

Super resolution imaging by compensating oblique lens with metallodielectric films

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Abstract: In this letter we propose a compensating oblique lens which can realize super resolution imaging. The imaging structure consists of two parts constructed by metallodielectric films but positioned in different orientation. Super resolution optical imaging can be obtained with uniform light intensity and tunable magnification by changing parameters of the structure. Design principles and examples are given and illustrated with numerical simulation.

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OCIS codes: (110.0180) Microscopy; (310.6860) Thin films, optical properties

References and links

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1. Introduction

Before the concept of perfect lens [1] was proposed in 2000, diffraction limited resolution in optical imaging systems [2] had been considered as an unconquerable nature law for a long time. By using a slab of negative material, a perfect lens can offer perfect imaging with unlimited resolution and free of aberration theoretically, due to the complete transferring of

propagating and evanescent waves. In the optical frequency range, superlens by metal and material with matched permittivity is sometimes preferred for circumventing the difficulty of manipulating negative permeability. A number of theoretical [3-7] and experimental works [4-9] have been reported to investigate it. Among these works, a variety of superlenses with different geometrical forms are presented by controlling the behavior of evanescent waves. For instance, a set of alternatively stacked metal and dielectric films with matched permittivity [12] or unmatched permittivity [13, 17] delivers subwavelength imaging effect by using the evanescent waves. However, images of superlens are often the reproduced object without magnification and restricted in the near field, which makes it inconvenient in practical applications. Also employing multi metallodielectric films but in a spherical or cylindrical form, hyperlens can realize magnified sub-diffraction images which can be observed in the far field with sufficient magnification [6, 11]. There are also other simple ways to realize super resolution imaging, such as the oblique lens (OL) proposed by A. Salandrino, *et al.* [7], as shown in Fig. 1. The lens is constructed by obliquely cutting a slab of metallodielectric films with matched permittivity. The evanescent waves are believed to transmit along the normal direction of the structure. The bottom and inclined plane of the OL are the object plane and image plane respectively. The distance between the two objects on the object plane can be magnified on the image plane, and thus sub-diffraction resolution is achieved. But this structure suffers from the fact that the lengths of ray traces (the ray here refers to the light bundle formed by all the wave components propagating in the structure) between the object plane and the image plane are not equal. When the material is not loss free, which is a common case, the different lengths of ray traces will lead to different losses. The intensity of images will be different when the inputs are of the same intensity. Thus the application of the oblique lens is severely restricted.

In this study, we propose a principle to design a new oblique lens. The new oblique lens consists of an oblique lens and a compensating structure. Both parts are constructed by metallodielectric films which are perpendicular to each other. The schematic of this lens is also shown in Fig. 1. We name it as compensating oblique lens (COL). The new oblique lens can ensure the lengths of ray traces from the object plane to the image plane are the same, and hence the loss during propagation should be the same. Without intensity difference, the COL can be used to achieve super resolution imaging with tunable magnification.

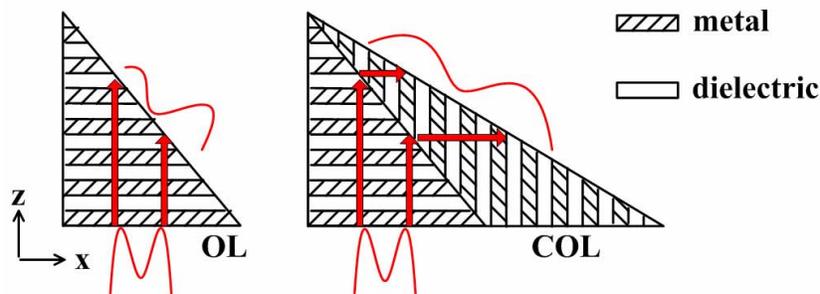


Fig. 1. Schematic of OL (left) and COL (right), the permittivity of metal and dielectric should be restricted with little difference.

