A DESIGN PROPOSAL OF THE DUAL BAND ALL-OPTICAL SWITCH BASED ON 3×3 MULTIMODE INTERFERENCE STRUCTURES

MỘT ĐỀ XUẤT THIẾT KẾ CỦA BỘ CHUYỂN MẠCH TOÀN QUANG HAI BĂNG DỰA TRÊN CÁC CẤU TRÚC GIAO THOA ĐA MODE 3×3

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Abstract - In this paper, a dual band all-optical switch based on 3x3 multimode interference structures is proposed. Two 3×3 multimode interference couplers are cascaded by Mach-Zehnder interformeter mechanism to create an all-optical switch operating at both wavelengths of 1550nm and 1310nm. Two nonlinear directional couplers at two outer-arms of the structure are used as phase shifters to control the switching states. Chalcogenide glass (As_2S_3) on silica material with high second order nonlinear coefficient is chosen to build the waveguides. In this study, analytical expressions using the transfer matrix method are presented, and then the beam propagation method (BPM) is used to design and optimize the whole device structure.

Key words - all optical switches, wavelength dual band switch, MMI coupler, nonlinear directional coupler, phase shifters

Tóm tắt - Trong bài báo này, một bộ chuyển mạch hai băng bước sóng (băng 1310 nm và băng 1550 nm) được đề xuất thiết kế dựa trên cấu trúc giao thoa đa mode 3×3. Hai bộ ghép giao thoa đa mode 3×3 được phân tầng theo cơ chế giao thoa kế Mach-Zehnder để tạo ra một bộ chuyển mạch toàn quang hoạt động trên cả hai dải bước sóng 1310nm và 1550nm. Hai bộ ghép định hướng phi tuyến được bố trí ở hai cánh ngoài cùng của cấu trúc được sử dụng để tạo ra các bộ dịch pha phi tuyến cho hoạt động chuyển mạch. Vật liệu sử dụng là chalcogenide (As_2S_3) trên nền thủy tinh silic với hệ số phi tuyến bậc hai cao để xây dựng các ống dẫn sóng. Trong nghiên cứu này, các biểu thức phân tích sử dụng phương pháp ma trận truyền đạt và sau đó phương pháp mô phỏng truyền chùm (BPM) được sử dụng để thiết kế và tối ưu toàn bộ cấu trúc linh kiện.

Từ khóa - Chuyển mạch toàn quang, bộ chuyển mạch hai băng bước sóng, bộ ghép giao thoa đa mode, bộ ghép định hướng phi tuyến, các bộ dịch pha

1. Introduction

All-optical communication networks have been rapidly growing in recent years. Optical switch is a key component that plays a very important role in an optical communication system. There are some different types of commercialized switches. One is thin-film based switch (expensive for packaging and difficult to integrate with other devices). Another is liquid crystal based switch [1]. Another is fiber couplers based switch [2]. The other type is based on planar lightwave circuits (PLCs) and is more promising due to its advantages such as small size, high reliability, and possibility for large scale production [3]. Some novel PLC-based optical switches have been reported and the total size is about several millimeters. Some compact optical switches are designed by using the decoupling performance of directional couplers based on planar waveguides [4], [5].

In recent years, multimode interference couplers (MMI) are attractive for PLCs based optical switches [6], due to their advantages of low loss, ultra compact size, high stability, large bandwidth and fabrication tolerance. In addition, two wavelengths of 1310nm and 1550nm are commonly used in optical communication networks, respectively. However, in the literature, the proposal of the switching devices operating at two wavelengths 1550nm and 1310nm has not been presented.

Chalcogenide (As_2S_3) waveguides have been proposed as a new platform for optical signal processing offering superior performance at ultrahigh bit-rates. Additionally, the high nonlinearity enables compact components with the potential for monolithic integration [7], 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 waveguides.

