Article ID：1004-4213(2011)12-1845-5

Enhancement Effect of Refractive Index Phase Shift Modulation Near Guided-wave Band Edge of Line-defect Photonic Crystal Waveguides

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Abstract：In the phase shift modulation type optical components constructed by traditional dielectric waveguides with the low refractive index constant based on the total inner reflection mechanism，the length of the modulation region is usually millimeter or centimeter order of magnitude，while their horizontal size is micrometer of order of magnitude，therefore，the most typical characteristics of optical waveguide devices are long and narrow. Reducing the size of optical waveguide devices is a hard problem in the development of highly dense integrated optical circuits. The emergence of photonic crystals provides a new approach to develop highly dense integrated optical circuits. The plane wave expansion method is used to calculate the dispersion curves of the line-defect type photonic crystal waveguides. It is observed that there is a large change of wave prorogation constant near the guided-wave band edge，corresponding to a little change of refractive index of the material. If the work frequency is selected near the guided-wave band edge，the phase shift modulation length is expected to largely reduce. The finite-difference time-domain method is used to demonstrate the results above. Calculated results indicate that there is strong enhancement effect of refractive index phase shift modulation near guided-wave band edge：for the refractive index change of 0.46%，the phase shift modulation length in these waveguides is only 11.7% of that in conventional uniform dielectric material. This enhancement effect is originated from the special flat dispersion properties near the guide-wave band edge，and it is expected to be applied to high dense photonic integrated circuits after further research.

Key words：Photonic crystals；Line-defect waveguides；Phase shift modulation

CLCN：TN252　**Document Code**：A　**doi**：10.3788/gzxb20114012.1845

0 Introduction

In many phase shift modulation type optical devices，some physical effects such as electro-optic effect and thermo-optic effect are used to change the refractive index of materials of optical waveguides. The change in refractive index（Δn）leads to the change in wave propagation constant（$\Delta\beta$），and this can be utilized to achieve a phase shift of $\Delta\beta\times L$ in a piece of optical waveguide with L length. This is called as the index phase shift modulation，which can be characterized by π phase shift modulation length L_π（$=\pi/\Delta\beta$）. Usually，a short L_π is expected for compactness of the optical devices.

In dielectric waveguides based on total inner reflection，including high index contrast dielectric waveguides，the relation between Δn and $\Delta\beta$ is approximately linear；at the same time，electro-optical or nonlinear optical effects，which are used to operate the devices，are very small［$\Delta n \sim O(0.01)$］. So，the required L_π is of the order of millimeters or more[1-2]，and it leads to the narrow and long structure characteristics of modulation type devices based on dielectric waveguides（for low-index waveguide devices，the small waveguide bend is another reason which leads to their narrow and long structure characteristics）. Therefore，the further development of high dense photonic integrated circuits（PICs）has been seriously challenged.

The emergence of photonic crystals provides a

Foundation item：The National Natural Science Foundation of China（No. 610070027），the Fundamental Research Funds for Central Universities，China

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Received date：2011－09－09　**Revised date**：2011－10－28

new approach to develop high dense PICs. Photonic crystal waveguides (PCWs) can be used to achieve low-loss propagation of waveguide bend with small radius of curvature[3-5]. What is more, if L_π in devices based on PCWs can be shortened; the size of devices can be largely decreased, so the integration degree of PICs based on PCWs is promised to be increased by several orders of magnitude.

Soljacic[6-7] used flat dispersion characteristics of coupled-cavity photonic crystal waveguides to substantially reduce L_π, and optical switches smaller than 20 μm × 200 μm in size were designed. Jiang[8], Camargo[9] and Chu[10] reported their experimental work on electro-optic modulator with 80 μm interaction length and on thermo-optic modulator based on line-defect PCWs, respectively. These experiments have demonstrated that L_π can be significantly shorten by using the flat dispersion characteristics near Brillion zone edge of guide-wave band in line-defect PCWs. However, further studies on refractive index phase shift modulation in line-defect PCWs haven't been reported as yet.

In this paper, the dispersion characteristics of line-defect PCWs are numerically calculated using plane wave expansion (PWE) method[11]. By comparing L_π of line-defect PCWs with that in uniform dielectric media, the enhancement factor of refractive index phase shift modulation in line-defect PCWs are obtained. Further numerical analysis of computed results above is made using finite-difference time-domain (FDTD) method[12]. Finally, some important conclusions are drawn.

