Modelling of All Optical Switch based on Symmetric Mach-Zehnder (SMZ) using Symmetric and Asymmetric Coupler

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Abstract - As increasing capacity demand in telecommunication system, the ultrahigh-speed optical network was developing rapidly. In these networks, it is important to the switching, routing and processing in optical domain to prevent bottlenecks of optoelectronic conversions. Using all optical switches based on Symmetric Mach-Zehnder (SMZ), characteristics and switching window profile was investigated in this paper. As compared to the various interferometer based switch configurations, the SMZ structure provides the most flexibility, compact size, low power operation, shortest switching window and thermal stability. This paper presents the modelling based on SMZ switch. The analysis of conventional and proposed SMZ switch by using symmetric coupler (50:50 couplers) and asymmetric coupler (60:40 couplers) placed at the end of this switch was shown and compared. The performance and advantages of these proposed SMZ switch coupler are also analyzed.

Keywords: Symmetric Mach-Zehnder (SMZ), Optical Time Division Multiplexing (OTDM), Semiconductor Optical Amplifiers (SOA), Full Width at Half Maximum (FWHM), Graphic User Interface (GUI).

1. Introduction

Optical Time Division Multiplexing (OTDM) technology is an alternative technique for future ultra-speed photonic networks that has attracted much attention [1]. At ultra-high speed, it is desirable to carry out the entire signal routing, processing and demultiplexing in the optical domain in order to avoid bottleneck due to the optical to electronic conversion. One of the key components in all-optical OTDM system is the all-optical switch, which is the main building block in all above optical functions.

All optical switches with the interferometric arrangement such as the Terahertz Optical Asymmetric Demultiplexers (TOADs) [2], the Ultrafast Non-linear Interferometers (UNIs) [3], Mach-Zehnder Interferometers (MZIs) [4], and Non-linear Optical Loop Mirrors (NOLM) [5], which are generally studied. Among these switching schemes, MZI switches are the most capable due to their compact size, thermal stability and low–power operation. Considering various MZI configurations, the SMZ structure provides the high flexibility and relatively symmetrical and shortest switching window profile [6].

2. Methodology

2.1 Operation Principle

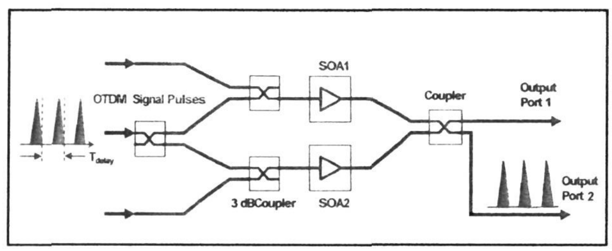

Figure 1: The model of SMZ switch without control signal

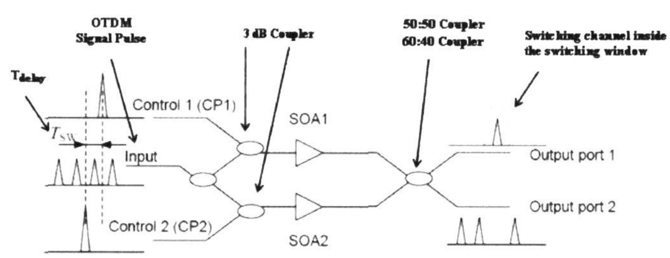

Figure 2: The model of SMZ switch with control signal

Figure 1 and Figure 2 shows the block diagram of a typical SMZ switch composed of two Semiconductor Optical Amplifiers (SOAs), one in each arm of the interferometer and a number of 3dB couplers. SOAs are positioned in the same relative location within the interferometer. Control and data pulses are fed into switch via 3dB couplers and co-propagate within the interferometer. With no control pulses, the SMZ is balanced in such a way that all the data signals emerge from the reflected output port (port 2). However, with the presence of control signals, a differential phase shift is introduced between the two arms of the interferometer thus causing the data pulses to be switched to the transmitted port (port 1) [7].

