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The optical one-way transmission in helical metal subwavelength slit

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ABSTRACT

A novel line-type optical one-way transmission structure is proposed, which consists of a helical subwavelength metal slit. The simulation results obtained from finite-difference time-domain method show that this structure has excellent one-way transmission properties. When a polarized light propagates forward through the structure, its polarization direction will be rotated 90 degree. The backward propagation is blocked.This helical slit can also be a one-way unit of a plane-type one-way transmission structure, in which the setting angle plays an important role in determination of the transmission properties of the one-way plane via the strong coupling effect between the waves in adjacent slits.

1. Introduction

Optical one-way transmission devices are fundamental components in all-optical circuits. The materials required in making the one-way transmission devices can be either nonlinear [1–4] or linear materials [5]. The latter will linearly respond the input signals with arbitrary strengths, so that the corresponding one-way devices are more suitable for working in all-optical circuits. Because of the optical reciprocity [6], the one-way transmission in linear materials is of a channel effect, i. e., different optical channels distribute in different transmission directions [7]. Based on this effect, the one-way transmission structures composed of photonic crystals with asymmetry dispersion relations [8–13], the gratings (or hole arrays) with asymmetry surfaces [14,15], and the metamaterial (epsilon-near-zero or negative refraction index) slabs [16] with asymmetry surfaces have been proposed and achieved. These structures have the channels marked with different wave vectors, which are related to different refraction orders. So they can be thought as the refraction-inspired one-way transmission structures [14]. The other kind of channels with different polarization directions can result in the diffraction-free one-way transmission. The polarization-inspired one-way structures have been realized in traditional optical devices, such as the optical isolators made of magneto-optic materials or other optical-rotation materials. Because of their large sizes, these traditional isolators are difficult to apply in all-optical circuits. Recently, the polarization-inspired one-way micorstructures by metamaterials were proposed and realized [17–22]. However, these metamaterials based on the designed periodic cells can be used to fabricate the planar one-way devices, instead of the line-type devices which are more suitable to work in the all-optical circuits.

It's available to review the results about the twist micrometer and millimeter structures [23–26], especially the 90-degree twist wave guides [25,26] that make the transmission waves have the 90-degree polarization rotation. In these structures, the twist transform regions are complicated and not smooth, so this will lead to the return-loss. We noticed some other waveguides [24,27] which rotate round their longitudinal axis smoothly, and these structures inspired our work.

In this paper, we propose a simple structure to achieve the polarization-inspired one-way transmission by making use of the extraordinary transmission properties assisted by metal surface plasmon polaritons (SPPs). The structure is a helical subwavelength metal slit, which not only performs the one-way transmission as a line-type optical device but also is a periodic cell being able to construct planar one-way devices.

The paper is arranged as follows. In Section 2 the transmission properties of the helical slit are calculated and discussed, which show the excellent one-way properties. In Section 3 the transmission properties of the helical slit array are calculated and the inter-slit coupling effect are discussed. Section 4 gives our conclusion.

2. The helical slit and the results

The proposed one-way structure is sketched in Fig. 1. A

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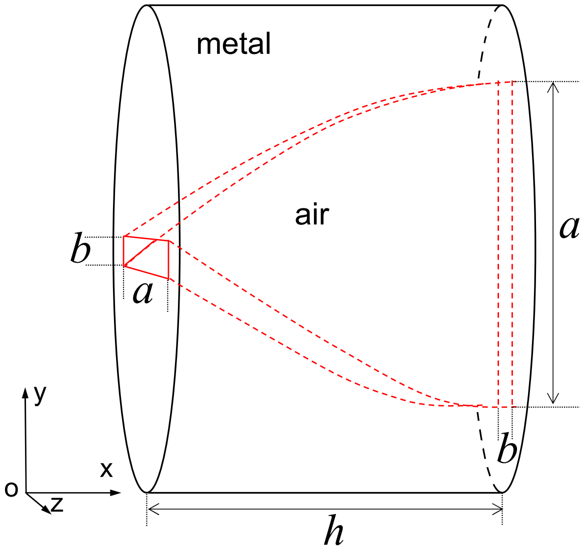

Fig. 1. Sketch of the one-way structure. A clockwise helical slit is cut onto the metal film with thickness h. The length and width of the slit are a=2000 nm and b=100 nm, respectively. On the two surfaces of the metal film, the slit directions are perpendicular to each other.

clockwise helical slit with the length a and width b is cut onto the metal film with thickness h. The Cartesian coordinate is set with the original point at the center of the slit mouth on the left surface of the film (for the sake of convenience, in Fig. 1 the coordination is drawn on the left-lower corner) and on this surface the length and width of the slit are along the z- and y-directions, respectively. Then the slit rotates in the film such that on the right surface, the slit mouth with the long edge parallels to y-direction, i. e., the slit has clockwise rotated 90 degree from the left surface to the right surface. This slit is called a helical slit.

Such a structure can work as a one-way device for the linearly polarized light. The principle is based on the well known properties that the excitation of the SPP wave needs the incident light with the electric field perpendicular to the narrow slit. Thus, when the y-polarized (electric field along y-direction) light coming from left side (along x-direction) and strikes on the left surface of the structure, the SPP wave can be excited so the transmission is allowed. But, as the slit is 90° rotated, when the backward y-polarized light strikes on the right surface, its electric field will be along the slit mouth, thus, the light will be blocked. It should be noticed that the slit width b must be in the subwavelength size so as to keep only the SPP wave being excited to travel in the slit. Otherwise, the higher-order modes of the y-polarized incident light from right side would be excited and pass through the slit, and as a result, the block effect would be violated.

