Optimized design and experiment of one-dimensional omnidirectional reflector using P-wave angle domain compensated overlapping method

Xia Li (李 夏), Wei Xue (薛 唯), Yurong Jiang (蒋玉蓉), Huaqing Wang (王华清), and Zhinong Yu (喻志农)

Department of Photoelectronics Engineering, School of Information Science and Technology, Beijing Institute of Technology, Beijing 100081

Received July 9, 2007

The optimized method of extending the omni-photonic band gap (omni-PBG) was discussed based on analyzing the P-wave reflectivity characteristics in one-dimensional (1D) periodic multilayer film. A visible omnidirectional reflector with hybrid structure was designed using P-wave compensated overlapping in angle domain. The experimental result was in good agreement with the theoretical simulation.

OCIS codes: 230.0230, 310.0310, 160.4670.

The visible reflectors with high reflectivity in wide incident angle range have been extensively used as basic optical components in laser technology and optical signal process, etc.[1−3]. Metal reflector and dielectric reflector are two types of traditional reflectors, the former is easy to realize full angle reflection but with absorption loss, the latter has low absorption loss but is very sensitive to the change of incident angle. To overcome the disadvantage of traditional reflectors, the perfect mirror employing photonic band gap (PBG) of one-dimensional photonic crystal (1D PC) is developed[4−6]. And further, to improve the performance of 1D PC mirror, several methods, such as introduced structure disorder, multi-sub-PC overlapping, multiple-periodic system, and incident angle domain method, have been suggested[7−12]. Compared with others, the structure designed by angle domain overlapping method[11] can greatly extend the PBG of 1D PC and be fabricated easily. Based on the angle domain method, we propose a new way to design 1D omnidirectional reflector using P-wave compensated overlapping in angle domain. Especially, the material dispersion of TiO_2 as high dielectric index material was taken into consideration, which takes a constant value for TiO_2 and makes the theoretical simulation more effective and performable. Utilizing the proposed method we have designed an optimized structure of 1D visible omnidirectional reflector and experimentally verified it.

Generally, the incident wave is treated as S- and P-wave which is dependent on the electric field direction, parallel or perpendicular to incident plane. It is well known from thin-film theory that the reflection curve of certain periodic multilayer film has blue-shift as incident angle increases for both S-wave and P-wave. But, as displayed in Fig. 1, the reflection spectrum of P-wave is more sensitive to the change of the incident angle than S-wave and strongly shrinks when shifting. The common full-angle high reflection region (omni-PBG) of S- and P-wave corresponds to complete PBG for this 1D periodic structure. Actually, the range of complete PBG is decided by P-wave reflection spectrum, which is limited by the short edge with angle of 0° incident and long edge with maximum incident angle (here taken 85° for convenience).

The correlation between complete PBG and P-wave omni-PBG edges is clearly indicated in Fig. 2. There are two 1D PC structures by periodic quarter-wavelength multilayer film with center wavelengths λ_{c1} and λ_{c2}, respectively. From frequency domain, it seems no common

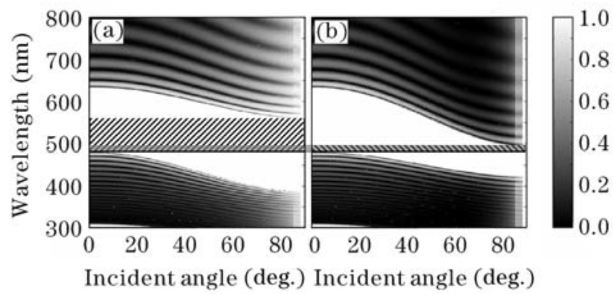

Fig. 1. Reflection spectra of (a) S- and (b) P-wave for certain 1D periodic multilayer structure. Rectangle regions filled with stripes show the omni-PBG of S- and P-wave, respectively. The complete PBG, stripe area filled with gray, is decided by S-wave.

