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A proposal for 1×8 all-optical switch using multimode interference

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We propose an eight-channel all-optical switch using a multimode interference phenomenon. This structure is based on the cooperation of self imaging and self guiding in nonlinear multimode interference. The switching operation is done with changing the intensity of the input signal. To the best of our knowledge, this is for the first time that a 1×8 all-optical switch is presented based on a continuous multimode interference region. Simulation results show low crosstalk and high efficiency in the output profiles. The mean values of the crosstalk and the insertion losses in eight states of the switching operation are –33.8 dB and –0.16 dB, respectively. Full-vectorial beam propagation method is used for the simulation of the device.

Keywords: all-optical switch, multimode interference, crosstalk, insertion loss.

1. Introduction

Optical switches are the key components in optical communication systems. Some of the well-known methods in optical switching are based on thermo-optic, electro-optic and all-optical configurations. Two first configurations have some disadvantages, such as low speed and hard to implement. In the past years, the demands for low cost, high speed and small dimension structures in optical switching have been increased. In optical communication, the demands for high channel numbers and high bandwidth have caused the replacement of the past configurations with all-optical alternatives. Recently, many structures have been proposed for all-optical switching that are based on Mach–Zehnder interferometer (MZI) structures using multimode interference (MMI) [1], ring resonators [2] or semiconductor optical amplifiers [3], photonic crystals [4], optical fibers [5] and individual MMI configurations [6–8]. Some of them have the problem of interaction of photon and electron that decreases the speed of the device. MMI structures are the desired configurations due to their compact size, low loss, polarization independency and easy fabrication properties. New attempts in MMI structures are based on applying them individually for desired purposes. Because a compact and simple continuous MMI region can work without any external device or any complexity, RODGERS *et al.* [6] presented a self-guiding effect in MMI structure and applied it for switching purposes. But this work had not good calculation and discussion. GANG JUN LIU *et al.* [9] introduced a variational technique to analyze the beam propagation in nonlinear multimode interference. This work had more focus on finding the best method for analyzing.

In this paper, we presented a nonlinear MMI structure for an eight-channel all-optical switch. We were looking for a simple structure for all-optical switching with high speed and high channel numbers that provide the demands for high level switching. In our proposed structure, the switching operation is based on the cooperation of self imaging and self guiding in nonlinear multimode interference in different intensities. To the best of our knowledge, this is for the first time that an eight-channel all-optical switch is proposed using one multimode region. The simulation results show high efficiency for receiving the input signal in output ports. In the next section, the theoretical background of multimode structures will be explained. The design characteristics and simulation results are shown in Sections 3 and 4.

2. Theoretical background

According to that the operation of the proposed structure for all-optical switch is based on the cooperation of self imaging and self guiding effects in multimode interference structure, there is a need that the theoretical background of these effects is presented.

2.1. Self imaging in multimode interference devices

In MMI structures, an input field profile is reproduced in single or multiple images at periodic intervals along the propagation direction based on self-imaging. For an MMI structure, the beat length of two lowest order modes of light with wavelength λ_0 which propagates in a step-index waveguide with effective refractive index n_r and effective width W_e, can be expressed as [10]:

$$L_\pi = \frac{4 n_r W_e^2}{3\lambda_0} \tag{1}$$

where W_e is

$$W_e = W_m + \frac{\lambda_0}{\pi}\left(n_r^2 - n_c^2\right)^{-\frac{1}{2}} \tag{2}$$

where W_m is the width of MMI and n_c and n_r are the refractive indices of the cladding and core layer, respectively. For different lengths of an MMI structure, the vertical position that the input field can be reproduced and the number of outputs will be different. In a length equal to even and odd multiple of $3L_\pi$, the input field can be produced in the same or mirrored position at the end of the MMI section, respectively.

The N-fold outputs will be formed in $L = (P/N)(3L_\pi)$ with integers $P \geq 0$ and $N \geq 1$ with no common divisor.

2.2. Self guiding principles

In a nonlinear waveguide, increasing the intensity of the input signal causes the change in the refractive index of the material. The refractive index of a nonlinear waveguide is proportional to the intensity of the input signal as:

$$n = n_0 + n_2 I \tag{3}$$

where n_0 is the linear refractive index, n_2 is the Kerr nonlinearity coefficient and I is the intensity.

With increasing the intensity of the light, the refractive index of material in front of the light will increase. Therefore, increasing the intensity of light to higher quantities makes a new thin waveguide in front of the light that can confine the light in it. When the light beam was confined in a self-induced waveguide, the self-guided beam is produced. For self guiding phenomena there have to be a waveguide of a material with positive Kerr nonlinearity.