Semiconductor Optical Amplifier (SOA) is used for non linear element to enhance the band filling nonlinearity in semiconductors by simulated emission. Optical amplifiers can be divided into two classes which are Optical Fibre Amplifiers (OFAs) and Semiconductor Optical Amplifiers (SOAs). Due to advances in optical semiconductor fabrication techniques and device design, the SOA is showing great promise for use in evolving optical communication networks. It can be utilized as a general gain element but also has many functional applications including an optical switching and wavelength conversion. These functions, where there is no conversion of optical signals into the electrical domain, are required in transparent optical networks [8].

Many of the all optical networks have been made possible by the application of SOA in wavelength conversion, all-optical modulators, demultiplexers and 3R regenerator (re-amplification, re-shaping and re-timing).

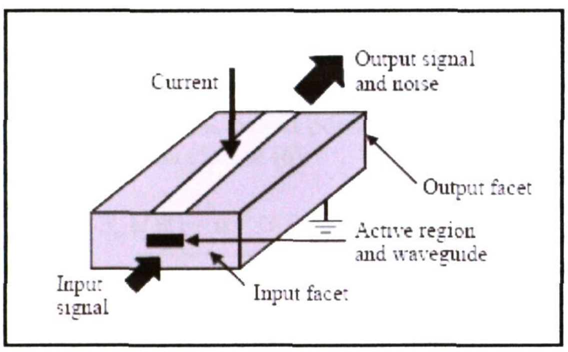

Figure 3: Schematic diagram of SOA

A schematic diagram of an SOA is shown in Figure 3 above. The device is driven by an electrical current. The active region in the device imparts gain, via stimulated emission, to an input signal. The output signal is accompanied by noise. The gain of an SOA is influenced by the input signal power and internal noise generated by the amplification process. As the input signal power increases the gain decreases as shown in Figure 4. This gain saturation can cause significant signal distortion [8].

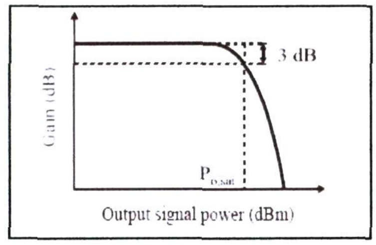

Figure 4: Typical SOA gain versus output signal power

Modelling of all optical switch based on SMZ, consist of modelling the conventional SMZ switch (using 50:50 coupler) and modelling the proposed SMZ switch (using 60:40 coupler). The difference of this proposed SMZ switch is at the end of his switch, an asymmetric coupler (60:40 coupler) is used instead of using symmetric coupler (50:50 coupler). The performance in term of contrast ratio is better when this proposed SMZ is used. High contrast ratio and low crosstalk are prerequisite for application of optical components.

2.2 Mathematical Equation

2.2.1 Mathematical Model of SOA

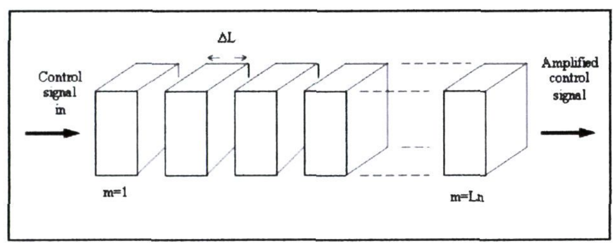

Figure 5: Modelling of SOA

Figure 5 shows a modelling of SOA. The carrier density N and the average power P_{av} is vary along SOA length. There are easy to solve numerically by breaking the SOA length into number of short length segment, L_n. Then, the segment length is set to be small so that N and P_{av} can be approximately as spatially independent within individual segments. It can be calculated locally for sequence of incremental time instances using equation below [9]:

