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INVITED REVIEW

Terahertz Diffractive Optics—Smart Control over Radiation

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Abstract
Over the last 20 years, thin and lightweight optical elements have become very desirable, especially for the terahertz (THz) range. Reduction of the volume of optical elements alongside an increase in their effective efficiency has begun a new direction of research leading to many practical applications. On top of that, diffractive optical elements can not only focus the incident beam, but also can shape the incoming wavefront into a desirable distribution or can redirect the energy. Starting from theoretical calculations of Fourier optics, diffractive elements have been transformed and nowadays form complicated structures that do not resemble a typical Fresnel lens. The precise control over a phase shift introduced by the designed element creates an opportunity to almost freely transform an incident wavefront. Moreover, the vast diversity of computer-generated holograms (also called synthetic) contributes substantially to this topic. Diffractive elements have a great impact on THz optical systems because their manufacturing is very simple in comparison with any other range of radiation (infrared, visible, ultraviolet, etc.). This review paper underlines developments in evolution of diffractive optics and highlights main principles and technological approaches for fabrication of diffraction optics within the terahertz range, thus serving as a guide to design and production considerations.

Keywords 040.2235 Far infrared or terahertz · 050.1970 Diffractive optics · 050.2770 Gratings · 090.1760 Computer holography · 090.1970 Diffractive optics · 090.2890 Holographic optical elements

1 Introduction

More than 50 years ago [1], scientists established that small thickness, low weight, and minimized absorption losses are advantageous features for optical elements. Such

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attributes can be achieved by using a diffractive optics approach, where the design is based not on the geometrical optics, but on the wave optics. Thus, the feature size of the modelled element is of the order of wavelength and therefore the phase shifts introduced by particular zones can be precisely controlled in order to achieve a constructive interference. This is the main advantage of diffractive elements over their refractive counterparts. Here, the phenomenon of diffraction, which sometimes may be troublesome, gives the opportunity to control the light by designing optical elements introducing particular phase shifts of the passing through radiation. Recently, THz beam-forming [2, 3], imaging [4], and communication [5] have started to play fundamental role in the development of THz technology. Thus, a precise and dedicated design of optical elements has been of such a great importance. Moreover, diffractive optics can provide even better performance in comparison to conventional lenses and enable designing elements with F-number (the ratio of focal length of the system to the diameter of its entrance pupil) lower than 1 corresponding to short focal length and large diameter at the same time [6]. The ability to replace volume elements with thin structures has become preferable at first for millimeter and then for THz waves. In many applications, it has been indispensable to minimize the setup assuring a large working area, a precise control over redirecting of the incident energy or shaping the beam.

Terahertz diffractive optical elements (DOEs) can be understood as structures with design governed by wave approach and thus allowing them to be smaller and lighter than corresponding refractive structures. The most popular and known diffractive elements are gratings and diffractive lenses, described in Sections 4 and 5, respectively. However, there are many more structures belonging to DOE family like diffractive lens arrays (Section 6), advanced diffractive elements forming various types of beams (Section 7), dynamically displayed diffractive elements on spatial terahertz modulators (STMs—Section 8), or holograms (Section 9). The last group allows to obtain arbitrary image at a desired plane. Such image can be larger than the hologram area, can consist of different planes and, depending on the design, can be created at different distances. Moreover, the shape of the incident wavefront can be corrected to form the truly desired image. Additional groups of elements that are thin and could be understood as kind of unconventional DOEs are sub-wave structures and metamaterials (Section 10). However, these innovative optical elements require different design methods.

Depending on the definition of the THz band, it can be either the radiation between 100 GHz and 10 THz according to [2, 7] or the radiation from the 300-GHz to 10-THz range [8]. Due to the fact that millimeter and terahertz waves are closely related to each other, the MMWs can be treated as part of the THz range or as the sub-THz band, located just next to it. MMWs are defined as electromagnetic radiation with frequency ranging from 30 to 300 GHz and they are also called extremely high frequencies EHF or Ka, U, and W bands, in radio and microwave frequencies, respectively [7]. Thus, in this article, MMW band is treated as a part of the THz frequencies.

2 Designing DOEs

Each optical beam, a wavefront, is defined by a complex amplitude $u(x, y) = A(x, y)e^{i\phi(x,y)}$ describing light-field distribution that consists of two physical quantities: an amplitude $A(x, y)$ and a phase $\phi(x, y)$. The latter is crucial due to the fact that it describes the direction and character of propagation of the described wavefront. When the propagating beam illuminates particular optical element, its complex amplitude $u_{in}(x, y)$ is modified by the transmittance of this element $t(x, y)$ giving the output distribution u_{out} equal to $u_{in}(x, y)t(x, y)$. In case of diffractive elements, their transmittance is determined by appropriate coding of the desired phase distribution that should be introduced by this element. Such phase delay map and type of coding result in amplitude and/or phase distributions introduced by our element. There are three parameters that determine the shape and thickness of the element: the phase distribution, the refractive index of the medium, and the design wavelength (DWL). Different methods of coding phase distribution determine the type and the efficiency of diffractive elements [9]—presented in Table 1. Each of the structures described in Table 1 has different maximal diffraction efficiency which is defined by the amplitude coefficient of the expansion of the transmittance of the grating into Fourier series [9].

