

4-channel Double S-shaped AWG Demultiplexer on SOI for CWDM

Nurjuliana Juhari, P Sushitha Menon *Senior Member IEEE*, Abang Annur Ehsan and Sahbudin Shaari* *Member IEEE*

Institute of Microengineering and Nanoelectronics (IMEN),
Universiti Kebangsaan Malaysia (UKM),
43600 UKM Bangi, Selangor, Malaysia

nurjuliana@unimap.edu.my, susi@ukm.edu.my, aaehsan@eng.ukm.my, sahbudin@eng.ukm.my

Abstract—We demonstrate the design, fabrication and characterization of silicon-on-insulator (SOI)-based Arrayed Waveguide Grating (AWG) with broad channel spacing of 20 nm (~2500 GHz) which has a unique double S-shaped pattern at the arrayed region. Beam propagation method (BPM) under TE polarization at a central wavelength of 2431GHz and Complementary-Metal Oxide Semiconductor (CMOS) technology are used to simulate and fabricate the AWG device with 340 nm thick top silicon (Si) guiding layer. Performance comparison of insertion loss and optical crosstalk between the simulated and fabricated AWG was discussed. SOI-based AWG is employed in the Coarse Wavelength Division Multiplexing (CWDM) system to investigate the functionality of the device at a system level as well as to analyse signal degradation using a bit-error rate (BER) analyzer when 10 Gb/s and 40 Gb/s data rates are applied.

Keywords— AWG; broad channel spacing; CMOS technology; CWDM system; SOI

I. INTRODUCTION

Arrayed Waveguide Grating (AWG) is a type of passive optical device that is widely employed in the wavelength division multiplexing (WDM) system. Different index-contrast materials such as silica-on-silicon, polymer, InP and silicon-on-insulator (SOI) can be used to develop the AWG devices. Recently, the idea to minimize the size of optical devices especially using high index contrast materials has become increasingly popular. However, the process of scaling down the size of the device to achieve an ultra-small design structure faces a few obstacles such as birefringence and high coupling loss. One successful AWG device fabrication has been reported by Zou. J et al. [1] in which crosstalk better than -14 dB and smaller birefringence of <3.5 nm is achieved using compensated silicon nanowire in CWDM optical interconnects. For optical communication application, optical devices must meet several requirements including having low insertion loss, low crosstalk (<-35 dB), high reliability and high temperature independence [2]. Thus, the selection of materials to fabricate optical devices is of a major concern. There have been a number of reports on the advantages of using SOI [2-4] which inspire us to fabricate an AWG device using this material.

In this work, we developed a unique design structure of AWG demultiplexer that has a symmetrical S-shaped pattern at the arrayed region to comply with the broad channel spacing of 20 nm (~2500 GHz) on SOI substrate. Limitation possessed by the AWG-simulation tools caused the preference on the rib waveguide structure over other waveguide structures. We found that the best geometry for the rib waveguide structure to perform single mode profile under TE mode polarization was 75 nm for the etch depth and 700 nm for the core width. Successful design of the 4-channel SOI-based AWG was then employed in CWDM system to investigate the functionality of this device as a demultiplexer at a system level when 10 Gb/s and 40 Gb/s data rate was applied. This device was fabricated using a standard CMOS process technology and characterized using direct coupling technique. A comparison was also made between the transmission spectrum of the simulated and fabricated 4-channel AWG device.

II. PROCEDURE OF DEVELOPMENT AWG-BASED SOI

A. Design Parameter and Operation of AWG-Based SOI

At the device level, the SOI-based AWG was designed using WDM-Phasar software and the simulation process was based on the algorithm of Beam Propagation Method (BPM) operated under TE mode polarization at a central wavelength of 1571 nm. The basic architecture of the AWG device consists of two free propagation regions (FPRs), an input/output waveguide and an arrayed waveguide with a constant path length difference (ΔL) of 7.118 μm . The AWG was constructed on a 340 nm thick Si guiding layer using the rib waveguide structure. To obtain single mode condition for this AWG device, a core width of 700 nm and etch depth of 75 nm were selected, resulting in an effective index of 3.38021. To make a compact and small-sized AWG layout, the bending radius of the arrayed waveguide must be close to 90°. However, for a broad channel spacing using S-shape design, decreasing the ending radius close to 90° is not preferable as it makes the arrayed waveguide highly lossy. In order to overcome this problem, the initial bending radius was increased until we achieved a 0.097 dB loss at the arrayed waveguide region. The end results were a first and last

