Planar Metallic Lens Based on an Array of Slits Modified by Perpendicular Cuts

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Abstract: A novel method for beam focusing in plasmonic lenses with an array of nanoslits perforated on a thin metallic film is proposed. Modifying the nanoslits with perpendicular cuts is utilized to change the effective length of the nanoslits which provides the possibility of manipulating the phase front profile based on the propagation property of the Surface Plasmon Polaritons (SPPs) in the metal-insulator-metal (MIM) waveguides. Using the dispersive finite-difference time-domain (D-FDTD) numerical method, simulations are conducted to explore the beam focusing phenomenon and the performance parameters of the lens include the focal length (FL), full-width half-maximum (FWHM) and depth of focus (DOF). The whole structure is formed on a planar thin film which is convenient for miniaturization and high density integration besides that it can be fabricated simply by well-known techniques such as focused ion beam (FIB) milling.

Keywords: Plasmonics, FDTD Numerical Method, Metal-Insulator-Metal Waveguide.

1. Introduction

The ability of metal/dielectric interfaces to sustain surface electromagnetic waves coupled to collective oscillations of free electrons in a metal known as Surface Plasmon Polaritons (SPPs), has attracted great attentions to surface plasmon-based photonics or Plasmonics in recent years [1-3]. With a rapid development in nanofabrication technology, it has become possible to pattern metallic structures at the nanoscale and realize the miniaturization of wide-band photonic devices compatible with current electronic architectures [4, 5].

Refractive lenses are one of the most ubiquitous optical components with applications ranging from imaging to concentrating light, but their light confinement capability deteriorates as their size approaches the wavelength of light due to the diffraction limit. Plasmonic lenses as an alternative to the ordinary refractive lenses are capable of super focusing beyond the diffraction limit and have great applications in optical data storage, nanofabrication, single molecular biosensing, circular polarizer analyzer, and so on [4, 6-8].

Single subwavelength slit surrounded by surface corrugations [9] or by chirped dielectric surface gratings [10], chirped circular slits corrugated on metallic film [11], quasiperiodic array of nano-holes [12] and nanometric cross-shaped aperture arrays in a metal screen [13] are some of the reported design principles to implement the focusing capability of plasmonic lenses. Nanoslits perforated on thin metallic films are recently employed to manipulate the phase front profile [14-16]. The single-pass phase shift experienced by light passing through the nanoslits is $\text{Re}(\beta L)$ with $L$ being the slit length and $\beta$ being the complex propagation constant of a wave propagating in the nanoslit. This phase shift is sensitive to the width of slits and refractive index of the incorporated material; in the result of the dependency of $\beta$ on these parameters, besides the slit length [4]. The required phase front profile for beam focusing action can be achieved by appropriate adjustment of the properties of each slit. Plasmonic lenses consisting of an array of nanoslits with variant width and length are thoroughly investigated in literatures. Active control of beam focusing and deflection by infiltrating the nanoslits with Kerr nonlinear material [17], Organic electro-optical material [18] and anisotropic nematic liquid crystal [19] are also explored.

In this contribution, for the first time to the best of our knowledge, we propose a plasmonic lens on the basis of an array of nanoslits perforated on a thin metallic film and modified by perpendicular cuts. We explore the effect of introduced cuts or bumps in the middle of the slits on their effective length and also on the transmission spectra. The required phase front profile for beam focusing action is obtained by proper positioning of cuts and tuning their dimensions.

This paper is organized as follows; In Section 2 the structure of the proposed lens and the simulation method are presented. The effect of cuts and bumps in the middle of the slits on the effective length of the slits and on the transmission spectra are explored in Section 3. Section 4
elucidates results of the detailed simulations of the lens and the conclusion will be in Section 5.

2. Device Structure and Model

Schematic view of the basic structure is presented in Fig.1. It is composed of seven nanoslits with \( w = 80 \) nm, \( L = 800 \) nm, and \( \Delta = 400 \) nm. The slit interspacing is large enough to avoid coupling between adjacent slits. The medium in the slit region is assumed to be air.

In our simulations, two-dimensional dispersive finite-difference time-domain (2D D-FDTD) numerical method is utilized, assuming the slit lengths (in z direction) to be infinite. This assumption is acceptable for slit lengths larger than 15 \( \mu \)m [20]. Obviously more accurate results by investigating the effect of finite slit length can be obtained by 3D FDTD but at a cost of large amounts of computer memory and increased computing time. The outer boundary of the computation lattice is terminated to the convolutional perfectly matched layer (CPML) to dissipate outgoing waves [21]. The grid sizes are chosen \( \Delta x = \Delta y = 10 \) nm and the time step is set achieved by Courant stability condition, where \( c \) is the speed of light in free space. The frequency dependent permittivity of the silver is calculated by the Drude model, when time dependency is taken

\[
\epsilon_n(\omega) = \epsilon_\infty - \omega_p^2 j / (\omega^2 - j \gamma \omega) 
\]

Where \( \epsilon_\infty = 3.7 \) comes from the contribution of the band electrons to the polarizability, \( \omega_p = 9.1 \) eV and \( \gamma = 0.018 \) eV are the plasma frequency and the collision frequency related to energy loss, respectively [22].

