Design Plasmonic Optical 4×2 Encoder based on 2D Photonic Crystal Ring Resonator

samaneh hamedi (hamedi@sutech.ac.ir)
Shiraz University of Technology https://orcid.org/0000-0003-1393-5609
Roozbeh Negahdari
Shiraz University of Technology
Hamid Reza Ansari
Shiraz University of Technology

Research Article

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Abstract

Digital encoders are one of the key devices required in optical communication and digital signal processing systems. In this paper, a new photonic crystal structure is used to design all optical 4x2 encoder constructed from GaAs rods with square lattice in the pentane bachground based on plasmonic effect. Gold rods have also been used at the interface of dielectric rods and lines defect, which create plasmonic properties into the photonic crystal structure. The designed optical device is composed of four input waveguides and two output waveguides with two ring resonators at the resonant wavelength of 1.4mm with TM polarization. The presented encoder platform has the small size of 19 mm ×33 mm, that makes it to integration into all optical communication systems. The encoder operation is simulated and analyzed with numerical Finite Difference Time Domain (FDTD) method hand Plane Wave Expansion (PWE) method. In the proposed structure, we have shown that by selecting the appropriate radius size for the resonant cavities, the desirable wavelength can be obtained. The maximum values of transmission efficiency for the first and second outputs are 82% and 96%, respectively. Resonant cavities are also located in the crystal lattice in such a way that by activating third input, 50% and 48% of the input signal will be obtained in each output ports indicating (1,1) logic state. So the new plasmonic photonic crystal encoder could be future applicable in the field of optical computing.

1. Introduction

In the future, with the development of high speed and high capacity telecommunication systems, electronic integrated circuits will be replaced by optical integrated circuits. So in recent years, the use of light for data transmission and signal processing in optical devices has been increased [1–3]. In fact, the new generation of communication systems, require high-speed signal processing devices because of the increased demand across domains and transmission platforms. Also, all of data processing require optical or electrical conversion, which ultimately leads to the limitations in the speed of electronic devices compared to optical transmission networks. All optical devices based on photonic crystals (PhC) with properties of high speed, low power consumption and very compact are good candidate to be used in the optical integrated circuits. Photonic crystals are optical periodic nanostructures that effect on the propagation of light with a special feature named photonic bang gap (PBG). PBG is the wavelength ranges which the propagation of light waves inside photonic crystal is forbidden [4]. Today, photonic crystals are used to transmit and analyze optical signals, which reduce the limitations and increases the efficiency compared to other methods [5–7]. On the other hand, the extraction of applications based on photonic crystal is very attractive and is used in the design of new compact digital devices such as all optical memories [8, 9], optical hard drives [10], all- optical programmable logic array (PLA) [11]. All Optical encoders [12–14], along with the other devices including logic gates[5, 14–16] filters [17, 18], switches[19–21] and multiplexers[22, 23] constitute a significant part of optical communication systems. The encoders play an essential role in digital electronics projects. The main application of encoders is all -optical switches used in optical telecomunication and nwetworking [13]. To date, a lot of research has been focused on the design of all-optical encoders. Some of encoders are designed based on the logic gates [24–26]. Tamer A. Moniem realized optical encoder based on 2D photonic crystal ring resonator NOR gates [27]. Mehdizadeh designed a 4-to-2 optical encoder based on photonic crystals with OR gate [28]. Yang presented All-optical photonic-crystal encoder capable of operating at multiple wavelengths based on two ring resonator that each ring act as OR gates [29]. Lee et al supposed a 4x2 all-optical encoder based on the combination of both line defect Y branch and coupler[14]. Ouahab et all proposed an all optical 4x2 encoder by employing Kerr effect in 2D square lattice of silicon rods in photonic crystals[13]. According to the study of the mentioned papers, it is concluded that using an encoder based on a photonic crystal, can be overcome the speed limitations on any signal conversion [29, 30]. One way to improve the light trapping in these structures is to use ring resonators[20, 31]. When all-optical devices should be used in the next generation of optical integrated circuits, it is important to reduce their dimensions. Fabrication problems that prevents from more integration of compact structures led to the use of plasmonic structures[32]. When the dimension of optical devices is comparable of the light wavelength, the limitation of light scattering in the optical devices will occur. The plasmonic nanostructures have unique features of metallic layers on the dielectric elements with the dimension lower than the coupling wavelength[33]. They have the ability to support surface plasmons polaritons and confine light into ultra-small volumes much beyond its free-space wavelength. The plasmons are the oscillation of free electrons that are the consequence of the formation of a dipole in the dielectric-metal interface due to electromagnetic waves. The plasmonic effect is the interaction between free electrons in metal nano particles and incident polarized light. Plasmonic are particles whose electron density can couple with electromagnetic radiation of wavelengths that are far larger than the particle due to the nature of the dielectric-metal interface. Since light couples with the electrons, polarized light can be used to control the distribution of the electrons and the confinement of light will occurs in a small dimension between metal and dielectric interface [34, 32]. There are some researches about plasmonic logic gates like AND, OR, XOR and NOT [35–38]. But photonic crystal has not been used in their optical structure. The results of the some works have shown that the use of plasmonic in photonic crystal structures leads to more light trapping in the line defects and less dimension of devices [39–42]. Using metals at the boundary between the air and dielectric leads to the plasmonic effect that is caused by interaction of the electromagnetic waves [43, 36]. As mentioned later, a lot of researchers have designed all optical encoder based on photonic crystal structure but none of them have used plasmonic effect. In this paper, a 4×2 encoder based on 2D photonic crystal structure using plasmonic effect in a new defect line architecture is designed for the first time. Using palsmonic in photonic crystal structure is especial feature of the designed encoder of this paper. In order to further trap light and increase waveguiding in the photonic crystal structure, gold nano rods has been used at the boundary between background and gallium arsenide rods. Also, with the design of two ring resonators, light resonating has been increased. We have used plane wave expansion (PWE) [44] method to simulate the band diagram of the photonic crystal structure and finite difference time domain (FDTD) [45] method to analyze the optical behavior of the proposed encoder. The rest of this paper is organized as follows: In Sect. 2, we have shown the basic structure of an encoder. The photonic band gap (PBG) and the band structure have been shown in Sect. 3 and also a schematic of the designed structure is shown in this section. Finally the simulation results are

