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

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Abstract: The development of innovative terahertz (THz) imaging systems has recently moved in the focus of scientific efforts due to the ability to screen substances through textiles or plastics. The invention of THz imaging systems with high spatial resolution is of increasing interest for applications in the realms of quality control, spectroscopy in dusty environment and security inspections. To realize compact THz imaging systems with high spatial resolution it is necessary to develop lenses of minimized thickness that still allow one to focus THz radiation to small spot diameters with low optical aberrations. In addition, it would be desirable if the lenses offered adaptive control of their optical properties to optimize the performance of the imaging systems in the context of different applications. Here we present the design, fabrication and the measurement of the optical properties of spectrally broadband metamaterial-based gradient index (GRIN) lenses that allow one to focus THz radiation to a spot diameter of approximately one wavelength. Due to the subwavelength thickness and the high focusing strength the presented GRIN lenses are an important step towards compact THz imaging systems with high spatial resolution. Furthermore, the results open the path to a new class of adaptive THz optics by extension of the concept to tunable metamaterials.

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OCIS codes: (160.3918) Metamaterials; (160.4670) Optical materials; (240.3990) Micro-optical devices; (080.3620) Lens system design; (110.6795) Terahertz imaging; (300.6495) Spectroscopy, terahertz.

References
1. Introduction

THz physics and metamaterials have raised a great deal of scientific interest in the last few years. While recent advances in the THz technology were strongly driven by efforts to transfer the fundamental knowledge about THz radiation to industrial applications, the metamaterial science – as the younger of both research fields – was mainly dedicated to the investigation of the fundamental physical properties of metamaterials. This especially applies to metamaterials at higher frequencies where high absorptive loss [1] and the enormous demands on sophisticated three-dimensional nano-fabrication techniques [2, 3] obstructs the development of competitive and applicable metamaterial-based optics. In respect thereof, the limitations lead to the pursuit of many interesting basic research topics such as e. g. metamaterials with gain [4–7] or the investigation of quantum effects in metamaterials [8–10]. In contrast, metamaterials at microwave frequencies are advantageous in terms of low optical loss and ease of fabrication. In consequence, microwave metamaterials have been developed to a maturity level that enables the integration into applied systems [11].

Another promising frequency band for the application of metamaterials is the range from 0.1 to 10 THz, the so-called THz range. Whereas THz physics was mostly concentrated on fundamental research about 7 years ago, the rapid development of the technology and the fabrication of improved THz emitters and detectors lead to the opening up of new markets and application fields in the last few years. The specific property of THz radiation to penetrate through most dielectrics as e. g. textiles, paper, concrete etc. has been exploited in many scenarios that are related to non-invasive quality control through packages [12–14], chemometrics of pharmaceutical substances [15], terahertz imaging systems [16, 17] and security inspections [18–21]. The rapid expansion of industrial target applications is attended by increasing demands for high quality optical components for the THz technology. Moreover, many potential applications cannot yet be addressed by the THz technology since the required components are not available. However, such optics cannot be easily devised since the insufficient electromagnetic response of most dielectrics prevents the development of standard optics that are based on the same principles as conventional optics used in laser systems. In this context, metamaterials have already proven to offer a novel approach for modulating THz radiation [22–25], perfect absorbers with designable properties [26, 27], frequency filters [28] or wave plates [29]. Another application field where metamaterials can provide an important contribution is the THz imaging technology. It is obvious that the performance and the compactness of current imaging systems could be significantly improved if thin lenses with strong focusing capabilities and low aberrations were available.

