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Study on the imaging characteristics of far-field superlens

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ABSTRACT

The optical transfer function of the far-field superlens imaging system is established in this thesis to make it easy to describe the corresponding relation between the far-field angular spectrum and the near-field object superresolution information. We utilized the established optical transfer function to make detailed research on the imaging characteristics of the far-field superresolution, also reconstruct the near-field nano-information through the far-field angular spectrum, which proves that the resolution of the far-field superlens with structure coupled with metal grating can reach 50 nm, and provides a helpful reference for the study of the new optical microscope imaging of superresolution.

1. Introduction

To pursue the high-resolution imaging has always been a permanent direction of the scientific research, and the human beings have made unremitting efforts to improve the resolution of the microscope during the past 500 years since the optical microscope was invented. But the resolution of the traditional optical microscope can hardly exceed 200 nm because of the diffraction limit. Although the NSOM (Near-field Scanning Optical Microscope) provides sub-wavelength and nanoscale resolution, it cannot work like routine lens, which can give complete projection imaging of an object each time; the information of the near-field object is collected by the probe which scans continuously point-by-point on the object surface [1–3], so, the damage on the object surface is unavoidable. In addition, the imaging speed and efficiency cannot be improved substantially, this forces the people to explore a new optical imaging technology of superresolution.

After research on the medium's negative index of refraction, the British physicist Pendry proposed the superlens concept since 2000, and after that the research on superresolution imaging has become the focus of the academic circles [4–7]. At present, the near-field superresolution optical imaging with silver layer superlens, photonic crystal, metal or medium metamaterial has been realized in the world. Among which, the use of SPPs (surface plasmon polaritons) with metal nano structure to enhance the evanescent wave of the nanoscale structure information to realize optical superresolution imaging receives more attention from the researchers [8–10]. Although the superlens can realize the high-resolution near-field imaging of the object, the practical application of such superresolution imaging technology has a lot of difficulty because it is hard to detect the near field. The superresolution imaging will have no practical value unless the near-field superresolution information is effectively transferred to the far field for detection. In 2006, the Zhang Xiang Team in US firstly proposed the concept of FSL (far-field superlens), which means to utilize to sub-wavelength metal grating to couple the near-field object superresolution information to the far field, and to get the super-resolution image of the near-field object through back calculation or optical inversion. This provides a new way for the superresolution optical imaging [11–16].

Presently, most of the reported researches on FSL imaging calculate through limited time domain differential, which is inefficient in parameter optimization and calculation. At the same time, it is unfavorable for analyzing the physical transfer process of the nano-material information to the far field. For this purpose, we will establish an optical transfer function to describe the transfer of the nano-material superresolution information from the near-field to the far field, also this function can be used to analyzing the far-field optical superresolution imaging system with metal grating structure, and can provides helpful reference for the research of the far-field superresolution imaging system.

2. Establishment of the far-field superlens optical transfer function

We takes the one-dimensional far-field superlens imaging system for an instance to establish the optical transfer function, and its structural devices are shown in Fig. 1, from the bottom to top, they

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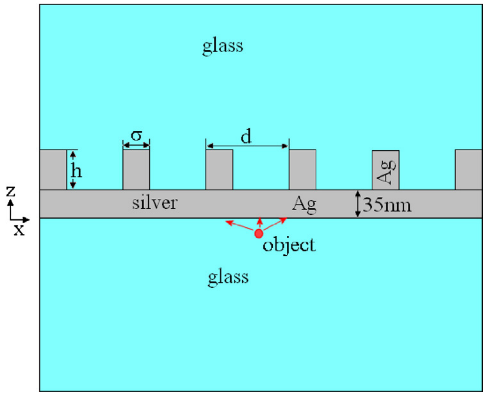

Fig. 1. Schematic of far-field superlens.

are respectively: object space, silver layer (the thickness is 35 nm), metal/medium grating (SPPs coupling output layer, the thickness is h, the period is d and the metal width is σ) and the far-field free space medium, among which, the combination of silver layer and metal grating is called far-field superlens (FSL).

The optical wave emitting by the near-field object, namely, the object wave, can be expressed by the Fourier spectrum $\tilde{H}_o(k_{0x}, z_o)$, the Fourier spectrum transferred to the optical field of the far-field detector by the FSL is $\tilde{H}_i(k(\theta), z_2)$, the relation between the far-field angular spectrum and the Fourier spectrum of the near-field object, $T(k_o, \omega)$ is the optical transfer function of the FSL system; therefore, the Fourier spectrum of the near-field nano-material and far-field optical field can be expressed as the following relation [17]:

$$\tilde{H}_i(k(\theta), z_i) = \exp(i \cdot Z_o \cdot k_{oz}) T(k_{ox}, \omega) \cdot \exp(i \cdot Z_{iz} \cdot k_{iz}) \cdot \tilde{H}_1(k_{ox}, z_i) \tag{1}$$

Wherein, k_{ox} is the x-direction component of the wave vector of the radiation optical wave of the near-field nano object; k_z is the Z-direction wave vector component, which is derived from formula (2):

$$k_{jz} = [\varepsilon_j (\omega/c)^2 - k_{ox}^2]^{1/2}, (j = o, 1, 2, i) \tag{2}$$

It can be seen from the above two formulas that the information of the near-field nano object can be inverted rapidly through the angular spectrum of the far field so long as the optical transfer function $T(k_{0x}, \omega)$ of FSL is obtained.