2. Principle and design

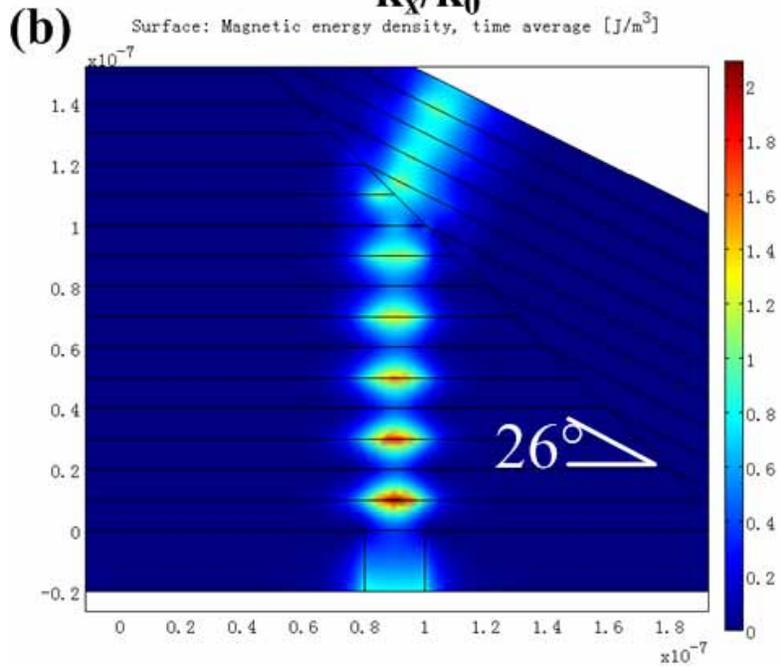
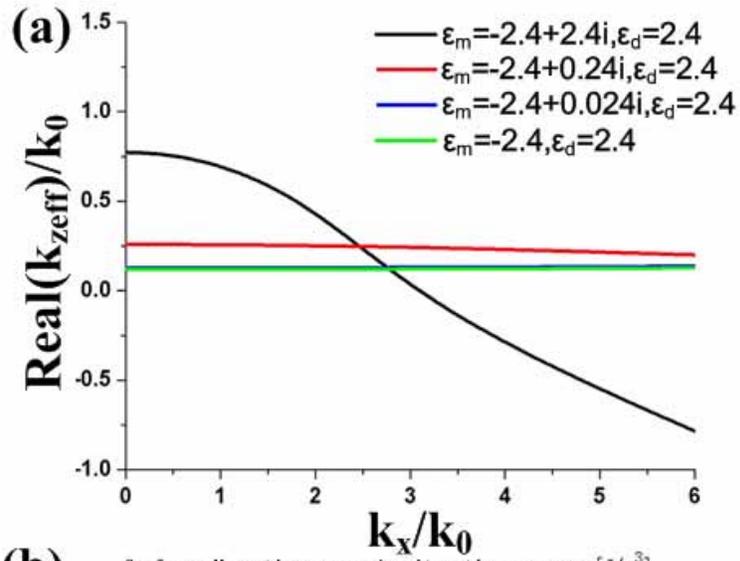
Before we present the principle of designing a COL, the optical characteristic of light propagation in metallodielectric films structure is briefly reviewed, which gives the theoretical basis of both the OL and the COL.

The dispersion relation of this periodically modulated films structure with finite thickness can be accurately obtained with the transfer matrix as discussed in many papers like Ref. [12]. To plot the contour of dispersion relation, the implicit equation below should be solved numerically.

$$\cos(k_{z\text{eff}}d) = \cos(k_{mz}d_m)\cos(k_{dz}d_d) - \frac{1}{2}\left(\frac{\varepsilon_d k_{mx} + \varepsilon_m k_{dx}}{\varepsilon_m k_{dx} + \varepsilon_d k_{mx}}\right)\sin(k_{mz}d_m)\sin(k_{dz}d_d) \quad (1)$$

where $k_{mz} = \sqrt{\varepsilon_m k_0^2 - k_x^2}$ is the z component of wave vector in the metal, and $k_{dz} = \sqrt{\varepsilon_d k_0^2 - k_x^2}$ is that in the dielectric. $k_{z\text{eff}}$ denotes the effective propagation constant in the direction normal to films. $k_0 = 2\pi/\lambda_0$ with λ_0 being the wavelength in vacuum. d_m and d_d are the film thickness of metal and dielectric respectively and the thickness of a period $d = d_m + d_d$.

