All-optical Switching Structure Using Nonlinear Photonic Crystal Directional Coupler

A. Eshaghi, **M. M. Mirsalehi**, **A. R. Attari**, and **S. A. Malekabadi**
Department of Electrical Engineering, Ferdowsi University of Mashhad, Iran

Abstract— In this paper, a new all-optical switching structure is proposed and analyzed. Switching is accomplished by embedded Kerr nonlinear rods in the coupling region of a photonic crystal directional coupler. We show that by modifying the supermodes dispersion curves, the switch length can be reduced 22% with respect to similar structures. Finite-Difference Time-Domain and Plane Wave Expansion methods are used to analyze the device characteristics. The results show that the transmission efficiency of the proposed structure has been significantly improved.

1. INTRODUCTION

Photonic crystals are of great importance because of their unique properties in integrating all-optical data-processing chips [1, 2]. Nonlinear photonic crystals are promising structures to realize optical devices such as: optical diodes, nonlinear bends [3], transistors [4], and switches [5]. Due to their important role in optical networks, all-optical switches were investigated during the past decade, in order to decrease the switching length, power and time [6, 7].

Directional couplers can be used to implement all-optical switches [8, 9]. Attempts were made to design couplers with shorter coupling length [10]. However, realizing switches with short lengths and high extinction ratio is still under research. In this paper, a photonic crystal all-optical switching structure with short length and low crosstalk is introduced. A modified 60° bend structure is used to improve the transmission from input to the outputs of the switch.

2. SWITCHING OPERATION IN DIRECTIONAL COUPLERS

In a directional coupler consisting of two parallel waveguides (Fig. 1), the wave confined to one of the waveguides consists of even and odd supermodes with a phase difference. If the phase difference is equal to an odd product of π, the wave will transfer to the other waveguide. This means

$$(k_{even} - k_{odd})L_c = (2n + 1)\pi \qquad (1)$$

where k_{even} and k_{odd} are the wavenumbers of even and odd supermodes, respectively, and L_c is the coupling length. When photonic crystal fabrication is finalized, L_c will be fixed. Through the use of nonlinearity, one can change the effective index of refraction in different input intensities and as a result, the wavenumbers of the supermodes will change and switching operation can be obtained. It can be shown that switch length is proportional to $(\Delta k_{even} - \Delta k_{odd})^{-1}$, where Δk_{even} and Δk_{odd} are the difference between the wavenumbers of even and odd supermodes in the two

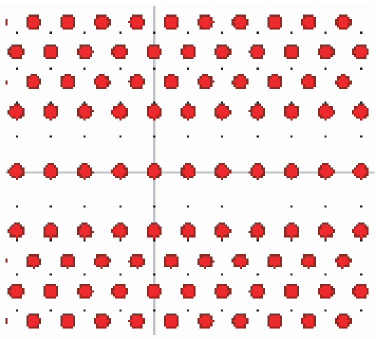


Figure 1: A photonic crystal directional coupler.

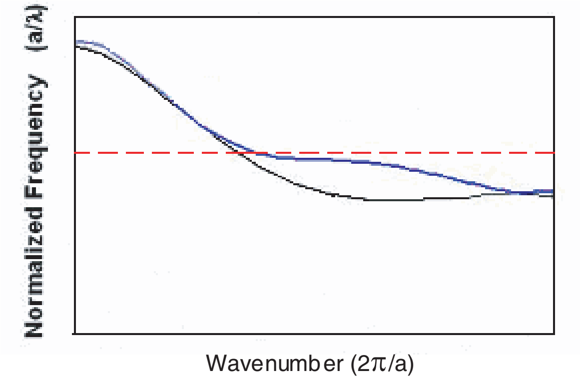


Figure 2: Desired dispersion curves of even (blue) and odd (black) supermodes. Red line shows the fixed-frequency region in the even supermode.

