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Broadband achromatic metalens in terahertz regime

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Abstract: Achromatic focusing is essential for broadband operation, which has recently been realised from visible to infrared wavelengths using a metasurface. Similarly, multi-terahertz functional devices can be encoded in a desired metasurface phase profile. However, metalenses suffer from larger chromatic aberrations because of the intrinsic dispersion of each unit element. Here, we propose an achromatic metalens with C-shaped unit elements working from 0.3 to 0.8 THz with a bandwidth of approximately 91% over the centre frequency. The designed metalens possesses a high working efficiency of more than 68% at the peak and a relatively high numerical aperture of 0.385. We further demonstrate the robustness of our C-shaped metalens, considering lateral shape deformations and deviations in the etching depth. Our metalens design opens an avenue for future applications of terahertz meta-devices in spectroscopy, time-of-flight tomography and hyperspectral imaging systems.

Keywords: Far infrared or terahertz; Achromatic; Metasurface; Diffraction theory

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1. Introduction

Conventional focused terahertz components, such as spherical single convex lenses or off-axial parabolic mirrors [1], are generally bulky, costly and time-consuming to manufacture with high precision. Furthermore, these terahertz instruments based on the bulky components still have several limitations, which either solely function at specific frequencies or bring significant difficulties to the design and construction of the terahertz system [2]. Compared to conventional bulky footprint devices realizing phase modulation through optical path accumulation, metasurface lenses [3, 4] or “metalenses” introduce an abrupt modulation of light wavefronts in two-dimensional (2D) space, composed of arrays

of metallic or dielectric micro/nano-scatterers [3–6]. The rapid advancements in metasurfaces have led to considerable research on many novel photonic devices [7–13] and phenomena such as wave deflection [10–13], focusing [14–16] and imaging [17–19]. However, these proposed metasurface functions still pose the challenges of large chromatic aberrations and considerable losses [9, 20]. In addition, few experimental works have been reported on efficient terahertz achromatic meta-devices based on all-dielectric metasurfaces [21–23].

Most imaging systems suffer from chromatic aberrations, because incident light with a continuous wavelength generates numerous focal spots at different spatial locations. For metasurface devices, chromatic aberration correction can be achieved by the careful design of complementary structures and contribute to high-performance imaging systems [24–30]. To date, several pioneering investigations for dispersion engineering and optimization algorithms [31–34] have been proposed to eliminate chromatic dispersions. For instance, Wang et al. [35] employed complex metallic unit elements with smooth and linear phase dispersions as well as geometric phases to design a broadband achromatic flat metalens with numerical aperture (NA) = 0.268. Recently, Chen et al. [36] proposed an achromatic metalens with NA = 0.2 by separately engineering the group delay and group delay dispersion of each constituent nanostructure, which are independent of its phase. Wang et al. [37] also demonstrated full-colour imaging of an achromatic metalens with NA = 0.106 by integrated resonances for the required phase compensation. The important aforementioned progress of metalenses was shown to be capable of achromatic imaging by tailoring the phase dispersion of each nanostructure. Most of the studies have focused on meta-devices in the visible or near-infrared region [38, 39]. However, investigations of achromatic metalenses using dielectric metasurfaces have seldom been reported in the terahertz regime possessing a high working efficiency. In addition, all the achromatic metalenses have a small NA, owing to the limited phase shift coverage of resonant units, which also limits the design. Therefore, it is still challenging to design an achromatic metalens that can eliminate the chromatic effect over a broad band of wavelengths in the terahertz region.

Here, in order to address these challenges from traditional terahertz lenses, we first demonstrate an ultra-broadband achromatic terahertz metalens that operates within 0.3–0.8 THz at about 91% of the central frequency. Based on terahertz near-field microscopy, the phase of the electric field component transmitted by the metalens coincides with the phase of the theoretical design. Owing to the extremely large etching aspect ratio of 1:25, we achieve a large phase compensation from the metalens unit elements, which enables us to simultaneously obtain a relatively high NA value, NA = 0.385, and a large metalens diameter, $D = 10$ mm. Moreover, the C-shaped unit elements we employed in this work exhibit a more robust phase accumulation than the usual rectangular structures. The metalens is fabricated on a silicon substrate with a thickness of only several hundred microns, which is quite desirable for integration and miniaturization. Our work significantly promotes the development of

achromatic meta-devices in terahertz hyperspectral imaging and can be used to investigate the robustness of metasurface functional designs.

