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High transmission with narrow bandwidth of metallic defect mode in 1-D dielectric photonic crystals

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Abstract Enhanced transmission peaks can be obtained in a dielectric photonic crystal with metal film defect. These peaks occur only in the band gaps, and their heights decrease sharply when they deviate from the band gaps. Theoretical analysis shows that, since the metal film defect mode possesses very high density of mode, high transmission of light in particular band can be achieved even by a metal "block" while high absorption of the light in other bands still exists. The physical mechanism of this phenomenon is essentially different from the resonant tunneling effect of layered metallic films. Since metal has high reflection and strong absorption of the light wave without being enhanced, so, basing on this mechanism, a narrow bandwidth filter with high transmission in UV range and suppression in while the visible, infrared, and even microwave range can be achieved.

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1 Introduction

Band gaps in photonic crystal (PC) [1, 2] attracted great interests in recent decades. The effect of impurity on the characteristics of band gaps has been widely studied. PCs containing metal became an important research topic because it possesses certain special properties. All the metal PC made by J.G. Fleming et al. [3] showed not only a wide band gap in 8–25 µm but also good transmission at 6 µm and strong absorption at the band edge. Zhenlin Wang et al. [4] investigated theoretically 3-D PCs implemented by self-assembling of metallic nanoparticles. It has complete band gaps in near infrared and visible ranges. Materials with negative refraction had also been implemented by metal-dielectric PC [5]. Zhiyuan Li et al. [6] have made experimental demonstration of non-near-field image formed by negative refraction. In metal-dielectric PC, the quasi-two dimensional planer structure has several special characteristics [7–10], which are generally considered to be induced by surface-plasma-polarization of the metal [11]. These studies on metal-dielectric PC made scientists to change their traditional knowledge about opacity, high reflection, and strong absorption of metal [12–15]. The studies reported in [12–15] were based on that metal is one of the elementary components of PC. The resonance tunneling of layered metallic films enhance the transmission of the pass band, and the existence of metal broadens the bandwidth in certain frequency ranges. In our present works, the band-gap property of a kind of 1-D dielectric PC was investigated in which a metallic aluminum film was inserted as the defect. It showed that this kind of PC is different from metal/dielectric PC made with a metal and a dielectric, it has both the band-gap properties of a dielectric PC and the high reflection and strong absorption of a metal. The investigation showed that a solid piece of metal rather than the layered metallic film may still possess good optical transmission. The mechanism of enhanced transmission of this kind of PC was also discussed basing on the band structure of the PC. It was postulated that, since a solid piece of metal has high reflection and strong absorption of light wave without enhancement, high transmission with narrow bandwidth can be achieved.

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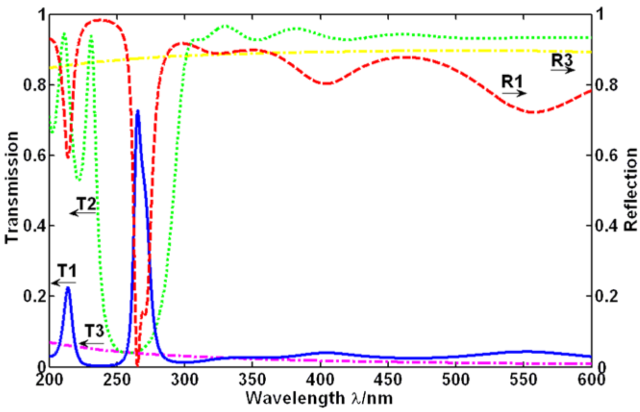


Fig. 1 The calculated spectra of single defect film $[\frac{Al_2O_3}{2}MgF_2\frac{Al_2O_3}{2}]^n[Al_2O_3^*|Al|Al_2O_3^*][\frac{Al_2O_3}{2}MgF_2\frac{Al_2O_3}{2}]^n$, the dielectric film $[\frac{Al_2O_3}{2}MgF_2\frac{Al_2O_3}{2}]^{2n}$, and single Al film. The *blue solid line* represents the transmission of the defect film, the *red dashed line* represents reflection of the defect film, the *green dotted line* presents the transmission of the dielectric film, the *magenta dashdotted line* represents the transmission of the single Al film, and the *yellow dashdotted line* represents the reflection of the single Al film. The values of the thickness of the films of Al_2O_3, MgF_2, $Al_2O_3^*$, Al, and the number of the period n are 36.1 nm, 47.3 nm, 82 nm, 23 nm, and 4 respectively

