Broadband asymmetric transmission of THz radiation through double metallic gratings

Marcin Stolarek[1], Dmitriy Yavorskiy[2], Rafał Kotyński[1], Carlos J. Zapata Rodríguez[3], Jerzy Łusakowski[2], Tomasz Szoplik[1]
[1]Faculty of Physics, University of Warsaw, Pasteura 7, 02-093 Warsaw, Poland
[2]Faculty of Physics, University of Warsaw, Hoża 69, 00-681 Warsaw, Poland
[3]Department of Optics, University of Valencia, Dr. Moliner 50, 46100 Burjassot, Spain

**Corresponding author: mstolarek@igf.fuw.edu.pl*

We analyse numerically and experimentally the asymmetric transmission through sub-wavelength double metallic gratings. The possibility of achieving a broadband unidirectional transmission of THz waves through the grating is confirmed. The proposed gratings allow for efficient one-way transmission in the wavelength range from 2.5 to 3.5mm.

Keywords: unidirectional transmission, double metallic grating, terahertz radiation

1. INTRODUCTION

Unidirectional nonreciprocal optical transmission can be obtained with the Faraday effect. Reciprocal asymmetric transmission can be for instance based on nonlinear and spatially nonuniform photonic crystals [1], where the photonic bandgap is affected by nonlinearity. A variety of other solutions have been proposed, for example involving gyromagnetic [2], or artificial chiral materials [3]. Asymmetric transmission has also been observed with diffraction-based elements with different number of diffraction orders at two sides [4,5]. Asymmetric transmission through such gratings or through photonic crystals, can be usually explained with reference to the isofrequency contourplots [6].

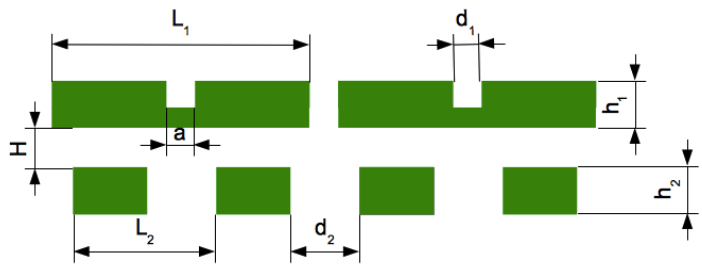

Figure 1. Schematic description of DMG structure.

Other approaches to asymmetric transmission include chirped photonic crystal waveguides [7], corrugated metallic layers [8-12], arrays of metal scatterers [13], and metal-dielectric nanogratings [14].

In this work we further analyze the concept of dual metallic gratings (DMG), which was proposed by Cheng et.al. [15-17]. Unidirectional transmission in such a structures is reciprocal and it occurs only in non-zero diffraction orders [18].

2. NUMERICAL ANALYSYS OF THE STRUCTURE

We analyse the structure presented in Fig. 1 with the Finite-Difference Time-Domain method (FDTD) [19]. We assume the metal to be a perfect electric conductor, which is a good approximation within the THz range for a variety of metals including silver and gold. We use periodic boundary conditions, and a pulse Gaussian source. Geometrical parameters of the structure under consideration are L_1=2.1 mm, L_2=4.2 mm, h_1=h2=1 mm, a=d_1=d_2=0.7 mm, H=0.8 mm. Corrugation depth of input surface is 0.5 mm. Transmission through this structure is defined as the flux spectrum transmitted through the structure divided by flux spectrum in the same location in an analogical simulation without the structure. Then we calculate the difference (D) and the quotient (Q) of transmission in opposite directions. The simulation results are presented in Fig. 2.

From the plots in Fig. 2, we can notice that it is difficult to achieve high values of both D and Q simultaneously in a broad spectral range. Focusing on the dependence of transmission asymmetry on d_2 we see that a large difference in transmission for a broad spectral range can be achieved for larger d_2, from 1 to 1.4 mm. However, for such a large aperture, Q is slightly reduced.

Analysing the plots in Figs. 2c and 2d, we recognize that the range of high difference of transmission in opposite directions (D) is weakly dependent on d_1. However, in order to achieve a high contrast (Q) in a broadband spectral range, the thickness d_1 should be taken from between 0.2 and 0.4 mm.

