Optical Focusing by Planar Lenses Based on Nano-scale Metallic Slits in Visible Regime

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Abstract

A kind of planar metallic lenses is proposed to realize optical focusing in the visible wavelength through a metallic film with nano-scale slit arrays, which have the same depth but tuning widths. Due to the subwavelength and aperiodic nature of planar metallic lenses, we present the rigorous electromagnetic analysis by using two dimensional finite difference time domain method. The electromagnetic wave transports through the tuning slits in the form of surface plasmon polaritons, and gets the required phase retardations to focusing at the focal plane. We analyze the focusing characteristics of planar dielectric lens and metallic lens with tuning widths that are obtained by generalizing the relevant phase delay, for different incidence polarization waves (TM polarized case and TE polarized case). The computational calculation results show that, extraordinary optical transmission of surface plasmon polaritons through non uniform nano-scale metallic slits is observed, and it has contributions to the optical focusing, but cannot increase the focal energy compared with dielectric planar lens with the same profile, and the metallic lenses are more sensitive to the polarization of incidence wave than that of dielectric lenses. The influence of metallic lenses’ thickness on the focal characteristics has been analyzed also.

1. Introduction

Metallic nanostructures have been a subject of considerable interest in recent years, since the discovery of extraordinary optical transmission phenomena through subwavelength metallic aperture array [1,2]. Such
light transmission phenomena may be explained as an excitation of a surface plasmon polaritons (SPPs) mode which is an electromagnetic excitation existing on the surface of noble metals, at the nano-scale aperture entrance where wave propagates through it before emitting into radiation modes at the exit[3-5]. Otherwise, with developments of nanofabrication techniques, such as laser beam writing, electron beam lithography, and focused ion etching, nano-scale metallic structures with high refinement are available. This has enabled to develop new nanophotonic integrated devices based on the plasmonic behavior of metals used for wave guiding, biosensing, and superfocusing, etc[6,7]. Recently, metal coated Fresnel zone plates (FZPs) have been proposed to realize superlens in the visible wavelength[8,9]. A metallic film with arrayed nano-slits, which have constant depth but variant widths, say, planar metallic lens, is proposed to focus beam by modulating light phase [10]. Lieven et al experimentally demonstrated planar lenses based on nano-scale slit arrays in a metallic film, and got an excellent agreement between electromagnetic simulations of the design and confocal measurements on manufactured structures [11]. Otherwise, in our previous study, we analyzed focusing characteristics of planar dielectric lenses with binary subwavelength structures based on the electromagnetic theory in detail [12]. Little work, however, has been done on analyzing focusing characteristics of planar metallic lenses with the same subwavelength structures as previous dielectric lenses.

So, in this paper, we present the rigorous electromagnetic analysis and design of planar metallic lenses that are finite in extent and have nano-slit array with variant width according to the phase modulation by using a two dimensional finite-difference time-domain method[13]. By using these effective analysis tools, we analyze the focusing characteristics of planar lenses with nano-scale slit arrays, which have the same depth but tuning widths, for different incidence polarization waves (TM polarized case and TE polarized case) and for different material (noble metal and dielectric). The comparative results have shown that metallic lens can indeed focus the light in visible regime, and its full width at half maximum (FWHM) at the focal plane is slightly narrower than the wavelength of incident wave, and its focusing characteristic is more sensitive to the polarization of incidence wave than that of dielectric lenses. The transverse magnetic (TM) polarization plane wave can be well focused by a metallic lens, due to TM polarization wave excites the plasmonic waveguide modes in the nano-slits upon incidence on the metallic structure, but the metallic lens can not focus TE polarization wave, because of no SPPs. By contraries, a dielectric lens can focus both TE polarization wave and TM one.

2. Theoretical background and Structure

The surface plasmon polariton (SPP) is the coupled mode of an electromagnetic wave and free charges on a metal surface, and it can propagate along metallic surfaces while keeping bounded near the boundary between a metal and a dielectric. Because of the charge distribution near the surface, SPPs can be excited only by TM polarization wave. According to the phase matching condition of Maxwell’s equations, and the Drude model, the SPP dispersion relation between air and the metal can be written as:

\[ \omega = \sqrt{\frac{\omega_p^2}{2} + (c_0 k_x)^2 - \left[ \frac{\omega_p^4}{4} + (c_0 k_x)^4 \right]^{1/2}} \]  

(1)

where \( \omega \) is the angular frequency of SPP, \( \omega_p \) is the plasma frequency, \( c_0 \) is the speed of light in vacuum, \( k_x \) is the propagation constant of SPP.
In our paper, the two-dimensional electromagnetic diffraction problem in a system of planar lens is schematically shown in Fig. 1, where D is the diameter of the lens, and d is the thickness of the planar lens. The material of the lens could be dielectric and noble metal, and the two sides of the lens is air. This planar lens structures consist of an array of nano-scale slits whose widths are specifically modified to make the required phase delay. The transmitted light in visible regime from slits is modulated and focus in free space. The focusing characteristics of the lens are then analyzed by a two-dimensional finite-difference time-domain method, and a plane wave is used as a source. The perfectly matched layers are applied at the outer boundaries to simulate the infinite space. To metallic lenses, the TM polarization plane wave will excite the plasmonic waveguide modes in the slits upon incidence on the metallic structure. In this paper, we use gold and fused silica (SiO2 glass) to be the lens material. At the incidence wavelength \( \lambda_0 = 637 \text{nm} \) (in visible regime), the relative dielectric constant for the gold and glass are set to \(-11.4 + 0.78i\) and 2.13, respectively. The propagation constant \( k_p \) for the slit plasmon can be calculated using the dispersion relation of the plasmon mode[14,15]:

