Optics Communications 368 (2016) 180–184

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

The imaging properties of the metal superlens

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ARTICLE INFO

Article history:
Received 28 October 2015
Received in revised form
4 February 2016
Accepted 5 February 2016
Available online 12 February 2016

Keywords:
Superlens
Nanolithograph
Imaging
Electromagnetic optics

ABSTRACT

The zero-refraction property of a metal film can be used to image so that the metal film behaves as a superlens. Experimentally, the metal superlens is sandwiched between the photosensitivity resist (PR) and the dielectric spacer in the photolithograph device to produce images. In this paper, the imaging conditions of the metal superlens, or the parameters of the device containing the superlens are investigated in detail. It is found that the energy zero-refraction effect is the intrinsic property of the metal superlens. The permittivities of the dielectrics at the two sides of the superlens will influence the imaging quality. The rule is drawn for obtaining best images: the two dielectrics should have the same permittivities, so-called symmetry case, and the real part of the permittivity of the metal superlens plus the dielectric permittivity is just equal to 1, i.e. $\epsilon(dielectric) + \epsilon_r(superlens) = 1$.

1. Introduction

The concept of perfect lens made of double negative (DNG) metamaterials [1–4] unlocked a way to obtain an image resolution beyond the traditional diffraction-limit. Because of the difficulties in fabrication of the DNG metamaterials, the applications of the perfect superlens in practice have been baffled. Fortunately, the simplest perfect lens made of silver slab had been proposed in 2000 [2], and demonstrated experimentally in 2005 [5]. After that a lot of works reported the sub-diffractive imaging by metal superlens [6–14]. In the demonstration experiment, the silver film was inserted into a photolithographic device and the sub-diffraction pattern was cut on a photosensitive resist (PR). Silver is an epsilon-negative (ENG) material, and this characteristic is essentially different from that of the original perfect lens made of DNG metamaterials. A theoretical analysis showed that [15] when a light beam entered into the ENG or permeability negative (MNG) film with an arbitrary incident angle, the energy flow would penetrate the film with the direction perpendicular to the film surface. This means that the zero-refraction occurs in a single negative film, either ENG or MNG one. As a result, the imaging by a single negative film is caused by the imprint effect, instead of the double focus phenomenon occurring in DNG perfect lens systems. The calculation results based on the zero-refraction principle agreed with the experimental results satisfactorily. Indeed, the zero-refraction has not been touched in standard text books. In the following, when we say a superlens, we mean an ENG or MNG film instead of a DNG perfect lens. In practice, as the superlens works in a complicated photolithograph device, the image quality is determined by several factors, such as the real and imaginary parts of permittivity of the superlens, the properties of the photosensitive resist and medium before the superlens. How these factors influence the image is not very clear yet. In this paper we investigate systematically the influence of the factors. The conclusions are helpful for the design of the photolithograph device in which the superlens works.

2. The intrinsic property of the superlens: zero-refraction

Although the zero-refraction occurring in superlens has been shown [15], a general and detailed discussion is desired. In this section, we present some new results. Let us consider an incident beam with the width of w illuminating the metal surface, as sketched in Fig. 1(a). The incident electric field is confined in the range from $-x'$ to x', where $2x' = w/\cos\theta$. This pattern will be printed at an observation plane away from the surface by distance z. At this plane, the electric pattern can be expressed as

$$E(x, z) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{(ik_x'x+ik_z'z)}dk_x' \int_{-w/(2\cos\theta)}^{w/(2\cos\theta)} te^{i(k_x-k_x')x'}dx' \tag{1}$$

Here t is the transmission coefficient (Fresnel formula), which means the influence of the incident surface on the transmission field. When $t=1$, the incident beam enters the metal entirely without any reflection. In this case, there is no surface influence

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http://dx.doi.org/10.1016/j.optcom.2016.02.007

