# Asymmetric transmission of radially polarized THz radiation through a double circular grating

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**Abstract:** We report on unidirectional and asymmetric transmission of radially polarized THz radiation through a dual circular metallic grating with sub-wavelength slits. Unidirectional transmission is shown theoretically for a super-Gaussian incident beam, and an asymmetric transmission is demonstrated experimentally, when the radially polarized beam of 0.1 THz is obtained by converting a linearly polarized beam with a discontinuous phase retarder and a tapered waveguide. The dual grating does not include nonlinear materials, its operation is reciprocal, and analogous to that of some planar metallic gratings.



**OCIS codes:** (050.1950) Diffraction gratings; (050.6624) Subwavelength structures.

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## 1. Introduction

Photonic components with an asymmetric transmission are the subject of extensive research. Systems in which Lorentz reciprocity theorem does not apply may be characterized by an asymmetric transmission. Lorentz reciprocity is not preserved in Faraday isolators, in magneto-optical devices such as interferometers containing waveguides in which the propagation constant depends on the propagation direction [1] as well as in optical diodes based on nonlinear chirped photonic crystals [2, 3]. On the other hand, asymmetric transmission in reciprocal systems has been recently analyzed in a variety of photonic and plasmonic elements such as grating with a slit [4], gratings with plasmonic insets [5], plasmonic crystals with out-of-plane scattering [6], or metamaterials with a hyperbolic dispersion [7].

Transmission through a thin metallic grating which period varies with depth can be asymmetric or even unidirectional [8]. Such stacked double or multiple gratings may consist of optically linear, isotropic and nonmagnetic materials [9, 10]. Therefore, electromagnetic reciprocity is preserved by these gratings [11] and if diffractive orders in transmission and reflection were considered as input/output channels, a corresponding scattering matrix would have a symmetrical form [12]. In fact, the term *asymmetric* in this context refers only to the difference in transmission of electromagnetic radiation incident from two opposite sides of the grating, which is not the same as a true optical isolation such as can be obtained using the magneto-optical nonlinearity or time-dependent permittivity.

A dual grating consisting of two parallel gratings [9, 13, 11], with the pitches $\Lambda_1$, and $\Lambda_2 = \Lambda_1/2$, such that $\Lambda_2 < \lambda$, and $\Lambda_1 > \lambda$, where $\lambda$ denotes the free-space wavelength, supports at most three non-evanescent diffraction orders $m = -1, 0, +1$. The geometry of the grating may be tuned to suppress the transmission in the zeroth order in both directions, while the transmission into the $\pm 1$ orders for normal incidence (i.e. from the zeroth order) is asymmetric, and possibly even blocked in one of directions.

These gratings had a planar geometry and operated for the transverse magnetic (TM) polarization. In the present paper we demonstrate an analogous diffractive element having cylindrical symmetry and operating for the radial polarization [14, 15]. Radially polarized THz radiation can be coupled to metal wires [16, 17, 18] and therefore the development of THz photonic components operating for radial polarization is particularly interesting. As far as we know, an asymmetric grating for radial polarization has not been demonstrated before.

## 2. Asymmetric transmission of radially polarized THz radiation

A radially polarized beam propagating in the direction $z$ in a set-up having a cylindrical symmetry contains field components $E_r(r,z)$, $H_\phi(r,z)$ and $E_z(r,z)$ and is rotationally symmetric. A vectorial Bessel beam with $E_z(r,z) = J_0(p \cdot r) \cdot exp(i\beta z)$ is an example of a non-diffracting radially polarized beam in the free space. The propagation constant $\beta$ and the radial wavenumber $p$ satisfy the relation $\beta^2 + p^2 = k_0^2 n^2$, where $n$ is the refractive index (we will further assume that $n = 1$), and $k_0 = 2\pi/\lambda$ is the free-space wavenumber. The remaining components of the field are $E_r(r,z) = -(i\beta/p) \cdot J_1(p \cdot r) \cdot exp(i\beta z)$ and $H_\phi(r,z) = k_0 n^2 \cdot E_r(r,z)/(\beta \cdot \eta_0)$, where $\eta_0 \approx 376.7\Omega$ is the free space impedance. The central part of a radially polarized Bessel beam

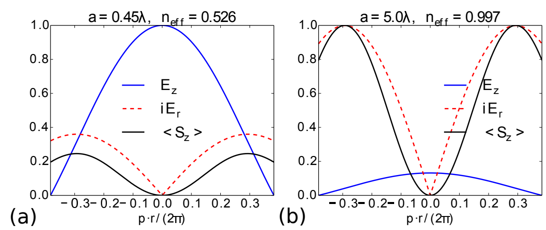


Fig. 1. Radial cross-section of the electric field components $E_r$, $E_z$ and time-averaged Poynting vector $< S_z >$ of the $TM_{0,1}$ mode of a cylindrical metallic waveguide (a) with a radius $a = 0.45\lambda$, and (b) with a radius $a = 5\lambda$.