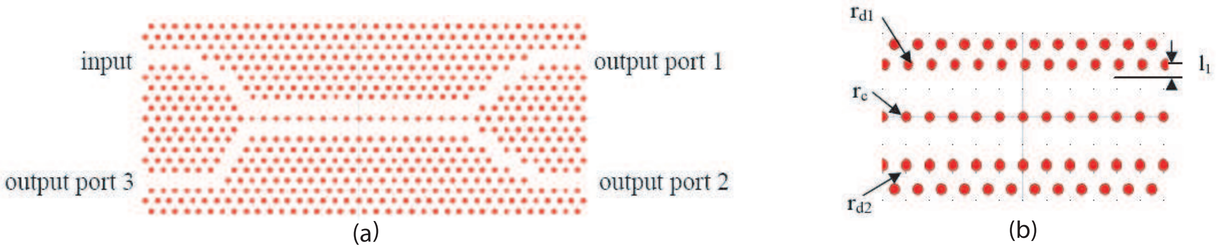
states of switch operation, respectively. Increasing the difference between Δk_{even} and Δk_{odd} will result in reduction of the switch length.

Different structures were proposed to reduce the switch length. The main idea is to modify the supermodes dispersion relation to enlarge the difference between the wavenumbers of linear and nonlinear regimes. Introducing a fixed-frequency region in the dispersion curve of one of the supermodes increases the wavenumber difference drastically. The related band diagram is depicted is Fig. 2. In this structure, the odd mode has a decreasing dispersion curve, while the even mode dispersion curve consists of two decreasing parts and a fixed-frequency region. If the operating frequency is set between the fixed frequencies before and after switching, by changing the input intensity and performing switching operation, Δk_{even} will be larger than Δk_{odd}, and as a result the switch length will decrease. Another advantage of such a structure is that in the fixed-frequency region, the small group velocity leads to reinforce the nonlinear interaction and hence, reduces the power consumption in comparison with optoelectronic devices.

Huang et al. proposed a structure that has a fixed-frequency region [11]. In this structure which consists of air holes in a dielectric substrate, index of refraction in the coupling region has been reduced and the desired dispersion curve was obtained. This directional coupler can be used in an all-optical switch. However, the amount of crosstalk between the output ports in photonic crystal switches with dielectric rods structure is more desirable [9].

3. PROPOSED SWITCH STRUCTURE

Figure 3(a) shows a schematic view of the proposed structure. The PC is formed by a triangular lattice of rods in air. The radius of the rods is $r = 0.2a$, where a is the lattice constant. Two parallel waveguides are obtained by removing two rows of rods. The coupling region is made of rods with Kerr nonlinearity. The Kerr coefficient is assumed $n_2 = 1.5 \times 10^{-17}\,\mathrm{m}^2/\mathrm{W}$. Introducing a new coupling region structure, as shown in Fig. 3(b), the difference between the wavenumbers of linear and nonlinear regimes has increased, so the coupling length is reduced to $18a$. This is



(a) (b)

Figure 3: (a) Schematic view of the proposed switch structure (b) Coupling region of directional coupler, used in the switch structure.