3. Design characteristics

A nonlinear two-dimensional multimode waveguide can be described by the nonlinear Schrödinger equation [9]:

$$2ik_0 n_{\text{eff}} u_z + u_{xx} + k_0^2 \left[n(x)^2 + \gamma |u|^2 - n_{\text{eff}}^2 \right] u = 0 \tag{4}$$

where $n(x)$ is the refractive index profile of the multimode waveguide, k_0 is the reference wave number in free space, n_{eff} is the effective index and γ is related to the nonlinear index coefficient n_2 by $\gamma = n(x)^2 n_2 c \varepsilon_0$.

Firstly, the behavior of multimode region in the different intensities has to be analyzed to show the cooperation of self imaging and self guiding effects. The basic structure of a multimode interference device is shown in Fig. 1**a**.

Equation (4) can be solved with a full-vectorial beam propagation method. As explained in the second section, for low intensity inputs, the multimode region works based on self imaging principle. The simulation of the structure in low intensity is shown in Fig. 1**b**. But with increasing the intensity, the self guiding effect will be seen. According to this effect, with increasing the intensity of the input signal, the high intensity points in MMI region will be stronger and low intensity regions will be weaker. Because the high intensity increases the refractive index and therefore high refractive index focuse the light, frequently. With increasing the intensity, the self guiding effects will conquer self imaging, gradually. But in higher intensities the Gaussian beam will be broadened and the power will be shifted to left and right sides. As shown in Fig. 1**b**, in the length of L_x the higher percent of the input field is

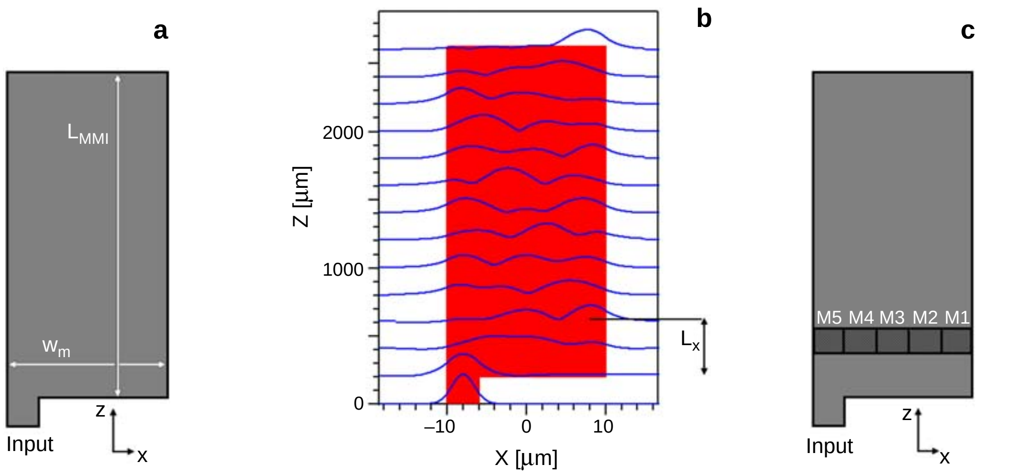

Fig. 1. Basic structure of multimode interference devices (**a**). Beam propagation simulation of the structure in linear state (input intensity is low) (**b**). Structure with five power monitors for the simulation of the specified region (**c**).

gathered for the first time. We choose this point for analyzing the behavior of MMI structure in different intensities. In a cross-section of the structure in this length in the right side of the MMI width, intensity is high, in the center is lower and in the left side, the intensity of light is almost zero. In that point we separated the width of MMI into five sections and placed five monitors to simulate the regions separately. These monitors can be seen in Fig. 1**c**. With injecting the low intensity input signal, the region of monitor M1 is the first region in which the intensity of light beam will be high. With increasing the intensity of input light, the Gaussian beam is broadened and the power is shifted to the side regions. The effect of increasing the intensity on the behavior of MMI is shown in Fig. 2.

As shown in Fig. 2, for low intensity, the power of monitor M1 is higher than the others. Therefore, with increasing the input intensity, the value of this monitor will

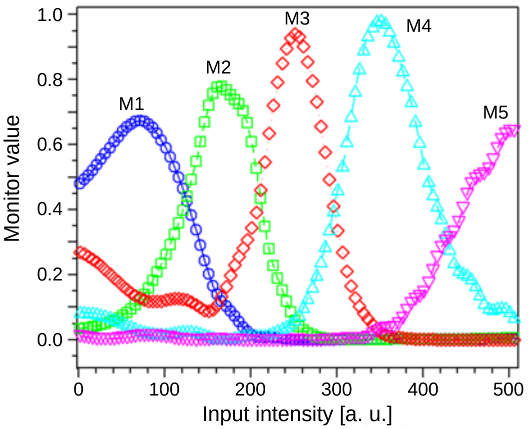

Fig. 2. The effect of input intensity in the power of monitors in length L_x.

