Vol 17 No 7, July 2008
1674-1056/2008/17(07)/2544-09

Chinese Physics B

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Effective permittivity and permeability of one-dimensional dielectric photonic crystal within a band gap*

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(Received 15 January 2008; revised manuscript received 24 January 2008)

We take a finite dielectric photonic crystal as a homogeneous slab and have extracted the effective parameters. Our systematic study shows that the effective permittivity or permeability of dielectric photonic crystal is negative within a band gap region. This means that the band gap might act as ε-negative materials (ENMs) with $\varepsilon < 0$ and $\mu > 0$, or μ-negative materials (MNMs) with $\varepsilon > 0$ and $\mu < 0$. Moreover the effective parameters sensitively rely on size, surface termination, symmetry, etc. The effective parameters can be used to design full transmission tunnelling modes and amplify evanescent wave. Several cases are studied and the results show that dielectric photonic band gap can indeed mimic a single negative material (ENM or MNM) under some restrictions.

Keywords: photonic crystal, negative permittivity, negative permeability
PACC: 4270Q, 4225B, 7820

1. Introduction

With the development of theory and experiment, many wonderful artificial materials[1−7] are designed and fabricated. All of these progresses give us much more spaces beyond nature in choosing material parameters. To obtain special values of permittivity or permeability is an attractive job for many potential applications.[8−10] It is convenient and significant to distinguish materials according to the values of their permittivity and permeability that characterize their responses to electromagnetic wave. Great attention has been paid to the research of these metamaterials: one is double negative materials (DNMs) with both $\varepsilon < 0$ and $\mu < 0$, or left-handed material. The other is single negative materials (SNMs), including ε-negative materials (ENMs) with both $\varepsilon < 0$ and $\mu > 0$, and μ-negative materials (MNMs) with both $\varepsilon > 0$ and $\mu < 0$. DNMs have many unusual properties and especially they can be used to form a perfect lens beyond diffraction limit by amplifying evanescent wave.[8] SNMs are opaque to electromagnetic wave and support only evanescent waves. However a pair of SNMs can be transparent under conjugate matching condition between two similar semi-infinite regions[11] In the meantime, the tunnelling mode appears and the evanescent waves in each slab of SNM are amplified remarkably. Most of SNMs are realized by using thin wires and split-ring resonators (SRRs).[12,13] The considerable loss and the difficulty in fabrication are huge obstacles when those structures are extended into shorter wavelength regions. Thus experiments are still far away from some theoretical predictions.

Relatively, a one-dimensional dielectric photonic crystal (PC) is one kind of artificial periodic structure and has been extensively studied for many years. It has many advantages in controlling light: the structure is simple and the loss is low even in a visible light regime. A band gap is a prominent character of PC and it behaves in some ways similar to the SNM. For example, they are all opaque to incident light and support only evanescent waves. So a natural presumption is that the PC band gap may mimic a special kind of SNM, and it is such a presumption that motivates the present study.

Under the restriction condition that a finite one-dimensional dielectric PC can generate the same transmission and reflection as a homogeneous slab, one may obtain the values of $\varepsilon_{\rm eff}$ and $\mu_{\rm eff}$ of the PC. We find that the band gap is of ENM or MNM within

*Project supported by the National Key Basic Research Special Foundation of China (Grant No 2006CB921701), the National Natural Science Foundation of China (Grant Nos 10474072, 10634050 and 50477048) and the Shanghai Science and Technology Committee of China (Grant No 07DZ22302).
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the band gap. Even all the elements of PC are of dielectric materials with $\mu = 1$, the effective permeability μ_{eff} fluctuates around unity in a transmission band and can reach a negative value within the gap region. Moreover the effective parameters of PC are sensitively related to size, surface termination, symmetry, etc.[14,15] We emphasize that the effective parameters exhibit the external unitary response of the band gap without considering any internal structure. Although the local permittivity and permeability may not be determined appropriately, it is still meaningful in that ε_{eff} and μ_{eff} can be used to describe the external response of a dielectric PC.[14] On the one hand, these effective parameters will help us further understand the properties of PC band gap. On the other hand, the effective parameters offer us exact conditions of tunnelling mode constructed by the heterostructure of PC band gap with other SNM. In the mean time, the evanescent waves in each unit are amplified and restored. The evanescent wave amplification is helpful for the understanding of perfect lens[8,16] and especially for its realization in a visible light region with a low loss. The rest of the present paper organized is as follows. The method is presented in Section 2. The properties of effective parameters are given in Section 3. In Section 4, three cases of tunnelling modes are designed and studied by using the effective parameters. Finally, conclusions drawn from the present study are given in Section 5.

2. The effective parameters of finite one-dimensional photonic crystals

We assume a finite dielectric photonic crystal (PC) to be a homogeneous slab. If there exists an artificial homogeneous slab that has the same reflection and transmission coefficients as the given PC, then we think that the PC has the same effective permittivity ε_{eff} and permeability μ_{eff} as the artificial homogeneous slab. The reflection and transmission coefficients of the one-dimensional PC can be obtained by using a transfer matrix method directly. Here we consider a finite dielectric PC denoted by PC $(\text{AB})_{20}$, with a refractive index $n_{\text{A}} = 3$, $n_{\text{B}} = 2$, and thickness $d_{\text{A}} = 50\,\text{nm}$, $d_{\text{B}} = 75\,\text{nm}$. The incident light comes from left to right. The reflection coefficient and the transmission coefficient of the PC $(\text{AB})_{20}$ are shown in Fig.1. As illustrated in the figure, there are one gap around 600 nm and an other gap around 200nm. They are similar to each other in both magnitude and phase.