1 Enhancement effect of refractive index phase shift modulation

In bulk two-dimensional photonic crystals, consisted of hexagonal lattice of air cylinder holes (index is n_B) embedded in a high-index dielectric material A (index is n_A; silicon), through the removal of a line of air cylinder holes along Γ-K direction, a line-defect PCW is formed, as shown in Fig. 1. The rectangular area surrounded by four dotted lines in Fig. 1 is the schematic drawing of a super-cell selected for PWE method. In numerical simulation, the width of 10-layer air cylinders at both sides of defect layer is used; to donate the refractive index change of material A due to some physical effects, the refractive index of material A is set as $n_{A_1}=3.464$ and $n_{A_2}=3.480$, respectively; $n_B=1$, $r=0.3a$, where a denotes the lattice constant.

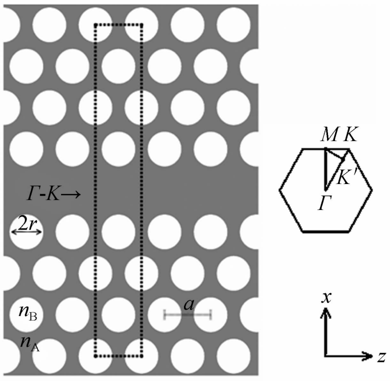

Fig. 1 A schematic drawing of line-defect PCWs

The dispersion curves for even TM guided-modes along Γ-K direction within the frequency of the photonic band gap in the two-dimensional photonic crystals are calculated. Thick solid line and thin solid line in Fig. 2 corresponds to $n_{A_1}=3.464$ and $n_{A_2}=3.480$, respectively. It can be observed from Fig. 2 that in the common frequency range of PBG, 0.211 5～0.311 3 $[2\pi c/a]$, there is the flat dispersion property near the guide-wave band lower edge, which is caused by the periodicity and symmetry of photonic crystal lattice[13]. When the refractive index of material A is varied by a small amount $+\Delta n_A$ (or $-\Delta n_A$), there is a corresponding frequency shift $-\Delta\omega$ (or $+\Delta\omega$). For a fixed frequency, $\Delta\beta$ near guide-wave band edge is much larger than that in the middle of band.

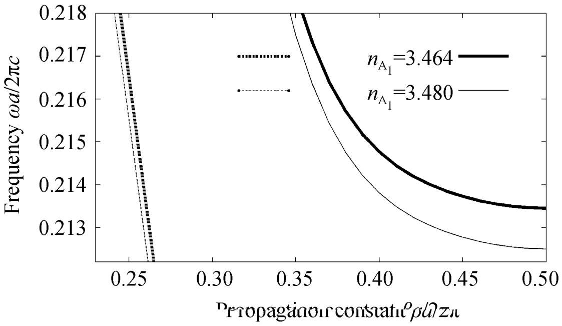

Fig. 2 The dispersion curves of even TM guided-mode corresponding to different n_A (The dotted lines are dispersion curve in uniform dielectric material)

For the identical Δn_A, if $\Delta\beta$ and $\Delta\beta'$ denotes the change in propagation constant in line-defect PCWs and that in uniform dielectric material, respectively, an enhancement factor of refractive index phase shift modulation in line-defect PCWs is defined as f_β

$$f_\beta=\Delta\beta/\Delta\beta' \tag{1}$$

Substituting equation $L_\pi=\pi/\Delta\beta$ into equation (1), we obtain

$$f_\beta=L'_\pi/L_\pi=(L'_\pi/a)/(L_\pi/a) \tag{2}$$

where L'_π/a and L_π/a is normalized π phase shift modulation length in uniform dielectric material and that in line-defect PCWs, respectively; they can be expressed as

$$\frac{L'_\pi}{a}=\frac{1}{\left(\frac{\omega a}{2\pi c}\right)}\cdot\left(\frac{1}{2\Delta n_{\mathrm{A}}}\right) \tag{3}$$

and

$$\frac{L_\pi}{a}=\frac{1}{\left(\frac{\Delta\beta\cdot a}{2\pi}\right)}\left(\frac{1}{2}\right) \tag{4}$$

respectively; where $\omega a/2\pi c$ is normalized frequency (ω is angular frequency and c is the speed of light in vacuum); and $a\Delta\beta/2\pi$ is the change in normalized propagation constant.