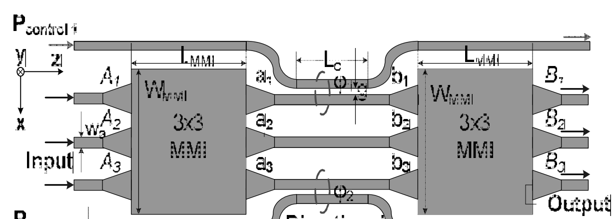

Figure. 1. A proposed optical switch based on 3x3 MMI couplers using directional couplers as phase shifters

The aim of this study is to propose a novel structure of all- optical switch based on two 3x3 MMI couplers using nonlinear directional couplers as phase shifters. Materials used is chalcogenide glass (As_2S_3) on silica (SiO_2). This device can operate at two wavelengths of 1310nm and 1550nm. Nonlinear directional couplers at two outermost arms in the inter-stage of two 3x3 MMI couplers play the role of phase shifters. In order to realize the phase shifters using nonlinear directional couplers, the control fields must be separated from input signals and enter the switching structure from a different single-mode access waveguide after the operation. The aim of this requirement is to reduce the powers transferring between control waveguide and structure waveguide. Beam Propagation Method (BPM) simulation is used to verify and optimize the operating principle of the proposed switch.

2. Device design and analysis

Figure 1 shows the proposed device structure in this study. It consists of two 3x3 MMI couplers with the same size cascaded to form the switching structure, where two nonlinear directional couplers are placed at inter-stage of two 3x3 MMI couplers to obtain all-optical phase shifters. This structure have three input ports A_1, A_2, A_3 and three output ports B_1, B_2, B_3.

The operation of proposal switch is based on 3x3 MMI couplers. The operation of an MMI coupler is based on theself-imaging theory. Self-imaging is a property of a multimode waveguide by which input field is reproduced in single or multiple images at periodic intervals along propagation direction of the waveguide [8]. MMI coupler can be characterized by the transfer matrix theory, where 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. The half-beat length of two lowest-order modes and can be written as:$L_\pi \approx 4n_r W_e^2 / 3\lambda_0$, where λ_0 is operation wavelength, W_e is effective width of the MMI and it can be determined by:$W_e \approx W_{MMI} + (\lambda_0/\pi)(n_r^2 - n_c^2)^{-0.5}$ for TE mode (n_r and n_c are refractive indices of core and cladding layers, respectively). In this design, three input ports and three output ports are located at positions:$x_i = (2i+1)W_e/6$ (i=0,1,2).

In our study, the material used in the core layer of the switch is chalcogenide glasses As_2S_3 with refractive index of n_r=2.45 and the silica (SiO_2) material is used in the cladding layer with a refractive index n_c=1.45. Material used in substrate layer is silicon (Si). 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 [9], [10], especially attractive for all optical switches in recent years because the fast response time associated with the near-instantaneous third order nonlinearity allows flexible ultrafast signal processing. In addition, the chalcogenide glass supports the operation of wavelengths range in telecom windows 1.31µm and 1.55µm; and As_2S_3 material has a high refractive index contrast to allow for a high confinement of light also ultra-compact size. Therefore, it is useful and important for large scale integrated circuits. In this study, first the 3D structure is converted to the 2D structure using the effective index method. The 2D BPM simulation is then used for designing and optimizing the whole device structure. The device is designed for operation of TE mode. The width of each 3x3 MMI couplers W_{MMI} is 18µm, the width w_a of access waveguides is 3µm for single mode operation.

In order for the proposed switch to operate at both wavelengths λ_1=1550nm, λ_2=1310nm, the length L_{MMI} of the multimode region is chosen to satisfy the condition as follows: $L_{MMI} = mL_\pi(\lambda_1) = nL_\pi(\lambda_2)$, where *m, n* are positive integers and λ_1=1550nm, λ_2=1310nm. The purpose of this requirement is that the wavelengths λ_1 and λ_2 can be switched selectively and optically at any output ports from any input ports. By using Sell Meier model, we can see that the refractive index difference for chalcogenide glass at the two wavelengths (λ_1 and λ_2) is Δn=0.02.