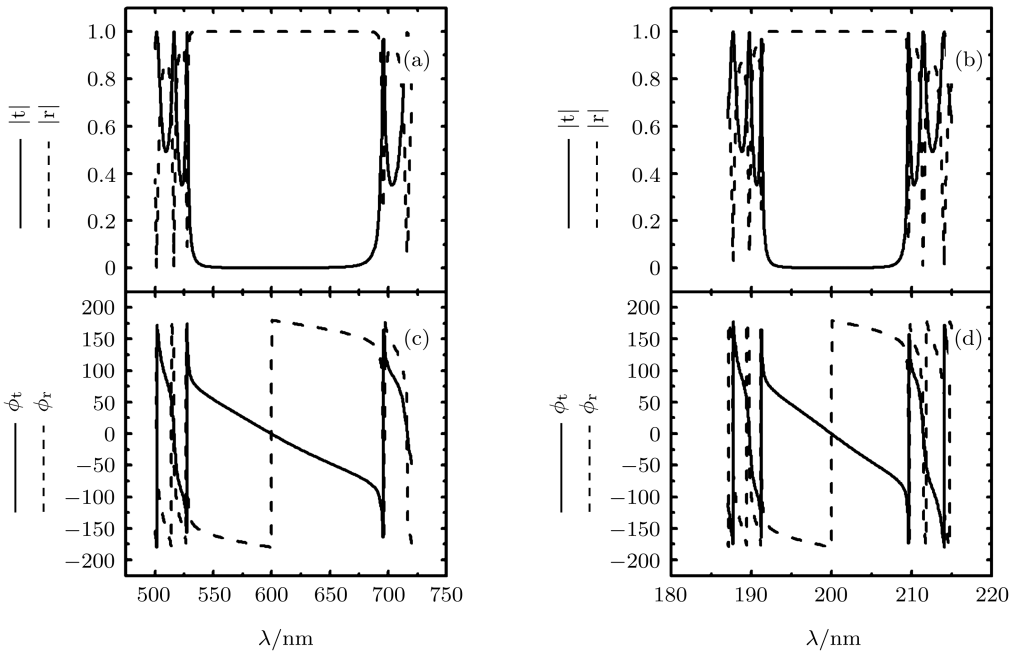


Fig.1. The transmission t (solid line), reflection r (dashed line), transmission phase ϕ_{t} (solid line) and reflection phase ϕ_{r} (dashed line) of the PC $(\text{AB})_{20}$ for the two band gap regions: around 600 and 200 nm.

The following is the method of obtaining effective parameters $\varepsilon_{\rm eff}$ and $\mu_{\rm eff}$. There are two simple relations of permittivity $\varepsilon_{\rm eff}$ and permeability $\mu_{\rm eff}$ each to refractive index and impedance: $\varepsilon_{\rm eff} = n_{\rm eff}/z_{\rm eff}$, $\mu_{\rm eff} = n_{\rm eff} z_{\rm eff}$. Through a standard retrieval procedure the effective refractive index $n_{\rm eff}$ and effective impedance $z_{\rm eff}$ are given as follows:[17,18]

$$z_{\rm eff} = \pm\sqrt{\frac{(1+r)^2 - t^2}{(1-r)^2 - t^2}} \tag{1}$$

and

$$\mathrm{e}^{\mathrm{i}n_{\rm eff}k_0 d} = \frac{t}{1 - t\dfrac{z_{\rm eff}-1}{z_{\rm eff}-1}}, \tag{2}$$

where

$$n_{\rm eff} = \frac{1}{k_0 d}\left\{\mathrm{Im}\left[\ln\left(\mathrm{e}^{\mathrm{i}n_{\rm eff}k_0 d}\right)\right] + 2m\pi - \mathrm{iRe}\left[\ln\left(\mathrm{e}^{\mathrm{i}n_{\rm eff}k_0 d}\right)\right]\right\} \tag{3}$$

with m being an integer, $k_0 = \omega/c$ is the wave number of the incident wave (in vacuum), and d is the total length of the PC. The signs on the right-hand sides in Eqs.(1) and (3) can be determined by the following condition:[17,18]

$$\mathrm{Real}(z_{\rm eff}) \geq 0 \tag{4}$$

and

$$\mathrm{Imag}(n_{\rm eff}) \geq 0. \tag{5}$$

The integer m means that there exist many branches for the refractive index. When the wavelength is much larger than the length d, m should be zero because the real part of $n_{\rm eff}k_0 d$ is less than 2π. For small wavelengths, the integer can be determined by the condition that $\varepsilon(\lambda)$ and $\mu(\lambda)$ are both continuous functions of wavelength. In fact Eqs.(4) and (5) may not be satisfied simultaneously at all times.[18] Some numerical errors may appear when the reflection or the transmission is too small. Within the transmission band, the real part of $z_{\rm eff}$ is relatively large and reliable. Equation (4) holds but Eq.(5) may fail to stay true to some regions. For the band gap region, the sign of z should be determined by condition (5). The effective permittivity and permeability are shown in Fig.(2). For the shorter wavelength section in Fig.2(a), we can see that the real effective permittivity is negative and the real effective permeability is positive. So the PC acts as an ε-negative material (ENM). At the longer wavelength part in Fig.2(a), the PC acts as a μ-negative material (MNM). So the PC behaviours are as like as those of an effective single negative material (ENM or MNM) in a band gap region around 600 nm. There are similar results within the gap around 200 nm as shown in Fig.2(b). The corresponding imaginary parts of $\varepsilon_{\rm eff}$ and $\mu_{\rm eff}$ given in Figs.2(c) and 2(d) neither mean any absorption (or gain) nor violate basic principle.[19]