$$N(k,t_k) = N(k,t_{k-1}) + \left[\frac{I}{q.V} - \frac{N(k,t_{k-1})}{T_{sp}} - \frac{\Gamma.g(k,t_{k-1}).P(k,t_{k-1})}{A_{SOA}.E_p}\right] \quad (1)$$

$$P_{av}(k,t_k) = P_{av}(k-1,t_{k-1}).\exp(\Gamma.g(k-1,t_{k-1}).\Delta L - \alpha_s.\Delta L) \quad (2)$$

where:

k = total no. of segment
I = bias current
q = electron charge
V = volume of active region
T_{sp} = spontaneous emission time
Γ = confinement factor
g = differential gain
A_{SOA} = SOA active area
α_s = scattering loss (internal losses)
E_p = electric field

The gains of the data signal at the output of SOA1 and SOA2 at the temporal point are given as:

$$G_1(t) = \exp\left[\int_0^{L_{SOA}} \Gamma . g\left(z, t + \frac{z}{V_g}\right) dz\right] \quad (3)$$

$$G_2(t) = \exp\left[\int_0^{L_{SOA}} \Gamma . g\left(z, t + T_{delay} + \frac{z}{V_g}\right) dz\right] \quad (4)$$

where:

t = time at which the temporal point of the data signal enters the amplifier.
T_{delay} = the control signal separation.
z/V_g = time increment in z direction.

2.2.2 Mathematical Model of SMZ switch

The power at the output ports of the SMZ can be define as equation (5) and (6):

$$P_{out1}(t) = P_{in}(t)\left[(1-\alpha)^3 G_1(t) + \alpha^2 (1-\alpha) G_2(t) - 2\sqrt{(1-\alpha)^4 \alpha^2 G_1(t) G_2(t) \cos\Delta\phi}\right] \quad (5)$$

$$P_{out2}(t) = P_{in}(t)\left[\alpha(1-\alpha)^2 G_1(t) + \alpha^2 (1-\alpha) G_2(t) + 2\sqrt{(1-\alpha)^3 \alpha^3 G_1(t) G_2(t) \cos\Delta\phi}\right] \quad (6)$$

where:

α = coupling factor
$G_1(t)$ = gain of SOA 1
$G_2(t)$ = gain of SOA 2

$\Delta\phi$ is the phase difference between the data pulses which is related to the gain ratio and the linewidth enhancement factor α_{LEF} and is given by [7]:

$$\Delta\phi = -0.5\alpha_{LEF} \ln(G_1 / G_2) \quad (7)$$

where:

α_{LEF} = linewidth enhancement factor
G_1 = complex gain of SOA1
G_2 = complex gain of SOA2

To obtain the expression for switching window of SMZ switch, the output signal power $P_{out1}(t)$ is normalized with respect to the input power $P_{in}(t)$

$$W(t) = \frac{P_{out1}(t)}{P_{in}(t)} \quad (8)$$

$$W(t) = (1-\alpha)^3 G_1(t) + \alpha^2 (1-\alpha) G_2(t) - 2\sqrt{(1-\alpha)^4 \alpha^2 G_1(t) G_2(t) \cos\Delta\phi} \quad (9)$$

For the SMZ switch using 50:50 coupler, the value of coupling ratio α is 0.5, therefore SMZ switching window simplified from equation (9) is shown in equation (10) below [10].

$$W(t) = \frac{1}{8}\left[G_1(t) + G_2(t) - 2.\sqrt{G_1(t) G_2(t) \cos\Delta\phi}\right] \quad (10)$$

SMZ switch using 60:40 coupler is used 0.6 as coupling ratio. Equation (11) shows the expression of switching window for proposed SMZ switch.

$$W(t) = \frac{1}{125}\left[8G_1(t) + 18G_2(t) - 24\sqrt{G_1(t) G_2(t) \cos\Delta\phi}\right] \quad (11)$$

The switching window provides information regarding the shape, amplitude, and temporal width of the optical switches transfer function. This characterization is important in determining the optical demultiplexing and sampling bandwidth of the switch.

