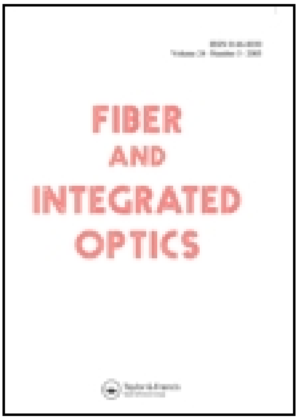

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All-Optical Multi-Mode Interference Switch Using Non-Linear Directional Coupler as a Passive Phase Shifter

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All-Optical Multi-Mode Interference Switch Using Non-Linear Directional Coupler as a Passive Phase Shifter

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Abstract *This article presents an all-optical multi-mode interference switch in which the non-linear directional coupler is utilized to realize a passive phase shifter. The proposed structure can be used either as a 1 × 2 or a 2 × 2 switch, with two inputs applied simultaneously in the latter case. The operation of the device is mainly based on the phase difference of the inputs of the multi-mode interference section. The beam propagation method is used for the design and simulation of the structure. The simulation results approve the low sensitivity on wavelength and fabrication tolerances. The crosstalk of the structure is equal to −31.6 dB.*

Keywords all-optical switch, crosstalk, multi-mode interference, non-linear directional coupler

1. Introduction

Nowadays, the use of all-optical devices is strongly demanded in optical communication systems. Highly flexible and reconfigurable structures are the most essential requirements of these systems. Meanwhile, in the new telecommunication systems, large optical bandwidth, small dimension, and also large fabrication tolerance are preferred. A multi-mode interference (MMI) structure is one of the key components of optical and especially all-optical devices. Optical devices designed based on MMI effects combine many attractive properties, beyond even the above-mentioned attributes [1]; thus, MMI structures have gained greater consideration in recent years. MMI structures can favorably realize many versatile functions, such as splitters, optical switches, and wavelength division multiplexers. There are many implementation methods to realize optical switching based on MMI structures. For switching purposes, MMIs can either be placed in a Mach-Zehnder interferometer (MZI) as splitter [2, 3] or used as a distinct region. Many MMI optical switches have been designed based on thermo-optic and electro-optic effects [4–9], some of which are fabricated on one MMI region [9]. But new communication systems that

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require high-speed devices is achievable by non-linear optics effects. Optical switching based on MMI implemented by non-linear optics effects is rarely reported [10, 11]. Rodgers et al. [10] proposed an all-optical switch based on one MMI region in 2000. But to the best of authors' knowledge, there has been no reported all-optical switching based on one single MMI since then. In a recent work, a 1×8 all-optical switch using MMI was proposed [11], but a detailed study shows that the problem of two later reported structures is that the high-intensity control field is coupled with the inputs while entering the structure and must be separated from input fields after the switching operation. This phenomenon initiates some other problems in optical communication systems.

This article introduces a new structure for all-optical switching based on a single MMI. In this work, the control field is separated from inputs and enters the structure from a different single-mode access waveguide to solve the mentioned problem in previous works. A non-linear directional coupler as a passive phase shifter is proposed for controlling the switching operation. In fact, passive phase shifting is a novel approach and is considered to be the main contribution of the proposed structure. This is a novel all-optical MMI switch that can be used either as a 1×2 or 2×2 all-optical switch, with two inputs applied simultaneously in the latter case. In the first case, the control field is only applied in the second state of switching. But the first state of the 2×2 switch works based on the phase difference of two input signals that take place in the non-linear coupler. In the second state, the control field with a proper intensity enters from the lower waveguide of the coupler and changes the coupling power ratio and phase of second input field.

Section 2 presents the principle of the MMI structures. Section 3 illustrates the design characteristics and device configuration. The simulation results of the proposed 1×2 and 2×2 switches are shown in Section 4, and the article is concluded with a discussion about the important parameters of an optical switch.

