Optics Communications 407 (2018) 41–45

Contents lists available at ScienceDirect

Optics Communications

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

The imaging properties of the curved superlens

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ARTICLE INFO

Keywords:
Superlens
Nanolithograph
Imaging
Electromagnetic optics
Thin film

ABSTRACT

The main function of the curved superlens is to magnify or minify the image of the pattern cut onto the mask in a photolithograph device. It is found theoretically, in this paper, that the magnifying or minifying function deals with two important properties: one is the magnifying (or minifying) effect and the other is the image quality. The magnifying (or minifying) effect of a specific superlens device can be expressed by a linear function and the image quality can be guaranteed by a quadratic function. The ways to obtain the two functions have been demonstrated in this paper.

1. Introduction

Enhancing the resolution is an important target for the photolithograph devices [1–4]. In 2000, a new approach was proposed by Pendry to achieve the sub-diffraction image with metal superlens [5,6] and later it was realized in photolithograph device experimentally by Zhang in 2005 [7]. Superlens is made of a metal slab, and the incident light can be transferred along the direction normal to the surface of the slab (the refraction angle inside superlens is zero). So the effect of superlens in photolithograph device equals to shorten the distance from the mask to the photosensitive resin (PR). Besides, the superlens possesses the filter effect, which suppresses the divergent components. In other words, the light beam arriving at the silver surface with a larger transverse component of wave vector will take a lower transmission coefficient. As a result, the two effects narrowed the line width of image. This physical phenomenon has been proved theoretically (zero-refraction theory) [8], and the corresponding results obtained by this theory are well in agreement with that from experiment [6]. According to the zero-refraction theory, it is important to note that superlens does not possess any focusing functionality. Instead, it utilizes the printing process to enhance the image resolution, achieving beyond diffraction limit. There has been significant progress in the fabrication process and techniques of superlens to increase imaging resolution. Superlenses made from multilayer structures were reported [9–13]. These composite superlenses can be calculated by effective medium theory, in which the multilayer structure is regarded as the anisotropy medium for both in-plane and out-plane directions [14–17]. However, the multilayered superlens typically consist of several dielectric-superlens structure repeated in a periodic fashion. On this basis, the theoretical studies on the imaging properties of single superlens is fundamentally important to help understand the underlying physical mechanisms in multi-layered superlens designs [18]. Motivated by the same idea, we noticed the curved composite superlenses consisting of multilayer structure, which have the more excellent imaging properties achieved in numerical and experimental works [19–22]. Our attention naturally is focused on the image properties of single curved metal layer. The curved superlens can be used as not only the magnifying superlens (Fig. 1(a)) but also the minifying superlens (Fig. 1(b)) [23]. There are some basic problems must be considered when designing the both kinds of superlens. For instance, the main function of the magnifying superlens is to magnify the imaging so that it can be distinguished easily. However, when the line intervals of the picture are magnified, the line widths will also be magnified, so it can hardly determine whether the magnified picture becomes clear. In other words, when the slit width is fixed, there exists a minimal distance of the line interval to keep the picture clear. The relationship of the line width W and the corresponding minimal line interval $2S$ is referred to as $W-S$ relationship in this paper. Different superlens has different $W-S$ relationship. For the same reason, the minifying superlens has also the $W-S$ relationship. In this paper, we investigate the imaging properties of single curved superlens by use of the analysis theory. The imaging quality, the magnifying (minifying) effect, and other important problems will be discussed. Although the results are related to the specific parameters, the qualitative discussions and the calculation method are valuable for the designing work of the curved superlens.