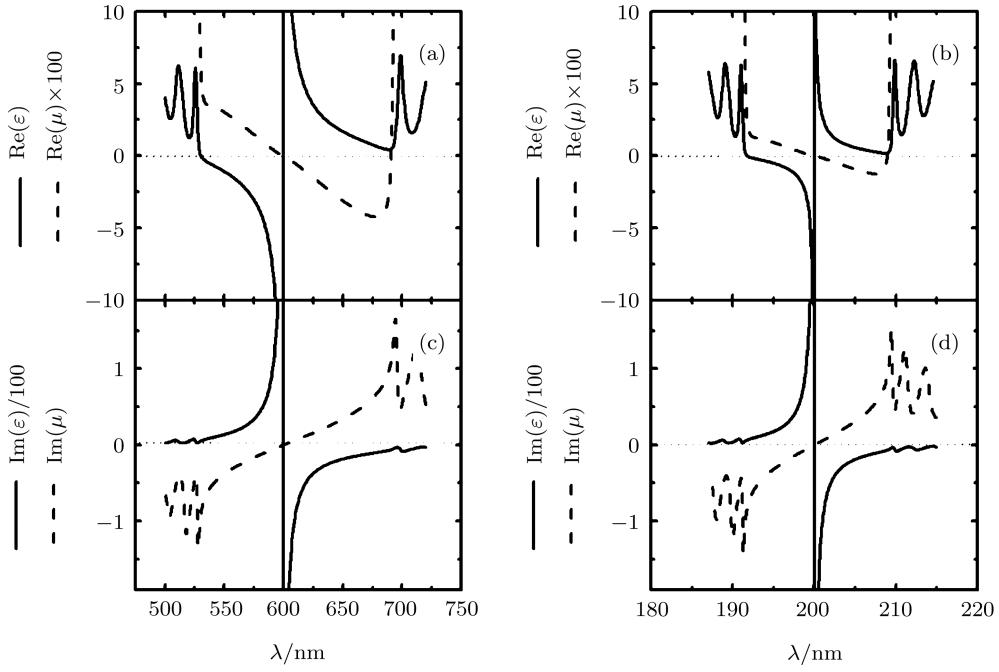


Fig.2. The effective parameters of the photonic crystal $(\mathrm{AB})_{20}$ within a band gap, where panels (a) and (b) show the real parts of permittivity (solid line) and permeability (dashed line, magnified 100 times), and panels (c) and (d) indicate the imaginary parts of permittivity (solid line, reduced 100 times) and permeability (dashed line).

Such kinds of imaginary parts of ε_{eff} and μ_{eff} are the artificial results of the employed retrieval method, which considers only ω-dependence and neglects k-dependence of the effective parameters of a periodic structure. The above results show that the band gap of a simple one-dimensional PC still has many complex characters, if one takes the PC as an artificial homogeneous slab. It is noted that most of SNMs have been realized by using metallic microstructures such as metallic split ring resonators for MNM and metallic stripes for ENM. So those SNMs have a high loss in a visible light region. The effective SNMs we obtained based on one-dimensional dielectric PCs have obvious advantages compared with those coming from metallic microstructures: low loss, broad frequency region of effective parameters and easily fabrication. Though the effective parameters might not correspond to those of a real homogeneous material,[20] these effective parameters indeed reveal some specific characters of PC that natural materials do not possess.

The effective real impedance and imaginary parts of impedance and refractive index are plotted in Fig.3. The real part of impedance decreases rapidly in the gap and the value is near zero. It is far away from impedance matching with air. So in this region the light does not propagate and only evanescent wave exists in the PC. The sign of imaginary impedance transforms from negative to positive, which is consistent with the results of Fig.(2). The imaginary part of refraction index is also split into two parts and the value becomes smaller in shorter wavelength regions. As depicted in the above three figures, it is easy to find that varieties of reflection phases and transmission phases within the band gap are closely related to the split of the gap.

