Plasmonic Nanolens Focusing Light in Subwavelength Scale

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Abstract

We report a metallic nanolens that can focus light into region comparable to wavelength. According to the finite different time domain (FDTD) method numerical calculation, it was found that the relative phase of emitting light scattered by surface plasmon in a single subwavelength metallic groove can be modulated by the groove depth. Consequently, the focal length of the slit-groove-based focusing structures can thus be adjusted in certain value if the groove depths are arranged in traced profile. With the regulation of the groove depth profile, it is possible to modify the focus position in the precision of nanoscale without increasing the size of the nanodevice. The numerical simulation results verify that the method is effective for the design of nano-optical devices such as optical microprobes. Advantages of the proposed nanolens are apparent. (i) The element is miniaturized and the modulating the groove depth trace profile would not increase the corrugation area and hence make the element compact, making it an excellent candidate for integrated optics. (ii) The obtained focal length is comparable to the wavelength and the focal width is less than a wavelength, which are difficult to obtain via conventional refractive element. (iii) The element's dimension is subwavelength in thickness, which may prove useful to act as surface device that integrated into other optical and optoelectronic elements.

Key words: Surface plasmon, subwavelength, FDTD

1. Introduction

In recent years, there has been continuing interest in Surface Plasmon Polaritons (SPPs) [1-7], which offers the potential for developing new types of miniaturized photonic devices that could manipulate photons in subwavelength scale. So far, numerous SPPs-based nanophotonic elements such as lens, waveguide, and reflector were proposed and validated.[6] Among these, the lens consists of a single aperture surrounded by surface corrugation on metallic film has been wildly investigated for theoretical and applied purpose.[8] Lately, it was demonstrated by modal expansion method that light could be focused in intermediate region though a single subwavelength metallic slit flanked by finite array of grooves with uniform depth. As grooves number N increases, both focal length and depth will increase with N^2 dependence.[9] However, as far as we know, little attention has been paid to the study of grooves with spatially variant depths on near field focusing ability of this type of lens. In this letter, by introducing spatially variation in grooves depths, we numerically demonstrate by finite-difference time-domain (FDTD) simulation that this type of slit-grooves based lens also exhibit near-field focus properties with focal length and width comparable to wavelength.

2. Design of the nanolens

The nanolens considered in this study consist of a single subwavelength silt surrounded by 6 grooves in output surface, the grooves are periodically distributed and has spatial variation in depth [Fig. 1(a) and Fig.1 (b)]. By introducing a linear chirping in grooves depth, we get a monotonically varying depth defined by: $h_1=h_2-\delta h$ and $h_3=h_2+\delta h$, where h_1 is the starting depth from center, h_2 is the second depth from center, h_3 is the ending depth from center, and δh the common difference of the grooves depth that either negative or positive ($\delta h<0$ and $\delta h>0$ represent the case in Fig. 1(a) and Fig. 1(b), respectively). The other geometric parameters are defined as follows: slit and all grooves width w, film thickness t and grooves period d. The incident light is a TM polarized wave (magnetic field parallel to the y direction) with wavelength λ=632.8nm, and silver dielectric constant ε=-16.23+i0.66 is used for employed wavelength in our FDTD simulation.

The basic principle of the device is based on the idea that the surface plasmon scattering at the grooves would interfere with light emerging from the center slit, creating a narrow focus at the point where the phase difference of the light emitted from the slit and grooves are equal. The physical process could be approximately explained as follow: the SPPs mode excited by the incident wave at the metallic slit entrance would propagate along the slit and separated into two portions at the slit exit. One portion directly decouples into radiation mode that diffracting into free space; the other propagates along the metal-air interface and scatters into radiation light at grooves region. If the grooves width are

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smaller than $\lambda/2$ and not extremely narrow, the phase of the emission at each groove is not only proportional to the distance travelled by the SPPs wave from its origin at the slit, but also varies with the grooves depth. Thus the focus properties could be dominated via modulating the grooves position and depth to obtain proper relative phase at grooves.