2. Encoder Basic Structure

Encoders are digital circuits that capture an input data and generate the equivalent binary code at the output. Encoders make decisions based on the value of all inputs at any time and produce an equivalent binary output. Therefore, a binary encoder is a combined logical circuit with several inputs that only one of the input is active at any time. In general, an n-bit encoder has 2^n input lines and n output lines. The most common encoders are 4×2, 8×3, and 16×4 encoders, which we have used a 4×2 encoder in this paper. As shown in Fig. 1, a 4 × 2 encoder has four inputs namely (I_0, I_1, I_2, I_3) and two binary outputs (Q_1, Q_2). Table 1 is the truth table of the mentioned encoder. It represents that, there are four cases for the output data while each input is active. From the truth Table 1 at a time, only one input is active (logic 1) and others are inactive (logic 0). Depending on the input active the equivalent binary value is placed at the output. The corresponding output binary values of the input signals (1000), (0100), (0010) and (0001) are digital values of (00), (01), (10) and (11) respectively.

Table 1 The truth table of a 4×2 encoder.

I_0	I_1	I_2	I_3	O_2	O_1
1	0	0	0	0	0
0	1	0	0	0	1
0	0	1	0	1	0
0	0	0	1	1	1

3. Encoder Design

In this work the unit cells for designing the optical encoder are arranged in a square lattice to form a 2D photonic crystal (PhC) structure. The unit cells are dielectric rods in the form of circular. Gallium Arsenide (GaAS) has been used as dielectric rods with a refractive index of 3.94. The radius for GaAs rods is 70nm and the distance from center to center (lattice constant) for GaAs rods is 375nm. As a result, the ratio of radius to lattice constant (r/a) will be 0.18. In the designed structure, the array of dielectric rods are with the total size of 19 μm ×33 μm that has been used in the pentane (C_5H_{12}) background with the refractive index of 1.35 at Infrared wavelengths. The band structure diagram or dispersion curve for the proposed PhC structure without defects is shown in Fig. 2. Plane wave expansion (PWE) method is used to plot the band structure diagram. In the dispersion curve, the horizontal axis is the most symmetrical directions (ΓX, XM, MΓ) of the input light beams and the vertical axis is frequency. As shown in Fig. 2, there is a PBG in TM mode (blue color) and a PBG in TE mode (red color). The PBG in TM mode, which is at the range of 0.255nm < a/λ < 0.34nm, is the preferred frequency range for plasmonic structure. As previously stated, the lattice constant (a) is 0.375nm, so the wavelength of PBG is in the range of 1102nm <λ<1470nm. So the wavelengths in the mentioned range can be used as light waveguiding in the line defects. The most on photonic crystals is selection of the appropriate wavelength in the range of common telecommunication to enter in the structure and guide in the line defects

The designed 4×2 optical encoder has four inputs and two outputs. So to implement the mentioned encoder we need to create six optical waveguides and two resonant rings. The proposed encoder structure based on 2D photonic crystal is shown in Fig. 3. It consist of four input waveguides namely as I_0, I_1, I_2, I_3 and two output waveguides labeled as output1 and output2. For implementation of the optical waveguides from the inputs to the outputs, the line defects have been created by removing two rows of GaAs rods. In this design, the aim is that all the light entered from the inputs I_1 and I_2 would be received at the outputs 1 and 2 respectively. For this purpose, the defect paths are connected from inputs 1 and 2 to outputs 1 and 2, respectively.