\[
\tanh \left( \sqrt{k_p^2 - \varepsilon_m k_0^2} \right) = \left( \frac{\sqrt{k_p^2 - \varepsilon_m k_0^2}}{\sqrt{k_p^2 - \varepsilon_d k_0^2}} \right) \left( \frac{\varepsilon_d}{\varepsilon_m} \right)
\]

where \( k_0 = \frac{2\pi}{\lambda_0} \) is the vacuum wavevector, and \( \varepsilon_m \) and \( \varepsilon_d = n_d^2 \) are the relative dielectric constant of the metal medium and the materials between slits, and \( w \) is the slit width. The dispersion relation between the effective refractive index and slit width implies that the phase delay can be modulated by simply tuning the slit width. For the whole dielectric planar lens, the phase delay \( \varphi(x) \) associated with a particular \( x \) location should be[12]:

\[
\varphi(x) = \frac{2\pi}{\lambda_0} \ n \ (f - \sqrt{f^2 + x^2})
\]

where \( n \) the refractive index of air and \( f \) is the focal length of a lens.

3. Numerical results

In this study, two-dimensional planar metallic lens is designed and analyzed. The lens is illuminated by a normally incident TE or TM polarization plane wave (the wavelength is 637nm). The parameters of the lens are as follow: the diameter of the lens \( D = 8 \mu \text{m} \), the focal length \( f = 2.4 \mu \text{m} \), and the thickness of slits \( d = 450 \text{nm} \). The distribution of slits is the same as the planar dielectric lens (Ref 12), but with different material (gold). Firstly, we will check the polarization dependence of this metallic lens, so we calculated characteristics of lens with different polarization wave, and the total electric field intensity distribution in the x-y plane are shown in Fig. 2(a) and (b), for TE polarization and TM polarization, respectively. For the TE polarization wave (light polarized parallel to the slits), no focusing is observed due to the absence of excitation of SPPs, as shown in Fig. 2(b), but for the TM polarization wave , a clear-cut focus appears in the focal region (about 2.3 micron away from the lens surface), as shown in Fig. 2(a). Besides, the
extraordinary optical transmission of surface plasmon polaritons through non uniform nano-scale metallic slits is observed in Fig. 2(a).

![Image of Fig. 2(a) and (b)]

Fig. 2. The total electric field intensity distribution of planar metallic lens, for different incident polarization wave: (a) for TM polarization wave, and (b) for TE polarization wave. The red districts indicate high field intensities, and the black ones indicate low field ones, respectively. The yellow lines are profiles of the metallic lens.

The axial electric field intensity distribution (along y axis), and the lateral intensity distribution (along x axis at the focal plane) are shown in Fig. 3(a), and (b), respectively. The full-width half-maximum (FWHM) of the beam extension for the lens with a focal length of 2.35μm is 310nm which is narrower than the wavelength of incident wave (637nm).

![Image of Fig. 3(a) and (b)]

Fig. 3. The electric field intensity distribution by a planar metallic lens in cross sections of the focus along the axis (y) direction (a) and x direction at the real focal plane (b).

Figure 4 depicts the transmitted electric field intensity from the metallic lenses with various thickness of Au along y and x (at the focal plane) directions. It is observed that the focal length along the axis direction and the light peak value at the focal plane are influenced with different Au thickness. This diversification may be due to the presence of strong coupling of SPPs, evanescent fields and the diffractive fields in the thin Au slits that contributes differently to the propagation field outside the metallic lens. And for the thickness of 450nm, a higher peak value is obtained.
In order to demonstrate the performance of planar metallic lens, the focusing characteristics of the metallic lens and the dielectric (glass) lens are compared with the same parameters except for the material, and both lenses have the same slit distribution. The relative dielectric constant for the glass is set to 2.13 for the incident wavelength (637nm). Total electric field intensity distributions are shown in Fig. 5(a) for TE polarization, and (b) for TM polarization. Axial electric intensity distribution and lateral intensity distribution are shown in Fig. 6(a) and (b), which shown that the focusing characteristic of planar dielectric lens is sensitive to the polarization of incidence wave, but not like the metallic lens, the dielectric lens can focus well for both TE and TM polarization. From Fig. 6(b) the FWHMs are 420nm and 340nm for TE polarization and TM polarization, respectively, which are larger than that of the metallic lens. The comparative results have shown that our planar metallic lens can be treat as a superlens to realize a higher resolution, which shows an avenue towards various potential applications, such as integrate optical system, high density date storage, etc.
4. Summery

We present the electromagnetic analysis of planar metallic lenses and dielectric lenses that are finite in extent and have the same depth but tuning widths, which have the ability for integration and can require only single step fabrication, by using a two dimensional finite-difference time-domain method. We analyze the focusing characteristics of metallic lenses and dielectric lenses, for different incidence polarization waves (TE polarization and TM polarization) and for different metal thickness. The comparative results have shown that SPPs has contributions to the optical focusing of metallic lenses which can get a smaller focal spot than that of dielectric lenses. Besides, the metallic lenses are more sensitive to the polarization of incidence wave than that of dielectical lenses with the same profile.

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References