2. Theoretical realizations of broadband achromatic metalens

As shown in the schematic in Fig. 1a, the proposed terahertz achromatic metalens is composed of silicon pillars arranged on a square lattice. The required phase distribution for each unit element at the position (x, y) satisfies the following equation:

$$\varphi(x, y) = -2\pi \left(\sqrt{x^2 + y^2 + F^2} - F \right) \frac{1}{\lambda}, \quad (1)$$

where λ represents the wavelength of the input wave and F is the focal length. The input plane wave is modulated into a converging wavefront through the elements. In order to clarify a terahertz broadband achromatic metalens, a fixed focal length is exactly maintained in a wide wavelength range. It can be found from Eq. (1) that the phase compensation should follow a linear relation with $1/\lambda$ (or frequency) in a continuous terahertz frequency range. Generally, for the case of the working wavelength range $\lambda \in \{\lambda_{\min}, \lambda_{\max}\}$, where λ_{\min} (or f_{\max}) and λ_{\max} (or f_{\min}) are the boundaries of the working wavelength range, the designed phase distribution can be divided into two components:

$$\varphi_1(x, y) = -2\pi \left(\sqrt{x^2 + y^2 + F^2} - F \right) \frac{1}{\lambda_{\max}}, \quad (2)$$

$$\varphi_2(x, y) = \varphi(x, y) - \varphi_1(x, y) = -2\pi \left(\sqrt{x^2 + y^2 + F^2} - F \right) \left[\frac{1}{\lambda} - \frac{1}{\lambda_{\max}} \right], \quad (3)$$

where the former $\varphi_1(x, y)$ in Eq. (2) is considered a basic phase profile, which is solely related to λ_{\max} and independent of the working wavelength λ . Such a phase profile can be acquired by exploiting the geometric phase, which only depends on the orientation of the unit elements. The latter $\varphi_2(x, y)$ in Eq. (3) is a function of the working wavelength and presents a linear relation with $1/\lambda$, which is considered the phase difference induced from various incident wavelengths. Such phase differences can be obtained by suitably designing the phase of each resonance unit of the metalens, which must also exhibit a phase dispersion with a linear relation with $1/\lambda$ such as $\varphi_2(x, y)$. As the mechanism of the resonant phase is completely different from the geometric phase, these two phase shapes will not disturb each other and can be simply merged together. An additional phase shift $\Delta\varphi$ should be introduced to realise the phase compensation effect from the specially designed metalens, as shown in Fig. 1b.

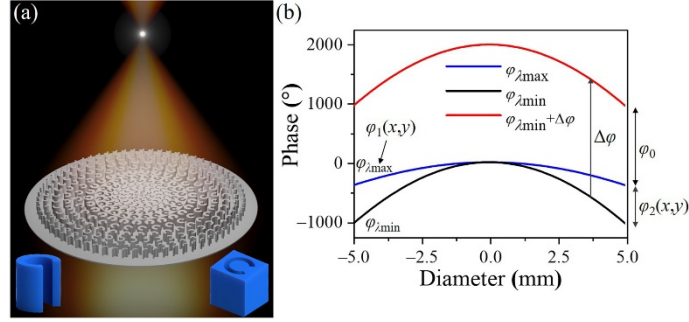


Fig. 1. (Color online) Schematic of achromatic metalens. (a) Schematic of C-shaped (or rectangular) unit element-based achromatic metalens. (b) Phase profile for achromatic metalens at the wavelength range of $\lambda \in \{\lambda_{\min}, \lambda_{\max}\}$, where $\Delta\varphi$ is a certain positive value.