First, we calculate the half-beat lengths of two wavelengths with proposed design parameters by using theoretical analysis. We have found that the optimum length of the multimode region is L_{MMI}=14335 µm ≈ $20L_\pi(\lambda_1)$ ≈ $17L_\pi(\lambda_2)$. At this length of MMI region, the first MMI will operate as a splitter and the second MMI will operate as a combiner at both wavelengths. To optimize the operation of the MMI regions in the role of the splitter and combiner, linear taper waveguides at access waveguides are used. By using the BPM, the width and length of the linear tapers are calculated to be 4.8µm and l_a=130 µm. Fabrication of two phase shift control waveguides include directional coupling waveguides that are symmetrically through the center line of the MMI region as shown in Figure 1. In Figure 1, sine-shape waveguides with a length of 1300 µm are used to connect straight waveguides to the coupling waveguides. The two parallel waveguides at the outer-arm of the structure can be viewed as a directional coupler with a gap of d=80nm and coupling length of L_c=360 µm. These values are calculated by using the BPM simulation. The aim is to reduce the power coupling between the control waveguide and signal waveguide.

As mentioned above, the proposed switch requires two nonlinear directional couplers as phase shifters at two outermost arms of the device. 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

$$-i\frac{dA}{dz} = \kappa B + \gamma_1\left(|A|^2 + 2|B|^2\right)A \quad (1)$$

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

Where:κ is the linear coupling coefficient,$\kappa = \pi / 2L_c$; A and B are field amplitudes of the control waveguide and signal waveguide, respectively, $\gamma_1$and $\gamma_2$are nonlinear coefficients describing the self-phase modulation (SPM) and cross-phase modulation (XPM) effects. Nonlinear coefficient is determined by $\gamma = 2\pi n_2/\lambda_0 A_{eff}$, where n_2 is nonlinear refractive index of the waveguide; A_{eff} is the effective modal cross–section area. Under influencing of self-phase modulation in the nonlinear directional coupler, the change of phase in directional coupler will be proportional to the intensity of input of electrical fields of waveguides.

Let φ_1 and φ_2 be relative phase shifts of outermost arms in comparison with the phase of the center access waveguide which link between two 3x3 MMI regions. We also assume that, the intensity of the signal introduced into control waveguide is I and the intensity introduced into signal waveguide of the switch is always set as I_0 =1 GW/cm^2. As presented, when applying a high-intensity control field to nonlinear waveguide, its refractive index is changed and therefore it causes a change in phase shift at outermost arm. The phase shift varies proportionally with intensity of field. There is a need for a substance with high nonlinear refractive index. Hence, material in the core layer of switch is chalcogenide glasses As_2S_3 with nonlinear coefficient n_2 about 2.92×10^{-6} μm^2/W.

Due to multimode interference principle, self-imaging is formed and mirrored on a periodic cycle that is an even and odd integer times of $3L_\pi$ respectively. Therefore, when the proposed structure is operated at wavelength λ_1=1550nm, the outputs of the imaging at $L=20L_\pi$ are equivalent to the length $2L_\pi$. When the proposed structure is operated at wavelength λ_2=1310nm, the outputs of the imaging at $L=17L_\pi$ equivalent to the length $2L_\pi$ and mirrored symmetry through the center line of the proposed structure. At length $2L_\pi$, the transfer matrix of the MMI coupler is determined by:

$$M=\frac{1}{\sqrt{3}}\begin{pmatrix} e^{j\frac{\pi}{3}} & e^{j0} & e^{j\pi} \\ e^{j0} & e^{j\frac{\pi}{3}} & e^{j0} \\ e^{j\pi} & e^{j0} & e^{j\frac{\pi}{3}} \end{pmatrix} \quad (3)$$

Hence, the transfer matrices at length L_{MMI} of the MMI couplers at wavelengths λ_1=1550nm and λ_2=1310nm for 3x3 MMI regions are

$$M_1=\frac{1}{\sqrt{3}}\begin{pmatrix} e^{j\frac{\pi}{3}} & e^{j0} & e^{j\pi} \\ e^{j0} & e^{j\frac{\pi}{3}} & e^{j0} \\ e^{j\pi} & e^{j0} & e^{j\frac{\pi}{3}} \end{pmatrix} \text{ and } M_2=\frac{1}{\sqrt{3}}\begin{pmatrix} e^{j\pi} & e^{j0} & e^{j\frac{\pi}{3}} \\ e^{j0} & e^{j\frac{\pi}{3}} & e^{j0} \\ e^{j\frac{\pi}{3}} & e^{j0} & e^{j\pi} \end{pmatrix} \quad (4)$$