2. Principle of MMI

MMI devices work based on reproducing the single or multiple images at periodic intervals along the propagation direction. The basic structure of an MMI device is a waveguide designed to support a large number of modes (typically $\geq$3), which is shown in Figure 1. In order to launch light into the multi-mode waveguide and recover light from it, a number of access single-mode waveguides are placed at its beginning as well as its end [1]. Due to the mode coupling at different phases, light in the MMI region

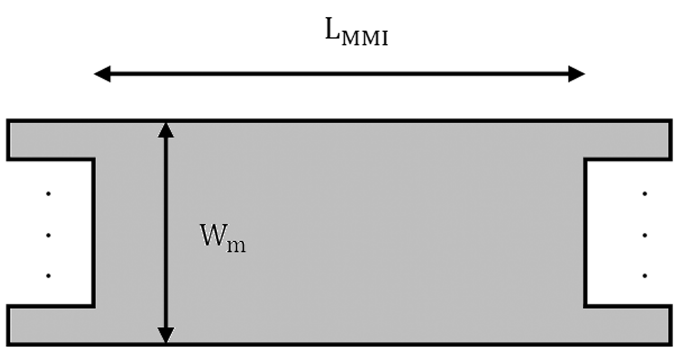


Figure 1. Basic structure of MMI devices.

exhibits various distributions as it propagates to different positions determined by L_π. L_π is the beat length of two first-order modes and can be expressed as

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4n_r W_e^2}{3\lambda_0}, \tag{1}$$

where β_0 and β_1 are the propagation constant of the first two guided modes, n_r is the refractive index of the core layer, W_e is the effective width of the MMI region, and λ_0 is the application wavelength [9]. The effective width W_e shows the penetration depth of the mode fields. In general, the effective width can be approximated by [1]

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

where $\sigma = 0$ is for TE and $\sigma = 1$ for TM.

When all modes are excited in the general interference case of multi-mode structures, the single image is formed in

$$L = p(3L_\pi) \quad \text{with } p = 0, 1, 2, \ldots. \tag{3}$$

Direct single images of the input field will be formed with even p, and the mirror single images will be formed with odd p [1].

3. Device Configuration

The schematic of the proposed MMI all-optical switch is shown in Figure 2. This structure is composed of an MMI region and a directional coupler. The MMI region has $3L_\pi$ length to produce the mirror images of the input fields. The design parameters of the proposed structure in Figure 2 are chosen as follows: the width of the multi-mode region W_{MMI} is 15 μm, the length L_{MMI} of the multi-mode region is 1,261 μm, the width of access waveguides W_a is 4 μm, and the length of directional coupler L_d is 180 μm. The refractive indices of the core and cladding are $n_r = 1.66$ and $n_c = 1.64$, respectively. The device has been designed for TE polarization and a 1,550-nm input wavelength. If the uniformity of the time harmonic of TE-polarized waves can be assumed along the y direction of Figure 2, the simulation can be done assuming it as a 2D structure [12].

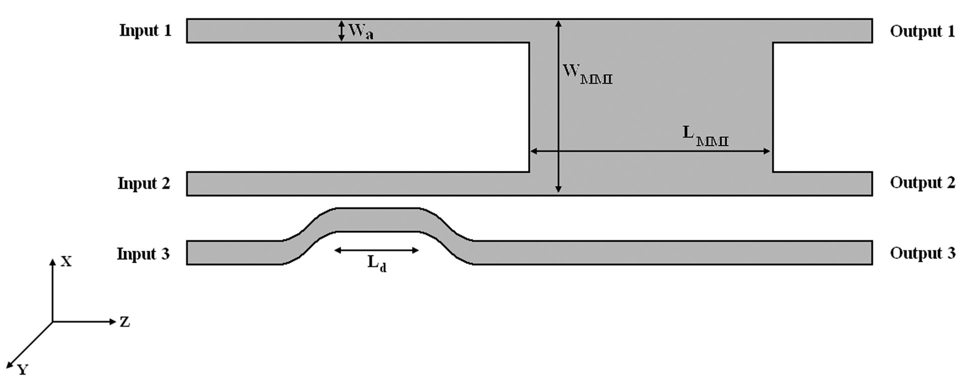


Figure 2. Schematic of the proposed MMI all-optical switch.