The method by which to tailor the resonance phase by adjusting the structural parameters is critical for broadband terahertz achromatic focusing. Here, the working frequency is chosen in the terahertz regime, that is, $\{f_{\min}, f_{\max}\} \rightarrow \{0.3 \text{ THz}, 0.8 \text{ THz}\}$ or $\{\lambda_{\min}, \lambda_{\max}\} \rightarrow \{375 \mu\text{m}, 1000 \mu\text{m}\}$. In our design, the basic unit element of the metalens contains solid and inverse high-resistance silicon nanostructures, from which we implement the phase compensation by carefully setting various parameters of the C-shaped unit elements. The unit elements contain the inner diameter, outer diameter and opening angle (or the rectangular unit elements have the parameters of length and width) at different specific positions. In addition, the basis phase distribution of the dielectric metasurface for focusing can be satisfied by rotating each unit element. Consequently, the achromatic focusing properties can be implemented simultaneously on a single-layer structure array.

The simulations are performed using the Lumerical FDTD software with a right circularly polarised (RCP) plane wave illuminated from the substrate and periodic boundary conditions set at the boundaries of the simulation domains for these two basic unit element shapes. Figs. 2a and 2b show the simulated amplitudes and phase distributions of the solid and inverse C-shaped unit element as a function of the terahertz frequency (f) with a lattice constant $p = 100 \mu\text{m}$. By varying the structural parameters, the linear phase coverage can achieve multiples of 2π in the working frequency range from 0.3 to 0.8 THz. The phase realization mechanism originates from the waveguiding effect. The phase is given by $n_{\text{eff}} \cdot h \cdot 2\pi / \lambda$ [18], where n_{eff} and h (structural height) are the effective index of the waveguide mode and the propagation length, respectively. Based on the waveguide model, the effective refractive index increases with the frequency, which is the reason for the greater phase changes with the frequency. The side views of the normalised magnetic densities in a periodic unit at frequencies of 0.3 and 0.8 THz are shown on the right side of Figs. 2a and 2b. The amplitude and the phase details of the rectangular unit elements are shown in Fig. S1 (online). More details for these two structures can be found in Table S1–S4 (online). Clearly, the field distributions of the inverse structures in the vertical cross-section present more wave nodes than those of the solid structures, which indicate that the

inverse structures have larger compensation phases compared to the solid ones. The electromagnetic field coupling effects between neighbouring units can be ignored, so the phase design for each unit is still accurate when they are arranged in a square lattice of the unit array.

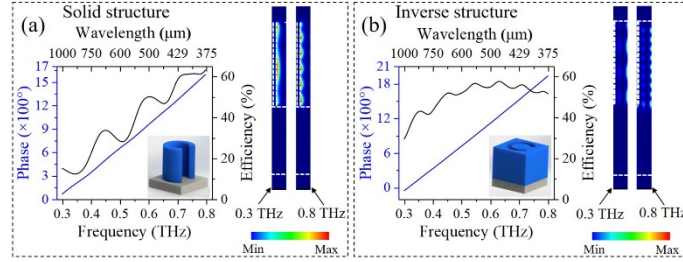


Fig. 2. (Color online) Phase distributions and conversion efficiencies of the solid and inverse C-shaped unit element. RCP-to-LCP polarization conversion efficiency (black curves) and phase profile (blue curves) of the (a) solid and (b) inverse C-shaped unit element. Side views of normalised magnetic density distributions in each typical unit at 0.3 THz (left) and 0.8 THz (right) on the right side of (a) and (b).