3. Results and discussion

In Fig. 1 (c) the energy flow through a nanolens is shown (Poynting vector component Sx is multiplied by 5 here in order to reveal details in the region around the focus) to illuminate the novel focusing property. The nanolens is characterized by: w=200nm, t=200nm, d=420nm, h_2=80nm and δh=-30nm, i.e. h_1=110nm, h_2=80nm and h_3=50nm. The result shows that the energy emerging from the structure overlaps at axis within 2 microns, concentrating most of energy in an extremely small region. The phenomenon is the result of the interference of the emissions from the slit and grooves, which can intuitively understand by grating scattering theory: $k_{SP}\pm 2\pi/d=k_0\sin\theta$, where k_{SP} is surface plasmon wave vector along output surface, k_0 is wave vector of the incident light, and θ is the diffraction angle. The in-plane component of the wave vector of diffracted light $k_0\sin\theta$ is negative when k_{SP} is smaller than the grating vector $2\pi/d$, i.e. the direction of the diffracted beam is opposite and will overlap at axis. The magnetic field $|Hy|^2$ profile through the nanolens is shown in Fig. 2 (a), the result indicates that the field distribution matches the energy flow distribution shown in Fig. 1(c), and a focus appears within several wavelength from the output plane where the beam emerging from the structure overlapped. The details of focus are given in Fig. 2(b) and Fig.2 (c), which reveal the focal length of 1.30μm and the full-width at half-maximum (FWHM) of the focus width of 0.56μm. Surprisingly, the far field pattern splits into two peak and the corresponding FWHM of divergence value is calculated to be ±23.8°, differ with the beaming effect previous work discussed [3], this should be due to the short focal length in our configuration. The scissor-like pattern at the exit is attributed to the large energy flow around the slit, which limits the minimum focus length of a wavelength. However, in the situation that the focal length smaller than a wavelength, the energy of the focus and the scissor overlap to form a "hot spot", whose dimension reduced rapidly and could comparable to the central slit width. On the other hand, there has no maximum focus length limitation. With designing proper grooves number and position, the focal length can extend to intermediate region and far field region.

The groove depth used in our calculation is small, i.e. smaller than $\lambda_{\text{cavity}}/4$, where λ_{cavity} is the surface plasmon wavelength in the groove which is related to groove width, and λ_{cavity}=560nm for w=200nm in our configuration. For shallow grooves, the relative phase at the grooves is steadily increased with the increasing of groove depth, which has an analogy to a refractive film.

It is interesting to note that the emission's phase at the grooves can be controlled by modulating its grooves depth, hence structures with concave and convex surfaces should show contrary imaging properties, as would an optical lens with different curved surfaces. By increasing δh from -50nm to 50nm with step of 10nm, the focal length increased from 1.22mm to 1.99mm and shows $(\delta h)^2$ dependence, while the FWHM of focal spot increase from 0.55mm to 0.67mm [Fig. 4]. For δh=-50nm, δh=0nm and δh=50nm, more details of focus are shown in Fig. 2 (a) and Fig. 2 (b). The results indicate that when the depths of grooves deviated from the uniform distribution, the focal length will decrease for the structure shown in Fig. 1(a) while increase for the structure shown in Fig. 1(b), it seems that the effect of spatial variant grooves depth on focal length resembles conventional refractive lens in the way that the focal length varies with the curvature radius of the lens. The case δh<0 (Fig .1 (a)) correspond to the addition of a convex lens, whose phase retardation value in the edge is smaller, to the structure with uniform grooves depth. Thus the focal length is shorter than the case of uniform grooves depth. While the opposite condition that δh<0 (Fig .1 (b)) shows a contrary performance.Shallow groove is used in previous calculation to ensure the concave and convex structures perform as expected. Nevertheless, when the grooves depth is deep, more calculations show that they behave like the grooves with depth of $(h-n\lambda_{\text{cavity}}/2)$, where n is a integer number, it is evident that this character is attribute to the large portion of standing wave in the grooves. Our results suggest that only by regulating the spatially variant grooves depth (without any change in grooves number N, grooves period d, and grooves width a), the slit-grooves based lens' near-field focusing performance vary significantly resemble conventional refractive lens, this provide a new angle of view for designing this type of nanolens.

Several advantages of the nanolens discussed and demonstrated above are apparent. First, the element is miniaturization. The whole element dimension is subwavelength in depth and several microns in plane, make it an excellent candidate for integrate optics and optoelectronics. Second, the focal length and width are comparable to wavelength, which are difficult to obtain via conventional refractive element. Moreover, the focusing properties could be controlled readily just by modulating the grooves depth, which can facility realized via various micro-fabrication methods.

4. Conclusion

In conclusion, we report a type of nanolens that consists of single subwavelength slit surrounded by period grooves, the nanolens focal length and width could be reduced to dimension comparable to wavelength. The effect of spatially variant grooves depth on focusing ability of the nanolens is studied; it reveals that the focusing properties can be controlled readily by modulating linear chirped spatially variant grooves depth. This kind of nanolens is of great advantage and could facilitate various nano-optical research fields and technologies, such as optical lithography, optical storage, optical microscopy, and integration optics. Furthermore, since the element's dimension is subwavelength in thickness, it may also prove useful to act as surface device that integrated into other optical and optoelectronic elements.