Now we use the finite-difference time-domain (FDTD) method to simulate the transmission. In the simulation, the dimensions of the slit are always fixed at $a = 2000\,\text{nm}$, $b = 100$ nm, and the incident light is a polarized wave with wavelength 800 nm and the electric filed is along the y direction. It is called forward (backward) propagation when the light propagates from the left (right) to right (left). The simulation results with the film thickness varying from 500 to 2800 nm are displayed in Fig. 2. Fig. 2(a) and (b) are the transmissivities corresponding to perfect metal and silver, respectively. In the simulation process [28], the simulation area is 6000 nm × 6000 nm × 5200 nm (in y, z, x directions respectively) and one step in any direction is 10 nm. We have tested with 8 nm per step, the difference of the transmissivity is only about 0.0001. So our results are believable. Here the transmissivity is defined as $T = P/P_0$, where P is the power measured with a simulation monitor put on the slit exit with both the shape and area same with the slit exit so as to collect all the energy passing through the exit. When light illuminates the left (right) surface, the slit exit is on the right (left) surface. The forward and backward transmissivities are denoted by T_1 and T_2, respectively. P_0 is the power measured by the same monitor but the film is removed away. It is well known that the transmissivity in metal subwavelength slits can exceed 1.This is because the energy received by P_0 is proportional to the section area of the slit, but P gathers SPP wave which is generated in the area around the slit mouth and concentrated into the slit by the 'funnel effect' [29].

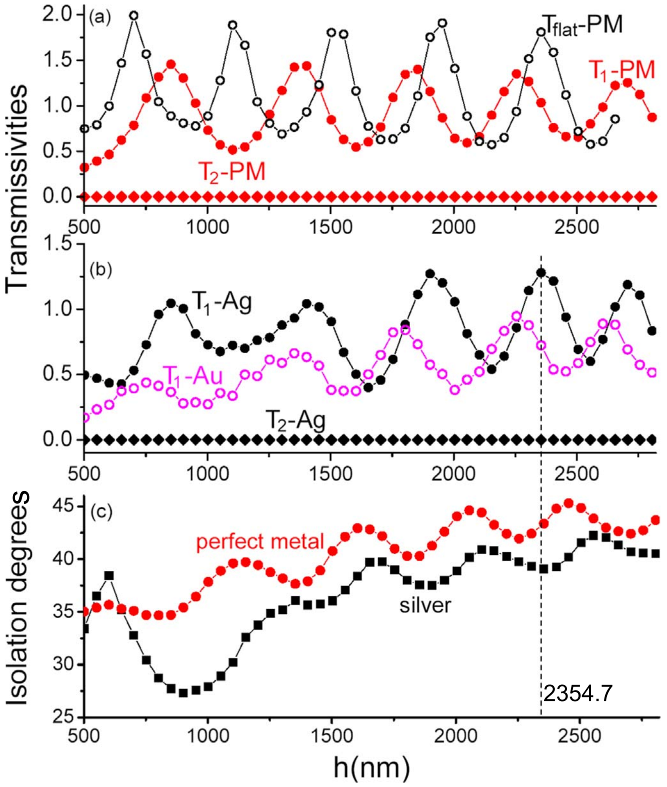

Fig. 2. The transmissivities as the functions of film thickness h when the film is (a) perfect metal and (b) silver and gold. All the symbols are the simulation results. The curves denoted by $T_1 - PM$, $T_1 - Ag$, $T_1 - Au$, are the positive transmissivites of the perfect metal, silver, and gold helical slits, respectively. $T_2 - PM$ and $T_2 - Ag$ are the corresponding backward transmissivites. $T_{flat} - PM$ is the transmission curve of the flat slit. (c) The isolation degree D as a functions of h. The circles and squares are the results corresponding to the perfect metal and silver, respectively.The lines are to guide eyes.

The results in Fig. 2(a) are for a perfect metal film. As the forward transmissivity $T_1 - PM$ is strong and the backward transmission $T_2 - PM$ is completely blocked, the helical metal slit exhibits the satisfactory properties of a line-type optical one-way structure. The prohibition of the backward transmission is due to the properties of the SPP in metal slit, which allows only the transmission of the TM-wave (the magnetic field parallel to the slit direction) to pass through but not TE-wave.

The periodic variation of $T_1 - PM$ is caused by the Fabry-Perot (F-P) multi-reflections. To confirm this, $T_{flat} - PM$, the transmissivity obtained from a flat slit was displayed by open circles in Fig. 2(a). It has been pointed out that the periodical variation in transmission of a flat slit was due to the F-P resonance [30]. In Fig. 2(a), the periods and amplitudes of $T_1 - PM$ and $T_{flat} - PM$ are close to each other. It is believed that the curve of $T_1 - PM$ varies because of the same reason. More explicitly, $T_1 - PM$ has a slightly lower peak height.

It is noticed that, compared with the $T_{flat} - MP$ curve in Fig. 2