Chapter 6

Summary

In this study, we investigate how symmetries affect the E-polarization and H-polarization band structures in the two-dimensional photonic crystal, which involving structural and rotational symmetries, and material. The plane-wave method is employed to calculate band structures and field patterns. First, the two-dimensional triangular and square photonic crystals are considered. The optimal parameters in obtaining the largest PBG are calculated and the parameters influencing the formed PBG are examined. The effects of structural and rotational symmetries associated with the deformation and rotation of rods on E-polarization and H-polarization band gaps has also been studied systematically. The results show the large complete PBGs can be widened by rotating the noncircular rods in the photonic crystal. Moreover, the features of band structures by the use of anisotropy materials in the photonic crystal have been examined.

It is well known that the complete PBG for square lattice exists in the case of square dielectric columns, but closes when the rods are replaced with circular dielectric columns. To understand how the regular shape and boundary of rods affects the formation of PBG in square lattice, the N-polygonal and corner-cutting structures are considered. The features for both E- and H-polarization bands are examined from the band-structure and the field-pattern perspectives. The photonic crystals of anisotropic N-polygonal rod obtain a larger complete PBG width than that of isotropic N-polygonal rod. The band structures of isotropic rods approach the same as that of circular rod for N is greater than twelve, while that of anisotropic rods resemble to circular rods for N is greater eighteen. The E-polarization bands of anisotropic photonic crystal are more sensitive to rods' boundary than that of isotropic structure, and the fabrication requirements of anisotropic photonic crystal consequently are more stringent than that of isotropic photonic crystal. For the corner-cutting structures, we little by little cut the corners of square rods to form octagonal shape at the fixed filling factor. In particular, the band-structure viewpoints are used to understand the features of formed PBG in the square lattice. The results in the E-polarization gap (E_8 gap) reveal that the cutting corner of rods strongly affects the E_9 band in resonance frequency and field distribution inside the rod. The decrease in resonance frequency and the increase in band width lead to close the E-polarization gap. The results in the H-polarization gap (H_6 gap) reveal a strong relationship between cutting corner of the rod and the H_6 or H_7 bands. The decrease in resonance frequency of H_7 band and the increase in band widths for both H_6 and H_7 bands lead to close the H-polarization gap. Accordingly, the complete PBG is closed in the square lattice when the square dielectric rods are replaced with the octagonal dielectric rods.

Next, we further investigate the formed PBG of hollow rods in the triangular lattice. Three deformed and two rotational structures are constructed to investigate the effects of structural and rotational symmetries on the E-polarization and H-polarization band gaps. The results in the H-polarization modes indicate that the air space among the rods dominates the low-frequency gaps while the shape of the rods affects mainly the high-frequency gaps. The results in the E-polarization modes reveal a strong relationship between the shape of the rods and the band gaps, as determined from the field patterns. The effect on the E-polarization mode for rotational structures is similar to that for deformed structures. However, H-polarization modes are affected not only by the field distribution among rods but also by the reduction of rotational symmetry.

The symmetry of photonic crystal plays an important role in opening complete PBGs. Analyzing the structural and rotational symmetries of photonic crystal is useful in understanding the properties of the formed PBGs and provides a path for designing proper photonic crystal structures with desired PBGs.

