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Low Input Power an All Optical 4×2 Encoder based on Triangular Lattice Shape Photonic Crystal

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Abstract: An all optical encoder based triangular lattice shape photonic crystal (PC) is proposed. The device is composed of two ring resonator waveguides and two OR gate with four input ports waveguides and two output ports waveguides in triangular lattice shape PC. The band diagram of base PC structure calculated by plane wave expansion (PWE) method. Also, transmission and distribution of electrical field behaviors of the proposed device are verified by two dimensional finite difference time domain (2D-FDTD) method. The proposed 4×2 encoder can operate at third communication window range, considering definitions of logic 0 and 1 being the normalized transmission as less than 3% and greater than 95% respectively. Despite the nonlinear encoders, in our case, due to the non-use of non-linear effects such as Kerr effect, low input power required for encoder.

Keywords: optical encoder, photonic crystal, ring resonator, OR gate

1 Introduction

Recently optical computing devices based on photonic crystals (PCs) structures that are applied in optical computing and signal processing [1, 2] has received more attention. Various sort of high speed optical communication systems have been implemented in various all-optical logic gates and encoder applications based on PCs [3–6]. However, most PC based logic gates are still limited by their complex arrangements of crystal rods, which can cause the component to generate extremely undesirable factors. In addition, significantly small number of all optical logic components can be operated on more of computing wave-

lengths; for logic gate applications and optical processing systems. Beside the optical logic gates, encoders [7, 8, 7–10, 11], optical filters [12–17], demultiplexers [18–24], switches [25–29], decoders [30, 31] as well as optical memories and optical modulators [32–35] are other cases of key optical components designed based on PCs. Optical encoders are the devices with 2^N input and N output ports (OUTs). This means that optical encoder is a logic device that designed for generating N-bit binary codes out of 2^N input ports (INs). These ports are binary ports, so they can suppose 0 or 1 values. At any given time only one of 2^N INs can be active (logic 1), and the other ports should be inactive (logic 0). Considering that which IN is active, an N-bit binary code will be harvested at the OUTs. Also optical encoder is a fundamental level in optical analogue to digital converters (ADCs) for introducing a suitable binary digital code from the opposite levels of input analog signal [36–38]. So far several designs have been proposed for realizing PC based optical encoders. Moniem [36] combined four resonant rings with T-waveguide to design a four – two optical encoder. The switching speed and foot print of this encoder is 500 GHz and $1225 \mu\text{m}^2$. Alipour-Banaei et al. [37] proposed PC based encoder by used self-collimation property. The main drawback of their work is high sensitivity upon the phase of input signals. Hassangholizadeh-Kashtiban et al. [38] proposed an optical reversible encoder by combining nonlinear Kerr effect with elliptical resonant rings.

In this paper we used the triangular array structures to embed dielectric rods in the air background to create a two dimensional PC all optical encoder without using nonlinear Kerr effect that makes low input power property. Optical encoders based on nonlinear-Kerr effect, needs to high input power for appearing nonlinearity and this issue causes some unwanted effects such as: increasing the temperature of device and enhancing the probability of damaging which is undesirable. The main layout involved three hexagonal ring resonator filters, four linear waveguides as INs, and two OR gates. Our proposed encoder was able to operate in third communication window range. For analyzing and simulating the proposed structure and

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obtaining its optical behavior, we used RSoft Photonic CAD software, which perform the simulations based on plane wave expansion (PWE) [39] and finite difference time domain (FDTD) methods [40].

