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Subwavelength Imaging Properties of Multilayered Metallodielectric Nanofilms

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Abstract: The characteristics of a metamaterial consisting of multilayered Ag/Si_3N_4 nanofilms are studied and the eigen mode expansion (EME) method is used to demonstrate the subwavelength imaging effect. A point source placed in the vicinity of the structure can form a image in the opposite side of the slab, the impedance match is not necessary since the Fabry-Perot condition is fulfiled (the thickness of the structure is an integer number of half-wavelengths) and the reflections from the interfaces are almost eliminated. The subwavelength imaging effect in this structure based on the self-collimation but not the negative refraction. This structure verifies that the use of one-dimensional metallodielectric (1D-MD) structure is a very prospective way of extending the use of near-field enhancement phenomenon into the optical region.

Key words: Subwavelength imaging; Sself-collimation; Metallodielectric nanofilms; Eigen-mode expansion method.
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0 Introduction

According to Abbe's diffraction limit, conventional lenses with curved surfaces are not able to resolve an object's fine details that are smaller than half of the light wavelength λ. This limitation occurs because the waves with transverse wave numbers larger than 2 πn/λ, which carry information about the fine sub-λ details of the object, decay exponentially in free space. It is predicted by Pendry that a slab of an isotropic 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]. The effect predicted by him has been experimentally observed and verified[2-3].

The performance limit of the metallic superlens was associated with the losses in the metallic film. In order to overcome the losses associated with a single metal film, a superlens based on multilayer metal-dielectric (MD) stacks having thin metal layers was designed. This combination of a positive and negative dielectric constant material results in a slightly different type of superlens[4]. It is shown that multilayer stack has advantages over the original configuration of a single slab. The effects of absorption are much reduced by the division into multilayers. Recently, one-dimensional metamaterials have attracted considerable attentions of researchers[5-10].

In this paper, we present an analysis of subwavelength imaging in a multilayered metallodielectric nanofilms structure, the structure operates in the self-collimation regime and does not involve negative refraction. The equal frequency contour (EFC) is almost flat, and the Fabry-Perot resonance condition is satisfied simultaneously. The impedance match is not necessary since the Fabry-Perot condition is fulfilled. Based on the EME method[11], we numerically demonstrate that the light forms a focus outside the structure, and this system can achieve a resolution that is not restricted by the well-known diffraction limit.

1 Method and theory

Fig. 1 (The period is $d = d_A + d_B$, m represents the number of periods. The incident plane and the transmitted plane are noted.) shows the geometry of the multilayered metallodielectric nanofilms structure studied in the present paper, which 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

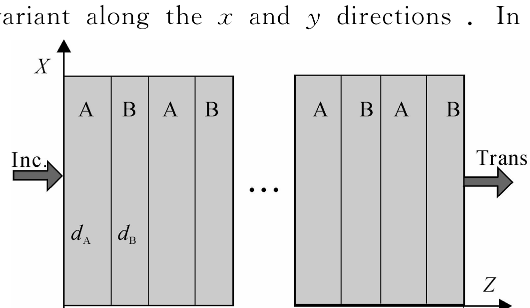

Fig. 1 Geometry of the periodic metal-dielectric structure.

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structure, each period composed of two thin layers whose thicknesses are d_A and d_B and permittivities are A (for metal) and B (for dielectric), respectively. For simplicity, we assume $\varepsilon_A = \varepsilon_A' + i\varepsilon_A''$(complex) and $\varepsilon_B = \varepsilon_B'$is real.

First, for simplicity, we neglect the imaginary part of the metal permittivity, and assume the permeability is constant ($\mu_A = \mu_B = 1$). At the operational wavelength of $\lambda = 400$ nm, we choosen $\varepsilon_A = -4$, $d_A = 23$ nm, and $\varepsilon_B = 6$, $d_B = 26$ nm[12].

The dispersion relation of a one-dimensional (1D) metal-dielectric (MD) is given by [13]

$$\cos(K_z d) = \cos(\alpha_A d_a)\cos(\alpha_B d_B) + \frac{\alpha_A^2 \varepsilon_B^2 + \alpha_B^2 \varepsilon_A^2}{2\alpha_A \alpha_B \varepsilon_A \varepsilon_B} \sin(\alpha_A d_A)\sin(\alpha_B d_B) \qquad (1)$$