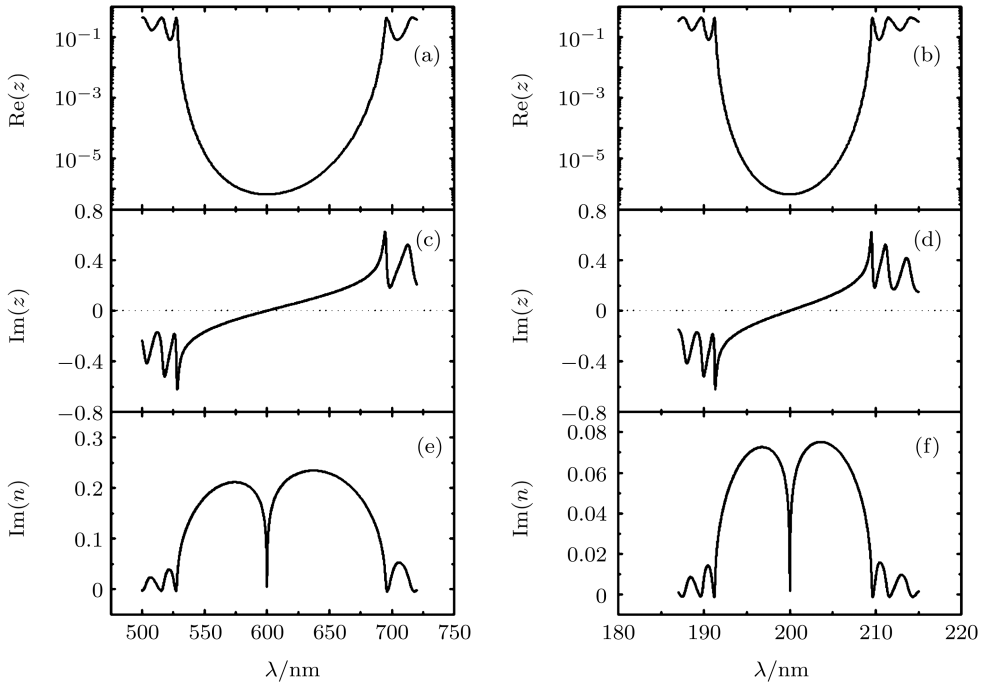


Fig.3. The effective parameters of the photonic crystal $(AB)_{20}$ within a band gap with the real parts of impedance in (a) and (b), the imaginary parts of impedance in (c) and (d), and the refraction indices in (e) and (f).

3. Properties of effective parameters

The effective parameters of PC are closely related to many factors and cannot be ascertained simply by using the basic cell of the periodic structures.[14] Firstly, we study the influence of periodic number. For example, the effective parameters of PC, discussed in Section 2, will be varied if we change the number of period. The real parts of effective permittivity and permeability for 10, 15 and 20 periods are plotted in Figs.4(a) and 4(b). The absolute values of negative permittivity or negative permeability in the gap increase with the increase of period and tend to be saturated when the number of periods is larger. This property offers us an adjustable way to obtain desirable values of the effective parameters.

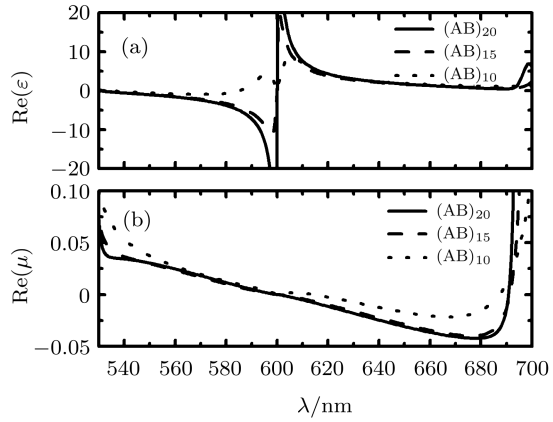


Fig.4. The real parts of effective permittivity in (a) and effective permeability in (b) for 10 (dotted line), 15 (dashed line) and 20 (solid line) periods.

In the above results, the PC $(AB)_{20}$ has been assumed that each layer in it has the same optical thicknesses, i.e. $n_A d_A = n_B d_B$. In the following, we will study the influence of the optical thickness. The optical thickness ratio between two layers A and B will change the scope of ENM and MNM. The variation of the split point with the optical thickness ratio between the two layers is plotted in Fig.5, where the ratio $(n_A d_A)/(n_B d_B)$ is changed by d_A, with other quantities kept unchanged. In Fig.5, δ_m represents the middle wavelength of the gap, δ_s is the split point between ENM and MNM regions, and the offset is defined as $\delta = \delta_m - \delta_s$. The results of Fig.5 indicate that with the increase of the ratio $(n_A d_A)/(n_B d_B)$, the offset δ decreases from positive to negative. So the split point moves from the left of δ_m to the right and the scope of MNM will become smaller (see Fig.2). So the scope of ENM or MNM within the gap can be easily controlled by the ratio of optical thickness.

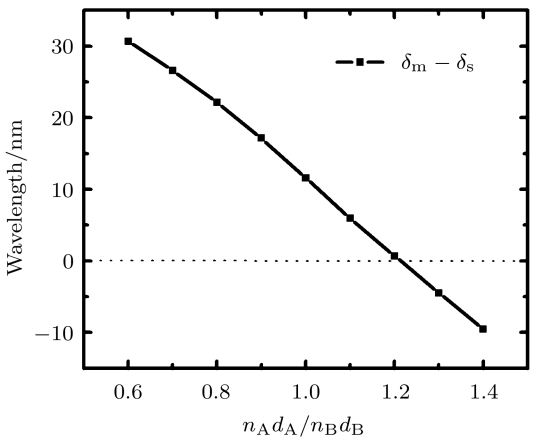


Fig.5. The shift of the split point versus the optical thickness ratio between materials A and B.

