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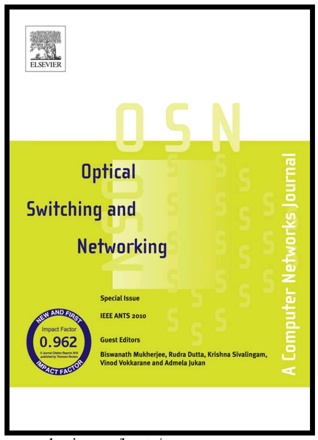

www.elsevier.com/locate/osn

PII: S1573-4277(16)30060-1
DOI: http://dx.doi.org/10.1016/j.osn.2016.07.002
Reference: OSN414

To appear in: *Optical Switching and Networking*

Received date: 25 February 2013
Revised date: 25 August 2015
Accepted date: 14 July 2016

ALL-OPTICAL SWITCH BASED ON 1x3 MULTIMODE INTERFERENCE COUPLERS

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Abstract- In this paper, a new all-optical switch based on 1x3 and 3x3 General Interference (GI) multimode interference (MMI) structures is proposed. By using nonlinear directional couplers in two arms of the structure as phase shifters, all-optical switching mechanism can be achieved. In this study, we use chalcogenide glass on silica for designing the device structure. The switching states of the device can be controlled by adjusting the optical control signals at the phase shifters. The transfer matrix method and beam propagation method (BPM) are used for designing and optimizing the device structure.

Index Terms – All-optical switch, MMI coupler, nonlinear directional coupler, phase shifter

I. INTRODUCTION

Optical communication networks have evolved into the era of all optical switching. In recent years, various approaches to realize all optical switches have been proposed. In recent years, there have been some optical switches using MMI structures based on thermo-optic [4], [5] and electro-optic effects [6], [7]. However, high speed optical communication systems require high speed optical switches. Therefore, it is particularly necessary to achieve all-optical switches. In comparison with other optical switches, the MMI based switch has the advantages of low loss, ultra-compact size, high stability, large fabrication tolerance and greater feasibility for integration [2].

In addition, chalcogenide (As_2S_3) waveguides have been proposed as a new platform for optical signal processing offering superior performance at ultrahigh bit-rates [8]. The high nonlinearity enables compact components with the potential for monolithic integration, owing to its large nonlinear coefficient n_2 and low two-photon absorption (good figure of merit), the ability to tailor material properties via stoichiometry, as well as its photosensitivity. These properties allow the fabrication of photo-written gratings and waveguides [9].

The main aim of this paper is to propose a new structure for 1x3 all-optical switch based on GI MMI couplers using nonlinear directional couplers as phase shifters. Chalcogenide glass on silica platform is used for our designs. Nonlinear directional couplers at two outermost arms in the inter-stage of 1x3 and 3x3 MMI couplers play the role of phase shifters. In order to realize the phase shifters using nonlinear directional couplers, the control signal is at an arm of the nonlinear directional coupler, and the information signal is at the other arm. The nonlinear directional couplers are carefully designed so that the control signal must be separated from input signals and enters the switching structure from a different single-mode access waveguide after the switching operation. The aim is to reduce the powers transferring between control waveguides and information signal waveguides. Numerical simulations using the BPM then are used to verify the operating principle of the proposed all-optical switch.

II. THEORETICAL ANALYSIS

A. Analytical expression of the MMI coupler

The operation of optical MMI coupler is based on the self-imaging principle [10]. Self-imaging is a property of a multimode waveguide by which as input field is reproduced in single or multiple images at periodic intervals along propagation direction of the waveguide. MMI coupler can be characterized by the transfer matrix theory [10], [11]. Following this theory, the relationship between the input vector and output vector can be obtained. To achieve the required transfer matrix, the positions of the input and output ports of the MMI coupler must be set exactly.