2.2.3 Contrast Ratio

One method to evaluate the performance of an all-optical switch is to determine the width and contrast ratio of the switching window, where both value depend on the shape of the switching window [11].

Contrast ratio refers to the different of highest power of unwanted signal to the lowest power of unwanted signal [12] measured in dB.

$$\text{Contrast Ratio (dB)} = \left[\begin{array}{c}\text{Highest} \\ \text{Power of} \\ \text{wanted signal}\end{array}\right] - \left[\begin{array}{c}\text{Lowest Power} \\ \text{of unwanted} \\ \text{signal}\end{array}\right]$$

High contrast ratios [13] and low crosstalk are prerequisite for application of optical components.

2.3 Flow Chart of Programming Design

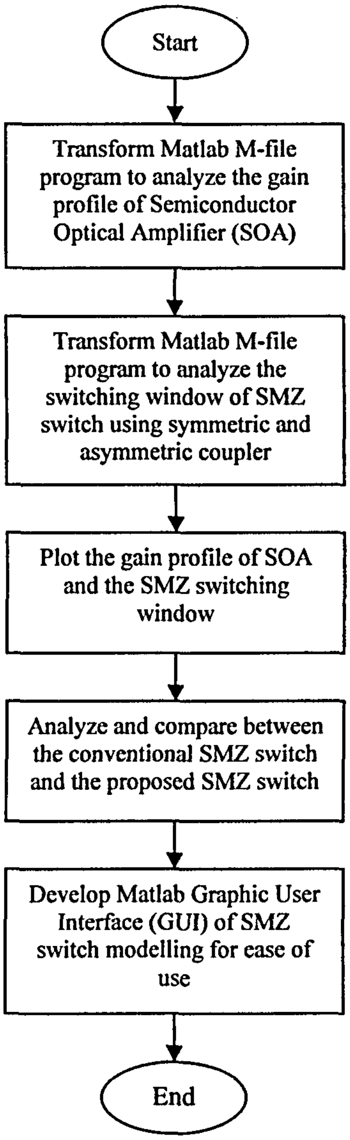

Figure 6: Flow chart of Program Design

3. Result and Discussion

The modelling of SMZ switch was built and simulated using Matlab 7.6 (R2008a). The main parameters used in the SMZ switch using 50:50 coupler simulations and the SMZ switch using 60:40 coupler simulations are given in Table 1. Then, all of results and comparisons of both SMZ switch will discuss in this section.

Table 1: MATLAB Simulation Parameters.

Parameters	Values
i) SOA	
Length, L_{SOA}	$3e^{-4}$ m
Active Area, A_{SOA}	$3e^{-13}$ m^2
Transparent Carrier Density, N_o	$1e^{24}$ m^{-3}
Confinement Factor, Γ	0.15
Gain coefficient, a	$2e^{-20}$
Linewidth Enhancement Factor, α_{LEF}	7
Total no. of segment, k	50
ii) Others	
Bias current	0.4
Group velocity, V_g	$8.5714e^{7}$m/s
Electron charge, q	$1.602e^{-19}$ C
Photon energy Eph	$1.2816e^{-19}$ C
Control pulse width, FHWM	$2e^{-12}$ s
Spontaneous emulsion time, T_{sp}	$100e^{-12}$ s
Time delay, T_d	$5e^{-12}$ s
Electrical field, E_{in}	$2.598e^{-13}$ V/m

3.1 SMZ switch using 50:50 coupler (conventional SMZ switch)

This SMZ switch uses coupling ratio α = 0.5. By injected bias current = 0.4 ampere and used linewidth enhancement factor, α_{LEF} = 7, the results are displayed in Figure 7 and Figure 8.

