Metamaterial-based optical components for THz radiation

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Abstract

We present different metamaterial-based optical components that open exciting new ways to deliberately manipulate the spatial or spectral properties of terahertz (THz) radiation. The central scope of the paper is the design, fabrication and optical characterization of a 3-layer gradient index (GRIN) lens that allows one to strongly focus THz radiation to a spot diameter in the order of one wavelength. The GRIN lens is based on a specific metamaterial structure that is fully embedded in a polymer background matrix and thus provides a free-standing optics with high transmission and minimal Fresnel reflection. THz lenses with such strong focusing capabilities are especially intriguing with respect to the resolution enhancement of THz imaging systems.

1 Introduction

The terahertz (THz) technology recently raised a great deal of scientific and industrial interest due to the ability to penetrate through dielectrics, as e. g. textiles, paper etc. By this method, it is possible to carry out non-invasive measurements that are related to security inspections, quality control and fundamental optical spectroscopy [1]. Though suitable terahertz sources and detectors have been developed in the last few years, this technology lacks of high performance optical components that are considered as standard optics in the infrared, visible or ultraviolet frequency range. The reason for this lies in the fact that most natural optical materials don't provide a sufficient electromagnetic response to THz radiation. As a very promising candidate to overcome these limitations, metamaterials can be deliberately designed to provide a well-defined response and thus a very specific functionality at THz frequencies. Though the oral presentation will include many examples for such metamaterial-based optics, we focus this summary on the design of a metamaterial-based gradient index (GRIN) lens [2]. The reason for this is that the most promising applications of THz radiation to date are related to the concept of THz imaging. Especially for this measurement technique it would be advantageous to have access to very compact lenses with strong focusing capabilites to enhance the optical resolution of the imaging device and allow one to increase the compactness of such systems. In the following, we will discuss the design, fabrication and measurement of the optical properties of a three-layer metamaterial GRIN lens with strong focusing capabilities to spot diameters in the order of one wavelength.

2 Design and Fabrication

Fig. 1(a) shows the structural design of the unit cell. The specific geometry is based on annular slots in a copper plane. The metal structure is fully embedded in a benzocyclobutene (BCB) background matrix. We calculated the optical properties of the metamaterial design by full wave simulations with the software CST Microwave Studio. As can be seen from Fig. 1(b) we could change the refractive index of the metamaterial from 0.08 to 1.65 at a center frequency of 1.3 THz by varying the inner radius of the slots between $r = 18$ to $23\,\mu$m while keeping the slot width constant. For the metamaterial lens we positioned the unit cells to obtain a refractive index gradient that radially decreased from the geometric center of the lens to the edge. In this specific case, the parts of a wave that propagate through the center of the GRIN lens experience a

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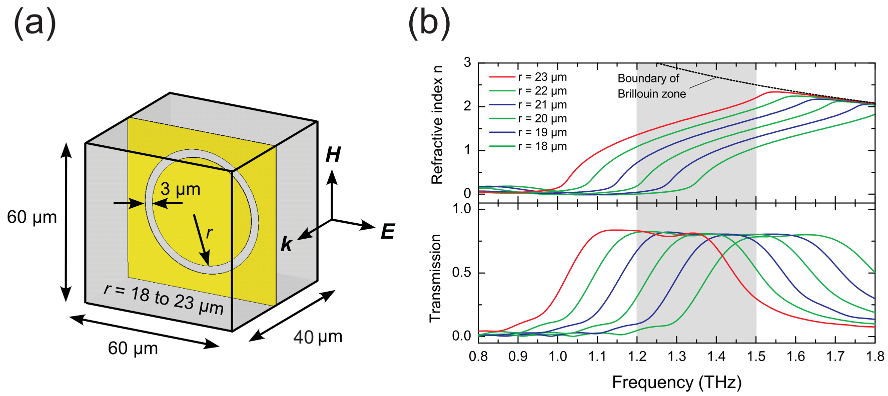

Figure 1: (a) Unit cell design based on annular slots in a copper plane that is fully embedded in a BCB background matrix (b) The refractive index was changed by varying the inner radius of the slots from $r = 18$ and 23 μm. As a result, a refractive index variation from 0.08 to 1.65 was achieved at a center frequency of 1.3 THz.

higher refractive index than the partial waves propagating in the vicinity of the edges of the lens. Since the spatially dependent phase delay results in converging wave fronts, such a lens is expected to focus incoming radiation to a small spot size.

