

Three-dimensional Nanoscale Far-field Focusing of Radially Polarized Light by Scattering the SPPs with an Annular Groove

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Abstract: Three-dimensional (3D) nanoscale focusing of radially polarized light in far field by a simple plasmonic lens composed of an annular slit and a single concentric groove is reported. The numerical calculations reveal that the incident light is coupled to surface plasmon polaritons (SPP) by the annular slit and a focal spot with a size less than a half of the illumination wavelength is formed in the far field due to the constructive interference of the scattered light by the groove. More importantly, the focal length can be modulated by changing the groove diameter. This structure provides an admirable choice for the nano-optical devices.

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1. Introduction

The nanoscale focusing devices based on surface plasmon polaritons (SPPs) bear the virtues of both a microscale dimension and a nanoscale focal spot [1–10], and they are of great significance for high density optical data storage, integrated optical circuits, and probes of the scanning near-field optical microscopy (SNOM). Based on the interference of circularly symmetrical SPPs, a plasmonic lens [1, 2] consisted of a single annular slit with subwavelength width has been utilized to actualize the high intensity focusing at the surface. However, as a result of the absence of the physical mechanism to convert the SPPs into propagating waves in free space, the focus is restricted in the near field, which accordingly limits the application of the plasmonic lens in many domains. Structures formed by linear slits and grooves [5–7] can be used as another type of focusing devices and 2D nanoscale focusing in far field can be realized by controlling the diffraction of the electromagnetic (EM) field in the periodic grooves irradiated by the SPPs, which establishes the foundation of 3D far-field nanoscale focusing. The structure consisted of several periodic concentric annular grooves on both sides of a silver nanolayer was reported by Piotr Wrobel *et al.* [9]. Utilizing the coupling of SPPs between the two sides of the nanolayer and scattering of SPPs by the grooves in the exit side, this structure actualized the 3D nanoscale focusing in far field. However, there is a lack of the clear design theory and therefore the procedure is quite complex to realize the desired focusing. Another structure, a plasmonic microzone plate reported by Yongqi Fu *et al.* [10], was formed by nearly ten annular slits of different widths. The phase distribution of the transmission light at the exit side was controlled by choosing appropriate widths for each slit, due to the interference of this transmission light in free space, the 3D nanoscale focusing was actualized in far field. However, due to the high depth-width ratio, it is difficult to fabricate and a number of the structure parameters have to be redesigned when the working distance is changed.

In this letter, we propose a simple structure that is just formed by an annular metallic slit and a concentric groove within the slit. By converging the propagating waves scattered from the SPPs by the groove, this structure can actualize the 3D nanoscale focusing in far field. Moreover, its focal length can be modulated flexibly just by changing the radius of the single groove.

2. Principle

Figure 1(a) illustrates a typical plasmonic lens, which is formed by an annular slit milled into a silver film. Part of the incident light is diffracted by the sharp edge of the slit, and then SPPs are excited by the diffracted light for it gaining an extra wave vector in the direction along the film surface. Due to the interference of the SPPs in all directions, the Bessel-like electric field distribution is generated near the exit surface, as the simulated electric field intensity distribution shown in Fig. 1(b). The intensity of this Bessel-like electric field gets stronger from the slit edge to the center, and reaches its maximum at the surface center, where an

obvious focal spot is formed in the near field. To actualize the 3D nanoscale focusing in far field, a mechanism, which can convert the SPP wave to propagating waves in free space and concentrate most energy in far field, must be introduced. As demonstrated in other works [11–13], the subwavelength metallic groove can scatter the SPPs into propagating waves in free space effectively according to a certain angular spectrum distribution. Utilizing this feature, a subwavelength concentric annular groove is added in the plasmonic lens. Figure 1(c) shows the modulated structure. The finite-difference time-domain (FDTD) simulation result shown in the Fig. 1(d) proves that a bright focal spot is generated as expected in far field.

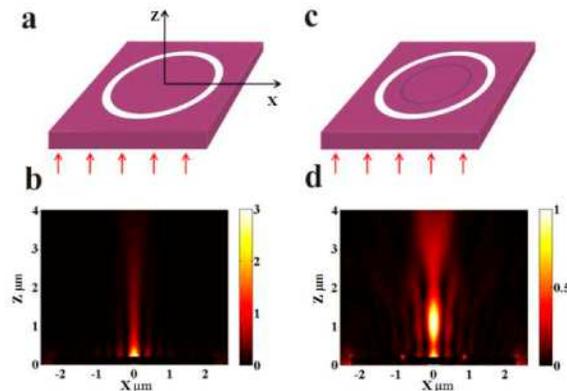


Fig. 1. Schematic diagrams of (a) the plasmonic lens; (b) $|E|^2$ distributions for the plasmonic lens in (a); (c) the two-annulus structure; (d) $|E|^2$ distributions for the two-annulus structure. The incident light is the radially polarized light.

