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Enhanced optical transmission through a nano-slit based on a dipole source and an annular nano-cavity

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A novel plasmonic structure, composed of a dipole source and an annular nano-cavity over a nano-slit, is proposed as a surface plasmon polaritons source to enhance the extraordinary optical transmission (EOT) simulated using a finite-difference time-domain (FDTD) method. We find that the annular nano-cavity has an obvious advantage to couple more energy from a dipole source compared with previous EOT configuration. Based on the fact of non-uniform electric field distribution of a dipole source, the transmission through nano-slit is effectively improved by selecting optimized structure parameters. In addition, the transmission spectrum can be well-tuned by adjusting the central angle of the annular nano-cavity, as such, the design holds great promise for its application in EOT-based optoelectronic devices.

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1. Introduction

Since the extraordinary optical transmission (EOT) phenomenon through arrays of nano-holes [1] milled in a metallic film has been first reported by Ebbesen et al., many nanoscale metallic structures, including single aperture [2–4], circular aperture arrays [5–9] and annular aperture arrays [10–12], have been widely studied on their physical mechanisms and applications in EOT. It is well known that surface plasmon polaritons (SPPs) excited at the interface between metal and dielectric material play a crucial role in EOT phenomenon. Therefore, the key to enhance EOT is by exciting, collecting and propagating more SPPs. A metallic nano-aperture [13–15] or nano-slit [16–19] surrounded with periodic corrugations can enhance transmission by increasing the interactions of light-metal, and acting as the SPPs concentrator. Valdivia-Valero et al. presented an another method, and completed a series of fruitful theoretical and numerical studies [20–23]. These works have utilized a resonance device (e.g. photonic crystal, metallic and dielectric nanocylinders or chains of nanocylinders), which can effectively improve the transmission efficiency by collecting light near the exit or the entrance of a nanoslit. In recent years, a new and simpler method which can significantly enhance transmission has been proposed. In this approach, a horizontal Fabry–Perot (F–P) resonance nano-cavity [24,25] or nano-cavity arrays [26,27], formed by a metallic nano-strip or nano-strip arrays over a nano-slit milled in a metallic film, are designed to collect incident light and allow energy flow out of the nano-slit. In these works, the device is based on a TM plane polarization wave and a horizontal nano-cavity. And the metallic film is rectangle with infinite length. Obviously, there exist two deficiencies. First, for a horizontal nano-cavity, the length of the nano-strip should be increased to couple more energy and enhance transmission from a plane wave while the metallic loss of the nano-cavity increases with the length of nano-strip, which would hinder the transmission to be further improved. Second, the method of enhancing EOT is restricted to an unrealistic plane wave source and the configuration with huge size and single shape. Then a point light source and an annular device with a finite length have great promise in some applications, such as near-field scanning optical microscopy [28], sensor [29,30], optical trapping [31,32] and photodetector [33,34] used in chemical, biochemical or biomedical researches.

In this paper, we propose a new device based on a dipole source and an annular nano-cavity formed by an annular metallic nano-strip over a nano-slit in a semi-annular metallic film. This device has some unique features. First, an annular nano-cavity can effectively harvest more energy by increasing the field angle of the dipole source and decrease the metallic loss by decreasing the radius and the arc length of the nano-strip. Second, since the electromagnetic (EM) field of a dipole source is non-uniform distribution, which changes with the radius and central angle of the annular nano-strip, an enhanced EOT is obtained by choosing suitable structure parameters of the device. This work is numerically calculated using

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the finite-difference time-domain (FDTD) method with perfectly matched layers (PML).

2. Results and discussion

Fig. 1 shows the two-dimensional (2D) schematic diagram of an annular nano-cavity formed by an annular metallic nano-strip over a nano-slit in a semi-annular metallic film. The nano-strip has a central angle θ, outer radius r and uniform thickness h. The nano-slit has a width W. The semi-annular metallic film has an inner radius R and uniform thickness H. The semi-annular metallic film and the annular nano-strip share a common center ($x=0$, $y=0$), and are separated by a distance d. A dipole source of TM polarization with the magnetic field perpendicular to the x–y plane and wavelength $\lambda 0=1.0$ μm impinges normally on the bottom of the structure from the center. Both the semi-annular metallic film and the annular nano-strip are made of silver, whose frequency-dependent complex relative permittivity is characterized by the well-known Drude model. At $\lambda 0=1.0$ μm, $\varepsilon_{Ag}=-48.8+3.16i$ [35]. For simplicity, the dielectric is assumed to be air with permittivity $\varepsilon_{Air}=1$. The transmission efficiency η of the nano-slit is defined as $\eta=S_{yo}/S_{yi}$, where S_{yo} is the y-component of the Poynting vector over the output opening of the semi-annular metallic film, S_{yi} is the y-component of the Poynting vector over the input opening of the bare slit (without the semi-annular metallic film and the annular nano-strip).