Diffractive optical elements are strictly related to the design wavelength (DWL), thus making them narrowband. The phase retardation is matched due to the proper structure thickness for the particular wavelength and the refractive index of the material, introducing very large chromatic aberration. However, such a drawback can be suppressed by designing a kinoform structure of higher order [10, 11]. Kinoform of first order introduces 2π phase shift while kinoform of higher order results in a maximal phase shift of $2p\pi$, where p is the order of a kinoform—being the natural number larger than 1. Normally, all wavelengths longer than DWL encounter too small phase retardation resulting in drastically decreased diffraction efficiency for these wavelengths, which means that such structures do not work for these wavelengths. However, in case of a high order kinoform, the DWL is related to a p times

Table 1 Diffraction efficiency in relation to phase coding method for DOEs

Method of coding phase	Diffraction efficiency η_m	Diffraction efficiency in 1st order
Amplitude binary ($a = 0.5$)[a]	$\frac{sin^2(\frac{\pi m}{2})}{(\pi m)^2}$	10.1%
Amplitude with different opening ratios a	$\frac{sin^2(\frac{\pi a m}{2})}{(\pi a m)^2}$	Up to 10.1% for a=0.5
Binary phase (2-level)	$\frac{sin^2(\frac{\pi m}{2})}{(\pi m)^2}[1-(-1)^m]^2$	40.4%
Multi-level phase (N = 4, 8, 16...)	$sinc^2\left(\frac{m}{N}\right)$	Up to 100%
$N = 4$		81%
$N = 8$		95%
$N = 16$		99%
Kinoform—with continuous phase profile	$sinc^2(1-m)$	100%
Kinoform of higher order	$sinc^2(p-m)$	100%

[a]Opening, also called fill factor, for binary amplitude grating is equal to $a = 0.5$

larger phase shift; thus, all p times higher harmonics are also perfectly matched—resulting in broadband working. High-order kinoform (HOK) structures are very effective assuming that a typical detector size is of the order of wavelength or larger. Even in case of small detectors, they predominantly require larger antenna; thus, in both situations, the whole focal spot is detected.

3 First Steps in THz Diffractive Optics

The year 1961 was significant for THz diffractive optics—a big scientific breakthrough came when F. L. Wentworth, J. C. Wiltse, and F. Sobel developed the first diffractive element for sub-THz waves and published their results [1]. They described and manufactured Fresnel zone plates—half-period and quarter-period (that corresponds to 2- and 4-level phase structure, respectively). Then, in the 1960s, next two works describing zone plates were reported: in 1962 by M. Cohn, F. Wentworth, F. Sobel, and J. Wiltse [12] and in 1967 by G. Weibel and H. Dressel [13]. Further development took place in the 1980s, according to [14], when next research articles concerning THz diffractive optical elements (DOEs) were published in 1982 by M. Lazarus, F. Pantoja, S. Novak, and M. Somekh [15], 1983 by J. Thornton and J. Strozyk [16], 1985 by J. Wiltse [17], 1987 D. Black and J. Wiltse [18], and 1988 by B. Huder and W. Menzel [19]. These articles describe structures like Fresnel zone plates assuming the use of different phase coding methods for both reflection and transmission configurations.

First, THz diffractive elements, for frequencies higher than 0.3 THz, were reported and experimentally verified not until 2002: Fresnel zone plate lens [20], multilevel Fresnel diffractive lens [21], and THz hologram [22]. The first measurement of the diffraction grating in the time domain spectroscopy (TDS) configuration was carried out in 2005 [23]. Without a doubt, the twenty-first century has become the time of greatest and fastest developments in terahertz technique accompanied with an impressive growth in optics, especially a large group of diffractive elements.

4 Diffraction Gratings

The first analyzed and the most representative group of diffractive elements are gratings. They play important roles in diffractive optics, because they can be used in spectrometers, monochromators, beam redirectors, and many other optical devices. Gratings enable measuring the diffraction efficiency of elements coded by different methods (described in Table 1). According to Fourier optics, the type of phase coding of the grating specifies the amount of the energy redirected into each order of diffraction in relation to all incident energy [9] and has already been discussed in [24]. In case of DOEs' design, choosing a phase coding method is crucial not only for diffraction efficiency but also for complicity and price of the element. For further considerations, it should be underlined that simple binary diffractive lens gives information about the amount of radiation focused not only at a designed distance, but also at other shorter distances [25]. Moreover, some radiation remains unchanged and some is diverged. All the radiation that is not focused at the desired distance forms unwanted noise; thus, it is crucial to ensure the highest possible diffraction efficiency of the designed structure.

The simplest grating is a binary amplitude structure that blocks part of the incoming radiation, and thus achieves maximally only 10.1% of diffraction efficiency. This value decreases when a fill factor of the grating is different than 50%. Mostly, such gratings are reported as metallic structures, very simple in manufacturing and theoretical description; thus, the focus is rather put on additional effects, like anomalous transmission of such gratings [26, 27], controlling the surface beam profile in case of circular concentric grating [28], laser beam shaping to collimate diverging radiation [3], creating vortex beams [29], arising surface plasmons, polaritons [30, 31], or prism-like behavior of metal grating with varying periods [32]. A beam can also be deflected by metamaterial structures [33].

Due to the fact that there are many transmissive materials for the THz radiation, additionally having a "reasonable" refractive index value (not very close to 1), not many amplitude structures have been created so far. Phase gratings have much larger diffraction efficiency. An example of binary one-dimensional Ronchi grating is shown in Fig. 1a. It can be clearly noticed that for DWL (0.667 THz), the far field intensity distribution corresponds to the one from ideal binary phase grating—no 0th order and equal ±1st order. As the frequency, and hence the wavelength, changes, the height of the structure starts to introduce phase delay different than π, the efficiency in ±1st order starts to decrease, and 0th order appears (Fig. 1b). Here, it becomes clear that a proper phase shift must be assured to obtain the maximal possible diffraction efficiency, and in this case, the attenuation of the material is not taken into account. Obviously, all these considerations can be expanded to 2D gratings [35]. Factors that influence efficiency are a step height defining the introduced phase shift and the fact that grating does not have infinitesimally small thickness as it is mostly assumed [36]. In case of kinoform (blazed) gratings [37], the presence of 0th order of diffraction (and all other despite 1st) is the evidence of not perfectly matched parameters of the grating.