A 2D finite difference beam propagation method (FD-BPM) is used for the design and simulation of the device. The 3D waveguide can be converted to a 2D structure using an effective index method. There is a good agreement between 2D approximation and the full vectorial solution [12, 13].

4. Simulation Results

The proposed structure can be used both as a 1×2 or 2×2 switch. In the first case, input 1 in Figure 2 is used as the input of the 1×2 switch, and input 2 is the control field. In this case, no input is applied to input 3. But in the second case, inputs 1 and 2, shown in Figure 2, are two input fields, and input 3 has the role of control signal. Input 3 is a high-intensity control field that changes the refractive index of the non-linear lower waveguide of the coupler and causes the coupling power and phase of the upper waveguide of the coupler that is named as the second input to be decreased. The simulation results of these proposed switches are discussed separately in the following subsections.

4.1. **1 × 2** *MMI Switch*

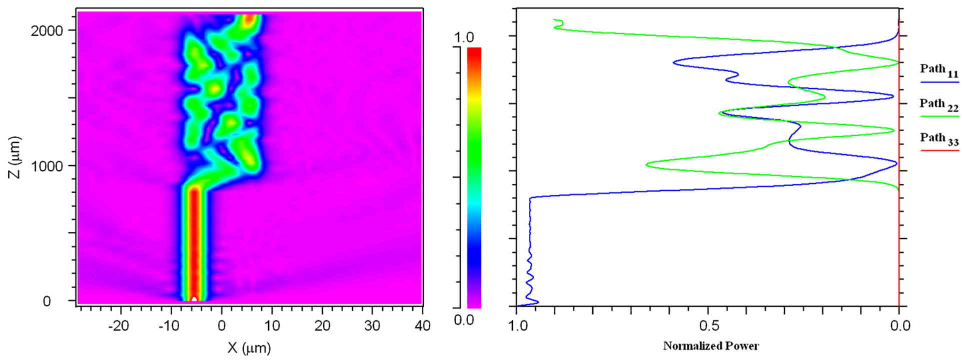
As mentioned before, in this case, the input field enters the system from the input 1 port, as shown in Figure 2. In the first state, there is just the input field and no control field. In this state, the input field exits from output 2, and the cross state takes place. In the second state, the control field with the same intensity as the input but with a different wavelength enters from input 2. The coupler has length equal to $2L_c$, where L_c is the full coupling length (that is, in one coupling length, the first full coupling to the lower waveguide takes place and then returns back to the higher waveguide of the coupler again in the end of the coupler). The control field passes through the coupler; thus, in this procedure, the π phase shift would take place. So, the inputs of the MMI region would have the same intensity but with π phase difference.

Two inputs with π phase difference do not have any interference effect on each other in the middle line of the MMI region. It can be supposed that the MMI region is separated into two individual MMI sections, where each of the inputs is accessible at its own output. So the input of the switch will be in the bar-state output and will exit from the upper port. In applying this structure as a 1×2 switch, the control field does not have high intensity. This is an advantage for an all-optical switch when it works based on the phase difference of inputs instead of intensity. Normalized output power and beam propagation along the propagation direction are shown in Figure 3. The expression $Path_{ij}$ shown in Figure 3 depicts the normalized power in the path from input i to output j.

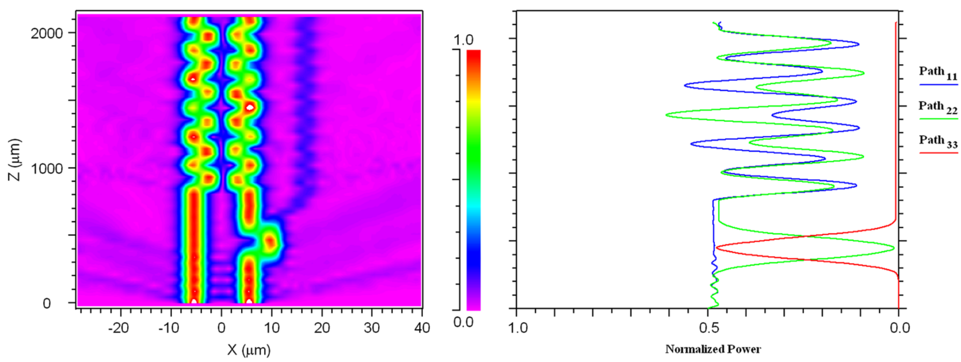
Figure 3a shows that the input field has been accessed in output 2, and there is no control field. In the second state, as shown in Figure 3b, the control field couples to a lower waveguide, returns completely back, and enters to MMI with π phase difference in comparison with input. In this state, the input field appears in the upper output.