Where K_z is the z-component of the Bloch wave vector and k_x its x-component, $\alpha_i = \sqrt{k_z^2 - k_0^2 \varepsilon_i \mu_i}$ $(i = A, B)$ and $k_0 = 2\pi/\lambda$ is the modulus of wave vector in free space. From Eq. (1), one can see K_z is dependent on k_x, and we can compute the equal frequency contours (EFCs) for a lossless case (see Fig. 2). EFC is a cross section of dispersion surfaces and a dispersion surface is a surface which characterizes the relationship between all allowed wave vectors in the structure and their corresponding frequencies. In the periodic metal-dielectric structure, the propagation direction of light, the direction of energy flow, is perpendicular to the EFC because the energy velocity is identical to the group velocity given by $V_g = \nabla_k \omega(k)$. The ability to shape the EFCs, and thereby engineer the dispersion properties of the photonic crystals, opens up a new paradigm for the design and function of optical devices.

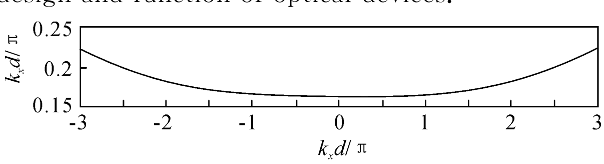

Fig. 2 EFCs of layered metadielectric structure with $\varepsilon_A = -4$, $d_A = 23$ nm, and $\varepsilon_B = 4$, $d_B = 26$ nm, for $\lambda = 400$ nm.

It can be seen from this figure that when $|k_x d/\pi| < 1$, the EFC is almost flat, so all the spatial harmonics of the source radiation in this range (including the evanescent components) can be transformed into propagating eigen-modes of the crystal. As a result, it is possible to vary the incident wave vector over a wide range of angles and yet maintain a narrow range of propagating angles within the 1D-MD. These propagating harmonics have practically the same group velocity along the direction normal to the surface and nearly the same longitudinal components of the wave vector[5]. We can also know that inside the slab, all the propagating harmonics have almost the same K_z (longitudinal component of the wave vector) around $K_x = 0$, and the structure can achieve a resolution of about $\lambda/8$.

The subwavelength lenses formed by such structure don' t involve negative refraction and amplification of evanescent waves, this regime was called canalization[5-14]. If the crystal has a flat EFCs and the thickness of the slab fulfills Fabry-Perot condition ($K_z N d = M\pi$, N is the number of periods and M is an integer), the implementation of such a regime is possible. In order to get subwavelength resolution it is required that the period of the structure is much smaller than the wavelength, and this is the same restriction as those working in the negative refraction regime.

2 Results and discussion

In order to demonstrate the canalization regime implemented using the metaldielectric layered structure, we present results of numerical simulation based on the eigen mode expansion (EME) method to show the field when a point source illuminates the slab. Before calculating the field pattern, 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 $\varepsilon_{Ag} = -4 + 0.2i$, and $\varepsilon_{Si_3N_4} = 4$[15]. The source is placed at 60 nm distance from a 294 nm thick multilayer slab composed of six periods of 23 and 26 nm thick layers. One can see from Fig. 3(a) that when the diverging EM waves emit from the point source impinge on the multilayered structure, there is an image located at 570 nm in the opposite side of the structure.

We also calculate the time-averaged field distribution when the structure contains eight layers of Ag and Si_3N_4, shown in Fig. 3(b). The imaging of this slab is somewhat degraded compared to the 6-period structure. This is due to

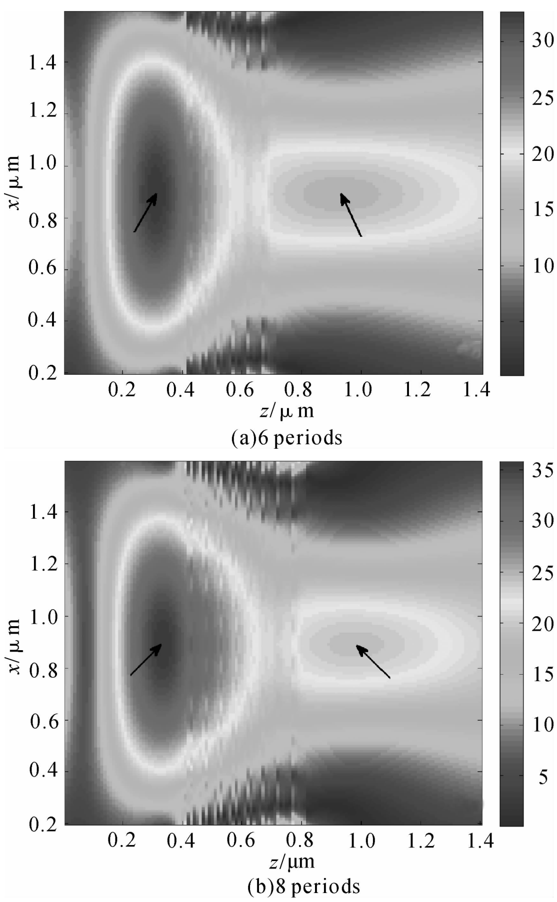

Fig. 3　The field intensity distribution for subwavelength imaging of 1D-MD structure composed of Ag-Si_3N_4 layers (TE mode).

