Available online at www.sciencedirect.com
ScienceDirect
Physics Letters A 372 (2008) 730–734
PHYSICS LETTERS A
www.elsevier.com/locate/pla

Optical properties of subwavelength metallic–dielectric multilayers

Guiqiang Du [a], Zhanshan Wang [b], Hongqiang Li [a], Yewen Zhang [a], Hong Chen [a,*]

[a] *Pohl Institute of Solid State Physics, Tongji University, Shanghai 200092, People's Republic of China*
[b] *Institute of Precision Optical Engineering, Tongji University, Shanghai 200092, People's Republic of China*

Received 9 April 2007; received in revised form 24 July 2007; accepted 28 July 2007

Available online 2 August 2007

Communicated by R. Wu

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.

PACS: 42.70.Qs; 42.25.Bs; 78.67.Pt

Keywords: Photonic crystals; Transparent band; Multilayers

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

* Corresponding author.
E-mail address: honchenk@online.sh.cn (H. Chen).

0375-9601/$ – see front matter
doi:10.1016/j.physleta.2007.07.066

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 $\varepsilon_{\mathrm{eff}} = 0$. 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 $d_{\mathrm{D}}/d_{\mathrm{M}} = 14$. From Fig. 1(a), one can see that, there is a transparent band insensitive to the lattice length $a = d_{\mathrm{D}} + d_{\mathrm{M}}$, 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 $d_{\mathrm{M}} = 4$ nm and different ratios $d_{\mathrm{D}}/d_{\mathrm{M}} = 12, 14, 16$ for curves S_1, S_2 and S_3. It illustrates that the longer-wavelength edge of the transparent band increases with $d_{\mathrm{D}}/d_{\mathrm{M}}$, 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 $d_{\mathrm{D}}/d_{\mathrm{M}}$. 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 $a = d_{\mathrm{D}} + d_{\mathrm{M}}$ 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

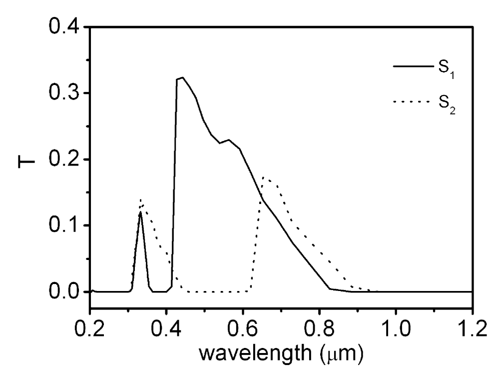

Fig. 2. The transmission spectra of the two structures S_1 and S_2 which have the same ratio $d_{\mathrm{D}}/d_{\mathrm{M}} = 14$ and periodic number $N = 20$, but the lattice lengths are 150 and 225 nm, respectively.

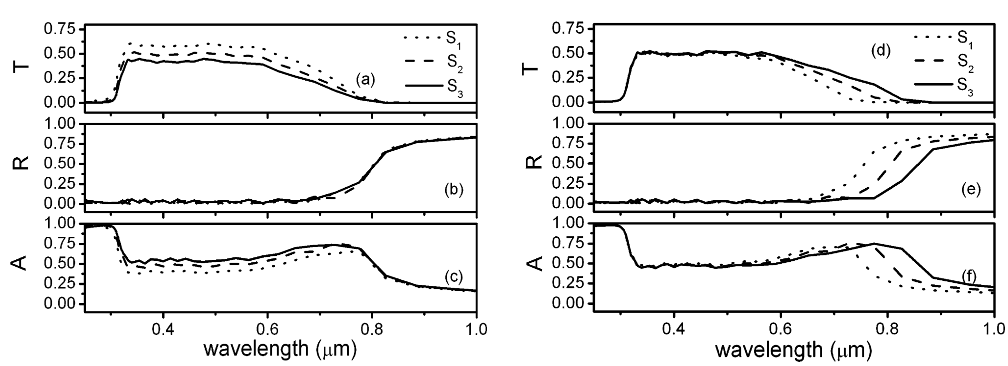

Fig. 1. All the structures have the same periodic number $N = 20$. (a), (b) and (c) are the transmission, reflection and absorption spectra of three structures S_1, S_2 and S_3 which have the same ratio $d_{\mathrm{D}}/d_{\mathrm{M}} = 14$, but the lattice lengths are 45, 60 and 75 nm, respectively.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

