Properties of PC filters in one-dimensional photonic crystals containing defects

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The properties of photonic crystal (PC) filters in one-dimensional photonic crystal (1D PC) containing a defect layer are studied theoretically using the transfer matrix method. The effect of thickness of defect layers is studied. It is shown that one defect mode and two defect modes appear inside the forbidden band gaps in its reflection spectra. By changing the thickness of the defect layer, the number and frequency of the defect modes can be tuned. Therefore, introducing a defect layer in 1D PCs provides possible method for various color filters. This may be useful in the design of bule-green color filters. Additionally, the method also showed that 20 nm is allowed for Ta_2O_5 and MgF_2 interfacial roughness in our system.

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1. Introduction

Photonic crystals (PCs) with single defect are interesting because of their potential application in the fabrication of lasers, light-emitting diodes, and filters [1-3]. Recently, the structure with coupled defects has attracted much more attention. Normally, a defective PC is constructed by introducing a disorder into the regular structure of the PC. With the introduction of a layer different in nature (materials and size) into a PC structure, it is possible to create highly localized defect modes within the PBG [4-6]. Such defect modes are localized at the position of the defect. The control of defect modes is of major interest for their application in narrow band filters [7,8]. However, the design of controllable defect modes in PCs requires predictive formulae for dependence of the defect mode frequencies on physical parameters of PCs and on the angle of incident light. But some technical challenges still remain, and one such challenge is the design of the controllable defect mode in the band gap structure with a periodicity equivalent to the visible wavelength. Recently, tremendous progress has been made in the development of green and red color filters [9-11], and blue, blue-green filters are still very scarce.

Because, the multiple interfaces have an important role on this behaviour, influencing the optical properties of the system. Understanding the origin of these effects requires knowledge of the interface structure, where the interfacial roughness is of prime importance. However, to the authors' knowledge the optical properties that determines the shape of the reflection spectrum inside the PBGs for a light with wavevector parallel to the plane of periodicity in one-dimensional PCs has not been investigated in detail. The interfacial roughness of multilayer thin films in the visible range must be considered because the size of the studied films is so thin (only some nanometers) that the interfacial roughness effect may not be seen anymore, which is significant to fabricate the PCs in the application. In this work, the defect modes and interfacial roughness of the 1D PC structure composed of the Ta_2O_5 and MgF_2 multilayer with a defect layer is analyzed theoretically. The theoretical analysis is based on transfer matrix method (TMM). This method allows us to investigate analytically the defect mode number, defect mode frequency and the influence of interfacial roughness to the PBG.

2. Model and computational method

The fabrication of Ta_2O_5/MgF_2 films based on 1D PC structures is considered. The geometry of the structure is shown in Fig. 1. The structure consists of the $(AB)_N$ array, where A is the Ta_2O_5 films, B is the MgF_2 films, N is the repeated periods of (AB), d_1 and d_2 are the layer thicknesses, and $d = d_1 + d_2$ is the periodic thickness. The propagation of electromagnetic waves along the z-axis normal to the interface in a 1D system is considered, in which the 1D system is composed of periodic arrays of two different materials with varying refractive indices according to different incident wavelengths at room temperature [12-14]. The PBG and defect mode appeared and varied with changes in d_1, d_2, the width of the central Ta_2O_5 layer d_3.

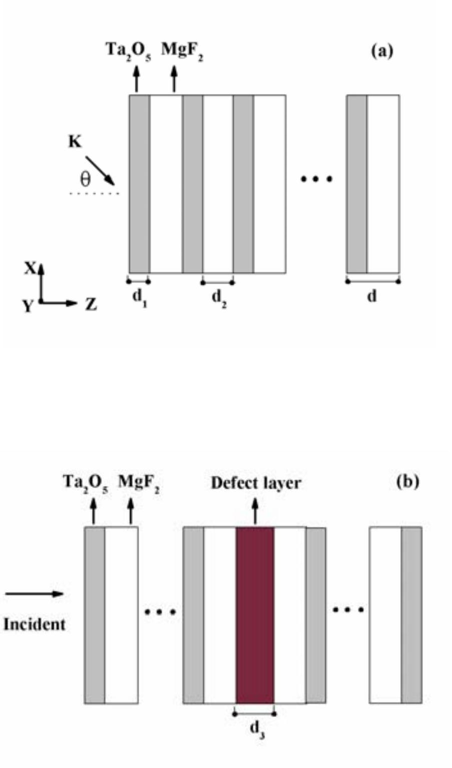

Fig. 1. Schematic diagrams of 1D PC Ta_2O_5 and MgF_2 alternate films, (a) without defect layer, (b) with defect layer