4.2. **2 × 2** *MMI Switch*

In this case, inputs 1 and 2 of the structure (Figure 2) act as inputs of the 2×2 MMI switch, while input 3 is used as the control field. The switching operation of the 2×2 structure requires a non-linear directional coupler as a phase shifter. Originally, the non-linear directional coupler includes two waveguides that have a small distance, and full coupling takes place between them in one coupling length, provided that one or both of



(a)



(b)

Figure 3. Normalized output power and beam propagation in: (a) cross state and (b) bar state. (color figure available online)

these waveguides have non-linear behavior. This non-linear behavior can be guaranteed with a high-intensity control field, which changes the refractive index of the non-linear waveguide. The evolution of the slowly varying mode amplitudes can be described by the coupled-mode equations [14]

$$-i\frac{dA}{dz} = \kappa B + \gamma_1 |A|^2 A, \tag{4}$$

$$-i\frac{dB}{dz} = \kappa A + \gamma_1 |B|^2 B, \tag{5}$$

where κ is the linear coupling coefficient, A and B are the field amplitudes of waveguides 1 and 2 of the directional coupler, and γ_1 and γ_2 are the non-linear coefficient describing the self-phase modulation $\gamma = 2\pi n_2/(A_{eff}\lambda_0)$ with n_2 being the non-linear refractive index coefficient, λ_0 being the wavelength in the vacuum, and A_{eff} being the effective modal cross-section in waveguide 1 or 2. In the phase matched case when the input wavelength and the refractive index of two waveguides are identical, maximum coupling will take place. But applying a high-intensity control field to non-linear waveguide will change its refractive index, decrease the coupling power, and also introduce a phase shift. The simulation results prove the possibility of a π phase shift with increasing the intensity of field. There is a need for a substance with a high non-linear refractive index. The material used in this structure is polydiacetylene PTS with $n_0 = 1.66$ that has Kerr non-linearity about 2×10^{-4} μm^2/W [10].

In first state of the 2×2 MMI switch operation when there is no control signal, the second input will experience π phase change after passing through the coupler, and the inputs of MMI will have π phase difference. Therefore, the outputs will appear in the bar state, like the second state of the previous 1×2 switch. In the second state, the precise high-intensity control field changes the refractive index of the lower non-linear waveguide. This change in refractive index leads to less coupling power than the previous state. In addition to this, with increasing the intensity of the control signal, the output phase of the coupler changes from π to 2π. This passive phase shifter is implemented with a simple non-linear directional coupler. It can be used in any optical communication systems when the phase shifting process is needed. The exact intensity equal to 93 W/μm was chosen for the control signal to have 2π (same as zero) phase in the input of MMI. This shows the intensity of the control signal when one dimension is normalized in 2D simulations. A comparison with the other works shows that this is a moderate value in all-optical switching [10, 11]. Therefore, in this state, two inputs of MMI have the same phase and can behave identically in the MMI region and will exit from cross-state outputs. The normalized output power and beam propagation of this switch are shown in Figure 4 for two states.

As shown in Figures 3 and 4, the first state of the 2×2 switch is the same as the second state of the previous 1×2 switch. In this 2×2 switch, it is necessary to have both of the outputs simultaneously.