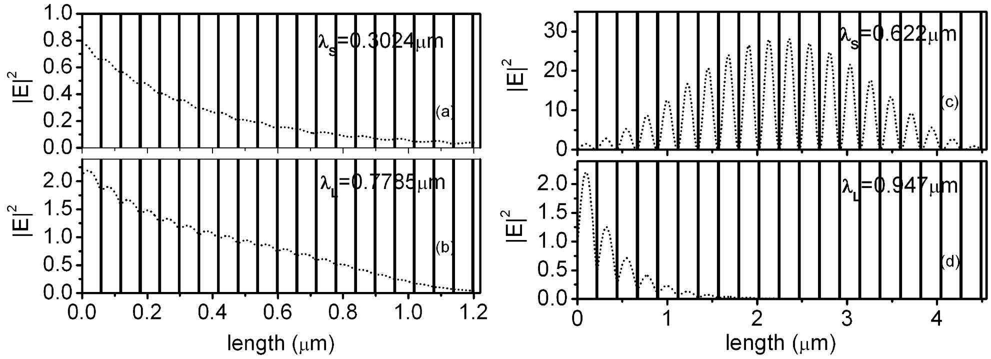

Fig. 3. (a) and (b) show the electric field intensity distribution $|E|^2$ of the two band edges inside the structure S_2 of Fig. 1(a); and (c) and (d) describe $|E|^2$ of the two band edges inside the structure S_2 of Fig. 2, where λ_S and λ_L represent the incident wavelengths of shorter-wavelength and longer-wavelength band edges, respectively.

$d_D/d_M = 14$, but different lattice lengths: $a = 150$ nm for curve S_1 and $a = 225$ nm for curve S_2. Comparing conventional MD PCs to subwavelength MD multilayers, there are two differences in the transmission spectra: (1) there are more than one transparent bands in the former case instead of just one such band in the latter case; (2) the transparent bands shift to the longer wavelength as the lattice length increases in the former case while it remains fixed in the latter case. In order to understand the difference in the band-gap structures between the conventional MD PCs and subwavelength MD multilayers, the electric-field intensity $|E|^2$ of the shorter-wavelength λ_S and longer-wavelength λ_L band edges for two different structures are shown in Fig. 3. Fig. 3(a) and (b) give $|E|^2$ of the shorter-wavelength and longer-wavelength band edges inside the subwavelength MD multilayers S_2 as showed in Fig. 1(a) with $\lambda_S = 302.4$ nm and $\lambda_L = 778.5$ nm, respectively. Fig. 3(c) and (d) show $|E|^2$ of the shorter-wavelength and longer-wavelength band edges inside the conventional MD PC S_2 as showed in Fig. 2 with $\lambda_S = 662.0$ nm and $\lambda_L = 947.0$ nm, respectively. One can see that the electric field intensities vary smoothly in the subwavelength MD multilayers, while they vary sharply in the conventional MD PCs with the nodes of $|E|^2$ located mainly inside the metals. The sharply oscillation behavior of the electric field intensities is the consequence of interference due to Bragg scattering and the field nodes are designed inside the metals are common features of conventional MD PCs [3–6], leading the strongly dependence of the transparent band on the lattice scaling as required by the Bragg scattering mechanism. The smoothly oscillation behavior implies that the subwavelength MD multilayers may be described as the effective media, where there may exit mechanisms beyond the Bragg scattering for the band-gap structures as observed already in 1D PCs consisting of metamaterials [18,19]. We will show in the next section that the lattice-scaling insensitive transparent band in the subwavelength MD multilayers is also controlled by mechanisms beyond the Bragg scattering.