2 Structure and its spectral properties

A symmetric structure of

$$\left[\frac{Al_2O_3}{2}MgF_2\frac{Al_2O_3}{2}\right]^n[Al_2O_3^*|Al|Al_2O_3^*]\left[\frac{Al_2O_3}{2}MgF_2\frac{Al_2O_3}{2}\right]^n$$

was employed in this work. Five parameters can be changed in this structure: namely, thickness of Al_2O_3, thickness of MgF_2, thickness of $Al_2O_3^*$ at the location of defect, thickness of Al film, and the number n of the periods. In the following example, their values were chosen as: 36.1 nm, 47.3 nm, 82 nm, 23 nm, and $n = 4$ respectively, and the optical constants of Al_2O_3, MgF_2, and Al were quoted from [16, 17], and [18]. The transmission spectrum of this structure was calculated using transfer matrix method and shown in Fig. 1, in which the blue solid line and the red dashed line represent the transmission and the reflectivity of the single defect mode, respectively. It can be seen that comparing with the transmission of the 23 nm thick Al film (the magenta dashdotted line in Fig. 1), there is an enhanced transmission peak higher than 70% near 265 nm, which is about 19 times that of the transmission of an Al film. This peak is just in the band gap of the $[\frac{Al_2O_3}{2}MgF_2\frac{Al_2O_3}{2}]$ dielectric PC (see the green dotted line in Fig. 1). There is a small transmission peak around 214 nm, which will be mentioned later. For other wavelengths (from UV to visible range), the transmissions are suppressed to less than 5% due to high reflection and strong absorption of the 23 nm thick Al film. Since the first band gap of this PC is located at around 265 nm, all of the visible, infrared, far infrared, and microwave bands are within conduction band, therefore, the transmission is mainly dependent on the reflection and absorption of the Al film. Figure 2 shows the transmission (the green solid line) and the reflectivity (the red dashed line) of a single 23 nm thick Al film. It can be seen that for all the infrared, far infrared, and microwave bands, the transmissions are less than 5% and almost close to zero for far infrared and microwave bands.

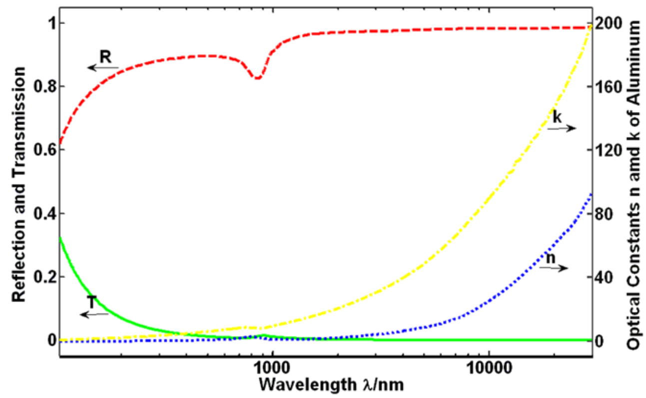


Fig. 2 Transmission and reflection of a 23 nm thick Al film in the range 0.2–30 μm

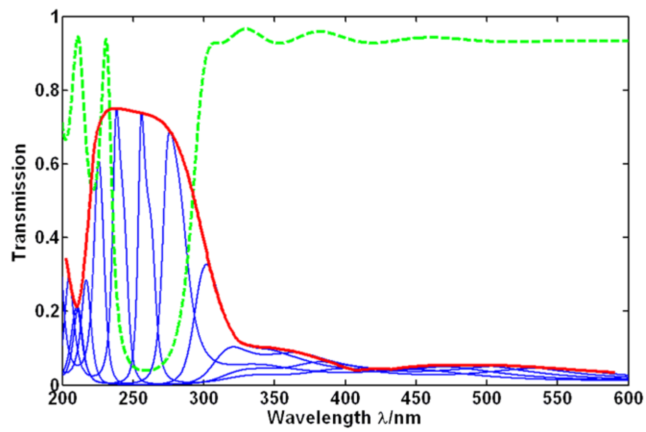


Fig. 3 Relationship between transmission peaks (*blue line*) of $[\frac{Al_2O_3}{2}MgF_2\frac{Al_2O_3}{2}]^n[Al_2O_3^*|Al|Al_2O_3^*][\frac{Al_2O_3}{2}MgF_2\frac{Al_2O_3}{2}]^n$ structure and band gap (*green dashed line*) of $[\frac{Al_2O_3}{2}MgF_2\frac{Al_2O_3}{2}]^{2n}$ dielectric PC. Transmission peak exists only in the band gap, and it reduces acutely with deviation from the band gap. The *red solid line* is the envelope line of the transmission peaks