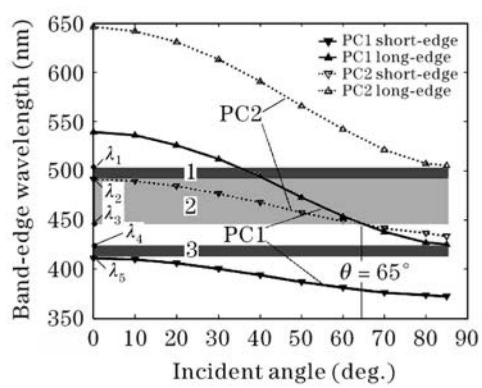

Fig. 2. Sketch map of P-wave compensated overlapping method in angle domain. 1: $\lambda_1 - \lambda_2$, omni-PBG of PC2; 2: $\lambda_2 - \lambda_3$, full-angle high reflection band; 3: $\lambda_4 - \lambda_5$, omni-PBG of PC1.

1671-7694/2007/110665-03

complete PBG region for PC1 and PC2. But considering the angle domain, take $\theta = 65°$, the short edge curve of PC2 and long edge curve of PC1 intersect, the high reflection in the range from λ_2 to λ_3 is partially provided by PC1 from 0° to 65° and by PC2 from 65° to 85°. In other words, an extended full angle high reflection band is obtained by partial-angle high reflection band of PC1 and PC2 compensation each other in the range from λ_2 to λ_3, and the hybrid structure formed by PC1 and PC2 can produce an uninterrupted full-angle high reflection band from λ_1 to λ_3. Figure 2 represents the general rule of using P-wave compensated overlapping method in angle domain. Here, the intersected angle θ plays crucial rule in omni-PBG extending. By adjusting the center wavelength of PC2 to increase θ, the full-angle high reflection band can be further extended and reach the maximum when $\theta = 89°$.

Employing above-mentioned method, we have designed a visible omnidirectional reflector. Taking $\theta = 85°$, as shown in Fig. 3, the full-angle high reflection band from 410 to 735 nm almost covers the whole visible region. It is a hybrid structure by five quarter-wavelength sub-PCs overlapping:

$$\text{air}/12(\text{H}_1\text{L}_1)10(\text{H}_2\text{L}_2)10(\text{H}_3\text{L}_3)$$

$$10(\text{H}_4\text{L}_4)10(\text{H}_5\text{L}_5)/\text{substrate}$$

corresponding center wavelengths were 831.6, 727.20, 633.6, 547.2, and 468 nm from PC1 to PC5. The high dielectric index material H is TiO_2, the low dielectric index material L is SiO_2. In visible region, the refractive

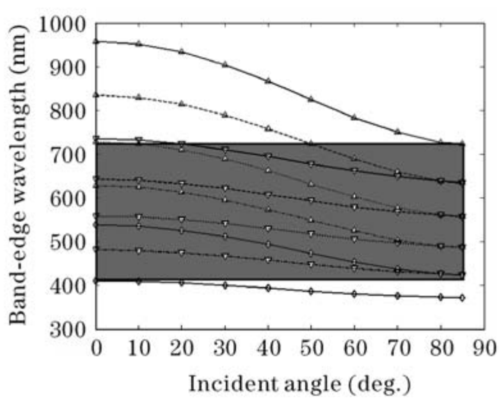

Fig. 3. Sketch map of visible omnidirectional reflector design, formed by five sub-PCs.

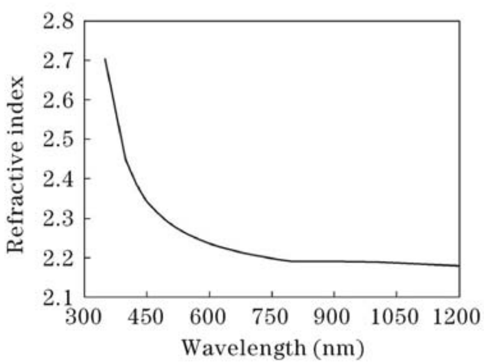

Fig. 4. Calibrated dispersion curve of TiO_2.

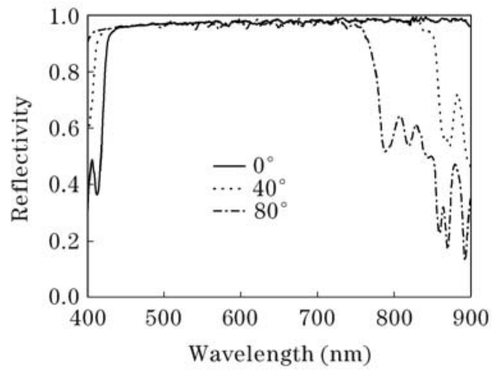

Fig. 5. Measured reflection of 1D reflector sample.

