Efficient terahertz metasurface-based flat lens

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***Abstract*—We present a nonuniform metasurface that operates as a flat lens at 400 GHz. Efficiency is enhanced by the use of a novel, tri-layer polarization-converting nonuniform metasurface structure. The device is fabricated and experimentally characterized. The results confirm that the flat lens is indeed capable of focusing radiation to a focal spot with ∼68% efficiency. Constrained by spatial dispersion, the −3 dB bandwidth is 150 GHz.**

I. Introduction

THE capacity to efficiently focus and collimate terahertz radiation is crucial for applications of terahertz technology. These include imaging, for which focusing is beneficial to provide adequate resolution, and communications, where beam-collimating devices can achieve high antenna gain. Devices of low thickness are generally preferred for integration into compact systems. Flat-profile, metasurface-based terahertz lens devices have previously been demonstrated employing polarization conversion, i.e. the polarizations of incident and transmitted waves are orthogonal. However, the efficiency of flat lenses of this sort has so-far been limited to ∼25% [1], [2]. Previously, higher-efficiency conversion to cross-polarization has been achieved using an innovative tri-layer metasurface structure [3]. In that work, beam deflection was achieved at frequencies ranging from 0.5 to 1.8 THz. Here, this approach is adopted to realize an efficient flat lens that operates in a broad range of frequencies centering on 400 GHz [4]. This lower frequency range is more compatible with compact electronic sources and detectors [5].

II. Design

As shown in Fig. 1(a), the metasurface consists of three layers; one micro-scale resonator layer and two orthogonal polarizer layers. The resonator is anisotropic, and hence it generates elliptical polarization when excited by incident terahertz radiation. This has a cross-polarized component that is passed through the second polarizer. However, the co-polarized component is reflected from this polarizer, and subsequently experiences further interactions with the resonator. As such, the polarizers act as a cavity that enhances the yield of cross-polarized transmission. Phase is controlled through a complete 360° cycle by employing sixteen different resonators, as shown in Fig. 1(b). It is noted that the transmission efficiency is at least 68% for each resonator.

In order to operate as a lens of focal length F, the metasurface must impart the following phase distribution onto transmitted radiation,