Blazed gratings have much larger possibilities especially that for the THz range, they are relatively easy to manufacture both in transmission [40] and in reflection modes [41]. Despite all advantages of kinoform gratings, there are also some drawbacks that should be taken into account while manufacturing like an angle-dependent fill factor [38] (Fig. 2a) and a shadow effect [39] (Fig. 2b), which lowers efficiency.

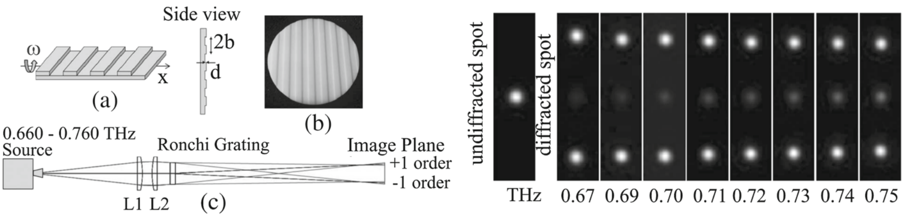

Fig. 1 **a** Grating design. **b** Photograph. **c** Optical far-field configuration. (right) Measured THz spots showing the frequency-dependent evolution of the −1, 0, and +1 diffracted orders. Reproduced from [34]

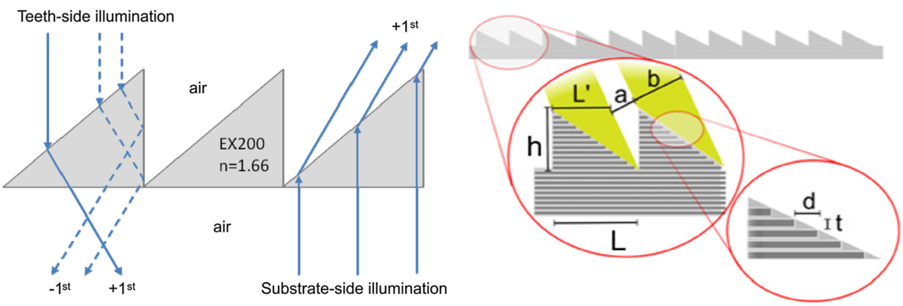

Fig. 2 Explanation of shadow effect based on geometrical optics, considering illumination from both sides (left) and at some angle (right). Dashed rays are misdirected into -1st order by the shadow effect. (right) ©2016 IEEE. Reprinted, with permission, from Busch et al. [38]. (left) Reproduced from Suszek et al. [39]

Basically, all optical elements are dependent on the angle of incidence and many of them are designed only for close to on-axis functioning. On the one hand, changing an illumination angle results in a change of the effective period of illuminated grating, but, on the other hand, it also results in additional internal reflections, which redirects the radiation in the wrong way. The impact of these effects changes with varying angles—the angle indicating the relief of the grating and the incidence angle—but can be suppressed by designing double-sided structures (thus, the relief becomes two times smaller) or illuminating the structure from the flat side of the substrate [42]. A shadow effect is also very dependent on the relief height which is related in the particular case to the refractive index of material. Thus, increasing the refractive index decreases the shadow effect due to the smaller step height. However, in such a case, the reflection from the surface (Fresnel losses) is larger.

In the THz range of radiation diffraction, gratings are also used as beam splitters [43, 44]. They have been applied to couple the light into a waveguide with the silicone grating engraved at its top [23]. Even an electrically controlled grating device with a nematic liquid crystal (NLC) has been reported [44].

5 Fresnel Zone Plates and Diffractive Lenses

Due to the nonconsistent naming of different types of lenses in the literature, this section gives some definitions for simplicity. There is no doubt what refractive lens is (called also simple lens or volume lens) (Fig. 3a). Then, a thinner lens consisting of multiple parts (used for the visible light in lighthouses from 18th century) is called a Fresnel lens (Fig. 3b). These two types of lenses are designed using geometrical optics and the size of each “zone” has thousands of wavelengths. A totally different design process is carried out in case of diffractive optics—based on wave design where structure details are of the order of magnitude of the design wavelength. Here, structures designed using different methods of coding of phase delay map can be distinguished creating amplitude or phase elements. Amplitude structures (Fig. 3c) block part of the radiation and have lowest diffraction efficiency. However, phase

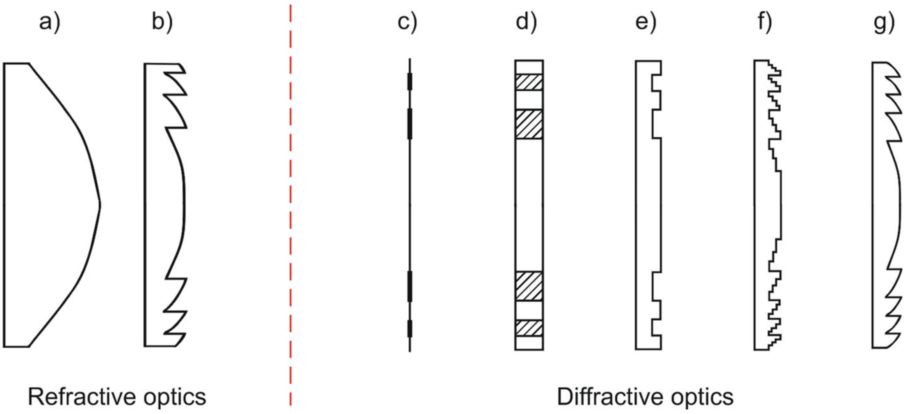

Fig. 3 Refractive (**a**, **b**) and diffractive (**c**–**g**) lenses. **a** Bulk lens. **b** Fresnel lens (not used in the THz range of radiation). **c** Fresnel zone plate—amplitude binary. **d** Planar dielectric zone plate—structure created from two materials with different refractive indices that corresponds to phase binary grating. **e** Binary phase—phase-reversing zone plate. **f** Multi-level zone plate. **g** Kinoform (Fresnel diffractive lens). Defined in Table 1. Adapted on the basis of [45]

structures can have different profiles—binary, multi-level, or kinoform—illustrated in Fig. 3d–g and defined in Table 1. Binary phase elements can consist of either two materials of the same thickness or one material having different thicknesses, thus introducing two different phase shifts. The difference between using refractive and diffractive lens is illustrated in Fig. 4—the performance is similar, but the volume of the material and the thickness are incomparable.