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REFERENCES

1. T.W. Ebbesen, H.J. Lezec, H.F. Ghaemi, T. Thio, P.A. Wolff, "Extraordinary optical transmission through subwavelength hole arrays," Nature 391, 667-669 (1998).
2. T. Thio, K.M. Pellerin, R.A. Linke, H.J. Lezec, T.W. Ebbesen, "Enhanced light transmission through a single subwavelength aperture," Opt. Lett. 26, 1972-1974 (2001).
3. C. Janke, J. Gomez Rivas, C. Schotsch, L. Beckmann, P. Haring Bolivar, and H. Kurz, "Optimization of enhanced terahertz transmission through arrays of subwavelength apertures," Phys. Rev. B 69, 205314 (2004).
4. L. Martin-Moreno, F.J. Garcia-Vidal, H.J. Lezec, K.M. Pellerin, T. Thio, J.B. Pendry and T. W. Ebbesen, "Theory of Extraordinary Optical Transmission through Subwavelength Hole Arrays", Phys. Rev. Lett. 86,1114-1117(2001).
5. K. J. Klein Koerkamp, S. Enoch, F. B. Segerink, N. F. van Hulst and L. Kuipers, "Strong Influence of Hole Shape on Extraordinary Transmission through Periodic Arrays of Subwavelength Holes," Phys. Rev. Lett. 92, 183901 (2001).
6. H.J. Lezec, A. Degiron, E. Devaux, R.A. Linke, F. Martin-Moreno, L.J. Garcia-Vidal, and T.W. Ebbesen, "Beaming light from a subwavelength aperture," Science 297, 220-222 (2002).
7. Degiron and T. W. Ebbesen, "Analysis of the transmission process through single apertures surrounded by periodic corrugations," Opt. Express 12, 3694-3700 (2004).
8. F. J. Garcıa-Vidal, L. Martin-Moreno, H. J. Lezec and T. W. Ebbesen, "Focusing light with a single subwavelength aperture flanked by surface corrugations," Appl. Phys. Lett. 83, 2000-2002 (2003).
9. L. Martin-Moreno, F.J. Garcıa-Vidal, H. J. Lezec, A. Degiron, and T.W. Ebbesen, "Theory of highly directional emission from a single subwavelength aperture surrounded by surface corrugations," Phys. Rev. Lett. 90,167401 (2003).

FIGURES AND CAPTIONS

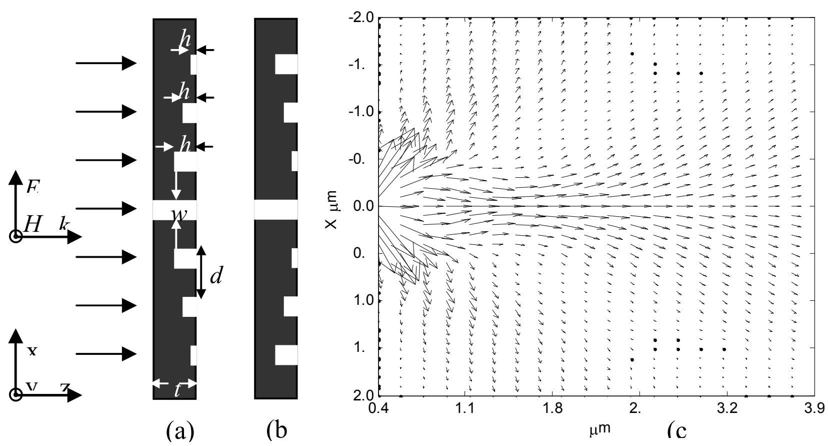

Fig. 1. Schematic view of the nanolens under study and a FDTD calculated energy flow distribution though a nanolens. t denotes the thickness of silver film, w denotes the width of the slit and all grooves, d denotes the grooves period and h_N the depth of grooves with the serial number of N. TM polarized light (H component parallel to y direction) is incident from the left. (a). The groove number $h_1>h_2>h_3$, and $h_1=h_2-\delta h$, $h_3=h_2+\delta h$ ($\delta h<0$). (b). $h_1<h_2<h_3$, and $h_1=h_2-\delta h$, $h_3=h_2+\delta h$ ($\delta h>0$). (c). FDTD calculation of the energy flow distributions though the nanolens, Poynting vector component Sx is multiplied by 5. the geometric parameters of the lens are: t=200nm, w=200nm, d=420nm, h_2=80nm and δh=-30nm.

