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Near-Field Optical Transfer Function for Far-Field Super-Resolution Imaging *

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The far-field superlens based on surface plasmon polaritons (SPP) has shown great application potential, but it is difficult and time-consuming to reconstruct the far-field image. We derive a near-field optical transfer function (NOTF) of a silver slab and analyse its validity so that accurate information of nano-scale object in the near-field can be computed rapidly. The NOTF is helpful not only for analysing the super-resolution imaging process in far-field, but also for providing a track to describe the transmission of optical information from near-field to far-field by using the optical transfer functions theory only.

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So far, many approaches of imaging beyond the diffraction limit with superlens have been reported.[1−7] Unfortunately, it was pointed out that these superlenses could only produce sub-diffraction-limited images in the near field.[8] Recently, an optical microscope capable of projecting the images with super-resolution to the far field has been noted,[9−12] although it is difficult and time-consuming to reconstruct the near-field image. In fact, the imaging process of far-field superlens (FSL) can be divided into two steps: super-resolution imaging with silver film, and the transmission of information from the near-field to far-field modulated by the coupling device.[11] Then, the far-field image can be easily reconstructed by optics or computer technology. In this Letter, we regard the near-field imaging of silver lamella as a linear spatially invariant system, and present the concept of a generalized near-field optical transfer function (NOTF) and its formula. We try to demonstrate that it is feasible to describe the imaging process by the NOTF formula. The simulations show that the computing time of the near-field imaging or object information reconstruction in the far-field will be reduced greatly by NOTF.

Figure 1(a) shows the scheme of far-field superlens system. Figure 1(b) is the near field silver superlens in the FSL system. Here the thickness of silver with permittivity ε_2 is d, and there are two kinds of dielectrics on both sides of the slab with dielectric constants ε_1 and ε_3, respectively. It should be noted that magnetic permeability $\mu = 1$ everywhere in such a system. Figure 1(c) shows the imaging process of silver superlens at $\lambda_0 = 441\,\text{nm}$ with the relative permittivity of silver $\varepsilon_2 = -3.372 + i0.253$ by FDTD method. In the FSL system, the evanescent waves can be enhanced by the silver superlens. Namely, the super-resolution information of object in the low refraction index medium can be coupled into propagating waves in high refraction index medium by the SPP effect, and then the propagating waves can be transferred to far-field by coupling elements such as prism grating, subwavelength metal grating and so on, when the matching condition is satisfied.[9,11] We assume a p-polarized monochromatic point object source in the medium 1 at a distance z_1. The near-field image plane is inside medium 3 at a distance z_2 from the edge of the silver slab. The object at $z = -z_1$ can be characterized by its emanating field distribution whose magnetic vector $\boldsymbol{H}_o(\boldsymbol{r})$ can be expressed as a Fourier integral over all the wave-vectors,

$$\boldsymbol{H}_o(\boldsymbol{r}) = \int \widetilde{H}_o(\boldsymbol{k}) \exp[i(\boldsymbol{k}\cdot\boldsymbol{r})] d\boldsymbol{k}, \tag{1}$$

where $\widetilde{H}_o(\boldsymbol{k})$ is the Fourier transfer of source object. The evanescent and propagating waves components are all contained in this formula. Supposing that the incident waves are in the $x-z$plane, the dispersion equation in different media can be written as $k_{ix}^2 + k_{iz}^2 = \varepsilon_i\omega^2/c^2 (i = 1, 2, 3$ denote the three media). For the propagating components ($k_{ix}^2 \le \varepsilon_i\omega^2$), we have $k_{iz} = (\varepsilon_i\omega^2 - k_{ix}^2)^{1/2}$ and for the evanescent waves components ($k_{ix}^2 \ge \varepsilon_i\omega^2$) we have $k_{iz} = i(k_{ix}^2 - \varepsilon_i\omega^2)^{1/2}$. To each of the components, the transmission coefficient for the Fourier spectrum across the slab can be written as

$$\begin{aligned} T = {} & 4\varepsilon_2\varepsilon_3 k_{1z}k_{2z}\exp(ik_{2z}d)\big[(\varepsilon_2 k_{z1} + \varepsilon_1 k_{2z}) \\ & \cdot(\varepsilon_3 k_{2z} + \varepsilon_2 k_{3z}) + (\varepsilon_2 k_{1z} - \varepsilon_1 k_{2z}) \\ & \cdot(\varepsilon_3 k_{2z} - \varepsilon_2 k_{3z})\exp(2ik_{2z}d)\big]^{-1}. \end{aligned} \tag{2}$$