Also, two circular ring resonators are created with different diameter between the output ports by eliminating two rows of GaAs in circular shape. The two resonant cavities have been used to intensify transmission of the light in the central part of the structure. As shown in Fig. 3, the two ring resonators are created on the place to connect the input I_3 to the output waveguides. The output waveguides are located at the end of the input waveguides I_1 and I_2 on one side and are connected to the rings on the other side. The interface between the line defects and the main structure of the photonic structure is covered with gold nano rods (gold rods are shown in blue color in the structure). The radius of the gold rods is set at 47nm and their lattice constant is 187.5nm. So, the interaction between the metal (gold) and the electromagnetic waves of the coherent input light occurs by placing gold rods at the boundary of the line defects and GaAs rods (dielectric). The result of this interaction is the creation of plasmonic properties into the metal –dielectric interface. So in the designed photonic crystal structure, maximum confinement of the light in the line defects occurs and more light would be trapped in the waveguides. As a result of the plasmonic is a greater monopoly of light in waveguide lines, which ultimately leads to transferring a higher percentage of the input power to the outputs. The center of the ring resonators consists of a combination of 12 gold rods leads to the creation of micro cavities. The encoder operation is obtained by the coupling action between the line waveguides and the rings that is created by the point defects with gold rods in two photonic crystal ring resonators which have a resonant wavelength of 1.14 μm with TM polarization. So the wavelength of the coherent light source that is used in encoder is considered to be $\lambda = 1.14$ μm. This means that the encoder can work in telecommunication applications.

It can be seen from Table 1, the output port 1 will be on (i.e. logic 1) when both input ports I_1 or I_3 are on state (logic 1) and any of other inputs are off state (logic 0). The digital circuit for combination of the input states is designed with 2 input OR gate. Similar to the first output, the second output port (Q2) is on state (logic 1) when the inputs I_2 or I_3 are on state (logic 1). These working state as Boolean function is represented in formula (1). As can be see the encoder structure will be designed from combination of 2 input OR gates.

$$Q_1=I_1+I_3 \qquad (1)$$
$$Q_2= I_2+I_3$$

Figure 4 shows the Boolean function and an electronic circuit of a 4 to 2 encoder. The relation between the outputs and inputs is composed of 2 OR gates which ring resonators are denoted as OR gate.

4. Simulation Results

After design the PhC structure, we are going to simulate the proposed all optical encoder and study its optical behavior. Excitation of light from the four inputs and their optical behaviors has been performed using finite difference time domain (FDTD) method. To simulate the optical waveguiding in the proposed encoder, a coherent Gaussian light source at a wavelength of 1.14μm with TM polarization is used at the input ports. The working states of the designed 4×2 encoder has 4 approaches. In approach 1 only input I_0 is ON and other inputs are OFF (I_1 = I_2 = I_3=0). As can be seen from Fig. 3, when input I_0 is excited, the light should not been received at any of the outputs 1 and 2 because I_0 input has no connection with the outputs. To do this, we first excited the input I_0 with a coherent light source at a wavelength of 1.14um and the result is illustrated in Fig. 5(a). When input port 0 is exited the logic state (0, 0) should be at the outputs. It is shown from the transmission spectrum that the optical power to the outputs is very low. As mentioned above, using gold rods at the boundary between the line defects and the main structure lead to the plasmonic effect. So the confinement of the light beam in the waveguide is so much and the light will not leak to the photonic crystal structure. This claim is proved by observing the light behavior in the first input waveguide (I_0) and transmission spectrum in Fig. 5. It is shown from Fig. 5 (b) that the value of the optical transmission at the outputs is minimum and in the order of 0.0001 at the wavelength of 1.14μm. As a result, the use of gold rods with the mentioned radius and lattice constant will increase efficiency and reduces the output loss.

As shown in Fig. 6, in designing the logic circuits if the output signal is higher than 45%, it is equal to logic 1, and if it is less than 5%, it will be logic 0.

As it was mentioned for approach 1, the value of transmission spectrum from the two outputs of encoder are less than %5, so the logic state in the output ports is (00). In approach 2, I_1 = 1 and I_0 = I_2 = I_3=0, and the encoder will generates the logic state (01) at the output ports. By exciting port I_1, the maximum output optical power is expected to be received at the output 1. As can be seen from Fig. 7, we have 82% of the input light at the output 1, and the rest has entered into the ring resonator. The point defect in the ring resonator prevents the optical transmission to the other inputs and outputs. So the maximum optical power is transferred to the output 1. As it is represented from the transmission spectrum (Fig. 6.b) the output port 2 has very little optical signal at the order of 0.01.

As a result of the output transmission spectrum, the output port 1 has the signal more than %45 and the output port 2 has the signal less than %5, so the logic state (01) is at the output ports for input I_1. In approach 3, the input port I_2 is active (logic 1) and the other inputs ($I_0 = I_1 = I_3$) are in logic state 0. So the encoder generates the logic state (10) at the output ports. As expected, by exciting port I_2, we receive 96% of the light at the output 2 and very less or no optical signal at the output 1. The transmission curve of the outputs is represented in Fig. 8.

In approach 4, $I_3 = 1$ and $I_0 = I_1 = I_2=0$ and the two outputs of the encoder will be in logic 1. By exciting I_3, the light couples to both ring resonators and enters to the output waveguides. Figure 9 shows the light behavior and transmission diagram when port I_3 is excited. It is shown that the light is splitted in two parts as follows: the upper ring resonator couples the light in to the output 1 and the lower ring resonator couples the light in to the output 2. It can be seen from transmission spectrum that at the wavelength of 1.14μm, the maximum amount of signal is received at the outputs 1 and 2. From the normalized value of transmission spectrum, 50% and 48% of the input power enters to the output 1 and output 2 respectively. Since the value of both signals is higher than 45%, the logic state of the output will be (11). From the light behavior of the encoder (Fig. 9.a), the coupled light to the output doesn't return back to the input waveguides and doesn't leak to the photonic crystal structure due to gold rods.