In this study, the MMI waveguide has a width of W_{MMI} and the access waveguides have the same width of W_a. The positions of the input and output ports are located at x_i [10]

$$x_i = \left(i + \frac{1}{2}\right)\frac{W_e}{3}, \ (i=0,1,2) \qquad (1)$$

where W_e is the effective width of the MMI coupler and N is the number of input/output.

In the general interference mechanism, the shortest length of the MMI coupler is set by

$$L_{MMI} = L_\pi \qquad (2)$$

Where L_π is the half-beat length of two lowest-order modes that it can be written as

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4 n_r W_e^2}{3\lambda_0} \qquad (3)$$

where n_r is the refractive index of the core layer, λ_0 is the free space wavelength.

An 3x3 general interference MMI coupler has length $L = L_{MMI} = L_\pi$, the resulting amplitudes from image input i (i=1,..,3) to output j (j=1,..,3) can be given in a compact form

$$A_{ij} = A_{ji} = \sqrt{\frac{1}{3}} \qquad (4)$$

where $|A_{ij}|^2$ is the normalized powers of the output images. The phases φ_{ij} of the equal output signals at the output waveguides can be calculated by

For i+ j: even, $\phi_{ij} = \phi_0 + \pi + \frac{\pi}{16}(j-i)(8-j+i)$ and for i+j: odd, $\phi_{ij} = \phi_0 + \frac{\pi}{16}(i+j-1)(8-j-i+1)$, where the input ports i (i=1, 2,..,N) are numbered from bottom to top and the output ports j (j=1, 2,..,N) are numbered from top to bottom in the MMI coupler. $\phi_0 = -\beta_0 L_{MMI} - \frac{\pi}{2}$ is a constant phase that depends upon the MMI geometry and therefore can be implied in the following calculations.

B. Operation principle of the 1x3 all optical switch

The configuration of our proposed all-optical switching is shown in Figure 1. It consists of 1x3 and 3x3 general interference MMI couplers having the same width. Here, two nonlinear directional couplers at two outer-arms of the structure are used as two phase shifters. We assume that input port of the switch is located at position A of the center line and output ports of the switch are located positions b_1, b_2, b_3 as shown in Figure. 1.

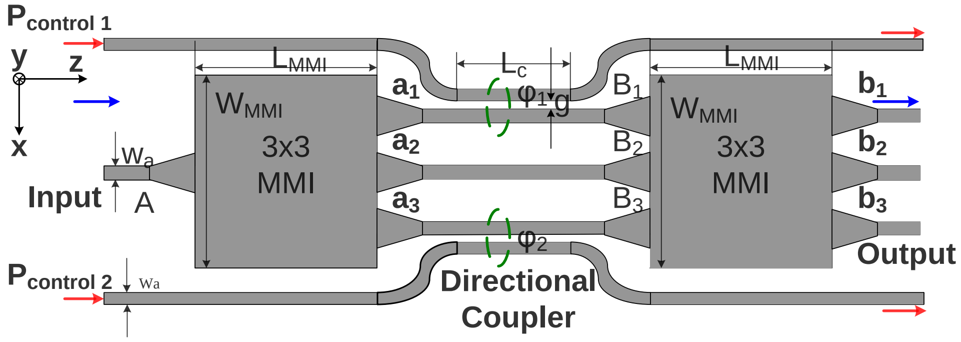


Figure. 1. A 1x3 all optical switching based on a 1x3 MMI and a 3x3 couplers using directional couplers as phase shifters

A 3x3 GI-MMI coupler can be described by a transfer matrix **M** which describes the relationships between the input and output fields of the coupler. The transfer matrix of the 3x3 GI MMI coupler can be expressed as [10], [11]

$$\mathbf{M}=\frac{1}{\sqrt{3}}\begin{pmatrix} -e^{-j2\pi/3} & e^{-j2\pi/3} & -1 \\ e^{-j2\pi/3} & -1 & e^{-j2\pi/3} \\ -1 & e^{-j2\pi/3} & -e^{-j2\pi/3} \end{pmatrix} \quad (5)$$

