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Subwavelength beam focusing via multiple-metal slits arranged along a triangle surface

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ABSTRACT

A compact plasmonic structure is proposed to actualize the subwavelength beam focusing, through a metal slit array arranged along a triangular or trapezium surface profile. The incident light passes through the metal slits in the form of surface plasmon polaritons (SPPs) and then scattered into radiation fields. The constructive interference of radiation fields from individual slits with different depths and widths gives rise to beam focusing. The advantages of the proposed plasmonic lens are having a much smaller lateral dimension and broad working wavelength range. This is of importance for realizing densely integrated photonic circuits. The finite-difference time-domain (FDTD) method is employed to verify the proposed design. The simulation results indicate that the focal spot is beyond the diffraction limit.

1. Introduction

Surface plasmon polaritons (SPPs), electromagnetic waves coupled with collective free electron oscillations at metal/dielectric interface, play a central role in the field of nanophotonics [1–4]. The most attractive feature of SPPs is their ability of manipulating light on a subwavelength scale with resonant field enhancement [5–8]. Therefore, there is a growing interest in developing plasmonic structures. Plasmonic lenses, with the ability to focus SPPs into a spot beyond the diffraction limit, which enables various applications such as super-resolution imaging, high density optical data storage, and integrated optical circuit, have attracted an increasing research interest in recent years [9–16]. Various geometries, including circular holes with concentric grooves [9], slits flanked by linear arrays of grooves [10], metal slits with variant depths [11] or widths [13–17], and single metallic slit surrounded with grooves [17–19], have been considered to implement the focusing capability of plasmonic lenses. However, although a few excellent designs of them are capable of focusing light beyond the diffraction limit [13,14], complex structure and sophisticated parameters make them especially difficult to fabricate by using the present techniques. On the other hand, the lateral dimensions of the focusing devices are at least 4 μm [7,9,10,12–16], which is a drawback for realizing densely integrated photonic circuits. The lateral dimensions of some structures are decreased to about 2 μm [11,17]; nevertheless, the full-width at half-maximum (FWHM) of the generated focal spot is larger than the half of incident wavelength.

In this paper, we design a plasmonic structure for producing subwavelength beam focusing. The structure consists of metal slits with different widths and intervals and the slits are arranged along a triangular or trapezium surface profile. The finite-difference time-domain (FDTD) method is employed to verify the proposed designs. The simulation results indicate that the proposed lens can yield a converging beam with a focal spot size beyond the diffraction limit. Compared to other existing counterparts, our structure combines the benefits of sub-diffraction-limit focal spot size, broad working wavelength range and smaller lateral dimension.

2. Principle and design

Fig. 1(a) shows the schematic of the proposed plasmonic lens. It consists of five metallic slits symmetrically arranged along a triangular surface. The metallic slits have different widths and intervals. When incident light illuminates the bottom side of the structure, the light wave is coupled to SPP modes at the entrances of the metallic slits and transferred to the other side. The complex propagation constant β of SPP mode is determined by the

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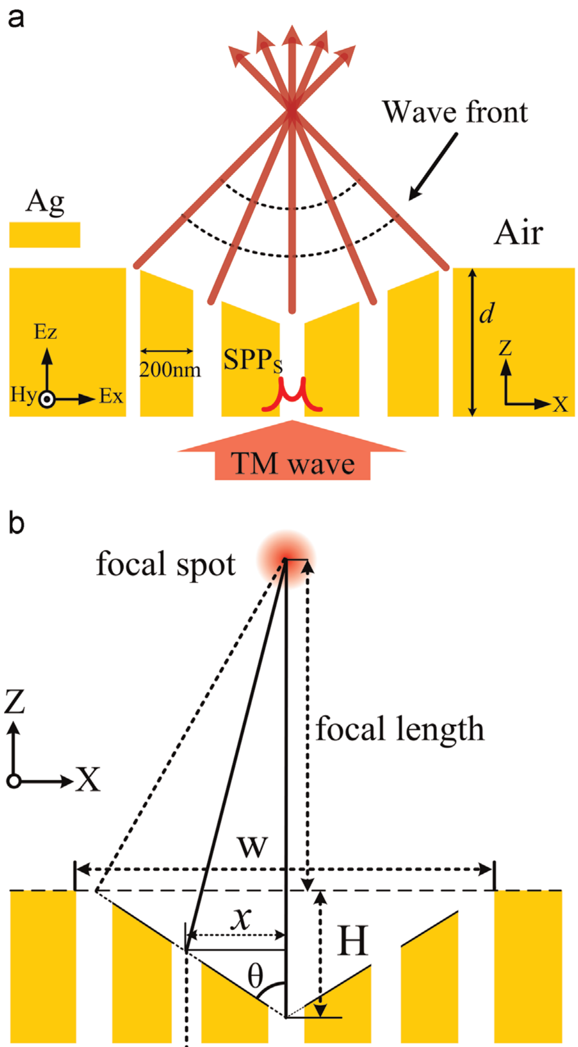