Figure 7 shows the gain profile of SOA1 and SOA2 separated by 5ps time delay between the control signals. Upper arm of SMZ switches is SOA1 and lower arm of SMZ switches is SOA2. Refer to the signal, initial gain of both SOA gain profile are 4.94dB. Then the gain profile drop rapidly to 4.59dB because the data signal entering SOA following the high power control signal. The high power control signal changes the carrier density of SOA due to the cross gain modulation (XGM) [8]. Thus changes the refractive index and phase of the SOA. This will alter the phase of the data signal. After that, the gain increase slowly to infinity.

Figure 8 shows the SMZ switching window of typical SMZ switch. It can be seen that, the switching window has a square and symmetrical shape due to propagating data and control signals that pass through the SMZ switch. The full wave at half maximum (FWHM) equal to 5ps since the time delay between the control signals is 5ps. A square shape of switching window profile is very important and desirable in OTDM network because there is need to multiplex or extract the target channel from the OTDM signal with crosstalk.

3.2 SMZ switch using 60:40 coupler (proposed SMZ switch)

This coupler type uses coupling ratio $\alpha = 0.6$. By using the same parameter value as SMZ switch using 50:50 coupler, (bias current = 0.4 ampere and linewidth enhancement factor, $\alpha_{LEF} = 7$), the result are displayed in Figure 9 and Figure 10.

Figure 9 shows the gain profile of the proposed SMZ switch which uses a 60:40 coupler. It can be seen that from the graph, initial gain of both SOA gain profile approximate by 4.94dB. Then the gain profile also drops swiftly same as gain profile of SMZ switch by using 50:50 coupler, to 4.59dB. The gain profile of SOA1 and SOA2 also separated by 5ps time delay between the control signals.

Figure 10 shows the switching window for the proposed SMZ switch. It can be seen that, switching window for proposed SMZ switch (using 60:40 coupler) has higher contrast ratio compared to conventional SMZ switch (using 50:50 coupler). In term of symmetrical shape, the conventional SMZ switch is more symmetrical. The full wave at half maximum (FWHM) for proposed switching window is 5ps since time delay that be use is 5ps.

