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Highly One-Way Electromagnetic Wave Transmission Based on Outcoupling of Surface Plasmon Polaritons to Radiation Modes

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***Abstract*—Unidirectional transmission of electromagnetic waves has attracted great interest due to its wide modern optical applications. This study theoretically demonstrates a one-way transmissive optical device with a high-contrast forward-to-backward ratio at the near-infrared region. The polarization-independent optical diode-like mechanism is designed using a metasurface diffraction grating configuration with symmetry breaking property along the wave propagation in which the working principle is based on the excitation of surface plasmon modes at the interfaces of thin metallic interlayer and their coupling to the radiation modes.**

***Index Terms*—Asymmetric transmission, diode-like behavior, diffraction grating, metasurface, long- and short-range surface plasmon polaritons.**

I. Introduction

The ability to rectify the electromagnetic transmission along one direction of propagation is a significant phenomenon realized in a wide range of optical applications. Such optical-diode property can be obtained by breaking the Lorentz reciprocity condition in the use of magneto-optical materials, nonlinear media, or spatial-temporal modulations of refractive indices. Recently, artificially engineered subwavelength metamaterials have opened up tremendous opportunities to develop versatile optical and terahertz devices offering great control at the unit cell level [1]–[6]. Optical devices with an asymmetric transmission (AT) or specifically one-way transmission characteristic can also be realized using artificial structures including photonic crystals, subwavelength metallic/dielectric gratings, metamaterials and their planar versions called metasurfaces [7]. In addition, AT effects based on the excitation of surface plasmons (SPs) have also been studied by utilizing double gratings with different periods, multilayer metasurfaces, and asymmetric metallic gratings with one or multiple subwavelength slits [8]–[10]. However, the realization of multilayer grating and slit designs separated by a thin dielectric is a challenging task from the fabrication perspective, and these plasmonic metamaterials usually exhibit low transmission amplitudes due to optical losses in the multilayer designs [8]–[10]. In the meantime, the outcoupling of SP modes to radiation modes was demonstrated in [11] using a diffraction grating. Therefore, adopting the aforementioned design architectures can provide the opportunity to achieve high-contrast AT. In an ideal scheme, it is required to reduce the optical loss while keeping the overall design simple. Accordingly, the excitation of long- and short-range surface plasmon polaritons (LR-SPP and SR-SPP) over both boundaries of a thin metal slab [12] can be an innovative approach to be exploited in AT optical devices. Here, we present a high-contrast AT optical device made of a diffraction grating waveguide over a thin silver (Ag) layer embedded on a thick substrate. This simple geometry is significantly distinct from other available plasmonic-metamaterial-based AT devices with multilayer configurations, multilayer metasurfaces, or subwavelength slits. When the proposed device is illuminated from the grating side, the SPPs modes will be excited by the diffraction grating at both interfaces of the Ag film and outcoupled to the radiation modes in the substrate, thereby achieving high forward transmission. For the backward illumination, the device can achieve near-zero backward transmission thanks to the strong reflection of the Ag layer.

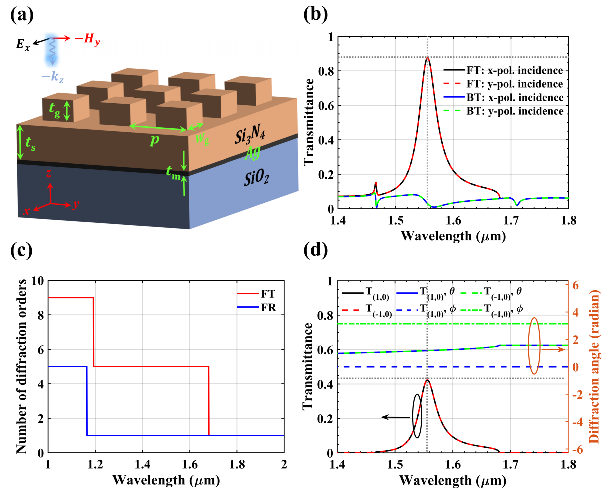

Fig. 1. (a) Schematic diagram of the proposed structure with a high AT property. (b) Calculated forward and backward transmission (FT and BT) spectra when the structure is illuminated by an $x-$ and $y-$polarized uniform plane wave propagating along the $\mp z$ directions. (c) The number of diffraction orders versus the wavelength obtained for the forward transmittance and reflectance (i.e., FT and FR). (d) The absolute transmitted powers and the corresponding diffraction angles of main diffracted orders $T_{(1,0)}$ and $T_{(-1,0)}$.

