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Optical properties of subwavelength metallic–dielectric multilayers

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Abstract

We present studies on the optical properties of periodic metallic–dielectric (MD) multilayers and numerical results show that there exists, insensitive to the lattice scaling, a transparent band as long as the layer thickness is in the subwavelength ranging. It illustrates the transparent band is controlled by mechanisms beyond the Bragg scattering: the shorter-wavelength band edge comes from the intensive resonant absorption behavior of the metals, while the longer-wavelength band edge is determined by zero (volume) averaged permittivity $\varepsilon_{\mathrm{eff}} = 0$. Moreover, a Lorentz–Drude model for the permittivity of a ε-negative (ENG) metamaterial is used to show that a transparent band may be obtained in a subwavelength structure consisting of ENG multilayers with total length less than both the center wavelength and the half width of the band.

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1. Introduction

Since Photonic Crystals (PCs) [1,2] are proposed, they have attracted intensive studies due to their unique electromagnetic properties and many potential applications. The Photonic Band Gap (PBG) in PCs originates from the interference of Bragg scattering in the periodic dielectric–dielectric or metallic–dielectric (MD) structure. In recent years, great interest has been focused on MD structures, especially on one-dimensional (1D) MD structures [3–9], because they have more intensive interface scattering, and then more stronger PBG effects than those of all-dielectric PCs. MD PCs have been designed to transmit in visible and near infrared ranges but reflect all longer-wavelength electromagnetic waves [3–6], enhance absorption [7,8] and nonlinearity [9–12]. Different structures have proposed to improve the properties of MD PCs. For example, a transparent band insensitive to the periodic number of the structures can be realized by using a special unit with the mirror symmetry in a MD PC [13]. Moreover, broader absorption band covering from the visible to near infrared regions has been demonstrated in a MD PC with quasi-periodic structure [8].

Metamaterials are another kind of artificial microstructure materials with novel properties on manipulating electromagnetic waves [14–19]. There are two types of metamaterials: double-negative (DNG) materials and single-negative (SNG) materials. The former have simultaneously negative permittivity and permeability, also called negative refractive or left-handed materials. The latter include the ε-negative (ENG) materials with negative permittivity but positive permeability and μ-negative (MNG) materials with negative permeability but positive permittivity. Conventional dielectric materials have simultaneously positive permittivity and permeability so that they are called double-positive (DPS) or right-handed materials. Recent studies show that there exist new mechanism of PBG beyond the usual Bragg scattering in 1D PCs consisting of metamaterials [14,15], especially when their lattice constants are in the subwavelength ranging [18,19], e.g., zero (volume) averaged refractive index (zero-$\bar{n}$) gap for PCs made of DPS and DNG media [14,15] and the zero effective phase (zero-ϕ_{eff}) gap for PCs made of ENG-MNG multilayers [16,17]. Contrasted

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to the Bragg gap in conventional all-dielectric or MD PCs, the zero-$\bar{n}$ gap and zero-ϕ_{eff} gap are invariant with lattice scaling and insensitive to disorder.

Below the plasma frequency ω_{p}, metals are typical ENG materials as their permittivity are negative, and therefore it would be interesting to know whether there also exist new mechanism of PBG beyond the Bragg scattering in a subwavelength MD PC, or more generally in a PC consisting DPS and ENG materials. In this Letter, we investigate optical properties of a 1D subwavelength MD PC. Different from conventional MD PCs [3–6], the numerical results show that it possesses a transparent band which is invariant with lattice scaling. Such pass band is also controlled by mechanisms beyond the Bragg scattering: the shorter-wavelength band edge comes from intensive resonant absorption and the longer-wavelength band edge is determined by zero average permittivity $\varepsilon_{\text{eff}} = 0$. In the next section, we describe the optical properties of 1D subwavelength MD PCs composed of stacking alternately MgF_2 and silver layers. The optical properties of 1D subwavelength DPS-ENG multilayers are studied in the third section, where the Lorentz–Drude (LD) model is used to represent metals or more general ENG materials. Summary will be given in the forth section.

2. The properties of periodic subwavelength MD multilayers

In this section, numerical results based on the transfer matrix method [20] are given for the periodical structures consisting of MgF_2 layers and usual metal layers such as silver (Ag). The refractive index of MgF_2 is 1.38 and we use the data given in Ref. [21] for the refractive index of metals. The thickness of MgF_2 is denoted by d_{D} and that of the metal by d_{M} and both of them are in the subwavelength ranging. The periodic number of the structure is N.