3. Experimental characterizations of the achromatic metalens

To verify our proposed approaches, we fabricate the terahertz achromatic metalens to focus the terahertz wave and explore the corresponding behaviour using terahertz near-field microscopy, as shown in Fig. 3a. The sample shown in Fig. 3b is fabricated by conventional photolithography and deep etching processing techniques. Scanning electron microscope (SEM) images of the C-shaped sample are shown in Figs. 3c and 3d. Fig. 3c represents the inverse C-shaped unit elements in the inner area of the metalens, while Fig. 3d shows the solid C-shaped unit elements in the margin area. The inner inverse structures provide a higher compensation phase than the margin solid structures, which are consistent with the phase distribution, as shown in Fig. 1b. The solid structures with a height of 550 μm are etched into the silicon substrate with a thickness of 1 mm, and the refractive index is $n = 3.45$ (resistivity $> 10^4 \Omega\cdot\text{cm}$). The experimental setup is illustrated in Fig. 3a, and the collimated terahertz waves radiate from a 100-fs ($\lambda = 780 \text{ nm}$) laser pulse-pumped photoconductive antenna emitter, are modulated with a proper polarised state, and then impinge on the sample. To enable a three-dimensional scan of the terahertz electric field in the x - y plane, a commercial terahertz near-field probe is mounted on a three-dimensional motorised stage. The sample is also mounted on a three-dimensional translation stage. The probe is located in the vicinity of ($\sim 3 \text{ mm}$) the sample to collect the signals to reconstruct the amplitudes and phase distributions of the electric field. Here, a microscope is used to identify the distance between the probe and the metasurface. The 2D motorised field distribution is detected with a discrete step size of 0.25 mm in the x - and y -directions.

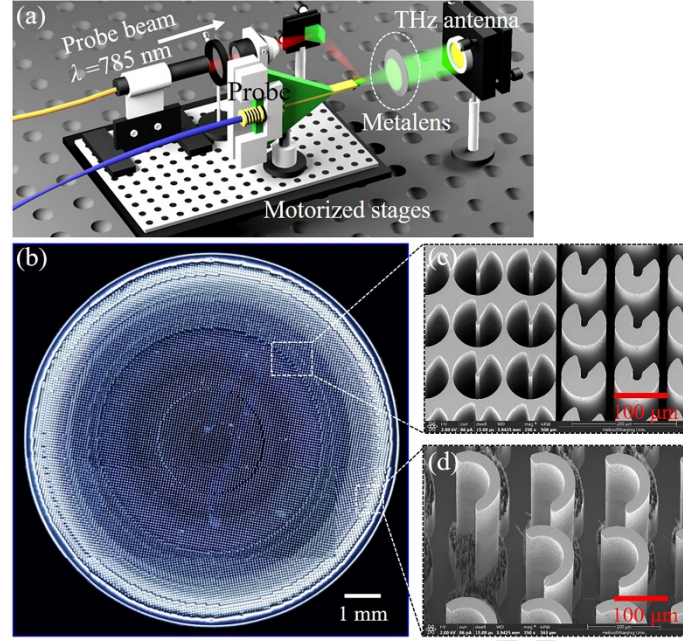


Fig. 3 (Color online) (a) Experimental setup of the terahertz near-field microscopy. The terahertz near-field probe is fixed on the motorised stage to detect the electric field distributions. (b) Top view of the fabricated sample with a diameter of 10 mm. (c) Enlarged view of the inverse and solid unit elements in the inner area of the metasurface. (d) Enlarged view of the solid C-shaped unit elements in the margin area of the metasurface.