The PC $(AB)_{20}$ has an asymmetrical structure and the effective parameters depend strongly on the choice of the first surface. If the incident light comes from the opposite direction, namely from right to left, this circumstance will amount to considering the PC $(BA)_{20}$ with an incident light coming from left to right. The transmission coefficient and the reflection coefficient of PC $(BA)_{20}$ are very similar to those of PC $(AB)_{20}$ and all the values are the same except the reflection phase (not shown here). However, the ENM region appears in a long wavelength section while the MNM region occurs in a short wavelength section. And these characters are completely opposite to the case of PC $(AB)_{20}$. Furthermore, the imaginary parts of impedances are of resonance form much different from that of PC $(AB)_{20}$. Obviously the PC $(AB)_{20}$ and the PC $(BA)_{20}$ have the same basic materials in a reversed sequence. In addition, the two PCs have the same dispersion relations. Then there might appear a little confusion about which is a correct method to calculate the effective parameters when the PC interacts with another structure. Our study validates that the connective surface should be chosen as the first surface in calculating the effective parameters of the PC. For example, if a given structure is on the left side of the PC $(AB)_{20}$, we should choose $(AB)_{20}$ in calculating the effective parameters. If it is on the right of PC $(AB)_{20}$, the PC $(BA)_{20}$ should be a right structure in calculating the effective parameters. This interesting phenomenon is very important for the understanding of asymmetrical PC, and we will give concrete examples later.

Our studies of the effective parameters of PC $(AB)_{20}$ and PC $(BA)_{20}$ show that, if a PC is of an asymmetrical structure, the gap will always split into two parts: an ENM region and an MNM region. Another interesting example that will be discussed is the symmetrical structure: $(ABA)_{10}$. Here the layer A and layer B have the same parameters as those in PC $(AB)_{20}$. Figure 6 shows the reflection spectrum and the transmission spectrum of PC $(ABA)_{10}$. In order to eliminate the numerical errors for this special structure, we assume that the permittivity of layer A (or B) has a very small part of absorption: $\mathrm{Im}(\varepsilon_A) = 10^{-10}$. This small value will not have a noticeable influence on reflection and transmission coefficients and will not exert an appreciable effect on $\varepsilon_{\mathrm{eff}}$ and μ_{eff} of the PC. The effective permittivity and permeability are shown in Fig.7. One salient feature as compared with the asymmetrical structure is that the gap around 900 nm

has only an MNM region and the gap around 460nm has only an ENM region. Especially, the real parts of ε_{eff} and μ_{eff} are straight lines within the band gap. As shown in Figs.8(e) and 8(f), the imaginary parts of refraction indices are very different from those in Fig.3. It is worth pointing out that the study has shown that a one-dimensional PC composed of symmetrical basic units such as ABA can be well described by using an effective homogeneous slab.[21]

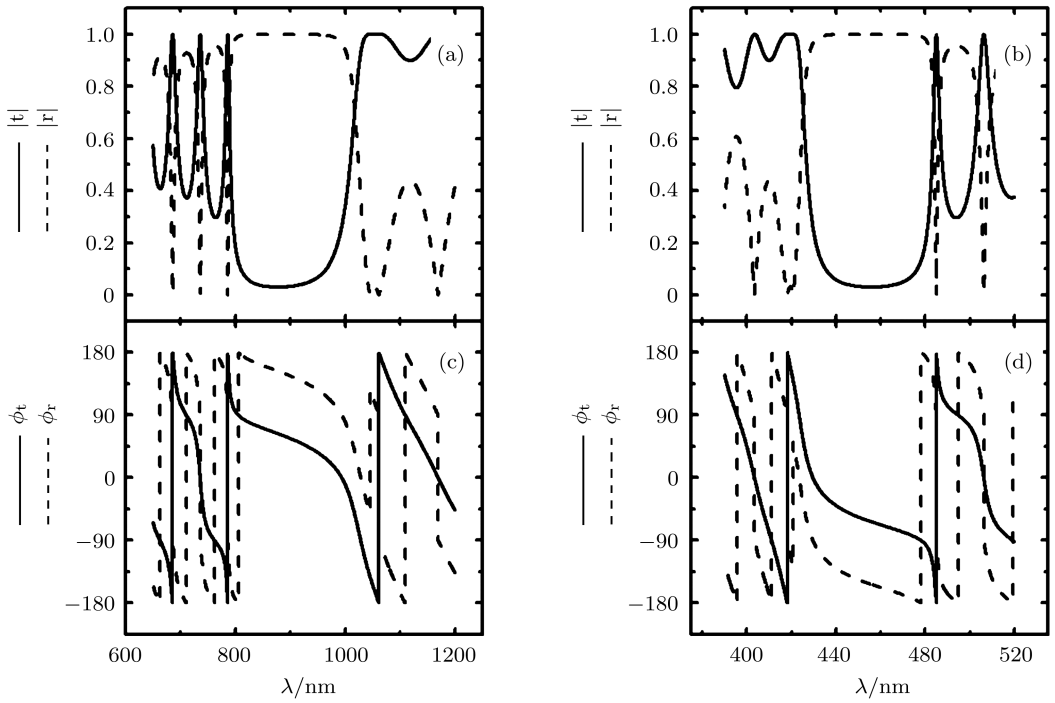


Fig.6. The transmission t (solid line), reflection r (dashed line), transmission phase ϕ_t (solid line) and reflection phase ϕ_r (dashed line) of the PC $(ABA)_{10}$ for the two band gap regions: around 900 and 460 nm.