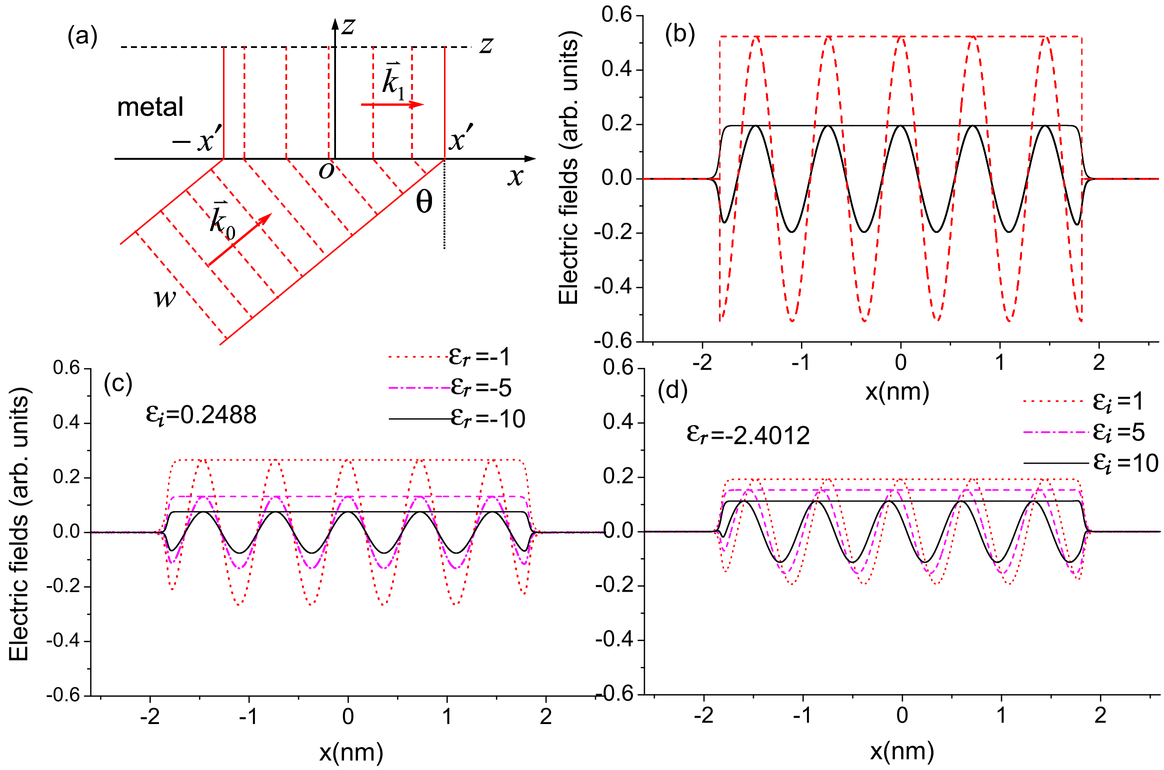

Fig. 1. (a) The sketch of the incident beam illuminating on a metal surface. The dashed lines in the incident beam mean the equiphase surfaces. When the light beam enters the metal, the dashed lines are almost vertical to the metal surfaces. (b) The electric fields on silver front surface (dashed curve) and on the observation plane in the inner of silver (solid curve). The envelope curves show the amplitudes of the corresponding fields. (c) The fields on the observation plane with the structural parameters are the same as those used in (b) but the ϵ_r is changed. (d) The fields on the observation plane with the structural parameters are the same as those used in (b) but the ϵ_i is changed.

and this is the intrinsic characteristics of the superlens. On the contrary, the case of $t \neq 1$ involves the surface influence.

First, we discuss the intrinsic characteristics of superlens ($t=1$). The wavelength of the incident electric field is $\lambda_0 = 365$ nm, at which the permittivity of $\epsilon_{Ag} = -2.4012 + i0.2488$ [5]. The width of the incident beam is $w = 3.1609$ μm and the incident angle $\theta = 30°$, which results in $x' = w/(2\cos 30°) = 1.825$ μm.