By using analytical expressions of the MMI coupler, at wavelength 1550nm, if (φ_1, φ_2) = ($-\pi/3$, π) then the signal is at output port B_1; if (φ_1, φ_2) = (π, $-\pi/3$) the signal is at output port B_3 and if (φ_1, φ_2) = ($\pi/3$, $\pi/3$) then the signal is at output port B_2. As an example, we investigate the switching mechanism for the case input signal at port A_1 and output signal at port B_1. First, we need to find the intensity I_1 introduced to control waveguide 1 (also see Figure 1) by varying the intensity slowly. We find out that the appropriate value is about 480GW/cm^2 to obtain a phase shift of $-\pi/3$ in comparison with the center access waveguide. Then we change the intensity I_2 introduced into control waveguide 2 to find out its value. We find out that the intensity is about 318 GW/cm^2 to make a phase shift of π in comparison with the center access waveguide. As a result, we reproduce the simulations by varying I_1 and I_2 slowly around these values again, we have obtained the optimal values I_1=310 GW/cm^2 and I_2=479 GW/cm^2. At these values, the minimum of the insertion loss and crosstalk is achieved. By using the similar analysis, we simulate the operation of the switch at both wavelengths and the results are presented in Table 1.

3. Simulation results and discussions

Due to symmetric nature of the proposed structure, the role of input ports A_1 and A_3 in Figure 1 are equivalent. Without loss of generality, we carry out simulations for the following cases: The signal is at input port A_1 at input port A_2 of the proposed structure.

***Table 1**. Optimal control fied intensities for operation of the proposed switch*

Wave length (nm)	Input port	Output port	I_1 (GW/cm^2)	I_2 (GW/cm^2)
1550	A_1	B_1	310	479
1310	A_1	B_1	568	360
1550	A_1	B_2	478	322.4
1310	A_1	B_2	365	571
1550	A_1	B_3	533	1031.5
1310	A_1	B_3	906.7	897.5
1550	A_2	B_1	480	320
1310	A_2	B_1	370.6	580.6
1550	A_2	B_2	543.9	543.9
1310	A_2	B_2	916	916
1550	A_2	B_3	480	320
1310	A_2	B_3	370.6	580.6
1550	A_3	B_1	533	1031.5
1310	A_3	B_1	906.7	897.5
1550	A_3	B_2	478	322.4
1310	A_3	B_2	365	571
1550	A_3	B_3	310	479
1310	A_3	B_3	568	360

By using the 2D BPM, the field propagation in the whole device is shown in Figure 2. The simulation results show that the operation of the switch has a good agreement with our theoretical analysis. The output powers at different output ports (normalized to the input power) are shown in Table 2.

The BPM simulation results have shown that high output field intensity can be achieved. As a result, high performance of the switch can be obtained (Table 2). Calculation formulas for insertion loss ($I.\ L.$) and extinction ratio (Ex. R.) are as follows [11]:

$$I.L.(dB)=10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \quad (5)$$

$$\text{Ex.}R.(dB)=10\log_{10}\left(\frac{P_{high}}{P_{low}}\right) \quad (6)$$

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 of input port respectively.