By employing the above-proposed design principle, a broadband achromatic metalens is demonstrated in a broadband terahertz frequency range from 0.3 to 0.8 THz. A metalens composed of C-shaped unit elements with $NA = 0.385$ is obtained with a diameter of 10 mm and focal length of 12 mm. The transmitted field intensity profiles of the horizontal polarization (E_y) on the transverse focal plane are shown in Figs. 4a–c. The measured results are highly consistent with the simulation, as shown in Figs. 4g–i, which indicate that the focal length of $F = 12$ mm remains almost unchanged in the broadband frequency range. The achromatic metalens focusing at the frequencies of 0.3, 0.6 and 0.8 THz is supported by the detected phase distributions, which are shown in Figs. S3 and S4 (online). Furthermore, additional information of the experiments for the metalens based on C-shaped unit elements are shown in Figs. S5 and S6 (online). In order to visually demonstrate the superiority of the achromatic metalens, we simulated the chromatic aberration effect of ordinary lenses in Fig. S2 (online). All the measured focal spots show values of the full-width at half-maximum (FWHM) close to the diffraction-limited size of $\lambda/(2NA)$, as shown in Figs. 4d–f. For example, Fig. 4d shows the horizontal intensity profile at the focal spot for the experimental and numerical results at the terahertz frequency of 0.3 THz with the corresponding wavelength of 1 mm. The theoretical diffraction-limited value of $\lambda/(2NA)$ is 1.298 mm, which is quite close to the experimental value of 1.3 mm. Similarly, the measured numerical apertures from the experimental results at the frequencies of 0.6 and 0.8 THz are also $NA = 0.385$, which match the designed value perfectly. These results prove that achromatic

focusing has been realised in such a terahertz broadband.

The experimental efficiency of the C-shaped metalens at the incident wavelength at 0.6 THz is shown in Fig. 4j, in which the efficiency has been calculated using $\Sigma I_E / \Sigma (I_{\text{ref}} \times n_{\text{si}})$, where I_E represents the sum of the intensity distributions at the focal plane with a diameter 1.5 mm (dotted white line) and I_{ref} is the transmitted terahertz power with a silicon wafer. We have demonstrated a metalens with an efficiency higher than 68% at the peak, which is promoted significantly higher than the efficiency of the metalenses based on plasmonic scatterers and recent reports of dielectric achromatic metalenses. In all cases, the reasons for efficiency reduction in the achromatic metalens include amplitude variations (not all meta-units have the same scattering efficiency), phase errors due to the mismatch between the required and actual phase responses of the meta-units, and fabrication errors (such as sidewall roughness and slope). In our transmission mode metalens, backscattering from the meta-units sacrifices about 30% of the overall efficiency. In order to clearly present the overall efficiency, Figs. 4k–m also show the incident, LCP focusing and RCP defocusing distribution at the frequency of 0.6 THz, respectively.

