行政院國家科學委員會補助專題研究計畫 ☑ 成果報告 □期中進度報告

光波在週期性媒質內傳播之理論與模擬（I）

計畫類別：☑ 個別型計畫 □ 整合型計畫
計畫編號：NSC 91－2215－E－002－032
執行期間： 91 年 8 月 1 日至 92 年 7 月 31 日

計畫主持人： 江衍偉
計畫參與人員： 王志洋、陳弘基、劉貴朝、陳廷仰

成果報告類型(依經費核定清單規定繳交)：☑精簡報告 □完整報告

執行單位： 國立台灣大學電信工程學研究所

中 華 民 國 九 十 二 年 十 月 十 七 日

行政院國家科學委員會專題研究計畫成果報告

光波在週期性媒質內傳播之理論與模擬（I）
Theory and Simulation of Optical Wave Propagation in Periodic Media (I)

計畫編號：NSC 91-2215-E-002-032
執行期間：九十一年八月一日至九十二年七月三十一日
主持人：江衍偉, 國立台灣大學電信工程學研究所
參與人員：王志洋、陳弘基、劉貴朝，台灣大學電信所；陳廷仰，台灣大學光電所

摘要

我們以數值方法探討含色散媒質之二維光子晶體波導之傳播特性。藉由時域有限差分法，我們計算了 Lorentzian 色散下光子晶體波導之模態色散關係式。吾人亦探討了此種波導的傳輸頻譜與脈波形狀之演變等效應。
關鍵詞：光子晶體波導、媒質色散、時域有限差分法

Abstract

The propagation characteristics of 2-D photonic crystal waveguides with dispersive materials are numerically investigated. Using the finite-difference time-domain (FDTD) method, we calculate the mode dispersion relation of the photonic crystal waveguides with material dispersion described by the Lorentzian model. Both the transmission spectrum and the pulse shape evolution are also examined.
Keywords: photonic crystal waveguides, material dispersion, finite-difference time-domain (FDTD) method

1. Introduction

In recent years, photonic crystals have attracted wide attention in both physics and engineering communities. Many numerical techniques have been developed for calculating the band structures. These include the finite-difference time-domain (FDTD) method [1], the plane wave expansion method [2], etc. Most of them were developed for treating the photonic crystals with nondispersive or frequency-independent materials. As to the photonic crystals with dispersive or frequency-dependent materials, the case of the Drude type dispersion was treated by the frequency-domain approach [3, 4]. However, the band structure calculations for general dispersive photonic crystals are quite difficult. Besides, the convergence rate of numerical schemes is still an issue. The time-domain approach may be a possible solution tool. Because of the success of the FDTD in band structure calculation of photonic crystals without material dispersion, we keep applying the FDTD to that with material dispersion. However, imposing the periodic Bloch boundary conditions to the problem with loss material implies that the steady state would never be attained, and the validity of the calculated result may not be guaranteed. In this study, we try to investigate the propagation characteristics of dispersive photonic crystal waveguides, such as the transmission spectrum and the pulse shape evolution, and then to see if these characteristics could be interpreted by the calculated band structures.

2. Theoretical Model

For treating the dispersive material with frequency-dependent dielectric constant, we adopt the modified FDTD algorithm involving a recursive scheme [5]. Figure 1 shows the problem geometry we considered. It consists of a 2-D dielectric-rod photonic crystal with square lattice and has a single line defect as a waveguide. The radius of the rods is set to be 0.2*a*, where *a* is the lattice constant. In our simulations, the Lorentzian type dispersion is used. The frequency-dependent dielectric constant is given by

$$\varepsilon_r(\omega) = \varepsilon_\infty + (\varepsilon_s - \varepsilon_\infty)\frac{\omega_0^{\ 2}}{\omega_0^{\ 2} + 2j\omega\delta - \omega^2}.$$

Here, the resonant frequency ω_0 is 0.5, the damping frequency δ is $0.005\omega_0$, ε_s is 7, and ε_∞ is 5. Note that all the mentioned frequencies are normalized by $2\pi c/a$, where c is the speed of light in vacuum.