The dispersion curves in uniform dielectric are shown as thick dotted line ($n_{\mathrm{A}_1}=3.464$) and thin dotted line ($n_{\mathrm{A}_2}=3.480$) in Fig. 2, respectively. According to Fig. 2, equations (3) and (4), L_π/a and L'_π/a is calculated and shown as thick solid line and thin solid line in Fig. 3, respectively. It can be observed from Fig. 3, in normalized frequency range 0.2136—0.218[$2\pi c/a$], L_π and L'_π is 7.69—65.38[a] and 143.35—146.30[a], respectively. Then, according to equation (3), f_β is 2.19—19.02, as shown in Fig. 4. It should be noticed that in the frequency range near guided-wave band edge 0.2136—0.2146[$2\pi c/a$], f_β is 6.84—19.02. Moreover, the closer to guided-wave band edge is, the larger f_β is, and the more significant the enhancement effect is. This is enhancement effect of refractive index phase shift modulation in line-defect PCWs.

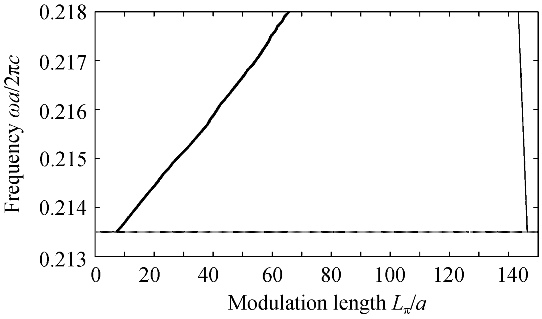

Fig. 3 The modulation length L_π/a (thick solid line) and L'_π/a (thin solid line)

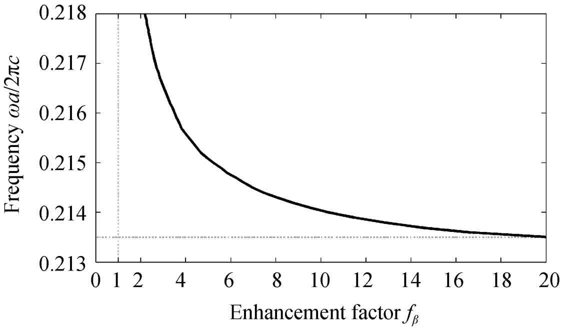

Fig. 4 The enhancement factor f_β in line-defect PCWs

For example, at the frequency 0.2143 [$2\pi c/a$], L_π and L'_π is 17.06a and 145.82a, respectively. The former is equivalent to only 11.70% of the latter, that is, the corresponding f_β is 8.55.

2 FDTD simulations

Next, further analysis of computed results above is made using FDTD method. In phase shift modulation type of optical devices, the model for two phase shift arms based on line-defect PCWs is shown in Fig. 5. To assume $n_{\mathrm{A}_1}=3.472$ in line-defect PCWs, its variation ratio caused by electro-optic effect is ±0.23%, that is, n_{A_1} and n_{A_2} in modulation regions are set as 3.464 and 3.480, respectively. L_{i} and L_{o} are input port length and output port length, respectively. In numerical simulation, both L_{i} and L_{o} are taken as 20a; 1# and 2# incident sources are identical; 1# and 2# observation lines are set in the middle of two defect channels, respectively; perfectly matched layer (PML) absorbing boundary conditions are adopted at boundaries of computed region.

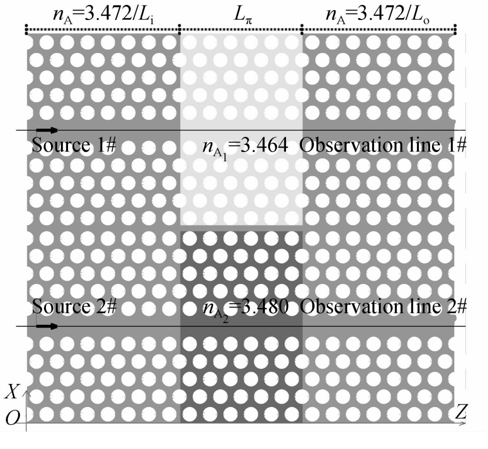

Fig. 5 The model of two phase shift modulation arms based on line-defect PCWs

If working frequency is located at 0.2143 [$2\pi c/a$], according to Fig. 4, L_π is set as 17.06a. The recorded distribution of H_y in 1# and 2# observation lines are shown in Fig. 6, where π phase shift difference between two output ports can be well achieved. The distribution of H_y for modulation region is shown in Fig. 7.