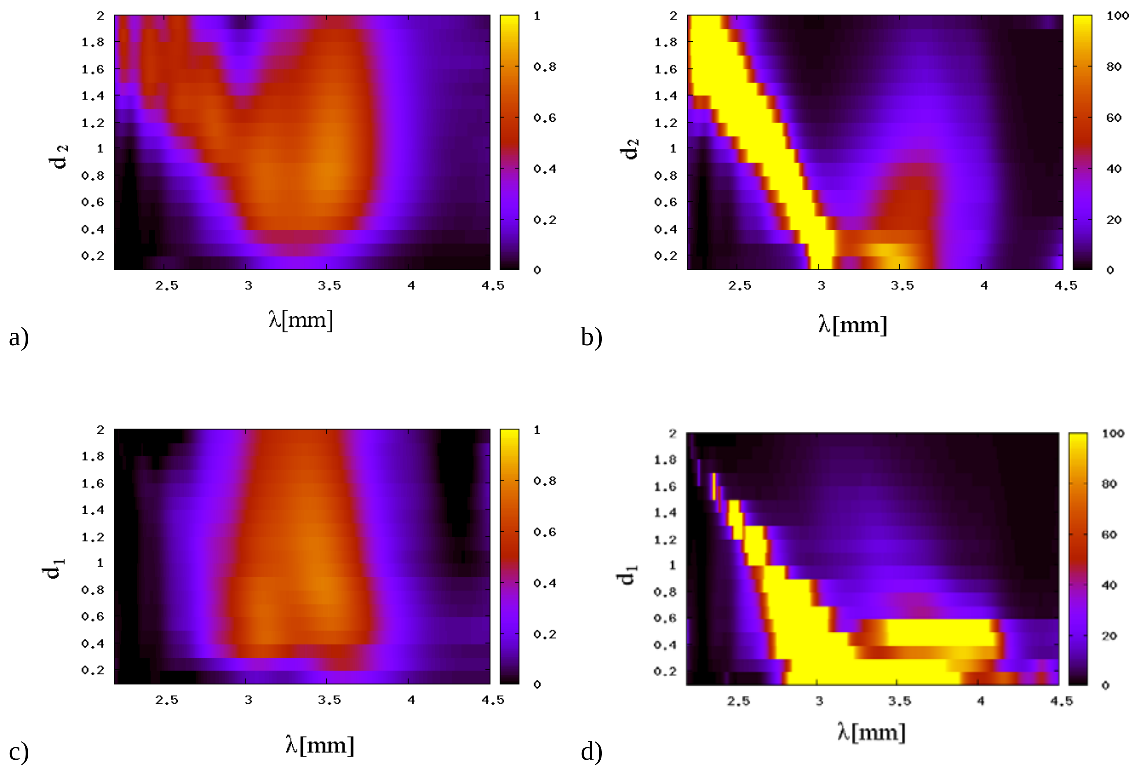

Figure 2. Dependence of a,c) difference (D), and b,d) quotient (Q) of the transmission in opposite directions on the aperture sizes d_1 and d_2, and on the wavelength.

The results from Fig. 2 indicate that the transmission through DMG with large slits is large in both directions, therefore such gratings can not be used to achieve a strong asymmetric transmission.

We have repeated the FDTD simulations using a continuous wave (CW) monochromatic source. Examples of these simulations are gathered in Fig. 3. Two different values of d_2 are considered. Other parameters of the structure remain unchanged.

It is clearly visible that larger values of d_2 lead to a stronger difference in transmission in opposite directions (See Figs. 3a and 3b). Unfortunately, for longer waves, higher d_2 leads to the appearance of transmission in the blocking direction (See Fig. 3d), which can be also observed in Fig. 2 as a region with lower Q values.

Simulations with periodic boundary conditions along the diffraction grating and perfectly matched layer at the left and right sides can lead to an apparent transmission in the 0-th order. However, the energy density distribution is in fact the result of interference of the -1-st and +1-st diffraction orders outcoming from infinite diffraction grating, while the 0-th order is blocked in both directions.

3. EXPERIMENT

We have measured the transmission thorough the DMG in both directions in the THz wavelength range using a Gunn diode with the central frequency f=100 GHz, which corresponds to the wavelength of 3 mm. The Gunn diode allows only for small frequency changes. Experimental verification of the broadband asymmetric transmission will be performed in our future work, and here we have focused on obtaining a high contrast (Q). The size of the grating is 42 mm×42 mm and the beam diameter is approximately equal to 2 cm. The parallel beam is formed with PTFE (Teflon TM) lens. Figure 3 presents a scan of electromagnetic energy behind the DMG. The experimental results prove that the transmitted beam is propagating in non-zero diffraction order. Transmission is reciprocal in contrast to previous reports.