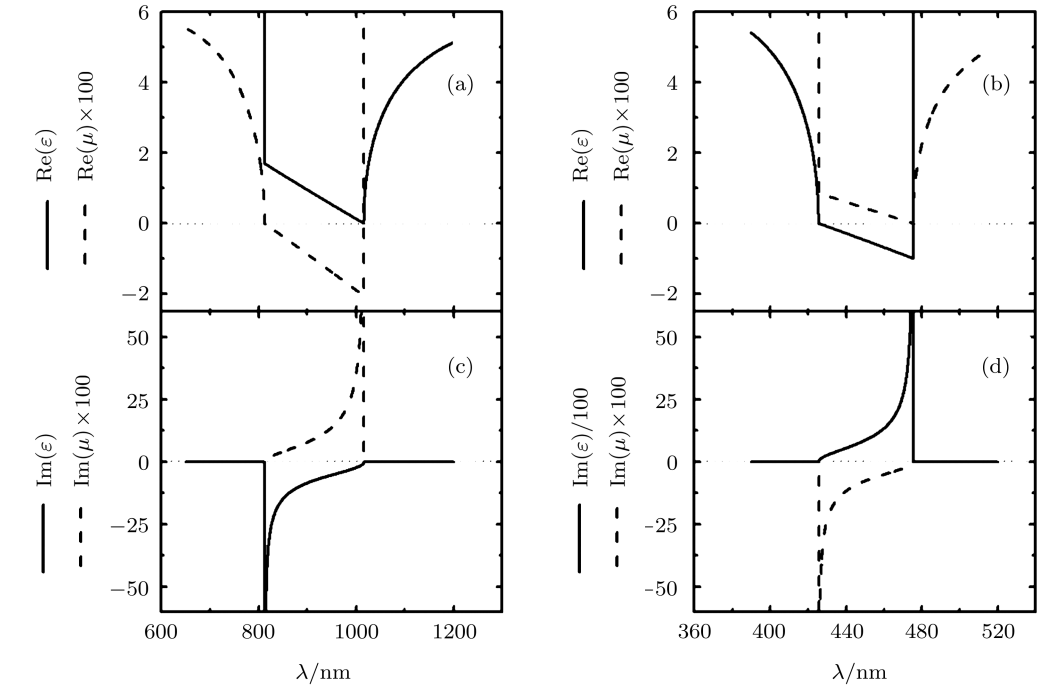


Fig.7. The effective parameters of the photonic crystal $(ABA)_{10}$ within a band gap, where panels (a) and (b) show the real parts of permittivity (solid line) and permeability (dashed line, magnified 10 times), and panels (c) and (d) indicate the imaginary parts of permittivity (solid line) and permeability (dashed line, magnified 10 times).

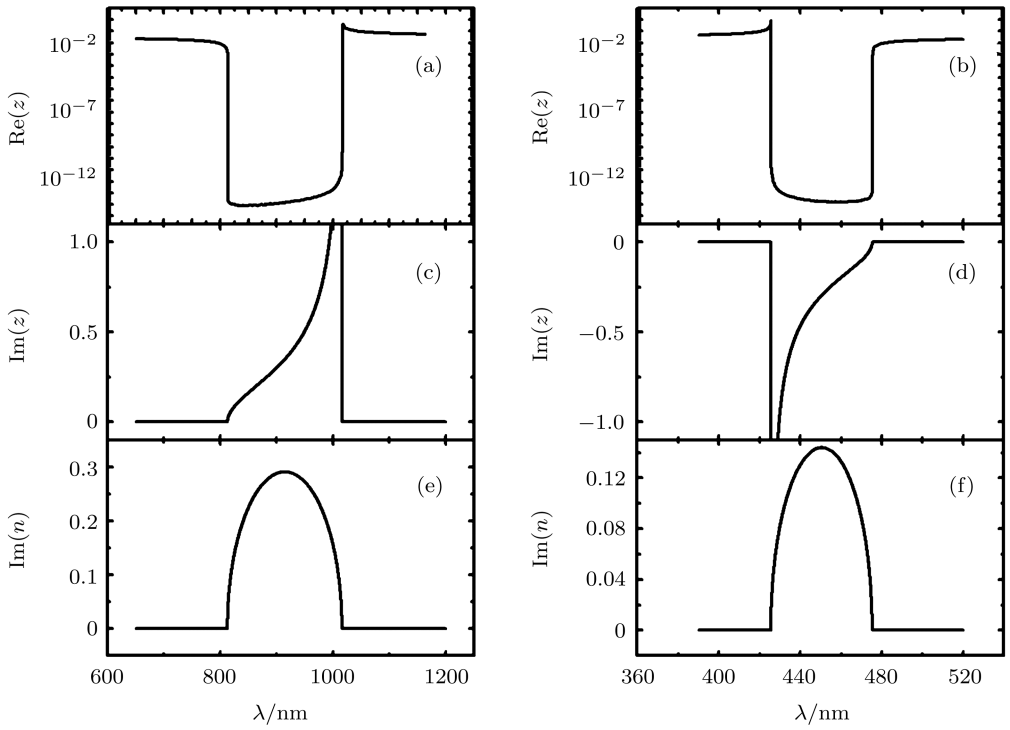


Fig.8. The effective parameters of the photonic crystal $(ABA)_{10}$ within a band gap with the real parts of impedance in (a) and (b), the imaginary parts of impedance in (c) and (d), and the refraction indices in (e) and (f).