$$\phi(r) = k_0 \left(\sqrt{F^2 + r^2} - F \right). \tag{1}$$

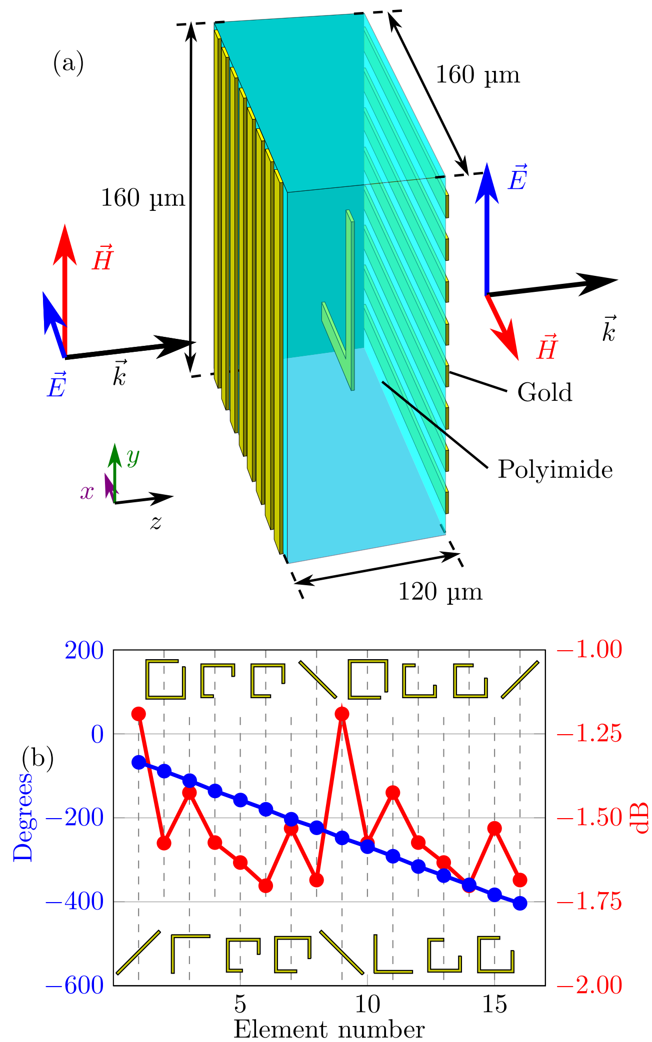

Fig. 1. Metasurface unit cell, showing (a) tri-layer construction, with cross-polarized transmission, and (b) response at 400 GHz for each resonator.

This is translated to a required resonator layout by mapping the required phase response at in-plane position r to the closest value of phase response, as per the analysis presented in Fig. 1(b). It is noted that phase is wrapped to a 2π cycle. The layout of resonator elements that is produced by this procedure is given in Fig. 2.

III. Fabrication

The multi-layer sample is fabricated with a procedure involving alternating passes of spin-coating and curing of

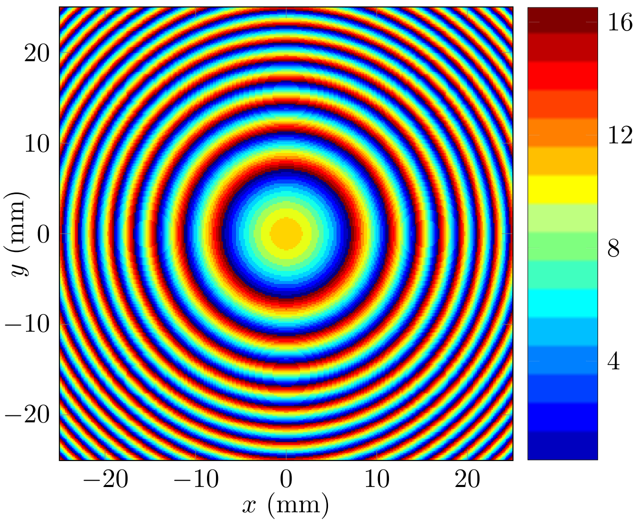

Fig. 2. Required layout of resonator elements, where the number in the colorbar corresponds to the resonator element numbers given in Fig. 1(b).

polymer layers, and the deposition and patterning of planar metal microstructures. A silicon wafer serves as a substrate, from which the sample is peeled off after this microfabrication procedure. The result is a flexible and pliable device, bearing a total of ∼98,000 individual resonator elements across an area of 50×50 mm^2.

IV. Results

The focusing behavior of the device is investigated using terahertz time-domain spectroscopy. A collimated beam of the appropriate polarisation (i.e. orthogonal to the input polarizer) is employed to excite the sample, and a detector is raster-scanned in the focal plane in order to evaluate the field distribution at the focus. The results of this procedure are shown in Fig. 3(a). A well-defined focal spot can clearly be seen, albeit surrounded by some spurious fields that are likely associated with input-beam irregularity.

V. Efficiency

It is of interest to evaluate the overall efficiency of the terahertz flat-lens metasurface device, as this is the main motivation for this study. To this end, the power delivered to the focal spot is compared to the performance of a poly-methylpentene lens, where the insertion losses of the lens are compensated for analytically. Results given in Fig. 3(b), show peak efficiency of ∼68%, at the operating frequency of 400 GHz. This is consistent with the simulations presented in Fig. 1(b). Furthermore, it is evident from these results that the −3 dB bandwidth of the device is 150 GHz, which is mainly limited by spatial dispersion, as is typical for flat lenses of this type. Theoretically, such spectral bandwidth can sustain high-volume communications links.