3. Numerical Results

For calculating the defect modes of the photonic crystal waveguide shown in Fig. 1, a supercell is chosen with appropriate boundary conditions. Figure 2 shows the simulated ω-k_y dispersion relation of the defect modes. The frequency range is about 0.33-0.42 corresponding to the bandgap of perfectly periodic structure. Figure 3 shows the group -velocity dispersion parameter D versus the normalized frequency, numerically calculated from Fig. 2. The points A and B marked in the figure denote, respectively, the carrier frequencies 0.373 and 0.396, used for simulating the pulse propagation scenarios. In simulating pulse propagation, a Gaussian pulse is fed into the photonic crystal waveguide of lattice constant a = 0.5 μm. For the two cases with different carrier frequencies, the initial bandwidths are both set to be 0.03. The initial pulse width is then about 0.03 ps, corresponding to a spatial extent about tens of lattice constant over the waveguide. Note that the length of the waveguide used for simulation must be as long as possible to avoid the reflection from the waveguide ends. Here, 300 lattice constants are chosen as the length of waveguide. Figure 4 shows the transmission spectrum of a short pulse propagating along the waveguide through 50 lattice constants. The intensity at frequencies within the bandgap is relatively stronger than that at other frequencies. This is consistent with the result shown in Fig. 2. To investigate the propagation scenarios along the dispersive photonic crystal waveguide, the pulse shape at three positions (0, 30, and 180 lattice constants away from the launching point) is plotted. Shown in Fig. 5 is the case with carrier frequency 0.396, corresponding to a small dispersion parameter D. Very little change of the pulse shape is observed when propagating over 30 lattice constants long. However, if the propagation distance is up to 180 lattice constants, the pulse is a little broadened with some ripples behind. This may be due to the rather broad initial bandwidth we chose in simulation to reduce the pulse width for the sake of computation load. Note also that from the time delay of pulse between two different observation positions, we can calculate the group velocity which is consistent with the value calculated by $\partial\omega/\partial k_y$ from Fig. 2. This comparison verifies the validity of our simulated dispersion relation or band structure by the FDTD for the photonic crystals with dispersive materials. Another case of pulse propagation at carrier frequency 0.373, corresponding to a relatively large dispersion parameter D, is shown in Fig. 6. Note that now the pulse broadening is larger than that in Fig. 5 when propagating over 30 lattice constants long. For propagation distance up to 180 lattice constants, very large pulse broadening occurs due to serious dispersion effect.

4. Conclusions

In conclusion, we have used the finite-difference time-domain method to calculate the band structure and to investigate the propagation characteristics of the dispersive photonic crystal waveguides. It has been shown that the band structures or the defect modes calculated in this sense can provide us meaningful information for propagation characteristics.

References

[1] K. S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," *IEEE Trans. Antennas Propagat.*,. **AP-14**, pp. 302-307 (1966).

[2] J. D. Joannopoulos, R. D. Mead, and J. N. Winn, *Photonic Crystals: Molding the Flow of Light*, Princeton University Press, Princeton, 1995.

[3] V. Kuzmiak, A. A. Maradudin, and F. Pincemin, "Photonic band structures of two-dimensional systems containing metallic components," *Phys. Rev. B*, **50,** pp. 16835-16844 (1994).

[4] V. Kuzmiak and A. A. Maradudin, "Photonic band structures of one- and two-dimensional periodic systems with metallic components in the presence of dissipation," *Phys. Rev. B*, **55,** pp. 7427-7444 (1997).

[5] K. S. Kunz and R. J. Luebbers, *The Finite Difference Time Domain Method for Electromagnetics*, CRC Press, Boca Raton (1993).

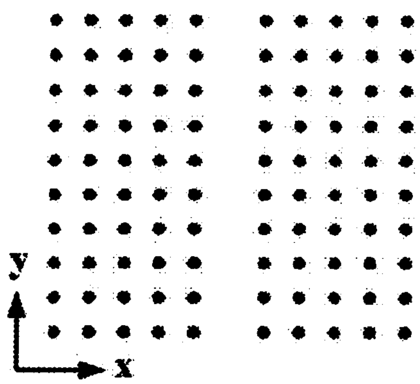


Fig. 1 Schematic diagram of a 2-D photonic crystal waveguide.

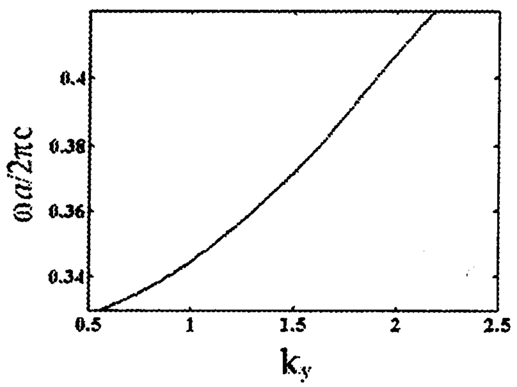


Fig. 2 The dispersion relation of defect modes of the photonic crystal waveguide.