truncated to the core-region of a circular metallic waveguide defines the $TM_{0,l}$ mode, when the $l$'th zero of $J_0(p \cdot r)$ is reached at the waveguide radius $a$. Following, the radial wavenumber $p$ is obtained from $J_0(p \cdot a) = 0$. As the source of the radially polarized incident beam in the experiment we will use the $TM_{0,1}$ mode of a cylindrical metallic waveguide. This mode is guided in a waveguide with a radius larger than $a > 0.383\lambda$. In Fig. 1 we present the radial cross-section of the $TM_{0,1}$ mode for $a = 0.45\lambda$ (the $TM_{0,1}$ mode of such waveguide is actually used by us in the experiment, and was used in Ref. [19] in a device which converts a linearly polarized beam into a radially polarized one), and $a = 5\lambda$ (for comparison). The effective index $n_{eff} = \beta/k_0$ is equal to 0.526 (due to the vicinity of cut-off) and 0.997, respectively. If $a \gg \lambda$, the axial component of the electric field $E_z$ becomes negligible. However, near the cut-off radius, a significant part of energy is contained in $E_z$, and mode coupling can not be accurately expressed with the overlap integrals [19]. The time-averaged Poynting vector $< S_z >$, also shown in Fig. 1, does not depend on $E_z$ and is always proportional to $J_1^2(p \cdot r)$.

A radially polarized mode can also be excited in a coaxial waveguide consisting of a circular slit in a perfect metal. The fundamental radially polarized $TEM_0$ mode in a perfectly conducting (PEC) coaxial waveguide has no cut-off and is free form wavguide dispersion [20]. The cut-off wavelengths of higher order radially polarized modes $TM_{0,l}$ are approximately equal to $\lambda = 2 \cdot d/l$ [20], where $d$ is the width of the waveguide. Therefore these modes can not be excited in slits narrower than half of the wavelength. A similar $TEM_0$ mode without a cut-off can also be exited in an infinite planar waveguide in PEC. In fact, at THz frequencies a PEC is a reasonable approximation for the permittivity of real metals, and THz radiation can be efficiently transmitted through sub-wavelength slits as small as $\lambda/(3 \cdot 10^4)$ [21]. For both the planar and coaxial waveguide geometries, the effective index of the $TEM_0$ mode is close to unity. Actually, a coaxial waveguide with a narrow slit $d \ll \lambda$ in the limit of large radius

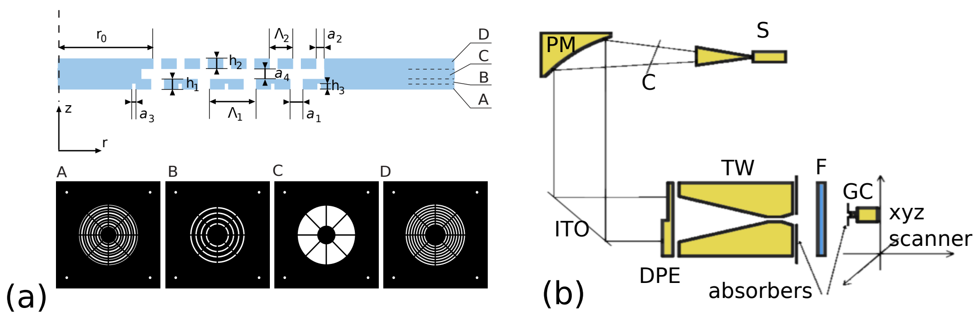


Fig. 2. (a) Schematic of the filter supporting asymmetric transmission of radially polarized light. The top part of the figure shows a radial (*r*-*z*) cross-section of the filter (dashed line denotes the optical axis). The bottom part includes the schematics of the metallic slices which form the filter after stacking together. Tiny metallic bridges connect circular regions. (b) Experimental set-up: S – Gunn diode operating at 0.1 THz, C – chopper, PM – parabolic mirror, ITO – ITO mirror, DPE– Teflon discontinuous delay plate, TW- tapered waveguide, F-asymmetric filter, GC – detector (Golay cell) mounted on a xyz stage.

$R \gg \lambda$ with radially polarized field resembles a planar waveguide with transverse magnetic field. We make use of this analogy to introduce a filter with an asymmetric transmission for radially polarized THz waves which operates in analogy to a planar filter consisting of a double grating [9, 13, 11].