The input, output complex amplitudes and phase shifters can be expressed by the following matrices

$$M_a=\begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix}, M_b=\begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} \text{ and } \Phi=\begin{pmatrix} e^{j\varphi_1} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{j\varphi_2} \end{pmatrix} \quad (6)$$

Where φ_1 and φ_2 are phase shifter angles at two outermost arms caused by directional couplers respectively. We have the following relations:

$$M_b = M.\Phi.M_a$$

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix}=\frac{1}{\sqrt{3}}\begin{pmatrix} e^{j\left(\varphi_1+\frac{\pi}{3}\right)} & e^{-j\frac{2\pi}{3}} & e^{j(\varphi_2+\pi)} \\ e^{j\left(\varphi_1+\frac{\pi}{3}\right)} & e^{j\pi} & e^{j\left(\varphi_2+\frac{\pi}{3}\right)} \\ e^{j(\varphi_1+\pi)} & e^{-j\frac{2\pi}{3}} & e^{j\left(\varphi_2+\frac{\pi}{3}\right)} \end{pmatrix}.\begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} \quad (7)$$

The 3x3 MMI coupler with two phase shifters φ_1 and φ_2 at input port 1 and 3. From equation (7), the input signal at any input port can be switched to output port 1 if the phase shifts at input ports 1 and 3 compared to the phase shift at input port 2 are (π, $\frac{\pi}{3}$), switched to output port 2 if the phase shifts at input ports 1 and 3 compared to the phase shift at input port 2 are ($\frac{5\pi}{3}$, $\frac{5\pi}{3}$), switched to output port 2 if the phase shifts at input ports 1 and 3 compared to the phase shift at input port 2 are ($\frac{\pi}{3}$, π). As a result, we find out matched phase shifts for all switching operation states. In summary, phase shifters required to direct the output signals from input signals can be expressed in Table 1.

TABLE 1. PHASE SHIFTER STATES FOR OPERATION OF THE 1X3 OPTICAL SWITCHES

Input port	Phase φ_1	Phase φ_2	Output port
A	$\frac{2\pi}{3}$	0	b_1
A	$\frac{4\pi}{3}$	$\frac{4\pi}{3}$	b_2
A	0	$\frac{2\pi}{3}$	b_3

C. Design of phase shifters using nonlinear directional couplers

As mentioned above, the structure of an all optical switching requires two nonlinear directional couplers based on the Kerr effect [12] as phase shifters at two outermost arms of optical device as shown in Figure 1. Originally, the nonlinear directional coupler includes two waveguides that have small distance and full coupling takes place between them in one coupling length, provided that one or both of them have non-linear behavior. This non-linear behavior can be guaranteed with high intensity control field which changes the nonlinear refractive index. When the distance of two nonlinear directional couplers is very small and mode field amplitudes vary slowly in the z- propagation direction, the interaction of electrical fields in nonlinear directional couplers complies with coupled mode equations

$$-i\frac{dA}{dz} = \kappa B + \gamma_1\left(|A|^2 + 2|B|^2\right)A \tag{8}$$

$$-i\frac{dB}{dz} = \kappa A + \gamma_2\left(|B|^2 + 2|A|^2\right)B \tag{9}$$

Where κ is the linear coupling coefficient, it is determined by $\kappa = \frac{\pi}{2L_c}$, L_c is coupling length, A and B are field amplitudes of the control and signal waveguide s of the directional coupler and γ_1, γ_2 are nonlinear coefficients describing the self-phase modulation (SPM) and cross-phase modulation (XPM) effects. Nonlinear coefficient is determined as follows

$$\gamma = \frac{2\pi n_2}{\lambda_0 A_{eff}} \tag{10}$$

Here λ_0 is wavelength in the vacuum, n_2 is nonlinear refractive index of the waveguide, A_{eff} is the effective modal cross–section area. Under the effect of self-phase modulation in the nonlinear directional coupler, the phase in directional coupler can be changed proportional to the intensity of input of electrical fields of waveguides. Nonlinear phase shifts in the directional coupling waveguide can be expressed by

