Applied Physics Letters

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Cite as: Appl. Phys. Lett. **90**, 051113 (2007); https://doi.org/10.1063/1.2437730
Submitted: 21 October 2006 • Accepted: 04 January 2007 • Published Online: 02 February 2007

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Off-axis directional beaming of optical field diffracted by a single subwavelength metal slit with asymmetric dielectric surface gratings

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(Received 21 October 2006; accepted 4 January 2007; published online 2 February 2007)

The authors propose a method for the off-axis directional beaming of optical field diffracted by a single subwavelength metal slit with dielectric surface gratings. In the proposed method, dielectric gratings are optimally designed to directionally couple the surface plasmon polariton modes induced by the metal slit into surrounding medium along a specific off-axis direction. Design of the gratings and the analysis are conducted based on the rigorous coupled wave analysis method. Their simulation shows the off-axis directional beaming of the oblique angle, 20.2°, with respect to the on axis by the proposed method. The beaming angle can be changed by adjusting the grating periods. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2437730]

Since the phenomenon of the enhanced transmission through subwavelength hole arrays was reported by Ebbessen *et al.*,[1] optical field diffraction by subwavelength apertures has been intensively researched in both theoretical and experimental aspects. Many interesting issues are derived from this fundamental problem. One of the recent interesting results is the beaming of optical fields diffracted by a subwavelength aperture with metal grating structures discovered by Lezec *et al.*[2] The resonant interactions between the evanescent diffraction fields and the grating structures hidden in the beaming mechanism are very interesting. The beaming mechanism of optical fields diffracted widely by subwavelength aperture is one of interesting physics derived from the study of these resonant interactions. There are many works related to the optical field beaming: on-axis beaming light from subwavelength apertures,[3–5] the phenomenon of enhanced transmission in subwavelength single hole,[6,7] and beaming light with photonic crystals.[8–10] Recently it was found that beaming through a subwavelength single metal slit using dielectric surface gratings is very effective.[11,12]

In this letter, we propose a method for the off-axis directional beaming of optical field diffracted by a single subwavelength metal slit with dielectric surface gratings. In the proposed method, dielectric gratings are asymmetrically arranged on the surface of the metal slit. It is shown that the dielectric gratings can be optimally designed to directionally couple the surface plasmon polariton (SPP) modes induced by the subwavelength slit into the light in surrounding medium along a specific off-axis direction.

Design of the grating structures for optimal directional beaming and the analysis of the field propagation are conducted based on the rigorous coupled wave analysis (RCWA) method.[13–15] The most attractive advantage of the RCWA provides the angular Fourier spectrum of the vector field distribution. From the angular Fourier spectrum of the vector field distribution, we can obtain plentiful information about the interactions of the optical fields and the structures. By analyzing the angular Fourier spectrum distribution, the understanding of directional beaming of the diffracted fields can be clear.

The subwavelength metal slit for beaming optical field is semi-infinite and the width of the air slit in the metal clad is 100 nm. Optical field is assumed to have the wavelength of 532 nm with p polarization. At this wavelength, the silver clad has the refractive index of $0.13+j3.19$. For nonperiodic structure modeling, the perfect matched layers are placed on the left and right sides of the computation region (free space).[16,17]

The slit width of 100 nm is much smaller than half of the wavelength of light. In this condition, the transmission of the optical field into the output region through the metal slit is insignificant.[1] However, when the optimally designed grating structures are attached on the metal surface around the metal slit, the transmission of the optical field into the output region can be greatly increased. Moreover, the diffracted field can propagate like a spatially confined beam.

For finding the dielectric grating structures resonantly diffracting the surface modes induced by the semi-infinite metal slit to the propagating modes in the output region, before doing the analysis for the proposed structure, we inspect the reflection characteristics of particularly chosen three binary dielectric gratings attached on a metal substrate for several incident angles, as shown in the inset of Fig. 1. These gratings have the same refractive index of 1.72, the same thickness of 80 nm, and the same fill factor of 0.5. The

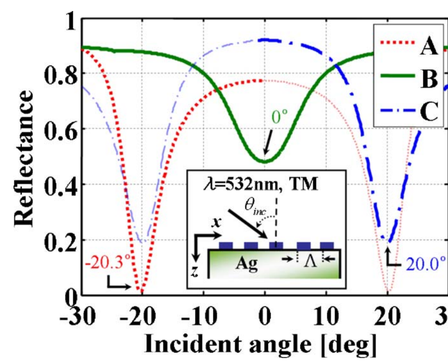

FIG. 1. (Color online) Reflection characteristics of gratings A, B, and C for several incident angles. The bright color line and the vague color line indicate the resonance region and the symmetric region, respectively.