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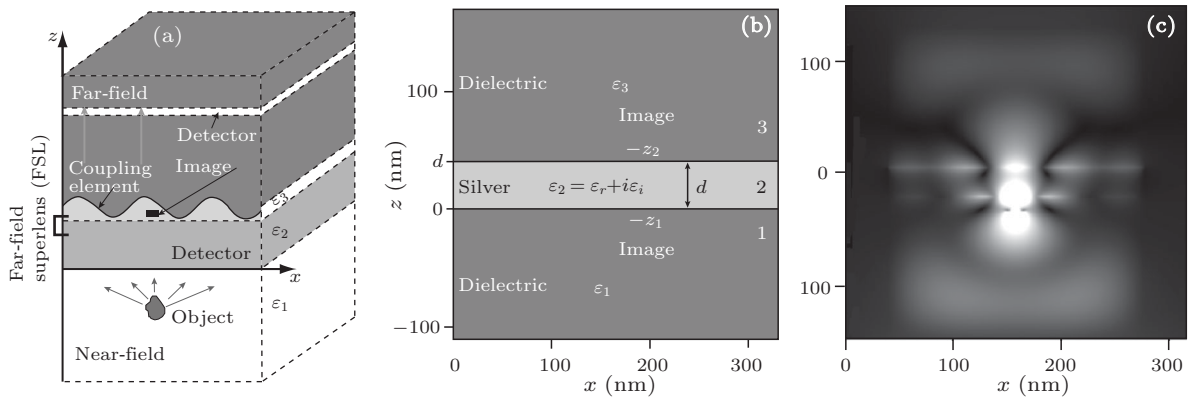


Fig. 1. (a) Scheme of FSL. In this system, the evanescent waves are enhanced by the silver layer due to the effect of SPPs, and then transform into propagating waves by the coupling devices. (b) The zooms of superlens system consisting of a silver slab. (c) Simulation of near-field imaging working at $\lambda_0 = 441$ nm, with a line source object 20 nm and separation 20 nm to the bottom margin of silver layer with FDTD method.

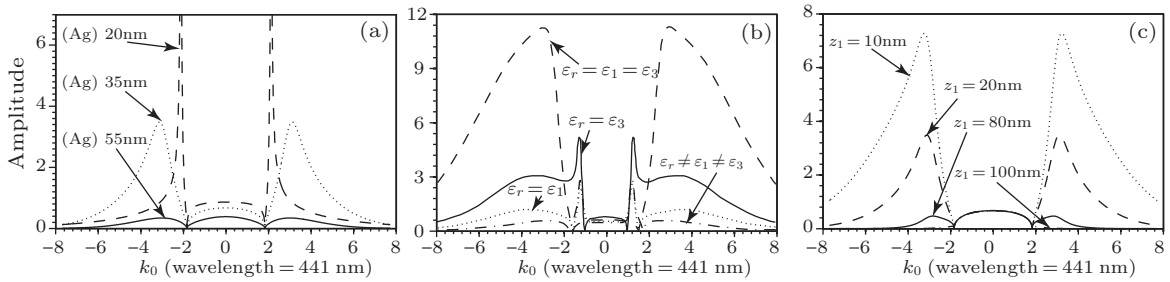


Fig. 2. NOTF in different conditions: (a) Fixing the optimum matching condition $\varepsilon_r = \varepsilon_1 = \varepsilon_3$, the silver thickness is varied from 25 nm to 55 nm. (b) Fixing silver thickness at 35 nm and varying different matching conditions. (c) Fixing the optimum matching condition and silver thickness at 35 nm, varying the displacement of object from 10 nm to 100 nm.

