Gradient Index Optics for Terahertz Waves and Confined Surface Waves

J. Neu[1], B. Reinhard[1], T. Fip[1], M. Volk[1,2], O. Paul[1], B. Krolla[1,3], and M. Rahm[1,2]

[1]University of Kaiserslautern, Department of Physics and Research Center OPTIMAS
Erwin-Schroedinger-Strasse, D-67663 Kaiserslautern, Germany
Fax: +49 631 205-5207; email: mrahm@physik.uni-kl.de
[2]Fraunhofer Institute for Physical Measurement Techniques IPM
Heidenhofstrasse 8, D-79110 Freiburg, Germany
[3] Current Address: Deutsches Forschungszentrum fuer Kuenstliche Intelligenz
Trippstadter Strasse 122, D-67663 Kaiserslautern, Germany

Abstract

We present a number of various gradient index (GRIN) devices for the manipulation of freely propagating terahertz (THz) waves and confined, surface plasmon polariton-like THz surface waves on meta-surfaces. We designed, fabricated and experimentally characterized a GRIN lens that allows focusing of THz radiation down to a focus diameter of the order of one wavelength at a center frequency of 1.3 THz. The operation bandwidth of the lens was 300 GHz. We further discuss the design of a GRIN lens and a GRIN-based beam bend for confined surface waves on a meta-surface based on a judicious split ring resonator design. While free-standing GRIN optics promises the seamless integration in compact and budget-priced THz measurement systems, GRIN optics on meta-surface chips may pave the way towards a new class of integrated optical networks for THz technology.

1. Introduction

Terahertz (THz) technology is an emerging field which has recently attracted considerable scientific and technological interest due to its applicability to a number of applications in the realms of non-invasive sensing, security screening as well as quality control of products in the pharmaceutical, chemical, paper, plastics, automotive and aviation industry [1]. Most of these applications require the acquisition of a THz image of the device under test to obtain information about the spatial distribution of e. g. local defects or cavities in three-dimensional objects or at structured surfaces, or to localize explosives behind a dielectric cover. As one drawback, current THz imaging systems are very spacious and high in price while very often being over-designed for the specific application and restricted in spatial resolution to about 3 times the wavelength of the THz radiation which corresponds to about 900 μm at a frequency of 1 THz. In order to arrive at budget-priced THz imaging systems it seems a promising approach to design compact devices that are customized for the specific application field rather than being over-designed and offering an unnecessary spectral bandwidth and versatility. In this context, continuous wave THz sources in combination with compact THz optics seem to be almost ideal components to reach this goal. Another interesting route towards ultra-compact measurement systems for THz sensing is the design of chip-based THz sensors. In this respect, surface plasmon polariton-like confined surface waves on meta-surfaces can be exploited for the implementation of highly integrated optical THz sensing networks. It has been shown that the lateral confinement of THz surface waves and the propagation can be reasonably controlled by perforating the surface of a metal [2, 3]. In a very versatile approach, it is also possible to control the spatial propagation as well as the spectral and temporal properties of confined surface waves on meta-surfaces and metafilms [4, 5]. Before this background, our presentation is twofold. First, we demonstrate that gradient index (GRIN) optical devices can be used for well-aimed

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manipulation of the spatial properties of freely propagating THz waves. In particular, we present the metamaterial design, fabrication and experimental characterization of a GRIN lens for the focusing of THz radiation to a spot diameter of the order of one wavelength at a frequency of 1.3 THz. Furthermore, we discuss a metamaterial-based optical design to deflect THz beams and discuss approaches to actively tune the electromagnetic properties of the metamaterial to obtain adaptive optical components. Second, we discuss GRIN optics for THz surface waves on specifically designed meta-surfaces. We designed a GRIN lens for surface waves and numerically calculated the focusing behavior. Furthermore, we devised meta-surfaces that guide THz surface waves around a bend or a corner.