The results of previous works have shown that the use of plasmonic in photonic crystal structures leads to more light trapping in the line defects and less dimension of device. Considering that these circuits should be used in optical integrated circuits, it is important to reduce their dimensions.

Conclusions

In this paper, a digital all optical 4×2 encoder based on 2D plasmonic photonic crystal using novel defective structures was proposed. The optical device was composed of the array of GaAs rods in the pentane (C_5H_{12}) background. Unlike many previous works use air as background, this structure used pentane with a refractive index of 0.3 higher than air. To prevent from light scattering to the PhC structure, we used gold rods at the interface of the line defects and the PhC background. Gold rods caused to plasmonic behavior in the interaction of light in the photonic crystal structure. The encoder structure was composed of 6 optical waveguides and 2 plasmonic ring resonators with a resonance wavelength of 1.4 μm which is in the Photonic band gap (PBG) range. The structure dimension was ultra-small with area (19μm ×33μm), that can be used for all optical integrated circuits. The ring resonators have been used to intensify the light and play a key role in the coupling the input I_3 to the two outputs indicating (1,1) logic state. The analytical simulation of the device to show the optical waveguiding behavior and the band diagram of PhC structure was based on FDTD and PWE methods respectively. The output optical power for this encoder was very low in the range 0.001 in OFF state, which causes an enhancement of the contrast ratio. The maximum optical values of output ports 1 and 2 were about 82% and 96%, in ON state respectively. So, the proposed plasmonic structure eliminates the dimension limitation and increases the performance of optical networks and signal processing in the future optical integrated circuits.

Declarations

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Conflicts of interest/Competing interests (The authors declare that they have no conflict of interest)

Availability of data and material (not applicable)

Code availability (not applicable)

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Figures

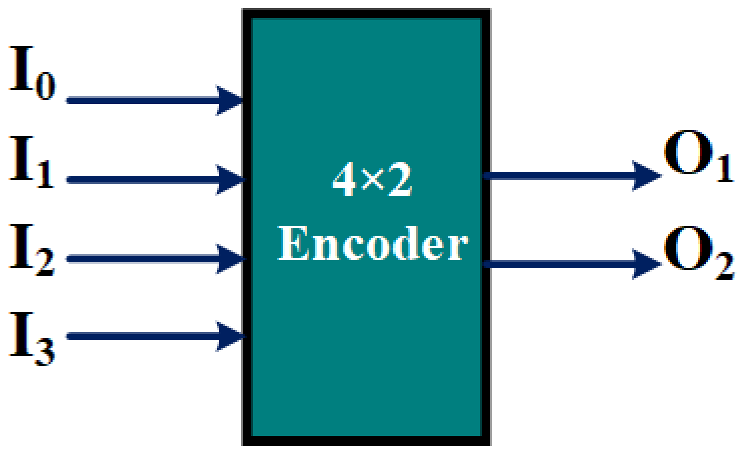

Figure 1

The schematic of the logic circuit of a 4×2 encoder.

