically shows the metasurface structure and the inset shows the details of geometry basic unit cell. Both the width $\boldsymbol{a}$ and length $\boldsymbol{b}$ are in the range of 0.3–1.9 mm, respectively. The width of the cross net shaped structure $\boldsymbol{w}$ is set to 0.3 mm. The period $\boldsymbol{T}$ and thickness $\boldsymbol{h}$ are 2 mm and 3.6 mm, respectively. The amplitude transmission and corresponding phase delay for x-polarized incident waves are calculated using a commercially available software package COMSOL Multiphysics (**Figures 1B,C**). The phase shift can cover the range of 0–360°, which facilitates the wave control. Eight unit cells are selected as $(a, b) = (0.8, 1.6\,\text{mm})$, $(0.58, 1.5\,\text{mm})$, $(0.54, 1\,\text{mm})$, $(0.35, 0.35\,\text{mm})$, $(1.9, 1.86\,\text{mm})$, $(1.65, 1.75\,\text{mm})$, $(1.25, 1.7\,\text{mm})$, $(0.95, 1.65\,\text{mm})$ for fully covering the phase range with an interval of 45°, as shown in **Figure 1D**. The average amplitude transmittance of the unit cells is ∼93%. To demonstrate modulation ability of the proposed metasurface, several THz functional devices are designed based on the eight unit cells.

We first demonstrate on-axis and off-axis focusings achieved using the proposed metasurface. The phase distribution on the metasurface for realizing this focusing can be described as: $\varphi(x) = \frac{2\pi}{\lambda_0}(\sqrt{(x-x_0)^2 + L^2} - L)$, where λ_0 for free space, and x and x_0 are the position coordinates of basic units and the focal spot, respectively, and L is the focal length. The obtained phase profiles are quantized into eight values, ranging from 0 to 360°. The eight basic units are placed on the corresponding positions. When x-polarized THz waves are normally incident on the designed metasurface device, the metasurface modifies the wavefront. The transmitted waves are then focused into an on-axis spot with the propagation distance $L = 5\,\text{cm}$, as shown in **Figure 2A**. The control efficiency is defined as the ratio of the power of E_x component on the focal plane to that of the incident wave. The on-axis focusing efficiency is 60%, which is much higher than the single-layer plasmonic metasurfaces [20].

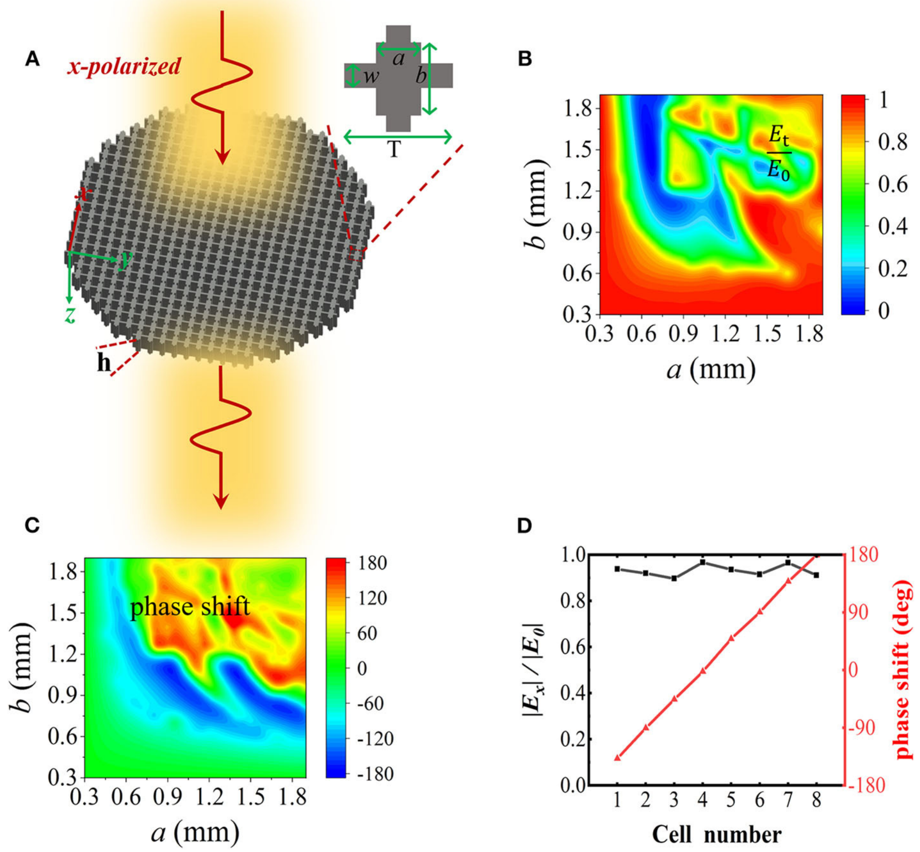

FIGURE 1 | Proposed dielectric metasurface and the control characteristics of metasurface unit cells. **(A)** Schematic of the proposed metasurface. The inset shows a basic unit cell of the metasurface. **(B,C)** Amplitude transmission and corresponding phase shift, respectively, of x-polarized wave with a frequency of 0.14 THz. **(D)** Phase shift and amplitude transmission for the selected eight unit cells.