$$\Delta\varphi_1 = \frac{2\pi n_2 L_c\left(I_s + 2I_{c1}\right)}{\lambda_0} \tag{11}$$

$$\Delta\varphi_2 = \frac{2\pi n_2 L_c\left(I_s + 2I_{c2}\right)}{\lambda_0} \tag{12}$$

where I_{c1}, I_{c2} are field intensities of the control signal 1 and 2 waveguides respectively; I_s is field intensity of the signal waveguide at outermost arms. In the phase matched case when the input wavelength and the refractive index of two waveguides are identical, maximum coupling will take place.

III. SIMULATION RESULTS AND DISCUSSIONS

A. Simulation results

In this study, we use the chalcogenide glass As_2S_3 for designing the whole device. The material used in core layer of the proposed optical switching structure is chalcogenide glass As_2S_3 with refractive index n_r=2.45. The silica material SiO_2 used in cladding layer has refractive index n_c =1.46. As_2S_3 (arsenic trisulfide) is a direct band-gap, amorphous semiconductor. By using a highly controlled deposition process, a photo-polymerizable film of As_2S_3 can be deposited on standard silica glass substrates. Chalcogenide As_2S_3 is chosen due to its advantages. For example, it is attractive for high rate photonics integrated circuits, especially attractive for all optical switches in recent years because of the fast response time associated with the near-instantaneous third order nonlinearity allows flexible ultrafast signal processing [13]. In- addition, the chalcogenide glass supports the operation of wavelengths range in the windows 1.55μm; and As_2S_3 material has a high refractive index contrast to allow for a high confinement [14] of light also ultra-compact size. Therefore, it is useful and important for large scale integrated circuits. The other advantage of the chalcogenide glass is that it has a high nonlinear coefficient n_2 about $2.92\times 10^{-6}\mu m^2/W$. From equations (11) and (12), we can see that phase angle in the phase shifter of the structure increases proportionally in the nonlinear coefficient and the control field intensity, so if nonlinear coefficient is high then control field intensity is low when we keep the phase angle constant. This would be better for operation of the proposed switch because a very high intensity of the control beam will overwhelm the signal. Moreover, since the control beam intensity is much higher than the signal beam one, the nonlinear directional coupler needs an extreme high isolation; so that it is difficult to design and optimize the proposed structure. Silicon dioxide SiO_2 is used in cladding layer because of high refractive index difference between core and cladding layers that allows for a high confinement of light and also supports a larger mode numbers in MMI region. In addition, both As_2S_3 and SiO_2 materials are available and cheap also they can implement in the practical fabrication. Recently, these materials are very attractive for ultrahigh bit-rate signal processing applications.

The device used in our designs is shown on Figure 1. Here, we use the TE (Transverse Electric) polarization and operating wavelength 1550-nm for analyses and simulations. If the uniformity of the time harmonic of TE-polarized waves can be assumed along the x direction of Figure 1, the simulation can be done assuming it as a 2D structure. In order to reduce time consuming but still have accuracy results a 3D device structure is converted to a 2D structure using the effective index method (EIM) first, then the 2D-BPM method is used for simulations [15].

The design parameters of the proposed structure are chosen as follows: the width of each 3x3 MMI coupler W_{MMI} is 24μm, the width of access waveguides W_a is 4μm in order for single mode condition can be obtained, the length of the multimode region L_{MMI} is set as L_π for the general interference mechanism and it can be calculated by the mode propagation analysis (MPA) method is 1259.8μm.