The realization of 3D nanoscale focusing could be attributed to the scattering of surface plasmons at near field and the corresponding in phase field superposition at far field. As shown in Fig. 2, the structure is formed by an annular slit and a concentric groove within the slit in the metallic layer. The slit is used to excite SPPs propagating along surface when it is irradiated by the incident light, and the groove is used to scatter SPPs to propagating waves into free space at a certain angular spectrum distribution. The propagating waves scattered by different positions of the groove interfere constructively on the optical axis because they are in-phase, thus a bright focal spot in far field can be generated. In order to attain a high SPPs coupling efficiency, radially polarized light is chosen to be the illuminating source due to its centrosymmetric TM polarized illumination for the annular slit. On the other hand, a radially polarized beam can form a smaller focal spot compared with linearly and circularly polarized beams [14–20]. The thickness of the metallic layer H is about several times thicker than the skin depth of the metal so that the direct transmission light, which may impact the focusing quality, is prohibited. To ensure the SPPs to be excited, the width of the annular slit w_1 is a little smaller than half wavelength of the incident light, which provides excess momentum for the light diffracted at the exit of the slit. It is obvious that the bigger the radius of the slit R is, the larger the circumference is, and the more energy is converted to SPPs. However, considering the energy loss of the SPPs in the propagating process, the slit radius R has an optimized value. The working mechanism of this structure shows that the key factor determining the focusing process is the scattering mechanism introduced by the subwavelength annular groove. The variation of the groove depth h can lead to the change of the EM field distribution in it, and further influence the EM field scattering in the free space and ultimately the intensity of the focal spot. The groove radius r decides the location where the SPPs scattering will happen. If the scattering angular spectrum is invariable, the focal length can be modulated just by changing the groove radius r .

3. Simulation and discussion

To investigate the influence of the groove depth h and the groove radius r on the focusing properties, three-dimensional FDTD simulations are carried out. In the calculation, the grid length is specified to be 10 nm and the metallic dielectric constant is taken from Reference 21. The parameters of the structure shown in Fig. 2 are set as the following: the thickness of silver layer $H = 200$ nm, the annular slit width $w_1 = 300$ nm, the annular groove width $w_2 = 100$ nm, the inner radius of the slit $R = 2300$ nm. The radially polarized light with the incident wavelength $\lambda = 632.8$ nm is generated by the superposition of the first order Hermite-Gaussian modes (TEM_{01} and TEM_{10}) [19]. The envelope amplitude of radially polarized light can be expressed as:

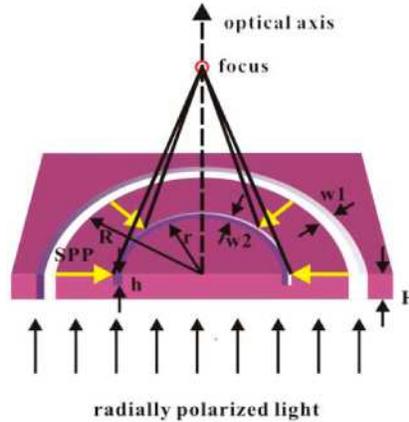


Fig. 2. Schematic diagram of the structure proposed to actualize radially polarized light focusing.

$$E(l) = (l/L)\exp(-l^2/2L^2) \quad (1)$$

In our simulations, L is set to be 2300 nm so that the radius of the maximum intensity of the incident light equals the inner radius of the annular slit R .