2. Gradient Index Optics for Free THz Waves

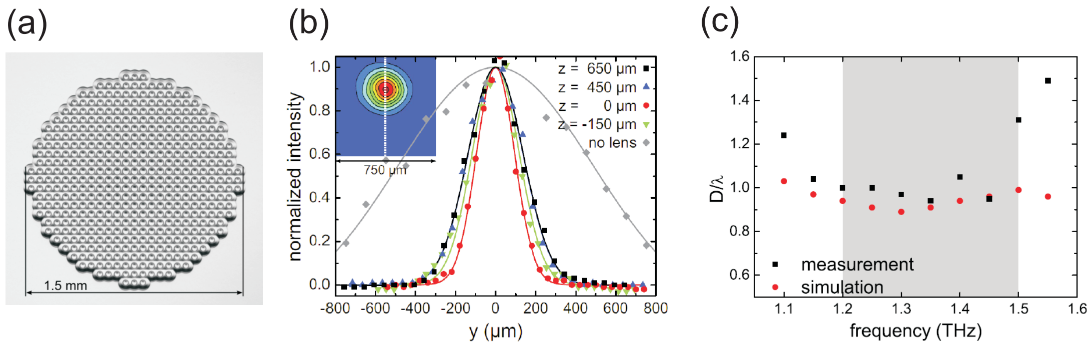

Fig. 1: (a) Microscope picture of the GRIN lens. (b) Intensity distribution of the THz wave along a cross section line through the 2-D intensity distribution of the THz beam (white line in y-direction in the inset) for different distances from the focal plane, (c) Focus diameter in units of the THz wavelength in dependence on the THz frequency. The grey shaded region corresponds to the effective medium regime of the metamaterial and the operation bandwidth of the lens.

We designed and fabricated a metamaterial-based GRIN lens whose unit cells consist of annular ring slits in a copper plane. By variation of the inner radius of the ring slits we changed the refractive index on a unit cell level from $n = 0.08$ to 1.65. A microscope picture of the lens is shown in Fig. 1(a). We implemented a focusing GRIN lens by establishing a radially decreasing refractive index from the center to the outer boundary of the lens. We fabricated the lens as a free-standing optics by embedding the metamaterial structure in a benzocyclobutene (BCB) matrix which is transparent for THz radiation. Figure 1(b) shows the intensity profile of the THz beam for different distances from the focal plane. The intensity was measured along a cross section line through the center of the beam as indicated in the inset of Fig. 1(b). The inset displays an example of a 2-D measurement of the beam profile. Figure 1(c) illustrates the dependence of the focus diameter on the center frequency of the THz radiation. The focus diameter is described in units of the wavelength of the THz wave. Within an operation bandwidth of 300 GHz, the focus diameter is of the order of one wavelength. Since the overall thickness of the GRIN lens was only 120 μm which corresponds to half the wavelength of the THz wave, metamaterial-based GRIN lenses are perfectly suited for integration in compact THz measurement systems. In the presentation, we will present more examples on free-standing GRIN optics for the manipulation of THz waves.

3. Gradient Index Optics for Confined THz Surface Waves

Figure 2(a) shows a meta-surface that is comprised of an inhomogeneous array of split ring resonators (SRRs). The shape and orientation of the SRRs has been varied to obtain an effective refractive index gradient with a maximum in the center of the meta-surface with respect to the y-direction and a minimum

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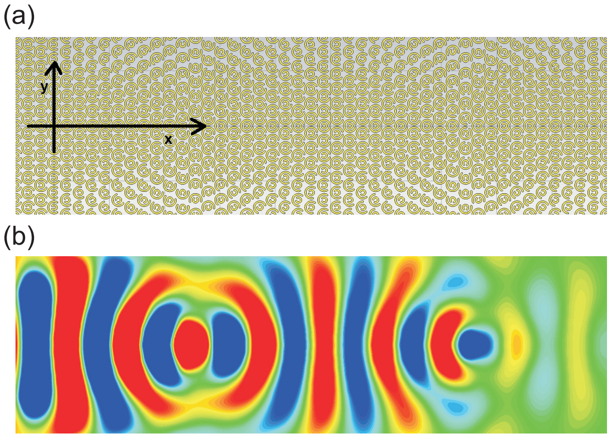

Fig. 2: (a) GRIN lens for THz surface waves. The meta-surface inherits its electromagnetic properties from split ring resonators whose geometry parameters and orientation vary in y-direction from the center to the boundaries.(b) Magnetic field of the surface waves along the normal of the meta-surface. The confined surface wave propagates along the x-direction and is focused twice at two different positions.

at the borders of the surface. Figure 2(b) illustrates the magnetic field of the propagating surface waves. The magnetic field is oriented along the normal of the meta-surface. As can be seen from Fig. 2(b), the surface wave propagates along the x-direction and is focused twice at two different locations along the propagation direction. In the presentation, we will present a variety of further examples of meta-surface designs for the control of the spatial properties of tightly confined THz surface waves.

4. Conclusion

We presented various designs of gradient index optics for the manipulation of the spatial properties of freely propagating terahertz waves. As a an example, we experimentally demonstrated a lens that focusses terahertz radiation to a diameter of the order of one wavelength. Furthermore, we showed that meta-surfaces offer proper means to control the spatial propagation properties of tightly confined terahertz surface waves. While gradient index optics for freely propagating terahertz waves promises the implementation of compact terahertz measurement systems, gradient index meta-surfaces may pave the way towards integrated optical networks for terahertz technology.

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