

Asymmetric transmission of THz radiation through a double grating

Marcin Stolarek¹, Dmitriy Yavorskiy², Rafał Kotyński¹, Carlos J. Zapata Rodríguez³,
Jerzy Łusakowski², Tomasz Szoplik^{1,*}

¹*Faculty of Physics, University of Warsaw, Pasteura 7, 02-093 Warsaw, Poland*

²*Faculty of Physics, University of Warsaw, Hoza 69, 00-681 Warsaw, Poland*

³*Department of Optics, University of Valencia, Dr. Moliner 50, 46100 Burjassot, Spain*

* *Corresponding author: tszoplik@mimuw.edu.pl*

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We report on experimental evidence of unidirectional transmission of THz waves through a pair of metallic gratings with different periods. The diffractive element is optimized for broadband transmission in one direction, accompanied with a high extinction rate in the opposite. In contrast to previous studies, we show that the zero-order nonreciprocity cannot be achieved. Nonetheless we confirm that the structure can be successfully used as an asymmetric filter. © 2012 Optical Society of America

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Nonreciprocal transmission is most often achieved in photonic devices through the Faraday effect. Another possibility is to use nonlinear and spatially nonuniform photonic crystals [1], where the nonlinearity affects the local extent of the photonic bandgap. A range of other approaches have been also investigated, for instance involving gyromagnetic [2], or artificial chiral materials [3].

However, even linear, isotropic, and planar diffraction-based elements with a different number of diffraction orders at the two sides, or with an asymmetric distribution of the diffraction efficiencies also show an asymmetric transmission [4,5]. Asymmetric transmission through such gratings or photonic crystals, can be usually explained with reference to the isofrequency contour-plots [6]. Optically linear unidirectional structures may find applications in prospect optical integrated circuits, detectors, circulators, and directional waveguiding elements. Recent experimental result showing asymmetric transmission through a chirped photonic crystal waveguide at microwave frequencies [7] is certainly a good example.

Strong one-way transmission may be achieved through Al layer with corrugations of different periodicity on both sides coupled with the extraordinary transmission through a subwavelength slit at the microwave frequencies and the telecommunication wavelengths [8–10]. In [10], directional selectivity results from different conditions for constructive interference of surface plasmon polaritons (SPP) in the area of the nanoslit at either of the two corrugated surfaces. Metal layers with correlated double-sided corrugations of the same periodicity, which allow for resonant tunneling, were earlier used for far-field focusing in the visible range [11,12]. Recently, an asymmetric transmission of SPP through an array of metal scatterers arranged in a triangular mesh on metal surface was reported [13].

Chen Cheng et al. [14–16] demonstrated strongly

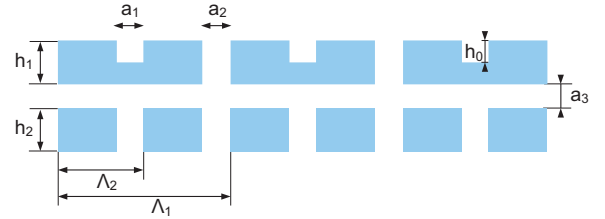


Fig. 1. Schematic view of the dual metal grating.

asymmetric transmission through double metallic gratings with periods that differ by a factor of two $\Lambda_1 = 2\Lambda_2$, when the wavelength takes an intermediate value $\Lambda_1 > \lambda > \Lambda_2$. This intriguing structure, which we also analyze in the present paper (see Fig. 1), makes use of the tuned coupling between the two gratings, each of which supports different diffraction orders. In fact, a lateral shift between the two gratings allows to tailor the phase delay of the element [17] thus the coupling strength may be easily modified. As a whole, the structure is periodic with the larger pitch Λ_1 such that $\lambda < \Lambda_1 < 2\lambda$. Therefore, when the surrounding medium is air at both sides, the only orders that may be present, both in reflection and in transmission, are diffraction orders $-1, 0, 1$. Still, some of them may be suppressed by matching a respective interference condition, which in turn is accomplished by tuning the phase delay between the slits at two sides of the device.