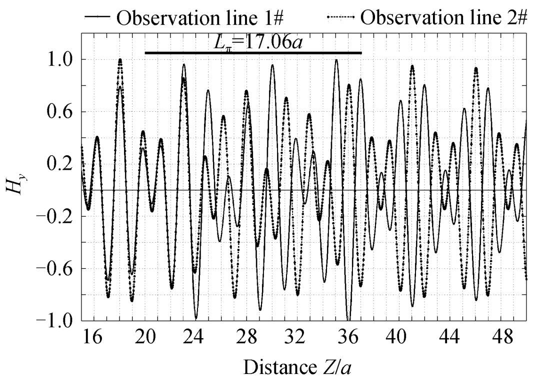

Fig. 6 The recorded distributions of H_y in 1# (solid line) and 2# (dashed line) observation lines shown in Fig. 5, at normalized frequency 0.214 3 [$2\pi c/a$]

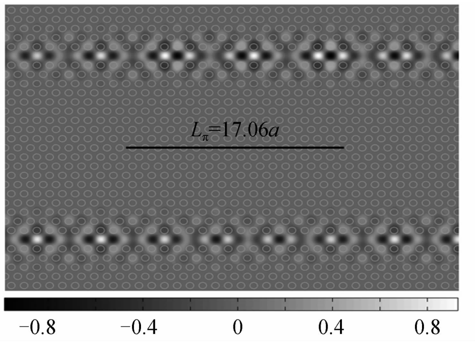

Fig. 7 The distributions of H_y for modulation region in the model shown in Fig. 5, at normalized frequency 0.214 3 [$2\pi c/a$]

If the optical communication wavelength of 1.55 μm is located at the frequency 0.214 3 [$2\pi c/a$], in phase shift modulation type optical devices based on PCWs, the required lattice constant and modulation length are 0.332 2 μm and 5.666 7 μm, respectively. However, the required modulation length is 48.437 5 μm if uniform material is used.

The dispersion curves discussed above are typical and universal in line-defect PCWs, so the conclusions drawn below have general significance: there is a strong refractive index phase shift enhancement effect near band edge of defect guided-wave mode, due to its flat dispersion characteristics. It should be emphasized that all the results and arguments presented in this paper (which has focused on simplified two-dimensional models) apply immediately to three dimensions.

3 Conclusions

The enhancement effect of refractive index phase shift modulation near guided-wave band edge of line-defect photonic crystal waveguides is studied further by numerical simulation. In phase shift modulation type optical devices based on line-defect photonic crystal waveguides, if the work frequency is located near the guided-wave band edge, the required π phase shift modulation length is less than 6 μm. This enhancement effect is expected to play an important role in development of high dense photonic integrated circuits.

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光子晶体线缺陷波导中的折射率相位移调制增强效应

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摘　要：在传统的基于全内反射原理的低折射率比介质波导所构建的相位移调制型光学器件中，调制区域的长度通常在毫米到厘米量级.由于器件横向尺寸保持在微米量级，因此狭长结构成为了传统光波导器件的典型特征，这限制了光学器件集成度的提高，严重制约了集成光路的进一步发展.光子晶体的出现为高密集成光路的发展提供了一条新的途径.本文使用平面波展开方法计算了光子晶体线缺陷波导中的色散曲线.研究发现：在色散曲线下边缘处，材料折射率的一个微小变化可以引起传输常数的较大变化，如果工作频率点选择在带下边缘附近，则可以大幅度减小相位移调制型器件调制区域的长度.本文使用时域有限差分方法进一步验证这种增强效应，计算结果表明，对于0.46％的折射率变化，光子晶体线缺陷波导中的相位调制长度仅为均匀媒质中相位移调制长度的11.7％.通过以进一步研究，这种增强效应有望应用与高密度集成光路.

关键词：光子晶体；线缺陷波导；相位移调制