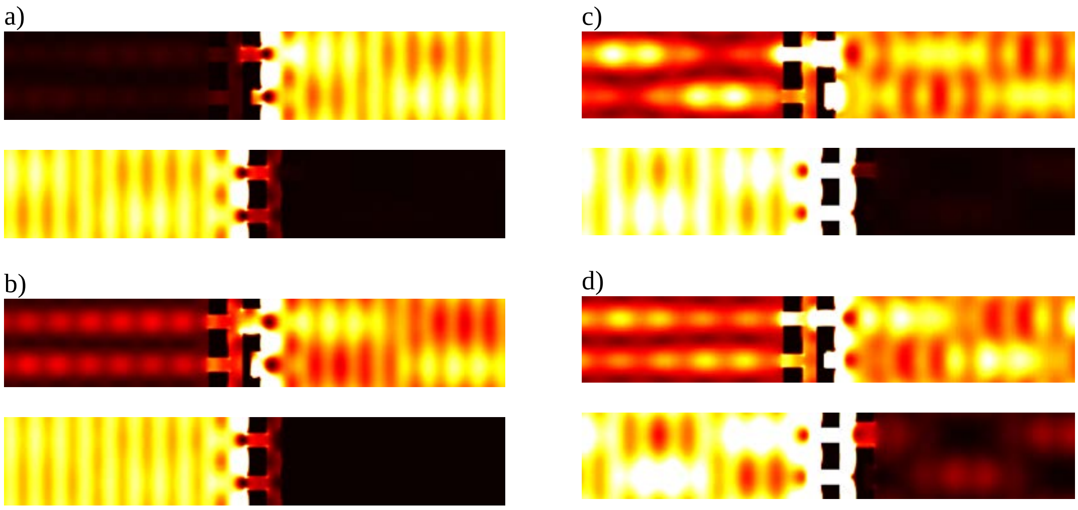

Figure 3. Energy density distribution for different wavelengths and structure parameters (periodic boundary conditions). The wavelength is equal to a,b) λ = 2.5 mm, c,d) λ = 3.0 mm .The aperture size is equal to a,c) d_2=0.7 b,d) d_2=1.2.

4.CONCLUSIONS

We present a possibility of achieving reciprocal, unidirectional transmission through the structure consisting of two metallic diffraction gratings. The 0-th order transmission is blocked for both directions and for one direction +1 and -1 diffraction order is observed. We have discussed the possibility of achieving a broad spectrum of asymmetrical transmission.

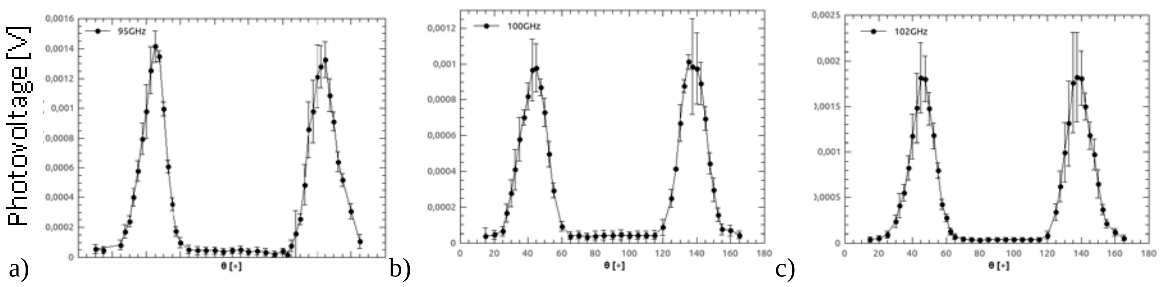

Figure 4. Angular scan of the outcoming beam for different source frequencies.

ACKNOWLEDGEMENTS

This work is supported by the research projects of the Polish National Science Center UMO-2011/01/M/ST3/05734, UMO-6081/B/TO2/2010/39. PL-Grid infrastructure is acknowledged for providing computational resources.

REFERENCES

[1] M. Scalora, J. P. Dowling, C. M. Bowden, and M. J. Bloemer, The photonic band edge optical diode, *J. Appl. Phys.* vol. 76, 2023, 1994.