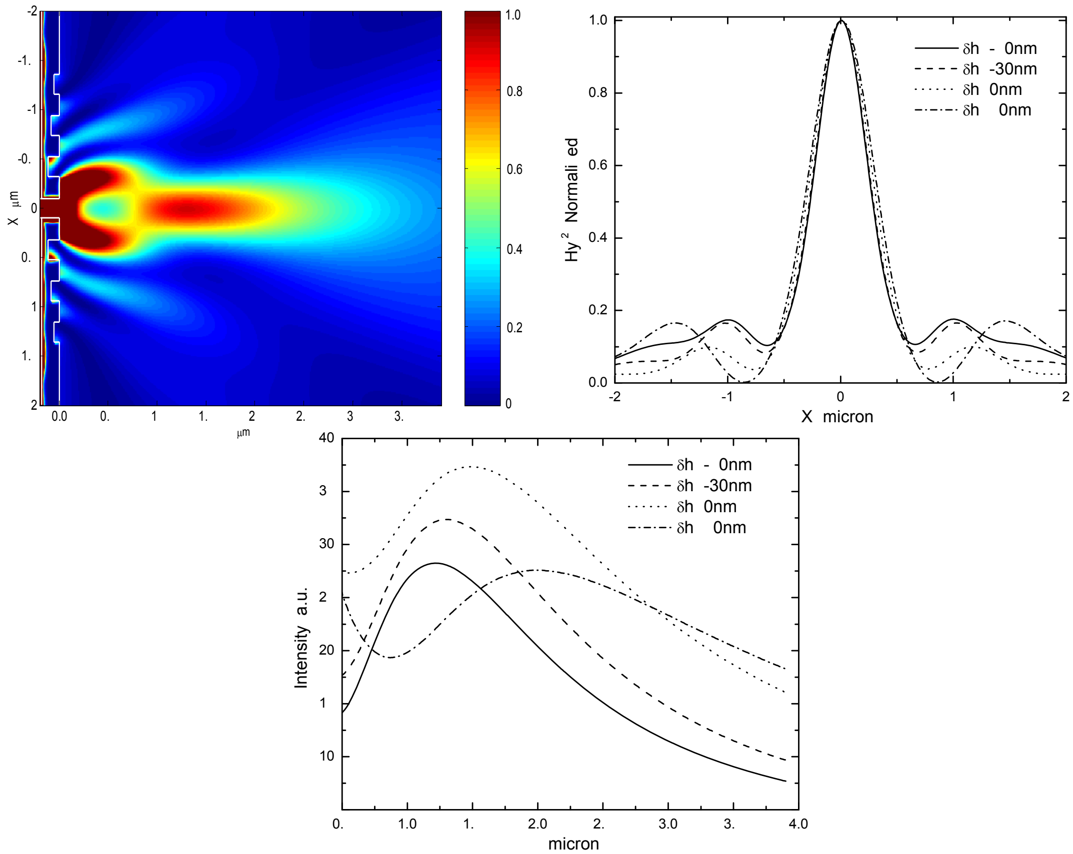

Fig. 2. (a). FDTD calculation of the normalized $|Hy|^2$ distributions though the nanolens. All geometric parameters are same as Fig. 1 (c). (b). $|Hy|^2$ distribution slice along z-axis at x=0 for δh=-50nm, δh=-30nm, δh=0 and δh=50nm. (c). Normalized $|Hy|^2$ distribution slice along x-axis at z=1.22μm, z=1.30μm, z=1.49μm and z=1.99μm for δh=-50nm, δh=-30nm, δh=0 and δh=50nm, respectively.

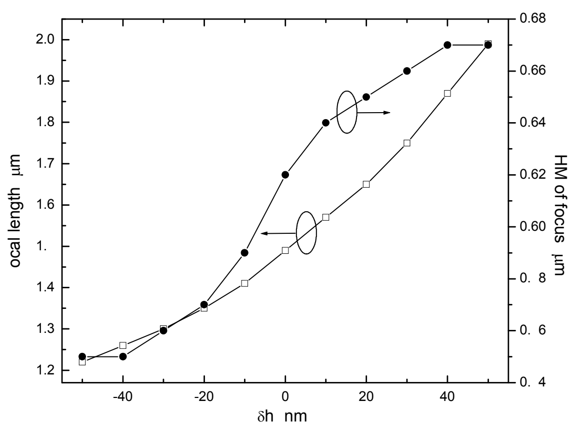

Fig. 3. Focal length and focal width as function of ŭh. The parameters are same as Fig. 1 (c) except for ŭh