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Beam bending through compound structure with two subwavelength metallic slits in each period

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ABSTRACT

To provide a more practical, easy-to-implement method to achieve directional modulation with a plasmonic lens, beam manipulation method via compound metallic gratings with two subwavelength slits filled with different dielectrics inside each period is proposed and numerically investigated by finite-difference time-domain (FDTD) method. Compared with conventional metal-grating based structures, phase retardation is tuned by the Fabry-Pérot (FP) resonant condition and light bending is achieved by constructing a carefully designed, curved phase front for the plasmonic lenses. Our designs have advantages in ease of fabrication and capability to perform in the far field. With these advantages, the designs are expected to be valuable in applications such as plasmonic circuits and photonic communication.

1. Introduction

Since the phenomena of extraordinary transmission [1] and directional beaming of light [2] were reported, much interest has been attracted in investigations about surface plasmon polaritons (SPPs) excited in subwavelength metallic structures, which opens up the potential applications in plasmonic elements. Metallic light beam manipulating devices such as splitters [3,4], deflectors [5], angle compensators [6] and lenses [7–18] have been demonstrated. Both theoretical predictions [7,8,10,13–18] and experimental demonstration [9,11,17] have been reported in the visible range. Such devices work by modulating the phase delay distribution at the metallic device's surfaces according to the constructive light interference principle. In [18], plasmonic lenses cannot only focus, but can also bend electromagnetic (EM) waves have been designed and characterized. The bending effect is achieved by constructing an asymmetric phase front caused by varying phase retardations in EM waves and the control of the phase front profile is achieved through two mechanisms: phase retardation caused by the width and shape of the individual slits in the lens, and the position of these slits. For certain applications, it would be highly desirable to realize positional modulation through a plasmonic lens without changing the period of array, or the length and width of slits.

In this paper, we extend the previous studies and examine ways of controlling the phase front of the transmitted beam by introducing compound metallic gratings with two subwavelength slits filled with different dielectrics inside each period. When suitable dielectrics are chosen, the Fabry-Pérot (FP)-like modes with the different orders can be found inside the two adjacent slits at a certain resonant frequency, an asymmetric phase front caused by varying phase retardations in EM waves as they pass through the plasmonic lens can be constructed based on the FP resonant condition. The slits used in our designs are rectangular that guarantee the simplicity in fabrication using the focused ion beam (FIB) technique.

2. Structure and simulated model

Fig. 1 illustrates the proposed compound structure under study, where each period of the grating comprises two slits, slit 1 and slit 2, with identical widths but filled with different dielectric media with relative permittivities ε_{d1} and ε_{d2}, respectively. The interspacing between the two slits (center to center) is denoted as d, the period and thickness of the grating are Λ and L, respectively. It is worth noting that the distance between any two slits is much larger than the skin depth of surface plasmon inside the silver, hence, no surface plasmon cross-talk will occur between adjacent slits.

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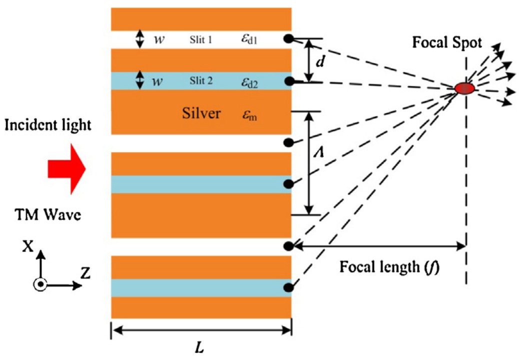

Fig. 1. Schematic diagram of the proposed structure: each period of the grating comprises two slits with identical widths but filled with different dielectric media. The input light is a TM-polarized plane wave from the left.

The frequency-dependent permittivity of the metal is expressed by the Drude model for the dielectric response of the metal which is mainly governed by its free electron plasmon

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \quad (1)$$

where ω_p is the plasma frequency, γ is the absorption coefficient, and ω stands for the frequency. The metal investigated is silver and the considered wavelength range is 600–1300 nm. The corresponding parameters are $\omega_p = 1.37 \times 10^{16}$ rad/s and $\gamma = 3.21 \times 10^{13}$ rad/s [19]. When $\omega < \omega_p$, the real part of the permittivity is negative, the standard time iteration scheme of the FDTD method becomes unstable. However, this problem can be solved by introducing the current density into Maxwell's equations [20]. We assume the monochromatic operation with the free space wave number $k_0 = \omega_0/c$, the time-dependency of $\exp(-j\omega t)$, and corresponding free space wave length $\lambda_0 = 2\pi/k_0$. Here, c is the speed of the light in vacuum.

To demonstrate the validity of designed structure, two-dimensional FDTD simulation is performed with the perfectly matched layer (PML) absorbing boundary conditions in x and z directions of the simulation domain. Since the width of the bus waveguide is much smaller than the operating wavelength in the structure, only the fundamental waveguide mode is supported. The incident light for excitation of the SPP mode is a TM-polarized (the magnetic field is parallel to y axis) fundamental mode. In the following FDTD simulations, the grid size in the x and z directions are chosen to be $\Delta x = \Delta z = 2$ nm and $\Delta t = \Delta x/2c$, which are sufficient for the numerical convergence, here c is the velocity of light in vacuum. The normalized time-averaged magnetic field intensity $|H_y|^2$ is employed to represent the field intensity.