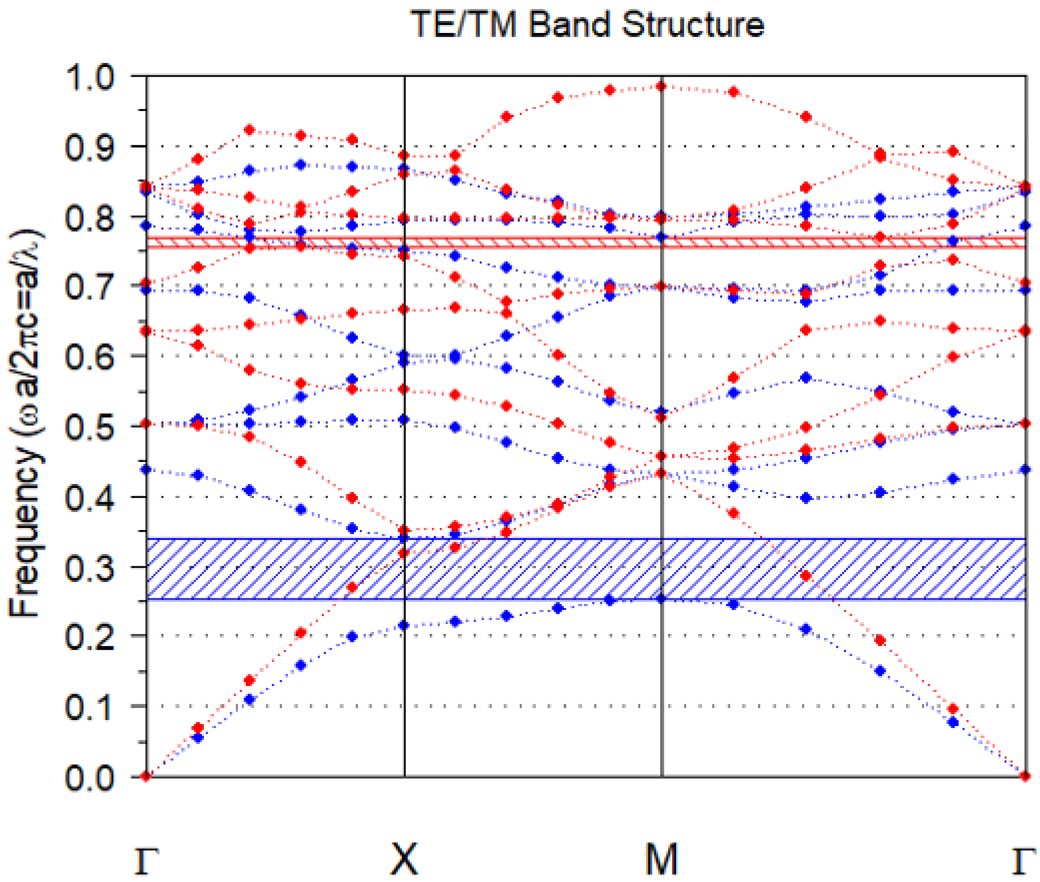

Figure 2

The band structure of the proposed structure for TE/TM mode.

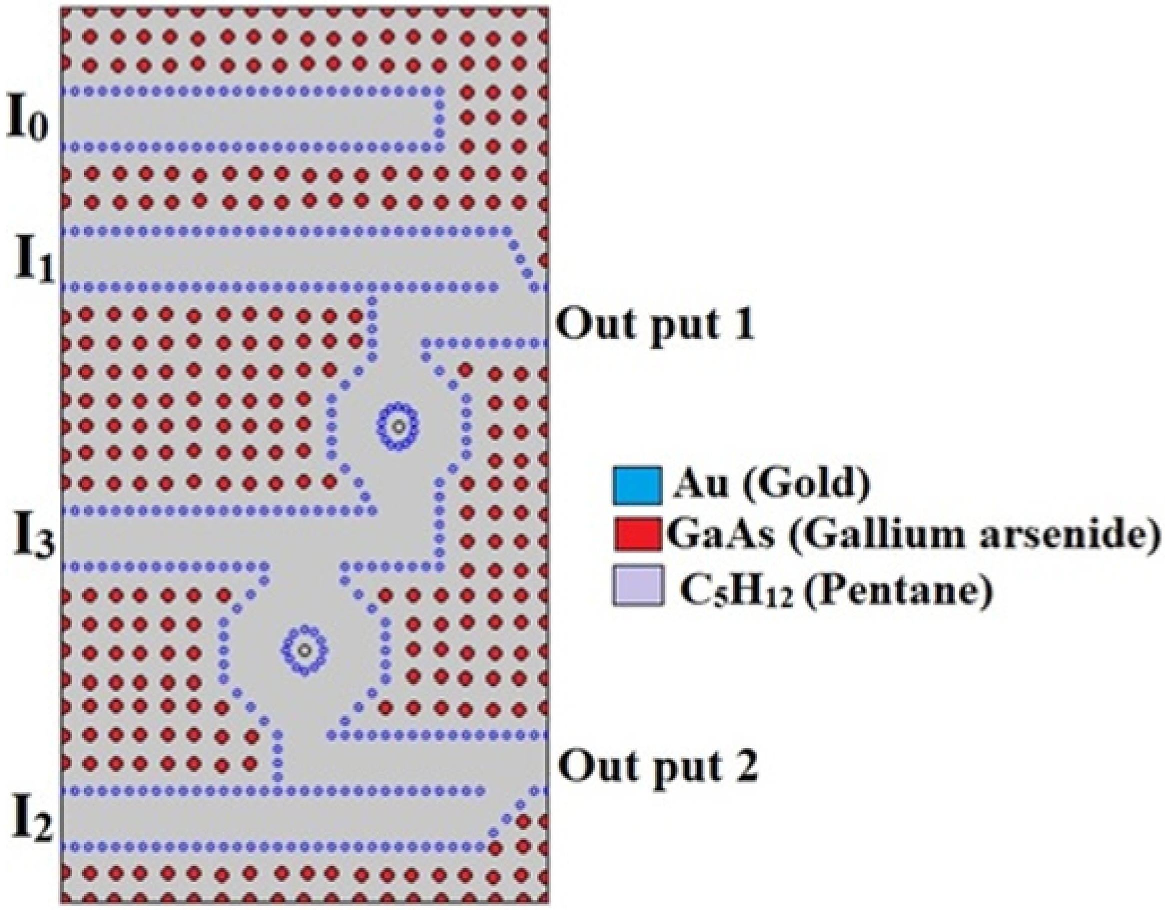

Figure 3

The structure of all optical 4×2 photonic crystal encoder.