5. Discussion

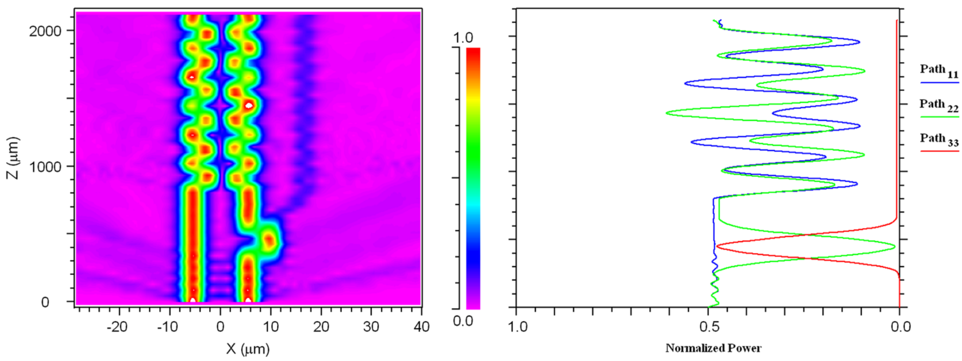
The simulation results show high output power intensity, which assures the qualitative performances of the structure in all aspects of a switch. Subsequently, a high-level switch should have the suitable insertion loss (I. L.), extinction ratio (Ex. R.), crosstalk, and good tolerance independency against the wavelength and fabrication. The I. L., Ex. R., and the total crosstalk of the proposed structure (i.e., in the first state of the 1×2 switch) are shown in Table 1.

The I. L. and Ex. R. can be calculated as follows:

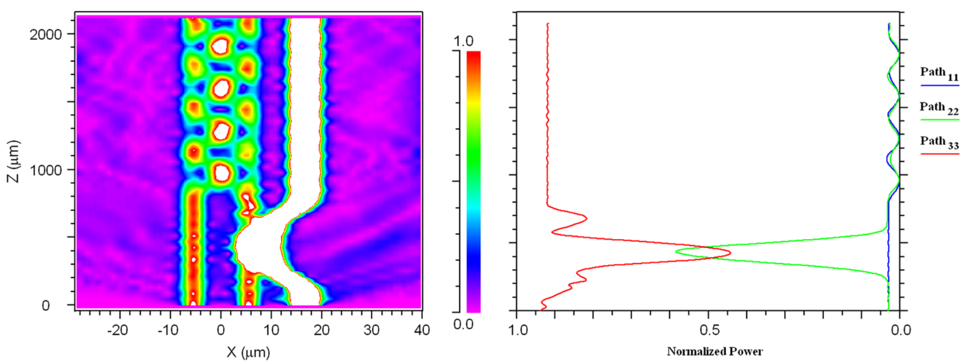
$$\text{I. L. (dB)} = 10 \log_{10}\left(\frac{P_{out}}{P_{in}}\right), \tag{6}$$

$$\text{Ex. R. (dB)} = 10 \log_{10}\left(\frac{P_{low}}{P_{high}}\right), \tag{7}$$

where P_{out} and P_{in} are the output and input power, and P_{low} and P_{high} show the lower and higher levels of the output in both ON and OFF states [2]. The power ratio was calculated at the outputs from the desired input to the other one. Finally, the crosstalk of the switch shown in Table 1 and defined in [15] achieves equality to −31.6 dB. Table 1 proves that all of the operation parameters of the proposed structure are very suitable for all-optical switching. If recent works are compared with the proposed structure, these distinguished performances can be more noticeable [5, 6, 16]. The effect of wavelength variation on



(a)



(b)

Figure 4. Normalized output power and beam propagation of proposed 2 × 2 switch in: (a) bar state and (b) cross state. (color figure available online)

