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Extraordinary refraction and self-collimation properties of multilayer metallic-dielectric stratified structures

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ABSTRACT

The extraordinary refraction with negative or zero refraction angle of the layered metamaterial consisting of alternating dielectric and plasmonic layers is theoretically studied. It is shown that the electromagnetic properties can be tuned by the filling factor, the permittivity of the dielectric layer and the plasma frequency of the metallic layer. At different frequency, the layered structures possess different refraction properties with positive, zero or negative refraction angle. By choosing appropriate parameters, positive-to-zero-to-negative-to positive refraction at the desired frequency can be realized. At the frequency with flat equal frequency contour, self-collimation and slow light properties are also found. Such properties can be used in the performance of negative refraction, subwavelength imaging and information propagation.

1. Introduction

Metals may display a plasmonic behavior in visible region below plasma frequency, which are plasmonic materials with negative epsilon ($\varepsilon < 0$, $u > 0$). Therefore, when the thickness is much larger than the skin depth, the metal slab is opaque since the light is strongly reflected. While one-dimensional (1D) metal-dielectric photonic crystal composed of the thin metal film and thick dielectric could be transparent through Bragg resonance [1,2]. Although the total thickness of metal is about ten times larger than the skin depth, the transmittances are still enhanced because the nodes of the electric field locate at each thin metal layer, which reduces the absorption effect greatly. Recent years, the dielectric-plasmonic multilayer structures (DPMS) with subwavelength lattice constant are known for at least decades [3–11] and are utilized to realize effective anisotropic metamaterials, that is so-called "indefinite media" [12]. They have attracted significant scientific interest because they offer a way to engineer optical materials with properties rare or absent in nature, such as negative refraction [7], superlensing [8,9] and giant optical activity [10].

In indefinite media, not all the principal components of the electric permittivity and/or magnetic permeability tensors have the same sign, which causes the equal frequency contours (EFCs) to become elliptical or hyperbolic in different frequency [12,13]. Certain properties of the electromagnetic (EM) wave propagation can be described and understood more clearly from its EFCs. The propagation direction of an EM wave is identical to that of the group velocity, $\nabla_k(\omega)$, which means that the group velocity is normal to the EFCs [14]. Specially, in artificial periodic structures, the EFC has been employed in understanding unusual light propagation phenomena, e.g., sub-wavelength imaging [7,8], directive emission [15] and self-collimation [16–18].

Self-collimation effect is a research hot spot in controlling EM beams and has been demonstrated in different types of structures, including two-dimensional (2D) or 3D dielectric photonic crystals [16–18]. It originates from the possibility to partly convert, in specially designed composed structures, the circular EFCs of free space into highly anisotropic EFCs with flat sections. The properties has been used to bend and split light beam in integrated photonic circuits and design a Mach–Zehnder interferometer and sensor [19–21]. Recently, self-collimation was discovered in 1D quasi-zero-average-index structures [22] and the complete tunneling structures [23] containing metamaterials. In Ref. [14] beam shaping properties in 2D metallic photonic crystals was also theoretically investigated. In this paper, we theoretically study the extraordinary EFCs properties of the 1D DPMS, which exhibits positive, negative, or zero refraction depending on the frequency. For case of zero refraction, the transmitted beam undergoes self-collimation and slow light in the composite structure.

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2. Model and theory

Fig. 1 shows a 1D DPMS, the period is $d=d_1+d_2$, where d_1 and d_2 are the thicknesses of the dielectric and plasmonic layers. The subscript 1 refers to the dielectric with nondispersive permittivity ε_1 and permeability μ_1. The subscript 2 refers to the metallic material with constant μ_2, and dispersive $\varepsilon_2(f) = 1 - f_p^2/f(f+i\gamma)$, f_p is the bulk plasma frequency of the metal, γ is the damping coefficient. In general, f_p is a function of not only electron density but also surface structure, such as subwavelength holes or slits. In the following, we consider a symmetric unit cell as it allows obtaining higher transmittance independent of the number of periods of the structure [2]. For the 1D DPMS, using effective medium model and transfer matrix method, we can obtain two dispersion relations $\omega(k)$, where $k=(k_x, 0, k_z)$ is the wave vector. The dispersion relation for TM polarization obtained by the transfer matrix method can be written as follows [5]:

$$\cos(k_z d) = \cos(k_{1z}d_1)\cos(k_{2z}d_2) - \frac{1}{2}\left(\frac{\varepsilon_1 k_{2z}}{\varepsilon_2 k_{1z}} + \frac{\varepsilon_2 k_{1z}}{\varepsilon_1 k_{2z}}\right)\sin(k_{1z}d_1)\sin(k_{2z}d_2) \tag{1}$$

where $k_0 = \omega\sqrt{\varepsilon_0\mu_0}$ is the wavenumber in free space, $k_{1,2z}^2 = \varepsilon_{1,2}k_0{}^2 - k_x^2$, $k_{1,2z}$ is z-components of the Bloch wave vector and k_x is x-component. Based on the above dispersion relation, k_x as a function of k_z could be seen as an approximately expression of the equi-frequency contours (EFCs). When the wavelength λ in air is larger compared with the period d, the DPMS can be modeled as a homogeneous uniaxial anisotropic medium. The characterization of the artificial material using the effective medium parameter is more accurate and the effective medium theory (EMT) is valid for studying the wave propagation in the DPMS, the effective relative permittivity tensor ε_{eff} is a diagonal matrix in Cartesian coordinates, $\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_p, \varepsilon_{zz} = \varepsilon_t$, which are approximated as follows [3,4]:

$$\varepsilon_p = \frac{d_2\varepsilon_2 + d_1\varepsilon_1}{d_1 + d_2}, \ \varepsilon_t = \frac{(d_2 + d_1)\varepsilon_1\varepsilon_2}{d_2\varepsilon_1 + d_1\varepsilon_2} \tag{2}$$