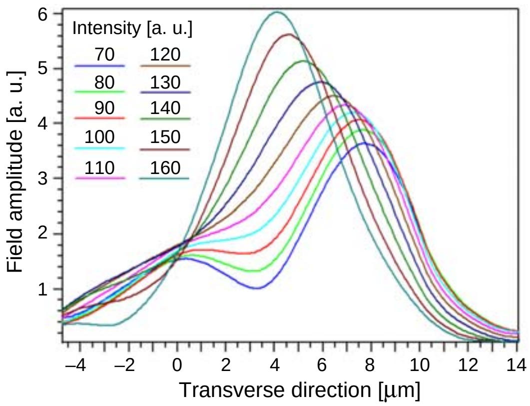

Fig. 3. Effect of changing intensity on field profile distribution in length L_x.

increase. But in higher intensities, according to self-guiding principle, the value of this monitor will decrease, because the light beams like to be focused in a straight path from input to output. Therefore, with increasing the intensity, power of light is shifted to the left-hand regions and is focused in front of the input port. This behavior can be clearly seen in Fig. 3.

As shown in Fig. 3, the field profile has been shifted with increasing the intensity. This figure shows that the light beam has tendency to be shifted to the left, which shows the self-guiding effect and emphasizes the behavior of the light in Fig. 2. Figure 2 shows that for achieving the straightforward path, the intensity of the input signal will be increased to very high levels which causes other problems like two photon absorption. But for the design of a switch, very high intensities are not necessary and this work can be done just with changing the intensity of different states of switching operation. The structure of the proposed device for 1×8 all-optical switch is presented in Fig. 4.

Fig. 4. The proposed structure for 1×8 multimode interference switch.

As shown in Fig. 4, the proposed structure is composed of a multimode interference region, one single mode input waveguide and eight single mode access waveguides in the output. The width and length of the MMI region is 50 µm and 12200 µm, respectively and the width of access waveguides are 4 µm. The used material is polydiacetylene PTS with the Kerr nonlinearity about 2×10^{-4} µm^2/W [6]. The refractive index of core and cladding layer is 1.66 and 1.652 that shows almost good confinement.

4. Simulation results

Figure 4 shows our proposed structure for 1×8 all-optical switch. In the low intensity input state, the structure behaves based on self-imaging principle in MMI structures. But while using a high intensity input signal, the cooperation of self-imaging and self-guiding effects takes place. In the high level input, changing the intensity of an input signal causes the change in the path of the light. We used this effect for designing an eight channel all-optical switch. The simulation results of the proposed structure in eight states of switching operation are shown in Fig. 5.

As shown in Fig. 5, with changing the intensity of an input signal, the path of the light beam has been changed. As explained in Ref. [9], when the intensity of the input signal is high enough, the light beam behaves as an integer and experiences a zigzag path. This behavior can be seen in Fig. 5. In first state, the intensity of the input signal is 56 W/μm^2 that shows the intensity of input signals when one dimension is normalized in 2D simulations. Simulation results show high performance