Table 1
I. L., Ex. R., and total crosstalk of the structure

<table>
<tr><th rowspan="2">Output state</th><th colspan="3">Parameters</th></tr>
<tr><th>I. L. (dB)</th><th>Ex. R. (dB)</th><th>Crosstalk (dB)</th></tr>
<tr><td>Bar</td><td>−32.2</td><td rowspan="2">−31.8</td><td rowspan="2">−31.6</td></tr>
<tr><td>Cross</td><td>−0.4</td></tr>
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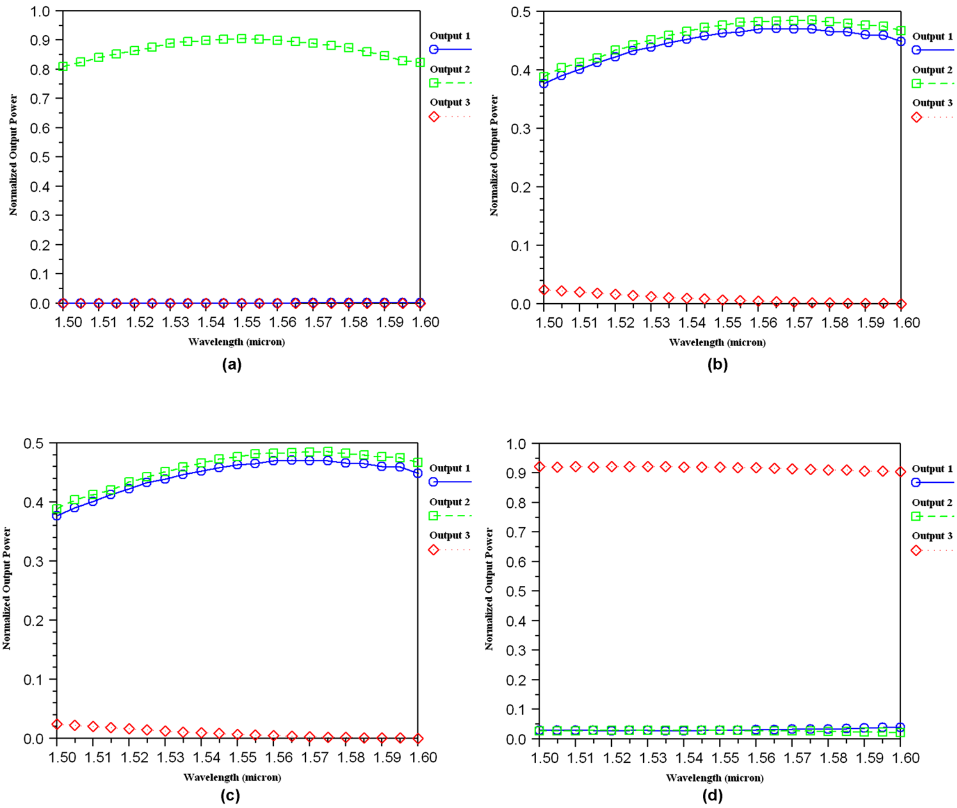


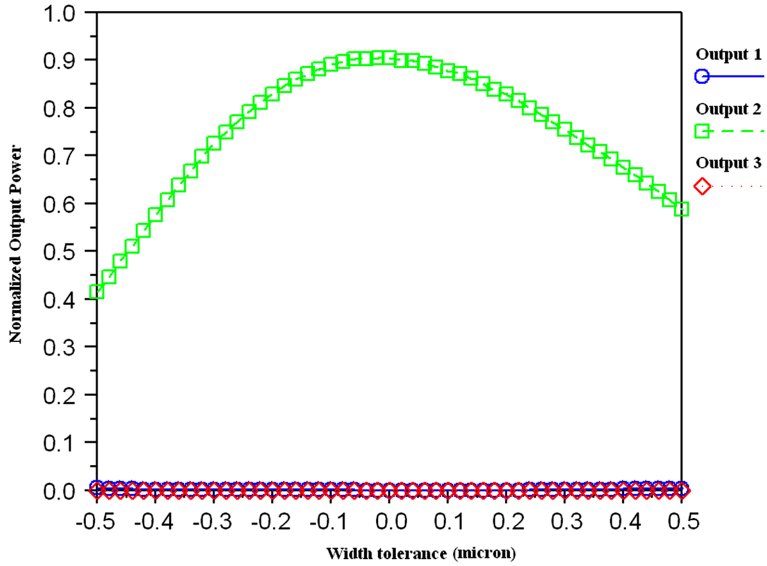
Figure 5. Effect of wavelength variation on the output power in: (a) first state of 1×2 configuration, (b) second state of 1×2 configuration, (c) first state of 2×2 configuration, and (d) second state of 2×2 configuration. (color figure available online)

the output power in the two states of switching in the 1×2 and 2×2 configurations is shown in Figure 5.

