New Design of All-optical Flip-flop Device Based on Multimode Interference Photonic Crystal Waveguides

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Abstract— In this paper, we proposed an all-optical flip-flop device based on the multimode interference (MMI) with photonic crystal (PC) waveguides. The proposed all-optical logic gate was numerically studied by the finite-difference time-domain method (FDTD). In recent years, the photonic crystal is a very popular topic due to photonic band gaps (PBGs) which were known to exist in the periodically modulated dielectric materials. We try to combine the MMI principle and photonic crystal waveguide to design a whole new all-optical RS flip-flop device based on the MMI PC waveguide structures. By introducing a point defect rod both in the control ports, we can make outgoing field propagating in the output waveguide or not. The intensity profiles show snapshots optioned at different times. This numerical results show that the proposed PC waveguide structure could really function as an all-optical RS flip-flop logic gate. Note that if we have an RS flip-flop, we can realize various much complex logic processing based on it.

1. INTRODUCTION

Since photonic band gaps (PBGs) were known to exist in periodically modulated dielectric materials [1, 2], which are the so-called photonic crystals (PCs), a large number of studies have been devoted to revealing their unique properties [3]. These artificial sub-micro structures provide flexible controls of light by breaking periodicity and by introducing defects. Recently, well-established fabrication technologies and advanced numerical methods have enabled the sophisticated engineering of PCs dispersion characteristics [4, 5]. In devices based on PBG, well-known lightwave behaviors, such as directional coupling and resonance effect in cavities, have been exploited as well as in conventional optical devices based on total internal reflection (TIR), and their characteristics have been thoroughly investigated in many papers [6, 7]. Compared with those in conventional TIR devices, the well-known behaviors of lightwave in PBG devices are observed in much smaller operating regions, due to the PCs ability to interact with light on a wavelength scale. For instance, the directional coupling between adjacent line-defect waveguides occurs within a few wavelengths [8, 9]. This strong interaction with light in PBG devices is expected to usher in an era of ultra-compact lightwave circuits that operate with much improved functionalities. While such lightwave behaviors have been successfully adopted into PBG devices, they are assumed to take place in structures that ensure single-mode operation for the robust performance of devices. Hence, few studies in the available literatures focus primarily on discussing PCs line-defect waveguides (PCWs) that support multi-mode operation. Furthermore, researches on self-imaging phenomena that might be observed in multi-mode PCWs, to our knowledge, have not been reported so far. In this paper, we observe the propagation of lightwaves in multi-mode PCWs to determine if self-imaging phenomena occur and, if so, to confirm that they can be utilized to control lightwaves in an ultra-compact structure. To demonstrate self-imaging phenomena in multi-mode PCWs, a numerical computation is performed with the finite-difference time-domain (FDTD) method. Asakawa's group proposed a different type of flip-flop operation using symmetric Mach-Zehnder switches implemented in PCs [10]. It has been proposed that all-optical flip-flops can be realized by using two nonlinear etalons with appropriate

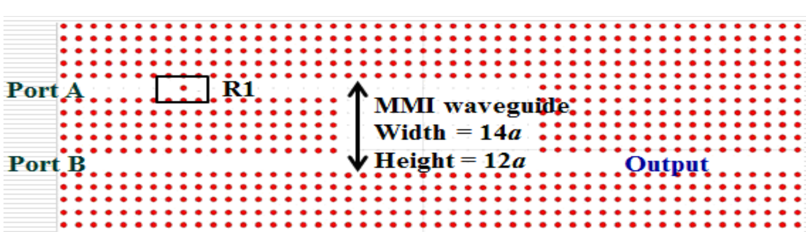

Figure 1: All-optical switch consisting MMI waveguide (width = $12a$, and height = $14a$).

cross-feedback [11, 12], but this proposal is unsuitable for on-chip integration. Notomi's group proposed a different design using two PCs nanocavitiesin [13]. In this paper, we proposed an all-optical flip-flop device based on the MMI with PC waveguide structure This numerical results show that the proposed PC waveguide structure could really function as an all-optical RS flip-flop logic gate.

2. ANALYSES AND NUMERICAL RESULTS

We consider a MMI PC all-optical switch composed of dielectric rods in air with a square array and a lattice constant a, as shown in Figure 1. The radius and the refractive index of the rods are $r = 0.18a$ and $n = 3.6$(Si), respectively. The proposed structure is composed two input ports, the MMI waveguide, and the output port. In this proposed structure, the signal port B will always on By properly changing the radius of the defect rod $R1$, the state of the output port will be changed Figure 2 shows the transmission efficiency of the outpour port for different $R1$ ($0.08a \sim 0.38a$). When $R1$ is $0.31a$, the control power will affect the MMI waveguide to turn off the output, due to the phase difference is 180° of the control port and signal port. Now we know the point defect effectiveness in this kind of structure, and then we will design a RS flip-flop. We introduce a point defect both in the CR and CS control ports, as shown in Figure 3. The radius and the refractive