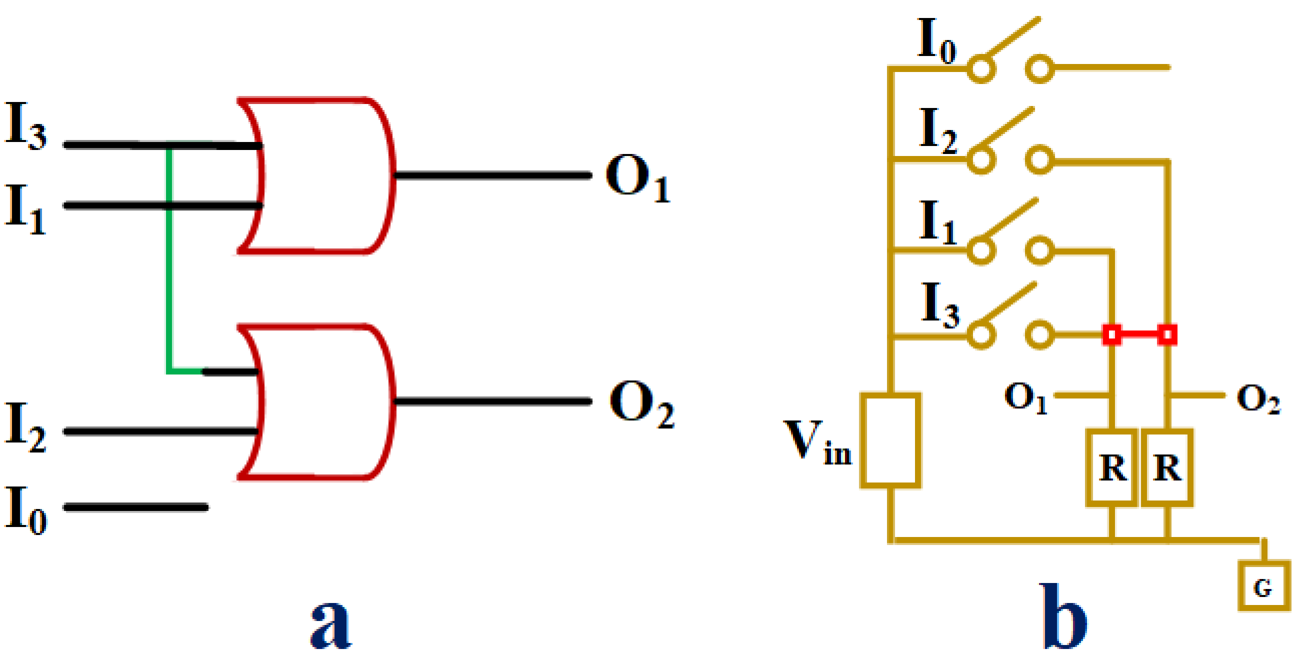

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Figure 4

Boolean function (a) and electronic circuit (b) of the designed encoder.

