Optical beam focusing by a single subwavelength metal slit surrounded by chirped dielectric surface gratings

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A method for optical beam focusing by a single subwavelength metal slit surrounded by surface gratings is proposed. In our proposed method, the period of each surface grating is chirped so that the radiation fields of surface plasmon polaritons can be controlled to make a beam spot at the desired focal length. Through our proposed method, it is numerically shown that we can make a beam spot which is located at the several times of wavelength distance from the slit, and its focal length can be controlled. © 2008 American Institute of Physics. [DOI: 10.1063/1.2828716]

Recently, study on subwavelength metal hole arrays accompanying the extraordinary transmission phenomenon has led to the finding of unprecedented ways to merge photons with electrons in the nanoscale regime.1,2 By utilizing the interaction of electromagnetic waves with collective electron oscillations called surface plasmon polaritons (SPPs), the directional beaming of an optical field emerging from the subwavelength metal slit with perforated periodic holes became possible. It is interesting that optical fields can be manipulated by controlling the radiation of SPPs on corrugated metal surfaces.3–8 In our previous work, we proposed a method for making the off-axis optical beaming with the specific deviation angle from the axis perpendicular to the metallic surface.9 Here, based on asymmetrically arranged dielectric surface gratings, the off-axis beaming configuration has been made by using the property that SPPs can possess the different radiation properties on each side of the corrugated surface. In other words, the SPPs passing through the one side of the metal substrate radiate a diverging light, and the SPPs passing through the other surface radiate a converging light. Here, the diverging and the converging features are shown in Ref. 7. Also, related to the shaping of the optical beaming, the beam focusing structures, based on multiple subwavelength metal slits or grooved metallic structures with a single period, have been reported.9–13 These beam focusing structures intend to make the beam spot at several times of wavelength distance from the substrate, which is difficult to achieve with the traditional convex lens configuration.

In this letter, we propose a method for focusing the beam by adopting a single subwavelength metal slit surrounded by chirped dielectric surface gratings. In our proposed method, to form the beam spot at the desired focal point from the metal substrate, the local period of each surface grating placed on the metal substrate is chirped. In other words, our method utilizes the property that the direction of the radiation fields generated by SPPs can be changed by adjusting the distances and widths of adjacent surface gratings, resulting in the chirped surface gratings. It seems that the configuration of our proposed method is similar to that of Fresnel lens or Fresnel zone plate. However, our proposed method can be discriminated because it manipulates the side coupling fields or radiation fields into the free space, while the Fresnel lens or the Fresnel zone plate controls the transmitted fields through its constituting components. For example, in Ref. 10, which can be considered as the Fresnel lens or zone plate version of SPP, the lights propagate through many slits and form an output field pattern. In our case, the light passes through a single slit and the SPPs propagate in the transverse directions along the surface and radiate light fields. Hence, in the design of the structure, the delay in the propagating SPP in reaching each local grating should be considered (which is similar to a phased antenna array) as well as its radiation directional characteristics. From our method with numerical analysis, we can form the beam spot of which focal length is approximately several times of the wavelength and its full width at half maximum (FWHM) is slightly narrower than the wavelength of incident wave.

The basic concept of our proposed beam focusing method is shown in Fig. 1. The SPPs are excited from the metal slit and they propagate along each side on the metal slit. Here, the subwavelength metal slit has the semi-infinite depth and the width of the air slit in the silver clad is 100 nm. The optical field is the p-polarized monochromatic wave with the wavelength of 532 nm in the air. At this wavelength, the silver clad has the refractive index of 0.129 +i3.193.14 When the SPPs are propagating on the corrugated surface, the radiation field can be generated from the surface gratings. The directions of the radiation fields are determined by the resonance property of each surface grating. Also, we assume that these radiations occur at the center of the surface grating height and at the boundary between the ridge and the
groove of the gratings, as shown in Fig. 1. Because the local period of dielectric surface gratings is chirped in overall along the metal substrate, which means that the resonance properties of each surface grating are not identical, the directions of the radiation fields are different from each other. Accordingly, if we make those radiated fields with different directionality converge toward the specific point in the free space, the beam spot can be formed at a distance away from the metal substrate. In other words, if the virtual ray lines emanating from the hypothetical radiating points correspond to the directions of the radiated fields from the surface gratings, as shown in Fig. 1) are able to pass the target focal point in the free space, the beam spot is formed at the desired focal length from the metal substrate.