According to the Drude formula $\varepsilon_2 = 1 - \omega_p^2/\omega(\omega + i\gamma) = \varepsilon_r + i\varepsilon_i$, ω_p and γ are the plasma frequency and loss component of metal, respectively, and $\omega = ck_0$ (c is the speed of light in vacuum) is the angular frequency of incident light. The Fourier spectrum of the image $\widetilde{H}_i$ can be obtained as

$$\widetilde{H}_i = \widetilde{H}_o(k_x) \exp\left(i \cdot z_1 \sqrt{k_1^2 - k_x^2}\right) \cdot T \cdot \exp\left(i \cdot z_2 \sqrt{k_3^2 - k_x^2}\right). \quad (3)$$

Since the near-field imaging of silver lamella can be regarded as a linear spatially invariant system, the generalized near-field optical transfer function can be defined as

$$\mathrm{NOTF} = \frac{\widetilde{H}_i}{\widetilde{H}_o} = \exp\left(i \cdot z_1 \sqrt{k_1^2 - k_x^2}\right) T \cdot \exp\left(i \cdot z_2 \sqrt{k_3^2 - k_x^2}\right), \quad (4)$$

where $\widetilde{H}_i$ is the Fourier transfer of image and $\widetilde{H}_o$ is that of the object.

NOTF strongly depends on the thickness of silver and matching conditions. Numerical analysis of thickness dependent optical transfer functions are shown in Fig. 2(a). The silver thickness is varied from 25 nm to 55 nm with fixed matching condition $|\varepsilon_r| = \varepsilon_1 = \varepsilon_3 = 3.372$. In the curve of NOTF, there is a peak owing to the enhancement of the specifically evanescent field by the surface plasmon resonance, and the low spatial frequency components are damped due to the absorption. In Fig. 2(b), the matching conditions are varied while the silver thickness is kept at 35 nm. There is a maximum field enhancement and broader band frequency across a silver slab on the condition of $\varepsilon_r = \varepsilon_1 = \varepsilon_3$, and there is also an enhancement in a broad band frequency in the case of $\varepsilon_r = \varepsilon_3$, which ensures the perfect imaging tenable in practice. Fixing the perfect matching condition and optimum silver thickness at 35 nm and varying the object displacement z_1, we can find that when $z_1 > 100$ nm, there is hardly high frequency across the silver as shown in Fig. 2(c). It is known that the macro-imaging system equals an optical low-pass filter (OLPF), whereas the superlens system is different. It is shown clearly in Fig. 2 that NOTF is composed of many high spatial frequencies (evanescent waves), and the silver film can be regarded as a special filter which allows high frequency components to pass through. From Eq. (4) and Fig. 2, it can be noticed that NOTF is related directly to the width of silver and separation between the object and the silver, and the perfect imaging is tenable only in the near-field.