[2] Z. Wang, Y. D. Chong, J. D. Joannopoulos, and M. Soljacic, Reflection-Free One-Way Edge Modes in a Gyromagnetic Photonic Crystal, *Phys. Rev. Lett.* vol. 100, 013905, 2008.

[3] A. S. Schwanecke, V. A. Fedotov, V. V. Khardikov, S.L. Prosvirnin, Y. Chen, and N. I. Zheludev, Nanostructured Metal Film with Asymmetric Optical Transmission, *Nano Lett*. vol. 8, 2940, 2008.

[4] M. J. Lockyear, A. P. Hibbins, K. R. White, and J. R. Sambles, One-way diffraction grating, *Phys. Rev.* E vol. 74, 056611, 2006.

[5] A. Mandatori, M. Bertolotti, and C. Sibilia, Asymmetric transmission of some two-dimensional photonic crystals, *J. Opt. Soc.Am. B* vol. 24, 685, 2007.

[6] A. E. Serebryannikov, One-way diffraction effects in photonic crystal gratings made of isotropic materials, *Phys. Rev. B* vol. 80, 155117, 2009.

[7] H. Kurt, D. Yilmaz, A. E. Akosman, and E. Ozbay, Asymmetric light propagation in chirped photonic crystal waveguides, *Opt. Express* vol. 20, 20635, 2012.

[8] S. Cakmakyapan, A. E. Serebryannikov, H. Caglayan, and E. Ozbay, One-way transmission through the subwavelength slit in nonsymmetric metallic gratings, *Opt. Lett.* vol. 35, 2597, 2010.

[9] S. Cakmakyapan, H. Caglayan, A. E. Serebryannikov, and E. Ozbay, Experimental validation of strong directional selectivity in nonsymmetric metallic gratings with a subwavelength slit, *Appl. Phys. Lett.* vol. 98, 051103, 2011.

[10] E. Battal, T. A. Yogurt, and A. K. Okyay, Ultrahigh Contrast One-Way Optical Transmission Through a Subwavelength Slit, *Plasmonics* vol. 8, pp 509-513, 2013.

[11] P. Wróbel, J. Pniewski, T. J. Antosiewicz, and T. Szoplik, Focusing Radially Polarized Light by a Concentrically Corrugated Silver Film without a Hole, *Phys. Rev. Lett.* 102, 183902, 2009.

[12] P. Wróbel, T. J. Antosiewicz, J. Pniewski, and T. Szoplik, Single-layer metal nanolenses with tight foci in far-field, *Appl. Phys. A* 103, 821, 2011.

[13] V. Kuzmiak and A. A. Maradudin, Asymmetric transmission of surface plasmon polaritons, *Phys. Rev. A* vol. 86, 043805, 2012.

[14] C. Cheng, J. Chen, Q.-Y. Wu, F.-F. Ren, J. Xu, Y.-X. Fan, and H.-T. Wang, Controllable electromagnetic transmission based on dual-metallic grating structures composed of subwavelength slits, *Appl. Phys. Lett.* vol. 91, 111111, 2007.

[15] C. Cheng, J. Chen, D.-J. Shi, Q.-Y. Wu, F.-F. Ren, J. Xu, Y.-X. Fan, J. Ding, and H.-T. Wang, Physical mechanism of extraordinary electromagnetic transmission in dual-metallic grating structures, *Phys. Rev. B* vol. 78, 075406, 2008.

[16] J. Xu, C. Cheng, M. Kang, J. Chen, Z. Zheng, Y.-X. Fan, and H.-T. Wang, " Unidirectional optical transmission in dual-metal gratings in the absence of anisotropic and nonlinear materials," *Opt. Lett.* 36, 1905, 2011.

[17] Z. Marcet, J. W. Paster, D. W. Carr, J. E. Bower, R. A. Cirelli, F. Klemens, W. M. Mansfield, J. F. Miner, C. S. Pai, and H. B. Chan, Controlling the phase delay of light transmitted through double-layer metallic subwavelength slit arrays, *Opt. Lett.* vol. 33, 1410, 2008.

[18] M. Stolarek, D. Yavorskiy, R. Kotyński, C. Zapata Rodriguez, J. Łusakowski, T. Szoplik, Asymmetric transmission of terahertz radiation through a double grating, *Optics Letters*, vol. 38, pp 839-841, 2013.

[19] A. F. Oskooi, D. Roundy, M. Ibanescu, P. Bermel, J. D. Joannopoulos, and S. G. Johnson, *Comput. Phys. Comm.* vol. 181, 687, 2010.