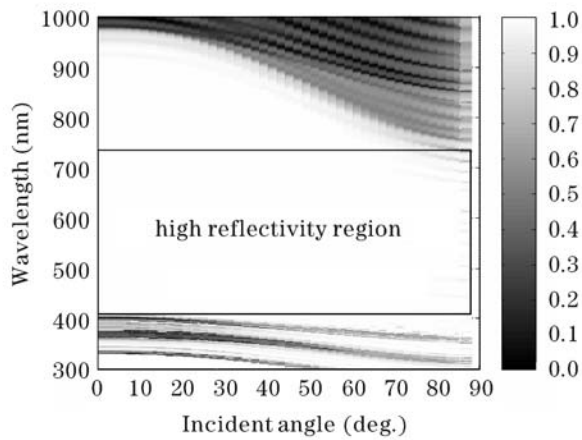

Fig. 6. Calculated reflection spectrum of designed 1D visible omnidirectional reflector.

index of SiO_2 is very stable and taken as 1.455, but for TiO_2, its refractive index is dependent on wavelength resulted material dispersion. So we use the experimentally calibrated refractive index for TiO_2 in design to take the place of a constant value used in Ref. [11]. The dispersion curve is plotted in Fig. 4.

Adopted ion-assisted electron beam evaporation technique, TiO_2 and SiO_2 have been layer-by-layer deposited on quartz glass substrate under vacuum condition of 1.8×10^{-2} Pa, in BEIYI ZZSX-800ZA film coating machine. Then after baking at 200 °C for 2 hours, the reflectance of sample has been measured by R&T function provided by Woollam VB400 VASE Ellipsometer. The maximum incident angle measured was 80° and little less than deigned 85°.

The measured reflection curves illustrated in Fig. 5 was smooth from 420 to 750 nm with average reflectivity higher than 97%. In contrast to the calculated reflection spectrum in Fig. 6, we have verified that the proposed method using P-wave compensated overlapping in angle domain is an effective way to extend the omni-PBG of 1D periodic structure and obtain omnidirectional reflector with excellent performance.

In conclusion, we developed a new approach to extending the omni-PBG of 1D PC based on the angle domain method. Further, we applied the method to optimally design a visible 1D omnidirectional reflector. The experimental result is in good agreement with the simulation and shows excellent performance of the sample. As an effectively feasible approach, the proposed method will be helpful to develop 1D PC components depending on the PBG characteristic, and it does not be confined to 1D omnidirectional reflector or the structure like multilayer film.

X. Li's e-mail address is xiafeng717@bit.edu.cn.

References

1. J. P. Dowling, Science **282,** 1841 (1998).
2. R. K. Lee, O. J. Painter, B. Kitzke, A. Scherer, and A. Yariv, Electron. Lett. **35,** 569 (1999).
3. S. Noda and T. Baba, *Roadmap on Photonic Crystals* (Kluwer Academic Publisher, Dordrecht, 2003).
4. D. N. Chigrin, A. V. Lavrinenko, D. A. Yarotsky, and S. V. Gaponenko, Appl. Phys. A **68,** 25 (1999).
5. E. Yablonovitch, Opt. Lett. **23,** 1648 (1998).
6. J. N. Winn, Y. Fink, S. Fan, and J. D. Joannopoulos, Opt. Lett. **23,** 1573 (1998).
7. H. Li, H. Chen, and X. Qiu, Physica B **279,** 164 (2000).
8. X. Li, Y. Jiang, W. Xue, Z. Yu, and H. Wang, Proc. SPIE **6414,** 64141J (2006).
9. A. Mir, A. Akjouj, E. H. El Boudouti, B. Djafari-Rouhani, and L. Dobrzynski, Vacuum **63,** 197 (2001).
10. X. Wang, X. Hu, Y. Li, W. Jia, C. Xu, X. Liu, and J. Zi, Appl. Phys. Lett. **80,** 4291 (2002).
11. B. Huang and P. Gu, Proc. SPIE **5280,** 143 (2004).
12. H.-Y. Lee and G.-Y. Nam, J. Appl. Phys. **100,** 083501 (2006).