3. Lorentz–Drude model for the permittivity of metals

In order to illustrate more clearly two mechanisms corresponding to the edges of the transparent band studied in the previous section, a model description is adopted in this section for the permittivity of ENG materials including metals. The Drude model is used, in general, for the permittivity of metals far below the plasma frequency ω_p. However, near the plasma frequency ω_p, the effect of resonance on the permittivity should be taken into account, and the Lorentz–Drude (LD) model [22] is a suitable description for metals, or more generally for ENG materials.

$$\varepsilon_{LD} = 1 - \frac{f_0}{\Omega^2 + i\Gamma_0\Omega} - \frac{f_1}{\Omega^2 - \Omega_1^2 + i\Gamma_1\Omega} \tag{1}$$

where $\Omega = \omega/\omega_p$, $\Omega_1 = \omega_1/\omega_p$, $\Gamma_0 = \gamma_0/\omega_p$ and $\Gamma_1 = \gamma_1/\omega_p$. The first term in Eq. (1) comes from the Drude model and the second term is a Lorentz-type resonance at the plasma frequency. The parameters in Eq. (1) are chosen as $f_0 = 0.8$, $f_1 = 0.4$, $\Omega_1 = 0.5$, $\Gamma_0 = 0.005$ and $\Gamma_1 = 0.05$.

In the following we study the optical properties of subwavelength MD multilayers composed of MgF_2 and metals described by the LD model. Firstly, we study the mechanism that controls the longer-wavelength edge of the transparent band. Fig. 4(a) gives the reflection spectra of three structures which have the same periodic number $N = 20$ and the same thickness of metal $d_M = 0.01\lambda_p$, but different ratios $d_D/d_M = 8$, 10 and 12 for curves S_1, S_2 and S_3, where the length has been scaled by the plasma wavelength λ_p. One can see that the results in Fig. 4(a) have the similar behavior as those in Fig. 1(e), implying the LD model captures main features of metals near the plasma frequency. The theoretical studies of Refs. [18,19] indicate that, in a 1D subwavelength PC made of lossless metamaterials, there exist a "spatially-average-single-negative" (SASN) gap whose edges are determined by the conditions of zero (volume) average permittivity ($\varepsilon_{eff} = 0$) and permeabity ($\mu_{eff} = 0$). These results lead to the conclusion that, in the subwavelength limit, both the zero-$\bar{n}$ gap for PCs made of DPS and DNG media [14,15] and the zero-ϕ_{eff} gap for PCs made of ENG-MNG multilayers [16,17] can be understood as SASN gaps. We are going to show that the longer-wavelength edge of the transparent band in Fig. 4(b) may also be described by the condition of zero (volume) average permittivity given by

$$\varepsilon_{eff} = \frac{\varepsilon_D d_D/d_M + \mathrm{Re}[\varepsilon_{LD}]}{d_D/d_M + 1} = 0 \tag{2}$$

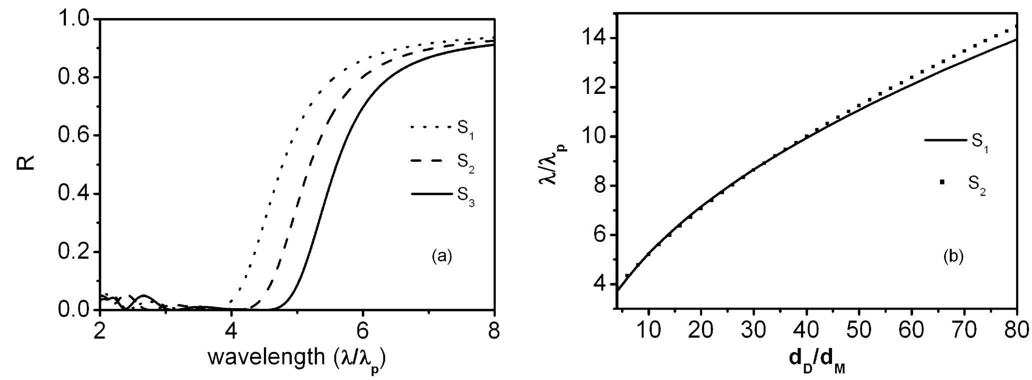

Fig. 4. (a) is the reflection spectra of the dimensionless structures S_1, S_2 and S_3 composed of MgF_2 and metals described by the LD model with the same periodic number $N = 20$ and $d_M = 0.01\lambda_p$, but different ratios $d_D/d_M = 8$, 10 and 12, respectively. (b) is the longer-wavelength edges as the function of the ratio d_D/d_M. The curve S_1 represents results given by Eq. (2) and curve S_2 for results determined by the reflection spectra.