The transverse electric (TE) or simply transverse magnetic (TM) waves is defined as those which have its H (or E) field confined to the *x*-*y* plane, and the corresponding E (H) field is parallel to the *y*-axis. The propagation characteristics of an electromagnetic wave inside Ta_2O_5/MgF_2 layers, such as the PBGs and the defect mode within the PBG, were calculated using the TMM [15-16]. As shown in Ref. 16, the information of the PBGs of a PC can be extracted from the reflection or transmission spectrum for a finite thickness PC embedded in an air background (with the refractive index of 1) by means of the standard TMM. Additionally, the information of the band gap mode allows us to consider the localized defect modes supported by the structure defect shown in Fig. 1(b). In this study, our calculations assumed that the Ta_2O_5/MgF_2 films have a finite thickness in the *z*-direction and is infinite in both the *x*-direction and *y*-direction.

3. Results and discussion

In this section, the numerical analysis of the proposed PC structures is presented. The spectra of reflection for $(AB)_N$ and the $(AB)_N$ X $(AB)_N$ (*N* is the repeated periods of (AB)) structure were calculated. To demonstrate the effects of band gaps, the reflection spectra for different layers of Ta_2O_5/MgF_2 were computed for normal incidence initially. High reflection regions can be observed as shown in Fig.2. The results of the computations show distinctly that the gap tends to be wider with the increasing number of layers and when the number of layers is greater than sixteen ($N \geqq 16$), a well-defined PBG has been formed. Our findings also show that the PBG location has an obvious trend to move to the longer wavelength and also, the gap becomes broader with the increasing periodic thickness d ($d = d_1 + d_2$). Additionally, varying the thickness ratio d_1/d (d_1 is the thickness of Ta_2O_5) shows that the bandwidth has a maximum value and that the PBG moves towards the longer wavelength. The forbidden band gap appears in the visible region from 439 to 559 nm when the periodic thickness d = 146 nm and the filled ratio d_1/d = 0.42 (Fig. 2). The TM mode reflection spectra for Ta_2O_5/MgF_2 were also computed and our findings show that both spectra are the same. Therefore, the TE and TM cannot be divided at the normal incidence.

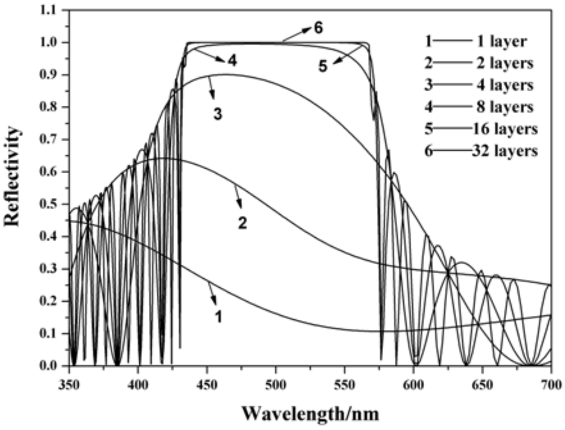

Fig. 2. The reflection spectra at the different period layers with d = 146 nm, d_1/d = 0.42.

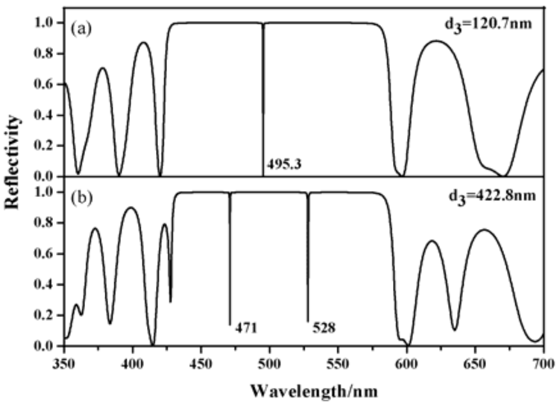

Fig. 3. The reflection spectra for different thickness defective of 1D PC for repeated period N = 16.