A possible means to obtain such lenses is the use of gradient index (GRIN) metamaterials, as has been proposed recently [30–32]. The use of metamaterials as focusing optics provides certain advantages over conventional dielectric lenses which are widely used in THz imaging systems. A flat and thin metamaterial lens inherently does not show spherical aberrations due to the lack of curved surfaces in the beam path. Although one could argue that the aberrations of dielectric lenses can be minimized by optimizing the surface curvature [33], this method only applies to a fixed incidence angle of the impinging radiation. For oblique incidence however,
the spherical aberrations cannot be minimized by this approach. In contrast to dielectric lenses it was shown in [32], that a properly designed metamaterial-based GRIN lens sustains high focusing capabilities for THz radiation at oblique incidence and thus becomes insensitive on the incidence angle. The main advantage of GRIN metamaterials over dielectric lenses however lies in the potential to develop a new class of adaptive optics for the THz technology. Since, in contrast to most other materials, metamaterials allow one to spatially tune the refractive index profile at the unit cell level by optical or electronic means [22,23,25,34–36], our approach offers a new way to realize GRIN lenses with adaptive focus position and focus diameter. Although the realization of an adaptive GRIN lens is out of the scope of this paper, the following results are an important step towards the realization of innovative metamaterial-based adaptive THz optics for flexible THz imaging.

Here we present the design, fabrication and the experimental testing of a three-layer metamaterial-based GRIN lens that allows one to focus THz radiation to a spot diameter of approximately one wavelength. We also compared the optical properties of a 3-layer GRIN lens to the focusing behavior of a 1-layer GRIN lens that is significantly easier to fabricate. We showed that a 1-layer lens already focuses THz radiation to a spot size in the order of the wavelength of the THz beam. The lenses offer broadband operation, are very thin and allow aberration-free optical imaging due to the avoidance of curved boundaries in the beam path.

2. Design and fabrication

Fig. 1(a) illustrates the underlying structural design of the GRIN lens with all necessary dimensions [32,37]. The unit cell geometry was based on an array of annular slots in a metal plane. This particular approach provides a large variation of the effective refractive index by simply altering the radius of the annular slot. In our design, we changed the inner radius of the annular slot between \( r = 18 \) and \( 23 \) \( \mu \)m at a constant slot width of \( 3 \) \( \mu \)m. The copper structure was fully embedded in a benzocyclobutene background matrix with a permittivity of \( \varepsilon = 2.67 \) and a loss tangent of \( \delta = 0.012 \). The dimensions of the unit cell were \( 602 \times 40 \) \( \mu \)m\(^3\). The copper layer had a thickness of \( 200 \) nm and an electric conductivity of \( \sigma = 5.8 \times 10^7 \) S/m. We retrieved the refractive index of the specific unit cell designs by use of three-dimensional full wave simulations with the software CST Microwave Studio. The numerical calculations showed that the investigated structure supports a refractive index gradient between the minimum and maximum values from 0.08 to 1.65 at a center frequency of 1.3 THz (see Fig. 1(b)). For the determination of the extrema we restricted ourselves to the effective medium regime and took carefully the boundary to the Bragg regime into account since operation of the lens in the Bragg regime would lead to undesired spatial patterning of the focus and thus distort the optical quality of the focusing device. For the lens design we chose a radially symmetric refractive index gradient. For this purpose, we introduced a spatial variation of the refractive index by arraying unit cells of different inner slot radius such that the refractive index gradually decreased from the center of the GRIN lens. This is indicated in the microscope picture in Fig. 1(c) and Fig. 1(d). In more detail, the spatial dependence of the refractive index could be approximated by a parabolic index profile. Such a lens is conceived to focus incoming radiation since it is expected from the refractive index profile that an electromagnetic wave travels faster in the outer annular segments of the lens than in the inner annular segments. In this regard the refraction power correlates with the maximal achieved difference between the phase advance of the wave across the outer border and through the center of the GRIN lens. Thus, a thicker lens should result in a higher refraction power. For this reason, we compared the optical performance of a 1-layer and a 3-layer thick GRIN lens.

We fabricated both the 1- and the 3-layer GRIN lens in a multilayer photolithography process with alternating layers of benzocyclobutene (BCB) and structured copper. The fabrication
Fig. 1. (a) Structural design of the unit cell. The underlying geometry was based on annular slots in a copper plane. (b) Refractive index and transmission of a three-layer metamaterial. The refractive index was changed by varying the inner radius of the annular slot between \( r = 18 \) and 23 \( \mu \text{m} \). This resulted in a total change of the refractive index from 0.08 to 1.65 at a frequency of 1.3 THz. (c) Microscope picture of the 3-layer GRIN lens. The aperture diameter of the lens is 1.5 mm. (d) Refractive index in dependence of the radial distance from the center of the GRIN lens.

