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Refraction Light Control by Constructing Output Interface Topography of Metal Waveguide Arrays *

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We investigate a nanoscale metal waveguide array (MWGA) structure and demonstrate that negative refraction effect exists from the visible to infrared frequency. Our numerical analysis shows that this effect is related to output interface of MWGAs. Refraction light would have different directions on the gradient shaped output surface as a result of phase retardation control by waveguide thickness. Finite-difference time-domain analysis shows that more sharp superdiffraction limit imaging can be obtained by constructing convex-like output interface topography.

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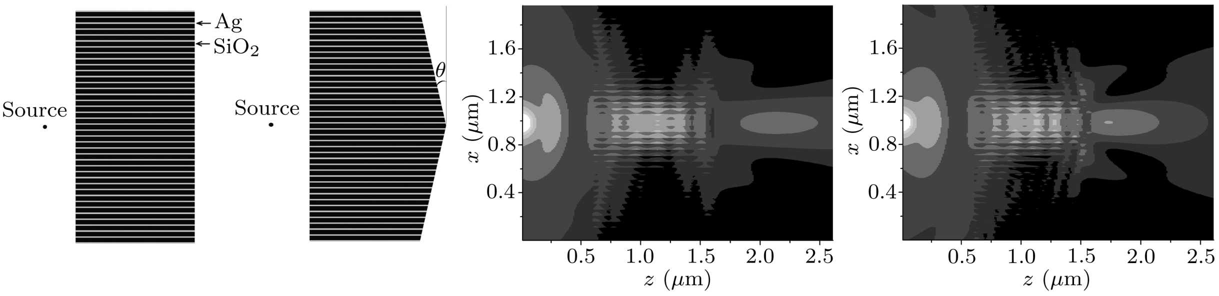
Because of unique properties,[1,2] negative refraction (NR) materials have been widely studied from microwave to visible lights.[3−8] Nanoscale metal waveguide array (MWGA) structures are studied and they have negative refraction effects in the visible-to-infrared frequency range.[9]

In this Letter, we construct the output interface to study its influence on refraction light control of MWGAs. By constructing output interface topography like a convex, more sharp superdiffraction limit imaging can be obtained. Further study shows that this NR effect is related with not only the structure parameters, but also the output interface topography of the MWGAs. Refraction light would have different direction on the different shaped surfaces, which is due to the fact that when the metal waveguide elements in the slits have different length, they transmit light with a phase relationship controlled by the thickness of MWGAs.

First we construct the MWGAs structure as suggested in Ref. [9]. Finite-difference time-domain (FDTD) method is used in this study. Figure 1(a) shows the setup of MWGA which is composed of 40 pieces of silver guides. Width of silver guides is set to be $w_1 = 10\,\text{nm}$, width and permittivity of dielectric material in guide regions $w_2 = 40\,\text{nm}$ and $\varepsilon_2 = 2.25$, so that the MWGA period $D = 50\,\text{nm}$. Here the MWGA length is $1\,\mu$m and a line source (wavelength $\lambda = 632.8\,\text{nm}$) is placed at 600 nm away from input interface between air and MWGAs. A superdiffraction limit image is obtained on the other side of the MWGAs, as mentioned in Ref. [9]. The simulation results approve our study method.

To compare with the above-mentioned results, output interface is constructed as shown Fig. 1(b), which is cut symmetrically by angle θ. There is still only



(a) (b) (c) (d)

Fig. 1. (a) Scheme of a 1.96-μm-long MWGAs composed of 40 pieces of waveguides with a 10-nm-thick Ag film and and a 40-nm-thick SiO$_2$ layer. (b) MWGAs with protuberant output interface. (c) $|H_y|^2$ distribution of structure in (a). (d) $|H_y|^2$ distribution of structure in (b).

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one image and is enhanced as shown Fig. 1(d), which is different from the results of negative refraction effects. When considering MWGAs as a symmetrical negative refraction material with refractive index $n = -1$, there would have two images on the other side.

Cut angle is chosen to be $\theta = 10°$, $15°$ and $20°$ respectively, the influence of output interface topography on the image can be found out. The intensities of image are 14%, 22% and 24% larger than normal MWGAs, and FWHM are respectively 72%, 62% and 56% of normal MWGAs, as shown in Fig. 2. When the angle of the bevel with respect to the output interface of MWGAs increases, the intensity of image becomes larger, FWHM is shorter and the distance from the image to MWGAs is smaller. By constructing MWGAs like a convex, more sharp superdiffraction limit imaging can be achieved.