4. The tunnelling modes determined by effective parameters

In this section we demonstrate that the effective parameters of PC can be used to give the exact conditions of the tunnelling modes when the PC band gap interacts with other SNMs. It is known that SNMs can support only evanescent waves and they are all opaque to incident light. However a carefully selected pair of ENM and MNM can form a fully transparent tunnelling mode. The condition is effective impedance match and effective phase match,[11] i.e.

$$\mathrm{Im}(z_{\mathrm{ENM}}) = -\mathrm{Im}(z_{\mathrm{MNM}}),$$

and

$$\mathrm{Im}(k_{\mathrm{ENM}})d_{\mathrm{ENM}} = \mathrm{Im}(k_{\mathrm{MNM}})d_{\mathrm{MNM}}.$$

In the meantime, the evanescent waves can be amplified and restored by the paired structure. So the PC in a gap region is expected to possess the same effect when it interacts with other SNM. Here we first consider the PC $(AB)_{20}$ and PC $(BA)_{20}$ interacting with an ideal ENM or MNM. For the ideal ENM and MNM we assume that they have Drude dispersion relations:

$$\varepsilon_{\mathrm{ENM}} = 1 - \frac{\omega_{\mathrm{E}}^2}{\omega^2}, \quad \text{and} \quad \mu_{\mathrm{ENM}} = 1;$$

$$\varepsilon_{\mathrm{MNM}} = 1, \quad \text{and} \quad \mu_{\mathrm{MNM}} = 1 - \frac{\omega_{\mathrm{M}}^2}{\omega^2},$$

where ω_{E} and ω_{M} are the plasma frequencies of ENM and MNM with thicknesses d_{E} and d_{M} respectively. For the PC $(AB)_{20}$ the gap splits into two sections. We consider the wavelength $\lambda = 650\,\mathrm{nm}$ and at this point the PC $(AB)_{20}$ is an effective MNM as shown in Fig.2. So an appropriately selected ENM may form a match pair with $(AB)_{20}$. The effective impedance and effective phase of PC can be calculated by using the retrieval method. The effective impedance match condition for the selected tunnelling mode at $\lambda = 650$ gives a plasma frequency (ω_{E_1} of $2.17350204\times10^{16}\,\mathrm{Hz}$. Then the thickness is given by the effective phase match condition as $d_{\mathrm{E}_1} = 770.047235\,\mathrm{nm}$. Consequently, a full transmission peak for the structure $\mathrm{E}_1(AB)_{20}$, where E_1 represents ENM, is expected to be within the PC band gap. As discussed in Section 3, the structure $(AB)_{20}\mathrm{E}_1$ will not form a full transmission at $\lambda = 650\,\mathrm{nm}$ as the PC also acts as an ENM for this kind of combination. The transmission coefficients are plotted in Fig.9(a) for each single structure and paired structure. A similar tunnelling mode can also be constructed by using the PC $(BA)_{20}$ at $\lambda = 650\,\mathrm{nm}$, where the PC $(BA)_{20}$ mimics an ENM, and then an ideal MNM is needed

to realize a tunnelling mode. It is easy to obtain $\omega_{M_2} = 1.615028 \times 10^{15}$ Hz and $d_{M_2} = 571.53945$ nm by using the same method. Then a sharp peak of tunnelling mode appears for the structure M_2 $(BA)_{20}$, where M_2 represents MNM, while there exists no such a peak for the structure $(BA)_{20}M_2$ as illustrated in Fig.9(b). The fields distributions for E_1 $(AB)_{20}$ and M_2 $(BA)_{20}$ are plotted in Figs.10 and 11. It is clear that the evanescent waves are amplified in the paired structure. The electromagnetic fields concentrate at the interface and form a kind of surface mode.

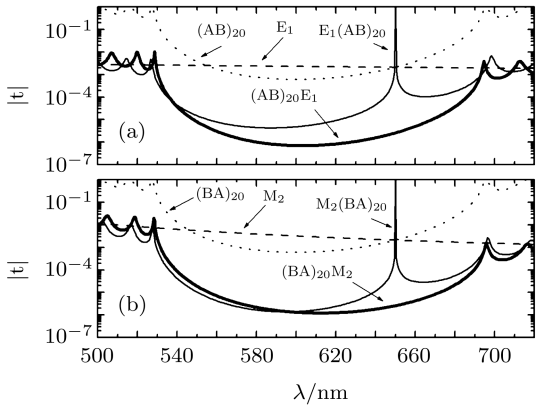


Fig.9. The transmission coefficients for several structures, showing the importance of the surface termination for (a) $(AB)_{20}$ (dotted line), E_1 (dashed line), E_1 $(AB)_{20}$ (solid thin line), and $(AB)_{20}E_1$ (solid thick line), and for (b) $(BA)_{20}$ (dotted line), M_2 (dashed line), M_2 $(BA)_{20}$ (solid thin line), and $(BA)_{20}M_2$ (solid thick line).