2 Design procedure

The logic circuit of a typical proposed 4×2 encoder is composed of four INs, three ring resonator filter, two OR gates in a two dimensional photonic crystal, as shown in Figure 1(b) which is formed of a triangular lattice of infinite circular dielectric rods emerged in air background. A, B, C and D are INs and O1 and O2 are the OUTs. So for realizing the proposed optical four – two encoder first we have to design a ring resonator filter and logic OR gate. The waveguides are formed by removing some of the dielectric rods from the two dimensional photonic crystal in xz plane. The refractive index and radius of dielectric rods are 3.43 and $r = 0.23 \times a$, respectively where $a = 538$ nm is the lattice constant of the PC. In the first step of our designing procedure we must calculate the band structure of bulk PC structure. In order to calculate photonic band gap (PBG) numerical methods are the best candidate. PWE is one of the numerical methods, which is used for extracting PBG by calculating Maxwell equation in frequency domain. The band structure of the fundamental PC is shown in Figure 2. According to Figure 2, the fundamental PC has two PBGs in TM mode and one PBG in TE mode. The first and widest PBG is in TM mode at $0.25 > a/\lambda > 0.37$, λ represents

Figure 1: Schematic diagram of 4×2 encoder.

Figure 2: Band diagram of the base PC.

wavelength of electromagnetic wave. By choosing the lattice constant to be $a = 538$ nm, the PBG will be at $1454 \text{ nm} < \lambda < 2152 \text{ nm}$, which completely covers the third communication window range, so the proposed structure will operate in this wavelength range.

2.1 Ring resonator filter

For design optical ring resonator filter which is one of the important parts of proposed encoder we used a 21×21 array of dielectric rods with aforementioned parameters as the fundamental PC. By removing the row of rods a line defect was created which can be used as an optical waveguide. To connect the IN to the OUT we put the one ring resonator that created by deleting some rods in the area of hexagonal shape ring in xz plane. The final sketch of proposed filter is shown in Figure 3(a). The transmittance spectra of the filter as shown in Figure 3(b). The results of Figure 3(b) shows the complete of wavelength $\lambda = 1550 \text{ nm}$ coupled from port (IN) to port (OUT).

2.2 OR gate

For designing the OR gate required for realizing the proposed encoder, we used a 21×21 array of dielectric rods with aforementioned parameters as the fundamental PC. By removing appropriate dielectric rods two Y shaped waveguide have been created at the bends of

Figure 3: Final sketch of proposed ring resonator filter(a) and transmission spectra of filter(b).

the Y shaped waveguides. The cross section in which these waveguides were connected to each other we located a small defect rod ($r = 0.35 \times a$) at the beginning of output waveguide to increase the amount of optical waves traveling toward output waveguide. The proposed OR gate is shown in Figure 4. X and Y are the input ports and OUT is the output port of the proposed structure. For two input of OR gate, there are four possible combination of input states. The output port (OUT) will be OFF (logic 0) when both input ports are OFF (logic 0). However when any of the input ports or both of them are ON (logic 1) the output port will be ON (logic 1). These working states are shown in Figure 5(a)–(c) and summarized in Table 1. Also, the power level of the output port for different cases is shown in Figure 6(a)–(c). As shown in Figure 6, when one of the input ports is ON the amount of optical power for output port at the steady state is about 0.98 normalized

Figure 4: Final sketch of proposed OR gate.

powers and when both input ports are ON, it will be about 1.96 normalized power.

The proposed optical 4×2 encoder is shown in Figure 7 consists of PC based waveguides, ring resonators and OR gates that created in appropriate locations inside the fundamental PC structure. A, B, C and D are input ports and O1 and O2 are the output ports. In fact the proposed encoder made by combining the three folds designed ring resonator filters and two fold OR gates together.

3 Simulation and results

After finalizing the design procedure, we are going to simulate the proposed encoder and study its optical behavior. For this gain, we employed optical waves with $\lambda = 1550$ nm at each input ports. The all cases of the encoder are as follows:

Case1: when all input ports are OFF ($A = B = C = D = 0$) as shown in Figure 8(a) all of the output ports will be OFF, and the encoder generates “00” at the output ports. The amount of optical power at the output ports for this state is shown in Figure 9(a).

Case2: when $A = 1$ and $B = C = D = 0$, as shown in Figure 8(b) the light waves entering the device from input A will propagate inside waveguide and reach to the one of the input ports of first OR gate by ring resonator so this gate will be ON. When input A is ON, the encoder produces “10” binary code at the binary output ports. The amount of optical power at the output ports for this state is shown in Figure 9(b). One can see that the

Figure 5: Different cases of the designed OR gate: (a) $A=1$, $B=0$, (b) $A=0$, $B=1$, and (c) $A=B=1$.

