The Talbot effect of plasmonic nanolenses

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Abstract: The Talbot effect of an Ag nanolens with five periodic concentric rings that are illuminated by the radially polarized light was numerically studied by means of rigorous finite-difference and time-domain (FDTD) algorithm. It was found that the Talbot effect occurs only when the incident wavelength is at the scale of less than half of period of the grating structures of the nanolenses. Specifically, in this work, the nanolenses with a 500 nm period grating structures has five focal points due to Talbot effect for the incident wavelength of $\lambda = 248$ nm. The diameter of the first focal spot after the exit plane in free space is 100 nm. In contrast, we analyzed the corresponding focal points on the basis of Talbot self-imaging by scalar diffraction theory. It was found that the scalar Talbot effect cannot interpret the Talbot effect phenomenon for the metallic nanolenses. It may attribute to the paraxial approximation applied in the Talbot effect theory in far-field region. However, the approximation does not hold in our nanolenses structures during the light propagation. In addition, the Talbot effect appears at the short-wavelength regime only, especially in the ultraviolet wavelength region.

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1. Introduction

In recent years, many researchers have paid much attention to surface plasmon polaritons (SPPs)-based metallic nanostructures because of their promising prospects of potential applications in imaging, data storage, near-field microscopy, sensing, and nanolithography [1–12]. Recently, an SPP-based nanolens for the application of nanophotolithography was reported [7]. Further study was carried out for the purpose of modifying the nanolenses generated focal spots by means of changing previous elliptical nanopinholes to be circular rings under radial polarized illumination at $\lambda_{\text{inc.}} = 248$ nm. However, our calculation results indicated that there are several focal points existing along central axis in free space after the exit plane of the nanolenses.

To explore its physical mechanism, we compared the phenomenon to another well-known story: the Talbot effect, i.e., self-imaging. The self-imaging means that when a one-dimensional (1D) periodic structure is illuminated by the monochromatic plane wave, the image of that structure can be observed at the periodical distance from the back side of the structure. It is a type of imaging by diffraction rather than an ordinary imaging of a lens. Actually, some researchers are still interested in the self-imaging effect since H. F. Talbot discovered it in 1836 [13]. Intensive theoretical and experimental studies regarding the Talbot effect have been done since then. For example, the plasmon analogue of the self-imaging Talbot effect of a row of holes drilled in a metal film was described and theoretically analyzed, and suggested the potential applications in sensing, imaging, and optical interconnects on the basis of plasmon focal spots aimed at plasmon waveguides [14]. Subsequently, the Talbot effect regarding SPPs imaging on the basis of a rather different system by a quite different approach was studied theoretically and experimentally [14–17]. Furthermore, the Talbot effect for volume electromagnetic waves has been used in a variety of applications [18–20]. In addition, it is expected that the analogue for SPPs will be found applications in numerous nanoscale plasmonic devices.

In this paper, the Talbot effect of an Ag nanolens with five periodic concentric through the rings illuminated by a radially polarized light was computationally studied. A rigorous finite-difference and time-domain (FDTD) algorithm was employed in the computational numerical calculation. The results indicate that several focal points can be obtained at different locations due to the SPPs-related Talbot effect at $\lambda_{\text{inc.}} = 248$ nm. The positions are quite different from that of values calculated by the Talbot distance equation reported in [15]. A minimum diameter of 100 nm at site of full width at half-maximum (FWHM) was derived at the propagation distance of $Z = 396$ nm. To further study the phenomenon in physics, it was compared with the traditional Talbot distance calculated using the scalar diffraction theory in the sections below.

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2. Structures description and simulation setup

As shown in Fig. 1, we considered an Ag nanolens of \( d = 100 \) nm in thickness and an on-axis hole of 100 nm in diameter, a set of five periodic concentric rings with lattice constants of \( \Lambda = 500 \) nm, and ring width \( w = 100 \) nm.

![Fig. 1. Schematic diagram of the nanolenses.](image)

The radially polarized light source being used here is a Z-normal radially polarized Gaussian beam, and the beam width in the \( X \) direction is equal to that of in the \( Y \) direction, which was designed to be 2.5 \( \mu \)m. The axis of symmetry of the corrugations coincides with the optical axis of the incident radially polarized beam. Intensity of the incident light propagating along the positive \( Z \) direction is assumed to be 1 in the calculation.

In our three-dimensional (3D) computational numerical simulations, simulation time and mesh size were set to be 150 fs and \( \Delta x = \Delta y = \Delta z = 5 \) nm, respectively. The perfectly matched layer (PML) boundary condition was applied at the simulation boundaries. In addition, symmetry and anti-symmetry boundary conditions were applied for the purpose of memory saving and high-speed calculation. To speed up the computer running, parallel running mode was adopted for the calculation by which all the 16 cores of dual CPUs with total 72 GB memory size in our workstation participate in the program running simultaneously.