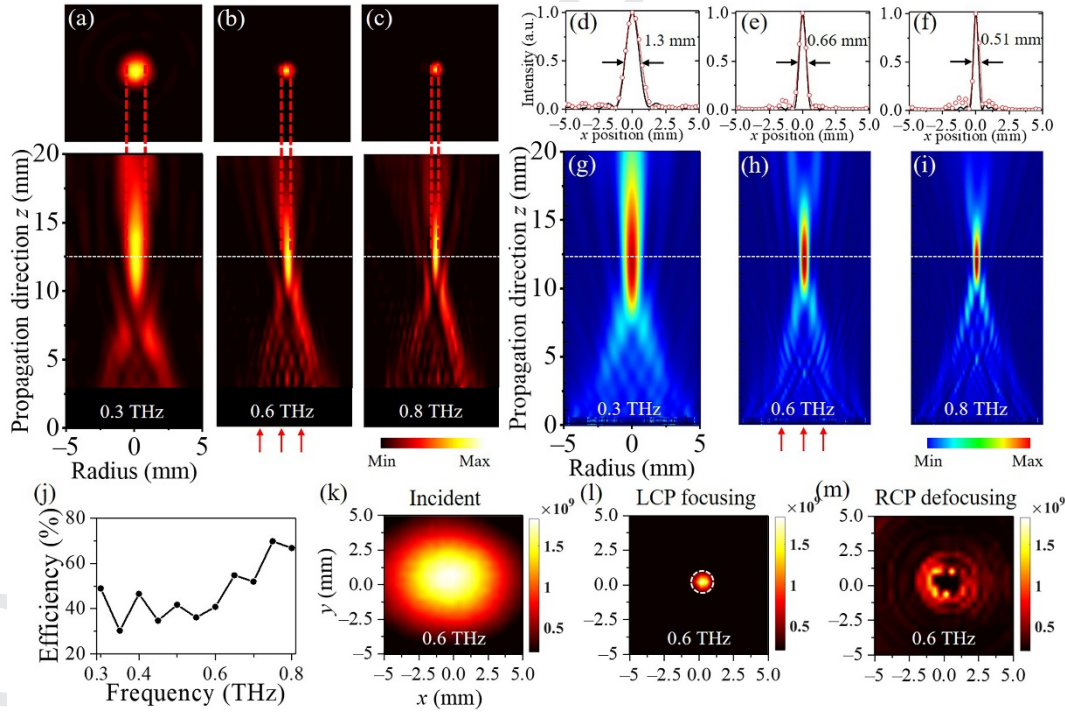


Fig. 4. (Color online) Characterization of the focusing effects for terahertz achromatic metalens based on C-shaped unit elements.

(a)–(c) Horizontal and vertical cross-sections of the intensity distributions at the focal plane for the frequencies of 0.3, 0.6 and 0.8 THz, respectively. (d)–(f) Comparison of the profiles of the focal spots between the simulation and experimental results. (g)–(i) Simulation results for frequencies of 0.3, 0.6 and 0.8 THz, respectively. (j) Efficiency of the achromatic focusing. (k)–(m) Incident, LCP focusing and RCP defocusing distribution at the frequency of 0.6 THz, respectively.

4. Discussion of influences due to fabrication defects

We found that the sensitivity of the focusing effects on the fabrication robustness for C- and

rectangular unit-based metalenses is different. These two metalenses with different structural shapes are adjacently fabricated on a silicon wafer, ensuring that the lens has the same fabrication error. Fig. 5a shows SEM images of two typical structure units of the metalens, and the fabrication defects. These defects which include the shape deformations and deviations of etching depth inevitably make negative impacts on the focusing effects and broaden the FWHMs of the focal spots, as shown in Fig. 5b. The simulated FWHM is 0.6 mm at the frequency of 0.5 THz, compared to the experimental value of 1.05 mm. In order to deepen the understanding of the influences of the shape deformations, we numerically illustrated the phase profiles with the variation in the fillet errors, as shown in Figs. 5c and 5d. We found that the deviations in the actual and ideal phase distributions of the metalens based on the C-shaped unit are smaller than those based on the rectangular unit, which indicate that the metasurface based on the C-shaped unit is less affected by the fabrication defects. Fig. 5e also presents the focal spot of the metalens based on the rectangular unit at the frequency of 0.5 THz. The focal length in the experimental data is $F \approx 10.5$ mm, which has a small offset from our designed value of $F = 10.5$ mm. The experimental results based on the amplitude and phase distributions of the rectangular metalens are presented in Figs. S5 and S6 (online). The simulation results of the focusing effect with C-shaped fillet errors are presented in Fig. S7 (online).