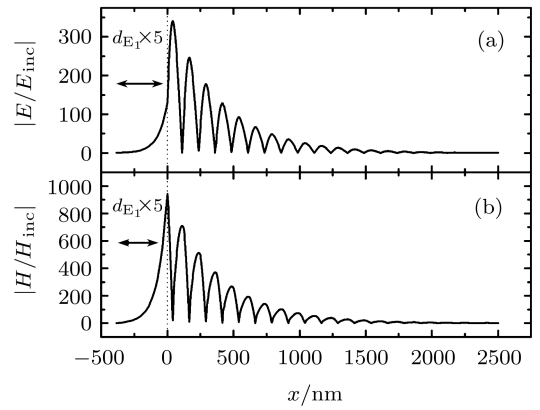


Fig.10. The field distributions of the structure E_1 $(AB)_{20}$, in which the thickness d_{E_1} is magnified five times in order to make the picture look more distinct.

A similar tunnelling mode can also be found in a paired structure composed of two PCs, namely, an MNM-like PC and an ENM-like PC. Here we use the PC $(ABA)_{10}$ to interact with the PC $(BAB)_{10}$. The PC $(ABA)_{10}$ acts as an MNM around 900 nm while the PC $(BAB)_{10}$ is an ENM in the same wavelength region. The tunnelling can be obtained if the match condition is satisfied. They are all of symmetrical structure, and the PC $(ABA)_n$ always has the same effective phase as the $(BAB)_n$. The effective match condition can be met generally within the gap. We find that at the point $\lambda = 921.662841$ nm the tunnelling conditions are matched. The transmission coefficients are plotted in Fig.12. The transmission peak appears in the region that is the common gap for both PCs. The field distributions are given in Fig.13.

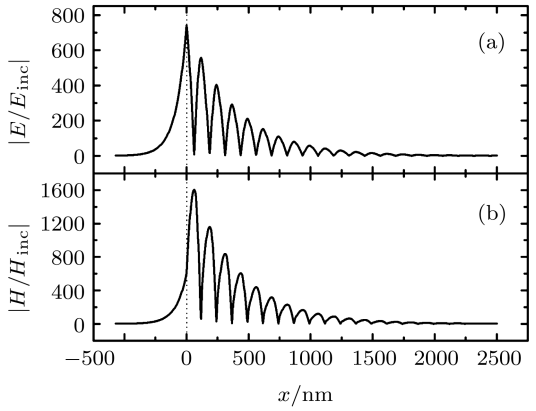


Fig.11. The field distributions of the structure M_2 $(BA)_{20}$.

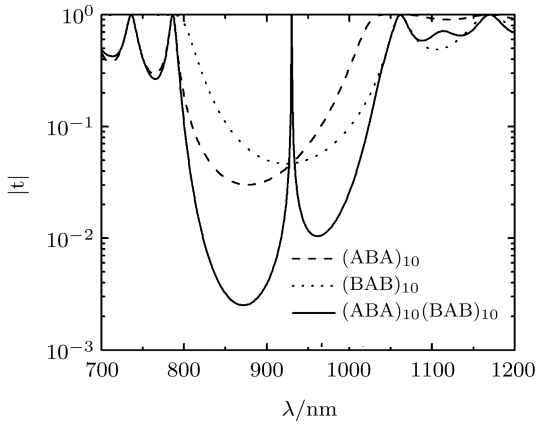


Fig.12. The transmission coefficients for the three structures: $(ABA)_{10}$ (dashed line), $(BAB)_{10}$ (dotted line) and $(ABA)_{10}$ $(BAB)_{10}$ (solid line).

The tunnelling mode is mainly located in the interface between the two components,[22] which is also called optical Tamm state.[23] In Refs.[22,23], the conditions for tunnelling modes are discussed mainly based on dispersion properties of infinite PC, though such modes are actually comprised of finite PCs. The present investigations reveal that the effective parameters of a finite PC are sensitively related to surface termination, length and symmetry.[14,15] So this kind of modes formed by finite PC could not be ascertained fully by using the periodic or dispersion properties

of the PC. The above three examples illustrate that the effective permittivity and permeability obtained by using our method do provide exact conditions for constructing tunnelling modes. This simple and effectual method may also be extended to the designing of optical Tamm mode applied to polariton laser.[24]

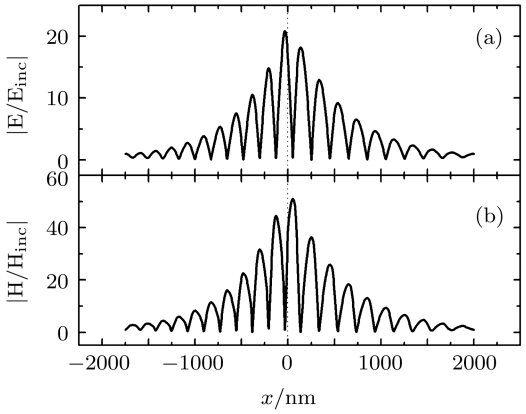


Fig.13. The field distributions of the structure $(ABA)_{10}$ $(BAB)_{10}$.

5. Conclusions

We have systematically studied the effective parameters of finite asymmetrical and symmetrical PCs. The results reveal that effective permittivity or permeability is negative within a PC band gap. Although all the layers are composed of dielectric materials, the effective permeability of the PC varies in a large scope and even reaches a negative value within the band gap. Furthermore, these effective parameters can offer exact conditions in designing and predicating tunnelling modes occurring in paired structures. In the meantime, the tunnelling mode can amplify evanescent waves in each individual structure. The amplification of evanescent wave in a visible light regime with a low loss will be helpful for the understanding of perfect lens imaging. In addition, the effective parameters are both closely related to the magnitude and phase of PC band gap, to which few papers have paid attention.

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