3. Results and discussions

A. FDTD-based calculation of the nanolenses

Distribution of total electric field intensity \( |E|^2 \) for working wavelength of 248 nm is presented, as shown in Fig. 2. It can be seen that total five focal points appear along the propagation direction symmetrically in both the \( X-Z \) and \( Y-Z \) planes due to the radial polarization illumination. Figure 3 shows the electric field transmission at \( Y-Z \) plane at position of \( X = 0 \). As can be seen, there is more than one peak transmission after the exit plane (\( Z = 0.1 \) \( \mu \)m) of the Ag film-based nanolenses. Specifically, there are five focal points appearing at positions of \( Z = 396 \) nm, 0.841 \( \mu \)m, 1.309 \( \mu \)m, 1.901 \( \mu \)m, and 2.963 \( \mu \)m, respectively. As can be seen, the first focal point has the strongest intensity, and the second focal point has an intensity of \( \approx 1 \). Intensity profiles for the different focal positions are shown in Figs. 4(a)–4(e). A minimum diameter of 100 nm at site of FWHM is derived at the propagation distance of \( Z = 396 \) nm, as shown in Fig. 4(e).
Fig. 2. E-field intensity distribution at (a) Y–Z plane and (b) X–Z plane at λ = 248 nm.

Fig. 3. Electric field transmission at the incident wavelength λ = 248 nm in Y–Z plane, X = 0, Y = 0. The propagation is from left to right as shown in the picture. The exit plane is in the Z = 0.1 μm plane.
Fig. 4. Distributions of electric field intensity $|E|^2$ at $\lambda = 248$ nm at the focal positions of $Z =$ 0.396 $\mu$m, 0.841 $\mu$m, 1.309 $\mu$m, 1.901 $\mu$m, and 2.963 $\mu$m, respectively. Inset, zoom in plot of the central peaks.

The first beam spot has a diameter of 100 nm, and the corresponding intensity of the peak is 4. Furthermore, diameters of the second and third beam spots are 120 nm and 300 nm, respectively. In comparison to the self-imaging of Talbot effect, we gave the calculated Talbot distances, which were deduced from scalar diffraction theory below using the same structure.

B. Scalar diffraction theory-based Talbot effect of the nanolenses structure

In this subsection, the phenomenon described above was analyzed in comparison to the result derived using the scalar diffraction theory. The Talbot self-imaging effect for volume electromagnetic waves was discussed below.

For simplification of the analyses, the structure is simplified that is equivalent to a 1D grating structure with the same geometrical parameters as the nanolens mentioned before due to its symmetry, as shown in Fig. 5.
The scalar field immediately behind an infinite grating at the original position ($Z = 0$) when it is illuminated by a unit-intensity plane wave can be described by a Fourier series representing a weighted set of plane-wave components as

$$U(x) = \sum_{n=-\infty}^{\infty} c_n \exp \left( j2\pi \frac{n}{d} x \right),$$

(1)

where $d$ is the grating period (is 500 nm here) and $c_n$ is the $n$th Fourier coefficient. The coefficients represent the complex intensity and the phase.

According to the frequency domain analysis method, the diffraction field distribution $U_z$ at a free-space propagation distance $Z$ is given by

$$U_z(x) = \sum_{n=-\infty}^{\infty} c_n \exp \left( j2\pi \frac{n}{d} x \right) \exp \left[ -j\pi\lambda \left( \frac{n}{d} \right)^2 \right] \exp(jkz).$$

(2)

Note that when

$$z = \frac{2md^2}{\lambda} \quad (m = 1,2,3\ldots)$$

(3)

then

$$\exp \left[ -j\pi\lambda \left( \frac{n}{d} \right)^2 \right] = 1.$$  

(4)

$U_z$ can be written as

$$U_z(x) = \sum_{n=-\infty}^{\infty} c_n \exp \left( j2\pi \frac{n}{d} x \right) \exp(jkz) = U(x) \exp(jkz).$$

(5)

Intensity distribution equals to the original intensity.
The Talbot distance of a grating with a period of \( d \) is

\[ z_T = \frac{2d^2}{\lambda}. \]  

Substituting \( d \) and \( \lambda \) with their corresponding values of 500 nm and 248 nm, respectively, we can get the Talbot distance of \( z_T = 2.016 \mu m \). It indicates that self-imaging of the periodic grating structures can be observed at positions of \( Z = 2.016 \mu m, 4.032 \mu m, \) and \( 6.048 \mu m \), etc., which is integral number times of \( z_T \).