Reference

1. J. D. Joannopoulos, P. R. Villeneuve and S. Fan, Nature 386, 143 (1997).
2. M. Notomi, T. Tamamura, Y. Ohtera, O. Hanaizumi and S. Kawakami: Phys. Rev. B **61**, 7165 (2000).
3. S.G. Lee, S.S. Oh, J.E. Kim, H.Y. Park and C.S. Kee: Appl. Phys. Lett. **87** 181106 (2005).
4. F. Du, Y.Q. Lu and S.T. Wu: Appl. Phys. Lett. **85** 2181 (2004).
5. H. Kosaka, T. Kawashima, A. Tomita, M. Notomi, T. Tamamura, T. Sato and S. Kawakami: Phys. Rev. B **58** R10096 (1998).
6. S.Y. Zhu, H. Chen and H. Huang: Phys. Rev. Lett. **79** 205 (1997).
7. E. Yablonovitch: Phys. Rev. Lett. 58, 2059 (1987).
8. S. John: Phys. Rev. Lett. 58, 2486 (1987).
9. E. Yablonovitch: J. Opt. Soc. Am. B 10, 283 (1993).
10. M. Born and E. Wolf: *Principle of Optics*, (Pergamon, Oxford, 1959).
11. S. John: Today 44, 32 (1991).
12. S. L. McCall et al.: Phys. Rev. Lett. 67, 2017 (1991).
13. E. Yablonovitch and T. Gmitter: Phys. Rev. Lett. 63, 1950 (1989).
14. E. Özbay et al.: Phys. Rev. B 50, 1945 (1994).
15. R. D. Meade, K. D. Brommer, A. M. Rappe, and J. D. Joannopoulos: Appl. Phys. Lett. 61, 495 (1992).
16. W. M. Robertson et al.: Phys. Rev. Lett. 68, 2023 (1992).
17. S. Y. Lin et al.: J. Mod. Opt. 41, 385 (1994).
18. K. Inoue et al., Phys. Rev. B 53, 1010 (1996).
19. H.-B. Lin et al., Appl. Phys. Lett. 68, 2927 (1996).
20. S. John and J. Wang: Phys. Rev. Lett. 64, 2418 (1990).

21. S. John and J. Wang: Phys. Rev. B 43, 12772 (1991).
22. M. Notomi, T. Tamamura, Y. Ohtera, O. Hanaizumi and S. Kawakami: Phys. Rev. B 61, 7165 (2000).
23. O. Painter, R. K. Lee, A. Scherer, A. Yariv, J. D. O'Brien, P. D. Dapkus and I. Kim: Science 284, 1819 (1999).
24. A. Mekis, J. C. Chen, I. Kurland, S. Fan, P. R. Villeneuve, and J. D. Joannopoulos: Phys. Rev. Lett. 77, 3787 (1996).
25. J. S. Foresi, P. R. Villeneuve, J. Ferrera, E. R. Thoen, G. Steinmeyer, S. Fan, J. D. Joannopoulos, L. C. Kimerling, H. I. Smith, and E. P. Ippen: Nature (London) 390, 143 (1997).
26. O. Painter, J. Vuckovic, and A. Sherer: J. Opt. Soc. Am. B 16, 275 (1999).
27. J. K. Hwang, H. Y. Ryu, D. S. Song, I. Y. Han, H. K. Park, D. H. Jang, and Y. H. Lee: IEEE Photonics Technol. Lett. 12, 1295 (2000).
28. W. D. Zhou, J. Sabarinathan, P. Bhattacharya, B. Kochman, E. W. Berg, P.-C. Yu, and S. W. Pang: IEEE J. Quantum Electron. 37, 1153 (2001).
29. M. Agio and L. C. Andreani: Rev. B. **61**, 15519 (2000).
30. C. Goffaux and J.P. Vigneron: Phys. Rev. B **64** 0751181 (2001).
31. R. Hillerbrand, W. Hergert and W. Harms: Phys. Status Solidi B. **217** (2000).
32. D. Cassagne, C. Jouanin and D. Bertho: Phys. Rev. B 53, 7134 (1996).
33. C. M. Anderson and K. P. Giapis: Phys. Rev. Lett. 77, 2949 (1996).
34. *International Tables for Crystallography*, edited by T. Hahn (Ridel, Boston,1987).
35. C. M. Anderson and K. P. Giapis: Phys. Rev. B 56, 7313 (1997).
36. P. R. Villeneuve and M. Piche: Phys. Rev. B 46, 4969 (1992).
37. R. Padjen, J. M. Gerard, and J. Y. Marzin: J. Mod. Opt. 41, 295 (1994).

