Bandgap Extension of Disordered 1D Ternary Photonic Crystals*

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Abstract Bandgap properties of disordered one-dimensional (1D) ternary photonic crystals are investigated by optical transfer matrix method for the first time . The results show that disordered structure provides strikingly extended bandgap compared with the corresponding periodic structure. The more ingredient of disordered dielectric multilayers adopted in the calculation, the wider stop band will be obtained. The influence of degree of disorder D and contrast of high and low refractive indices to the photonic bandgap are also calculated and discussed.

Keywords Photonic crystal; Degree of disorder; Bandgap extension

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0 Introduction

Since the concepts of photonic crystal and light localization suggested by Yablonovitch and John[1,2], a lot of efforts have been devoted to designing materials so that they can affect the properties of photons. In particular, photonic crystals forbid propagation of photons in a certain range of energies known as photonic band gap, and spontaneous emission of atoms and molecules will be inhibited in such a crystal[3]. Due to promising application prospective as photonic devices[4~12], such as time delay, high-quality filter and nonlinear optical diodes, and easiness of fabrication to meet current technology needs, one-dimensional (1D) photonic band gap materials (PBGs) are attracting more and more interests.

Wide bandgap is one goal to be pursued in the study of photonic crystal[13~15]. According to theoretical[16] and experimental[17] studies of light localization in 1D systems, disorder introduced into periodic layered systems can lead to enhanced coherent light backscattering in any frequency range and light can be localized. Therefore, one may expect that the combining effect of Bragg reflection and light localization induced by disorder will possibly extend these narrow stop bands into a continuous extended stop band when disorder is introduced into 1D polybasic periodic photonic crystals. It has been reported that disordered binary $\lambda_0/4$ stack reflectors can possess a wider high reflection range (HRR) compared to standard binary $\lambda_0/4$ stack reflectors[3,18,19]. In this paper, taking 1D ternary photonic crystals for example, the bandgap extension of disordered 1D polybasic photonic crystals is investigated through optical transfer matrix method for the first time to our knowledge. The results show that disordered structure provides strikingly extended bandgap compared with the corresponding periodic structure. The more ingredient of disordered dielectric multilayers adopted in the calculation, the wider stop band will be obtained. The influence of degree of disorder D and contrast of high and low refractive indices to the photonic bandgap are also calculated and discussed.

1 Theoretical model

The model consists of alternative layers of three materials with refractive indices n_1, n_2 and n_3 . Fig . 1 shows the schematic structure of 1 D

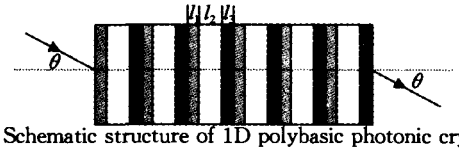

Fig. 1 Schematic structure of 1D polybasic photonic crystals consist of alternative layers of three kind of materials

polybasic photonic crystals consist of alternative layers of three kind of materials. By introducing structural parameter a and b, 1D ternary periodic photonic crystal with m periods and center wavelength λ_0 can be defined as

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$$l_1=(1+a/2+b/2)\lambda_0/4n_1 \quad (1a)$$

$$l_2=(1-a)\lambda_0/8n_2 \quad (1b)$$

$$l_3=(1-b)\lambda_0/8n_3 \quad (1c)$$

where l_1, l_2 and l_3 are thickness of high, middle and low refractive ingredient layers in each unit cell, the optical length of each unit cell is kept as $\lambda_0/2$. a and b ranges from -1.0 to 1.0. Different periodic structures can be achieved by changing a and b.

1D disordered ternary photonic crystals can be obtained by introducing disorder into 1D periodical ternary photonic crystals. For example, changing the thickness of ingredient layers randomly while keeping the average optical length of each ingredient layer in unit cell unchanged as $\bar{l}_1$, $\bar{l}_2$ and $\bar{l}_3$. The degree of disorder D can be defined by the optical length deviation from $\bar{l}_1$, $\bar{l}_2$ and $\bar{l}_3$[3]

$$D=\{\sum_{i=1}^{m}\{n_1^2[l_1(i)-\bar{l}_1]^2+n_2^2[l_2(i)-\bar{l}_2]^2+n_3^2[l_3(i)-\bar{l}_3)]^2\}\}^{1/2}/[(n_1\bar{l}_1+n_2\bar{l}_2+n_3\bar{l}_3)m] \quad (2)$$