Because the TM wave is usually utilized to excite the SPPs, so on the incidence of TM wave will be discussed in this thesis. The TM wave in the x–z plane can be expressed by the y component H_y of the magnetic field, the Helmholtz equation is met when there is no surface density of residual free charge at the boundary.

In Zone 1 (object space), the Helmholtz equation can be written as:

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} + \varepsilon_o \frac{\omega^2}{c^2} \right) H_y^{(o)}(x, z_o, \omega) = 0 \tag{3}$$

In Zone 2 (metal silver layer), the Helmholtz equation can be written as:

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} + \varepsilon_1 \frac{\omega^2}{c^2} \right) H_y^{(1)}(x, z_1, \omega) = 0 \tag{4}$$

In Zone 3 (metal/medium grating layer), the Helmholtz equation can be written as:

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} + \varepsilon_2 \frac{\omega^2}{c^2} \right) H_y^{(2)}(x, z_2, \omega) = 0 \tag{5}$$

In Zone 4 (space of the detector)

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} + \varepsilon_i \frac{\omega^2}{c^2} \right) H_y^{(i)}(x, z_i, \omega) = 0 \tag{6}$$

In above formulas, $H_y^{(j)} (i = o, 1, 2, i)$ respectively stands for the object space, the metal silver layer, the metal/medium grating layer and the y component of the magnetic field intensity of the detector zone, wherein, the effective dielectric coefficient ε_2 of the metal/medium grating can be calculated by the following formula [18]:

$$\varepsilon_2 = \frac{1}{2(N-1)} \{ (Np-1)\varepsilon_m + (N-1-Np)\varepsilon_d) \pm \sqrt{[(Np-1)\varepsilon_m + (N-1-Np)\varepsilon_d]^2 + 4(N-1)\varepsilon_m \varepsilon_d)} \} \tag{7}$$

The selection of "±" shall ensure that the imaginary part of the effective dielectric coefficient ε_2 calculated from formula (7) is positive value. Among which, "p" is the duty ratio; "N" is the integral number, when the groove-shaped metal/medium shows a three-dimensional distribution, N = 3; when it shows two-dimensional distribution, N = 2; we shall select N = 3 according to the structure adopted for the calculation in this thesis; "ε_m" is the metal dielectric coefficient, "ε_d" is the dielectric coefficient of the filling medium in the groove. After the effective dielectric coefficient ε_2 of the metal grating is obtained by formula (7), it can be regarded as a single medium layer whose dielectric constant is ε_2, then the FSL's transmissivity to each space-frequency component can be derived by utilizing the multi-layer medium theory:

$$T(k_{ox}, \omega) = \sqrt{\frac{\varepsilon_o}{\varepsilon_i}} \left[\left(\frac{\varepsilon_o/k_{oz} + \varepsilon_1/k_{1z}}{2\varepsilon_o/k_{oz}} \right) \right] \left[\left(\frac{A + Br_{o1} e^{jk_{1z}d_1}}{r_{2i} e^{jk_{2z}d_2} + e^{jk_{1z}d_1}} \right) \right] \tag{8}$$

$$A = \left[\frac{\varepsilon_1/k_{1z} + \varepsilon_2/k_{2z}}{2\varepsilon_1/k_{1z}} \right] \left[\frac{1 + r_{12} r_{2i} e^{2jk_{2z}d_2}}{e^{jk_{1z}d_1}} \right] r_{mn} = \left(\frac{k_{nz}/\varepsilon_n - k_{mz}/\varepsilon_m}{(k_{mz}/\varepsilon_m + k_{mz}/\varepsilon_m), (m, n = o, 1, 2, j)} \right)$$

Input formula (8) to formula (1), then the relation between the superresolution information of the near-field nano object and the far-field angular spectrum can be obtained.

3. Analysis on the FSL optical transfer function

To explain the practical applicability of the optical transfer function, we adopts the superlens structure in reference [18] and selects the line source with the wavelength of 441.6 nm as the object, the distance to the lower surface of the silver layer superlens, namely, z_o = 10 nm; the thickness of the metal/medium grating layer, h = 30 nm, the period, d = 150 nm; the metal width, σ = 40 nm; the dielectric coefficient of the object space medium, ε_o = 2.40; the dielectric coefficient of the image space medium, ε_i = 2.69, then the optical transfer function of the far-field superlens can be obtained through formula (2), as shown in Fig. 2.

It can be seen from Fig. 2(a) that, the far-field superlens has two higher resonance peaks, and the space-frequency scope of the enhanced evanescent wave is from 2.1 k_0 to 4.7 k_0. The angular spectrum when the evanescent wave of the near-field object is coupled to far-field can be obtained from $mG \pm k_{0x} = \sqrt{\varepsilon_2}\omega/c \sin(\theta)$, wherein, θ is the radiation angle which the FSL grating couples the SPPs to the far field, its scope is from $-\pi/2$ to $\pi/2$, the scope of radiation angle θ is generally determined according to the exploration scope of the far field; $G = \frac{2\pi}{d}$ is the reciprocal lattice vector of the coupling grating, where, "d" is the period of the grating, "m" is an integral number. The two peak values appearing on the curve of the optical transfer function respond to k_{0x} = 2.2 k_0 and