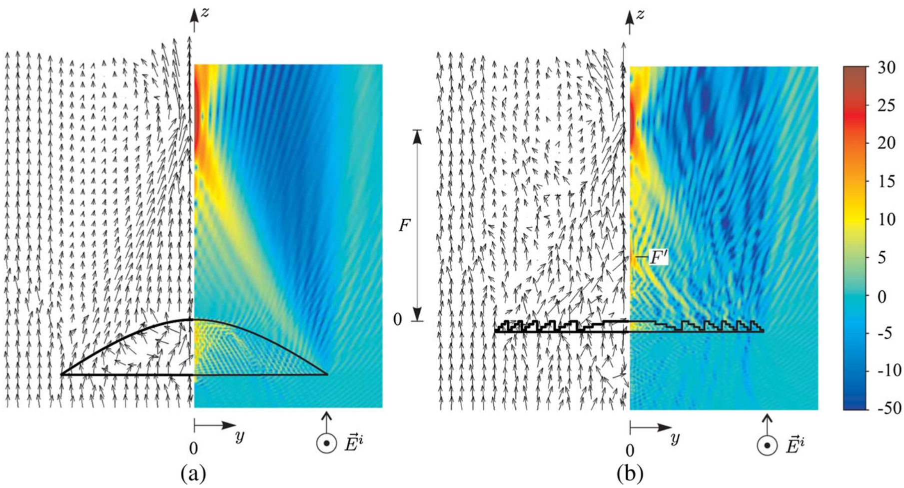

Fig. 4 Magnitude and direction of the time average of the Poynting vector—comparison of hyperbolic lens (**a**) with phase correcting zone plate (**b**), having the same focal lengths and diameters. © 2007 IEEE. Reprinted, with permission, from Reid et al. [46]

Due to extensive applications, thin lens-like structures have been designed and manufactured by many groups for almost 60 years. The first research concerning THz and sub-THz diffractive optics was related to James C. Wiltse—the research team carried out numerous investigations of Fresnel zone plates (FZPs) [1, 14, 17, 18, 45, 47–50]. This research analyzed the shape of FZPs and invented tilted cuts of each groove—so called stepped conical zone plate. Efficiency and operating angles were also discussed. Additionally, feed considerations, losses, far-field patterns, multiple-frequency operation, and many more were analyzed. A thorough description of Fresnel zone plate antennas (FZPA) in different configurations was given by groups of Matti H. A. J. Herben and Hristo D. Hristov—[51–57]. Their work on FZPAs was supplemented by Paul F. Goldsmith [58] and Glenn S. Smith groups [46, 59] and [60]. At some point, a need to develop technology for efficient manufacturing of FZPs arose, and thus David R. S. Cumming and Edward D. Walsby groups contributed with [20, 21, 61–64], together with group of Boris A. Knyazev [65–69]. The manufacturing of multi-step lenses is a demanding task and in many cases requires etching or laser ablation processes as shown in Fig. 5. The last group continued research in applying the diffractive optics for imaging purposes with free electron laser illumination [70] and [71]. The group of Gintaras Valušis described manufacturing of lenses by laser patterning of silicon [72], next used for imaging [73], or used laser ablation to integrate FZP on-chip of detector [74]. They also proposed a manufacturing technique using cross-shaped apertures (being a resonant filter) [75–78] to select the THz frequencies (Fig. 6) and here, a thin structure with focal length smaller than the lens diameter was designed which unequivocally determined dominance of DOEs over their refractive counterparts in such applications. Using smaller THz frequencies (in the range of 0.3 THz) opened a new possibility for optics because a feature size could be larger and thus also other materials could be used [79, 80].

Other papers state that the distribution corresponding to Fresnel zone plate can be obtained by illuminating the silicon wafer by either imaging on it a mask [81] or using a DLP projector [82, 83]. The latter method allows for displaying dynamically reconfigurable distribution in the FZP plane.

FZPs can also be used in a more eccentric manner—THz FZP (copper plate) as tunable THz filter [84] or IR FZP can act as THz antenna [85].

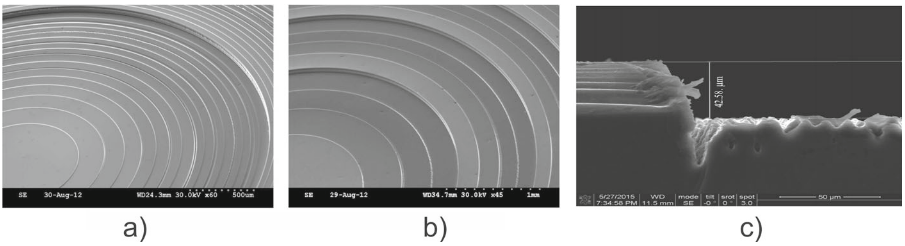

Fig. 5 SEM images tilted at 60 deg of **a** 16-level and **b** 4-level lenses and **c** cleaved lens fragment. © 2013 IEEE. Reprinted, with permission, from Saha et al. [64]. Reproduced from Komlenok et al. [68]