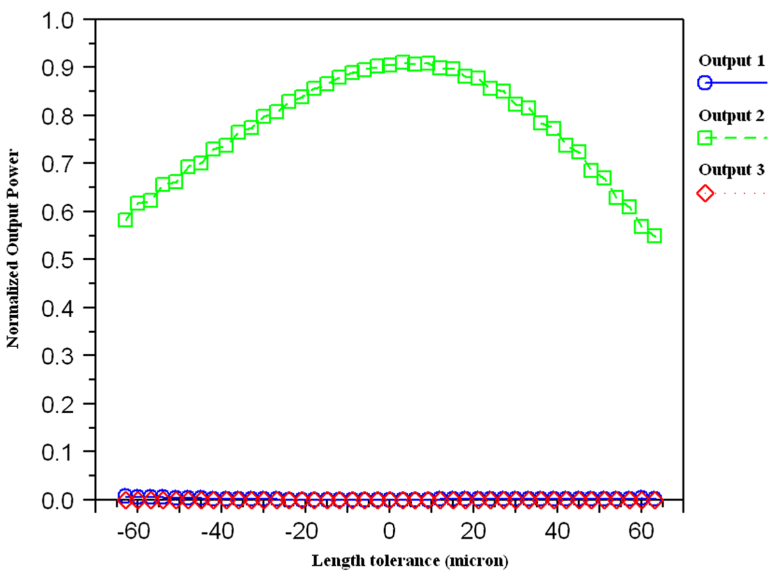
As shown in Figure 5, the wavelength dependency of the proposed structure remains low in a wide range. In Figure 5d, due to existing high-intensity control signal, the output powers are normalized to it.

The effects of fabrication tolerances of the multi-mode region on a switching operation are calculated and shown in Figures 6 and 7. The normalized output power versus the width and length of the switch for the first state of the 1×2 switch are shown in Figure 6. Finally, the effect of the refractive index variation was simulated on the switching operation shown in Figure 7.

As shown in Figure 6, changing the length of the MMI causes a little variation in the output power, which proves the better performance of this designed structure. But the output power is more sensitive to the tolerance of MMI width, which can be understood from the principle of MMI structures. This is due to the fact that, according to Eq. (1), a small change of MMI width results in higher variations of the length of MMI. Figure 7 shows a very small output power variation when the refractive index is changed.



(a)



(b)

Figure 6. Effect on the normalized output power in first state of 1×2 switch of variation on: (a) width of MMI and (b) length of MMI. (color figure available online)