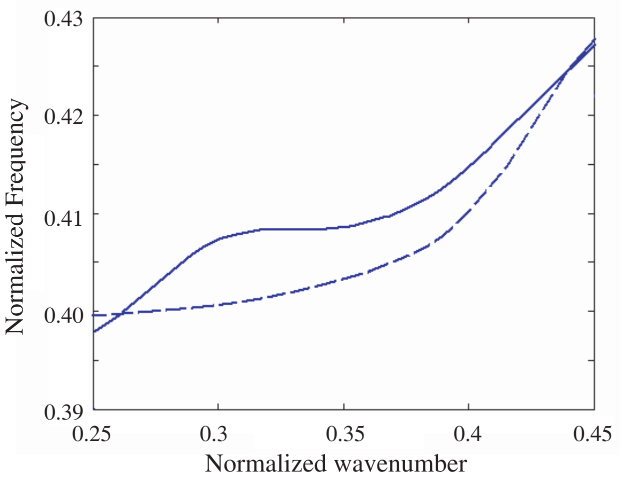


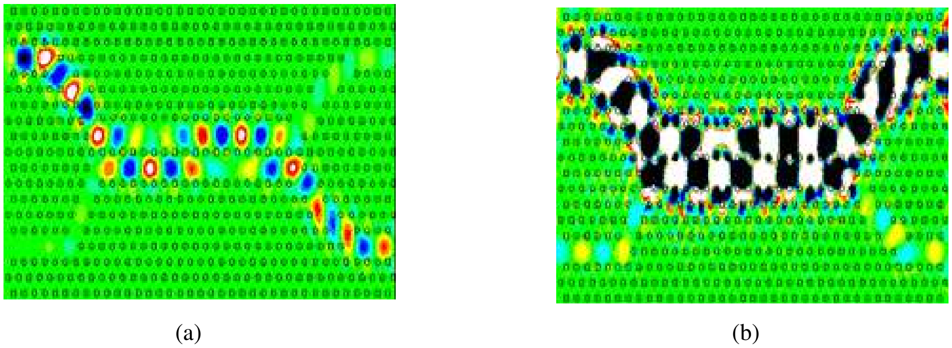
Figure 4: Band diagram of even (solid line) and odd (dashed line) supermodes of the proposed structure. The fixed-frequency region occurs at a normalized frequency of 0.407.

equivalent to a reduction of 22% in comparison with similar structures [9, 12]. The radius of central rods (r_c) and those in the two rows adjacent to the waveguides (r_{d1}, r_{d2}) and the amount of shift of rods from their regular positions in the above mentioned rows (l_1 and l_2) were used as the design parameters. By adjusting these five parameters to the following values, the band diagram, shown in Fig. 4 was obtained by PWE simulations

$$r_c = 0.18a,\ r_{d1} = 0.19a,\ r_{d2} = 0.2a,\ l_1 = 0.18a,\ l_2 = 0.$$

The operating frequency is $\frac{a}{\lambda} = 0.405$ (in the fixed-frequency region). The operating wavelength is chosen $\lambda = 1.55\,\mu\text{m}$, therefore $a = 627.75\,\text{nm}$.

Switching operation is accomplished by tuning the input intensity. In the linear regime, where the input intensity is so low that the nonlinear effects are negligible, the switch output is port 2. By intensifying the input wave, the index of refraction of coupling region increases due to the Kerr effect. This results in transferring the input signal to port 1.


(a)

(b)

Figure 5: Different states of the proposed switch (a) In the linear regime, where the input intensity is low (b) In the nonlinear regime, where the input intensity is high.

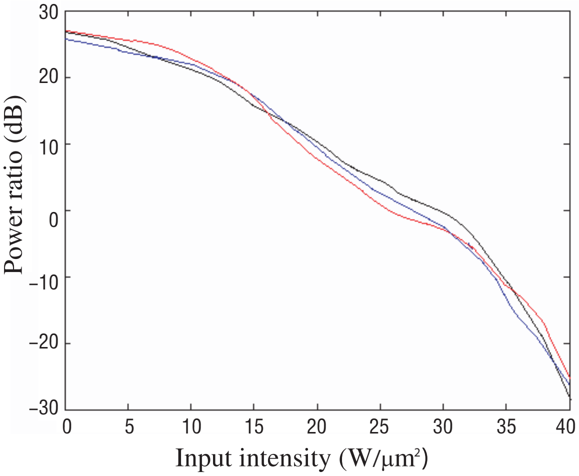
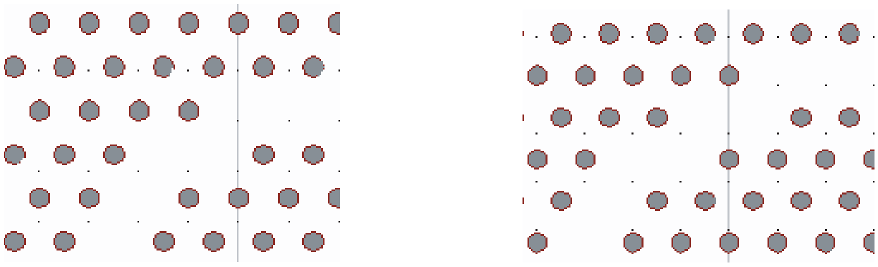