We fabricated a 3-layer metamaterial lens by a multilayer UV lithography procedure that we developed earlier and was described in more detail in Ref. 3. By this fabrication method we obtained a 3-layer GRIN lens with a lattice constant in propagation direction of approximately 40 μm. Thus, the total thickness of the lens was about 120 μm which is thinner than one wavelength for THz radiation at a frequency of 1 THz (corresponding to a wavelength of 300 μm) in vacuum. The diameter of the lens was 1.5 mm which relates to 25 unit cells.

3 Measurement setup

We examined the optical properties of the GRIN lens by measuring the spatial distribution of the amplitude and phase of the electric THz field vector by utilizing the methodology of electro-optic sampling. We generated THz pulses with a duration of 2 ps and a spectral bandwidth from 0.1 to 2 THz by focusing the beam of an ultrashort pulse laser with a pulse length of 15 fs between the electrodes of a photoconductive switch. The emitted THz pulses were polarized in x-direction. In order to match the THz beam diameter to the aperture of the lens, we first collimated the THz beam from the antenna by a parabolic mirror and focused the collimated beam to a spot diameter of about 1 mm by a second parabolic mirror. The spot diameter was measured at a frequency of 1.3 THz. Hereby and in the following the beam diameter is defined as the full width at half maximum (FWHM) of the Gaussian intensity beam profile. We aligned the GRIN lens in the focal position of the THz beam to ensure that the phase fronts of the incident beam were plane at the entrance facet of the lens. Furthermore, we carefully adjusted the lateral position of the lens with respect to the optical axis of the incident THz beam to avoid undesired beam distortion and steering.

For the measurement of the spatial beam profile and spot diameter of the focused THz beam behind the GRIN lens we utilized electro-optic sampling in reflection geometry [4] . We used a gallium phosphide (GaP) crystal with a thickness of 400 μm and an aperture size of $20{\times}20\,\text{mm}^2$ as electro-optical detector.. The GaP crystal was cut in the (110)-direction such that the electro-optic effect was only sensitive to the x-polarization of the THz beam. The detection scheme was conceived as follows: Due to the electro-optic effect, the incident THz pulses induce an instantaneous change of the refractive index of the GaP crystal.

This change is proportional to the momentary amplitude of the electric THz field. Since the electro-optic effect in GaP is anisotropic, it is possible to determine the amplitude of the electric THz field by measuring the change of the polarization state of ultrashort probe pulses that propagate through the crystal. For this purpose, we focused linearly polarized probe pulses to a spot size of 60 μm at the position of the GaP crystal. The wavelength of the probe pulses was 800 nm and the pulse duration was 40 fs. The entrance facet of the GaP crystal was coated by a highly reflective layer for a wavelength around 800 nm while the exit facet was anti-reflection coated for the same wavelength range. The optical coatings prevented a modification of the propagation properties of the THz beam at the boundaries of the GaP crystal and reduced the Fresnel loss to a minimum. On the other hand, the probe pulses did not suffer from reflections at the GaP crystal surface on entrance and were highly reflected at the second crystal surface where the THz pulses entered. During the propagation through the crystal the probe pulses changed their polarization state due to the optically induced change of the refractive index by the momentary THz field. Because of the anisotropy of the electro-optic effect, the difference in the induced phase delay of two orthogonally polarized field components of the probe pulses resulted in elliptically polarized probe pulses when the THz field was non-zero. Hereby, the orientation of the major and minor axes of the polarization ellipse was sensitive to the polarity and thus the phase of the momentary THz field. To measure the THz electric field with high sensitivity we analyzed the polarization of the probe pulses by combination of a quarter wave plate, a wollaston prism and a balanced detector. Since we obtained the probe pulses from deviating a small fraction of the energy of the pump pulses used for the THz generation by a beam splitter, the probe pulses were inherently coherent with the generated THz pulses. Furthermore, the pulse length of 40 fs of the probe pulses was a factor of 50 smaller than the pulse length of the THz pulses. This allowed us to sample the temporal shape of the electric field of the THz pulses by delaying the probe pulses with respect to the THz pulses. The coherence between the THz pulses and the probe pulses in combination with the phase sensitivity of the used detection scheme enabled us to measure both the amplitude and the phase of the electric field. It should be mentioned that a major advantage of the measurement method is the possibility to measure the spatial distribution of the complex THz field with subwavelength resolution with respect to the wavelength of the THz beam. The reason is that the spatial resolution of the setup is determined by the focal diameter of the optical probe beam that was focused in our case to a spot diameter of 60 μm. A subwavelength resolution was required in order to accurately measure the focal spot diameter of the focused THz beam behind the GRIN lens.