As illustrative examples, we take the parameters as $d_m=d_d=10\text{nm}$, $\lambda_0=365\text{nm}$. As a condition for the OL, the permittivity of the metal (ε_m) and dielectric or insulator material (ε_d) constructing the films are assumed to be matched, i.e. $\text{Re}(\varepsilon_m)=-\varepsilon_d$. To see the contour of the dispersion relation in matched case, the calculated result is plotted in Fig. 2(a) for the matched permittivity $\varepsilon_d=2.4$ and ε_m with variant imaginary part for light absorption. As we can see, the curves are relatively flat over a broad spatial frequency range. The direction of group velocity is almost normal to the isofrequency curve as indicated by B. Wood, *et al.*, [13] and D. R. Smith, *et al.*, [14]. Also it can be seen is that slight loss in metal does not deliver serious effects to the characteristics of directional light propagation normally to the films. So the light emitted from the objects close to the metallodielectric films goes forward directly normal to the films and yields magnified images at the oblique cut edge, as depicted in the left part of Fig. 1. Unfortunately, the images display different magnitudes of intensity due to the variant length of light path. This effect gets much more serious as we want larger magnification. A method of compensating the loss difference at the object plane by using different inputs is offered by A. Salandrino, *et al.*, [8]. However, it is inconvenient and impractical to calculate and make the exact compensation for each object.