In a different perspective, a structure consisting of gratings and spacers can be also seen as a system of planar metallic waveguides, or in the case of optical frequencies and noble metals as metal-dielectric-metal plasmonic waveguides [4]. In both cases, owing to the subwavelength core size $a_1, a_2, a_3 < \lambda/2$ the waveguides are single-moded and operate only for the TM polarization. Interestingly, an analogous behavior may be also

achieved for the TE polarization in a Si/SiO₂ grating element [18] with a comparable transmission and lower directional selectivity.

Finally, let us recall a recent work [19] by Zhu et al. who propose to use a metal-dielectric grating structure, reporting a single-directional transmittance exceeding 90% for a linear polarization. Both gratings are sub-wavelength, and are oriented at 45 degrees to each other. Therefore they both transmit and reflect only the 0th order, and the geometry is no longer planar, so the analysis can not be brought to either TE or TM case. This structure resembles a wire polarizer attached to a half wave plate oriented at 45°. In fact a subwavelength grating may be approximated by a uniaxial homogenized material and serve as a retarder.

In this letter we present experimental evidence of an asymmetric transmission for THz waves in a structure proposed and studied theoretically by Cheng et al. [14–16], and optimized by us for a broadband response. It has been suggested [16] that the element breaks the reciprocity in the 0th diffraction order. However, this order is suppressed in both directions, and the asymmetry appears in the ± 1 orders like in similar previous studies [4,5]. We have confirmed this both with finite difference time domain method (FDTD) and rigorous coupled wave analysis (RCWA) simulations, using respectively an open-source package [20] and a home-made code based on [21], as well as experimentally. It ought to be emphasized that reciprocity is generally maintained and the coupling efficiencies between particular incident and diffracted orders do not depend on the propagation direction. Still, the device may be used to achieve asymmetric transmission, and this has a practical importance. In fact, the element illuminated from the opposite sides at normal incidence blocks transmission in one direction, at the same time assuring a high diffraction efficiency in other.

We have optimized the double grating structure for a broadband unidirectional transmission with the central frequency of 0.1 THz. The metallic element consists of a stack of 0.1 mm thick slices made of stainless steel. In the FDTD simulations aimed at optimization of the structure, the metal is assumed to be a perfect conductor, a Gaussian pulse is used to determine the transmission spectrum, and periodic boundary conditions are imposed to terminate the computational mesh. Similar simulations with CW illumination, and with a finite size of the grating containing 10 periods terminated with perfectly matched layer boundary conditions give consistent results, with the difference in transmission spectra smaller than 2%. An example of the field distribution obtained with a CW source is presented in Fig. 2. Supplementary RCWA simulations gave only a qualitative confirmation of the device operation due to convergence problems resulting from the attempt to use a Fourier harmonic expansion for highly conducting materials with abrupt subwavelength boundaries. FDTD results showing a possibility to achieve broadband ($\lambda \sim 2\text{--}4$ mm)

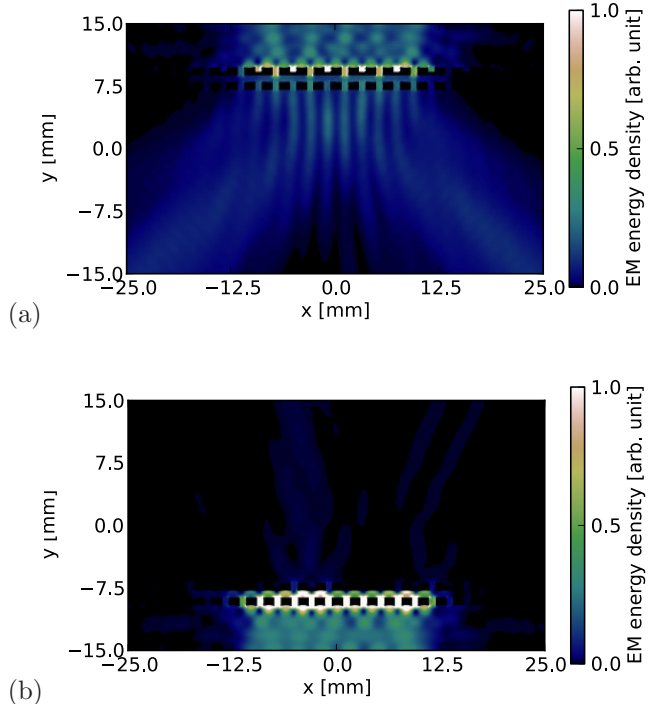


Fig. 2. Distributions of the energy density calculated with FDTD at the frequency of 0.1 THz for the two opposite directions of incidence. (a) incidence from the top side, transmission in the ± 1 orders; (b) incidence from the bottom side, transmission is suppressed.