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TABLE I. Designed parameters for dielectric surface gratings arranged on the semi-infinite subwavelength metal slit (k_0: wave number in vacuum).

Grating	Period (nm)	Angle (deg)	k_{sp}/k_0
A	305	−20.3	1.397
B	376	0	1.415
C	503	20.0	1.400

grating periods of gratings A, B, and C are 305 nm, 376 nm, and 503 nm, respectively.

Gratings A, B, and C are optimally designed to resonantly excite the surface plasmon modes for the incident plane waves with the incidence angles of −20.3°, 0°, and 20.0°, respectively. Their reflection characteristics are shown in Fig. 1. In gratings A and C, the SPPs are the negative first and the positive first order diffracted wave, respectively; the excited SPPs propagate along the $+x$ direction at those resonance angles. Those different resonant angles determine whether the beamed light converges or diverges and the sign "−" or "+" represents the converging or diverging case, respectively, as in Ref. 12. For the configuration of three gratings, the SPP wavevector k_{sp} of the resonantly excited surface modes and the resonance incident angles are summarized in Table I.

The strong absorption equivalently indicates the strong coupling to the surface modes on the metal surface. Inversely, we can imply that through these gratings, the surface mode can be strongly coupled to the propagating modes with specific diffraction angles.[5,12] Perceiving this resonant diffraction property, we devise a configuration for exploiting these diffraction properties to realize the on- and off-axis directional beaming of optical field diffracted by a single subwavelength metal slit.

Grating B optimized for normal direction diffraction can be used to generate the on-axis directional optical field. Figures 2(a) and 2(b) show the RCWA results of the subwavelength semi-infinite metal slit surrounded by grating B. As shown in Fig. 2(a), the diffracted field has a well-collimated on-axis beam pattern.

In the RCWA framework, the electric field distribution in the output region is expressed by the Rayleigh representation of angular Fourier spectrum distribution as

$$\mathbf{E} = \sum_{m=-M}^{M} (T_{x,m}\hat{x} + T_{z,m}\hat{z})\exp[j(k_{x,m}x + \sqrt{(2\pi/\lambda)^2 - k_{x,m}^2}z)], \quad (1)$$

where m and $k_{x,m}$ are diffraction order and the x-direction wave number of the mth diffraction order spectral component.[13]

We can see that the distribution of the transmission coefficients in Fig. 2(b) has the shape of the center symmetry. In particular, the distribution within the propagation region shows the angular Fourier spectrum distribution shape similar to that of collimated Gaussian beams,[18,19] which enables the resulting high directionality and collimation of the diffracted field. Also, two distinct peaks in the evanescence region of the transmission coefficient distribution are observed at the points corresponding to the surface modes. Their wave vector normalized to k_0 (wave number in vacuum) is 1.397 and it is slightly deviated from designed value of 1.415. The periodic modeling scheme of the RCWA attributes to this slight mismatch. However, with longer period (40 μm is used in the present simulation) in the RCWA, the deviation would be reduced.

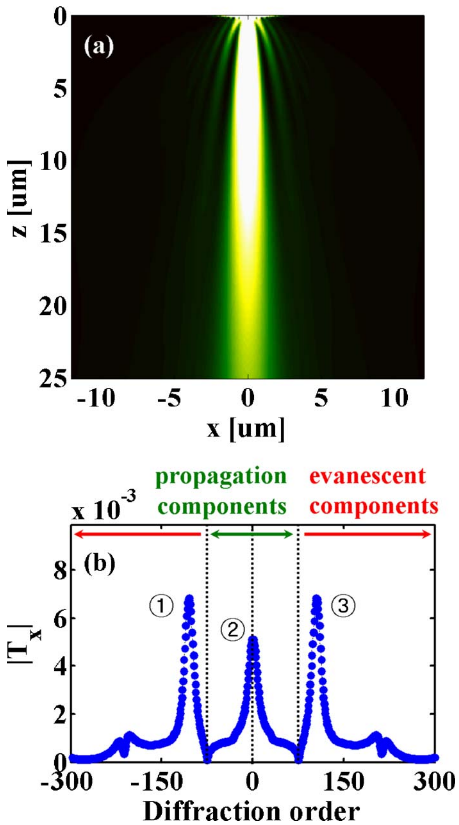

FIG. 2. (Color online) (a) Intensity distribution of the on-axis directional beamed optical field generated by grating B arranged around the slit. (b) Angular Fourier spectrum distribution of the on-axis directional beamed field by using grating B. Wave number normalized by k_0: ① −1.397, ② 0, and ③ 1.397.