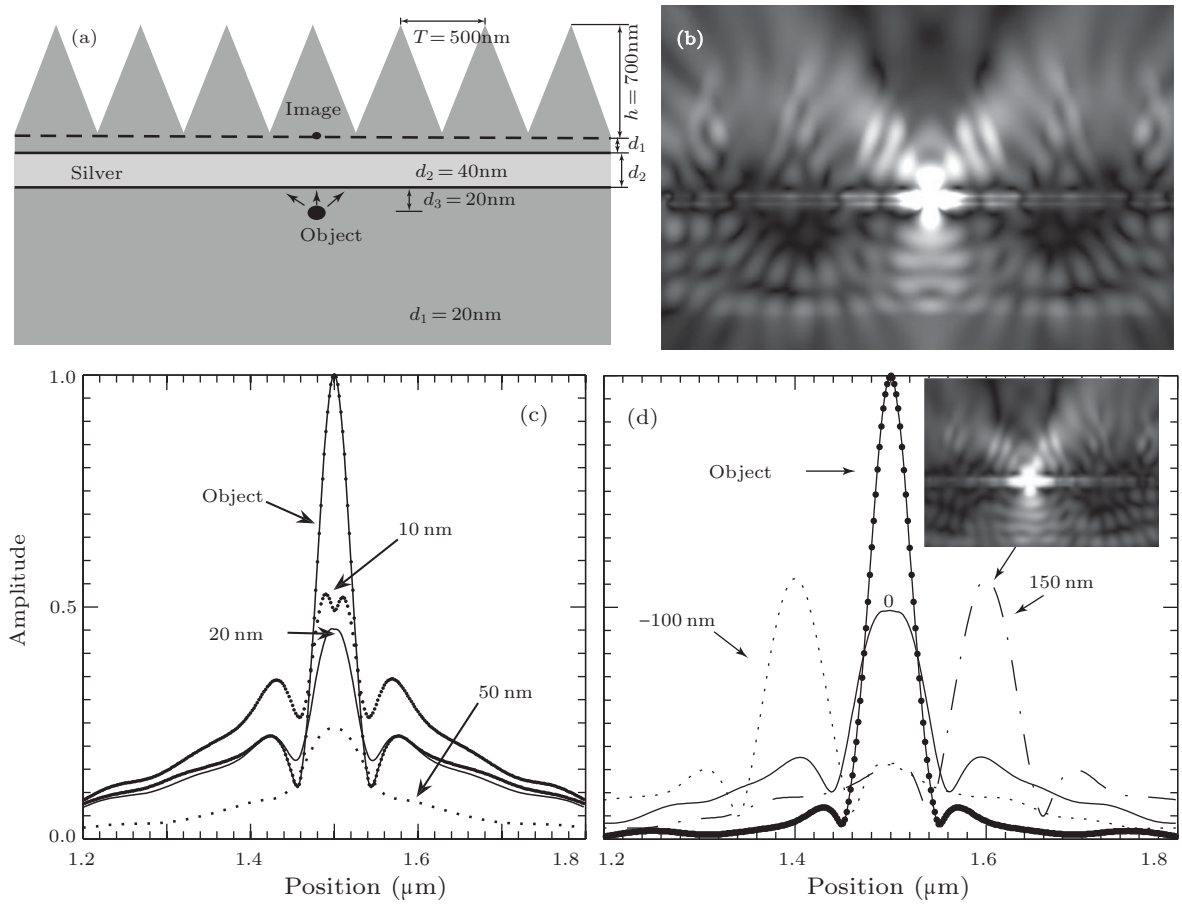


Fig. 3. (a) Scheme of an FSL system. (b) The field distribution with the source object at the centre of scheme with FDTD method. (c) The image in the near-field with different thicknesses of matching layers from 10 nm to 50 nm calculated by FDTD method. (d) Simulation of the light source with 100 nm and 150 nm offset to the centre, insert: the field distribution of offset object.

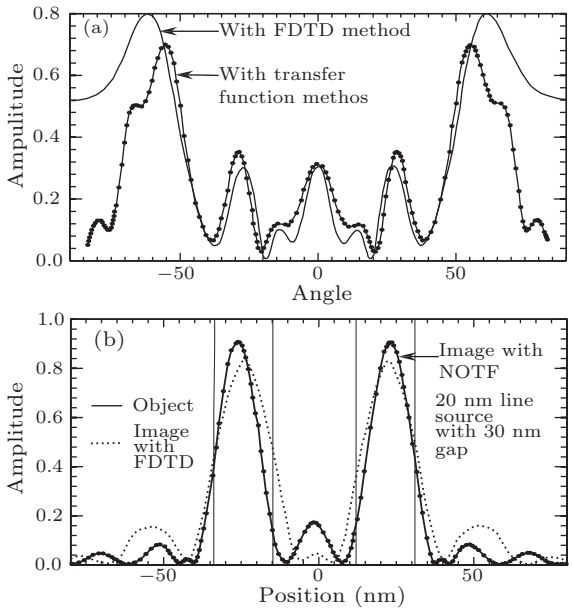


Fig. 4. (a) The far-field distribution of one dotted object calculated by NOTF and FDTD methods, respectively. (b) The near-field image of two line-source objects of 30 nm width and 40 nm gap with methods of NOTF and FDTD, respectively.