where $l_1(i)$, $l_2(i)$ and $l_3(i)$ are thickness of the high, middle and low refractive ingredient layers, respectively, the average of $l_1(i)$, $l_2(i)$ and $l_3(i)$ are $\bar{l}_1$, $\bar{l}_2$ and $\bar{l}_3$, respectively. i varies from 1 to m. m is the total number of periods. D, a, b, λ_0, n_1, n_2, n_3, and m are the characteristic parameters of 1D ternary disordered photonic crystals, 1D ternary periodic photonic crystals is a special case of 1D ternary disordered photonic crystals, i. e., $D=0.0$.

Known from theory of optical transfer matrix, characteristic matrix of each single dielectric layer can be written specifically as

$$M(z)=\begin{bmatrix}\cos(k_0 nz\cos\theta) & -\frac{\mathrm{i}}{p}\sin(k_0 nz\cos\theta)\\ -\mathrm{i}p\sin(k_0 nz\cos\theta) & \cos(k_0 nz\cos\theta)\end{bmatrix} \quad (3)$$

where $p=\sqrt{\varepsilon/\mu}\cos\theta$. Thus the characteristic matrix of the total photonic crystal can be written as

$$M(z_N)=M_1(z_1)M_2(z_2-z_1)\cdots\cdots$$

$$M_N(z_N-z_{N-1})=\begin{bmatrix}m_{11} & m_{12}\\ m_{21} & m_{22}\end{bmatrix} \quad (4)$$

The reflective coefficient r and transmissive coefficient t can then be written as

$$r=\frac{m_{11}p_1+m_{12}p_lp_1-m_{21}-m_{22}p_l}{m_{11}p_1+m_{12}p_lp_1+m_{21}+m_{22}p_l} \quad (5)$$

and

$$t=\frac{2p_1}{(m_{11}+m_{12}p_l)p_1+(m_{21}+m_{22}p_l)} \quad (6)$$

where $p_1=\sqrt{\varepsilon_1/\mu_1}\cos\theta_1$, $p_l=\sqrt{\varepsilon_l/\mu_l}\cos\theta_l$. Hence the reflectivity R and the transmissivity T will be

$$R=|r|^2$$

$$T=(p_l/p_1)|t|^2 \quad (7)$$

In this paper, the optical spectra are calculated by transfer matrix method. The refractive indices n_1, n_2 and n_3 are chosen to be 3.30, 2.0 and 1.38, which correspond to that of GaP, ZrO_2 and MgF_2 which are transparent and are not dissipative from visible to infrared. The refractive indices of the three kind of materials vary little in the optical wave band of 400～2000 nm, so they can be seen as constants.

2 Results and discussions

The center wavelength λ_0 is 976 nm, and the number of periods m is 24, Taking TE wave as example in the calculating process, when the structure parameter a, b varies, it is found that the width of the bandgap varies obviously. Fixing $D=0$ and $\lambda_0=976$ nm, we adjust the structural parameter a, b to investigate the impact of structural change to the optical properties of 1D ternary periodic photonic crystals. By calculating again and again, we find that the maximum width of the bandgap is abtained at $a=0.9$, $b=-0.9$ which is shown in Fig. 2(a). Then we investigate the bandgap properties of disordered one-dimensional (1D) ternary photonic crystals at the premise that the structural parameters are $a=0.9$, $b=-0.9$, i. e., $l_1=73.94$ nm, $l_2=6.1$ nm, $l_3=167.97$ nm, respectively.

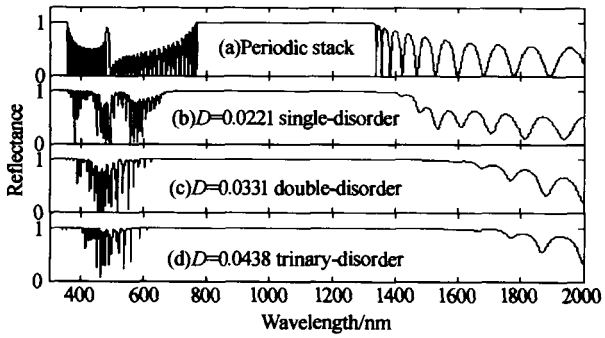

Fig. 2　Calculated reflection spectra for GaP-ZrO_2-MgF_2 photonic crystals with $\lambda_0=976$ nm and $m=24$

