Asymmetric transmission of terahertz radiation through a double grating

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

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Faraday isolators are the most popular photonic devices that operate thanks to nonreciprocal transmission. Another way to achieve nonreciprocity 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 also has been investigated, for instance involving gyromagnetic materials [2], artificial chiral materials [3], or interaction of light with guided acoustic resonances [4]. Even linear, isotropic, and planar diffractive gratings 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 [5,6]. Their operation usually can be explained using isofrequency contour plots [7]. Recently, asymmetric transmission through a chirped photonic crystal waveguide has been demonstrated at microwave frequencies [8]. In another work, asymmetric transmission was achieved in a planar silicon photonic crystal waveguide interface in the infrared thanks to out-of-plane scattering [9]. Prospect applications of optically linear unidirectional structures may include novel designs of detectors, circulators, and integrated circuits.

Asymmetric transmission through a corrugated metallic layer with a subwavelength slit, with the corrugations of different periodicity on both sides, recently was demonstrated at microwave [10,11] and telecommunication frequencies [12]. In [12], directional selectivity resulted from different conditions for the constructive interference of surface plasmon polaritons (SPP) in the area of the nanoslit at either of the two corrugated surfaces. An asymmetric transmission of SPP through an array of metal scatterers arranged in a triangular mesh on a metal surface was reported in [13]. In [14], single-directional transmittance exceeding 90% for a linear polarization was shown in a structure consisting of a metallic and dielectric nanogratings oriented at 45 deg to each other. Since a subwavelength grating may be approximated by a uniaxial homogenized material, this structure resembles a wire polarizer attached to a half-wave plate.

Cheng *et al.* [15–17] demonstrated strongly 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 structure, which we analyze in this Letter (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 us to tailor the phase delay introduced by the structure [18], and thus the coupling strength may be modified easily. A structure consisting of gratings and spacers also can be seen as a system of planar metallic waveguides, or in the case of optical frequencies and noble metals, as metal–dielectric–metal plasmonic waveguides [5]. 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. An analogous behavior may be achieved for the TE polarization in a Si/SiO_2 grating [19] with a comparable transmission and lower directional selectivity.

In this Letter, we present experimental evidence of an asymmetric transmission for terahertz waves in a structure studied earlier [15–17] and optimized by us for a broadband response. As a whole, the structure presented in Fig. 1 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 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. It has been suggested [17] that the grating breaks the reciprocity in the zeroth diffraction

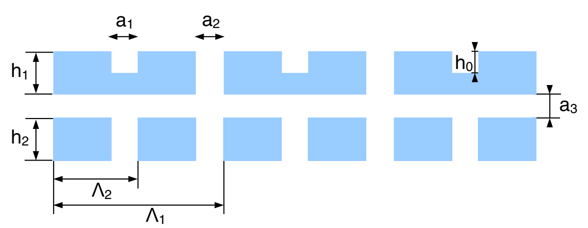

Fig. 1. (Color online) Schematic view of the dual metal grating.

order. This order is suppressed in both directions, however, and the asymmetry appears in the ± 1 orders like in similar previous studies [5,6]. We have confirmed this with both the finite difference time domain method (FDTD) and rigorous coupled wave analysis (RCWA) simulations, using an open-source package [20] and a homemade code-based package [21], respectively, as well as experimentally. Diffraction efficiency in the ± 1 order for the beam impinging from the upper side is equal to that calculated in a reversed direction—that is, for a beam impinging from the bottom side at an oblique angle $\theta_{\pm 1} = \pm \arcsin(\lambda/\Lambda_1)$ and outgoing upward perpendicularly to the grating. Although reciprocity is maintained, the device may be used to achieve asymmetric transmission, and this has a practical importance. In fact, when the direction of incidence is normal to the grating, transmission is suppressed almost entirely for a beam impinging from the bottom side and is allowed for a beam impinging from the upper side.

We have optimized the double grating structure for a broadband unidirectional transmission with the central frequency of 0.1 THz. 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 continuous wave (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%. 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. The respective optimized geometric parameters are as follows: $\Lambda_1 = 2\Lambda_2 = 4.2$ mm, $a_1 = a_2 = a_3 = 0.7$ mm, $h_1 = h_2 = 2h_0 = 1$ mm. FDTD results showing a possibility to achieve a broadband ($\lambda \sim 2.5$–4 mm) unidirectional transmission are presented in Fig. 2. An example of the field distribution obtained with a CW source is presented in Fig. 3.

