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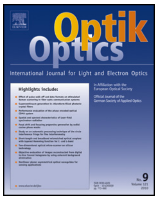

Subwavelength imaging through one-dimensional metallodielectric photonic crystals at optical frequencies

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ABSTRACT

We present a study of mode characteristics of multilayer metal-dielectric (M-D) structure and use the Eigen mode expansion (EME) method to simulate the subwavelength imaging effect that can be realized at the designed position. We show that the quality of the image is affected not only by absorption but also the finite width of the layers. By proper design and considering the real losses, a super lens with a resolution of about $\lambda_0/6$ (λ_0 is the wavelength in the air) can be obtained. Our researches of this structure point to that a transparent material can be composed from non-transparent materials by alternatively stacking different materials of thin nanofilms, which also provide an opportunity to expand the exploration of the wave propagation in metals, both in the linear and nonlinear regimes.

1. Introduction

It is predicted by Pendry that a slab of medium with both negative permittivity and permeability can be made as a perfect lens, which can focus both the far and near field components of a point object with nearly unlimited resolution [1]. He showed that a thin metal acts as a superlens for TM polarized light. The presence of evanescent modes makes it possible for the image to be resolved beyond the limits imposed by ordinary optical materials and by diffraction. The effect predicted by him has been experimentally observed and verified [2,3]. However, there are no known natural materials that exhibit a negative index of refraction, and the formidable challenge of fabricating homogenous negative refraction media (NRM) structures greatly hampers the applications of super lens, especially in the optical frequency range. Recently, the concept of perfect lens is extended to the 1D-MD photonic crystals [4–13,15]. It is shown that 1D-MD structures have advantages over the original configuration of a single slab. They have the advantage of reduced size, easier fabrication, and lower costs compared with the dielectric photonic crystals.

In this paper, we present a one-dimensional metallodielectric (1D-MD) photonic crystal, in which each unit cell consists of a metal and a dielectric layer. Basing on the eigen mode expansion (EME) method [14], we numerically calculate the electromagnetic fields both inside and outside the structure, this structure can achieve a resolution that is not restricted by the well-known diffraction limit. We find the diverging EM waves are highly concentrated in the structure. Though the permittivity of metal and dielectric are not matched, the structure can still act as a super lens.

2. Numerical model and simulations

Fig. 1 shows the schematic diagram for the structure studied in the present paper, it is composed of alternating layers of metal and dielectric, periodic with respect to the z-axis, and invariant along the x and y directions. In this structure, each period is composed of two thin layers whose thicknesses are d_A and d_B and permittivities are ε_A (for dielectric) and ε_B (for metal), respectively. For simplicity, we assume $\varepsilon_A = \varepsilon'_A$ is real, and $\varepsilon_B = \varepsilon'_B + i\varepsilon''_B$ (complex) and the permeability is constant ($\mu_A = \mu_B = 1$). Here we only consider the H-polarization case.

Before calculating the field distribution for subwavelength imaging of 1D-MD structure, we consider the losses in the metal layer. At the operating wavelength $\lambda = 400$ nm, the dielectric constants for Ag and Si_3N_4 are $\varepsilon_{Ag} = -4 + 0.2i$ [15] and $\varepsilon_{Si_3N_4} = 4$.

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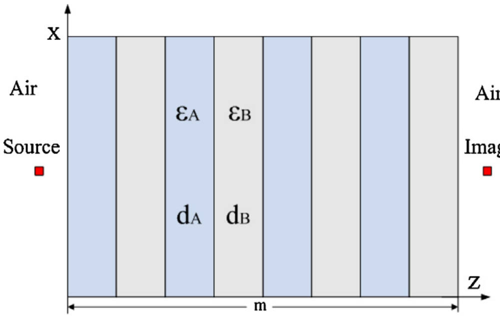

Fig. 1. Geometry of the one-dimensional metal-dielectric photonic crystals. The period is $d = d_A + d_B$. m represents the number of periods. The incident wave (source) and the transmitted wave (image) are noted.

In the considered model, the incident wave is limited only along one direction, thus the incident electric field is given by:

$$H_{iy} = \int_{-\infty}^{\infty} dk_x \exp[i(k_x x + k_{iz} z)]\psi(k_x) \quad (1)$$

where

$$\psi(k_x) = \frac{g}{2\sqrt{\pi}} \exp\left\{-\left[\frac{g^2(k_x - k_{ix})^2}{4}\right]\right\} \quad (2)$$

The incident beam centered about $k_i = \hat{x}k_{ix} + \hat{z}k_{iz} = \hat{x}k_0 \sin\theta_i + \hat{z}k_0 \cos\theta_i$, θ_i is the incident angle, g represents the width of the waist, in the following simulation work, we choose $g = 0.6\lambda$. The incident point source located at 100 nm away in air from the left slab surface.