When the dielectric surface gratings are symmetrically arranged on both sides of the metal slit, the diffracted optical fields can be diverging, converging, or on-axis beaming along the on-axis direction.[5,12] However, when the dielectric surface gratings are nonsymmetrically arranged, we can adjust the direction of the beam propagation. The devised configuration is that gratings C and A are, respectively, arranged in the left side and the right side of the slit, as shown in the inset of Fig. 3(a). Both gratings A and C have the beaming deviation angles of −20.3° and +20.0°, respectively, as discussed in Fig. 1.

The surface plasmon mode entering into grating A from the left side to the right side is diffracted into the opposite transverse direction of the surface plasmon propagation. The diffraction angle is given by −20.3°. The minus sign indicates the opposite propagation directions of the incident surface mode and the diffracted field. The surface plasmon mode entering into grating C from the right side to the left side is diffracted into the same transverse direction of the incident surface plasmon mode. The diffraction angle is given by 20.0°. The positive sign indicates the same propagation directions of the incident surface mode and the diffracted field. As a result, the diffracted fields generated on both sides of the slit propagate along almost the same direction. By this simple mechanism, the off-axis beaming of the diffracted field can be realized, as shown in Fig. 3(a).

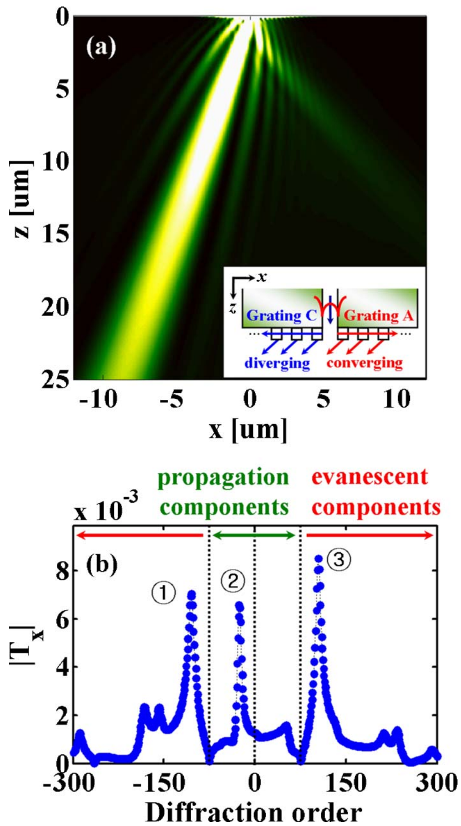

FIG. 3. (Color online) (a) Intensity distribution of the off-axis directional beamed optical field generated by gratings A and C arranged around the slit. (b) Angular Fourier spectrum distribution of off-axis directional beamed light by using gratings A and C. Wave number normalized by k_0: ① −1.397, ② −0.346, and ③ 1.383.

In Fig. 3(b), the propagation Fourier components are the bell-shaped curve like the on-axis beaming light shown in Fig. 2(b), but the peak value is slightly shifted when compared to the spectrum of the on-axis beaming light with the deviation angle of 20.2°.

Since the SPPs excited by the gratings A and C are the negative first and the positive first order diffracted wave, respectively, to reduce the deviation angle, the period of grating A is required to be increased, and that of grating C decreased, and vice versa to extend the deviation angle. For example, if the grating periods of gratings A and C are adjusted to 336 and 438 nm, the beaming angle becomes 10°.

In conclusion, we proposed a method for the off-axis directional beaming of optical field diffracted by a single subwavelength metal slit using asymmetric dielectric surface gratings. With the RCWA, we analyzed and proved the beaming mechanism of optical field generated by a subwavelength metal slit. From the RCWA, we can observe that the on-axis beamed light has bell-shaped propagation spectrum components such as Gaussian beam, and surface modes can be excited on the metal surface by dielectric surface gratings. By attaching optimally designed dielectric surface gratings around a single metal slit, we can design and control the off-axis directional beaming of optical field diffracted by the single metal slit.

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