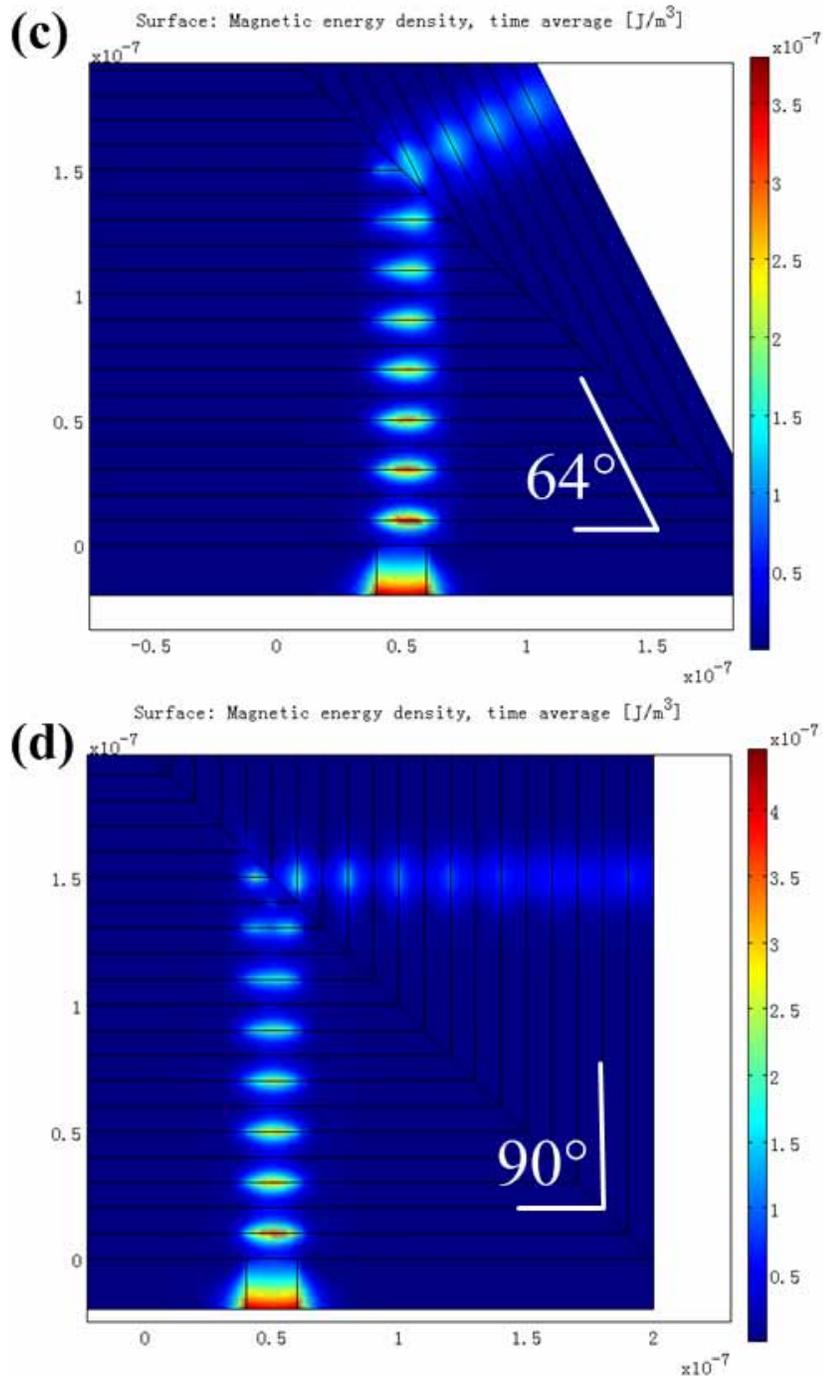


Fig. 2. (a). Isofrequency curves of dispersion relation of the oblique lens structure with $\text{Re}(\epsilon_m) = -\epsilon_d$; the thickness is 10nm for each film and the wavelength of incident light is 365nm. (b) (c) and (d) are numerical simulations of light deflection at the interface of two metallodielectric films structures with variant deflection angle as depicted in the figure. All of the films are 10nm in thickness, and the matched permittivities are $\epsilon_m = -2.4 + 0.24i$, $\epsilon_d = 2.4$.

To solve this problem, the same metallodielectric films structure are added to the OL but with different film directions. It is expected that the light traveling in the OL would be refracted into the new structure at the interface. Also the refracted light travels along the direction normal to the films direction. These process are simulated in Figs. 2(b), 2(c), and 2(d) with variant angles between the film directions. Deflection of light can be observed with 26° , 64° and 90° when the angles formed by two film directions are 26° , 64° and 90° respectively. These simulations show that the refraction direction is controlled by the film directions. In addition, no reflection can be seen since they are just along the reversed direction of the input light. The deflection of light in this kind of structure is the basis principle for the design of a new compensating OL.

Next, we discuss the principle to design a COL. The key point is to compensate the path difference of light emitted from different objects at the object plane. As shown in Fig. 3, the COL structure consists of the OL and a compensating part. They are both metallodielectric structures with matched permittivity, but the films in the two structures are perpendicular to each other. The light refraction in this case occurs with a right angle. (The compensation to the oblique lens can also be realized with other deflected angles.

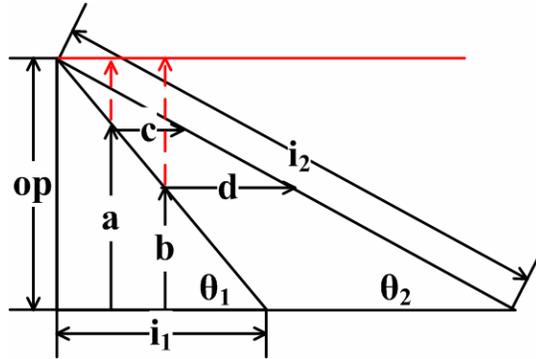


Fig. 3. Geometrical relation of COL based on OL. i_1 and i_2 are object plane and image plane respectively. The compensation is to the lengths of the ray traces, so each beam from the input plane to the output plane will cover the same propagating length. The length for a fixed OL or COL is equal to the height of the structure.

Only the 90° case is considered here to simplify the geometrical relation between the oblique lens and its compensating structure). Taking two arbitrary object points, one path of light from one object is denoted with length a and c , and the other one b and d . a and b are the lengths of light propagation in the OL for the two points and c and d are that in the compensating part. In order to make up for the loss for different ray traces, we must ensure that all of the lengths of ray trace from the input plane to the output plane are the same. That is to say the relation

$$a + c = b + d \quad (3)$$

holds for any two points at the object plane. By employing some simple geometrical manipulation, the condition for Eq. (3) can be given as

$$\tan \theta_1 = \frac{\tan \theta_2}{1 - \tan \theta_2} \quad (4)$$

which shows that the oblique angle of the COL is determined by the oblique angle of the OL. Also we can get the magnification of this lens as

$$\frac{1}{\cos \theta_1} \sqrt{(\sin \theta_1 + \cos \theta_1)^2 + \sin^2 \theta_1} \quad (5)$$