two reasons, first, we consider the real losses, the transmission and the resolution are greatly degraded when the total thickness of metal layers increase; second, to enhance the transmission through the slab, N must satisfy the Fabry-Perot condition, but $N=8$ does not fulfill this condition.

To investigate the properties of optical waves inside the structure, the field pattern is shown in Fig. 4, here we choose x from 0 to 1 μm, z from 0.3 to 0.7 μm. One can see that the diverging EM waves are collimated by the slab and travel across the slab along a guiding channel. Thus we can confirm that the subwavelength imaging in this

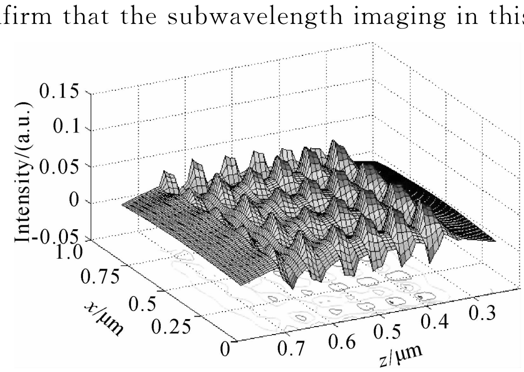

Fig. 4　Magnetic field H_y distribution inside the slab.

structure based on the self-collimation effect, but not the negative refraction.

Inside such a structure, the field attenuation due to the material loss is uniform for nearly all the spatial harmonics. At the output interface of the slab all the propagating harmonics are transformed back to the original spatial spectrum (including the evanescent components) as before entering the input surface of the slab. A good subwavelength image of a point source is thus achieved at the image plane [16].

Moreover, the excitation of surface plasmon polaritons (SPP) at the boundary between a metal with negative dielectric permittivity and a dielectric with positive dielectric permittivity play a key role in the enhancement of evanescent waves. As is well known, the interface between a metallic film and a dielectric can sustain SPPs in the form of coherent longitudinal charge oscillations of the conduction electrons, thus leading to a surface wave confined within one dimension perpendicular to the surface. The spatial extension of surface plasmon modes can be estimated by the skin depths at both sides of the metallic flat surface [17]

$$\delta_d = \frac{\lambda}{2\pi}\left|\frac{\varepsilon_d+\varepsilon_m}{\varepsilon_d^2}\right|^{1/2}$$

$$\delta_m = \frac{\lambda}{2\pi}\left|\frac{\varepsilon_d+\varepsilon_m}{\varepsilon_m^2}\right|^{1/2} \tag{2}$$

where λ is the wavelength of light in vacuum, the subscript d denotes the dielectric side, and m denotes the metal side. The skin depths of surface plasmons modes could be very small.

3　Conclusion

We have analyzed the dispersion relation of a multilayered metallodielectric nanofilms structure. Using the EME method and considering realistic material parameters, we have studied the subwavelength imaging effect in the 1D-MD structure. We have found out that diverging EM waves are collimated by the slab and travel across the slab along a guiding channel, the subwavelength imaging in this structure based on the self-collimation effect, but not the negative refraction. The excitation of SPPs plays a key role in the enhancement of evanescent waves.

According to the results presented in this paper, the use of metallodielectric nanofilm is a very prospective way of extending the use of near-field enhancement phenomenon into the optical region.

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金属-电介质多层膜结构亚波长成像特性分析

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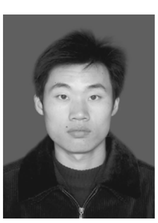
摘　要:分析了由 Ag 和 Si_3N_4 多层纳米薄膜组成的特异材料的模式特性,使用本征模展开法(EME)结合完全匹配层(PML)边界条件模拟了该结构的亚波长成像行为,在法布里-珀罗(Fabry-Perot)条件(结构的长度是半波长的整数倍)条件下,研究发现邻近系统的点源会在另一侧成实像,这种成像基于自准直而并不是负折射.研究结果证实了金属—电介质多层膜结构可以在光波段实现近场成像.

关键词:亚波长成像;自准直;金属-电介质多层膜;本征模展开法



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