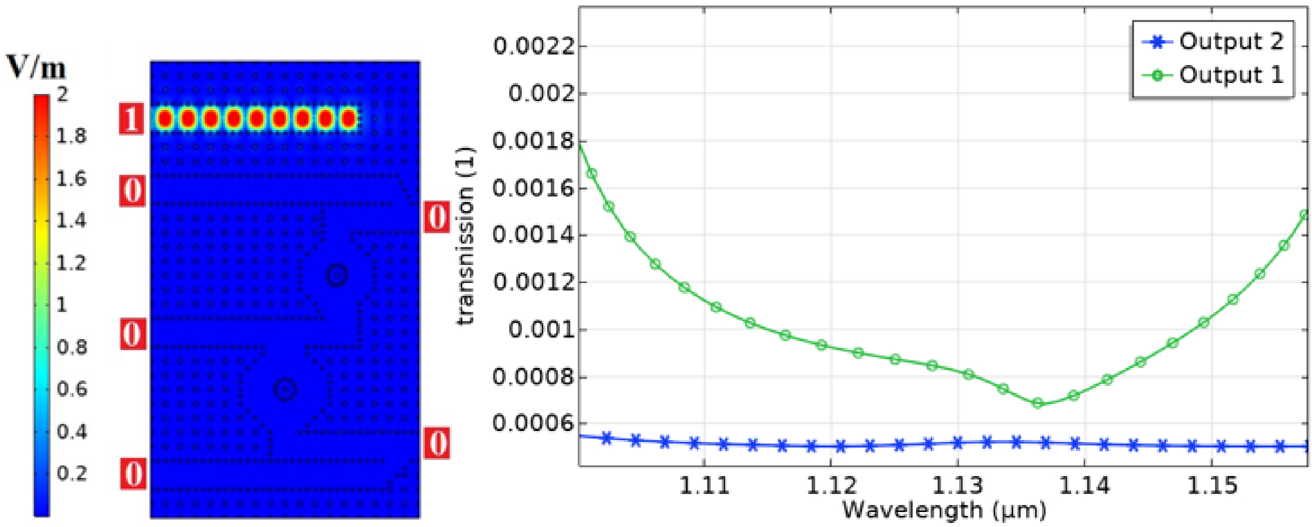

Figure 5

(a) Light behavior and (b) transmission diagram, while port I0 is excited

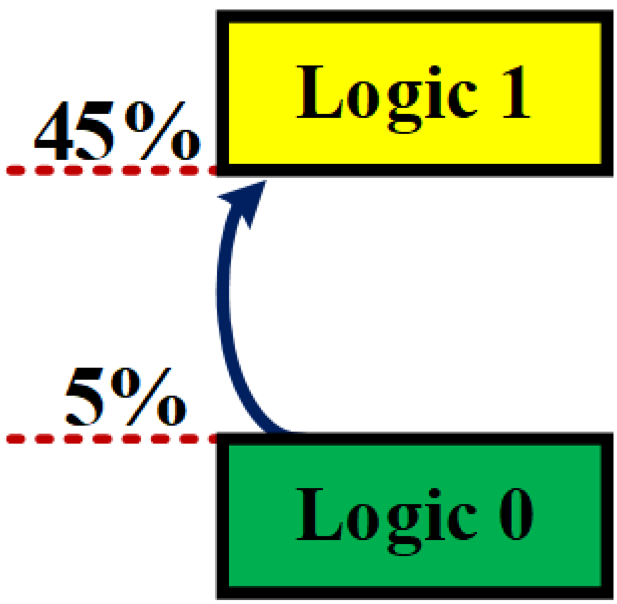

Figure 6

Transmission level ranges

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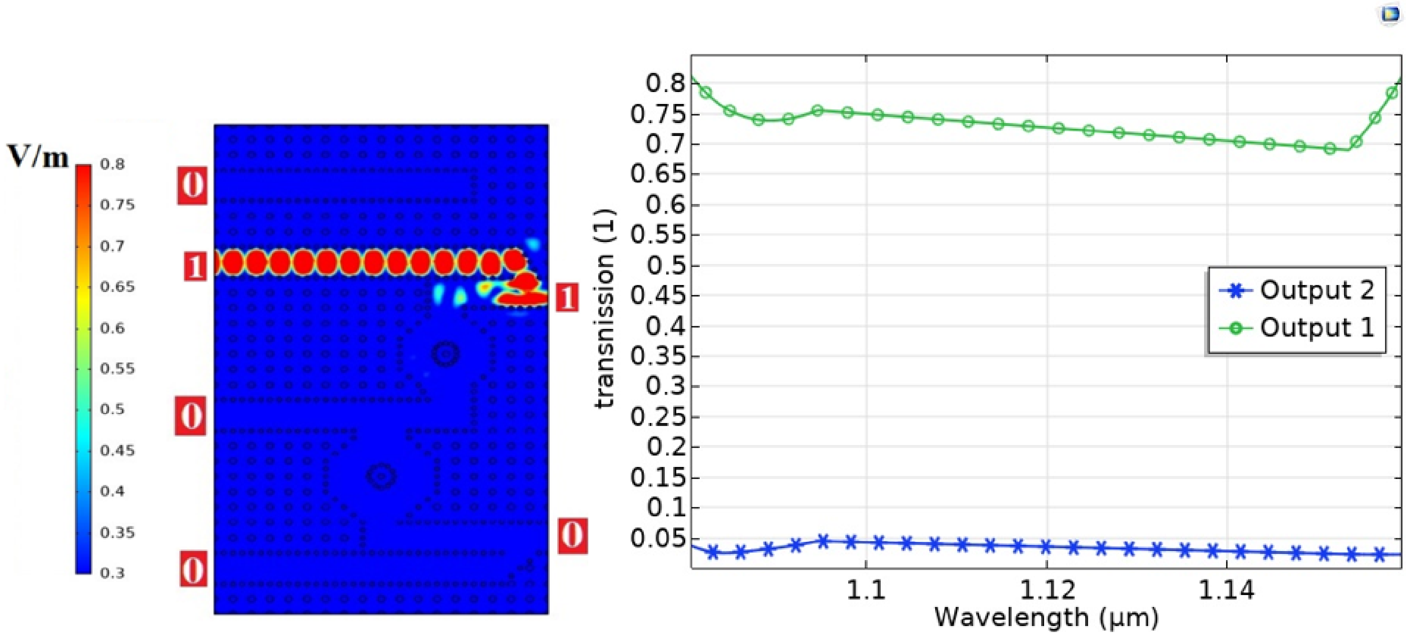

