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Asymmetric transmission through metallic grating with dielectric substrate

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ABSTRACT

We show the phenomenon of asymmetric TM light transmissions through metallic grating with dielectric substrate, which depends on neither magneto-optical nor nonlinear materials. Numerical evidence shows that the asymmetry in total transmissions is induced by first-order transmissions, while the zero-order transmissions keep symmetric. With optimized parameters, the asymmetry can be as high as 0.4279.

1. Introduction

Asymmetric light transmission (ALT) components, such as optical diodes, are crucial to the development of optical-based functional systems. With the emerging of integrated optical system, minimization of these components has attracted more and more attentions. Usually ALT is achieved by utilizing magneto-optical (MO) components, which can break time-reversal symmetry of electric-magnetic waves [1]. Based on MO effect, nonreciprocal waveguides [2,3] and resonators [4,5] have been proposed. Specially, utilizing gyromagnetic effects induced by MO materials, unidirectional edge modes can be realized [6–8]. Furthermore, based on the nonlinearity in asymmetric structures, ALT through one-dimension (1D) multilayer resonators have been widely studied [9,10]. For the simplicity in fabrication and analysis, grating structures have also been studied to realize ALT. MO effect assisted [11–13] and nonlinearity assisted [14] nonreciprocal transmissions have been reported.

However, the large external magnetic field (for the saturation magnetization of MO materials, which usually are more than 1500 G [6,15]) and high incidence power (for instance, the energy flux density of the incident light needed in Ref. [14] is 1.6 MW/cm^2) required by MO effect and nonlinearity, respectively, bring new challenges into the technological applications. Recently, ALTs through gratings without MO materials or nonlinearities have been investigated [16–19]. The ALTs are mainly induced by the asymmetric structure. Different geometry at opposite grating surfaces has been used to realize the asymmetric diffraction. In this paper, we propose a new kind of double-layers hybrid grating consisting of metallic grating with dielectric substrate. Beside the symmetric zero-order transmission, we focus our investigation on the first-order transmissions, which can show distinguish ALT. Numerical evidences show that the ALT is enhanced when the wavelength is approaching the grating constant from shorter wavelength. Different from former proposed asymmetric gratings, our proposal is composed of a metallic grating and a dielectric substrate. The ALT is proved to be induced by the dielectric substrate, which breaks the space-inversion symmetry of single-layer metallic grating. At wavelengths near grating constant, the dielectric substrate can induce total internal reflection (TIR) in first-order transmissions if the dielectric substrate is at the emergence side. TIR effect suppresses the first-order transmission whose emergence angle is near 90°. However, if the light is transmitted in opposite direction, the case is much different. Metal grating at the emergence side can induce spoof surface plasmons (SSPs) [20] excited by the first-order transmissions, at the wavelength near grating constant. The SSPs can enhance first-order transmission. Meanwhile, suppressing effect by TIR is relatively weak. Thus, the total outgoing field including zero- and first-order transmissions can show distinguished ALT. This asymmetric grating can have possible applications

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in compact ALT components. Prospect applications of ALT components may include novel designs of detectors, circulators, and integrated circuits. For example, ALT effect in the semiconductor waveguide can be utilized to realize high power superluminescent diodes [21,22].

2. Simulation model

Depicted in Fig. 1, our simulation model consists of a metallic grating with a dielectric substrate. The metallic grating is assumed as silver film with periodic slits parallel with z axis, whose grating constant is $d=1$ μm. The choice of 1 μm is somewhat arbitrary, and is only intended to serve as a representative model for a generic grating device. The length of the grating is assumed infinite in the x and z directions. Thicknesses of the metallic grating and the substrate, and the width of the slits are defined as h_m, h_d and g, respectively. To evaluate the ALT effect induced by different dielectric substrate, we consider a wide permittivity ε range of the substrate, from 1 to 12.5, which includes many available dielectric materials. For simplicity, light is normally incident on the surface of the grating. The uniformity of the grating structure along z direction ensures that wave vectors for the transmitted and reflected field are both in x–y plane. We focus our discussion in wavelengths between 0.5d and d, which only support zero- and first-order transmissions, and the same orders exist in reflections. In detail, the first-order transmissions and reflections are $+1$ and -1 order, which are same for the normal incidence. Thus, we only need to consider the $+1$ order transmission and reflection for the first-order discussion, and count the first-order part twice for the total transmission and reflection. Two-dimensional (2D) finite elements methods (FEM) is used in our simulation, with commercial solver package COMSOL Multiphysics. We neglect the dispersion and loss of the dielectric substrate, and utilize the experimental complex refractive index for the silver [23], allowing a wide-frequency analyzing. Here we would like to point out that the dispersion and loss of the dielectric substrate are small, comparing with those of the metal in the grating, so we can neglect the dispersion and loss of dielectric substrate in our simulation. For our proposed grating, we assume the incident light is with TM polarization (with nonzero E_x, E_y and H_z), which can excite SSPs at the surface of silver grating in x–y plane. For convenience in the following discussion, we define the transmission along $+y$ and $-y$ direction as U case and D case, representing upward and downward transmission, respectively. To clearly show the ALT, we simulate both zero- and first-order transmissions, and the total transmission as well. We utilize the difference between the D case and U case transmissions to define the ALT. The Transmissions in our discussions can be expressed as T_{ij}, where i is U, D or A, for U case, D case or ALT, and j is 0, 1 or t, for zero-order, first-order or total transmissions, respectively. Thus, we have $T_{Aj}=|T_{Dj}-T_{Uj}|$, $T_{it}=T_{i0}+2\times T_{i1}$. Different order transmissions are distinguished technologically by their different wave vectors k in the transmitted field. For wavelength λ between 0.5d and d, the total transmitted field is composed of zero-order transmission with $k_{x,0}=0$, $k_{y,0}=\pm k$, and first-order transmissions with $k_{x,1}=k\cos\theta$, $k_{y,1}=\pm k\sin\theta$ ($\pm$ for U case and D case, respectively). Here $k\equiv 2\pi/\lambda$ is the norm of the wave vector in free space, and $\theta\equiv\arcsin(\lambda/d)$ is the emergence angle of the first-order transmission.

