Metamaterial-based gradient index lens for strong focusing in the THz frequency range

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Abstract

We present the design, fabrication and experimental investigation of a three-layer metamaterial-based gradient index (GRIN) lens that allows focusing of THz radiation to a spot diameter of approximately one wavelength at a center frequency of 1.3 THz. We measured an operation bandwidth of the lens of 300 GHz and compared the experimental data to numerical calculations.

1. Introduction

The progress of the terahertz(THz) technology is currently suffering from a lack of adequate optical components, such as waveplates, lenses, beam splitters etc. that on the other hand belong to standard optical components in other frequency ranges. Although there exist several classes of classical lenses such as e. g. silicon lenses, tsurupica lenses or polyethylene lenses, most of them usually introduce strong spherical aberrations since the underlying focussing principle is purely based on refraction phenomena at curved boundaries. Moreover, none of these lenses can possess adaptively controllable optical properties. Although there were several attempts for creating adaptive THz lenses with common materials, these approaches were unpractical due to the large dimensions of such devices or a slow temporal response to external tuning [1]. Here, we present an alternative approach for the design and fabrication of ultra-thin THz lenses with strong focusing capabilities that is based on metamaterials with refractive index gradients. Such thin, free-standing metamaterial membranes do not only enable the integration in very compact THz systems but also possess the potential to open up novel ways to realize a new class of adaptive THz optics that can be controlled by optical and/or electrical means [2, 3].

2. Design and Fabrication

Fig. 1(a) shows the design and the typical dimensions of a specific unit cell of the GRIN lens. The metamaterial structure was based on annular slots in a 200 nm thick copper layer. The copper was enclosed by two 20 µm thick BCB films. We fabricated the multi-layer GRIN lens by repeating this specific structure in propagation direction of the THz beam. Each layer consisted of 469 unit cells. The effective refractive index of each individual unit cell could be tuned by changing the inner radius of the annular slots. The structure was fabricated by standard UV-lithography [4]. We varied the diameter of the rings between 23 µm in the center of the GRIN lens and 18 µm in the outer region. Since a large ring diameter corresponds to a high refractive index, a decreasing ring radius of the unit cell structure in the radial direction of the lens resulted in a high refractive index in the center and a low refractive

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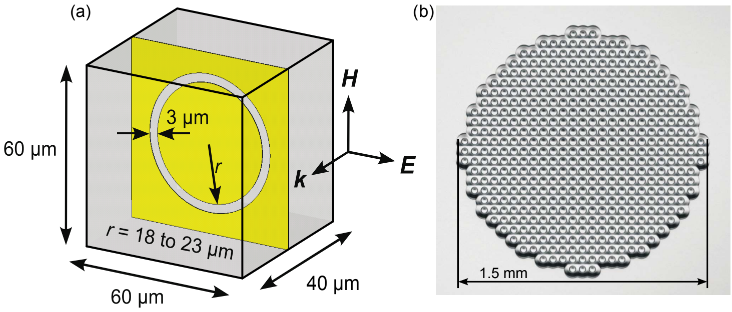

Fig. 1: (a) The unit cell of the fabricated metamaterial consists of a 200 nm thick copper layer embedded between two BCB layers. (b) Optical microscope picture of the fabricated metamaterial.

index at the edge of the lens (see Fig. 1(b)). That way we created a parabolic refractive index gradient that resulted in a strong focusing of THz radiation. Due to accumulation effects in the phase advance of the propagating THz wave the focusing effect scaled with the number of unit cell layers. Although we restricted our considerations to a 3-layer GRIN lens in this summary, we also studied and compared the optical behavior between a 1-layer and a 3-layer lens. In all cases we performed full wave simulations of the fabricated GRIN lenses and compared the numerical results with the experimental data. We performed spatially resolved THz-time-domain spectroscopy (THz-TDS) [5] to measure the beam profile of the THz radiation inside and outside the focal plane. In THz-TDS an optical probe pulse coherently samples the THz electric field and thus provides amplitude and phase information. As a specific detection scheme of the THz pulses we utilized the technique of electrooptic (EO) sampling in a 20 mm x 20 mm large GaP crystal, similar to Ref. [6]. The crystal was centered around the optical axis of the beam path and then raster scanned by the optical probe beam. By this method we could measure the 2D electric field distributions of all frequency components of the THz pulses with a bandwidth up to 3 THz. Thereby, the spatial resolution of this setup was not limited by the wavelength of the THz radiation of approximately 300 µm but only limited by the focus size of the optical beam, which was approximately 60 µm.