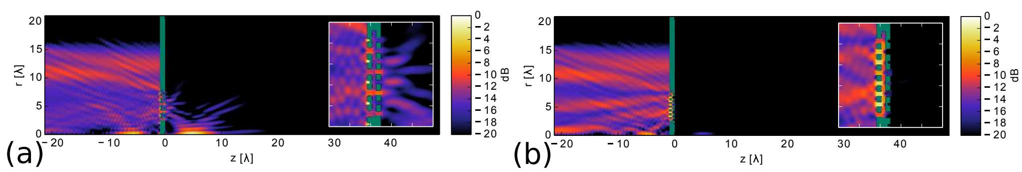


Fig. 3. Demonstration of the unidirectional transmission and focusing – radial (*r*-*z*) cross-section through the energy density calculated with BOR-FDTD shows the transmission of a super-Gaussian radially polarized beam through the double grating. Optical axis is at the bottom of each figure. Insets show the magnified area of the grating. Field is incident onto the filter (a) from the side of the grating with the period $\Lambda_1$ (transmission is allowed), and (b) from the side of the grating with the period $\Lambda_2$ (transmission is blocked).

The schematic of the proposed asymmetric filter is shown in Fig. 2(a). The filter consists of two gratings with circular slits in a PEC shown in the top part of the figure, and is made of a stack of thin ($\lambda/30$) metallic layers with four different profiles (A,B,C,D) shown in the bottom of the figure. The dimensions of the double grating have been tuned to demonstrate suppressed transmission in one of the directions. Transmission through the filter was modelled with the Body-of Revolution Finite-Difference-Time-Domain (BOR-FDTD) method using the Meep software package [22]. A series of simulations with parameters' scanning were performed to maximize the ratio $C = |I_b - I_t|/(I_b + I_t)$ between the intensities of transmitted $I_t$ and blocked $I_b$ radiation calculated at the right side of the grating as $2\pi Re\int E_r \cdot H_\phi^* \cdot r \cdot dr$. A perpendicular direction of incidence was assumed at this point. The contrast $C$ takes the values between 0 and 1 and is a measure of the asymmetry of transmission.

The two gratings contain 4, and 8 slits, respectively, and the radial periods of the gratings are equal to $\Lambda_1 = 4/3 \cdot \lambda$, and $\Lambda_2 = 2/3 \cdot \lambda$. The slits have the widths of $a_1 = \lambda/3$, and $a_2 = 0.267\lambda$. The distance from the axis to the innermost slit is equal to $r_0 = 2.67\lambda$. The thickness of each grating is equal to $h_1 = h_2 = \lambda/3$, and the spacing between the gratings is equal to $a_4 = 0.233\lambda$. Additional grooves in the bottom grating have the thickness of $a_3 = 0.133\lambda$ and the depth of $h_3 = h_1/2$.

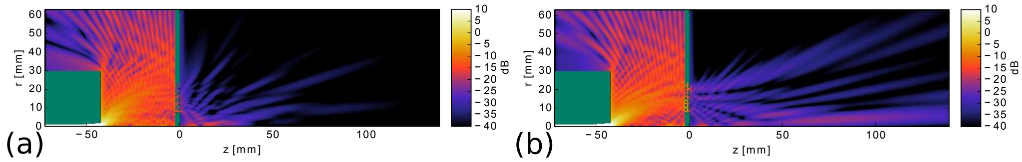


Fig. 4. Energy density in the radial cross-section of the set-up calculated with BOR-FDTD. The radially polarized $TM_{0,1}$ mode of a metallic waveguide is used as the source. The optical axis is at the bottom of each figure. Field is incident onto the filter (a) from the side of the grating with the period $\Lambda_1$ (transmission is partly blocked), and (b) from the side of the grating with the period $\Lambda_2$ (transmission is allowed). The contrast $C$ is equal to 72%.

In Fig. 3 we show the transmission through the double grating made of PEC calculated with BOR-FDTD. The filter is illuminated from either of the sides with a super-Gaussian radially polarized beam of a high order ($E_r \propto exp(-((r-r_0)/2\sigma)^{10})$), with $r_0 = 7.5\lambda$ and $\sigma = 4.7\lambda$), which within a doughnut-like shape resembles a plane-wave. The plot shows the electromagnetic energy density. Transmission amounts to approximately 40% and is almost unidirectional with the contrast $C = 99.8\%$. The transmitted wave is focused at the distance of $4.3\lambda$ from the filter into an elongated axially polarized focal spot with axial and transverse full width at half maximum of energy density equal to $3.0\lambda$ and $1.1\lambda$ respectively. In the inset of Fig. 3(a) we observe a strong enhancement of the local field inside the tiny grooves with thickness $a_3$. These grooves play an important role in the coupling of incident wave to the slits [23, 24, 9] and have been included in the optimization of the filter.