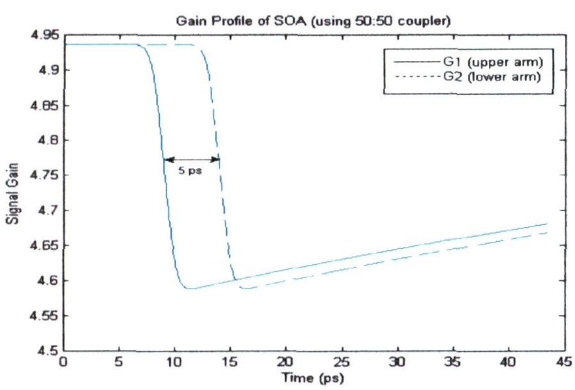

Figure 7: The Gain Profile of SOA

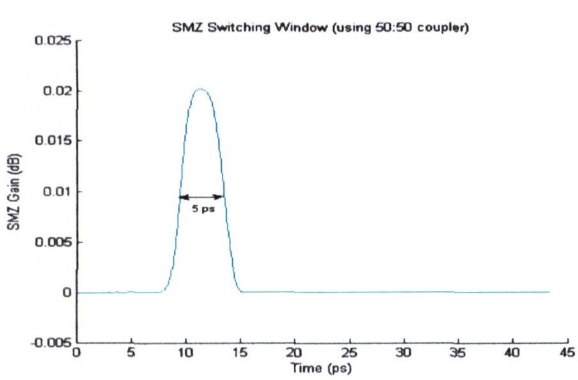

Figure 8: SMZ Switching Window for the typical SMZ switch

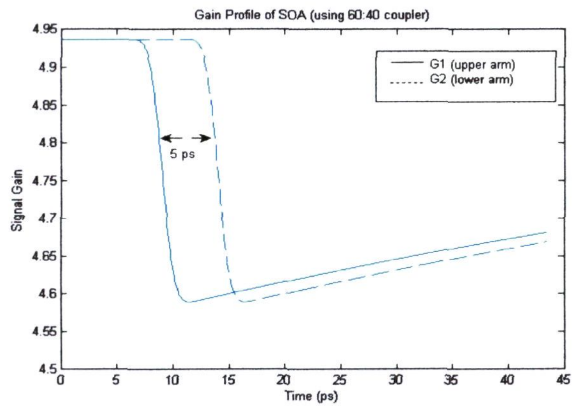

Figure 9: The gain profile of SOA

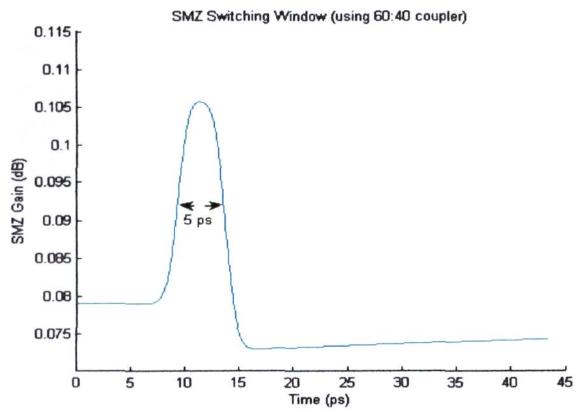

Figure 10: SMZ Switching Window for the proposed SMZ switch

3.3 Comparison between SMZ switch using 50:50 coupler and 60:40 coupler

Figure 11 shows the graph of contrast ratio versus the bias current. The bias current is injected constantly to the SOA1 and SOA2 by range from 0.1 ampere to 1 ampere. Linewidth enhancement factor α_{LEF} that used in this analysis is equal to 2. From the Figure 11, the red line referred to the typical SMZ switch and the blue line referred to the proposed SMZ switch. It can be seen that from the graph, a significant increase in contrast ratio for bias current more than 0.6 ampere for both SMZ switch. Then, by comparing between the conventional SMZ switch using 50:50 coupler and proposed SMZ switch using 60:40 coupler, it can be seen that a higher contrast ratio is achieved by using the proposed SMZ switch which use the 60:40 coupler.

Figure 12 shows the graph of contrast ratio versus the SOA length. Bias current is set to 0.6 ampere and linewidth enhancement factor α_{LEF} is set to 3. The range of SOA length that be analyzed is from 0.5 x 10^{-4} meter to 6 x 10^{-4} meter. The red line is referred to the conventional SMZ switch and the blue line referred to the proposed SMZ switch. From the graph, it can be seen that the longer of SOA length, the lower contrast ratio will reach for the both of SMZ switch. By comparing these two switches, it can be seen that, the higher contrast ratio is achieved by using proposed SMZ switch which use 60:40 coupler. A practical value of SOA Length is in the range 1 x 10^{-4} to 3 x 10^{-4} meter.

Figure 13 shows the contrast ratio versus the linewidth enhancement factor. The range of linewidth enhancement factor α_{LEF} that used for analyze is from 1 to 7 for 0.6 ampere bias current. The red line is referred to the SMZ switch using 50:50 coupler and the blue line is referred to the SMZ switch using 60:40 coupler. It can be seen that from the graph, the higher linewidth enhancement factor, the better contrast ratio will achieved for both SMZ switches. The linewidth enhancement factor describes the coupling between the induced phase changes of a signal within the material. The linewidth enhancement factor should be small to keep the linewidth small and the chirps narrow. A high linewidth enhancement factor is advantageous to obtain high contrast ratio in all optical devices. By comparing these two types of SMZ switch, the proposed SMZ switch (using 60:40 coupler) has significant increase in contrast ratio for linewidth enhancement less than 6.