Fig. 2. shows the calculated reflection spectra for GaP-ZrO_2-MgF_2 photonic crystals with the same $\lambda_0=976$ nm, $m=24$, $a=0.9$, $b=-0.9$, but different ingredient numbers of disorderd layer. For comparison, the reflectance from a periodic photonic crystal is shown in Fig. 2(a), which has a HRR less than 570 nm. The curve in Fig. 2(b) is

from a single - disorder photonic crystal with $D = 0.0221$, where only $l_1(i)$ (the GaP layers) are varied which is randomly chosen from a Gaussion distribution around $\bar{l}_1$, while all $l_2(i)$ are equal to $\bar{l}_2$ and all $l_3(i)$ are equal to $\bar{l}_3$. The HRR is obviously extended in both the shorter and longer wavelength directions and is about 730 nm wide. Fig. 2 (c) gives the reflection spectrum for a double-disorder photonic crystal with $D=0.0331$, where both $l_1(i)$ and $l_2(i)$ are changed, randomly chosen from Gaussion distributions around $\bar{l}_1$ and $\bar{l}_2$, respectively, while l_3 (i) are equal to $\bar{l}_3 = 167.97$ nm. The HRR is extended to 1070 nm wide. The curve in Fig. 2(d) is from a trinary disordered photonic crystal with $D = 0.0438$, where $l_1(i)$, $l_2(i)$, $l_3(i)$ are all varied, randomly chosen from Gaussion distributions around $\bar{l}_1$, $\bar{l}_2$ and $\bar{l}_3$, respectively. In this case, the reflectance can be higher than 90% for the whole range of 550 ~ 1800 nm, and at certain wavelengths the reflectance can reach 99%. Compared Fig. 2(b), (c) and (d) to Fig. 2(a), we conclude that the larger ingredient number of disorderd layers adopted in the calculation, the wider HRR will be obtained.

Fig. 3 is the relationship between the reflectance and the number of periods for three single-disorder GaP-ZrO_2-MgF_2 photonic crystals, which have the same $a = 0.9$, $b = -0.9$, $D = 0.0221$ and $\lambda_0 = 976$ nm but different periods $m = 8$, 16, 24, respectively. The results show that the HRR becomes wider as m increases while the extending trend becomes gradually slowly. Additional calculations show that the bandgap extension are negligible when the number of periods are larger than 2 4 . This is why $m = 24$ are adopted in the calculation of the whole paper. This behavior is the same with that of 1 D ternary periodic photonic crystals. We should consider this remarkable feature from the practical point of view.

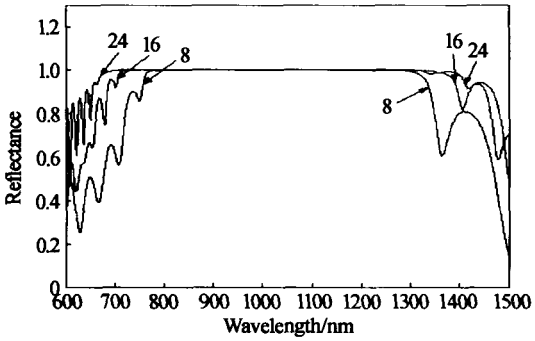

Fig. 3 Calculated reflection spectra for GaP-ZrO_2-MgF_2 single-disorder photonic crystals with $\lambda_0 = 976$ nm, $D=0.0221$, but different periods