Parameters of the control waveguides are designed as follows: the width is set as Wa; at the beginning, a straight waveguide has the length of 2059.15μm calculated by using the BPM. Next, it is connected to a sine waveguide which has the length of 1000μm in z propagation direction and the distance of 9μm in x-direction. Then it is concatenated to another straight waveguide. By using the BPM, the length of the straight waveguide of the nonlinear directional couplers Lc is chosen to be 360μm to satisfy the eliminating condition of the cross transfer power between control and structure waveguides. Gap g between this straight waveguide and the outermost arm is small (Figure 1) to enable mode coupling. Finally, a sine waveguide and a straight waveguide are in turn connected (as shown on Figure 1). We choose the sine waveguide for two purposes: First, the sine waveguides are used to connect the straight waveguides together in which it puts a waveguide near outermost arms which link between MMI regions in order to make a full coupling and a phase shift between nonlinear directional waveguides and the second aim is that light beam power can be conserved when propagated through it. Both control beams and input signal beams have the same wavelength, amplitude and polarization state in all of switching states.

Now we optimize the whole device structure. Firstly, the length L_{MMI} is optimized by the 2D-BPM method to find the optimal value by changing the values of the length around L_π. Finally, we find out the optimal value as 1260μm. The optimal gap g between two parallel waveguides of the directional couplers used as phase shifters can be found by using the BPM. The simulations are shown in Figure 2. We need to find the optimal value g to minimize the cross transferring power between outermost arms and the control waveguides and split the total power entering into one input port equally into 3 arms a_1B_1, a_2B_2, a_3B_3 as P_{a1B1}, P_{a2B2}, P_{a3B3}, respectively. This can be done by introducing power into ports a1, a2 and a3 and use 2D-BPM method. Due to the symmetry of the proposed structure, we only need to consider the power inserted into control waveguide 1. By changing the value of g gradually from 0.09μm to 0.11μm and monitoring and normalizing the power P_{a1B1} as well as $P_{control1}$, we choose the optimal value of g as 0.1μm according to Figure 2.

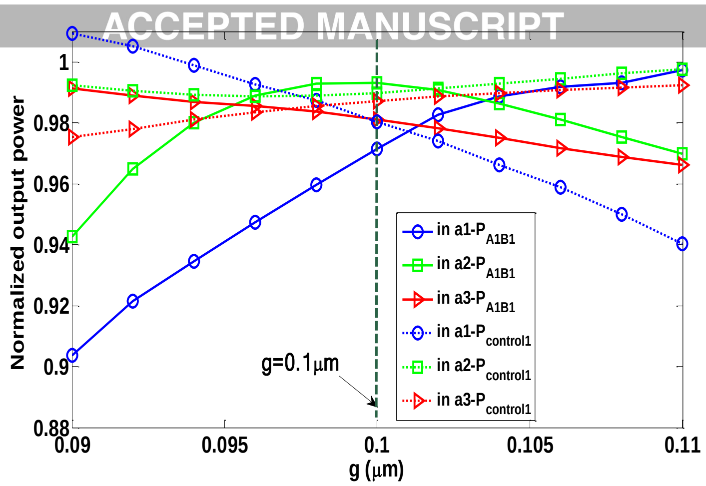
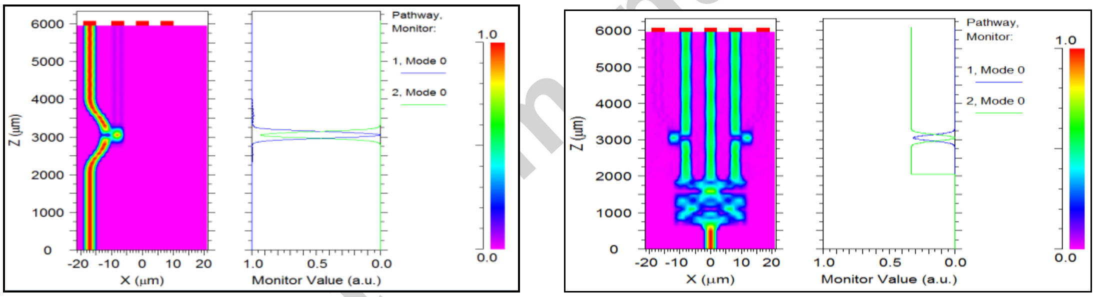


Figure 2. 2D BPM simulation results for the optimal values of the distance between control and structure waveguide in two cases: a) In case of the control power is on and b) In case of the control is off

Simulation results implemented by the 2D-BPM method in Figure 3 also show that at the optimal value of the distance between control and structure waveguides, the coupling power between them is reduced to the minimum value.