The method is described in detail in earlier work [38]. The final metamaterial sample consisted of a free-standing, flexible BCB membrane containing the micro-patterned copper layers. The main uncertainty in the fabrication process were the thicknesses of the BCB spacer layers between the copper planes which had to be estimated from the used process parameters. The resulting lattice constant in the direction of propagation was about 40 \( \mu \text{m} \) with an accuracy of 7 \( \mu \text{m} \). That way we obtained a 1-layer GRIN lens with a thickness of approximately 40 \( \mu \text{m} \) and a 3-layer lens of approximately 120 \( \mu \text{m} \) thickness. The diameter of the lenses was 25 unit cells, which corresponds to 1.5 mm.

3. Measurement

We investigated the GRIN lenses with respect to their optical properties by mapping the spatial distribution of the complex electric THz fields. A schematic of the used experimental setup is shown in Fig. 2. We generated short THz pulses with a duration of 2 ps and a spectral bandwidth from 0.1 to 2.0 THz by focusing ultrashort laser pulses with a duration of 15 fs between the poles of a photoconductive switch. The emitted THz beam was polarized along the x-direction. In order to match the THz beam size to the aperture of the investigated GRIN lenses, we colli-
mated the emitted THz pulses by an off-axis parabolic mirror PM1 and focused the THz beam by a second parabolic mirror PM2 to a spot diameter of about 1 mm at a frequency of 1.3 THz. Hereby and in the following the spot diameter is defined by the full width at half maximum (FWHM) of the intensity distribution. We carefully aligned the GRIN lens with respect to the optical axis of the THz beam and positioned it in the beam waist of the THz radiation. By this method, we ensured that the wave fronts of the incident THz radiation were plane at the entrance facet of the GRIN lens. Uttermost care was advised for the lateral alignment of the GRIN lens since the THz waves would have experienced an asymmetric refractive index gradient if slight lateral shifts of the center point of the GRIN lens had been introduced. Such a misalignment and the resulting asymmetric refractive index profile would cause highly undesirable beam shape distortions.

To determine the beam profile and the spot size of the focused THz beam we measured the spatial distribution of the complex electric field by use of electro-optic sampling in a reflection geometry [39, 40]. This configuration is illustrated in Fig. 2. As an electro-optic material we employed a gallium phosphide (GaP) crystal with a thickness of 400 µm and an aperture size of 20 × 20 mm². The GaP crystal was cut in the (110)-direction and oriented such that the electro-optic effect was only sensitive to the x-polarization of the THz beam. We focused linearly polarized probe pulses to a focal 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 surface of the GaP crystal facing the THz beam was coated by a highly reflective layer for a wavelength of 800 nm while the opposite facet was equipped by an anti-reflection coating for the identical wavelength range. The optical coatings were designed in such a way that they did not affect the propagation properties of the THz beam. Consequently, the THz pulses could penetrate the GaP crystal without significant loss. On the other hand, we herewith ensured that the probe pulses could enter the GaP crystal with strongly reduced loss and were efficiently reflected at the other facet of the crystal where the THz pulses entered. To enhance the sensitivity of the
Fig. 3. (a) 1D intensity profile of the THz beam for different z-positions in propagation direction of the THz wave for the 1-layer GRIN lens. The THz fields were evaluated at a frequency of 1.3 THz. The intensity profiles were obtained by extracting the intensity values along the 1D cross section line of the 2D transversal x-y-intensity profiles along the y-direction as shown in the inset. The z-position was measured relative to the focal plane. (b) Same as (a) for a 3-layer GRIN lens. (c) THz beam diameter $D$ as defined by the full width at half maximum (FWHM) of the intensity profile of the beam normalized to the wavelength $\lambda$ in dependence of the z-position in propagation direction of the THz wave for the 1-layer GRIN lens. For comparison, the theoretical data as obtained from 3D full wave simulations are plotted as solid lines. The assumed error for $D$ is the standard deviation of the width parameter of the gaussian function that was fitted to the experimental data. (d) Same as (c) for a 3-layer GRIN lens.

measurement we analyzed the polarization of the probe pulses by combination of a quarter wave plate, a wollaston prism and a balanced detector. Furthermore, since the optical probe beam was focused to a spot size of 60 µm the spatial resolution of the system was only limited by the spot size of the probe beam. Thus, we could measure the spatial field distribution of the THz beam with subwavelength resolution with respect to the wavelength of the THz radiation.