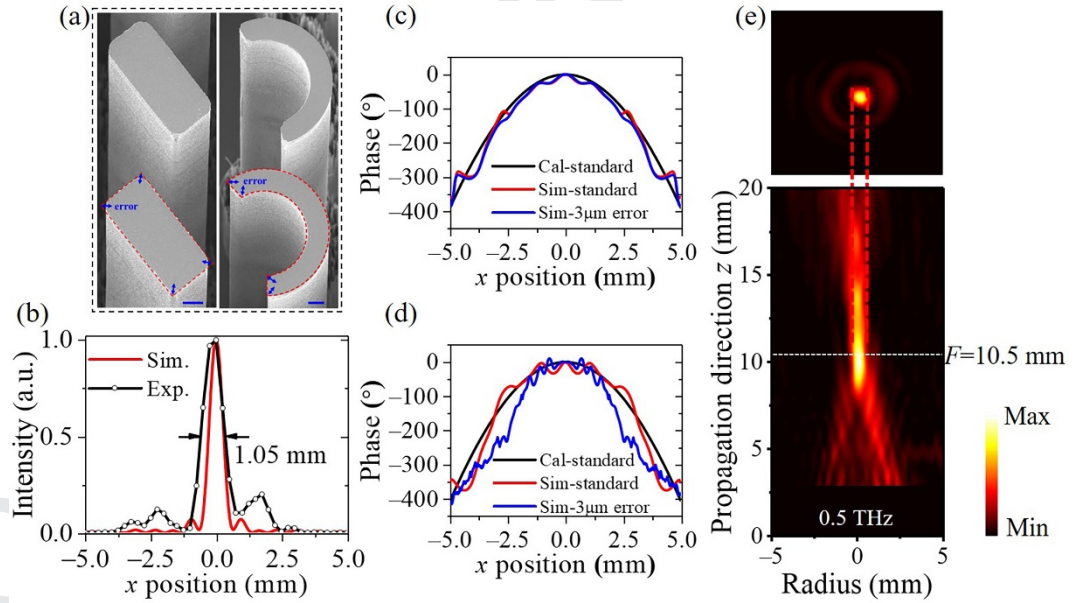


Fig. 5. (Color online) Phase distributions of the metalenses with different fabrication defects. (a) Fillet errors for the metalenses based on the rectangular and C-shaped unit, where the blue scale bar is 10 μ m. (b) Comparison of the FWHM between the experimental and simulation results. (c), (d) Actual phase deviations from the ideal distributions corresponding to situations when the fillet error is 3 μ m for the C-shaped and rectangular unit elements. (e) Electric field distribution along the cross-plane (x - z plane) and the focal spot distribution at $F = 10.5$ mm.

Furthermore, we compare the achromatic focusing distributions of various etching depths using simulations (Fig. 6). The greater the depth, the higher the compensation phase, which in turn achieves a

broader achromatic bandwidth or larger numerical aperture. From the simulation results in Figs. 6a–c at the frequency of 0.3 THz, the focal length increases from 12 to 19 mm, which implies decreased numerical apertures when the unit element depth decreases from 550 to 350 μm . This is consistent with the above-mentioned relationship between the depth and resonant modes. In addition, the focal lengths in Figs. 6d–f at the frequency of 0.8 THz obey the same tendency. Fig. 6g summarises the profiles of Figs. 6d–f at the frequency of 0.8 THz with the etching depths of 550, 450 and 350 μm . Importantly, it is found that the focal lengths in Figs. 6a and 6d remain the same at the frequencies of 0.3 and 0.8 THz, which also demonstrate the achromatic effects within the wavelength range between these two frequencies. The same cases are shown in Figs. 6b, 6e, 6c and 6f, respectively, which again prove the robustness of the achromatic metalens. The transmitted field intensity profiles of the metalens with varied structural depths at various incident wavelengths are shown in Figs. S8 and S9 (online) for the C-shaped and the rectangular structures, respectively.