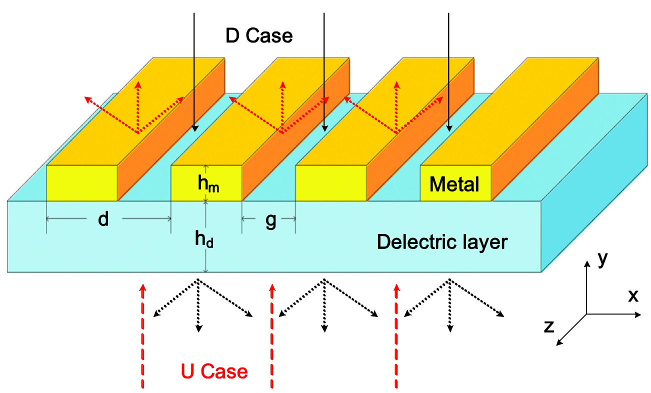

Fig. 1. Schematic structure of silver grating with dielectric substrate. D Case and U Case incidence are illustrated with black solid and red dash arrows, respectively. The transmitted lights are illustrated with dot arrows.

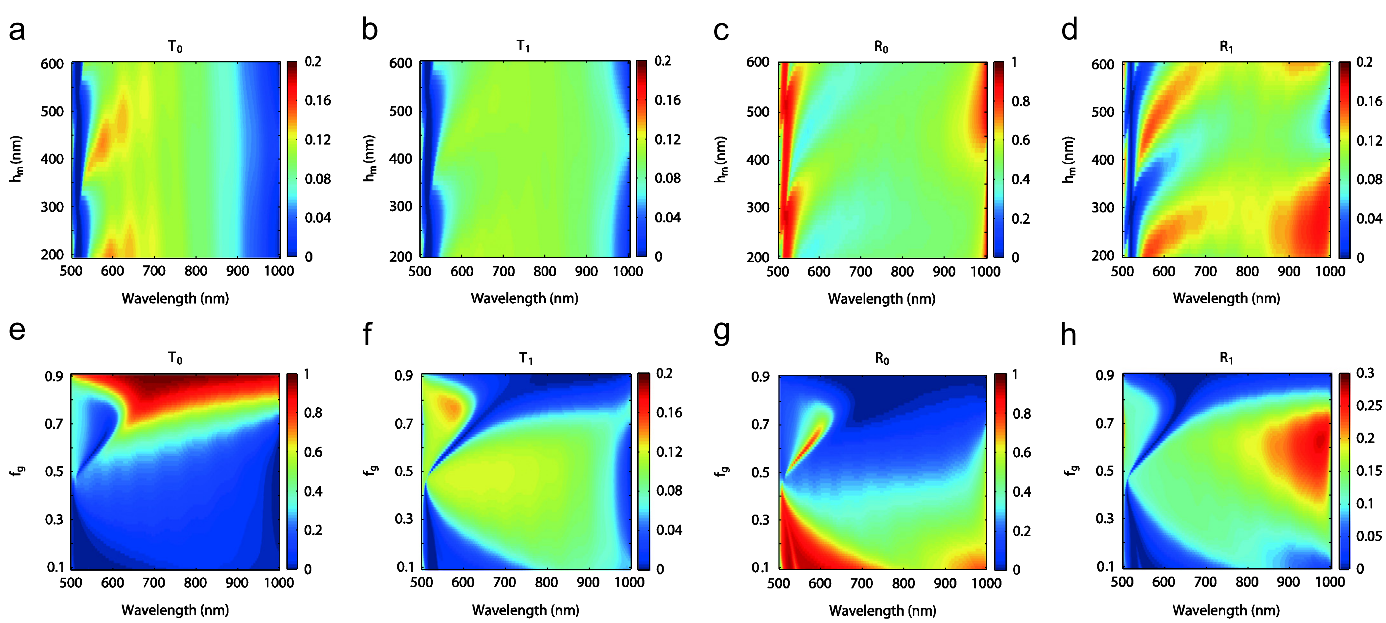

Fig. 2. Transmissions and reflections for single-layer metallic gratings. (a)–(d) are zero-order transmission, first-order transmissions, zero-order reflection and first-order reflections, respectively, for gratings with different h_m, and fixed $f_g=0.3$. (e)–(h) are zero-order transmission, first-order transmissions, zero-order reflection and first-order reflections, respectively, for gratings with different f_g, and fixed $h_m=200$ nm.