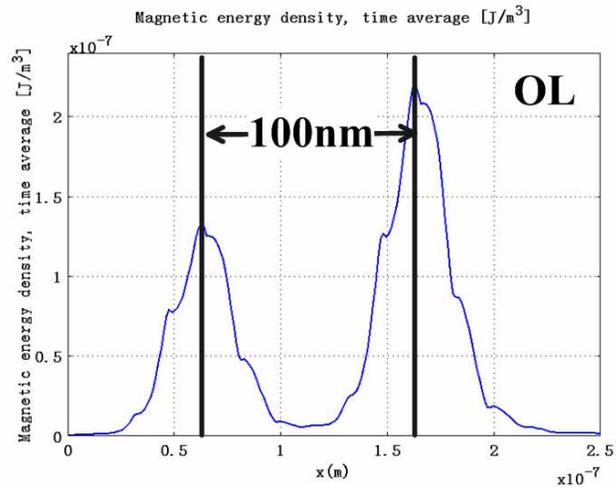
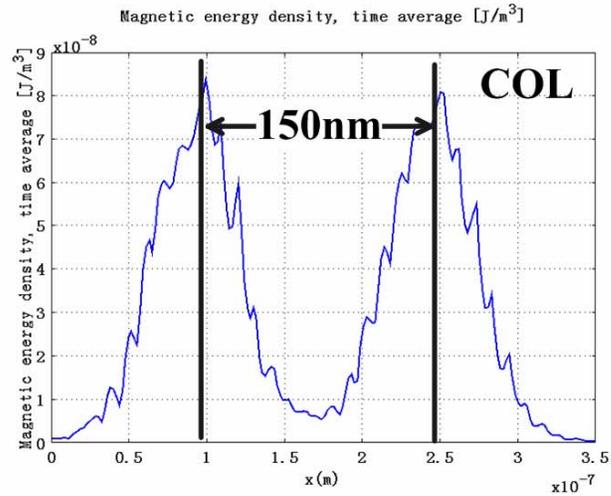
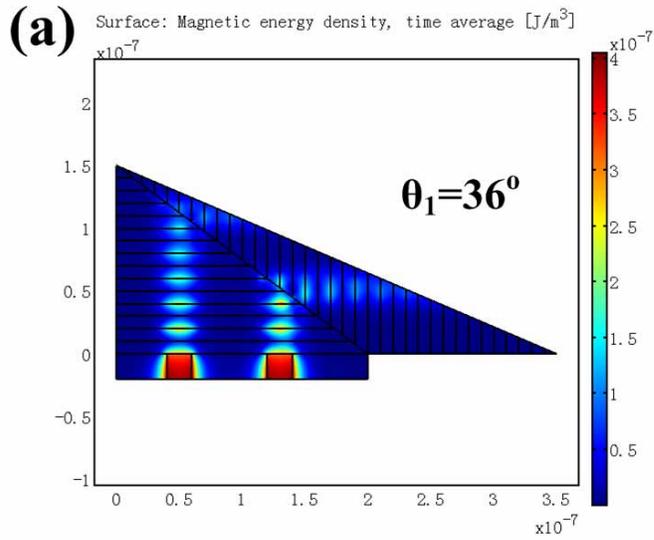
where $1/\cos\theta_i$ is the magnification of the OL without the compensating part. Eq. (5) indicates that the COL with a compensating structure shows stronger magnified ability than the OL.

3. Simulation and discussion

Illustrative instances for the COL are simulated by using finite element method. The wavelength we use is 365nm; and the permittivity of silver is $-2.4+0.24i$ [15]. The imaginary part of metal here denotes the loss in the structure. The permittivity of the dielectric material is set to be 2.4 to meet the matched permittivity condition. The mask is Cr with permittivity of $-10+10.8i$ [16] at 365nm and it is used to block the input light. Since the finite element method is used here, sufficient elements are needed to represent the accurate case. So the simulated area is divided into about 200,000 parts. The default boundary condition is perfect electric conductor. The thickness is 10nm for each of the films in the COL structure, and the two spike-like objects are of the same intensity and separated with 80nm distance, and each object is 20nm in width. The bottom side (object plane) of simulated COL is fixed and 200nm in length. Two oblique angles θ_i of 36° and 56° have been selected to testify the validity of COL over a broad range of angles as expected.