Fig. 1 (b) plots the electric field before and after entering the silver film. The dashed curve expresses the electric field observed on the metal surface, and its envelope line means the amplitude which determines the energy distribution. The solid curve and its envelope line are observed at the plane set at $z=35$ nm. It is shown that the pattern printed on the incident surface propagates perpendicularly to the observation plane without any lateral shift. In other words, the energy transmission direction is normal to the incident metal surface. The decrease of the envelope line is caused by the damping effect. However, the phase change is along the lateral direction, which can be expressed as $k_1 = k_{0x}i$. This result means that the light energy is transmitted with the refraction angle of zero.

The zero-refraction phenomenon in Fig. 1(b) has been noticed in silver superlens [14]. Yet it is unclear whether the zero-refraction is a general phenomenon. Now we investigate this problem in detail and will give a general result. In the following calculation, the structural parameters are taken as that used in Fig. 1(b) but the permittivity can be changed. To do so, we let the real and imaginary parts of the permittivity $\epsilon = \epsilon_r + i\epsilon_i$ vary, so that the metal can be any one, not limited to silver. First, ϵ_r, the real part of the permittivity is changed but the imaginary part is fixed at that of Ag, $\epsilon_i = 0.2488$. The results are displayed in Fig. 1(c). It is seen that when ϵ_r is negative, the zero-refraction remains.

Now we fix $\epsilon_r = -2.4012$, the real part of the permittivity of Ag and change the imaginary part ϵ_i. The results are shown in Fig. 1 (d). In this case, the equiphase surfaces of the electric field shift in lateral direction. They shift more severely when ϵ_i is larger. The physical picture is analyzed as follows. The lines presenting the equiphase surfaces are vertical to the film in Fig. 1(a), but they slope to the left in this case, and the wave vector k' has obtained a small z-component. Nevertheless, all the envelope lines do not shift in lateral direction. It is these envelope lines that determine energy transmission directions. So zero-refraction is also valid.

In fact only when $\epsilon_i = 0$, the lateral shift of the pattern is exactly zero. In the cases of Fig. 1(b) and (c), the pattern shifts are negligible because the imaginary parts of the permittivities is much smaller compared to the real parts. This conclusion can be understood by the wave vector analysis. Suppose that the permittivity of the metal is $\epsilon_m = \epsilon_{mr} + \epsilon_{mi}i$ and the wave number in vacuum is k_0. Inside the metal, the wave number is $k' = k_0\sqrt{\epsilon_m}$ and its tangential component is $k'_x = k_x = k_0 \sin\theta$ when a plane wave illuminates a metal surface with the incident angle θ. So we have $k'^2 = k_0^2\epsilon = k_0^2 \sin^2\theta + k_z'^2$. Here k'_z is the z-component of the wave number in metal, its real and imaginary parts can be expressed as

$$\left.\begin{aligned} k'_{zr} &= k_0\left(\sqrt{(\epsilon_{mr} - \sin^2\theta)^2 + \epsilon_{mi}^2} + \epsilon_{mr} - \sin^2\theta\right)^{1/2} / \sqrt{2} \\ k'_{zi} &= k_0\left(\sqrt{(\epsilon_{mr} - \sin^2\theta)^2 + \epsilon_{mi}^2} - \epsilon_{mr} + \sin^2\theta\right)^{1/2} / \sqrt{2} \end{aligned}\right\} \tag{2}$$

Since $\epsilon_{mr} < 0$, we have $\epsilon_{mr} - \sin^2\theta < 0$. It is seen from Eq. (2) that as long as ϵ_{mi} is a small quantity, $k'_{zr} \to 0$ is irrespective of the incident angle θ. This is the case appearing in Fig. 1(b) and (c). Eq. (2) is deduced from the situation where the incident light is a plane wave. In the case of Fig. 1(a), the incident beam can be expanded by a series of plane wave components with different incident directions. For each of the component, $k'_{zr} \to 0$. Consequently, the fields, as the superposition of these components, shown in Fig. 1 (b) and (c) do not exhibit the behavior with real wave numbers in z-direction. When ϵ_i is nonnegligible compared to ϵ_r, $k'_{zr} \neq 0$. This is the case shown in Fig. 1(d).