To optimize the operation of the MMI regions in the role of the splitter and combiner as well as minimize the insertion loss and crosstalk effect, linear taper waveguides are used to connect between MMI regions and access waveguides. In our design, linear tapers have the length l_a=150µm and the widths from 3µm to 5µm are calculated and optimized by BPM simulations.



a) b)

Figure 3. 2D BPM simulation results for optimal value of the distance between control and structure waveguide when: a) the control power is on, the data power off and b) the control power off, the data power on

As mentioned before in results are shown on the Table 1, when the input field enters the switch from the input A port, if the phase shift in the first linking arm is 2π/3 radian and the second linking arm is zero radian, it will switch to output b_1 port.

For switching from an input to an output of the structure, we implement numerical simulation by 2D–BPM method to find optimal values of field intensities of control waveguides. The simulation has to satisfy two requirements: the first, we find the values of field intensities of control waveguides to produce exactly matched phase shifts for switching operations; then those values must be optimized so that the transfer power between signal waveguides and control waveguides is minimal.

We assume that the normalized input power in optical switching device is set as 1 normalized unit; input field intensity I_0 equals 1 GW/cm^2. This value is chosen because it can generate the largest nonlinear phase shift. To reach the switching state from port a1 to port b1, firstly we find the intensity I_1, which is introduced into control waveguide 1 (also see Figure 1), by varying the intensity slowly. The appropriate result is about 14.38GW/cm^2 making phase shift 2π/3 radian in comparison with the center access waveguide. Secondly, we can also change the value of the intensity I_2, which is introduced into control waveguide 2. The appropriate result is about 450GW/cm^2 making phase shift zero radian in comparison with the center access waveguide. Finally, if we use these results to reproduce the simulation and adjust their values very slowly around them again, we obtain the optimal values I_1=14.38 GW/cm^2 and I_2=27.38GW/cm^2, respectively. The reason for this is due to the loss when the light travels in the MMI region and also because the length of MMI region is too long to be operated as a splitter or a combiner accurately. Table 2 lists optimal field intensities and states of control waveguides used in two control waveguides.

TABLE 2. POWER AMPLITUDE AND INTENSITTY STATES FOR OPERATION OF THE 1X3 OPTICAL SWITCHES

Input	Output	I_{c1} W/μm^2	I_{c2} W/μm^2
A	b_1	14.38	27.38
A	b_2	27.72	50.84
A	b_3	27.09	18.73

B. Discussions

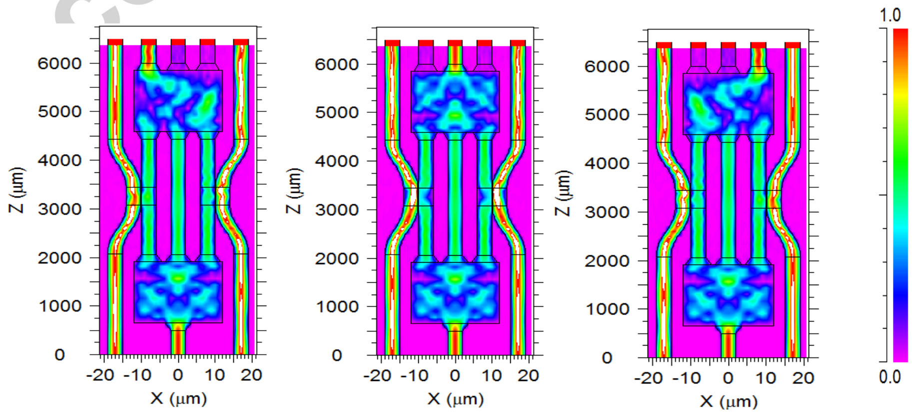
In this section, we investigate the performance of the device using the insertion loss and extinction ratio parameters. The insertion loss (I. L.) and extinction ratio (Ex. R.) [16] are defined by