The focal length and focusing efficiency are mainly determined by the groove position. In the following simulations, the groove depth h is fixed to be 80 nm, and the groove radius r is changed from 200 nm to 1250 nm with a step of 50 nm. The calculation results are presented in Fig. 3, and the curves show the $|E|^2$ distributions on the optical axis with different values of the r . As we know that the amplitude distribution of the surface electric field is Bessel-like standing waves inside the annular slit if there was no groove in it [2]. The groove is set at the exact location where the node appears, and the corresponding groove radius r is equal to 200 nm, 500 nm, 800 nm, and 1100 nm, respectively. In these cases the simulation curves show that an intensity peak (focal spot) appears on the optical axis several wavelengths away from the silver film surface, and the focal length (the distance from the brightest point to the surface) is 360 nm, 625 nm, 870 nm and 1140 nm, respectively, which means that the focal length increases monotonically with the increase of the groove radius. When the location of the groove is moved 100 nm inside the position of nodes, namely groove radius r becomes 400 nm, 700 nm and 1000 nm, respectively, the focusing phenomenon still exists. The monotonic increasing of the focal length with the groove radius is still valid, and even the slopes of the linearity are close to each other (shown in the inset in Fig. 3). The difference between these two situations is the focus intensity, which is stronger when the groove is just in the location of nodes. However, when the groove is moved to the location of antinodes, corresponding to the groove radii of 350 nm, 650 nm, 950 nm, and 1250 nm, respectively, the curves show that the value of $|E|^2$ damps exponentially with the increase of the distance away from the surface,

and approach to the condition of the absence of the groove in the metal film. This result indicates that the groove cannot scatter the SPPs into radiation light and the 3D nanoscale focusing in far field cannot be actualized when the annular groove is set in the location of antinodes.

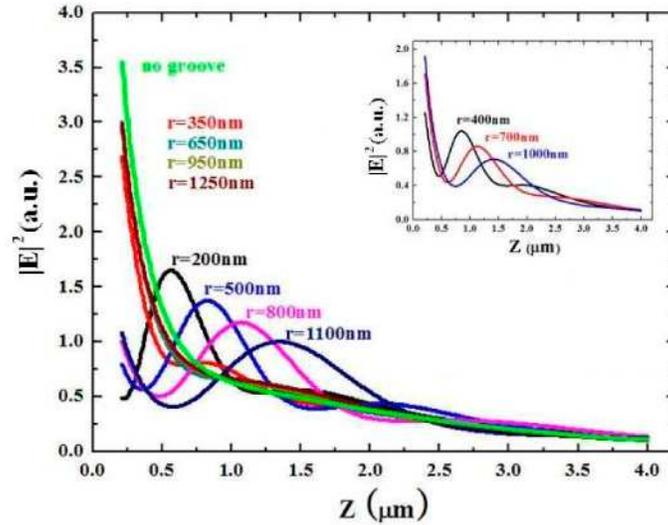


Fig. 3. $|E|^2$ distributions on the optical axis for the structures with grooves in the position of nodes and antinodes. The inset depicts the $|E|^2$ distributions on the optical axis for the structures with groove radius 100 nm smaller than antinode.

On the other hand, the groove depth also influences the focusing efficiency. We set the groove radius r to 1100 nm (corresponding to the location of nodes); while the thickness of the sliver layer H varies from 200 nm to 800 nm to systematically explore the influence of the groove depth on the focusing efficiency. The simulations are carried out with the groove depth h changed from 0 to 550 nm with a 10 nm step. Figure 4 shows the variation of the intensity of $|E|^2$ at the focal spot as a function of the h . It can be seen that the intensity of $|E|^2$ varies periodically with the groove depth. The variation period is 240 nm which is about half of the SPPs wavelength when the groove width is 100 nm [22]. Further examination shows that there exists a standing wave inside the groove with the distance about 240 nm between the nodes. When the groove depth h is changed, the scattering efficiency will be different. It is worth to note that most energy of the SPPs is scattered into radiation light and forms a brightest focal spot if the groove depth fulfills the condition of maximum scattering. On the contrary, there is little SPPs scattered into radiation light by the groove depth of minimum scattering, and hence no focus can be formed. Interestingly, when the groove radius is changed to 950 nm (corresponding to the radius of the location of antinodes), the simulation results show that whatever the depth of the groove is, the focus cannot be formed in the far-field.

From the results obtained above, the optimized focusing condition can be determined. If the groove is located at or close to the nodes of the SPPs standing wave generated in the planar metal surface, the focusing will be generated. The shorter the distance between the groove and the nodes is, the better the focusing effect will be. Moreover, the groove depth must be set to satisfy the maximum scattering condition of the surface plasmon wave.