Fig. 1. (a) Schematic diagram of the proposed plasmonic lenses. A metal slit array is embedded in the metal slab with a triangular surface profile. A transverse magnetic (TM) light is incident on the bottom of the metal slab. (b) Schematic diagram of the proposed plasmonic lenses.

following equation [12]:

$$\tanh\left(\frac{w}{2}\sqrt{\beta^2 - k_0^2\varepsilon_d}\right) = \frac{-\varepsilon_d\sqrt{\beta^2 - k_0^2\varepsilon_m}}{\varepsilon_m\sqrt{\beta^2 - k_0^2\varepsilon_d}} \tag{1}$$

where k_0 is the wave vector of light in free space, ε_m and ε_d are the relative dielectric constants for the metal and the materials between slits, respectively, and w is the slit width.

The value of $\mathrm{Re}(\beta/k_0)$ represents the effective refractive index of SPPs modes in the slit and determines the phase retardation. The electric permittivity of air is 1. On the other hand, because of slits arranged along a triangular surface, the depths of slits are also different. The phase retardation $\Delta\phi$ of light passing through metal slits with variant depths can be calculated by the following equation [14]:

$$\Delta\phi = \mathrm{Re}(\beta h) + \arg\left[1 - \left(\frac{1 - \beta/k_0}{1 + \beta/k_0}\right)^2 \exp(2j\beta h)\right] \tag{2}$$

where h is the depth of center position of metal slit. The frequency-dependent complex relative permittivity of silver is characterized by the Drude model:

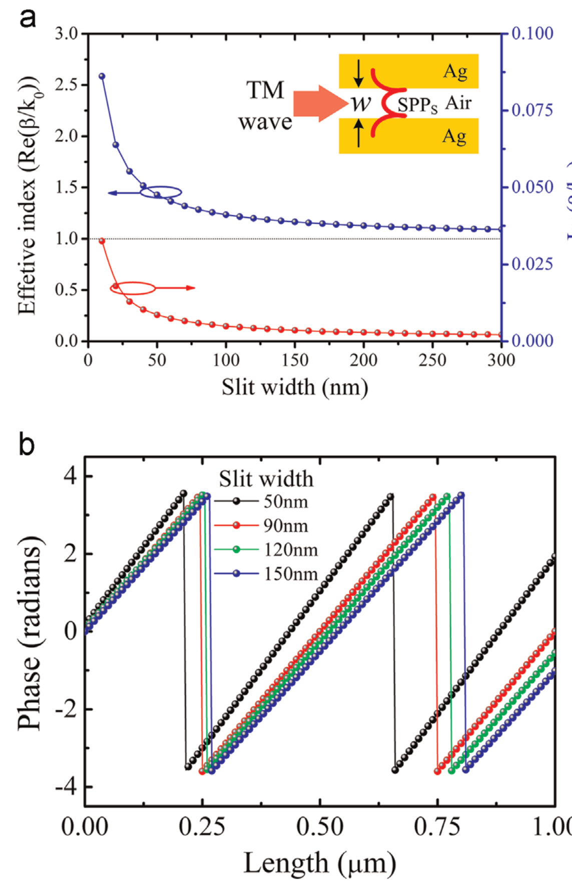

Fig. 2. (a) Dependence of effective index of SPPs in the silver slit on the slit width. The black dot line represents the value for a plane wave in air. The inset shows the schematic diagram of the metal slit structure. (b) Dependence of phase retardation of SPPs in the slit on the slit depth.

$$\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \tag{3}$$

Here $\omega_p = 1.38 \times 10^{16}$ Hz is the bulk plasma frequency; $\gamma = 2.73 \times 10^{13}$ Hz is the damping frequency of the oscillations, ω is the angular frequency of the incident electromagnetic radiation, and ε_∞ stands for the dielectric constant at infinite angular frequency with a value of 3.7 [20].

Fig. 2(a) shows the dependence of effective index of SPPs mode on the slit width using silver at a wavelength of 633 nm. Fig. 2(b) plots the phase retardation introduced by the slits with different widths and depths. The transmitted SPPs will be converted to radiating fields at the ends of metallic slits by scattering. If the parameters of metal slits such as width, depth, and interval are appropriately chosen, the radiating fields from individual metallic slits will focus at the specific point due to the constructive interference. Fig. 1(b) shows the geometric relations. Here, we define the distance from spot to the plane of metal film as the focal length. According to the geometry in Fig. 1(b), it is easy to obtain that the phase difference between the light radiated from different slits at the focusing spot position is about

$$\varphi \approx \frac{2\pi}{\lambda}\left(f + H - \sqrt{(f + H - |x|/tg\theta)^2 + x^2}\right) \tag{4}$$

where, f is the focal length, and $k_0 = 2\pi/\lambda$ is the free space wave vector of the incident light. W and H represent the width and height of the triangular $tg\theta = W/2H$. There are two notable advantages to using the triangular surface profile: This design enables decreasing the number of metal slits by constructing the