$$\mathrm{I.L.}(\mathrm{dB}) = 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \quad (16)$$

$$\mathrm{Ex.R.}(\mathrm{dB}) = 10\log_{10}\left(\frac{P_{high}}{P_{low}}\right) \quad (17)$$

where P_{out} and P_{in} are the output and input power of the switch in operation state, P_{high} and P_{low} are output power levels in ON and OFF states respectively.

Simulation results presented in Figure 4 prove that all of the important parameters of the proposed optical switch are suitable for all optical switching. Refractive index of As_2S_3 in this design is calculated by Sellmeier's equation [17]. Calculation results show that when the wavelength varies from 1545nm to 1555nm, the refractive index of As_2S_3 varies in a small range 0.006 around refractive coefficient 2.435. This variation is very small so we can be neglected. Therefore, in all of simulation results, we consider refractive index of chalcogenide glass as a constant.



Input A →Output b_1 **Input A →Output b_2** **Input A →Output b_3**

Figure 4. Simulation results implemented by BPM method for all switching states of the 1x3 all optical switches

Figure 5 shows the dependency of extinction ratio and crosstalk in 10nm of the wavelength bandwidth. Results show that extinction ratio of the proposed switch vary from 32dB to 34dB, whilst crosstalk vary from 26dB to 38dB. Those results are very good for application of the optical switch.

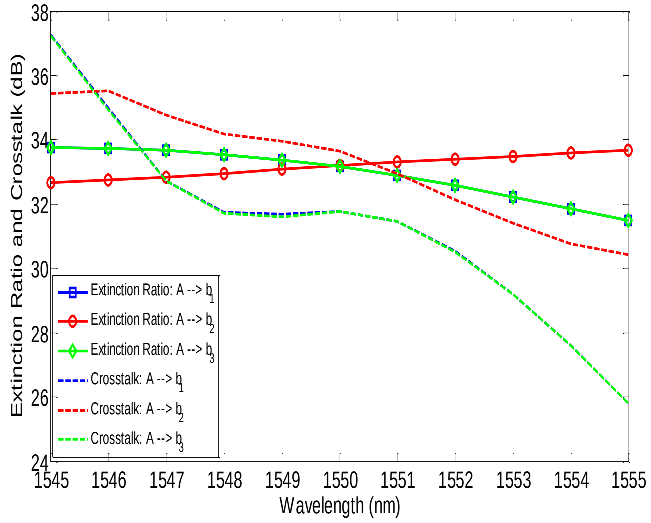


Figure 5. Wavelength dependency of the extinction ratio and crosstalk of the proposed switch

Figure 6 describes the wavelength dependence of the insertion loss of the proposed switch. In 10nm wavelength bandwidth (from 1545nm to 1555nm), results show the variation of the insertion loss in all of operation states of the proposed switch is not exceed 0.5dB.

As shown in Figure 7, the length and the width dependence of MMI sections in proposal design structure are simulated by the BPM method. The output power is normalized unit dB by the input power. Results denoted a variation about 0.4 dB of the output power in a quite large range 1μm of the width and a range 30μm of the length of MMI regions. Hence, the fabrication tolerance of proposed design is very large.