To demonstrate this concept, we prepare various sets of dielectric surface gratings which are to be attached on the semi-infinite metal substrate so that we can control the direction of the radiation fields from the surface gratings, and the resonance properties of surface gratings are shown in Fig. 2. Here, to analyze the resonance properties of various dielectric surface gratings attached on the semi-infinite metal surface and field distributions, the rigorous coupled wave analysis launched with perfectly matched layers is used.\(^{15-19}\)

As shown in Fig. 2, the resonance property of each dielectric surface grating on the metal substrate can be obtained by varying the incidence angle and the process of the radiation is opposite to that of the SPP excitation. In our calculation, the refractive index, the thickness, and the fill factor of surface gratings are 1.72, 120 nm, and 0.5, respectively, and the periods of gratings are ranging from 225 to 348 nm. These surface gratings show the converging radiation property and their resonance angles are approximately ranging from \(-65^\circ\) to \(0^\circ\). The negative sign of the resonance angle is due to the fact that the direction of the propagation of the excited SPPs is opposite to the transversal direction of the incident optical fields.\(^{7,8}\)

In other words, the SPPs propagating along the corrugated surface radiate internally, so they make converging fields. From the resonance properties of SPPs, the resonance angles corresponding to the radiation angles, shown in Fig. 2, coincide with the negative resonance angles. In addition, since the difference of \(k_{sp}\) (wavenumbers of surface plasmon) between each end is relatively small when compared to their absolute values, the phase mismatching problem of SPPs propagating along the chirped surface gratings is negligible. From the investigated set of surface gratings, we select a number of surface gratings which have the specific period to make the optimized beam spot form at the focal length of 1.5 \(\mu m\). These gratings are selected by considering the direction of the radiation fields of SPPs to be matched with the focal point to minimize the focal length error, \(f_{\text{error}}\) in Fig. 1. The number of selected surface gratings is 12 and they are indicated by the vertical green lines in Fig. 2. As shown in Fig. 2, the radiation angle can be increased if we decrease the period of surface gratings. We arranged the gratings so that, from the metal slit to the each end of the substrate, the local period of surface gratings steadily decreases to make a larger radiation angle. Thus, the local period of surface gratings is chirped in overall.

The intensity distribution of the radiated light of SPPs from the selected gratings is shown in Fig. 3. In this figure, the designed focal length is 1.5 \(\mu m\) and the beam spot is formed at \(z=1.51 \mu m\) away from the metal substrate. As shown in Fig. 3, the SPPs are excited from the subwavelength metal slit and they propagate along the corrugated surface. Propagating along both sides, the radiation fields of SPPs are generated from the surface gratings. And then, they converge at the desired focal length. At the focal point, the cross section of the generated beam spot is shown in the inset of Fig. 3 and its FWHM is 409 nm. The important point of our result is that the focal length can be just several times of the wavelength.

Moreover, we simulate other cases with different focal lengths or different numbers of surface gratings, and they are shown in Fig. 4. The intensity distribution corresponding to the change of the focal length is shown in Figs. 4(a) and 4(b). Here, the designed focal lengths are 1 and 2 \(\mu m\), respectively. However, the generated focal lengths are 1.06 and 1.97 \(\mu m\), respectively, and their FWHMs at each focal length are 407 and 423 nm, respectively. In the case of the designed focal length of 1.5 \(\mu m\), the intensity distribution according to the number of surface gratings is shown in Figs. 4(c) and 4(d), and the numbers of surface gratings are nine and six, respectively. Here, the focal lengths are fixed at 1.5 \(\mu m\), but the corresponding FWHMs are increased by decreasing the number of surface gratings. It is due to the fact that more radiation elements are needed to make the narrower beam spot according to the Fourier transform relation between the field distribution in real space and the spatial frequency domain.

In conclusion, we proposed a beam focusing structure composed of a single subwavelength metal slit surrounded by chirped surface gratings, and we provided a simple and intuitive design method for the beam focusing structure using the virtual ray lines from the surface gratings. This
The method is based on the radiation properties of SPPs which can be controlled by adjusting the local period of surface gratings on the metal substrate. By adjusting the local period of surface gratings, the focal length of the beam spot can be changed in the range of the order of wavelength. Furthermore, we investigated the relation between the beam spot size and the number of the surface gratings from the viewpoint of the Fourier transform relation.

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