When the layers are thin, $k_z d \ll 1$, $k_{1,2z}d \ll 1$, the second order expansion of (1) over the arguments of trigonometric functions leads to the dispersion relation for an uniaxial anisotropic medium is

$$k_x^2/\varepsilon_t + k_z^2/\varepsilon_p = k_0^2 \tag{3}$$

It is shown that a composite metal-dielectric structure with an appropriate metal filling factor can operate at practically any desired wavelength in the visible and near-infrared ranges. Firstly, we analyze the structure consists of metal Ag and dielectric layers HfO_2 with ε_1=4.6 and infinite in x and y directions. For the sake of simplicity, we consider a lossless Drude model to describe the dielectric function of the metallic layers. As an example, in Fig. 2 we plot the effective permittivities ε_p and ε_t with frequency, where we assume d_1 = 36 nm, d_2 = 24 nm and f_p = 1.2 PHz, the absorption loss of dielectric is also neglected. In the graph, there are two regions in which ε_p and ε_t take opposite signs. In the first region, which includes frequency up to approximately 0.42 PHz, ε_p is negative; in the second, between 0.6 PHz and 1.2 PHz, ε_p is positive. It is worth noting that there are also two regions in which ε_p and ε_t are two positive signs, where $f >$ 1.2 PHz and around 0.5 PHz. From Eq. (3), when ε_p and ε_t are both positive, the relationship between k_x and k_z is elliptical (or circle) similar to that in free space. For a certain k_x, k_z is real, but when k_x becomes large, k_z becomes imaginary, which indicates that the wave is evanescent, it decays exponentially with z. However, when ε_p and ε_t have opposite signs, k_z is real for a much wider range of values of k_x. Even the high spatial frequency components with large k_x, which would normally be evanescent, now correspond to real values of k_z, and hence to propagating waves. The group velocity for waves propagating within such medium can be calculated by $v_g = \nabla_k\,\omega(k)$, v_g specifies the direction of energy flow and is not necessarily parallel to the wave vector but must lie normal to the EFC. On the whole, by choosing a suitable value of the ratio of layer thicknesses, we can make the real parts of ε_p and ε_t take opposite or same signs over the frequencies of interest.

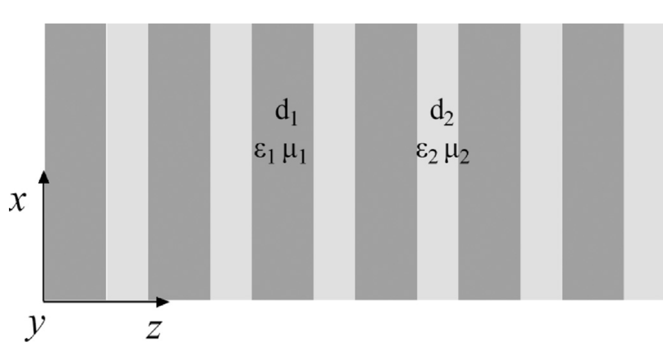

Fig. 1. One-dimensional alternating layers of dielectric (subscript 1) and metallic material (subscript 2). The thicknesses of the dielectric and metal layers are $d1$ and $d2$, respectively, with period $d=d1+d2$. The layers are infinite in the x–y plane.

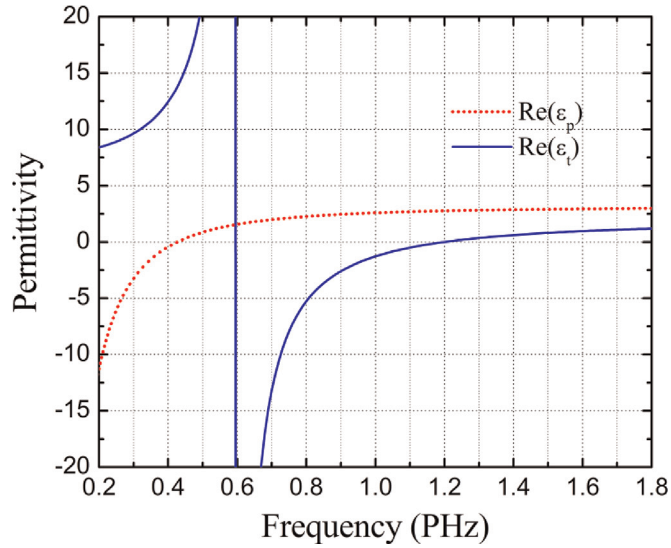

Fig. 2. The effective dielectric permittivity ε_p and ε_t of the metallic–dielectric multilayer consists of silver and HfO_2, where the permittivity of HfO_2 is ε_1 = 4.6, the lossless Drude model to describe the dielectric function of Ag i.e. $\varepsilon_2 = 1 - f_p^2/f^2$ with $f_p = 1.2 \times 10^{15}$ Hz, d_1 = 36 nm and d_2 = 24 nm.

3. Numerical results and discussion

It should be noticed that although the dispersion relation of Eq. (3) based on the EMT is capable of providing analytic results coinciding with ones of transfer matrix method, Eq. (1) is the most correct electromagnetic description of the DPMS in a wide frequency band. The EFCs of this kind of DPMS from Eq. (1) are shown in Fig. 3. It is clear that the dispersion curves become concave to flat to convex, that is the curvatures change from positive to zero to negative to positive with frequency [14,24]. Since the EFC is flat at 0.56 PHz, the curvature of the EFC is zero, which implies good self collimation properties in this region, where the diffraction is substantially suppressed and the nondiffractive propagation is limited to functions using a rather wide beam. The pointing vector of the refractive wave will always be along z axis