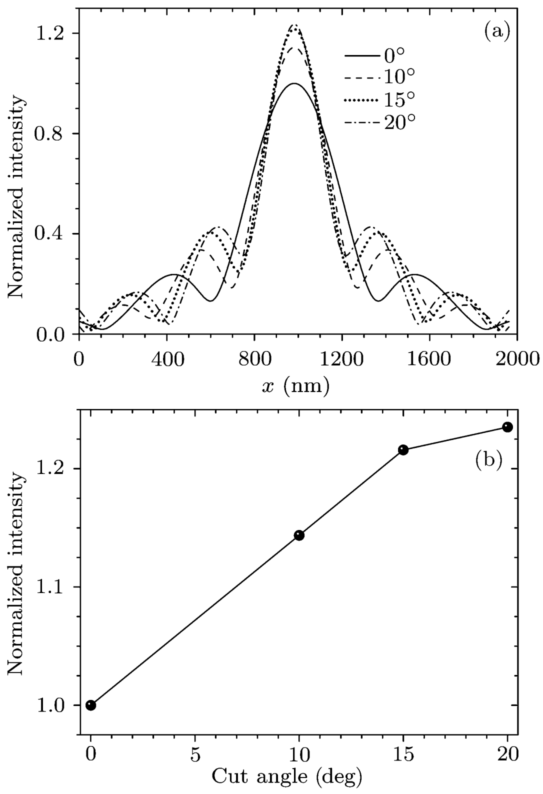

Fig. 2. (a) $|H_y|^2$ distribution in the image plane. (b) Dependence of peak value of $|H_y|^2$ distribution in the image plane on the cut angles of output interface.

For further study, output interface of MWGAs is constructed as shown in Fig. 3(a), which is cut symmetrically by angle θ like a concave lens. We choose the cut angle $\theta = 5°$, $10°$ and $15°$. It can be seen from Fig. 3(b) that when the angle of the bevel on the output interface of MWGAs increases, the intensity of image are smaller and FWHM is wider.

The FDTD simulation results present a positive refraction on the output interface. To give explanation to this phenomenon, each waveguide element can be considered as a line source on the output interface,[10] and the optical fields can be expressed as a summation of the cylindrical waves from each nanoslit element,

$$H_y(x,z) = \sum_{\alpha} \frac{A_\alpha}{r_\alpha} e^{i\phi_\alpha} e^{ik_0 r_\alpha}, \qquad (1)$$

where $r_\alpha = \sqrt{(x-x_\alpha)^2 + (z-z_\alpha)^2}$, and k_0 is the wave vector of the transmitted beam in the air region; A_α and ϕ_α are the amplitude and phase of the radiation component emanating from the αth waveguide located at x_α and z_α, respectively. Though there are SP waves coupling in the MWGAs, the refraction direction must satisfy the phase matching condition at the output interface, which makes the light refract in the way similar to the dielectric lens.[10] The MWGA

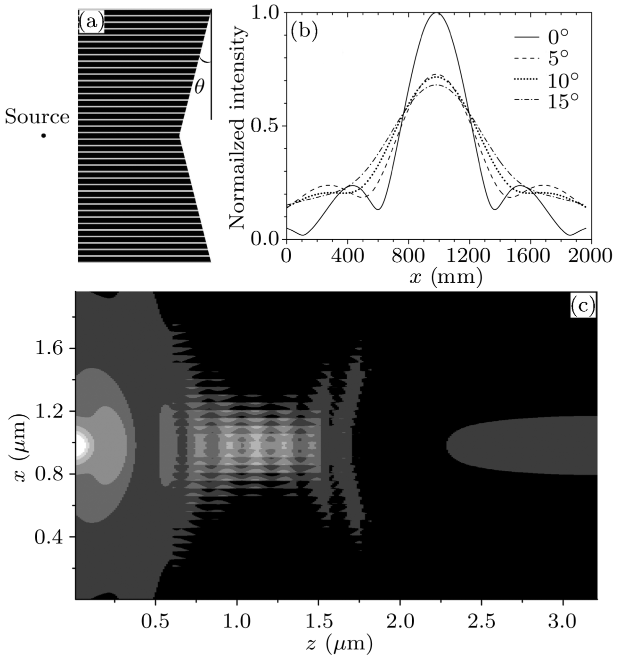

Fig. 3. (a) MWGAs with concave output interface. (b) $|H_y|^2$ distribution in the image plane. (c) $|H_y|^2$ distribution of structure in (a).