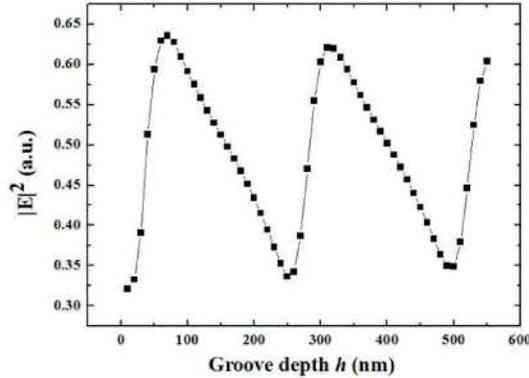


Fig. 4. The curve depicting $|E|^2$ variation of the focus as a function of the groove depth h .

Figures 5(a)-5(d) illustrate the corresponding $|E|^2$ distributions for the cases that the groove radius equals 200 nm, 500 nm, 800 nm, and 1100 nm, respectively. It reveals that most of the transmitted energy has been concentrated in an extremely small region away from the exit surface. The focal spot in far field is moved further from the metal surface when the groove radius is increased. From Fig. 3, the values of the $|E|^2$ at the focus are 1.65, 1.37, 1.17, and 1, respectively, which are much larger than the maximum intensity of the incident light, 0.3679 (calculated from the Eq. (1)). The transmitted energy of the structure is about 13%. When choosing the groove radius to be 1100 nm, the $|E|^2$ distribution in the focal plane is given in Fig. 5(e), which presents that the shape of the focal spot is perfect circular symmetry. At the condition of the same structure parameters, the $|E|^2$ profile of the focal spot is shown in Fig. 5 (f), the full width at half maximum (FWHM) of the focus is calculated to be $0.46\lambda_0$, which is smaller than half of the incident light wavelength (λ_0). An exhilarating phenomenon is that the FWHM of the focus is less sensitive to the groove radius r . When r is 200 nm, 500 nm, 800 nm, and 1100 nm respectively, the corresponding FWHM is $0.40\lambda_0$, $0.41\lambda_0$, $0.43\lambda_0$, and $0.46\lambda_0$, respectively. It means that the FWHM of the focal spot can always be kept below half a wavelength of the incident light when the focal length is tuned by varying the groove radius.

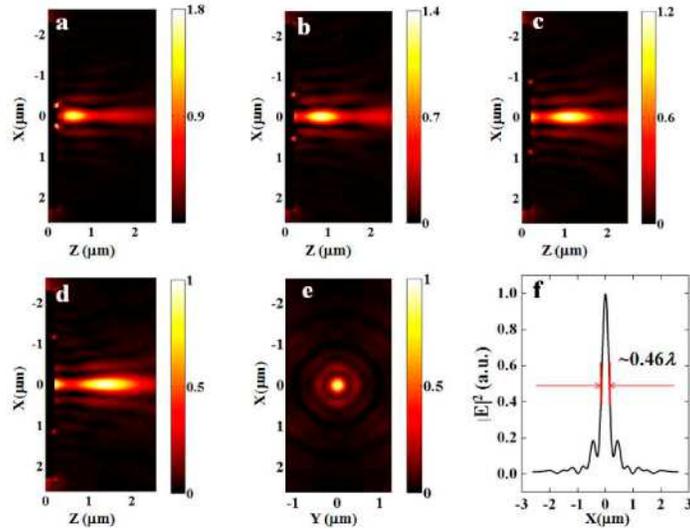


Fig. 5. $|E|^2$ distribution for (a) $r = 200$ nm, (b) $r = 500$ nm, (c) $r = 800$ nm, (d) $r = 1100$ nm. (e) Cross section of $|E|^2$ at the focal plane for $r = 1100$ nm, (f) $|E|^2$ profile of the focal spot for $r = 1100$ nm.

4. Conclusion

We have demonstrated a subwavelength plasmonic focusing lens with a simple structure which is consisted of an annular slit and a concentric groove. The annular slit is used to excite the SPPs by the incident light, the radially polarized light is chosen to attain a high SPPs coupling efficiency, and the concentric groove is introduced to convert the SPP wave to propagating waves in free space and concentrate most energy in far field to form the 3D nanoscale focusing. The energy of the focal spot ($|E|^2$ at the focus) is several times larger than that of the incident light. The focal length can be modulated by simply tuning the groove radius, and the FWHM of the focal spot can always be kept less than a half wavelength of the incident light. Such a device has the potential applications in high density optical data storage, nanophotolithography, near-field microscopy and integrated optics.

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