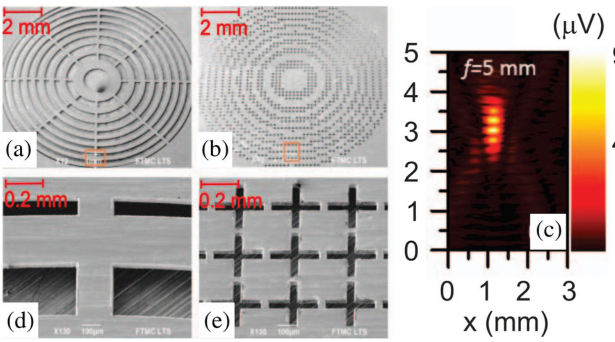

Fig. 6 The SEM images of the diffractive optical components with the focal length of 5 mm and the diameter of 16.5 mm. **a** The Fresnel zone plate and b the terahertz zone plate (TZP) both processed on metal film. **d**, **e** correspond to magnified regions marked in a and **b** with red rectangles. Images of the THz beam focused with the conventional zone plate (**c**) and the TZP (**f**). Pixel size 25×25 μm^2. © 2015 IEEE. Reprinted, with permission, from Minkevičius et al. [77]

6 Lens Arrays

Generally, lenses have two main properties—focusing the radiation and ability to form images. Indeed, these features become crucial in case of coupling the light into a detector to increase the amount of incident radiation or to perform light-field (plenoptic) imaging. Efficient functioning of the matrix of lenses was theoretically discussed in [86] by comparing a seven-step diffractive small lens array with an extended hemispherical lens. Described refractive and diffractive approaches had similar efficiency, but the latter counterpart should have had the limited working bandwidth. A diffractive design was used to focus the radiation on the matrix of detectors in [87] and [88] to improve the coupling efficiency and decrease the optical cross-talk. Lens arrays can be also designed as metasurface flat lens array [89].

7 Advanced Diffractive Optical Elements

The burst of diffractive optical elements having a different design idea than typical grating or Fresnel diffractive lens for the THz radiation started in 2010; however, first THz theoretical works go back to early the 2000s [90] and [91]. Obviously, the first sub-THz optical element was reported even earlier—in the 1990s and was able to generate Laguerre-Gaussian modes using a spiral phase plate [92]. Therefore, the design of more advanced optical elements to match a particular application has become very interesting and will be discussed in this section.

More advanced structures can be formed on the basis of a simple Fresnel diffractive lens that can serve as a part of a more complicated system. Such an element can focus and bend the radiation to be outside its geometrical shadow [93]. Thus, a peripheral area of the distribution corresponding to the lens is used as an optical element, designed using an off-axis approach.

To obtain better performance of focusing, the typical design of the Fresnel zone plate can be substituted by fractal and Fibonacci lens–like structures [94]. The Fibonacci structure has been used for bifocal imaging which enables obtaining better resolution [95]. Additionally, DOEs can focus the incident wavefront into different shapes of focal curves [96, 97]—like segments shorter and longer than the size of the structure, rings, lines, and matrix of points [98, 99]. Designing process can contain correction of incident wavefront influence, which mostly is not a plane wave. Then, it is necessary to determine parameters of illuminating beam consistent with experimental conditions. Knowing them, during simulation, the performance of the designed structure can be verified, assuming real illumination conditions, and can be corrected according to needs [24]. Sometimes, it is even necessary to introduce a correcting layer helping to obtain larger diffraction efficiency due to suppressing the influence of the material thickness even by a thin DOE [100].

Another type of diffractive structures of a particular interest constitutes elements that generate focal distribution extended along optical axis, also called elements with increased depth of focus. In the same group, we can consider elements that form non-diffractive vortex beams. Such DOE performance can be obtained using different approaches, for example, by using two diffractive structures—one resembling a "drop" and second like a typical lens (Fig. 7c). Such two structures are able to create

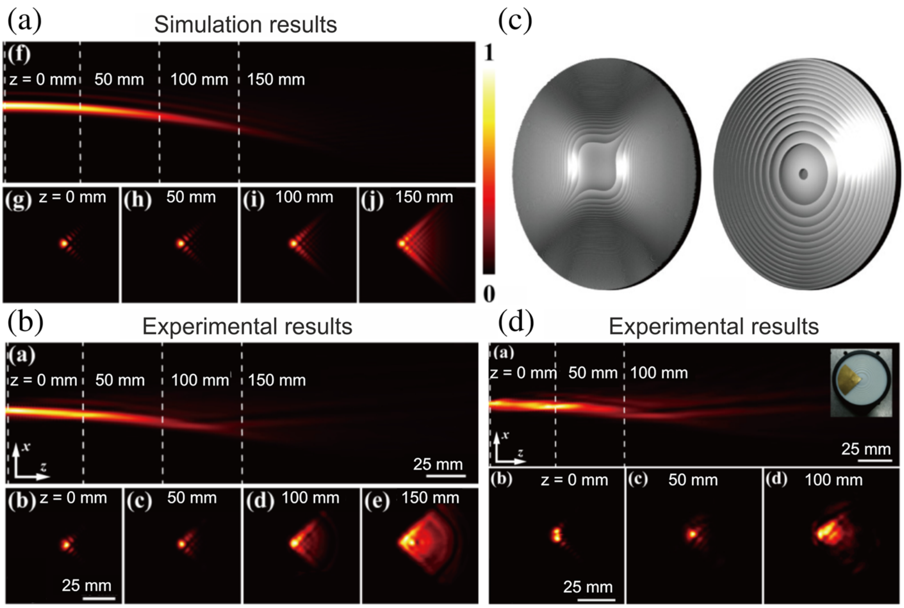

Fig. 7 Simulation (**a**) and experimental (**b**) results of the finite-energy accelerating THz airy beam. The upper row indicates the *xz*-normalized intensity profiles of the airy beam. The lower row indicates the *xy*-normalized intensity profiles of the experimentally generated airy beam measured at the dash line positions of the upper image. **c** Profiles of two elements creating airy beam. Additionally, experimental results of airy beam creation for "damaged" lens are shown (**d**). Reproduced from [101]

airy beam with diffraction-free distance reported to be equal to 100 mm [101]. Moreover, if a part of the diffractive element has been covered by metal foil, a very similar diffractive pattern has been observed, and thus the authors report "healing" property of such distribution (Fig. 7d).