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http://dx.doi.org/10.1016/j.optcom.2017.09.003
Received 12 April 2017; Received in revised form 28 August 2017; Accepted 1 September 2017
Available online 14 September 2017
0030-4018/

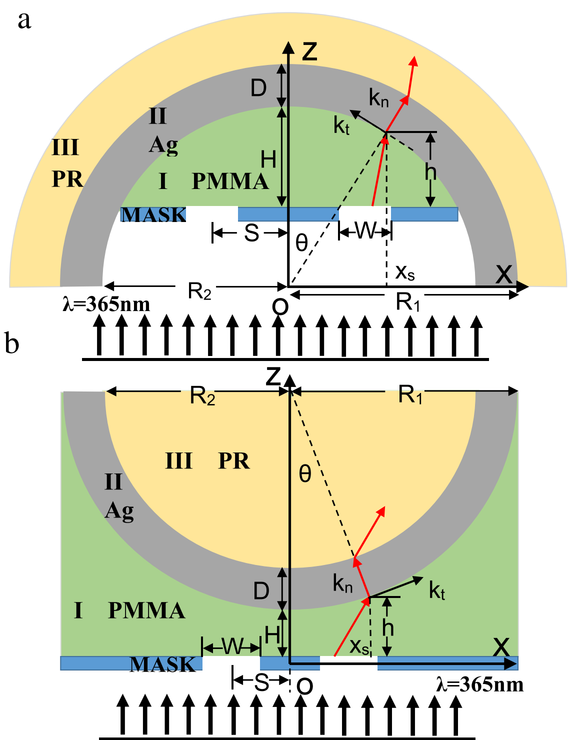

Fig. 1. (Color online) The sketches of curved superlenses. (a) Magnifying superlens. (b) Minifying superlens.

2. The magnifying and minifying properties

The cross sections of curved superlens devices are sketched in Fig. 1. The figures (a) and (b) correspond to the magnifier and minifier respectively. In Fig. 1(a), the superlens is made of a half cylindrical silver film with inner radius R_2 and outer radius R_1, respectively. The film thickness is $D = R_1 - R_2$. Two slits with the slit width W are cut onto the mask. The Cartesian coordinate is set with the origin point at the center of the cylinder and the directions of x and z-axes are as shown in the figure. The distance from the z-axis to the center of one slit is defined as S. The polymethyl methacrylate (PMMA) is used as a filler between the mask and the internal surface of Ag film. The external surface of Ag film is covered by photosensitive resin (PR). The mask is irradiated by a plane wave using a 365 nm source from below. Light propagating through the slits will illuminate the PR surface layer (located above the Ag film) creating notches. Consequently, the slits will be imaged on the PR surface. The shape and depth of the notch will be dependent on the energy distribution of the incident light (365 nm), which also enable us to infer the geometry of the slit. Although the image can be influenced by the light reflected from the back surface of PR layer, this effect is very weak when the PR layer is thick enough, and can be neglected as the absorption effect. To focus on the main characteristics of the curved superlens, we assume the PR thickness is large enough to neglect the light reflected from the PR back surface. The red arrows indicate the propagation path, which is normal to the surface of superlens, while light travels inside superlens. The zero-refraction theory was previously demonstrated only in flat superlens. In this paper, we demonstrate that it can be applied to a curved superlens.

The energy distribution $|E|^2$ depends on the electric field, which can be calculated by [18]

$$E^{s,p}(x) = \int_{-W/2-S}^{W/2-S} A(x')H_0\left(\frac{2\pi}{\lambda_0}\sqrt{\varepsilon_1}\sqrt{(x_s-x')^2+h^2}\right)T^{s,p}dx' + \int_{-W/2+S}^{W/2+S} A(x')H_0\left(\frac{2\pi}{\lambda_0}\sqrt{\varepsilon_1}\sqrt{(x_s-x')^2+h^2}\right)T^{s,p}dx' \quad (1)$$

$$T^{s,p} = \frac{t_{12}^{s,p}t_{23}^{s,p}e^{ik_{n2}D}}{1-r_{21}^{s,p}r_{23}^{s,p}e^{2ik_{n2}D}} \quad (2)$$