Fig. 2(a) shows the transmission efficiency η as a function of the central angle θ of the annular nano-strip at different thickness of the semi-annular metallic film. First, in order to explain the physical mechanism for data shown in Fig. 2(a), we analyze the characteristics of the device, which contains two F–P resonance cavities (Fig. 1). The first F–P resonance cavity is formed by placing an annular metallic nano-strip over a semi-annular metallic film, and separated by an air gap (with thickness $d=44$ nm), namely the annular metal–insulator–metal (AMIM) resonance cavity. The second F–P resonance cavity is the vertical MIM waveguide formed by milling a nano-slit in the center of a semi-annular metallic film, when the phase length of the nano-slit reaches an even integer of $\pi/2$, the transmission of light through the nano-slit becomes maximal due to constructive interference [36]. On the contrary, when the phase length reaches an odd integer of $\pi/2$, the transmission will be minimal due to destructive interference. In this paper, the phase length of the SPPs in the nano-slit is $\pi/2$ ($H=240$ nm, $W=25$ nm) and $3\pi/2$ ($H=390$ nm, $W=25$ nm), respectively. Therefore, at the central angle $\theta=0^\circ$ [i.e. without first F–P resonance cavity], the transmission of the red-dotted curve (thickness $H=240$ nm) reaches 8, much bigger than other curves [Fig. 2(a)]. This is because the red-dotted curve corresponds to a resonant nano-slit, while the other

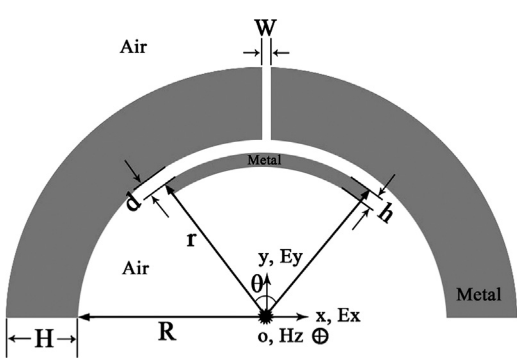

Fig. 1. Configuration of an annular nano-cavity formed by an annular nano-strip over the opening of a nano-slit in a semi-annular metallic film. A dipole source of TM polarization with the magnetic field perpendicular to the x–y plane and wavelength $\lambda_0=1.0$ μm impinges normally on the bottom of the structure from the center.

curves correspond to a non-resonant nano-slit. Fig. 2(b) and its inset show the magnetic field distribution corresponding to points A and B in Fig. 2(a), respectively. At the central angle $\theta\neq 0^\circ$ [i.e. there exist two F–P resonance cavities], the two F–P resonance cavities play different roles in EOT. The first F–P resonance cavity effectively collects the incident light as the annular nano-strip can excite SPPs by interacting with the incident light. The second F–P resonance cavity makes the energy flow out of the first F–P resonance cavity.

The transmission efficiency η depends on the configuration of two F–P resonance cavities, when an annular nano-strip (central angle $\theta=84^\circ$, thickness $h=50$ nm) is placed over the semi-annular metallic film (thickness $H=390$ nm, without vertical nano-slit), the magnetic field distribution shows five peaks due to 5π phase length in the first resonance cavity [Fig. 2(c)]. When a vertical nano-slit ($H=390$ nm, corresponding to a non-resonant state) is placed in the center of the semi-annular metallic film, the magnetic field distribution in the annular cavity [Fig. 2(d)] is similar as in Fig. 2(c). The transmission efficiency η reaches 15, corresponding to point C in Fig. 2(a). These results suggest that there is very weak EM field interaction between the two resonator cavities where the vertical nano-slit is non-resonant and the annular nano-cavity is resonant. Therefore, the SPPs can flow out of the nano-slit and enhance the transmission efficiently. On the other hand, when the vertical nano-slit is resonant ($H=240$ nm), the magnetic field distribution in the annular cavity becomes significantly distorted [Fig. 2(e)], and is very different from Fig. 2(d). Meanwhile, the corresponding transmission efficiency becomes smaller [$\eta=8$, corresponding to point D in Fig. 2(a)]. This is because that the EM field interactions of two resonator cavities significantly increase and the annular cavity can no longer keep its optimal internal field distribution to harvest light. In order to diminish the interactions, we adjust the central angle θ of the annular cavity and show that the transmission reaches maximal ($\eta=25$) as $\theta=77^\circ$. Fig. 2(f) shows that the magnetic field distribution in the annular cavity [corresponding to point E in Fig. 2(a)] almost remains the same as that in Fig. 2(g) (without a vertical nano-slit). In summary, when two F–P resonator cavities simultaneously achieve resonance, their EM field interactions become very strong, thus preventing the improvement of the transmission.

We further analyzed other curves (blue, green and pink) and found that the same order peaks of these curves have different values and positions. The value of the same order peak in general does not change monotonously when the thickness of semi-annular metallic film decreases, and vice versa. This can be explained as follow. When the thickness of the semi-annular metallic film decreases monotonously (compared with $H=390$ nm), the metallic loss due to the absorption of the metallic wall located on both sides of the vertical nano-slit will become smaller, thus enhancing transmission. At the same time, since the length of vertical nano-slit becomes closer to 240 nm, the EM field interactions between the vertical nano-slit and the annular nano-cavity increases, thus reducing transmission. In order to weaken the interactions and achieve a transmission peak, we enlarge the central angle of the annular nano-strip to increase its arc length. This drives the annular nano-cavity to a non-resonant state and right-shifts the transmission peak. On the other hand, when the arc length of the annular nano-strip becomes larger, the metallic loss of the annular nano-cavity increases, therefore diminishing transmission. Meanwhile, the light-collecting area of the annular nano-strip becomes larger, therefore increasing transmission. As such, the transmission peak arises from the competition of the four factors, i.e. the absorption of the vertical nano-slit, the metallic loss of the annular nano-cavity, the interactions of the two resonator cavities and the light-collecting area of the annular nano-cavity. The transmission will achieve its maximum at the optimal combination of the four factors.

Fig. 3(a) shows the transmission efficiency η as a function of the central angle θ for different thickness of the annular nano-strip

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