Figure 7

(a) Light behavior and (b) transmission diagram, while port I1 is excited

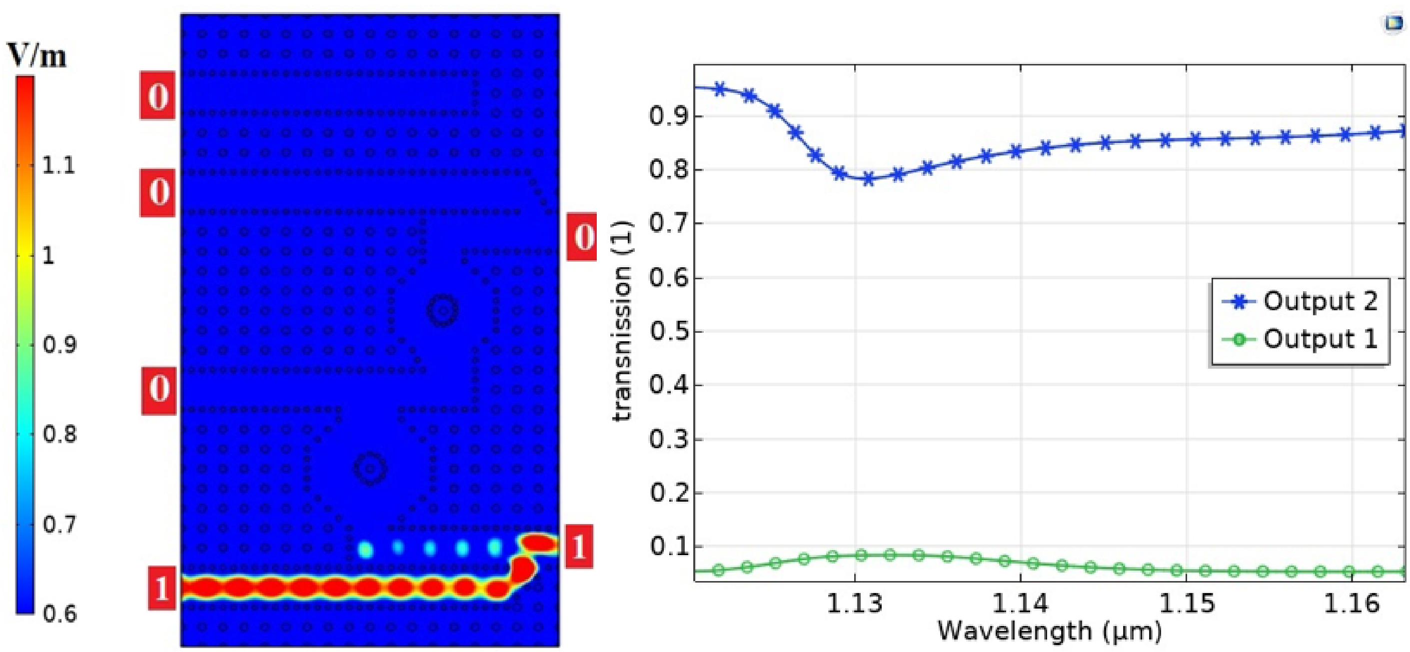

Figure 8

(a) the electric filed distribution of proposed plasmonic encoder Light behavior and (b) transmission diagram, while port I3 is excited.

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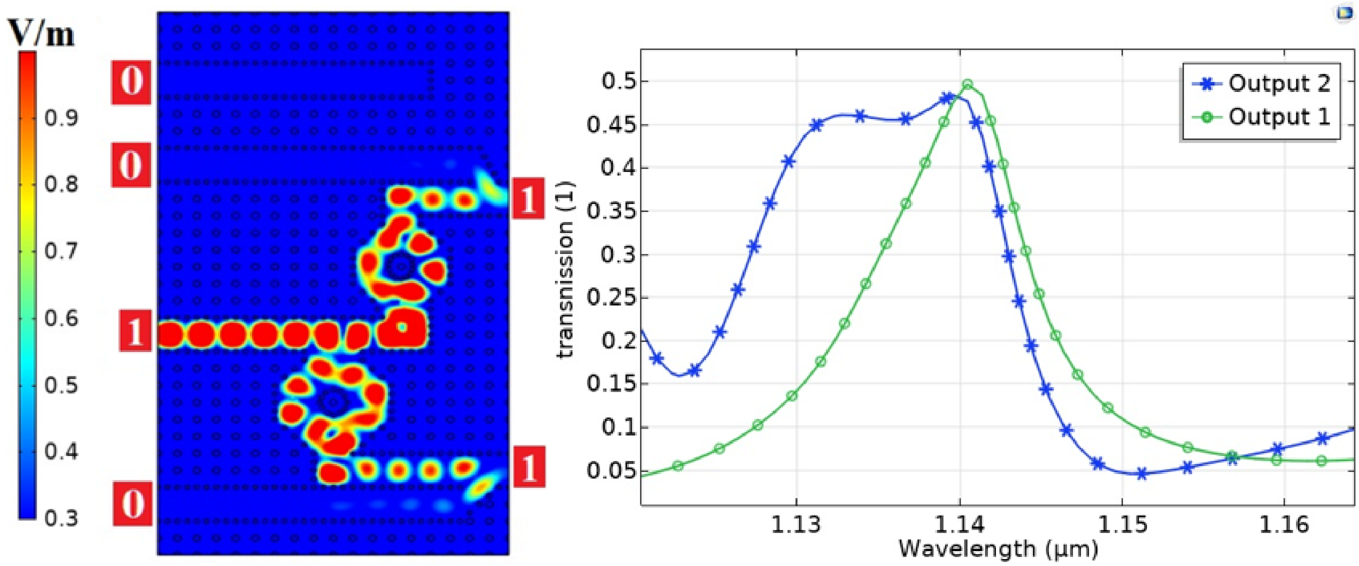

Figure 9

(a) Light behavior and (b) transmission diagram, while port I2 is excited.

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