4 Results

Fig. 2(a) shows the spatial intensity distribution of the THz beam in dependence of the relative distance from the focal plane of the GRIN lens. The inset illustrates an example of a two-dimensional measurement of the x-y-intensity profile. The one-dimensional intensity distributions were extracted from two-dimensional measurements along the cross section line in y-direction as indicated by the white line in Fig. 2(a). The field distributions were measured at a frequency of 1.3 THz. We determined the focal plane of the GRIN lens by measuring the THz beam diameter in dependence of the distance from the exit facet of the lens and interpolation of the obtained data. The focal plane was located 0.8 mm behind the exit surface of the lens. As can be seen from Fig. 2(a), we observed strong focusing of the THz beam down to a diameter $D = 220\,\mu$m at a frequency of 1.3 THz. In units of the wavelength λ of the THz radiation this corresponds to a value of $0.96 \times \lambda$. The high focusing power of the fabricated GRIN lens in combination with the subwavelength thickness of the lens opens new ways for constructing ultra-thin optics for compact THz systems and can play a crucial role for future THz applications.

We also investigated the spectral operation bandwidth of the lens. Fig. 2(b) shows the focus diameter D in units of λ in dependence of the frequency of the THz wave. As can be seen, we obtained strong focusing to spot diameters in the order of one wavelength over a frequency band from 1.2 to 1.5 THz. As compared to the typical operation bandwidth of metamaterial structures, the usable frequency range for the lens is rather wide. The reason for this is the specific design of the unit cell and the fact that we operated the metamaterial structure away from resonance.

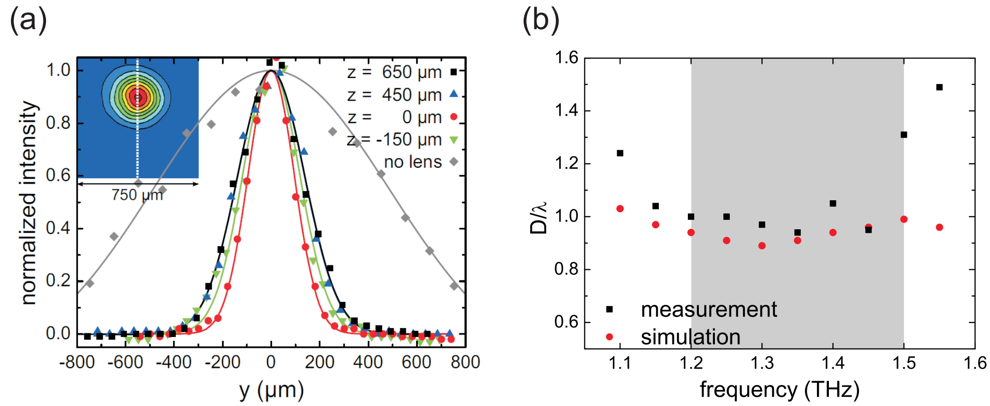

Figure 2: (a) Intensity profile of the THz beam in dependence of the relative distance from the focal plane. The intensity profile was determined along the cross section line in y-direction. The inset shows an example of a two-dimensional intensity profile measurement. (b) THz beam diameter D in units of the wavelength λ of the THz wave in dependence of the THz frequency. The shaded region corresponds to the suggested operating range of the GRIN lens.

5 Conclusion

We presented the design, fabrication and measurement of the optical properties of a gradient index (GRIN) lens based on a three-layer metamaterial structure that was fully embedded in a polymer background matrix. The lens was designed to operate at a comparably wide frequency range from 1.2 to 1.5 THz. Over the whole frequency band we obtained strong focusing to spot diameters in the order of one wavelength with respect to the wavelength of the THz radiation. Due to the extremely small, subwavelength thickness of the GRIN lens and the strong focusing strength the demonstrated metamaterial-based approach opens new exciting ways towards the design and fabrication of ultra-thin optics in compact THz systems. Though we focused on the specific case of a GRIN lens in this summary, our presentation will include many more examples of metamaterial-based optical components for the THz technology, as for example plasmonic THz sensors among others.

6 References

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