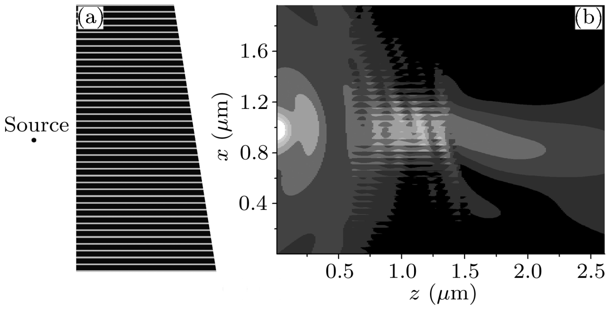

Fig. 4. (a) Scheme of a 1.96 μm-long MWGA composed of 40 pieces of waveguides with a 10-nm-thick Ag film and a 40-nm-thick SiO_2 layer. The gradient angle of output interface is 20°. (b) $|H_y|^2$ distribution of structure in (a).

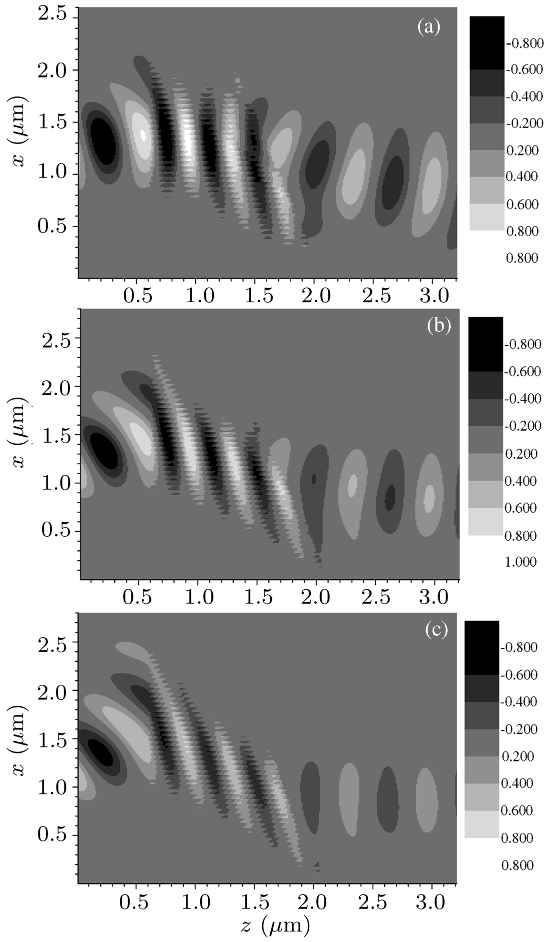

Fig. 5. H_y distribution for the structure shown in Fig. 4(a) on the 10000th simulation step when a gaussian beam is incident into it with the incident angle of (a) 15°, (b) 30° and (c) 45°. Beam has negative refraction on the input interface and positive refraction on the output interface.

structure suggested by Fan and Wang *et al.*[9] is capable of coupling and propagating for evanescent waves, so that when MWGAs are constructed like a convex, it can present more sharp superdiffraction limit imaging without NR effect.

The FDTD simulation result demonstrates the above analysis. A gradient output interface topography is constructed, the gradient angle is 20°, as shown in Fig. 4(a). The image is on the positive side of the normal line of the output interface, as shown in Fig. 4(b). To give a clear refraction image, a TM-polarized Gaussian light beam with the full width at half maximum (FWHM) of 600 nm is incident into the MWGAs constructed as shown in Fig. 4(a) with angles 15°, 30° and 45° respectively. The simulated H_y distribution of structure in Fig. 4(a) on the 10000th simulation step is presented in Fig. 5. It can be found out that for all the incident angles, the beam has negative refraction on the input interface and positive refraction on the output interface.

In summary, we have suggested a simple way to provide positive and negative refractions on MWGAs. The output interface cut symmetrically cannot support negative refraction because of the phase matching condition. The numerical results show that NR effect is also related with the output interface. MWGA structures still have unique properties to gather and transfer the evanescent waves, so that when a convex-like output interface topography is constructed, though negative refraction is not supported, more sharp superdiffraction limit imaging can be obtained.

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