The simulated results are presented in Fig. 4 for two oblique angles. Both of them display the same process of imaging with magnification. The light emitted from two objects propagates normally to the film direction and turns right at the oblique interface of the OL then goes into the compensating part. At the edges of the compensating structure, two clearly resolved images with almost even intensity can be seen in the intersection plots. The saw toothed feature of the images is caused by discontinuous permittivity distribution on the image plane. The function of compensating OL is obvious; and this can be well illustrated from the ratio of two image spike-like peaks, shown in Fig. 5(b). For small oblique angles, the difference of peak intensity of image in the OLs is weak but increases greatly for large oblique angles. While in the COLs the ratios remains near unity.

The COL also delivers greater magnification, as plotted in Fig. 5(a). The measured magnification in the simulations agrees well with Eq. (5) with slight deviation, which could be caused by the broadening effect of images at the output plane. Another thing should be noted is that the brightness of the images decrease greatly (Fig. 5(c)). The brightness of images in the OL are about 0.3 to 0.5 that of objects, depending on the oblique angle. Inevitably, the extra compensating part of the COL delivers much lower imaging brightness (about 1/3 to 1/10 of the intensity of objects for the oblique angle ranging from 26° to 56°). The loss grows rapidly as the slope of the OL gets sharper, due to the elongated light traveling path both in the OL and its compensating part. The great loss of light, we believe, can be reasonably accepted, considering the improved imaging quality with uniform intensity and increased magnification. In addition, we believe the compensation also works well for very small oblique angles and those near to 90° . But they suffer from slight magnification (small oblique angles) and great loss of light (very large angles), as can be predicted from Fig. 5.



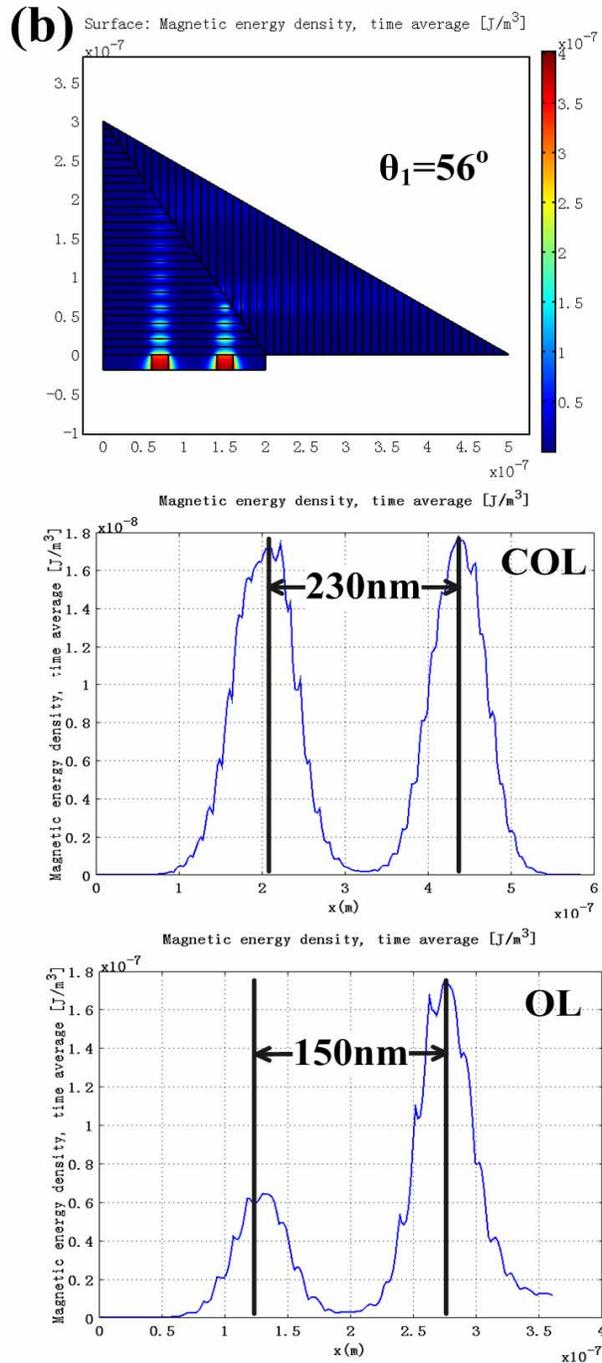


Fig. 4. Simulation results of the COL and OL with two oblique angles. (a) oblique angle of 36° ; (b) oblique angle of 56° . Two objects with 80nm separation on the object plane are magnified on the image plane. The uneven intensity distribution of images in OL can be compensated in the COL.