It was found that the result analyzed above by the scalar diffraction theory is quite different from the results calculated by the FDTD numerical analysis method. The former is far-field diffraction, but the latter is SPPs coupling and interfering at near field. Thus the focal points do not repeat at the same positions as that of the scalar one along the propagation direction. The phenomenon described before can be attributed to that of the surface plasmons (SPs). SPPs are excited at all azimuthal directions that interfere each other constructively and create a strongly enhanced localized field at the focal points. The size of the focal spots is less than half a wavelength, and the focal positions are not determined by the Talbot distance.

In comparison to the results of above mentioned Talbot distances from scalar theory, only the contribution from the field of SPPs is taken into account in the calculations of the interference pattern. In the geometry considered in this paper, the conversion of the incident SPPs into the volume electromagnetic waves is weak. The Talbot distance of 2.016 \( \mu m \) (first order) calculated by formula \( z_T = k\lambda^2/\pi \) (It is the same as Eq. (7) actually. They were written in two different forms.) from Maradudin et al. [14] and van Oosten [17] is different also from our calculated value of 0.3962 \( \mu m \) (first order) here. The reason we get a different answer compared to the other two methods is because the other two methods use the paraxial approximation in far-field regime, which state that the pitch of the structure is much greater than the incident wavelength. However, the near-field regime in which we operate is when the wavelength is about half the period. For our structures, the paraxial approximation does not hold anymore. Therefore, we can draw a conclusion that the theoretical equations deduced for the structures of metallic dot arrays [14,15] are not suitable to our nanolens structures. The approach of computational numerical calculation must be employed for the study of the Talbot distance.

To further study dependence of the Talbot effect on the incident wavelength, we calculated E-field intensity distribution and corresponding two-dimensional (2D) intensity profiles for the wavelengths ranging from 193 nm to 633 nm, as shown in Figs. 6(a)–6(g) and Fig. 7. As can be seen, the Talbot effect appears at the short-wavelength regime only, especially for the ultraviolet wavelength. Only one focal point can be observed for the case of \( \lambda > 300 \) nm, which is a threshold value for the SPPs-based Talbot effect. The color level in the images shows that the SPPs wave propagation through the slits is weak also in this case. With increasing of the wavelength, the surface plasmon is less bound to the surface and has weaker coupling to the electric dipole [21]. Therefore, for the extreme case of \( \lambda = 633 \) nm, there is no focusing appearing in the free space because insufficient SPPs wave participates in the interference to form the focusing region. Surface plasmon launching through the slits and aperture dominates the electrostatic plasmon, and it reaches an high efficiency of plasmon launching to emitted light \( (I_{SP}/(I_{SP} + I_{free})) \) close to 100% at the violet-wavelength regime in silver (see Fig. 17 in [18]). It was claimed a transition from surface plasmon to perfect-conductor behavior. This is the reason that more focal points appear in the violet wavelength regime. It means that the Talbot effect exists on the condition of \( \lambda \leq \Lambda/2 \). The shorter the incident wavelength, the more focal points will appear. The SPPs wave propagation through both the slits and the exit surface is strong as well. It causes the interference-generated focal
points close to the exit plane of the nanolenses. Undoubtedly, it will be exciting news for nanophotolithography.

Fig. 6. E-field intensity distribution in Y–Z plane for the incident wavelength of (a) 633 nm, (b) 532 nm, (c) 448 nm, (d) 325 nm, (e) 300 nm, (f) 248 nm, and (g) 193 nm, respectively. The intensity distribution in X–Z plane is the same as that of Y–Z plane due to symmetrical circular focused beam spot under illumination of radial polarization and hence omitted here.
4. Summary

In summary, we have theoretically analyzed the focusing properties of an Ag film corrugated with five penetrated concentric circular rings under illumination of a radially polarized beam. It was found that the radially polarized light has more than one focal point due to the SPPs-related Talbot effect. The mechanism governing beam focusing in free space after the exit plane of the Ag nanolenses can be interpreted as follows: an SPPs wave excited at the azimuthal directions interferes with each other constructively and creates a strongly enhanced localized field at the focal region with the spot size beyond the diffraction limit. The calculated five Talbot distances at $Z = 396 \text{ nm}$, $0.841 \mu\text{m}$, $1.309 \mu\text{m}$, $1.901 \mu\text{m}$, and $2.963 \mu\text{m}$, respectively, is different from that of the Talbot distances calculated by scalar diffraction theory. The reason can be explained that in our structure, the wavelength is about half the period, and thus the paraxial approximation does not hold. For the extreme case of $\lambda = 633 \text{ nm}$, no focusing appears in the free space because insufficient SPPs wave participates in the interference to form the focusing region. The Talbot effect exists on the condition of $\lambda \leq \Lambda/2$. The shorter the incident wavelength, the more focal points will appear.

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