VI. Conclusion

We present the design, fabrication, and experimental characterization of a terahertz flat lens structure operating at 400 GHz. The device consists of a transmissive, polarization-converting metasurface, where an innovative tri-layer structure enhances the yield to cross polarization. The intended lens functionality is confirmed, with overall efficiency of ∼68%, and 150 GHz bandwidth.

References

[1] D. Hu, G. Moreno, X. Wang, J. He, A. Chahadih, Z. Xie, B. Wang, T. Akalin, and Y. Zhang, “Dispersion characteristic of ultrathin terahertz planar lenses based on metasurface,” Opt. Commun. 332, 164–168, 2014.

[2] Q. Wang, X. Zhang, Y. Xu, Z. Tian, J. Gu, W. Yue, S. Zhang, J. Han, and W. Zhang, “A broadband metasurfacebased terahertz flatlens array,” Adv. Opt. Mater. 3, 779, 2015.

[3] N. K. Grady, J. E. Heyes, D. R. Chowdhury, Y. Zeng, M. T. Reiten, A. K. Azad, A. J. Taylor, D. A. Dalvit, and H.-T. Chen, “Terahertz metamaterials for linear polarization conversion and anomalous refraction,” Science 340, 1304, 2013.

[4] C.-C. Chang, D. Headland, D. Abbott, W. Withayachumnankul, and H.-T. Chen, “Demonstration of a highly efficient terahertz flat lens employing tri-layer metasurfaces,” Opt. Lett. 42(9), 1867–1870, 2017.

[5] U. R. Pfeiffer, Y. Zhao, J. Grzyb, R. Al Hadi, N. Sarmah, W. Frster, H. Rcker, and B. Heinemann, “A 0.53 THz reconfigurable source module with up to 1 mW radiated power for diffuse illumination in terahertz imaging applications,” IEEE J. Solid-State Circuits 49, 2938–2950 2014.

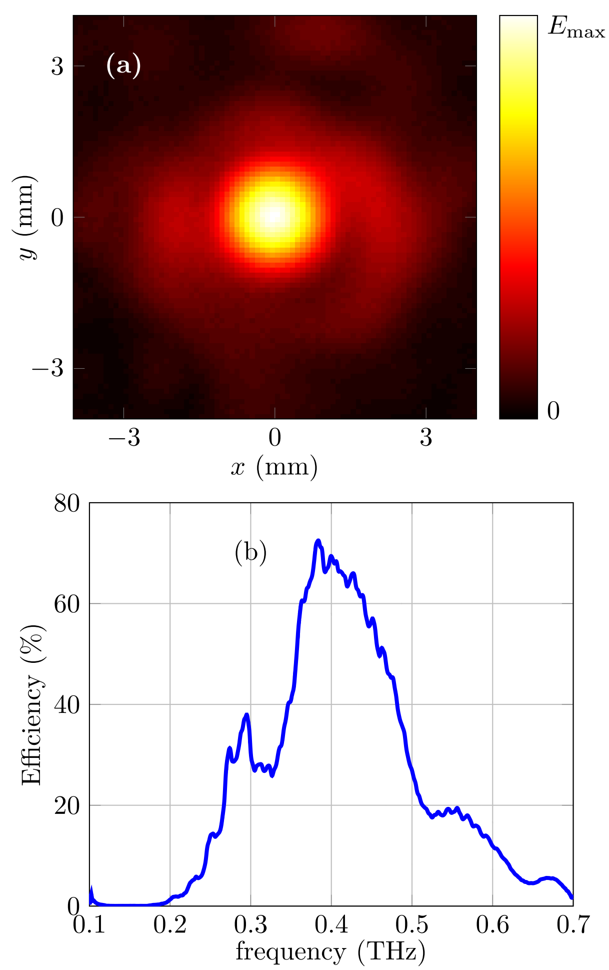

Fig. 3. Measured results, showing (a) focal spot at 400 GHz, and (b) overall efficiency.