However, typically, a non-diffractive Bessel beam is generated by the use of axicon-like structures [102] or plate with spiral phase distribution [103]. An axicon is an element having the shape of a cone that focuses the radiation into a line segment along optical axis. Instead of a bulk structure, a diffractive alternative can be used [104] assuring the same intensity and shape of the transformed wavefront (Fig. 8). The comparison of Bessel beam generation by an axicon, a helical axicon and a spiral phase plate [105, 106], gives the alternative to use thinner structures to obtain vortex beams. Spiral binary structures manufactured in silicone [103, 107] can be sucessfully used to form non-diffractive Bessel beams. Also, more complicated configurations were used as a spiral phase plate with two 3D-printed DOEs correcting structures [108], a complementary V-shaped antenna structure [109], being a kind of metamaterial, or using photo-generated carriers displaying a computer-generated hologram forming a THz vortex beam [29]. Complex patterns can be displayed by spatial terahertz modulators (STMs) described in Section 8. It is a convenient way to form airy [110] or vortex beams [111].

Also, a spiral-like shape is used to create a gradient index lens (GRIN lens) focusing the radiation into a diffraction-limited spot [112]. The effective refractive index is introduced by changing spacing between following polystyrene and air slabs and acts like a lens despite its polarization.

Normally, diffractive optical elements have huge chromatic aberrations which can be partially suppressed by the use of different methods of coding phase—called the high-order kinoform, described in Section 2. Introducing a particular phase shift in a DOE is strongly dependent on the wavelength; thus, design wavelength (DWL) is a crucial parameter. The possibility of using DWL and its higher harmonics to eliminate chromatic aberration was discussed in [10] and [11].

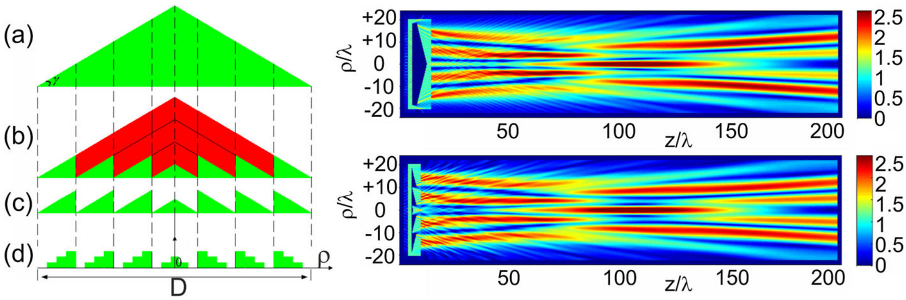

Fig. 8 (left) The design process of a diffractive axicon. **a** A bulk axicon. **b** An axicon with removed unwanted material (red part). **c** An equivalent kinoform axicon. **d** An equivalent 4-level phase axicon. (right) Electric-field amplitude patterns plotted in a pseudo-color representation: (upper) for the bulk axicon, (lower) for designed axicon (**d**). Reproduced from [104]

8 Spatial Terahertz Modulators (STMs—THz SLMs)

This section is devoted to a dynamic displaying of the desired light-field distribution corresponding to the functioning of spatial light modulator for the visible light. Devices forming amplitude or phase distributions at the particular plane have been given for the THz frequencies. In this plane, a semiconductor Si wafer is mounted and on its surface, a pattern of photo-generated carriers is created by illumination with control beam [111, 113]. The density of these carriers determines the transmission of THz beam. The pattern on the wafer has been displayed using conventional SLM, due to the fact that 800-nm-fs laser has been used. Additionally, graphene-based STMs have been reported [114, 115]. STMs can be also designed with C-shaped metasurface [110]. Using active terahertz metamaterial also enables designing a modulator of THz waves controlled by external voltage [116].