3 Discussions

The position of the transmission peak can be controlled by changing the thickness of the $Al_2O_3^*$ film. Figure 3 shows the relationship between the transmission peak and the band gap. It can be found that, in the structure of the above example, the transmission peak appears only in the band gap of the $[\frac{Al_2O_3}{2} MgF_2 \frac{Al_2O_3}{2}]^{2n}$ dielectric PC and decreases rapidly when it deviates from the band gap (see the blue solid line in Fig. 3). The envelope of the transmission peaks is coincident with that of the band gap (the red solid line in Fig. 3), and there is only a little difference at the short wavelength side of the band gap where the envelope is a little wider than that of the band gap. The reason is that, for the film system $[\frac{H}{2} L \frac{H}{2}]^n$ (H and L represent the mediums with high or low refractive indexes respectively), pass-band corrugation exists at the short wave pass-band of the first band gap. Therefore, the short wave pass-band is not an ideal pass-band. Because of the existence of this pass-band corrugation, the transmission will oscillate acutely in the short wave pass-band, especially at its edge. This oscillation will result in a phenomenon similar to the resonant transmission in a band gap. Besides, the transmission of the Al film will also increase when the wavelength becomes shorter (see Fig. 2). The combined influence of the above two factors makes the envelope to move towards the short wave side of the band.

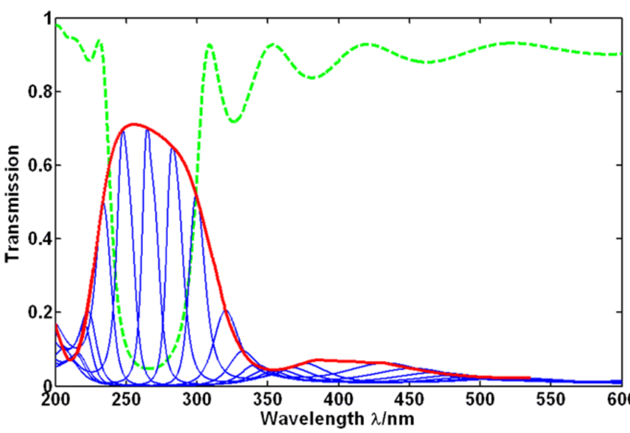


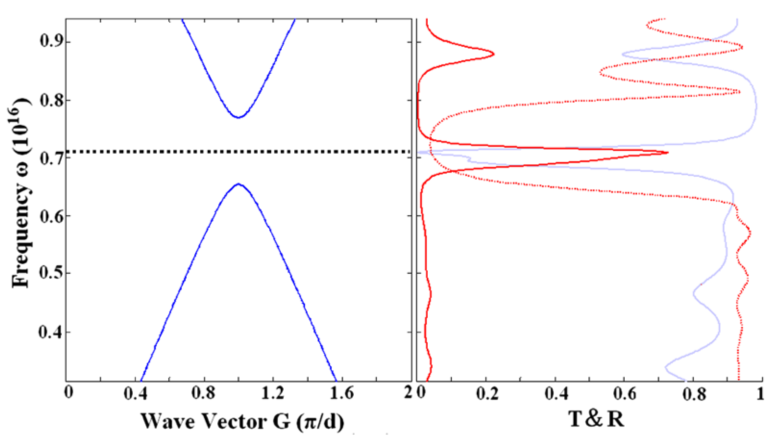
Fig. 4 Relationship between transmission peaks (*blue solid line*) of $[\frac{MgF_2}{2} Al_2O_3 \frac{MgF_2}{2}]^n [MgF_2{}^*|Al|MgF_2{}^*][\frac{MgF_2}{2} Al_2O_3 \frac{MgF_2}{2}]^n$ structure and band gap (*green dashed line*) of dielectric PC $[\frac{MgF_2}{2} Al_2O_3 \frac{MgF_2}{2}]^{2n}$. Transmission peaks exist only in the band gap and reduce acutely with deviation from the band gap. The *red solid line* represents the envelope line of the peaks. It superimposes with band gap

When the $[\frac{H}{2} L \frac{H}{2}]^n$ film changes to the $[\frac{L}{2} H \frac{L}{2}]^n$ film, the pass-band corrugation appears at the long wave pass-band of the first band gap, while the short wave pass-band becomes an ideal pass band. In this case, the pass-band corrugation will induce a "red shift" of the envelope, while the transmission property of the Al film will induce a "blue shift." These two influences act antagonistically, therefore, the envelope line of the transmission peaks and the band gap in this dielectric PC superimposed almost perfectly (see Fig. 4).