II. Design Procedure and Simulation Results

A thin metal film surrounded by dielectrics that stretch infinitely on both sides of the metal film will theoretically support the excitation of SPP modes at both interfaces. Overlapping of the modes give rise to mixed modes [LR-SPP (symmetric mode) and SR-SPP (antisymmetric mode)] as solutions of Maxwell's equations in each medium [12]. This means that if the thickness of the metal film increases, the propagation constants of the two modes are getting closer, resulting in SPPs only at the top interface. From a practical point of view, the successful coupling of an incident wave to SPPs has been reported in several studies [11], [12]. Fig. 1(a) shows a schematic representation of the proposed structure with AT property obtained by generating and outcoupling SPP modes to radiation modes. The structure consists of

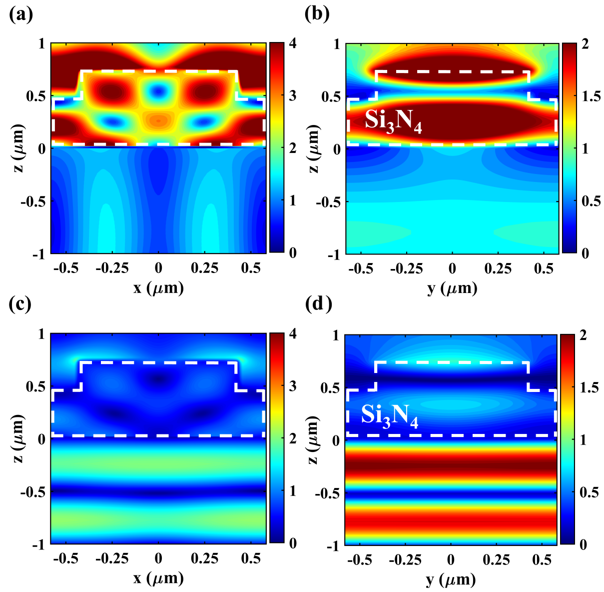

Fig. 2. Absolute values of electric-field distributions on the (a), (c) $x-z$ and (b), (d) $y-z$ planes calculated for one-unit cell when the structure is normally illuminated by an $x-$polarized uniform plane wave from (a), (b) the top side (forward illumination) and (c), (d) the reverse side (backward illumination). The Si_3N_4 boundaries are shown as white dashed lines.

square-shaped dielectric diffraction gratings with a period p that are regularly patterned on top of the same-material dielectric slab waveguide with a thickness of t_s and a thin silver (Ag) film with a thickness of t_m. The height and width of the dielectric grating structure are t_g and w_g, respectively, and the entire structure is deposited onto a silicon dioxide (SiO_2) substrate. Silicon nitride (Si_3N_4) with a permittivity of 4.2025 is used for the dielectric grating and the dielectric slab waveguide, and the spectral refractive index of Ag is taken from the Johnson and Christy database [13]. The dielectric slab as a Fabry–Perot cavity is used to improve the coupling efficiency and tune the resonance wavelength. When the grating is normally illuminated by an $x-$ or $y-$polarized uniform plane wave, the incident wave is diffracted and then coupled into the waveguide and mixed SPP modes. These SPPs are modulated by the grating and can be outcoupled to the radiation modes in the substrate [11]. The commercial finite-difference time-domain (FDTD) software package is employed in calculations to seek out optimum geometries and dimensions as $p = 1165$ nm, $t_g = 260$ nm, $w_g = 880$ nm , $t_s = 470$ nm , and $t_m = 20$ nm to have a transmission peak at 1555 nm. The calculated transmission spectra are shown in Fig. 1(b) when the structure is illuminated by an $x-$ and $y-$polarized uniform plane wave propagating along the $\mp z$ directions (forward and backward illuminations). The proposed structure has an AT characteristic at the target wavelength of 1555 nm, with a maximum power transmission of 0.88 for the forward illumination and 0.028 for the backward illumination resulting in a maximum contrast ratio of 14.92 dB (see the dotted gray lines in Fig. 1(b)). In other words, the power transmitted in the forward direction is at least 31 times greater than the reverse direction. The obtained result for a $y-$polarized uniform plane wave demonstrates the independence of the structure to the polarization of the incident wave. The backward transmission within the operating wavelengths is very low since SPPs cannot be excited. The period of the three-dimensional diffraction grating is considered to be smaller than the desired operating wavelength of an incidence beam to ensure that only the low-order diffraction modes can be excited and transmitted into the substrate. The further analyses, given in Figs. 1(c) and 1(d), represent that $T_{(1,0)}$ and $T_{(-1,0)}$, among the five diffracted waves in the transmission mode, are the main reason of transmittance to the substrate. At the same time, each above-mentioned order carries almost half of the transmitted power at the angle of $(\theta, \phi) =$ (67.66,0) and (67.66,180), respectively. Near-field light-matter interactions of the proposed AT structure, including both forward and backward illuminations on the $x-z$ and $y-z$ planes (at the center of a single diffraction grating), are shown in Fig. 2 at the resonance wavelength of 1555 nm to visualize the wave behavior of the asymmetric transmission. The electric-field results demonstrate the excitation of SPPs at the interfaces of the Ag layer when the structure is normally illuminated by an $x-$polarized uniform plane wave from the top side. In contrast, the Ag layer mostly reflects the incident wave from the backside.

III. Conclusion

We proposed a simple periodic nanoarray design with a high AT property, which works based on the excitation and outcoupling of SPPs to the radiation modes. In contrast to the other works, the proposed design has a high contrast asymmetric light transmission ratio and provides near-zero inverse transmission. Furthermore, the operating principles can be extended to a different spectrum range due to the scalable property and flexible design of the proposed structure.

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