4. Results and discussion

In order to identify the position of the focal plane and the focus diameter of the 1- and 3-layer GRIN lens we measured the transversal x-y-intensity profile of the THz beam in dependence of the position $z$ along the propagation direction. Examples of the obtained 2D intensity profiles are shown as insets of Figs. 3(a) and 3(b). From the 2D profiles we determined the 1D intensity
distribution of the THz beam along the cross section line in y-direction through the center of the intensity distribution. This is illustrated in Fig. 3(a) for the 1-layer lens and in Fig. 3(b) for the 3-layer lens as measured at a center frequency of 1.3 THz. Thereby, the position $z$ was defined relative to the position of the corresponding focal plane. From the 1D intensity distributions we extracted the spot diameter $D$ in dependence of the $z$-position as illustrated in Fig. 3(c) and Fig. 3(d) for the 1- and 3-layer lens, respectively. For comparison, we also plotted the spot diameter that we obtained from numerical full wave calculations.

As expected, both GRIN lens designs provoked a strong focusing of the THz radiation. By interpolation, we determined the focal plane of the 1-layer lens to be located 1.1 mm behind the exit facet of the lens. From the measurements we determined a focal beam diameter of $D = 320 \mu m$ at 1.3 THz which relates to $D/\lambda = 1.45$ where $\lambda$ is the wavelength of the THz radiation. For the 3-layer lens, the focal plane was located 0.8 mm behind the lens exit surface. We measured a focus diameter of 220 $\mu m$ at 1.3 THz which corresponds to a ratio $D/\lambda = 0.96$. A focus of subwavelength size was expected from numerical calculations for the 3-layer GRIN lens. The stronger focusing capabilities of the 3-layer lens in comparison with the 1-layer lens can be intuitively understood by considering the focus mechanism of a GRIN lens. The longer the propagation length through the GRIN lens is, the more the phase difference between the outer part and the inner part of the propagating wave accumulates. For this reason, we expect a larger curvature of the phase fronts of the beam which implicates a stronger focusing.

The deviation of the experimentally obtained spot sizes from the numerical data can be explained by the sensitivity of the refractive index gradient to the thickness of the dielectric layers of the metamaterial structures. The layer thickness is a parameter that was difficult to control precisely during the fabrication process. Inaccuracies therefore are likely to cause a deviation from the ideal refractive index gradient and to result in a decreasing performance of the lenses.

In addition, we determined the transmissivity of the 3-layer lens with respect to the transmitted power. Assuming a FWHM maximum (intensity) of the incident Gaussian beam of about 1 mm in front of the lens, we calculated from the simulation data that about 36% of the total incident THz power was transmitted through the device. In the experiment, we achieved a value of 20%. The obtained transmission level in the experiment was smaller than the values derived from the simulation data. This was expected since imperfections in the fabrication process inherently reduce the transmissivity of the metamaterial structure.

We also studied the spectral operation bandwidth of the lenses by measuring the diameter $D$ of the THz beam normalized to the wavelength $\lambda$ at the focal plane for different center frequencies (see Fig. 4). For comparison, we plotted the numerically calculated ratio $D/\lambda$ of the considered lenses in dependence of the center frequency. Equivalent to the foregoing discussion, the numerical and experimental results show better quantitative agreement for the 3-layer lens (Fig. 4(b)) than for the 1-layer lens (Fig. 4(a)). The measurements evidence that the GRIN lenses operated in a frequency range from 1.2 to 1.5 THz. Within this range, the ratio $D/\lambda$ varied between 1.45 and 1.75 for the 1-layer lens and between 0.94 and 1.05 for the 3-layer lens. Therefore, we could achieve strong focusing of THz radiation with a 3-layer GRIN lens over almost the complete frequency band for which the lens was designed. Note that the GRIN lenses operated in the Bragg regime for frequencies higher than 1.5 THz (grey shaded region in Fig. 4). Since the beam shape was distorted by scattering in this frequency range the FWHM definition of the beam diameter was not longer valid. As mentioned before, lens operation in the scattering regime is not recommended.