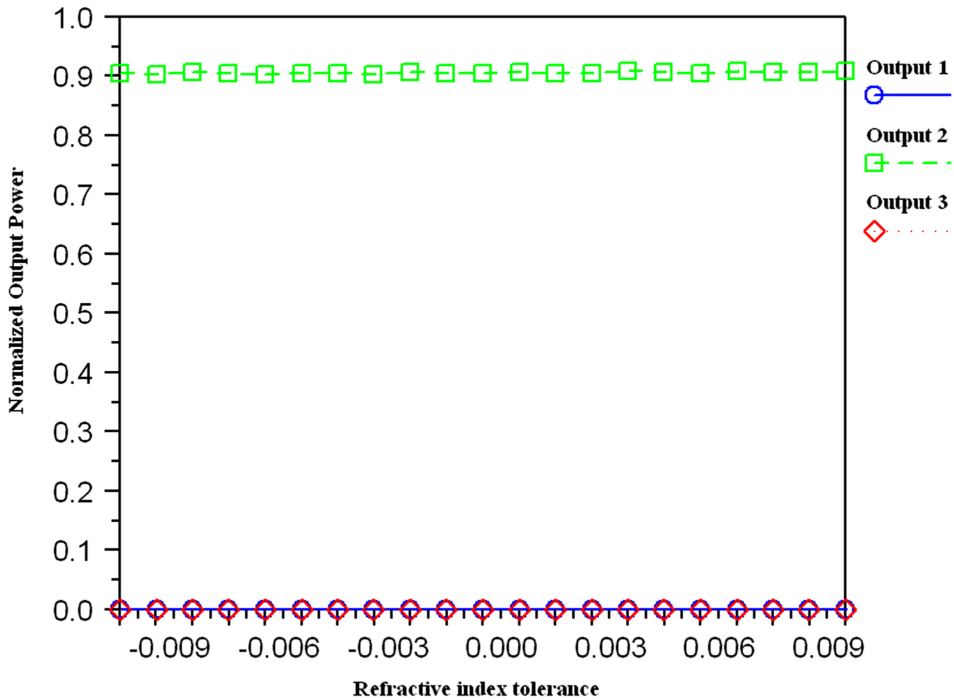


Figure 7. Effect of refractive index variation on the normalized output power. (color figure available online)

6. Conclusion

A novel all-optical MMI switch is presented in which the non-linear directional coupler is utilized to realize a passive phase shifter. The proposed structure can be used either as a 1×2 or a 2×2 switch, with two inputs applied simultaneously in the latter case. In the case of the 1×2 switch, the control field has the same intensity as the input signal, and the operation of the switch is based on the phase difference of inputs. But there is a high-intensity control signal for the switching operation in the 2×2 case. The beam propagation method is used for the design and simulation of the structure. The simulation results show that the switching operation is done carefully, and the sensitivity of the operation on wavelength and fabrication tolerances is relatively low.

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Biographies

Ali Bahrami was born in Naghadeh, Iran, in 1984. He received his B.Sc. in electrical engineering from the Urmia University, Urmia, Iran, in 2006, and the M.Sc. in electronics engineering from University of Tabriz, Tabriz, Iran, in 2009. He is currently pursuing his Ph.D. at the Iran University of Science and Technology (IUST), Electrical and Electronics Engineering Department, where his research interests include semiconductor optoelectronic devices and optical integrated circuits.

Shahram Mohammadnejad received his B.Sc. in electrical engineering from the University of Houston, Houston, TX, in 1981, and his M.Sc. and Ph.D. in semiconductor material growth and lasers from Shizuoka University, Shizuoka, Japan, in 1990 and 1993, respectively. He invented the PbSrS laser for the first time in 1992. He has published more than 200 scientific papers and books. His research interests include semiconductor material growth, quantum electronics, semiconductor devices, optoelectronics, nanoelectronics, and lasers. He is a scientific committee member of the Iranian Conference of Electrical Engineering (ICEE) and Photonics, a member of the Institute of Engineering and Technology (IET), and a member of IET-CEng. He has been the director of *IJEEE Journal of Iran University of Science and Technology* (IUST) for several years and is also an editorial board member for several international scientific magazines. He is currently an active professor at IUST and has established and is directing the Nanoptronics Research center at IUST.

Ali Rostami was born in Tabriz, Iran. He received his Ph.D. in photonic/electronic engineering from Amirkabir University of Technology, Tehran, Iran, in 1998. He spent his sabbatical leave at the University of Toronto in 2004–2005 at the Photonic Group. He is currently a full professor in electronic engineering and photonics science at the University of Tabriz. His teaching and research interests include optical integrated circuits and optoelectronic devices. He is a member of the Optical Society of America. He is the author/co-author of more than 220 scientific international journals and conference papers and 10 text books and book chapters, as well as collaborating with various international journals on review boards and being on the editorial committee of 2 Iranian journals. He has served on several other committees and panels in government, industry, and technical conferences. He is the founder of the Photonics and Nanocrystals Research Lab (PNRL) at the University of Tabriz, and the School of Engineering–Emerging Technologies is another project that he established at the University of Tabriz in 2008. He was selected as the distinguished researcher of the University of Tabriz several times, and in 2007, he was elected as a distinguished researcher in the engineering field in Iran. Since 2008, he has been the vice chancellor for research and technology at University of Tabriz.