Figure 6: Power ratio of output port 2 to 1 versus input intensity in wavelengths; 1550 nm (black line), 1542 nm (blue line), and 1555 nm (red line).

The FDTD simulations show two states of the device in Fig. 5. The power ratio of output port 2 to 1, versus the input intensity is depicted in Fig. 6. The simulations demonstrate that the device can be considered an optically-controlled switch with a power ratio more than 25 dB in a wide range of wavelengths.

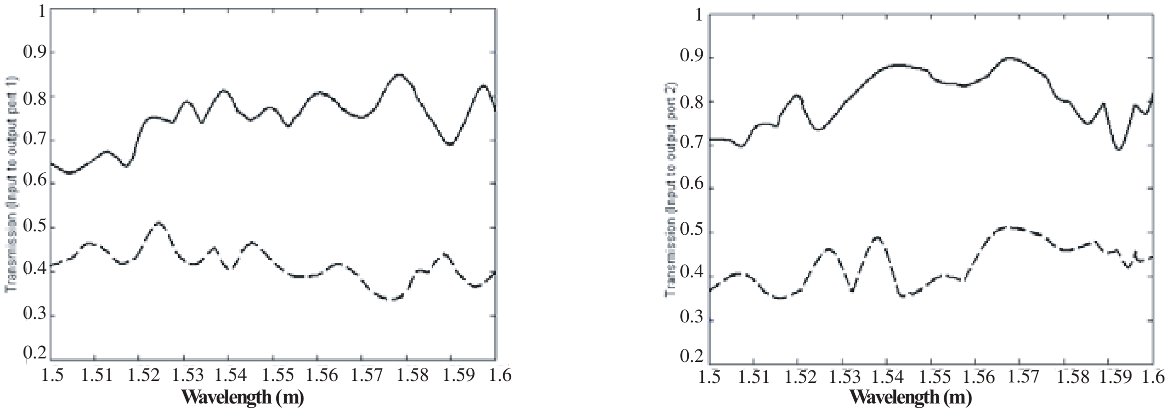
4. IMPROVEMENT OF TRANSMISSION SPECTRA

In order to reduce the crosstalk between output ports, waveguide bends is used in most of the optical switches. Although these bends increase the power ratio in the switch outputs, they decrease the transmission efficiency from the input to the outputs. Attempts were made to improve the efficiency of the waveguide bends [13, 14]. In this work, modified bends, presented in reference [14], are applied. To decrease the crosstalk and at the same time increase the transmission efficiency, different bend types are used in this structure. Bends, placed at the end of the coupling region have the one-rod-moved structure (Fig. 7(a)) while the bends placed near the input and outputs have the three-rods-moved structure (Fig. 7(b)). In order to prevent signal leakage to the output port 3, bends at the beginning of the coupling region are remained unchanged. Other combinations of bends were analyzed. Although those structures improve transmission spectra in some cases, they were not used, due to the crosstalk increase. Fig. 8 shows the transmission spectra from the input to the outputs in the case of modified and usual 60° bends. Transmission efficiency in the proposed switch is improved in comparison with the case of usual bends.



(a) (b)

Figure 7: Modified 60° bends, applied in the proposed switch (a) one-rod-moved structure (b) three-rods-moved structure.



(a) (b)

Figure 8: Transmission spectra from the input to (a) output 1 (b) output 2; solid line (proposed structure), dashed line (usual bends).