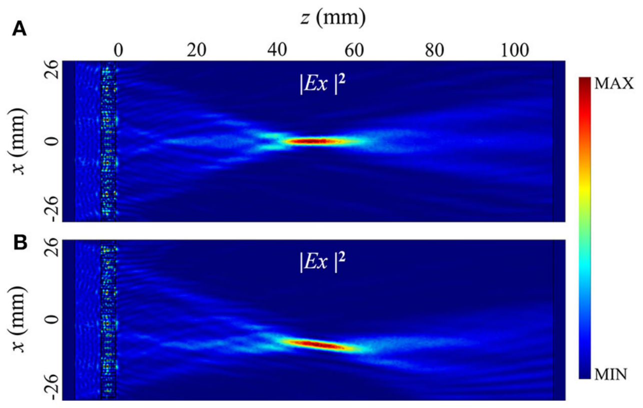

FIGURE 2 | Simulated intensity distributions of **(A)** on-axis and **(B)** off-axis focusings with a focal length $L = 5$ cm.

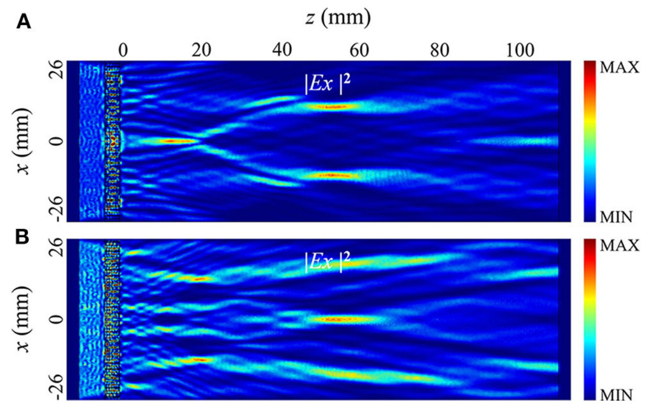

FIGURE 4 | Simulated intensity distributions of **(A,B)** double-spot and tri-spot focusing, respectively, with a focal length of 5 cm.

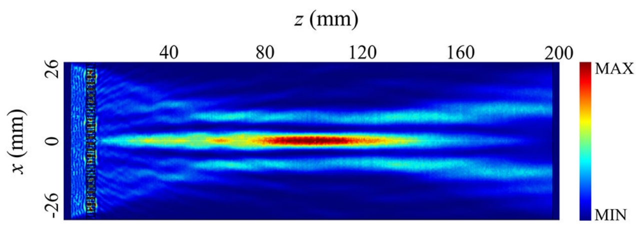

FIGURE 3 | Simulated intensity distribution of generation of a non-diffracting Bessel beam.

Furthermore, an off-axis focus lens with the same focal length ($L = 5$ cm) is designed. The off-axis distance is 8 mm, as shown by the simulated results in **Figure 2B**. The simulated control efficiency is 62%.

Furthermore, we demonstrate generation of a non-diffracting Bessel beam using the dielectric metasurface. The phase distribution on the metasurface for generating a Bessel beam can be described as: $\varphi(x) = C\frac{2\pi}{\lambda_0}|x|$, where C is a coefficient. When x-polarized waves are normally incident on the metasurface with a width of 52 mm, the arranged unit cells transform the wavefront into an axisymmetrical slope shape, so that a Bessel beam can be formed by the wave interference [21]. The simulated intensity distribution of a one-dimensional Bessel beam is shown in **Figure 3**. The control efficiency is 45%. Compared with the focusing in **Figure 2A**, the focal depth of the Bessel beam is much longer and the beam width changes much more slowly along the long propagation direction, which are consistent with the typical characteristics of the non-diffractive Bessel beam.

To demonstrate the versatile control of the proposed metasurface, a one-dimensional multi-spot focusing lens (MSFL) is designed. The phase distributions for obtaining one-dimensional double-spot and tri-spot focusing are calculated, respectively, using the Gerchberg-Saxton (GS) retrieval algorithm [22] on the basis of Fresnel diffraction. In the simulations using the COMSOL Multiphysics, the required phase distributions can be obtained by arranging the aforementioned unit cells in the one-dimensional metasurface with a width of 52 mm. Then the double-spot and tri-spot focusing are formed by the wave interference, respectively. The simulated intensity distribution of one-dimensional double-spot focusing is shown in **Figure 4A** (off-axis $\pm$ 11 mm). The control efficiencies for the two spots are 25 and 24% respectively. Thus, the total control efficiency is 49%. Tri-spot focusing with the same focal length is also demonstrated, as shown in **Figure 4B** (on-axis and off-axis $\pm$ 17 mm). The efficiency for each is 19, 18, and 18%, and thus the total control efficiency is 55%. The simulated field distributions on the focal plane are consistent with the predesigned results.

CONCLUSION

In summary, a dielectric metasurface based on a fused silica resonator, consisting of a cross net shaped structure with a rectangular pillar placed in the center, is proposed to manipulate THz waves. As a proof of concept, several transmission-type devices for THz spatial modulation are designed, including on-axis and off-axis focusing, generation of a non-diffracting Bessel beam, and multi-spot focusing. The simulated control efficiencies range from 45 to 62%. The versatile control with high efficiency makes the metasurface valuable for the practical applications in THz communications and imaging.

METHOD SECTION

All simulations were using a commercial finite element simulation software COMSOL multiphysics. The refractive index of fused silica at the target frequency of 0.14 THz is 1.95. The perfect matching layers (PML) with a thickness of 3 mm were used along z-direction. The periodic boundary conditions were used in both x- and y-directions to simulate the control characteristics of basic unit cells. In the simulations of functional devices, the scattering and periodic boundary conditions were used along the x- and y-directions, respectively.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

JL and HL proposed the idea and conceived and performed the simulations. TN designed the TMFL. MZ designed the Bessel beam. IL and HS guided the theoretical work. All authors analyzed and discussed the results.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.