3. Analysis and Transmission Spectrum

For calculating the transmission spectrum which is depicted in Fig.2 (a), by utilizing the fast Fourier transform (FFT) method, the structure is illuminated by a broadband Gaussian plane wave with TM polarization consisting of \( E_x \), \( E_y \) and \( H_z \) field components. The magnetic field intensity distributions in nanoslits for four peaks in transmission spectrum are shown in Fig.2 (b)-(e). The incident wavelengths are 1940, 970, 655 and 510 nm correspond to the mode numbers 1, 2, 3 and 4 respectively.

![Fig. 1: Schematic of the basic structure consisting of an array of bare slits perforated on a thin metallic film](image)

![Fig. 2: (a) Transmission spectrum of the basic structure (b)-(e) Magnitude of magnetic field distribution for four transmission peaks](image)

The resonant wavelength of Fabry-Perot (F-P) resonances in a bare slit can be determined by [23]:

\[
2kL_{FP} + \theta = 2N\pi 
\]

Where \( k = 2n\pi / \lambda \) is the wave vector, \( n \) is the effective refractive index which depends on the slit width, \( L_{FP} \) is the length of the cavity, \( \theta \) originates from multiple reflections of light between the entrance and exit surfaces of the slit and \( N \) is a dependent value [23].

For a bare slit, current density standing waves are established on both metal walls of the slits. The current flow on one wall of the slit is opposite to that on the other wall. Quasi standing waves of charge density with opposite signs are also formed on both metal walls of the slits in the x direction. So a bare slit can be assumed as a parallel-plate capacitor which its ability of accumulating charges determines its capacity. The ability of accumulating charges and hence the capacity is proportional to its length in the x direction. Introducing the cuts affect the length of current flow and the effective length of charge distribution denoted by \( \delta l \) and \( \delta Q \) respectively. While the existence of cuts increases the length of current flow, it diminishes the ability of accumulating charges which is equivalent to a reduction in slit length. So the total effect of the cut on F-P cavity effective length can be determined by [23]:

\[
L_{eff} = L_{FP} + \delta l - \delta Q 
\]

If \( \delta l > \delta Q \) the effective length will be larger than the actual length and red-shift in resonant wavelength is observed in transmission spectrum while blue-shift in resonant wavelength is expected if \( \delta l < \delta Q \).
The surface current \( J \) and surface charge density \( \sigma \) are calculated by [23, 24]:

\[
\mathbf{n} \times \mathbf{H} = J
\]

(4)

\[
\mathbf{n} \cdot \mathbf{D} = \sigma
\]

(5)

Where \( \mathbf{n} \) is a unit normal vector directed from metal into air in slit, \( \mathbf{H} \) and \( \mathbf{D} \) are magnetic field and electric displacement. Considering Equations (4) and (5), if the cut locates at the center of antinode of magnetic field (node of electric field) like the center of slits for odd modes, the current density and charge density reach their maxima and minima respectively, hence the effective length of the F-P cavity and the resonant wavelength increase while for even modes the situation is reverse and the resonant wavelength decreases.

For the case of appearance of the bumps, the length of current flow shortens while the ability of accumulating charges and the effective length of charge distribution increase. The total effect of the bump on F-P cavity effective length can be determined by [24]:

\[
L_{\text{eff}} = L_{FP} + \delta Q - \delta I
\]

(6)

By the same reasoning for the case of the cuts, if the bump locates at the center of antinode of electric field (node of magnetic field) the effective length of the cavity and the resonant wavelength increase but if the position of the bump be at the center of node of electric field, the effective length of F-P cavity decreases.

The unit cells of the basic structure with perpendicular cut and bump at the center of slits are presented in Fig.3 (a) and (b). The transmission spectra in Fig.3 (c) illustrate the effect of these modifications with \( w_c = 50 \) nm, \( h_c = h_b = 300 \) nm and \( w_b = 20 \) nm on resonant wavelength of even (\( N=2 \)) and odd modes (\( N=3 \)) of F-P resonances.

According to the above discussion, we found that the required phase front profile for beam focusing action can be achieved by modification of the slits with the cuts and bumps. As previously mentioned, the existence of cut at the middle of the slits for even modes, which is the location of the node of magnetic field, reduces the F-P cavity effective length and hence the phase retardation of the transmitted light through them. As can be seen in Fig.3 (c), the effect of bumps and cuts at the center of slits on second resonant F-P mode is more than the third one and in what follows we investigate the light focusing phenomenon at this mode by introducing perpendicular cuts to the middle of slits with increasing dimensions from center to side. The schematic structure of the proposed lens is depicted in Fig. 4.

4. Beam Focusing
The time-average distribution of magnetic field intensity is shown in Fig. 6 clearly indicating the appearance of the focal point. The FL is measured 1930 nm and the side lobe levels on the focal plane are -7.8 dB.

5. Summary and Concluding Remarks

In this work, for the first time to our knowledge, we have shown the potential of an array of modified slits by perpendicular cuts and introduced on a silver layer for beam focusing action. According to our analysis and also our simulations with FDTD method, the existence of cuts and bumps in the slits affects the effective length of the slits considered as F-P cavities as well as the resonant wavelength of F-P cavity modes and the phase retardation of the transmitted light through them. We have achieved the required phase front profile for beam focusing action by precise selection of the operating wavelength, proper positioning of the cuts and tuning their dimensions. The proposed lens can find valuable potential applications in ultrahigh integrated optical circuits on flat metallic surfaces.

References