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Gradient–curvature nanolens for nano-imaging

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ABSTRACT

In this work, we study the sub-wavelength imaging properties of a plano-convex nano-lens consisted of alternatively arranged dielectric and metallic thin layers. The thickness of one layer is not uniform, and the curvatures of the layer boundaries vary gradually from layer to layer. The image resolution of this nanolens at wavelength 365 nm is about 40 nm, far below the diffraction limit, and its image magnification is much better than that of the original proposed hyperlens of the same size. We also study the imaging properties of the corresponding 3D structures. Numerical simulations reveal that the image recognition ability of the 3D nanolens can be controlled by changing the polarization of the source waves. Devices of this kind may find applications in biological morphology and nano-structured materials researches.

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1. Introduction

Traditional optical devices such like optical microscope are important in many branches of scientific research, for example, biological morphology, pharmaceutics research, microelectronics, and mineralogy. However, their resolution ability is restricted by the diffraction limit, which means the fine features of an object much smaller than one wavelength cannot be resolved using these devices. This limitation is mainly caused by the fact that the sub-wavelength information of the object encoded in the evanescent waves is lost once they leave the tiny object. Since 2000, this seemed unconquerable restriction has become conquerable, at least in principle, if the traditional devices are replaced by the metamaterial devices such like superlens. According to Pendry's theory, a perfect lens is a slab of metamaterial having negative permittivity and negative permeability, both close to -1 (for the reason of impedance matching). Such a slab also has negative refractive index close to -1, and it not only can compensate the phases of propagating waves of the source but also can recover the amplitudes of the evanescent waves. These unusual properties help to make an almost perfect image of the sub-wavelength sized object, breaking the diffraction limit [1]. Recent developments of metamaterial research indicate that such a slab can indeed be realized by using properly designed structures such as that consisting of parallel conducting wires together with split-ring resonators (SRRs) [2].

A lot of metamaterial structures based on the original idea of perfect lens have been proposed and tested, and high resolution imaging beyond diffraction limit has indeed been achieved [3,4]. However, in the optical frequency range, it is very difficult to realize negative permeability even in principle. A number of theoretical and experimental works concerning this issue have been done [5–8]. If our purpose is sub-wavelength resolution of nano-object and do not care about whether the image is located at the far field zone, then it can also be achieved by using a thin slab of metal which has negative permittivity only. The most prominent example is a slab of sliver in which surface plasmon modes can be excited due to its negative permittivity [9–12]. However, the material thickness and loss restrict the imaging quality of such a ‘superlens’. In addition, the image formed by a superlens is often of the same size as the object without magnification and it is restricted in the near field zone.

An ideal optical imaging system should overcome not only the diffraction barrier but also be compatible with conventional optical system so that post-processing can be easily implemented. The recently proposed hyperlens structure can satisfy this requirement [13,14]. A hyperlens is a cylindrical multilayer structure consisting of alternatively arranged negative permittivity (metallic) and positive permittivity (dielectric) layers. Under the effective medium limit (which means the operating wavelength is much larger than the layer thickness), it leads to anisotropic dielectric tensor of the structure, which means the principal permittivity along the radial and azimuthal directions have opposite signs. This property leads to a hyperbolic dispersion relation in cylindrical coordinates, so it converts the evanescent waves into propagating ones, making some new applications possible [15–17].

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In a hyperlens, the streamlines of the energy flow direct mainly along the radial directions. Usually two sources close to each other with distance smaller than half wavelength are not recognizable from their images if usual lens is used. However, if we put these two sources on the inner surface of the hyperlens, two distinguishable magnified images can be found in the far field zone outside the hyperlens. The image is magnified and the magnifying power (MP) is proportional to the ratio between the outer and inner radii. Although hyperlens magnifies subwavelength objects and makes images in the far field zone if the ratio of outer-to-inner radius is appropriately chosen, the curved inner surfaces brings inconveniences in locating objects on the object surface.

For this reason, other methods for obtaining breaking-diffraction-limited resolution such as the oblique lens [18], the planar hyperlens [19] and the pyramid-shaped hyperlens [20] were proposed. The working principle of most of these structures is based on the fact that the energy flows can be guided along certain directions as desired. It reveals that the electromagnetic waves can be controlled under some implementable conditions (canalization regime) if we design the structure appropriately [21–24]. Inspired by these research results, we propose in this paper a gradient curvature (GC) structure of a new plano-convex lens, working near the canalization regime. Our design is similar to that of [19] but we use simpler method to define the layer thickness, which is desirable for fabrication purpose. In addition, we also study the imaging characteristics of the generalized 3D structure, which is lacking in [19]. The simulation results show that the resolution down to 40 nm can be achieved and the magnifying power is more than 5 nm at 365 nm wavelength, much better than the original hyperlens of the same size can do. In addition, we also demonstrate that the corresponding 3D GC lens structure can also work very well, and its imaging quality can be controlled by the source polarization.