Can NOTF from the formula (4) be used in calculation and analysis of the far-field superlens imaging? The key problem is whether the back-reflections effects from additional coupling layers can be neglected, namely, whether the imaging process of far-field superlens (FSL) can be divided into two steps. The imaging simulation with FDTD method shows if there is a thin dielectric matching layer with several decade nanometres between silver and coupling device and the object scale is much smaller than the coupling elements, the back-reflections is negligible. Figure 3(a) is a scheme of the FSL system in our FDTD simulation. Figure 3(b) is the near-field imaging with 20 nm thickness of matching layer and Fig. 3(c) is the curves of amplitude of the image with thickness changing from 10 nm to 50 nm. We can see that the distortions of the image from the back-reflections and boundary affections are unapparent when an appropriate thickness of the matching layer is selected, such as 20 nm. Figure 3(d) shows the variation of the image with position of object on fixed matching layer 20 nm. Although the light distributions in the far-field are different, the images in the near-field are nearly invariable. It implies that the effects from the coupling layer can be neglected

under the proper conditions.

In order to verify the reliability of NOTF from Eq. (4), we calculate the far-field distribution of one dot object as Fig. 4(a) and near-field image of two line-source objects of 30 nm width and 40 nm gap as Fig. 4(b). Figure 4(a), real line is obtained by FDTD method, the dotted line is calculated by optical transfer function method, and the computing results are congruous approximately by the two methods. Figure 4(b), the rectangle curve is the object and the real dotted line and dashed line denote the near-field images of two objects calculated by the optical transfer function method and FDTD method respectively, and the figure shows that the images with optical transfer function method agree well with the FDTD methods.

We have also simulated other cases by FDTD method and NOTF method, such as single slit, multiple slits and so on. The simulations show NOTF is an available in the far-field superlens system, and the imaging computing time will be greatly reduced by comparing to the vector algorithms for the computation of electromagnetic field. It demonstrates that the far-field super-resolution image can be simply reconstructed by using only NOTF and information optics. The NOTF not only offers a convenient way to analyse and to compute the near-field imaging of subwavelength information, but also is helpful to the development and application of the far-field silver-superlens system.

References

[1] Pendry J B 2000 *Phys. Rev. Lett.***85** 3966
[2] Podolskiy V A, Sarychev A K and Shalaev V M 2003 *Opt. Express* **11** 735
[3] Yen T J, Padilla W J, Fang N, Vier D C, Smith D R, Pendry J B, Basov D N and Zhang X 2004 *Science* **303** 1494
[4] Linden S, Enkrich C, Wegener M, Zhou J, Koschny T and Soukoulis C M 2004 *Science* **306** 1351
[5] Zhang S, Fan W J, Minhas B K, Frauenglass A, Malloy K J and Brueck S R 2005 *Phys. Rev. Lett.* **94** 037402
[6] Kwon D H, Werner D H, Kildishev A V and Shalaev V M 2007 *Opt. Express* **15** 1647
[7] Lezec H J, Dionne J A and Atwater H A 2007 *Science* **316** 430
[8] Podolskiy V A and Narimanov E E 2005 *Opt. Lett.* **30** 75
[9] Durant S, Liu Z, Steele J and Zhang X 2006 *J. Opt. Soc. Am.* B **23** 2383
[10] Liu ZW, Lee H, Xiong Y, Sun C and Zhang X 2007 *Sience* **315** 1686
[11] Zhang Z Y, Du J L and Guo X W 2007 *J. Appl. Phys.* **102** 074301
[12] Xiong Y, Liu Z W, Sun C and Zhang X 2007 *Nano. Lett.* **7** 403
[13] Anantha S, Pendry J B, Schurig D, Smith D R and Schultz S 2002 *J. Mod. Opt.* **49** 1747