Figure 14 shows the contrast ratio versus time delay. Switching window profile for different time delay experiment has been done by [14] before. For this analysis, bias current is set to 0.6 ampere and linewidth enhancement factor α_{LEF} is set to 3. The range of time that be analyzed is from 1 ps to 10 ps. From the Figure 14, it can be seen that both SMZ switches show there is no increase in contrast ratio for time delay more than 5ps. By comparing these two switches, it can be said that a higher contrast ratio is achieved using proposed SMZ switch.

Figure 15 shows the comparison of full wave at half maximum (FWHM) for different time delay between the 2 types of SMZ switches. It can be seen that from the graph, it is only a slight different between the two types of SMZ switches. FWHM increase almost linearly as the time delay increase for both types of switches.

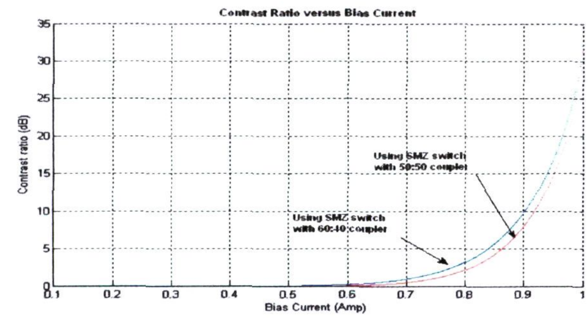

Figure 11: Contrast ratio v/s Bias Current

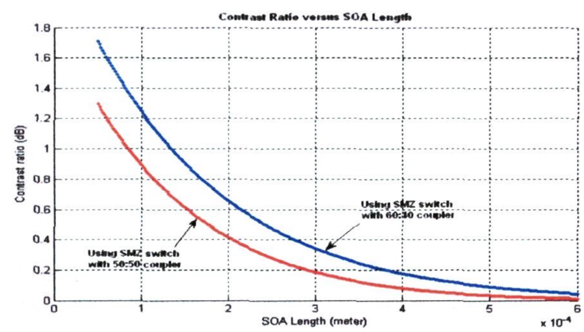

Figure 12: Contrast ratio v/s SOA Length

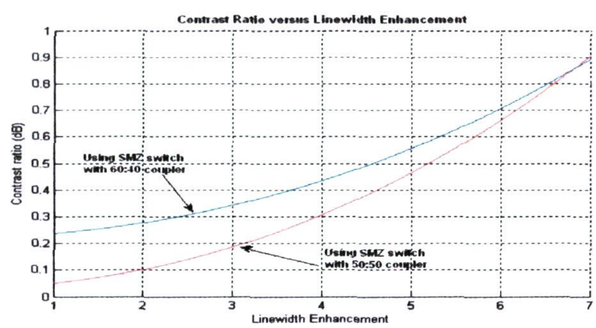

Figure 13: Contrast ratio v/s Linewidth enhancement factor

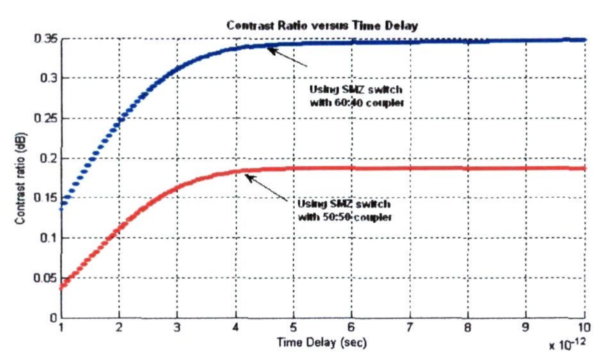

Figure 14: Contrast ratio v/s time delay

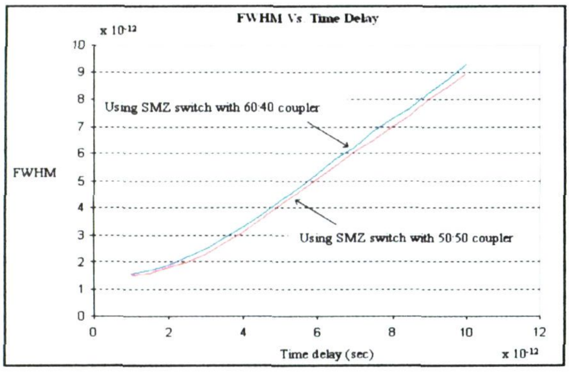

Figure 15: FWHM (full wave at half maximum) v/s time delay

3.4 Matlab GUIs Application

For both Matlab Graphic User Interface (GUI) shows in Figure 16 and Figure 17, user can get their plotting signal by entering the parameter that they need like bias current, time delay, linewidth enhancement factor, length of SOA, and area of SOA. This GUI makes it easy to user to display the SOA gain profile and the SMZ switching window.

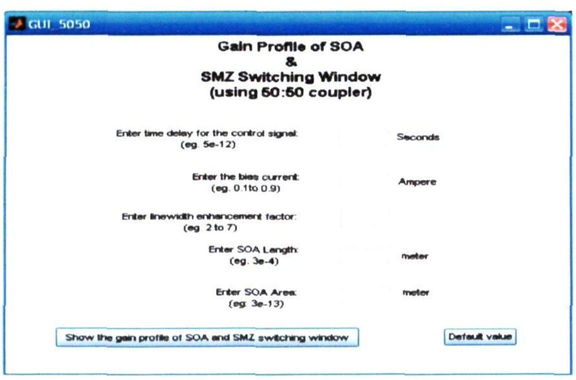

Figure 16: GUI for SMZ switch using 50:50 coupler