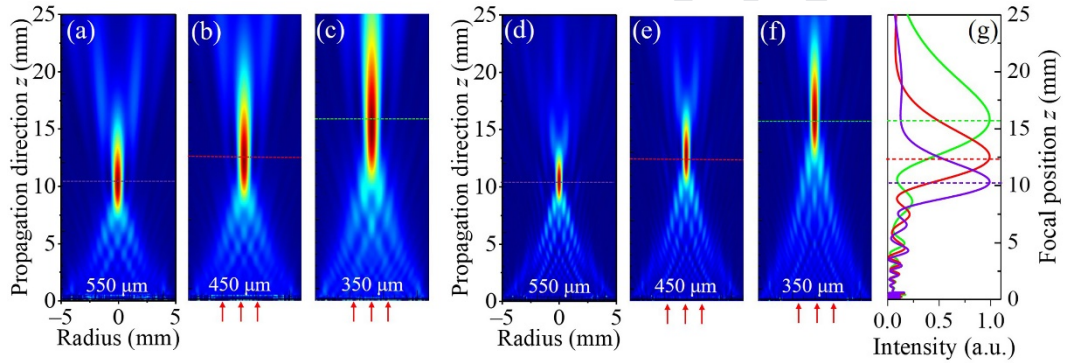


Fig. 6. (Color online) Focusing effects of the metalens with varying unit depths. Cross-section of field distributions of the metalens based on C-shaped unit elements with various depths of 550, 450 and 350 μm at frequencies of (a)–(c) 0.3 and (d)–(f) 0.8 THz, respectively. The dotted lines of each colour represent the focal length at the corresponding depths, and the lines of the same colour represent the same focal length at frequencies of 0.3 and 0.8 THz. (g) Summary of the profiles of Fig. 6a–f at frequencies of 0.3 and 0.8 THz with the etching depths of 550, 450 and 350 μm .

The design principle of the achromatic metalens is based on tailoring phases to compensate the dispersion, which ignores the polarization conversion efficiency to some extent. Therefore, achieving a high-efficiency achromatic metalens is an urgent issue that must be resolved. Although we have numerically demonstrated the robustness of the metalens, the fabricated sample may suffer from various problems, such as the variation in the achromatic focal lengths and other problems in engineering applications. Furthermore, as the vital limiting factor in the deep etching process is the aspect ratio, which is the main factor that causes fabrication defects, reducing the aspect ratio will be the focus of our next step.

5. Conclusion

In conclusion, a high-NA achromatic metalens based on C-shaped or rectangular unit elements has been designed by combining the resonant phase with the geometric phase, which is first reported

theoretically and experimentally within a broadband terahertz frequency range. Moreover, the effects due to shape deformations and etching depth deviations are simulated separately, and the results indicate that the achromatic lens possesses a suitable robustness. The realizations of terahertz broadband achromatic focusing lenses have potential applications as metasurfaces in practical engineering for hyperspectral terahertz bio-imaging.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Qingqing Cheng, Meilin Ma and Dong Yu developed the theoretical aspects and performed the numerical design and terahertz near-field measurement; Meilin Ma and Dong Yu carried out the simulation; Jingya Xie, Juncheng Wang and Nianxi Xu fabricated the samples; Dong Yu, Zhixiong Shen and Hanming Guo built-up the near-field system for measurement; Qingqing Cheng, Dong Yu and Zhixiong Shen performed the sample preparation and data analysis; Qingqing Cheng, Dong Yu, Zhixiong Shen, Wei Hu, Shuming Wang and Tao Li analysed the data; Qingqing Cheng and Songlin Zhuang organised the project, designed the experiments, analysed the results and prepared the manuscripts. All authors discussed the results and commented on the manuscript.

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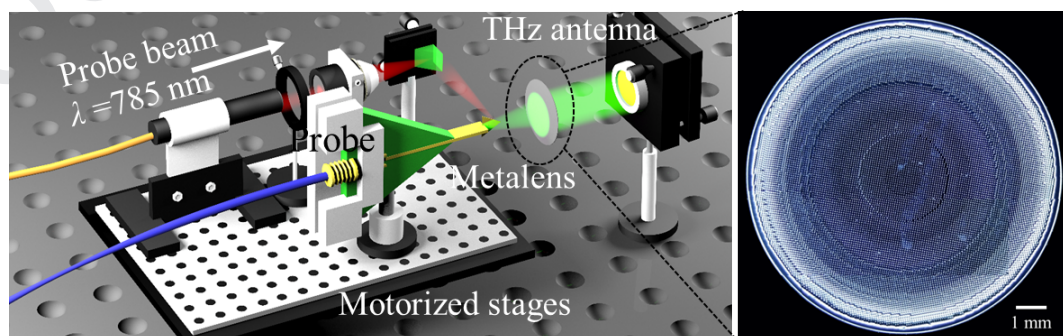
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Terahertz near-field microscopy is used to detect the phase of the electric field component

transmitted by the metalens, which coincides with the phase of the theoretical design. The demonstrated metalens works from 0.3 to 0.8 THz with a bandwidth of approximately 91% over the centre frequency, possesses a high working efficiency of more than 68% at the peak and a relatively high numerical aperture of 0.385.