We have measured the angular transmission spectrum of the dual grating in the frequency range of 0.095–0.110 THz at room temperature. The setup and the measurement results for 0.1 THz are shown in Figs. 4 and 5, respectively. A Gaussian beam formed by the lens L1 is incident normally on the filter (F). The grating consists of a stack of 0.1 mm thick slices made of stainless steel. The size of the grating is 42 mm × 42 mm, the beam diameter is approximately equal to 2 cm. The diffracted

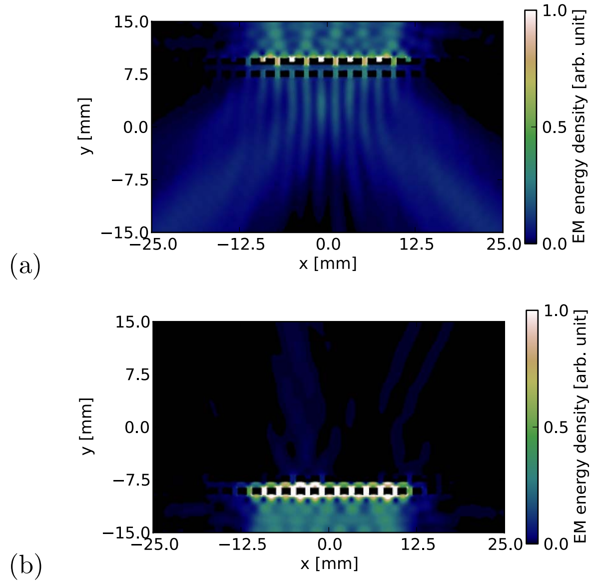

Fig. 3. (Color online) Distributions of the energy density calculated with FDTD at the frequency of 0.1 THz for the two opposite directions of incidence: (a) incidence from the top side, transmission in the ± 1 orders and (b) incidence from the bottom side, transmission is suppressed.

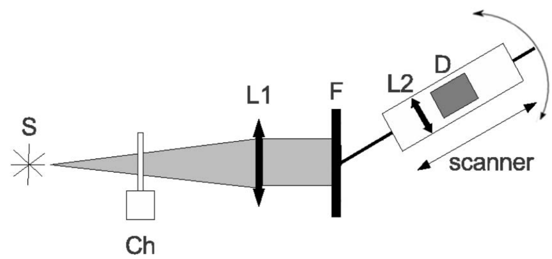

Fig. 4. Measurement setup. S, Gunn diode; Ch, chopper; F, asymmetric filter; L1, L2, lenses; and D, detector.

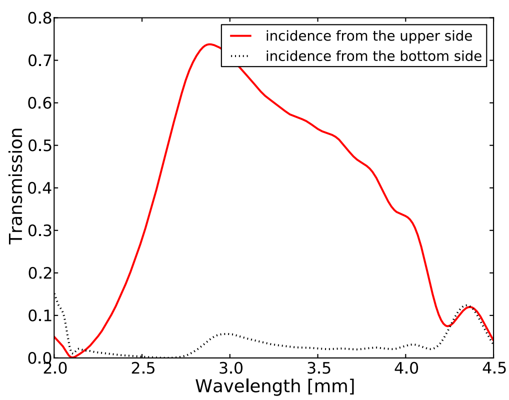

Fig. 2. (Color online) Total transmission spectra of the double grating calculated using FDTD in the two opposite directions.

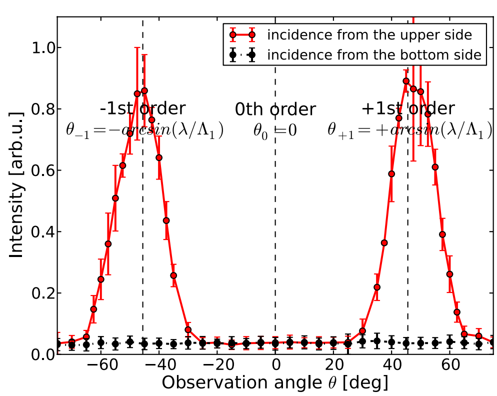

Fig. 5. (Color online) Intensity of the angular transmission spectrum of the double grating measured at the frequency of 0.1 THz in both directions.

beam is focused by the lens L2 on a pyroelectric detector D placed on a $\theta - r$ scanner. Both lenses are made of Teflon. For each angle of observation, a scan along the radius r was carried out, which allowed us to estimate the amplitude of interferences appearing due to reflections between the detector and the filter (shown as error bars in Fig. 5).

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 ~20–30 dB). Reciprocity in the zeroth-order is evident from Fig. 5.

We have optimized a double metallic grating for a broadband unidirectional transmission in the terahertz 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 zeroth-order, a high extinction ratio is confirmed experimentally at 0.1 THz.

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