5. CONCLUSION

In this research, an all-optical switch based on photonic crystal directional coupler was proposed and analyzed. By introducing a new coupling region structure the difference between wavenumbers of linear and nonlinear regimes has been enlarged, so the coupling length is reduced to $18a$. The crosstalk between output ports is decreased in comparison with similar devices. Taking into consideration the effect of waveguide bends on the extinction ratio in the switch outputs and the amount of signal leakage to the output port 3, modified 60° bends were applied in this structure. As a result, the transmission spectrum of the proposed switch is improved in comparison with usual bends.

REFERENCES

1. Joannopoulos, J. D., R. D. Meade, and J. N. Winn, *Photonic Crystal; Molding the Flow of Light*, Princeton University Press, 1995.
2. Slusher, R. E. and B. J. Eggleton, *Nonlinear Photonic Crystals*, Springer, 2003.

3. Mingaleev, S. F. and Y. S. Kivshar, "Nonlinear transmission and light localization in photonic-crystal waveguides," *J. Opt. Soc. Am. B*, Vol. 19, 2241–2249, 2002.
4. Yanik, M. F., S. Fan, M. Soljacic, and J. D. Joannopoulos, "All-optical transistor action with bistable switching in a photonic crystal cross-waveguide geometry," *Opt. Lett.*, Vol. 28, No. 24, 218–219, 2003.
5. Soljacic, M., M. Ibanescu, C. Luo, S. G. Johnson, S. Fan, Y. Fink, and J. D. Joannopoulos, "All-optical switching structure using optical bistability in non-linear photonic crystals," *J. SPIE*, Vol. 5000, 200–214, 2003.
6. Cuesta-Soto, F., A. Martinez, J. Garcia, F. Ramos, P. Sanchiz, J. Blasco, and J. Marti, "All-optical switching structure based on a photonic crystal directional coupler," *Opt. Express*, Vol. 12, No. 1, 161–167, 2003.
7. Li, Z., Y. Zhang, and B. Li, "Terahertz photonic crystal switch in silicon based on self-imaging principle," *Opt. Express*, Vol. 14, No. 9, 3887–3892, 2006.
8. Cuseta-Soto, F., A. Martinez, B. Garcia-Banos, and J. Marti, "Numerical analysis of all-optical switching based on a 2-D nonlinear photonic crystal directional coupler," *IEEE J. of Quantum Elec.*, Vol. 10, No. 5, 1101–1106, 2004.
9. Locatelli, A., D. Modotto, D. Paloschi, and C. D. Angelis, "All optical switching in ultrashort photonic crystal couplers," *Opt. Comm.*, Vol. 237, 97–102, 2004.
10. Martinez, A., F. Cuesta, and J. Marti, "Ultrashort 2-D photonic crystal directional couplers," *IEEE Photonics Technol. Lett.*, Vol. 15, 694–696, 2005.
11. Huang, S. C., M. Kato, E. Kuramochi, C. P. Lee, and M. Notomi, "Time-domain and spectral-domain investigation of inflection-point slow-light modes in photonic crystal coupled waveguides," *Opt. Express*, Vol. 15, No. 6, 3546–3549, 2007.
12. Zhou, H., X. Jiang, T. Yu, J. Yang, and M. Wang, "Two-mode interference switching in photonic crystal waveguide," *Proceedings of International Symposium on Biophotonics, Nanophotonics and Metamaterials*, 332–334, 2006.
13. Rauscher, K., D. Erni, J. Smajic, and C. Hafner, "Improved transmission for 60° photonic crystal waveguide bends," *Proceedings of Progress In Electromagnetics Research Symposium*, 2004.
14. Talneau, A., L. Gouezigou, N. Bouadma, M. Kafesaki, C. M. Soukoulis, and M. Agio, "Photonic-crystal ultrashort bends with improved transmission and low reflection at 1.55 µm," *Appl. Phys. Lett.*, Vol. 80, No. 4, 547–549, 2002.