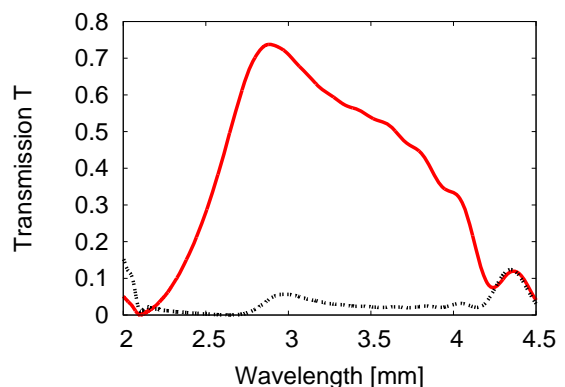


Fig. 3. Total transmission spectra $T(\lambda)$ of the double grating calculated using FDTD in the two opposite directions. Continuous line (red on-line) corresponds to the incidence from the top side, black dashed line denotes the incidence from the bottom side.

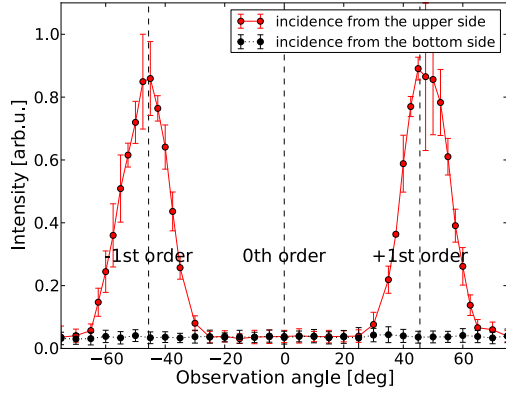


Fig. 4. Intensity of the angular transmission spectrum of the double grating measured at the frequency of 0.1 THz in both directions.

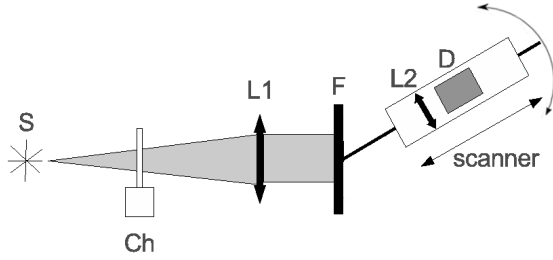


Fig. 5. Measurement set-up (S - Gunn diode, Ch - chopper, F - asymmetric filter, L1,L2 - PTFE lenses, D detector.)

unidirectional transmission are presented in Fig. 3. The respective optimized geometric parameters are the following: $\Lambda_1 = 2\Lambda_2 = 4.2$ mm, $a_1 = a_2 = a_3 = 0.7$ mm, $h_1 = h_2 = 2h_0 = 1$ mm.

We have measured the angular transmission spectrum of the dual grating in the frequency range of 0.095–0.110 THz at room temperature, and the results for 0.1 THz are shown in Fig. 4. The experimental set-up is presented in Fig. 5. The size of the grating is 42 mm×42 mm, the beam diameter is approximately equal to 2 cm, a PTFE (TeflonTM) lenses are used to control the divergence of the beam. Measurements are consistent with FDTD simulations, transmission is observed only in the ± 1 diffraction orders and only in one direction, the suppressed orders are at the level of the background noise (Signal to noise ratio SNR \sim 20–30 dB). Reciprocity in the 0th order is evident from Fig. 4.

In conclusion, we have optimized a double metallic grating for a broadband unidirectional transmission in the THz frequency range. Its operation is reciprocal, despite previous reports of zero order nonreciprocity. The filter has an asymmetric transmission in one direction

in the ± 1 diffraction orders, and blocks the 0th order, a high extinction ratio is confirmed experimentally at 0.1 THz.

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