## 3. Experimental results

We have measured the transmission of radially polarized THz radiation through the dual grating discussed in the previous section at the frequency of 0.1 THz. The set-up, depicted in Fig. 2(b), consists of a Gunn diode, a linear to radial polarization converter, the filter, and a Golay cell detector mounted on a translation stage which enables to capture surface or volume scans. The polarization converter is adapted from the work by Grosjean et al. [19] and consists of two elements. One is a Teflon discontinuous delay plate, which shifts the phase of half of the Gaussian incident linearly polarized beam by $\pi$ with respect to the other half. The other element is a tapered Al waveguide. In its the narrowest part, the waveguide supports only two guided modes - the linearly polarized fundamental mode $TE_{1,1}$, orthogonal to the field distribution that leaves the delay-plate (and therefore not excited), and the radially polarized $TM_{0,1}$ mode, which is the only mode that remains. The expanding tapered part of the waveguide helps to couple the mode out of the waveguide. The filter shown before in Fig. 2(a) consists of a stack of 0.1 mm thick slices made of a stainless steel combined to form the circular gratings.

Double gratings considered previously [9, 13, 11], were illuminated with a plane wave incident in the normal direction. In the previous example (see Fig. 3) the super-Gaussian radially polarized beam was also incident perpendicularly onto the grating. Conversely, in the experiment, the incident beam originates from a narrow waveguide with a radius of $0.45 \cdot \lambda$, and is therefore strongly divergent mimicking incidence from the $\pm 1$'st diffraction order onto a planar grating. Owing to the reciprocity of the system, in order to obtain transmission, now the grating has to be placed in the set-up in the opposite way than for a super-Gaussian beam.

In transmission, the filter produces a characteristic diffraction pattern resembling that of an

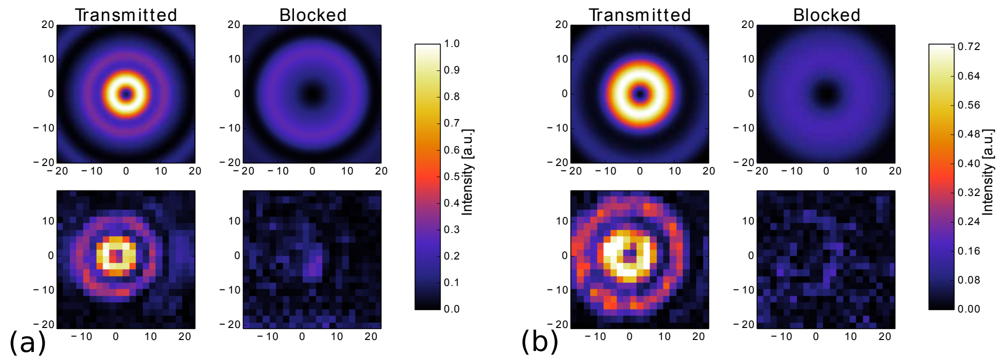


Fig. 5. Cross-section with the field at the distance of (a) 80 mm, and (b) 110 mm from the filter obtained when the beam is transmitted (left) or blocked (right). The top figures show the energy density calculated with BOR-FDTD. The bottom figures demonstrate the field measured experimentally. Units on the axis are given in mm.

axicon (see Fig. 4). Part of the energy radiates away from the optical axis in the close vicinity of the filter. Farther, the slowly-diffracting field forms an elongated cylindrical radially-polarized focal region with the central part of field distribution similar to a radially polarized Bessel beam.

In Fig. 5, we match the field cross-section measured at the distances of 80 mm and 110 mm from the filter with the corresponding results of numerical modeling. The experimental results are consistent with BOR-FDTD simulations. Transmission is largely blocked in one of the directions and in this case due to the presence of background noise resulting from scattering on the detector and other elements of the experimental environment, the signal can not be clearly resolved from the noise. For the other, the field forms a radially-polarized Bessel-shaped pattern.

## 4. Conclusions

We have developed a circular double diffractive grating with sub-wavelength slits which transmits a radially polarized THz beam asymmetrically. As far as we know, an asymmetric grating for radial polarization has not been demonstrated before. For a super-Gaussian incident beam, unidirectional transmission with focusing is shown theoretically. The intensity contrast for transmission in opposite directions reaches $C = 99.8\%$.

We have measured the transmission through the grating at 0.1 THz with the incident radially polarized beam obtained by converting a linearly polarized beam using a discontinuous phase retarder and a tapered waveguide. Transmission efficiency has not been optimized for the specific experimental set-up geometry but a strong asymmetry of transmission was observed for the two directions of incidence.

THz radially polarized radiation can be guided in cylindrical as well as coaxial waveguides, can be propagated in free-space and can be coupled to metallic wires. The proposed asymmetric filter may find prospect applications for unidirectional coupling between some of these elements.