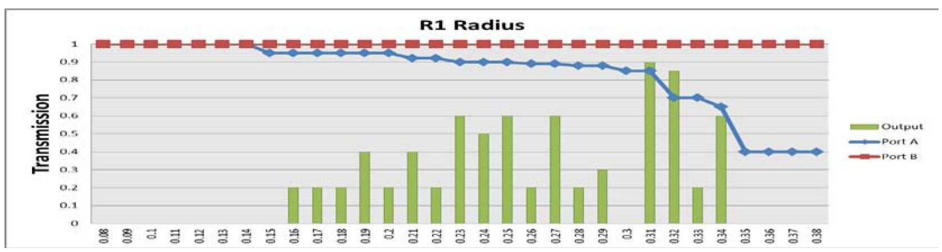

Figure 2: The output chart of $R1$ radius in the control port and output transmission power.

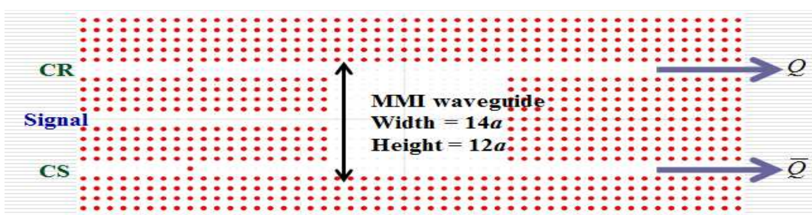

Figure 3: The proposed all-optical flip-flop based on the MMI PC waveguide structure.

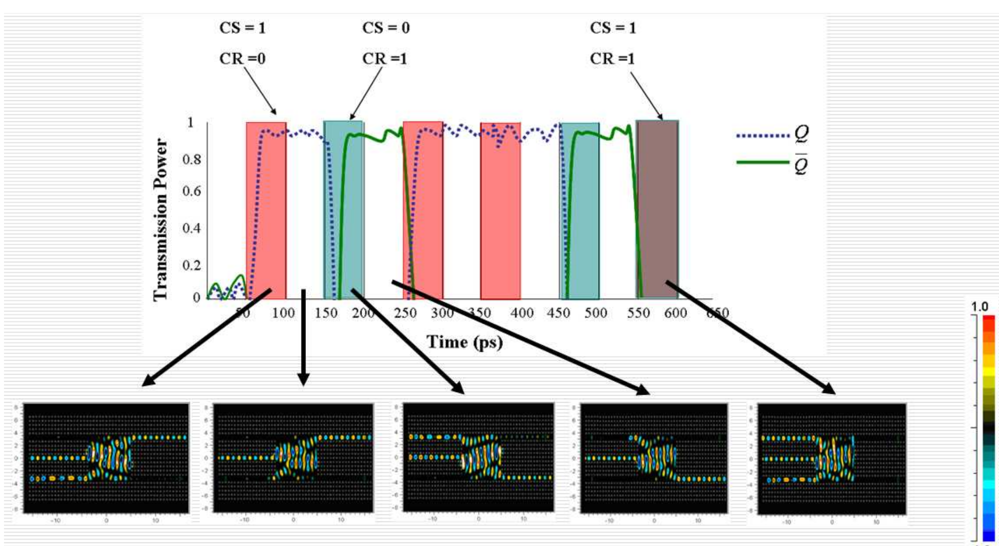

Figure 4: Time sequence of three inputs (single, control set, and control reset), and two outputs (Q, and $\bar{Q}$). The bottom plots are snapshots of intensity profiles of the RS flip flop device.

index of the rods are $r = 0.18a$, and $n = 3.6$. The radius of the point defect $R1 = 0.31a$ in the control R (CR) and control S (CS) waveguide.

By changing the states of two control ports (CS and CR), the states of the output port will also be changed. In this simulation, the incident wave with wavelength $\lambda = 1.55\,\mu\text{m}$ is launched as a signal. Here, we assume the boolean values "0" and "1" corresponding to the absent of the output field or not. For the case 1, when the states of CS and CS are "1" and "0", respectively, the output Q is "1" and $\bar{Q}$ is "0". If the control set is turned off in the next timing, the output port will remain the same state. For the case 2, when CS is "0" and CR is "1", the output Q is "0" and $\bar{Q}$ is "1". If the control reset is turned off in the next timing, the output result was not be changed. For the case 3, when CS is "1" and CR is "1", the output Q is "0" and $\bar{Q}$ is "0". All of the numerical results are shown in Figure 4.

3. CONCLUSIONS

We propose a new design of an all-optical RS flip-flop based on the MMI PCW. By introducing a point defect rod both in the control ports, we can make outgoing field propagating in the output waveguide or not. The intensity profiles show snapshots optioned at different times. This numerical results show that the proposed PC waveguide structure could really function as an all-optical RS flip-flop logic gate. Note that if we have an RS flip-flop, we can realize various much complex logic processing based on it.

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