3. Simulation results and discussion

In calculation, the whole length of the structure in the x-direction (see Fig. 1) is 2 micrometers (μm). In addition, two power monitors are placed at the input and output side of the grating for calculating the incident power (P_{in}) and the transmitted power (P_{out}). Subsequently, the transmission (T_r) is defined to be $T_r = P_{out}/P_{in}$.

Fig. 2(a) displays the calculated zero-transmission spectra of the simple gratings with subwavelength slits filled with different dielectric $\varepsilon_{d1} = \varepsilon_{d2} = 1$, $\varepsilon_{d1} = \varepsilon_{d2} = 2.48$ and $\varepsilon_{d1} = \varepsilon_{d2} = 4.5$, respectively. The parameters are chosen as: $w = 50$ nm, $d = 200$ nm, $L = 700$ nm, $\Lambda = 600$ nm. For $\varepsilon_{d1} = \varepsilon_{d2} = 1$, the transmission peaks at wavelengths 730 nm and 1050 nm are associated with the third- and second-order FP-like modes, respectively [21]. Similarly, the transmission peaks at wavelengths 670 nm, 800 nm and 1050 nm

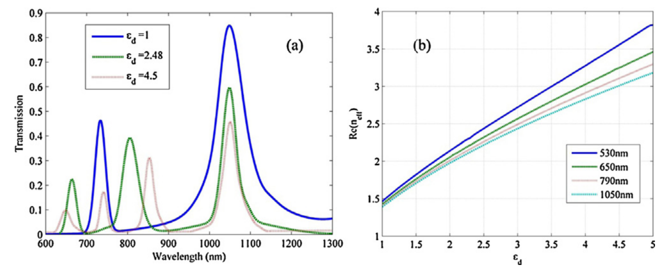

Fig. 2. (a) The calculated transmission spectra of the simple metallic gratings. (b) Variation of the real part of n_{eff} with permittivity for coupld-SPPs inside the metallic slit.

for $\varepsilon_{d1} = \varepsilon_{d2} = 2.48$ attribute to the fifth-, fourth- and third-order FP-like modes, respectively, and the transmission peaks at wavelengths 650 nm, 740 nm, 860 nm and 1050 nm for $\varepsilon_{d1} = \varepsilon_{d2} = 4.5$ attribute to the seventh- sixth-, fifth- and fourth-order FP-like modes, respectively.

For the bare metallic slit array, current density standing waves are established on both metal alls of each slit by incident oscillating light [22]. Owing to the existence of current flow, the distribution of charge density has been rearranged on the both surfaces of each slit. The length of FP cavity approximately equals to the distance of current flow on one wall, which is the extent of charge distribution in the y direction. The resonant wavelength of F–P mode in a bare slit array can be obtained by [23]:

$$2k_0 Re(n_{eff})L + \Delta\varphi = N \cdot 2\pi \quad (2)$$

where $k_0 = 2\pi/\lambda$ is the wave vector of light in vacuum, λ is the wavelength of the incident light in vacuum, n_{eff} is the effective refractive index of coupled-SPPs (waveguide mode) inside the slit, $\Delta\varphi$ is an additional phase shift experienced by the fundamental mode when reflecting at the grating interfaces, and N is an arbitrary integer. For TM-polarized case, n_{eff} can be approximately solved from [24]:

$$\frac{\varepsilon_d\sqrt{n_{eff}^2 - \varepsilon_m}}{\varepsilon_m\sqrt{n_{eff}^2 - \varepsilon_d}} = \frac{1 - \exp(k_0 w\sqrt{n_{eff}^2 - \varepsilon_d})}{1 + \exp(k_0 w\sqrt{n_{eff}^2 - \varepsilon_d})} \quad (3)$$

Fig. 2(b) plots the variation of the real parts of n_{eff} for the metallic slit filled with different dielectric media with four wavelengths.

Fig. 3(a)–(d) further illustrate the corresponding field intensity distributions when the slits are filled with different material at FP resonant wavelengths. The results show that the energy emerging from the structure tends to focus within several micrometers in an extremely small region (i.e., small FWHM). As seen from Fig. 3(b) and (d), the focal length will be changed when the resonant wavelength is different.

To deflect the beam, curved phase front of the transmitted beam should be achieved. The authors in Ref. [18] proposed a method to control the phase front profile by the width and shape of the individual slits and the position of these slits. Unlike previous studies [7–10,18], phase retardation in our structure is tuned by FP resonant condition. There is no need to change the period of array, or the length and width of slits. Thus the structure proposed in this paper is a much smaller, more compact device and convenient for integration. The position of focus and the bending angle are determined using the image processing software, ImageJ [25], to capture the area with the highest intensity within the main beam. Under normally incident radiation with different wavelengths, field distributions are shown in Fig. 4, where one can find the off-axis focusing phenomenon. Bam deflection can be observed from the simulation due to the constructive interference of the phase-delayed, transmitted waves from the rectangular slits.

The positional and directional modulation functionalities of a plasmonic lens are determined by the relative phase difference