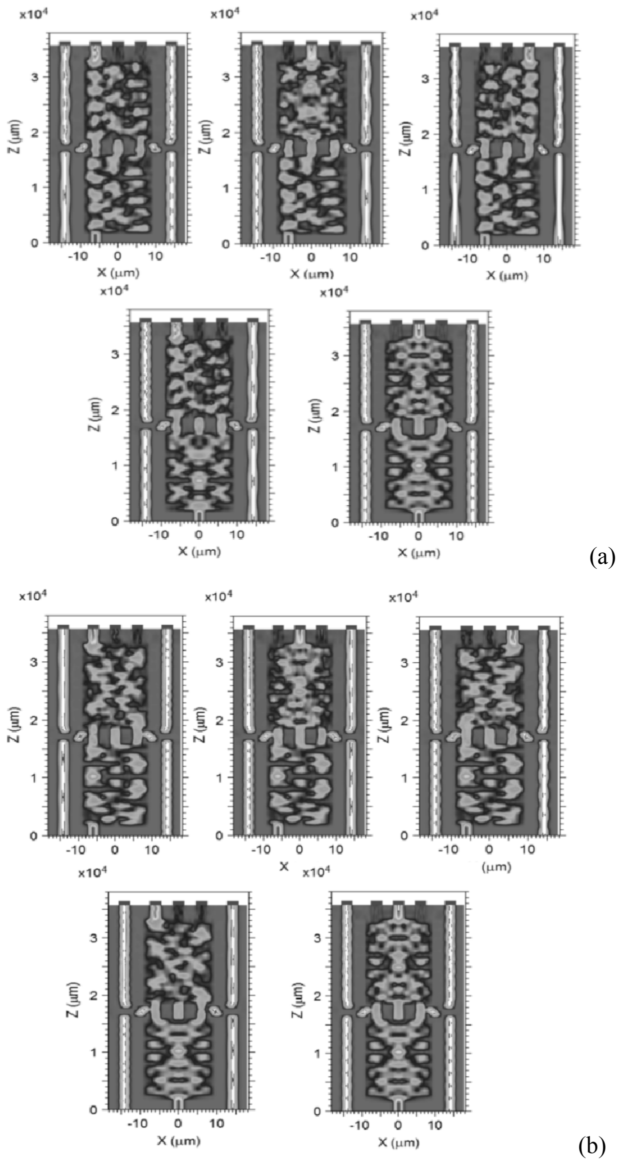

Figure 2. *2D BPM simulation of electric field pattern in the switch when (a) λ_1=1550nm; (b) λ_2=1310nm*

The results presented in Table 2 show that almost all important parameters of the proposed structure such as insertion loss, cross-talk, extinction ratio, etc. can be obtained.

By using the BPM, we calculate the insertion loss and cross-talk of the switch at two wavelengths 1550nm and 1310nm as shown in Figure 3. We can see that: at ±1nm bandwidths of the spectral responses at output ports around the center wavelengths (1550 nm or 1310 nm) insertion losses do not exceed 1dB and crosstalks are from -8 dB to -15 dB, respectively.

Table 2*. Insertion loss, extinction ratio and crosstalk of the proposed switch*

Wave length (nm)	I.L (dB)	Cr.T (dB)	Ex.R (dB)
1550 $(A_1$-$B_1)$	-0.46	-10.83	-25.7
1310 $(A_1$-$B_1)$	-0.42	-15.33	-36
1550 $(A_1$-$B_2)$	-0.57	-9.93	-30.1
1310 $(A_1$-$B_2)$	-0.42	-12.73	-38.34
1550 $(A_1$-$B_3)$	-0.44	-10.86	-35.25
1310 $(A_1$-$B_3)$	-0.3	-15.43	-41.32
1550 $(A_2$-$B_1)$	-0.29	-11	-29.74
1310 $(A_2$-$B_1)$	-0.46	-15.3	-40.68
1550 $(A_2$-$B_2)$	-0.27	-10.23	-25.88
1310 $(A_2$-$B_2)$	-0.44	-12.71	-37.43
1550 $(A_2$-$B_3)$	-0.29	-11	-29.74
1310 $(A_2$-$B_3)$	-0.46	-15.3	-40.68
1550 $(A_3$-$B_1)$	-0.44	-10.86	-35.25
1310 $(A_3$-$B_1)$	-0.3	-15.43	-41.32
1550 $(A_3$-$B_2)$	-0.57	-9.93	-30.1
1310 $(A_3$-$B_2)$	-0.42	-12.73	-38.34
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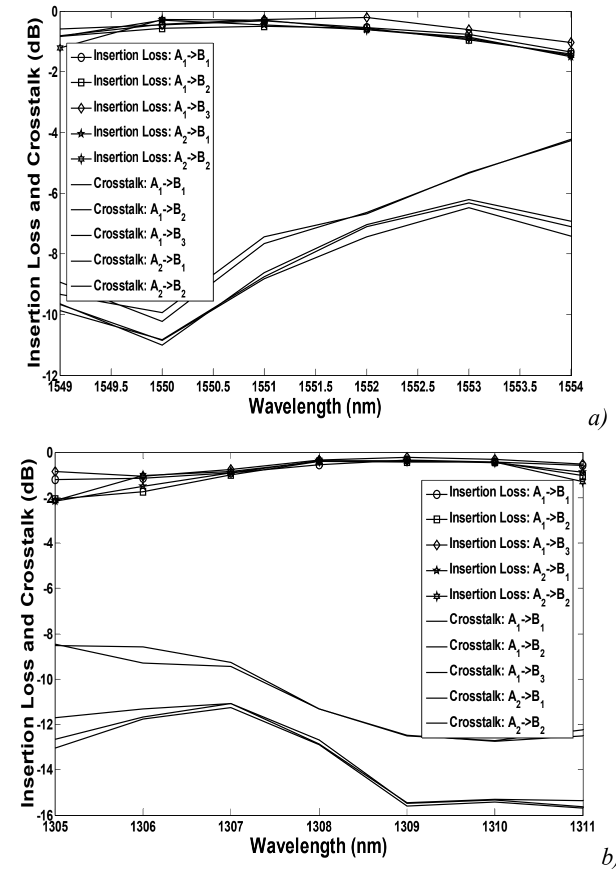