38. T. Baba and T. Matsuzaki: Jpn. J. Appl. Phys., Part 1 34, 4496 (1995).

39. X. H. Wang, B. Y. Gu, Z. Y. Li and G. Z. Yang: Phys. Rev. B 60, 11417 (1999).

40. M. Qiu and S. He: Phys. Rev. B 60, 10610 (1999).

41. N. Susa: J. Appl. Phys. 91, 3501 (2002).

42. C. S. Kee, J. E. Kim and H. Y. Park: Phys. Rev. E. **56**, R6291 (1997).

43. J. D. Joannopouls, R. D. Mead and J. N. Winn, *Photonic Crystals: Modeling the Flow of light* (Princeton University Press, NJ, 1995).

44. K. M. Leung, in Photonic band gaps and localizations, Ed. by C.M. Soukoulis, (Plenum Press, NY., 1993).

45. K. M. Leung and Y. F. Liu, Phys. Rev. Lett. 65, 2646 (1990).

46. J. B. Pendry and P. M. Bell, in Photonic band gaps and localization, C. M. Soukoulis Ed., (Plenum Press, NY., 1993).

47. K. Busch, C. T. Chan, and C. M. Soukoulis, in Photonic band gap materials, Ed. By C. M. Soukoulis (Plenum Press, NY., 1996).

48. D. H. Choi, W. J. R. Hoeffer, IEEE Trans. Microwave Theory Tech. 34, 1464-1470 (1986).

49. J. Yonekura, J. Lightwave Technol. 17, 1500 (1999).

50. F. Brechet, J. Marcou, D. Pagnoux, Opt. Fiber Technol. 6, 181 (2000).

51. K. P. Chang and S. L. Yang: J. Appl. Phys. 100, 1 (2006).

52. K. P. Chang and S. L. Yang: Jpn. J. Appl. Phys.45 6964 (2006).

53. C Jin, B Cheng, B Man, D Zhang, S Ban, B Sun, L Li, X. Zhang and Z. Zhang: Appl. Phys. Let.75, 1201 (1999).

54. L. L. Lin and Z. Y. Li: Phys. Rev. B. 63, 33310 (2001).

55. Y. Qiu and K.M. Leung: Phys. Rev. B **64** 45108 (2001).

56. H.Y Ryu, J.K. Hwang and Y.H. Lee: Phys. Rev. B **59** 5463 (2002).

57. K. Sakoda: Phys. Rev. B **52** 7982 (1995).

58. P. R. Villeneuve and M. Piche: Phys. Rev. B 46, 4973 (1992).

59. M. Plihal and A. A. Maradudin: Phys. Rev. B 44, 8565 (1991).

60. J. B. Nielsen, T. Sondergaard, S. E. Barkou, A. Bjaklev, J. Broeng and M. B. Nielsen: Electron. Lett. 35, 1736 (1999).

61. R. Z. Wang, X. H. Wang, B. Y. Gu and G. Z. Yang: J. Appl. Phys. 90, 4307 (2001).

62. W. Kuang, Z. Hou, Y. Liu and H. Li: J. Opt. A. 7, 525 (2005).

63. Z. Y. Li, B. Y. Gu and G. Z. Yang: Phys. Rev. Lett. 81, 2574 (1998).

64. Z. Y. Li, J. Wang and B. Y. Gu: Phys. Rev. B 58, 3721 (1998).

65. Z. Y. Li, L. L. Lin, B. Y. Gu and G. Z. Yang: Physica B 279, 159 (2000).

66. T. Pan and Z. Y. Li: Solid State Commun. 128, 187 (2003).

67. T. Pan, F. Zhuang and Z. Y. Li: Solid State Commun. 129, 501 (2004).

68. E. D. Palik, *Handbook of Optical Constants of Solids* (Academic Press, New York, 1991).

69. S. Ades and C. H. Champness, J. Appl. Phys. **49**, 4543 (1978).