2. Theory and models

The working principle of the proposed nanolens is based on the highly anisotropic property of the effective permittivity, which can be realized by using multilayered periodic structure made of alternatively arranged dielectric and metallic layers. One period of the structure consists of one dielectric layer of permittivity ε_d and thickness d_d, together with one metallic layer of permittivity ε_m and thickness d_m. The dispersion relation for the propagating mode in this structure is given by [25].

$$\cos(K_d) = \cos(K_m d_m)\cos(K_d d_d) - \frac{1}{2}\left(\frac{k_m\varepsilon_d}{k_d\varepsilon_m} + \frac{k_d\varepsilon_m}{k_m\varepsilon_d}\right)\sin(k_m d_m)\sin(k_d d_d) \tag{1}$$

where $d = d_d + d_m$ is the period of the structure, k_d and k_m are the normal (the direction perpendicular to the layers) components of the wave vectors in the dielectric and metallic layers, and K is the Bloch wave number of the mode. When the wavelength is much longer than the period of this structure, an effective dispersion can be extracted:

$$\frac{k_n^2}{\varepsilon_t} + \frac{k_t^2}{\varepsilon_n} = \frac{\omega^2}{c^2} \tag{2}$$

where

$$\varepsilon_t = \frac{d_d\varepsilon_d + d_m\varepsilon_m}{d}, \qquad \varepsilon_n^{-1} = \frac{d_d\varepsilon_d^{-1} + d_m\varepsilon_m^{-1}}{d} \tag{3}$$

are the two principal values of the effective permittivity tensor, ω is the angular frequency of the wave, c is the speed of light in vacuum, and k_t and $k_n = K$ are the tangential and normal components of the wave vector of the plane wave propagating inside, respectively. It is known that if the working frequency ω and thickness ratio d_d/d_m are chosen appropriately, we can make $Re(\varepsilon_t) > 0$ and $Re(\varepsilon_n) < 0$. This leads to a dispersion curve of hyperbolic type (see Eq. (2)), which implies that an evanescent wave outside can be transformed to a propagating wave inside. This is the underlying working principle for the (original) hyperlens.

As mentioned in the introduction, the GC lens structure works near the canalization regime [21–23], which means we choose to design the structure having very large principal permittivity value along the normal direction of the layers (i.e., $\varepsilon_n \to \infty$, assuming that the imaginary parts of ε_d and ε_m are both small enough). According to Eq. (3), this implies that the following condition must be satisfied:

$$d_d Re(\varepsilon_m) + d_m Re(\varepsilon_d) = 0 \tag{4}$$

For simplicity we set ($d_d = d_m$), thus we must choose an appropriate frequency such that $Re(\varepsilon_m) \approx -Re(\varepsilon_d)$. Under this condition the dispersion curve at one single frequency becomes very flat along the direction parallel to the layers, and the streamlines of the energy flow go along almost the same direction, normal to the dispersion curve. This property can be used to design a new kind of nanolens for making images of nano-scale objects by bending the flat multilayer structure in a new way. The information encoded in the propagating and evanescent waves from a tiny object can thus be transferred to the output surface of the nanolens along trajectories locally normal to each dielectric–metal interface.

Hereafter we name the nanolens gradient–curvature (GC) lens, which is made of multilayer dielectric–metal films having different curvature in each layer. The proposed GC lens structure is formed by cutting a part of the elliptical shaped reference structure (inside the dashed-line rectangle), as indicated by the left part of Fig. 1. The downward A-axis and the horizontal B-axis define the two axes of the ellipse, and their ratio B/A determines the shape of the reference structure and the curvature of each layer. In the limiting case of $A = B$, the shape of the reference structure becomes circular. The aperture width C of the lens is shorter than the waist width $2B$ of the ellipse but long enough to make the lens structure work. We assume in this paper that each layer has a fixed local thickness of 10 nm along the A-axis, but the layer thickness is not uniform and it shrinks to zero as we move sideward along the B-axis direction. Specifically, the lower boundary of the nth layer (counting downward) is defined by the equation of the ellipse $\frac{x^2}{B^2} + \frac{y^2}{(10n)^2} = 1$, here nanometer is adopted as the length unit. For simplicity, we first consider the 2D structure. The dashed-line rectangle in the right

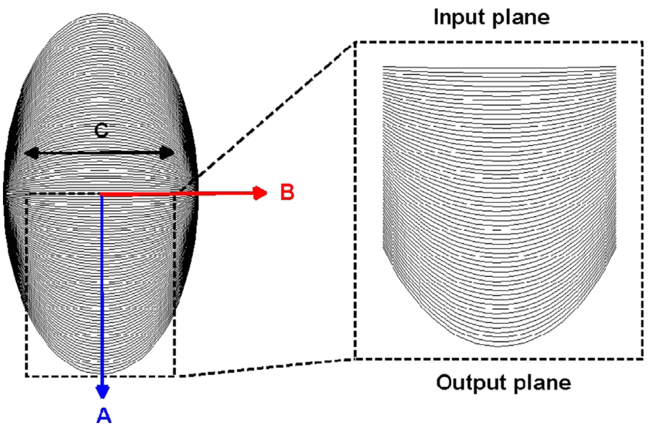

Fig. 1. The gradient curvature (GC) lens structure made of multilayer dielectric–metal films having different curvature in each layer. Left: The elliptical shaped reference structure defined by the two axes A and B. Right: The lens is formed by cutting a part of the reference structure with aperture width C. The dashed-line rectangle represents the working area of the lens. Each layer has a fixed local thickness of 10 nm along the A-axis and shrinks to zero sidewardly.

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