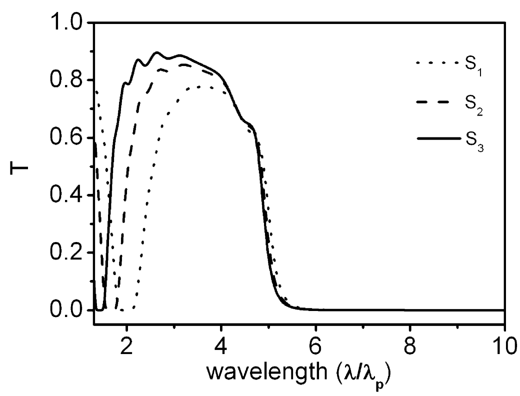

Fig. 5. The transmission spectra of the three dimensionless structures S_1, S_2 and S_3 composed of MgF_2 and metals described by the LD model which have the same ratio $d_D/d_M = 10$, periodic number $N = 40$ and total length $L = 4.4\lambda_p$, but the resonant frequencies are 0.5, 0.6 and 0.7, respectively.

where $\mathrm{Re}[\varepsilon_{LD}]$ denotes the real part of ε_{LD}. Comparison of band edges given by Eq. (2) as solid line with those obtained by the reflection spectra as squares, respectively, is illustrated in Fig. 4(b) as a function of the ratio d_D/d_M. From Fig. 4(b), one sees that, the band edges determined by $R = 0.5$ in the reflection spectra agree well with those given by $\varepsilon_{\mathrm{eff}} = 0$ for $d_D/d_M \leqslant 40$ (or $a = d_D + d_M \leqslant 0.44\lambda_p$). As the lattice length increases, such agreement is becoming worse for the reason that the effective media description of Eq. (2) is valid only in the subwavelength ranges.

Next, the mechanism for the shorter-wavelength edge of the transparent band is considered. Fig. 5 gives the dependence of the optical properties on the resonant frequency Ω_1, where $d_D/d_M = 10$, $N = 40$, and $L = 4.4\lambda_p$. The resonant frequencies Ω_1 for curves S_1, S_2 and S_3 in Fig. 5 are 0.5, 0.6 and 0.7, respectively, and it shows that the shorter-wavelength edge of the transparent band increases as the resonant frequency decreases, while the longer-wavelength edge nearly remains fixed.