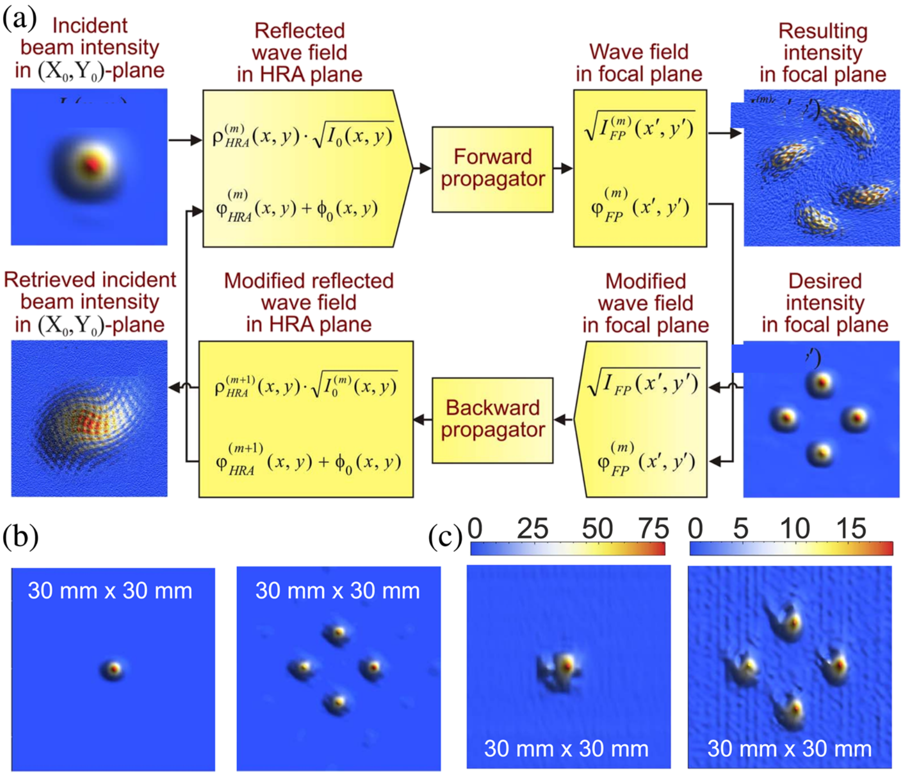

Fig. 9 **a** The work-flow of the Gerchberg-Saxton iterative algorithm for retrieving surface distribution. **b**, **c** Focusing performance of the holographic metasurface. Theoretical (**b**) and experimentally measured (**c**) intensity distributions in the focal plane at the frequency of 0.35 THz forming one and four focal spots, respectively. Reproduced from [117] under Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/)—Fig. 2 from original article has shortened caption, parts of Fig. 6 are used with rephrased caption

9 THz Holograms

Computer-generated holograms (CGHs), also called synthetic, are a kind of very advanced DOEs. Mostly, the design of CGH requires using some additional methods increasing their efficiency—like the Gerchberg-Saxton algorithm [118]— (Fig. 9), which is also the case in described examples. In each step of iterating phase distribution, the algorithm forces desired amplitude distribution in the hologram plane and in the image plane. After the first iteration, the obtained image is not satisfactory, but after repeating this process few times, the quality of the reconstructed image increases significantly. Moreover, due to computer design, an arbitrary image can be created.

CGHs have been used to generate vector beams and enabled dynamic regulation of displayed distribution [29]. Synthetic holograms can be used as competitive modelling of Bessel and vortex beams in the THz region [22]. The conventional design method is described in Section 7. Terahertz holograms have been also used to generate a matrix of spots using the Gerchberg-Saxton algorithm [63, 117]. Such an element corresponds to the performance of the Dammann grating realizing fan-out pattern [98] and may become very useful for MIMO (multiple-input and multiple-output) technology.

Available manufacturing methods for the THz radiation open up many possibilities to construct dedicated phase plates like synthetic holograms able to create

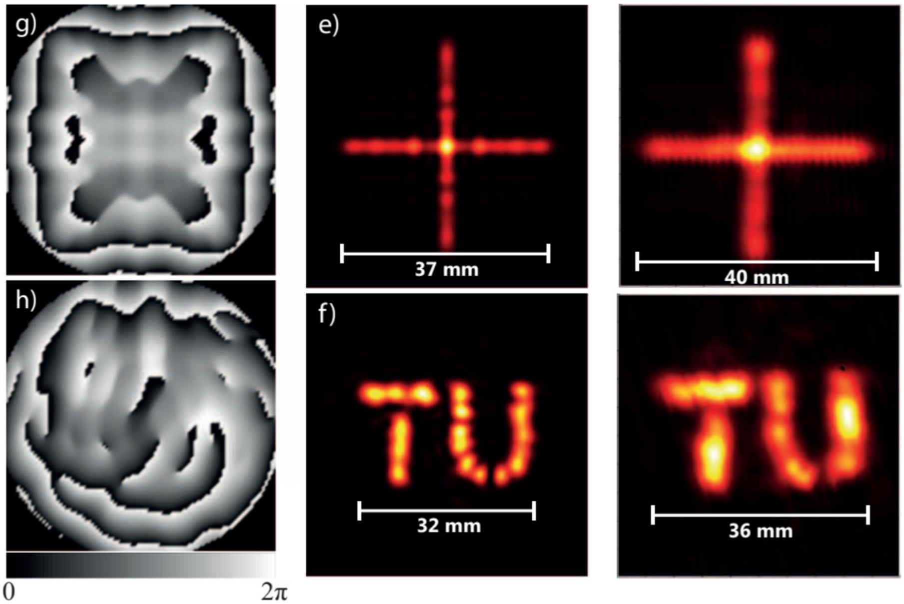

Fig. 10 Calculated phase modulation profiles (left). Calculated intensity distributions (middle) after the last iteration step of the GS algorithm. Experimental intensity distributions (right) of the optical field produced by an incident THz beam that was phase modulated by the two printed elements. Reproduced from: Gospodaric, J., Kuzmenko, A., Pimenov, A., Huber, C., Suess, D., Rotter, S., Pimenov, A.: 3d-printed phase waveplates for THz beam shaping. Applied Physics Letters 112(22), 221104 (2018), https://doi.org/10.1063/1.5027179,gospodaric20183d, with the permission of AIP Publishing and author

almost any desired distribution at a particular plane behind the hologram [119]. Two holograms—one generating “TU” letters and second a cross—are illustrated in Fig. 10.

10 Sub-wavelength Structures and Metamaterials

In this review article, different diffractive optical elements are discussed. These thin and lightweight components are subject to the phenomenon of diffraction. Planar structures may also be obtained by using subwave design or metamaterial structures. Mostly, they can be modelled using the effective grating theory, finite-difference time-domain (FDTD) method, effective medium approximation, or amplitude and phase retrieval algorithms. Here, they are mentioned to introduce the possibility of obtaining flat elements resembling DOEs rather than bulky refractive optics.