The close relationship between the transmission peaks and the gaps of the dielectric PC demonstrates that transmission peaks are elicited by band gaps. The introduction of $[Al_2O_3^*|Al|Al_2O_3^*]$ into dielectric PC as a defect brings up the defect mode of the dielectric PC. Figure 5 depicts the band structure of the PC shown in Fig. 1. The dotted line is the defect mode in the band gap. As is known, the flat defect band corresponds to a high density of defect mode. Comparing left part with right part of Fig. 5, it can be seen that it is just the high density of mode that makes the defect mode to acquire enhancement of resonant transmission and resonant absorption simultaneously with nearly zero reflection.

The normalized field distribution of the defect mode at 265 nm in a PC is shown in Fig. 6 calculated by the Finite-Difference Time-Domain (FDTD) method. It shows that, due to the existence of defect, the optical field concentrates at the defect and makes the intensity at the defect to be 2.38 times that of the incident light. The highest ratio between field intensities at the two sides of the metal film is 0.77. Figure 7 shows the effect of number of period on spectral properties. It shows that the width at half amplitude of the transmission peak decreases gradually with increase of the number n of periods, while the peak increases and then decreases after an optimal number of periods. This is because with the increase of n the defect mode is more concentrated at the location of the prior defect mode and makes the density of the mode higher and enhancement of transmission

Fig. 5 Band gap and defect mode and its corresponding spectral properties



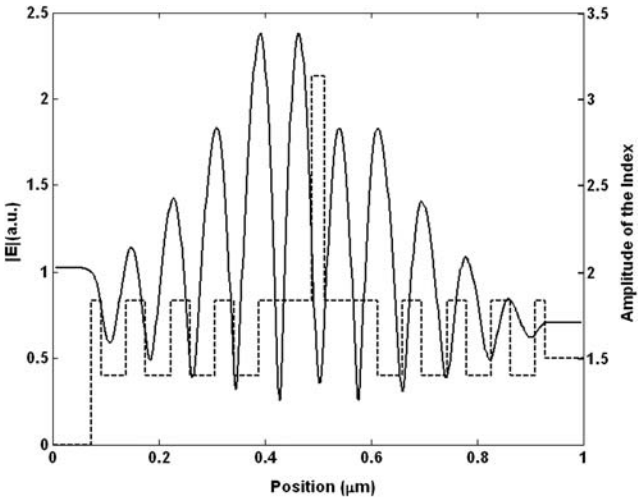


Fig. 6 Normalized Optical field distribution of defect mode at 265 nm in a PC

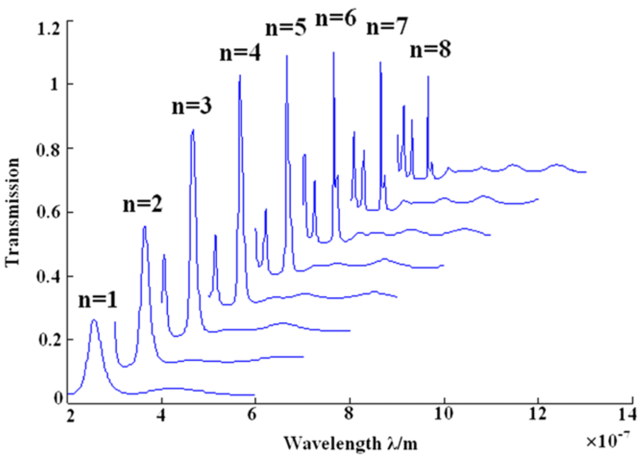


Fig. 7 Effect of number of period on transmission $(10^{-7}, 0.1)$

more vigorous. But, due to the metal enhanced absorption of the corresponding light energy, the combined effect makes the transmission to increase first and then decrease.

4 Summary

The present work investigated the spectral properties of 1-D dielectric PC with metal defect and found that an enhanced transmission peak higher than 70% appears in this band gap of the dielectric PC. This peak appears only in the band gap. It reduces acutely when deviating from the gap. Due to strong reflection and high absorption by the metal, the transmissivity of the conduction band of the PC is strongly suppressed to less than 5%. Through comparative analysis between the spectral properties and band structure of this PC, another physical mechanism of metal film—defect mode enhanced transmission is found. It is different from the layered metal film resonant tunneling enhanced transmission reported by other authors (see [12–15]). The metal film we used was not "layered" but was just a single thick layer of Al which can be considered as a solid metal "block." The high transmission expressed by the metal "block" is totally due to the high density possessed by the defect mode in the dielectric PC. The absorption at the defect mode is enhanced to certain extent. Since a metal "block" has high reflection and strong absorption of non-enhanced light, it can achieve a narrow band width filter which has high transmission in the band gap in ultra-violet range and strong suppression of an ultra wide range covering the visible, infrared, far-infrared, and microwave range of light. This kind of PC can be used in suppressing the spontaneous radiation in visible and infrared bands, and enhancing the efficiency of ultra-violet emission.

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