The present studies can be extended to 1D structures consisting of subwavelength DPS-ENG structures in longer-wavelength ranges, since the permittivity of ENG materials may also be described by LD model. Nowadays, many kinds of artificial electromagnetic materials are engineered with the effective plasma frequency depressed from the ultraviolet to GHz regions [23–25], therefore, the lattice-scaling insensitive transparent band may be obtained in longer-wavelength ranges with compact structures as shown in the following examples, where the total length of subwavelength DPS-ENG structures may be engineered less than the center wavelength of the transparent band. Fig. 6 represents transmission spectra of DPS-ENG structures, where DPS is chose as MgF_2 and ENG as a metamaterial with $\mu = 1$ and ε given by the LD model. Fig. 6(a) shows the transmission spectra of the subwavelength structures S_1 and S_2 with the same total length $L = 3.6\lambda_p$ and same ratio $d_D/d_M = 29$, but different lattice lengths $0.03\lambda_p$, $0.12\lambda_p$ and different periodic numbers 120, 30, respectively. The center wavelength and the half width of the transmission spectra are $\lambda_c \approx 5.3\lambda_p \approx 1.472L$ and $\Delta\lambda \approx 5.565\lambda_p \approx 1.546L$, respectively. One can see that the transmission spectra are insensitive to the periodic number N when the lattice length is within the subwavelength range. Similar properties are observed in the subwavelength structures S_1 and S_2 of Fig. 6(b) with $\lambda_c \approx 3.5\lambda_p = 1.75L$ and $\Delta\lambda \approx 2.426\lambda_p = 1.213L$. All the structures in Fig. 6(b) have the same total length $L = 2\lambda_p$ and same ratio $d_D/d_M = 9$, but different lattice lengths $0.02\lambda_p$, $0.2\lambda_p$, $0.5\lambda_p$, $0.67\lambda_p$, $1.0\lambda_p$ and different periodic numbers 100, 10, 4, 3, 2, respectively. However, the transmission spectra are modified when the lattice length is beyond the subwavelength range as shown in structures S_3, S_4 and S_5 of Fig. 6(b); the transmission is enhanced with increasing periodic number N for the constant total length, which has been proposed [26]. For P-polarization light, such properties can be used to improve the resolution of the nearly perfect lens made of the subwavelength DPS-ENG structures [26]. These examples indicate that one may obtain a transparent band in a subwavelength DPS-ENG structure with the total length less than both the center wavelength and the half width of the band. On the other hand, these examples indicate that the transparent band is insensitive to the periodic number N in the subwavelength DPS-ENG structure with the constant total length. Such subwavelength structures may have more potential applications for compact devices in far infrared and microwave regions.

4. Summary

We have presented detailed studies on optical properties of periodic subwavelength MD multilayers. A lattice-scaling in-

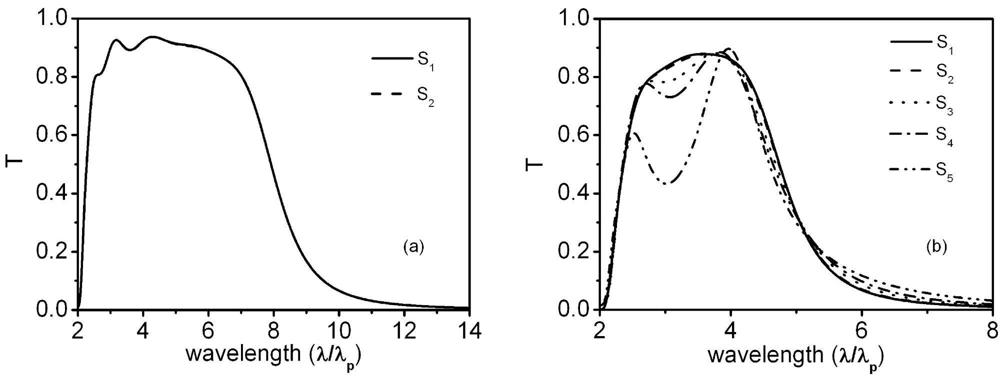

Fig. 6. Both of (a) and (b) are the transmission spectra of the dimensionless structures composed of MgF_2 and ENG materials described by the LD model. In (a), the structures S_1 and S_2 have the same total length $L = 3.6\lambda_p$ and same ratio $d_D/d_M = 29$, but different lattice lengths which are $0.03\lambda_p$ and $0.12\lambda_p$, respectively. In (b), S_1, S_2, S_3, S_4 and S_5 have the same total length $L = 2\lambda_p$ and same ratio $d_D/d_M = 9$, but different lattice lengths which are $0.02\lambda_p$, $0.2\lambda_p$, $0.5\lambda_p$, $0.67\lambda_p$ and $1.0\lambda_p$, respectively.

sensitive transparent band is obtained with edges determined by mechanisms beyond the Bragg scattering: the shorter-wavelength edge depends on the resonant absorption behavior of the metals, while the longer-wavelength edge relays on zero (volume) averaged permittivity $\varepsilon_{\text{eff}} = 0$. The Lorentz–Drude (LD) model is employed to show these are common properties of 1D subwavelength structures consisting of DPS-ENG multilayers.