Firstly, we consider the periodic subwavelength MD multilayers composed of MgF_2 and Ag, and the transmission, reflection and absorption spectra of the structures with different lattice lengths are shown in Fig. 1, where all the structures have the same periodic number $N = 20$. The three structures in Fig. 1(a), (b) and (c) have the same ratio of $d_{\text{D}}/d_{\text{M}} = 14$. From Fig. 1(a), one can see that, there is a transparent band insensitive to the lattice length $a = d_{\text{D}} + d_{\text{M}}$, for example, comparing curve S_1 with $a = 45$ nm to curve S_3 with $a = 75$ nm. Fig. 1(b) and (c) show that, there exists a same edge for three different lattice lengths in the reflection and the absorption spectra, which are coincided to the longer-wavelength and shorter-wavelength edges of the transparent band in Fig. 1(a), respectively. Fig. 1(d), (e) and (f) give the transmission, reflection and absorption spectra of the structures with the same thickness $d_{\text{M}} = 4$ nm and different ratios $d_{\text{D}}/d_{\text{M}} = 12, 14, 16$ for curves S_1, S_2 and S_3. It illustrates that the longer-wavelength edge of the transparent band increases with $d_{\text{D}}/d_{\text{M}}$, while the shorter-wavelength edge of the transparent band remained fixed. These results imply that the transparent band may be controlled by two different mechanisms: the shorter-wavelength edge relies on the intensive absorption behavior of the metals and the longer-wavelength edge depends on the periodical structure characterized by the ratio $d_{\text{D}}/d_{\text{M}}$. Moreover, the lattice-scaling insensitive transparent bands can also be obtained for the subwavelength MD structures composed of other metals such as gold and tungsten.

We would like to emphasize here that lattice-scaling insensitive behavior obtained above is the properties of MD multilayers satisfying the subwavelength-unit condition. When the lattice length $a = d_{\text{D}} + d_{\text{M}}$ is comparable to the wavelength such as in conventional MD PCs [3–6], this behavior breaks down as shown in Fig. 2 for two MD PCs composed of MgF_2 and Ag with the same periodic number $N = 20$ and ratio

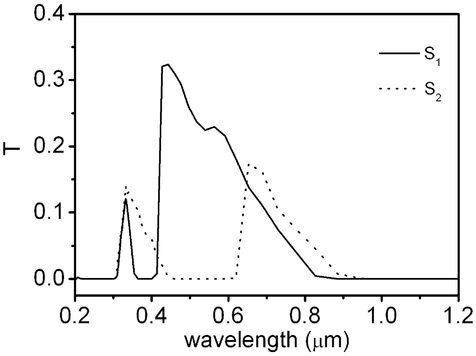

Fig. 2. The transmission spectra of the two structures S_1 and S_2 which have the same ratio $d_{\text{D}}/d_{\text{M}} = 14$ and periodic number $N = 20$, but the lattice lengths are 150 and 225 nm, respectively.

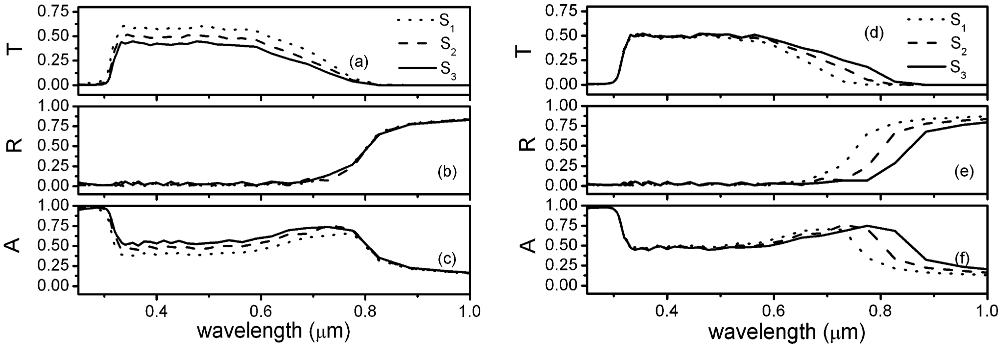

Fig. 1. All the structures have the same periodic number $N = 20$. (a), (b) and (c) are the transmission, reflection and absorption spectra of three structures S_1, S_2 and S_3 which have the same ratio $d_{\text{D}}/d_{\text{M}} = 14$, but the lattice lengths are 45, 60 and 75 nm, respectively. (d), (e) and (f) are the transmission, reflection and absorption spectra of three structures S_1, S_2 and S_3 which have the same thickness $d_{\text{M}} = 4$ nm, but the ratios $d_{\text{D}}/d_{\text{M}}$ equal 12, 14 and 16, respectively.