Even a simple metallic grid has been reported to introduce an effective refractive index profile and act as a subwave structure [32], which has also been considered in case of surface waves [120]. Sub-wavelength metal slits with additional depth-modulated grooves can redirect the energy along some angle (forming directional beams) [121]. Off-axis regime with effective grating theory enabled sub-wavelength design of a diffractive lens based on a resonance domain grating theory [122]. During designing subwave structures, principles of photonic crystal devices can be applied to create a lens [123]; however, no experimental verification has been carried out. Moreover, thin metal subwave gratings can work as polarizers [124] or triangular surface-relief sub-wavelength gratings can decrease the reflection forming AR (anti-reflection) coating [125–127]. In these cases, the feature of the designed element

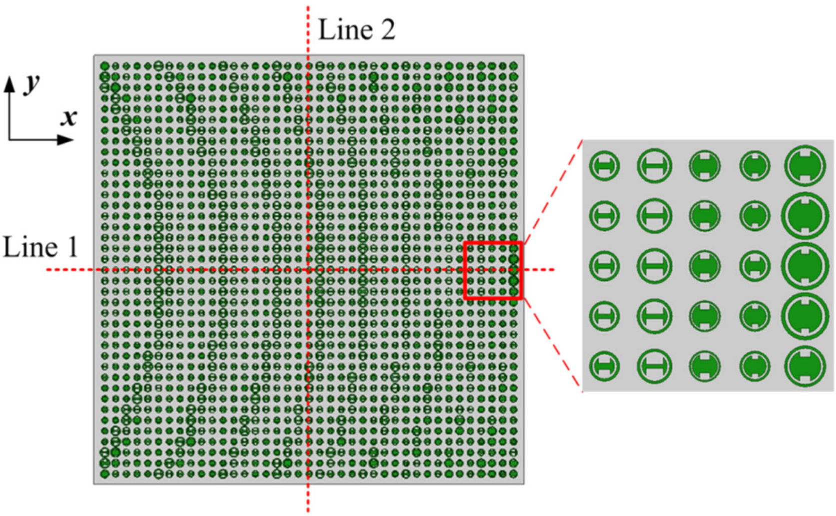

Fig. 11 Element arrangement of the THz transmitting and reflective metasurface. Reproduced from [136] under Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/)—part a of the whole original figure

is smaller or similar to the wavelength; thus, some effective refractive index profile is introduced, while the metamaterial structures generate abrupt phase changes [33, 128]. The subwave design has also been used to create hybrid lenses to increase their performance and reduce their volume [129, 130].

Already-described hologram structures generated by morphing patches to split-ring resonator elements [117] have enabled creating a 2×2 matrix of points from one source beam (Fig. 9). The C-shaped metamaterial design allows to obtain the rectangular FZP profile, wave-deflecting structure [33] and flat lens array [89], to create 1 to 4 (multifocus) beams (with the result corresponding to Dammann structure) [131] and to create the spatial terahertz modulator (STM) which displayed four-focus lens [110]. Another type of V-shaped metamaterials has been reported to form vortex beams [109], planar lenses [132], and thin lenses with long focal depth [128]. Flat lenses have been also designed with the use of square-like metamaterial [133] or tri-layer metasurface [134, 135]. The metamaterial structure (circular shape meta-structure with H-shaped elements) is used for phase compensation, thus can be treated still as diffractive [136](Fig. 11). Metasurface with circular slits can form vector beam creating vortex [137].

11 Conclusions

Bearing in mind that the last 20 years has brought tremendous evolution in the field of THz diffractive optics, it should be emphasized that designing thin and lightweight THz optics is still one of the most crucial goals to complement growing research achievements concerning efficient THz emitters and detectors also working in room temperatures. Some of the possible development paths are presented in the form concluding remarks.

Diffractive optical elements for the THz range of radiation are unique in a way that their manufacturing is much more accessible and simple in comparison to any other part of radiation. Nowadays, techniques of 3D printing, cutting, milling, ablating, or etching easily allow to create such elements with appropriate resolution and transmittance; thus, many advanced shapes and ideas may be executed. The easiness in manufacturing diffractive optical elements for this range of radiation also may open a new way in designing “flat” diffractive elements on not-flat surfaces, thus combining refractive and diffractive optics in an easy way.

Using new materials gives also the opportunity to focus effectively the radiation on detectors—using single lenses or arrays, which opens up the door to efficient detection.

It should be underlined that using kinoform structures of higher order diffractive elements can be designed not only for narrowband but also for broadband functioning, at the same time suppressing chromatic and geometric aberrations. Using an iterative optimized design to redistribute or shape the incoming radiation in a desired way is a very promising direction. Here, it should be also emphasized that diffractive optics gives the possibility to obtain the desired distribution larger than the size of a diffractive element in a relatively easy way, which allows for the miniaturization of the system maintaining large active area. Moreover, in case of focusing elements, such a design allows to obtain values of F-number below 1.

Taking into account all possible applications of THz waves [138], it becomes more and more crucial to fully control the beam and to be able to display different shapes at particular distances. Assuming practical utilization of the THz radiation, it should be obvious to incorporate THz diffractive optics in such fields as non-destructive industrial testing [139–141], security [142–144], and automotive industry [145–147]. Moreover, the diffractive wave approach could be expanded with the help of subwave structures or metamaterials, which seems to be future continuation of basic optical designing.

In all considerations described in this article, the polarization has not been discussed due to the fact that in dielectric materials, it has relatively insignificant influence, but in case of metal structures, meshes, or metamaterials, it is a subject for further considerations.

THz diffractive elements open up a new way of designing optical setups for the THz range—they enable creating dedicated solutions to meet the requirements of radiation, joining the world of optics and electronics.

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