Figure 3. *Insertion loss and Crosstalk (normalized to the input power at the three output ports as the wavelength varies: a) 1510 nm band, b) 1310nm band.*

Figure 4 shows the spectral responses of the extinction ratios of the switch. It can be seen that the extinction ratio of the proposed structure are quite good. The extinction ratios at the window of the wavelength 1550nm (Figure 4a) are in the range from -21 dB to -35 dB (from 1545 nm to 1554 nm). The extinction ratios at the window of the wavelength 1310nm (Figure 4b) are in the range from -35 dB to -50 dB (from 1305 nm to 1311 nm). Clearly, extinction ratios are below -20 dB (corresponding to 0.01) so they are good performances for application of the optical switch.

4. Conclusions

A novel all-optical switch has been presented in this paper. The switch can be operated at two wavelengths of 1550nm and 1310nm. By using two non-linear directional couplers as phase shifters, 3x3 all-optical switch is realized.. The proposed device structure are analyzed and designed by using analytical expressions and the beam propagation method. The simulation results have shown that a good performance of the proposed device can be obtained. As a result, the proposed structure can be useful for applications in optical networks.

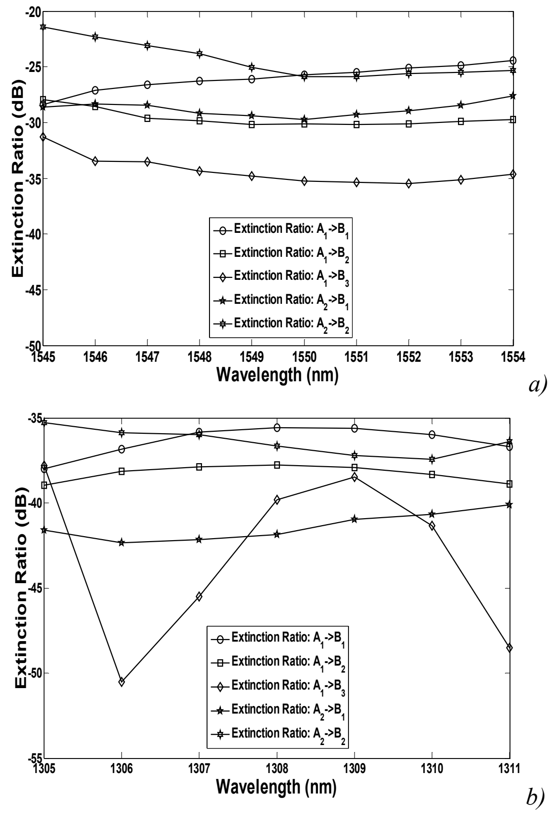

***Figure 4.** Extinction ratio at the three output ports as the wavelength varies: a) 1550 nm band, b) 1310nm band*

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