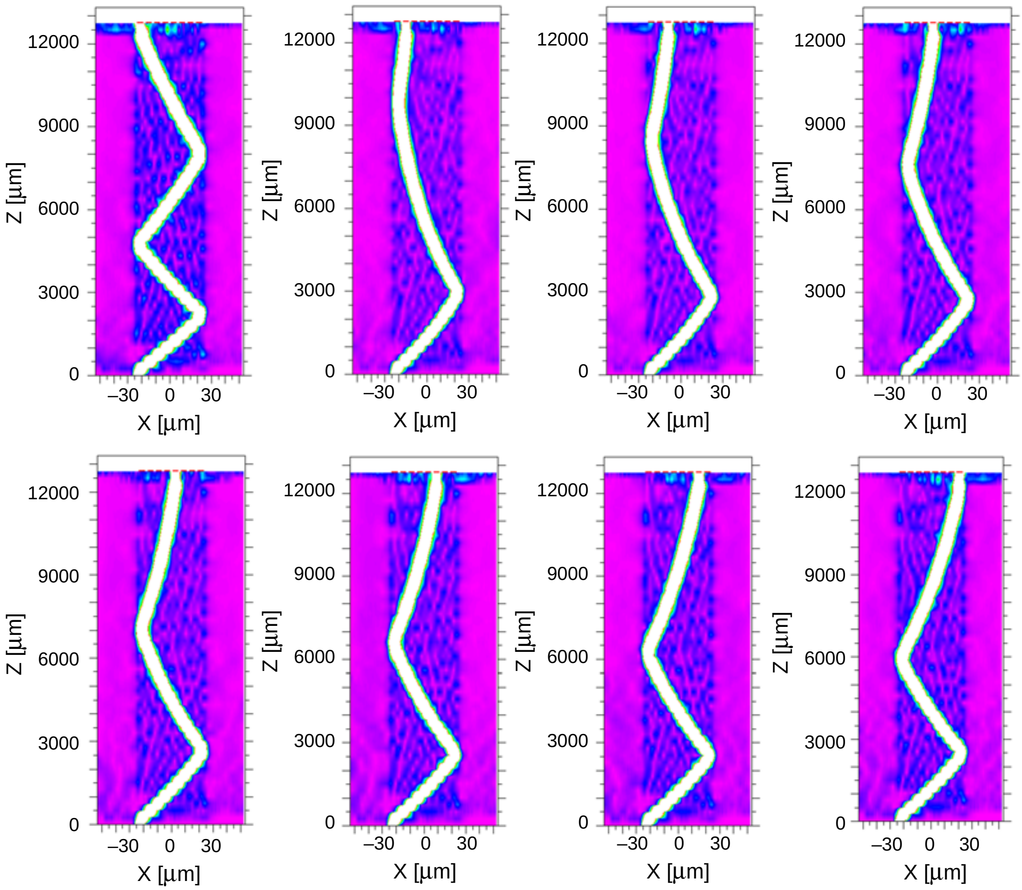

Fig. 5. Simulation results of the proposed structure in eight states of switching operation.

Table. Insertion loss and crosstalk of the proposed switch.

	State 1	State 2	State 3	State 4	State 5	State 6	State 7	State 8
Intensity [W/μm²]	56.25	63.2	62.52	61.87	61.3	60.75	60.2	59.6
Output port	Out 1	Out 2	Out 3	Out 4	Out 5	Out 6	Out 7	Out 8
Insertion loss [dB]	−0.27	−0.15	−0.12	−0.17	−0.10	−0.15	−0.11	−0.24
Crosstalk [dB]	−36.7	−36.8	−32.0	−39.8	−29.9	−30.3	−29.9	−35.0

of the structure. Insertion loss in ON state and the crosstalk of the device are shown in the Table.

The insertion loss I.L. can be calculated as:

$$\text{I.L.(dB)} = 10 \log \frac{P_{\text{out}}}{P_{\text{in}}}$$

where P_{out} and P_{in} are the output and input power.

Crosstalk is the ratio of output power in effect of the desired input per the output power in effect of all of the unwanted inputs. But there is one input in this structure. Therefore, for calculating the crosstalk value, second input field is assumed to be injected from the other side of width of the structure. As shown in the Table, the best and worst case of crosstalk is –39.8 dB and –29.9 dB, respectively. These results are very good in all-optical switching that show high performance and good design of the proposed structure.

5. Discussion

This structure was designed for optical telecommunication purposes and works in 1.55 μm wavelength. But in the same time, the other output ports can guide the other

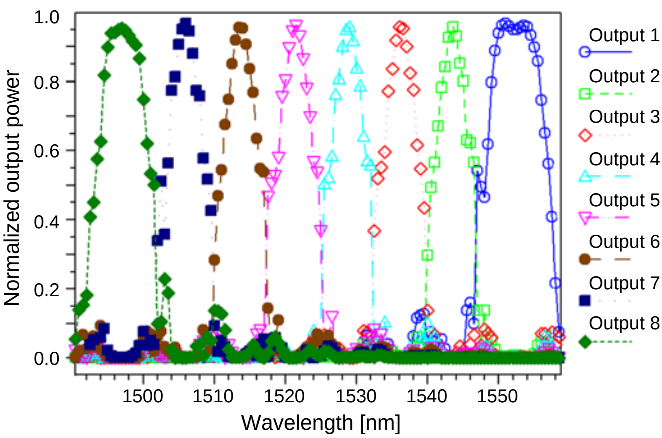

Fig. 6. Output spectral transmission of the proposed structure in first state.

wavelengths. Figure 6 shows the transmission spectrum of the structure in first state of the intensity.

With changing the intensity of the input signal, the wavelengths can be shifted. This performance is a good idea for designing a dynamic wavelength division demultiplexer.

6. Conclusions

We presented an eight-channel all-optical switch using multimode interference phenomenon. Operation of the device is based on the cooperation of self imaging and self guiding in nonlinear multimode interference. The switching operation is done with changing the intensity of the input signal. To the best of our knowledge, this is for the first time that a 1×8 all-optical switch based on multimode interference is presented. The mean value of the crosstalk and insertion loss in eight states of switching operation is –33.8 dB and –0.16 dB, respectively. As shown in simulation results, this structure has low crosstalk and insertion loss.

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