$$\begin{cases} t_{i,j}^{s} = \dfrac{2k_{ni}}{k_{ni}+k_{nj}} \\ r_{i,j}^{s} = \dfrac{k_{ni}-k_{nj}}{k_{ni}+k_{nj}} \\ t_{i,j}^{p} = \dfrac{2k_{ni}/\sqrt{\varepsilon_i}\sqrt{\varepsilon_j}}{k_{ni}/\varepsilon_i+k_{nj}/\varepsilon_j} \\ r_{i,j}^{p} = \dfrac{k_{ni}/\varepsilon_i-k_{nj}/\varepsilon_j}{k_{ni}/\varepsilon_i+k_{nj}/\varepsilon_j} \end{cases} \quad (3)$$

$$k_{nj} = \sqrt{\left(\frac{2\pi}{\lambda_0}\right)^2\varepsilon_j - k_t^2}. \quad (4)$$

Cylindrical wave superposition is used in the numerical calculation of image profile. $E^{s,p}(x)$ represents the electric field of TE polarization and TM polarization respectively. Here H_0 is the zero-order Hankel function and each wave component has its own transfer function, which is represented as $T^{s,p}$ in Eqs. (1) and (2). Eq. (3) gives the representation of transmission coefficients and reflective coefficients on each interface. $A(x')$ is the normalization constant of the incident field. x' is the horizontal coordinates of incident plane. k_t refers to the tangential wave vector of each cylindrical wave, and k_{nj} are the components of wave vectors along the radius. There $i, j = 1, 2, 3$ mean the PMMA, Ag, and PR, respectively. The meaning of x_s and h are the X and Z value at the point where the light reaches the Ag film surface. For the magnifier,

$$k_t = \frac{2\pi}{\lambda_0}\sqrt{\varepsilon_1}\sin\left(a\tan\left(\frac{x_s-x'}{h}\right)-\theta\right) \quad (5)$$

$$h = H - R_2(1-\cos\theta) \quad (6)$$

$$x_s = xR_2/R_1 \quad (7)$$

$$\theta = a\sin\frac{x}{R_1}. \quad (8)$$

For the minifier,

$$k_t = \frac{2\pi}{\lambda_0}\sqrt{\varepsilon_1}\sin\left(a\tan\left(\frac{x_s-x'}{h}\right)+\theta\right) \quad (9)$$

$$h = H + R_1(1-\cos\theta) \quad (10)$$

$$x_s = xR_1/R_2 \quad (11)$$

$$\theta = a\sin\frac{x}{R_2} \quad (12)$$

where θ is the angle of the line linking the incident point on the Ag film surface to the center of circle of the curved silver film against the Z axis (see Fig. 1(a)). In Fig. 1, two slits are cut onto the mask, and the magnifying effect can be expressed by the distance of the two slit images on PR when S is fixed. Our calculation shows that the positions of the two slits are independent. Thus, for simplicity and clarity, we would first like to observe the shape and position of the image formed by only one slit on the mask. For this purpose, the left slit in Fig. 1(a) is closed, and in this case Eq. (1) degenerated to

$$E^{s,p}(x) = \int_{-W/2+S}^{W/2+S} A(x')H_0\left(\frac{2\pi}{\lambda_0}\sqrt{\varepsilon_1}\sqrt{(x_s-x')^2+h^2}\right)T^{s,p}dx' \quad (13)$$

and Eqs. (2)–(9) are also available. In this paper, the incident light is always assumed to be a non-polarized wave, so the energy distribution $|E(x)|^2 = [|E^s(x)|^2 + |E^p(x)|^2]/2$. For the normalization constant, $A(x')$ will be simplified from

$$A(x') = \begin{cases} \dfrac{1}{\sqrt{2W}} & -S-W/2 \le x' \le -S+W/2 \text{ and } S-W/2 \le x' \le S+W/2 \\ 0 & |x'| > S+W/2 \text{ and } |x'| < S-W/2 \end{cases} \quad (14)$$