The calculated field patterns for a structure with different periods of layers are displayed in Fig. 2(a–d), respectively. Though the lossless exists, the superlensing effect still appears. For the 4-period slab, a well-shaped bright image spot is formed (at a distance w from the right surface of the slab). This image spot is peaked at (0.92 μm, 0.70 μm), very close to the right surface of the slab, the image distance $w = 0.3$ μm. We should also note that the intensity of the image is smaller than the source', especially when the periods become more. From a mathematical study, we find that the image distance becomes smaller as the thickness of the structure becomes larger. We estimate the resolution limit to be [4] $\Delta \approx 2\pi\varepsilon''_m d$, therefore the best resolution for the structure we have designed is about $\lambda/6$.

3. Results and discussions

The metallodielectric films structure also provides a method to construct super lens when the metal and dielectric's permittivity do not meet Pendry's imaging condition. We choose $\varepsilon_A = -2.51 - 0.6i$, $\varepsilon_B = 4$, $d_A = 23$ nm, $d_B = 27$ nm. Fig. 3 is the typical result of field distribution, which clearly shows an image in the opposite side of the structure in air.

Though the permittivity of metal and dielectric are not matched, we can see in Fig. 3 that the structure can still act as a super lens. Ref. [4] shows that stacking films of permittivity matched metal and dielectric greatly relieve the deleterious effect of metal loss on the image resolution. Here, we can see the same effect happens for the multilayered structure with unmatched permittivity as well. When the layers are sufficiently thin, the whole system can be seen as a single anisotropic medium, the effective medium theory (EMT) can present good guidance and description of their optical behaviors. The permittivity of metal and dielectric are not matched, but when the effective transversal permittivity tends to be zero or the vertical one approaches infinity, subwavelength imaging can be obtained [14]. The two conditions are not met here, but $\bar{\varepsilon} = (\varepsilon'_A d_A + \varepsilon_B d_B)/(d_A + d_B) \approx 1$, the impedance match is satisfied. The formation of images is attributed to the fact that the existing waveguides modes provide a mechanism to amplify the optical near field.

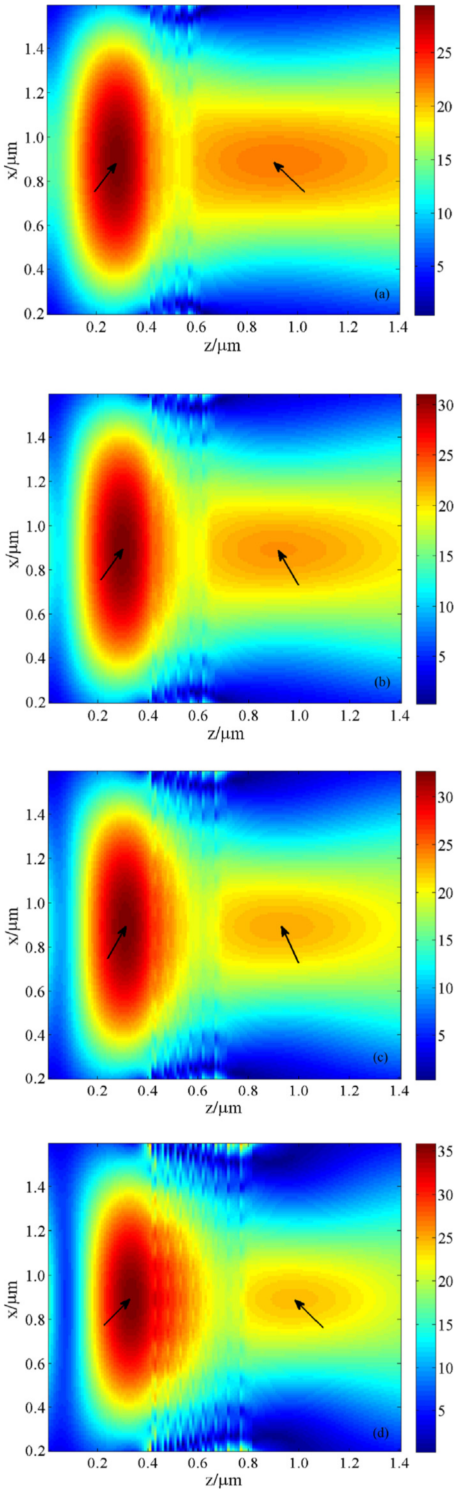

Fig. 2. The field intensity distribution for subwavelength imaging of 1D-MD structure (H polarization). (a) 4 periods. (b) 5 periods. (c) 6 periods. (d) 8 periods. We use arbitrary units for the power density in all the maps, the left and right arrows indicate source and image, respectively.