Fixing $a=0.9$, $b=-0.9$, $\lambda_0 = 976$ nm and $m=24$, by adjusting the degree of disorder D, we investigate the influence of D to the distribution of the bandgap of 1D disordered ternary photonic crystals. For simplicity, disorder only exists in high refractive layers while the thickness of the ith middle and low refractive layers are kept as constants, i. e., $l_2 = 6.1$ nm, $l_3 = 167.97$ nm, respectively. The thickness of the ith high refractive layers $l_1(i)$ are randomly chosen from a Gaussian distribution around 73.94 nm. Reflective spectra of normal incidence for $D=0.0$, 0.0075, 0.0169, 0.0221, 0.0367, 0.0440, 0.0569, 0.0677 are shown in Figs. 4(a) - 1(h). With the increase of D while D is less than 0.0367, the stop band tends to shift towards both high and low frequency range. Several stop bands expand and connect with each other, forming a wider HRR. When D is around 0.00367, a clear HRR from 630 nm to 1550 nm is obtained with reflectance higher than 95%, which can be higher than 99% in a certain range as shown in Fig. 4(e). When D is greater than that but less than 0.0677, the stop band tends to shift towards the high frequency range while some defect modes emerge in the low frequency direction of HRR, shown in Fig. 4(f) and Fig. 4 (h), but the whole stop band is extending. When D is larger than 0.0677, the stop band is broken and the original stop band is divided into many sub-stop bands, which can be seen in Fig. 4(i). So there

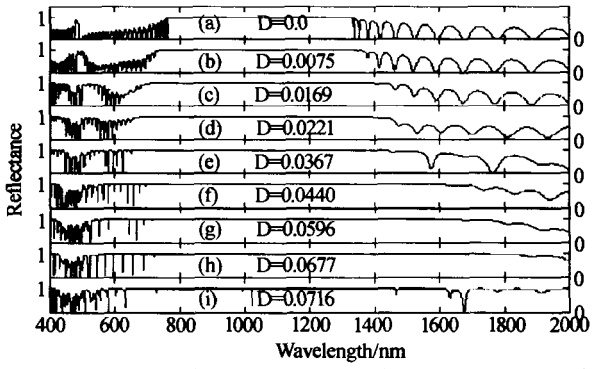

Fig. 4 Calculated reflection spectra for GaP-ZrO_2-MgF_2 single-disorder photonic crystals with $\lambda_0 = 976$ nm, $m=24$, but different disorders $D(D=0, 0.0075, 0.0169, 0.0221, 0.0367, 0.044, 0.0569, 0.0677, 0.0716)$

is an upper limit to D which is about 0.0677. It is seen that disorder is favorable for a wider HRR, when a suitable degree of disorder is chosen.

Furthermore, the reflection spectrum of a single-disorder photonic crystal of PbTe-ZrO_2-NaF, with reflective indices of 4.1-2.0-1.3, D= 0.0221, λ_0=976 nm, and m=24 is calculated too. Compared with the corresponding disorder photonic crystal of GaP-ZrO_2-MgF_2, the HRR is expanded from 654 nm (695～1349) to 995 nm(632～1627), shown in Fig. 5. In addition, when high and low coating materials with larger refractive contrast are used, this broadening effect be comes mone obvious.

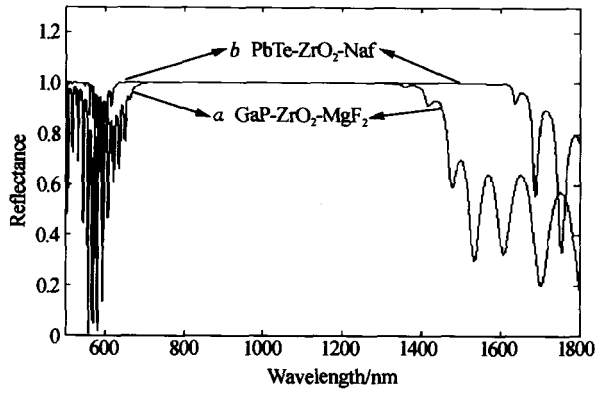

Fig. 5 Calculated reflection spectra of disordered photonic crystals with a=0.9, b=−0.9, D=0.0221, λ_0=976 nm, m=24

3 Conclusions

It proves that a disordered 1D ternary photonic crystal can possess a much wider HRR compared to that of periodical photonic crystal. It is expected that this kind of photonic crystal may have broad applications in tunable lasers and optical equipment, where broadband reflection with high quality is essential.

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无序一维三元光子晶体的带隙展宽

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摘 要 采用光学传输矩阵法首次研究了无序一维三元光子晶体的带隙特性.研究发现,无序结构光子晶体与周期结构光子晶体相比其带隙显著加宽.取无序的介质元数越多,得到的禁带越宽.论文还计算和讨论了无序度和高低折射率之差值对光子晶体带隙的影响.

关键词 光子晶体;无序度;带隙展宽

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