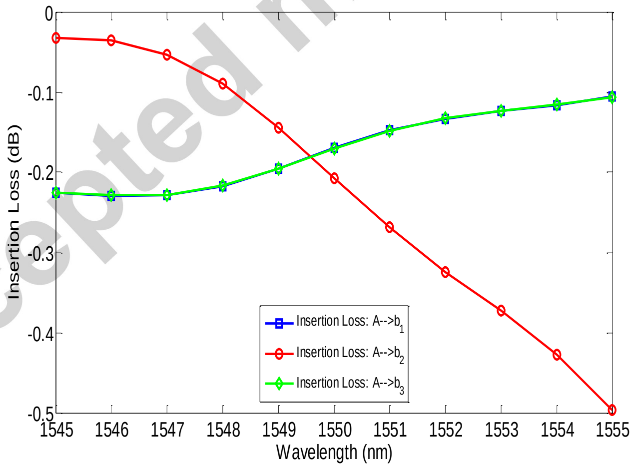


Figure 6. Wavelength dependency of the insertion loss in all operation states of the proposed switch

Clearly, the proposed switch has an ability to switch none blocking from any input ports to any output ports. In comparison with an existing 3x3 optical switch using a 3x3 fiber coupler, we can see that the 3x3 fiber coupler cannot switch none blocking between input and output ports despite having phase shift in each input port [18].

Compared with the existing approach structure in the literature which used the 3x3 MZI structure and electro-optic effect [19], our proposed structure has a better insertion loss. In addition, our proposed switch is an all-optical switch that can be useful for all-optical networks and other all-optical signal processing applications.

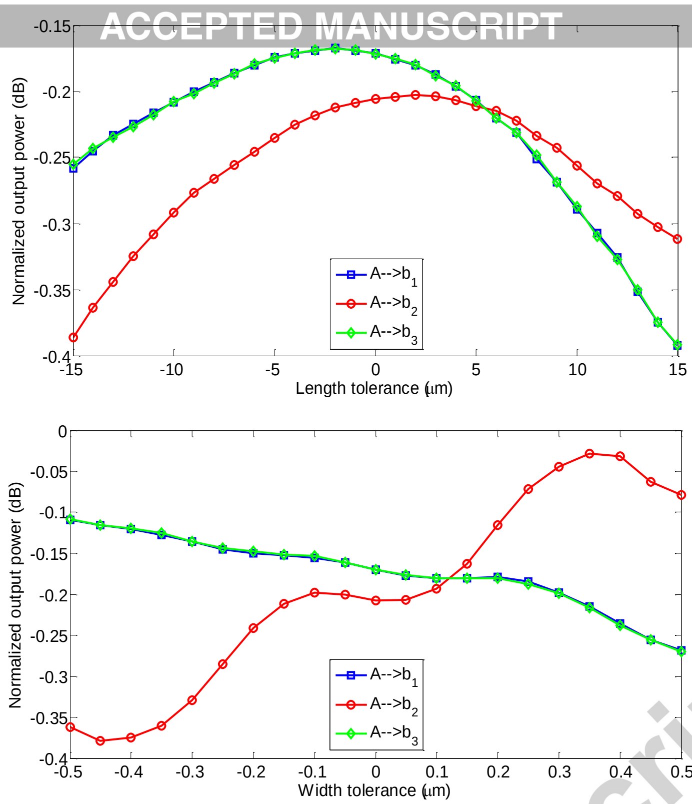


Figure 7. Normalized output power on the variation of width and length of MMI regions in all operation states of the proposed switch: a) the variation of the width and b) the variation of the length

IV. CONCLUSIONS

A novel all-optical MMI switch is designed and presented in this paper, in which the non-linear directional couplers are utilized to realize all-optical phase shifters. The proposed structure can be used as an 1x3 all-optical switch. The optical control signals are used to achieve phase shift. For the first time, an 1x3 all-optical switch based on 3x3 MMI structures is proposed. The simulation results show that the switching operation has a very good agreement with the theoretical analysis. In addition, the fabrication tolerance of the switch is relatively large. The performance of the switch is also analyzed and it is shown that the proposed all-optical switch can be useful for all-optical networks in the future.

ACKNOWLEDGEMENTS: This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number “103.02-2013.72" and Vietnam National University, Hanoi (VNU) under project number QG.15.30.

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