We perform some numerical calculations on the reflection properties of the one dimensional photonic crystal for different thickness of defect layer. The introduction of the optical thickness definition, which is the product of the refractive index and layer thickness, is necessary to explain the rule of the appearance of defect mode. Our computations indicate that one defect mode will appear when the optical thickness of the defect layer n_3d_3 satisfies $n_3d_3 = n_1d_1 + n_2d_2$, and two defect modes will appear when $n_3d_3 = 4\ (n_1d_1 + n_2d_2)$. The upper part of Fig. 3(a) shows one defect mode appearing in 495.3 nm, the critical site of the blue and green light, in which the transmittance reaches to 99% when the thickness of the central Ta_2O_5 defect layer is 120.7 nm. Moreover, the thickness of the central Ta_2O_5 defect layer in the blue-green light region was increased to 422.8 nm, and two defect modes appear as shown in the lower part of Fig. 3(b), in which the transmittances of both modes are more than 83%. In our calculations, the thickness of the defect layer around 120.7 nm or 422.8 nm was also changed, for instance, the defect modes move linearly as shown in Fig. 4. Thus, the defect mode moves towards the longer wavelength with the increasing thickness of the defect layer.

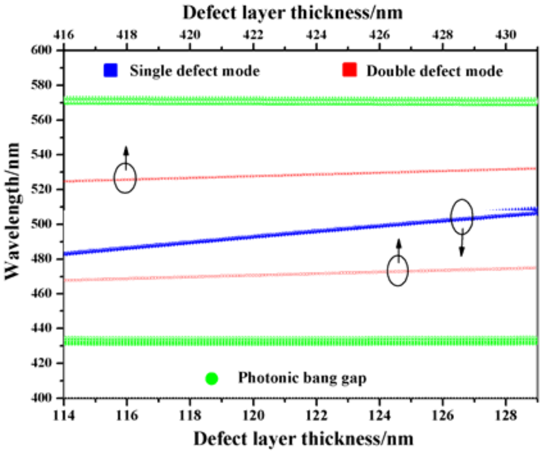

Fig. 4. Dependence of wavelength peaks on the thickness of the defect layer in blue-green light region

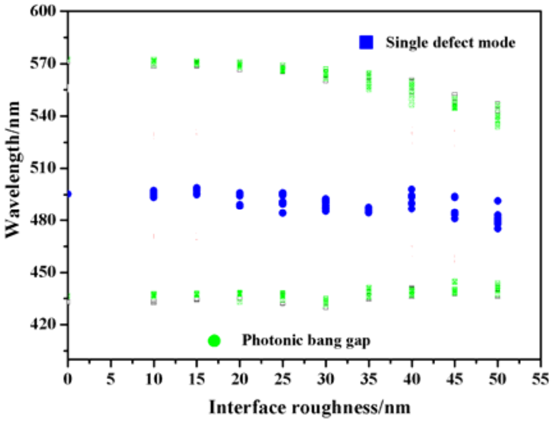

Fig. 5. Influence of interfacial roughness between Ta_2O_5 and MgF_2 on PBG and defect modes

Finally, the dependency of the band gap properties on the interfacial roughness (D) between Ta_2O_5 and MgF_2 is investigated. The following conditions are considered: the roughness in each Ta_2O_5/MgF_2 interface exists, each width of the interfacial roughness are random (in computation, the width varied from $0 \leqq D \leqq 50$ nm, the thickness of Ta_2O_5 in our system is about 61 nm), and the refractive index of the interfacial region is a random variable between 1.38 to 2.10. The thickness of each interfacial roughness field was also changed at random from 0 to D, and the value of D is 0, 10, 15, 20, 25, 30, 35, 40, 45, and 50 nm in our designed system. Results show that the width of the band gap becomes narrow gradually towards the general trend with the value of D varying from 0 nm to 50 nm independently. Its influence can be neglected when the thickness of interfacial roughness is below 25 nm. As shown in Fig. 5, the position of defect modes fluctuates around the position of defect modes with smooth interface, in which D is varying from 0 – 50 nm, and its effect cannot be considered when the value of D was thinner than 20 nm. Thus, a certain interface roughness is allowed in PCs (20 nm are allowed as shown in this paper), which can be used to fabricate PCs in practical applications.

4. Conclusion

In summary, 1D PC structures consisting of alternate layers of Ta_2O_5 and MgF_2 films with a defect layer using TMM in visible region were studied theoretically. The influence of the interfacial roughness between Ta_2O_5 and MgF_2 was also discussed. The number and frequencies of the defect modes can be controlled in the visible range by adjusting the thickness of the defect layers. Additionally, the method also showed that 20 nm is allowed for Ta_2O_5/MgF_2 interfacial roughness in our system. Ta_2O_5 and MgF_2 PC structure was also observed for its potential use as good candidates for the high transmission blue-green color filter for normal incidence. These results may pave the way for studying bule-green color filters. In addition, the study of interfacial roughness will be useful for a deeper understanding of the properties of PCs.

Acknowledgments

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