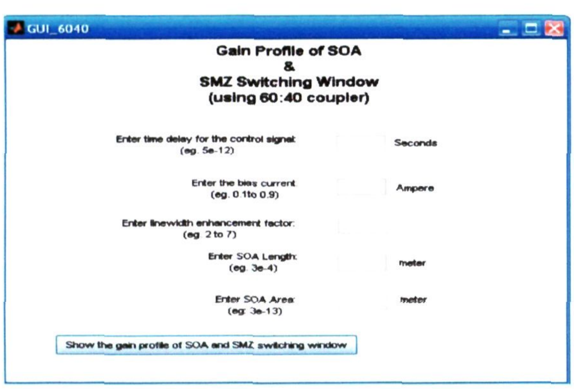

Figure 17: GUI for SMZ switch using 60:40 coupler

4. Conclusion

As a conclusion, the SMZ switch which is one type of all optical switches is one of the most reliable optical switches because it has the fastest and symmetrical switching windows, highest flexibility and most promising due to compact size. The key component for ultra high speed Optical Time Division Multiplexing (OTDM) networks is the application of all optical switch by using Symmetric Mach-Zehnder (SMZ). The application of SMZ switches in all optical signal processing including all optical switching, all optical demultiplexing, clock extraction, ultra fast wavelength conversion, 3R regeneration etc.

Back to the project objectives, the gain profile of SOA and SMZ switching window have been model. Then, conventional SMZ switch (using 50:50 coupler) and proposed SMZ switch (using 60:40 coupler) also have been analyzed. Comparing both conventional and proposed SMZ switch, it can be conclude that the proposed SMZ switch has a high contrast ratio. Therefore, it can be suggest that using SMZ switch with 60:40 coupler are more efficient than conventional SMZ switch.

5. Future Work

In the future, a system can be developed to model the SMZ switch, so that it can be using in more efficient way. Besides that, this modelling can be fabricated since it has been proved through the modelling that SMZ switch is very practical to be implemented. In addition, SMZ switch can be develop on specific application to ensure a more practical modelling so that the SMZ switch can be applied effectively. Above and beyond, research and modelling on the noise and crosstalk of SMZ switch can also be done [7].

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