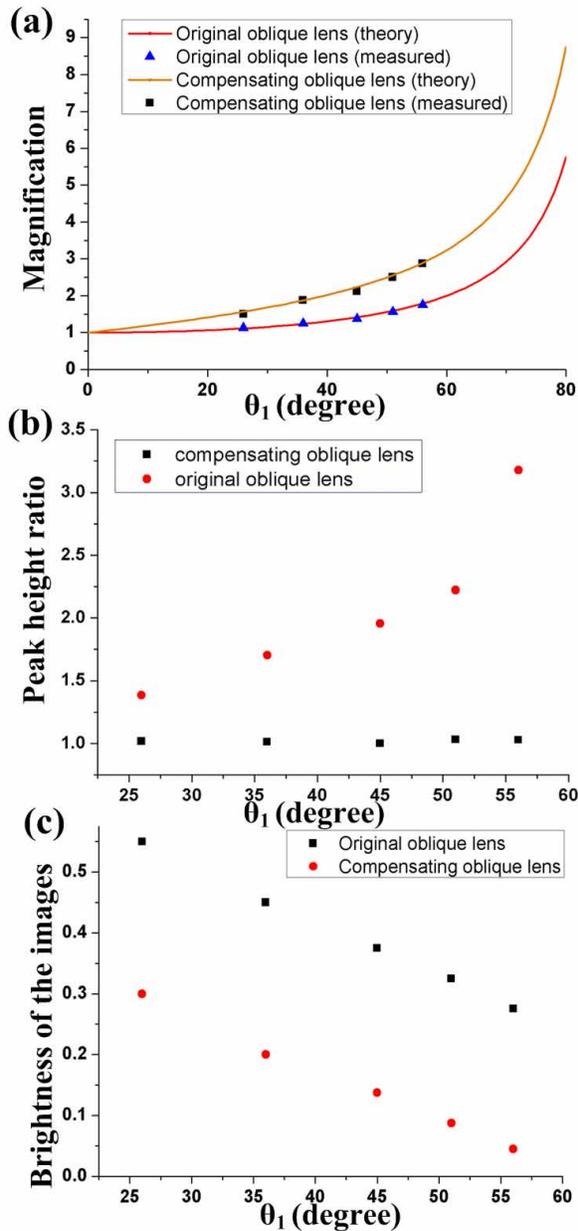


Fig. 5. (a). Theoretical and simulated magnification of COL and OL versus deflection angle. (b) Measured peak height ratio of the OL and the COL. (c) The brightness of images of OL and COL normalized by that of the objects.

The most challenging problem of the COL and the OL may focus on the fabrication method. It seems hard to fabricate a COL in a three dimensional space. But the difficulty can be greatly relieved by confining the COL and the imaging process in a planar space on a substrate. By using electron beam lithography, it is easy to obtain the COL structures consisting of multiple metal and dielectric stripes with reasonable height. This method has been utilized to demonstrate the imaging of the hyperlens on a substrate in the visible frequency range [10].

Compared with the superlens and the hyperlens constructed by the metalodielectric films, the COL has several advantages. First, it can realize a far field super resolution imaging because the magnified image with features larger than half of a wavelength can be seen in the far field with the help of microscopes, which is not possible by using the superlens. Secondly, the COL can work with tunable magnification, as shown in Fig. 5(a). Finally, the object plane of the COL is planar rather than a curved profile like that of hyperlens, which is much preferred in applications.

4. Conclusion

In conclusion, we propose a method to design a compensating oblique lens. The compensating oblique lens can compensate the different light losses caused by different ray traces in oblique lens. Super resolution imaging with magnification can be achieved using this lens. It can also deliver the near field information to the far field. The magnification can be tuned by adjusting parameters of the structure. In addition, the COL presented here is restricted for imaging one-dimensional objects. But this does not give obstacles for its potential applications in integrated planar optical circuits on substrates for optical storage, beam manipulation and optical information processing etc.

Acknowledgments

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