Acknowledgements

This research was supported by CNKBRSF (Grant No. 2006CB921701), by CNSF (Grants Nos. 10474072, 10634050 and 50477048), by Shanghai Science and Technology Committee.

References

[1] E. Yablonovitch, Phys. Rev. Lett. 58 (1987) 2059.
[2] S. John, Phys. Rev. Lett. 58 (1987) 2486.
[3] M.J. Bloemer, M. Scalora, Appl. Phys. Lett. 72 (1998) 1676.
[4] M. Scalora, M.J. Bloemer, A.S. Pethel, J.P. Dowling, C.M. Bowden, A.S. Manka, J. Appl. Phys. 83 (1998) 2377.
[5] M.J. Keskinen, P. Loschialpo, D. Forester, J. Schelleng, J. Appl. Phys. 88 (2000) 5785.
[6] M. Scalora, M.J. Bloemer, C.M. Bowden, Opt. Photon News 10 (1999) 23.
[7] J.F. Yu, Y.F. Shen, X.H. Liu, R.T. Fu, J. Zi, Z.Q. Zhu, J. Phys.: Condens. Matter 16 (2004) L51.
[8] J.W. Dong, G.Q. Liang, Y.H. Chen, H.Z. Wang, Opt. Exp. 14 (2006) 2014.
[9] R.S. Bennink, Y.K. Yoon, R.W. Boyd, J.E. Sipe, Opt. Lett. 24 (1999) 1416.
[10] M.C. Larciprete, C. Sibilia, S. Paoloni, M. Bertolotti, F. Sarto, M. Scalora, J. Appl. Phys. 93 (2003) 5013.
[11] N.N. Lepeshkin, A. Schweinsberg, G. Piredda, R.S. Bennink, R.W. Boyd, Phys. Rev. Lett. 93 (2004) 123902.
[12] M. Scalora, N. Mattiucci, G. D'Aguanno, M.C. Larciprete, M.J. Bloemer, Phys. Rev. E 73 (2006) 016603.
[13] S. Feng, M. Elson, P. Overfelt, Phys. Rev. B 72 (2005) 85117.
[14] J. Li, L. Zhou, C.T. Chan, P. Sheng, Phys. Rev. Lett. 90 (2003) 083901.
[15] H.T. Jiang, H. Chen, H.Q. Li, Y.W. Zhang, S.Y. Zhu, Appl. Phys. Lett. 83 (2003) 5386.
[16] H.T. Jiang, H. Chen, H.Q. Li, Y.W. Zhang, J. Zi, S.Y. Zhu, Phys. Rev. E 69 (2004) 066607.
[17] L.G. Wang, H. Chen, S.Y. Zhu, Phys. Rev. B 70 (2004) 245102.
[18] G.S. Guan, H.T. Jiang, H.Q. Li, Y.W. Zhang, H. Chen, S.Y. Zhu, Appl. Phys. Lett. 88 (2006) 211112.
[19] L. Gao, C.J. Tang, S.M. Wang, J. Magn. Magn. Mater. 301 (2006) 371.
[20] P. Yeh (Ed.), Optical Waves in Layered Media, Wiley, 1988.
[21] E.D. Palik (Ed.), Handbook of Optical Constants of Solids, Academic Press, Orlando, 1985.
[22] A.D. Rakic, A.B. Djurisic, J.M. Elazar, M.L. Majewski, Appl. Opt. 37 (1998) 5271.
[23] X. Xu, Y. Xi, D. Han, X. Liu, J. Zi, Z. Zhu, Appl. Phys. Lett. 86 (2005) 091112.
[24] J.B. Pendry, A.J. Holden, W.J. Stewart, I. Youngs, Phys. Rev. Lett. 76 (1996) 4773.
[25] D.R. Smith, W.J. Padilla, D.C. Vier, S.C. Nemat-Nasser, S. Schultz, Phys. Rev. Lett. 84 (2000) 4184.
[26] S.A. Ramakrishna, J.B. Pendry, M.C.K. Wiltshire, W.J. Stewart, J. Mod. Opt. 50 (2003) 1419.