Table 1: Input–output logical relationship table of OR gate.

Input X	Input Y	Out
0	0	0
1	0	1
0	1	1
1	1	1

optical normalized power, for port O1 and O2 is about 95 % and 0 % respectively.

Case3: when $B=1$ and $A=C=D=0$, one of the input ports of the both OR gates is ON, so according to Table 2, the output ports of the both OR gates (O1 and O2) will be ON. Also as shown in Figure 8(c) the light waves entering the device from port B by two ring resonators to one of the input ports of OR gates so the output ports O1 and O2 will be ON. Therefore when B is ON the encoder produces “11” binary code at the binary output ports. As shown in Figure 9(c) the amount of optical normalized power at both output ports O1 and O2 are 45.5 %.

Case4: when $A=B=D=0$ and $C=1$, as shown in Figure 8(d) the light waves entering the device from port C will propagate inside waveguide and reach to the one of the input ports of second OR gate by ring resonator so this gate will be ON. Thus, when input C is ON the encoder produces “01” binary code at the binary output ports. The amount of optical power at the output ports for this state is shown in Figure 9(d). One can see that the optical normalized power, for port O1 and O2 is about 0 % and 95 % respectively.

Case5: When $A=B=C=0$ and $D=1$ as shown in Figure 8(e) the input ports of the both OR gates are OFF, so all of the output ports will be OFF, and the encoder generates “00” binary code at the binary output ports. As shown in Figure 9(e) the amount of optical normalized power at both output ports O1 and O2 are 0 %.

These all cases of simulated encoder are summarized in Table 2. As shown in the optical power detecting from output ports for case 1 ($A=1$ and $B=C=D=0$), case 2 ($A=C=D=0$ and $B=1$) and case 3 ($A=B=D=0$ and $C=1$) roughly have the same logic

Figure 6: The normalized optical power at the output port when, (a) X port is ON, (b) Y port is ON and (c) X and Y ports are ON.

Figure 7: Final sketch of the proposed optical 4×2 encoder.

levels, but for the case1 ($A = B = C = D = 0$) and case4 ($A = B = C = 0$ and $D = 1$) it is different from other cases and the output power from ports O1 and O2 is zero. The total footprint of the proposed structure is about $723 \mu\text{m}^2$ and it is good candidate for optoelectronic and optical circuits.

4 Conclusions

In summary, we proposed and investigated all optical 4×2 encoder based on PC structures. In the proposed structure without nonlinear optics we performed the switching tasks with low input power and very high speed performance. Each input port had a corresponding output port. Logic 0 and logic1 were defined under the 3% and over the 95% transmission, respectively. They exhibited a high contrast ratio, high transmission, and high compatibility. The proposed 4×2 encoder can be used as key component in third communication window range (1550 nm) and optical computing.

Figure 8: The cases of the proposed encoder, (a) $A=B=C=D=0$, (b) $A=1$ and $B=C=D=0$ (c) $B=1$ and $A=C=D=0$, (d) $A=B=D=0$ and $C=1$, (e) $A=B=C=0$ and $D=1$.

Figure 9: The output power of the proposed encoder when, (a) $A=B=C=D=0$, (b) $A=1$ and $B=C=D=0$ (c) $B=1$ and $A=C=D=0$, (d) $A=B=D=0$ and $C=1$, (e) $A=B=C=0$ and $D=1$.

Table 2: All cases of the proposed 4×2 encoder.

Inputs				Power states		Logic levels	
A	B	C	D	O1	O2	O1	O2
0	0	0	0	0	0	0	0
1	0	0	0	$0.95 I_{in}$	$0.03 I_{in}$	1	0
0	1	0	0	$0.455 I_{in}$	$0.455 I_{in}$	1	1
0	0	1	0	$0.03 I_{in}$	$0.95 I_{in}$	0	1
0	0	0	1	0	0	0	0

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