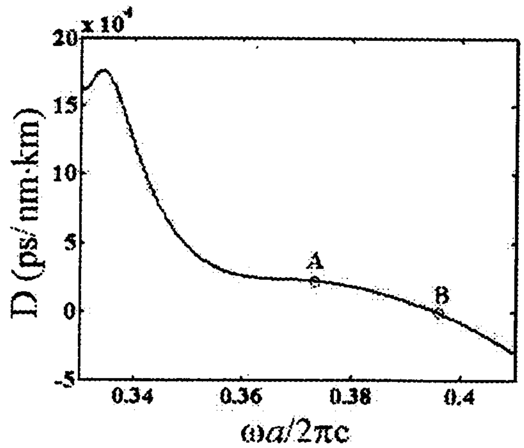


Fig. 3 The dispersion parameter D versus the normalized frequency.

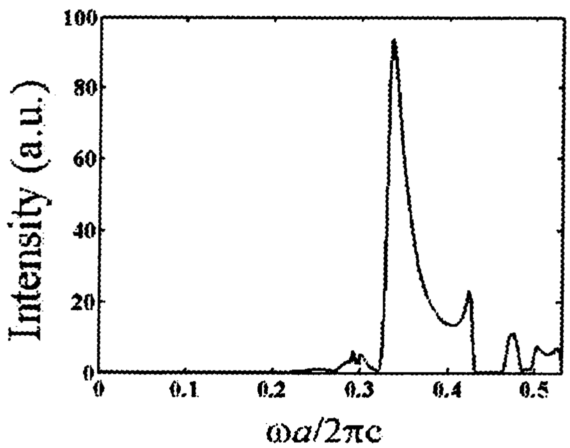
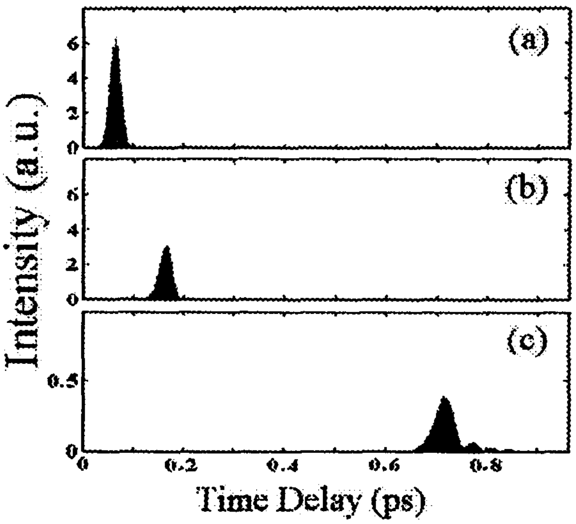


Fig. 4 The transmission spectrum of a short pulse propagating through 50 lattice constants in the photonic crystal waveguide.



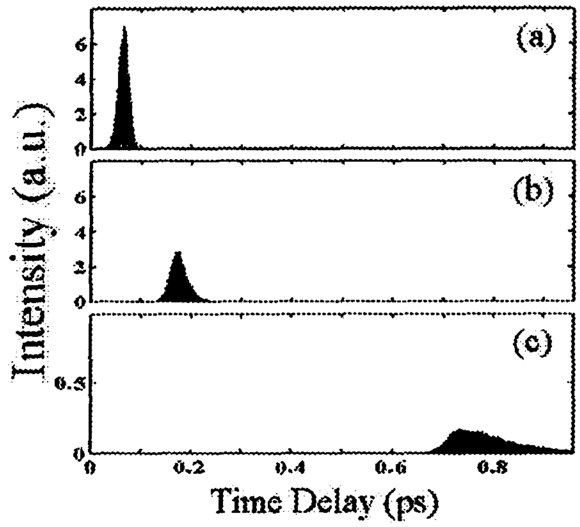


Fig. 5 The propagating pulse detected at the positions (a) 0 lattice constant, (b) 30 lattice constants and (c) 180 lattice constants from the launching point. The normalized carrier frequency of the pulse is 0.396, and the bandwidth is 0.03.

Fig. 6 The propagating pulse detected at the positions (a) 0 lattice constant, (b) 30 lattice constants and (c) 180 lattice constants from the launching point. The normalized carrier frequency of the pulse is 0.373, and the bandwidth is 0.03.