3. Results

To determine the optical properties of the GRIN lens we measured the spatial THz-field distribution in dependence of the distance from the lens. Fig. 2(a) shows the THz intensity profile at different distances from the exit surface of the GRIN lens. The intensity distribution was evaluated at a frequency of 1.3 THz

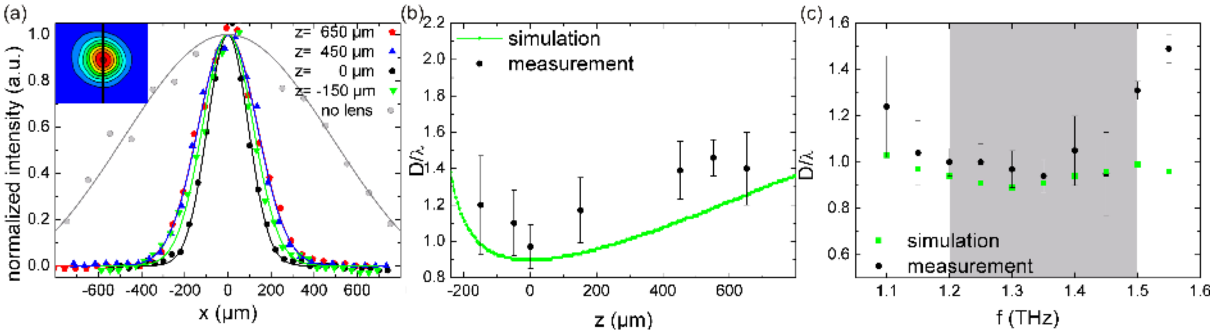

Fig. 2: (a) Measured and simulated THz intensity profile in dependence of the distance from the lens at 1.3THz, (b) Measured and numerically calculated beam diameter at 1.3 THz in dependence of the relative distance from the focal plane, (c) Spectral dependence of the focus diameter obtained by measurements and numerical calculations.

along an intersection line through the center of the 2D intensity distribution as indicated in the inset of Fig. 2(a). The grey line indicates the intensity profile of the unfocused THz beam. It can be seen that the GRIN lens strongly focused the incident THz radiation to a spot size in the order of one wavelength. This is also evidenced by Fig. 2(b) where the FWHM of the intensity profile is plotted in dependence of the relative distance from the focus. The converging and diverging behavior of the beam diameter clearly proves that the metamaterial was not just working as an aperture but was truly focusing the beam.

Furthermore, we could also show that the fabricated lens provided strong focusing capabilities over a broad frequency range. Fig. 2(c) shows the focal beam diameter in dependence of the frequency of the THz radiation. It is obvious, that the GRIN lens focused THz radiation to focal diameters in the order of one wavelength in a frequency band between 1.2 and 1.5 THz. In this frequency range, we could assure that the lens operated in the effective medium regime. For frequencies higher than 1.5 THz, the lens approached the Bragg regime and thus could not be longer considered as an effective medium. The spectral dependence of the focus diameter is in good agreement with the numerical results obtained by full wave simulations. Although not shown in this summary, we also fabricated and characterized 1- and 2-layer GRIN lenses. The measured optical properties of these lenses were also in good agreement with the simulated data [8].

4. Conclusion

We devised and fabricated a metamaterial-based 3-layer gradient index (GRIN) lens that focused THz radiation to focus diameters in the order of one wavelength. The operation bandwidth of the GRIN lens was 300 GHz around a center frequency of 1.3 THz. Within the whole operation bandwidth, the focus diameter stayed in the order of one wavelength. The GRIN lens consisted of a thin free-standing membrane of approximately 120 μm thickness. The aperture of the lens was 1.5 mm. Due to the small thickness and the strong focusing strength the lens is perfectly suited for the integration in ultra compact THz systems. Due to the inherent possibility to actively tune the optical properties of metamaterials by electric or optical means, such lenses could pave the way to a new generation of adaptive THz optics.

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