In order to evaluate the appropriateness of the metamaterial GRIN lens, we compared the achieved results with other lens types used for THz imaging systems. In most cases, conventional lenses made of homogenous, low-loss materials with shaped surfaces are commonly used in THz systems because these lenses provide a high transmission and a broad spectral band-
Fig. 4. (a) Experimental and numerical values of $D/\lambda$ as defined by the ratio between the diameter $D$ of the THz beam and the center wavelength $\lambda$ of the THz radiation for the 1-layer GRIN lens. At frequencies higher than 1.5 THz the lens no longer operated in the effective medium regime and the optical behavior was governed by scattering. Operation at frequencies higher than 1.5 THz is therefore not recommended. (b) Same as (a) for the 3-layer lens. As envisioned by the design, the GRIN lens focused incident THz radiation to a focus diameter of approximately one wavelength. Over a frequency band between 1.2 and 1.5 THz the ratio $D/\lambda$ was close to unity.

width. However, in order to achieve a small spot size, a conventional lens must exhibit either a large diameter or a short focal length. The former requires additional optics to expand the THz beam which results in a difficult alignment, a voluminous set-up and introduces additional loss in the system. The latter implies a highly curved lens surface which leads to unwanted spherical aberration. For the proposed GRIN lens, the effect of spherical aberration is a priori not present due to the flat geometry. Therewith, we can achieve a short focal length, and thus a small spot size, even with lenses of small aperture. This allows a convenient integration of the GRIN lens in existing THz systems.

It has to be mentioned that for conventional lenses, the spherical aberration can also be reduced by using an aspherically shaped surface. This was demonstrated in Ref. [33] where a FWHM of 0.68$\lambda$ was demonstrated at 0.7 THz. Such aspheric lenses, however, are generally very sensitive to the angle of incidence, which limits the number of possible applications. In contrast, for the flat metamaterial GRIN lens, the focusing capabilities are maintained even for oblique incidence which was numerically verified in Ref. [32] for an incident angle of 30°.

A general advantage of a metamaterial GRIN device is that the refractive index profile can be accurately designed by simply altering the geometric parameters in each individual unit cell. This allows a large freedom for engineering the optical properties of the GRIN optics and enables the creation of THz components with a well-aimed functionality.

The most important point, however, is that the metamaterial approach allows the realization of tunable, adaptive optics since the effective parameters of the composite can be directly controlled, for example, by an optical or electrical stimulus as already demonstrated by several groups [22, 23, 25, 34–36]. By combining these techniques with the proposed metamaterial GRIN device, this enables the realization of THz optics in which both the temporal and spatial distribution of the refractive index can be dynamically tuned. This inaugurates a variety of novel opportunities for the THz technology including an all-optical THz scanner or adjustable THz lens systems which cannot be achieved by conventional THz components.
5. Summary

In conclusion, we have demonstrated the design, fabrication, and measurement of the optical properties of a 1-layer and a 3-layer GRIN lens and compared the optical performance of both lens types. We showed that a 1-layer GRIN lens already offers strong focusing capabilities and allows one to focus THz radiation to a spot diameter in the order of the wavelength. At a frequency of 1.3 THz we obtained a focus diameter of $D = 320\mu m$. For a 3-layer GRIN lens, we measured a focus diameter of $D = 220\mu m$ at a frequency of 1.3 THz, which corresponds to a ratio between the focus diameter $D$ and the wavelength $\lambda$ of $D/\lambda = 0.96$. Both lens types operated over a comparably large frequency range from 1.2 to 1.5 THz due to the non-resonant design of the metamaterial structure. The strong focusing capabilities of the demonstrated metamaterial-based GRIN lenses in a broad frequency range can be considered as an important step towards the improvement of the spatial resolution of compact, industrial THz imaging systems. The flexibility of such metamaterial devices as to the design of optical components with arbitrary refractive index profiles and the possibility to optically or electrically tune the optical properties further increases their versatility and applicability.

Acknowledgments

J. Neu and B. Krolla contributed equally to this work.