bending radius of 221.273 μm and 283.620 μm respectively. The overall total device size for the 4-channel AWG is 8.4 μm x 1600 μm . The AWG operates as follows; first, the optical beam is launched at the input port towards the first free propagation region (FPR). The divergent beam at the first FPR is then coupled to each of the 14 arrayed waveguides and will arrive at the output aperture with the same amplitude and phase distribution. From the output aperture, each beam enters the second FPR in a convergent pattern and subsequently reaches the individual waveguide at the output with each possesses different wavelengths. A summary of the SOI-based AWG design parameters are tabulated in Table 1.

TABLE 1. DESIGN PARAMETERS OF SOI BASED AWG

Parameter	Values
Minimum I/O waveguide separation	1.96 μm
Minimum array waveguide separation	1.94 μm
Free propagation length	41.77 μm
Array waveguide length increment (ΔL)	7.12 μm
Phasar order	15
Non-uniformity	0.52 dB
Crosstalk level	-36.29 dB
Channel spacing	2434 GHz

B. Fabrication Process and Characterization of SOI-based AWG

Figure 1 (a) shows the image of the fabricated SOI-based AWG taken using Olympus Microscope model SZ61-CCD. The electron-beam lithography (EBL) and inductively coupled plasma-reactive ion etching (ICP-RIE) techniques were used to respectively transfer the pattern and etch the silicon layer. The parameters such as etching time, power rate and combination of gases were controlled in order to achieve a target etch depth of 75 nm with 700 nm width. This device was fabricated using outsourced facilities at the Institute of Materials Research and Engineering (IMRE). The profile of the AWG device was characterized using scanning electron microscope (SEM) with different image resolutions as illustrated in Figure 1 (a), (b) and (c). The enlarged image of FPR with tapered configuration at the input/output waveguide and the arrayed waveguide can be observed in Figure 1 (b). Meanwhile, 65 nm etch thickness as illustrated in Figure 1 (d) was achieved using the ICP-RIE process.

The setup configuration for the transmission measurement of the fabricated device is shown in Figure 1 (e). The tunable light source (TLS) model AQ4320 with a total power of 0 dBm was launched towards the device under test (DUT). The range of scanning wavelength of the TLS was set from 1480 nm to 1580 nm. Meanwhile the remaining wavelength from 1580 nm to 1610 nm used Fabry Perot (FP) as the laser source. The output port of the DUT was then connected to an optical spectrum analyzer (OSA) model AQ6317B. Finally, the transmission spectrum for each channel of the AWG device was observed from the OSA.

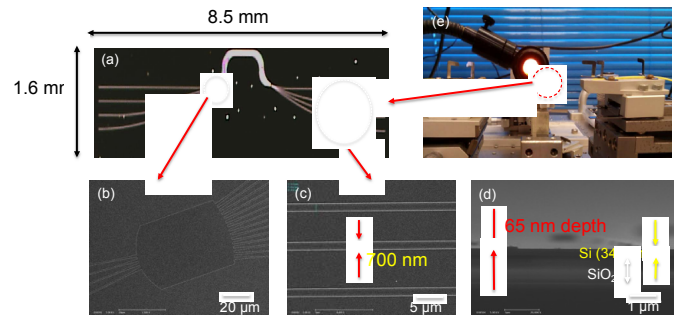


Figure 1. (a) Overall image of SOI-based AWG taken from optical microscope, (b) enlarged image of FPR with tapered configuration at arrayed waveguide and I/O region, (c) enlarged image for core width of 700 nm (d) enlarged image for etch depth profile and (e) alignment setup for measuring transmission spectrum for the AWG device.

C. Configuration of AWG Device in CWDM-System for 10 Gb/s and 40 Gb/s Data Rate

For system level simulation, the setup of the SOI-based AWG demultiplexer that is employed in the CWDM system is depicted in Figure 2. At the transceiver part (T_x), two electrical generators namely Pseudo-Random Bit Sequence (PRBS) and non-return to zero (NRZ) that carry binary data with rectangular pulses were fed into the Mach Zehnder Modulator (MZM). At the same time, 0 dBm optical carrier generated from continuous wave (CW) laser with the wavelength range of 1551 nm to 1611 nm was connected to the MZM. Each CW was modulated using MZM under NRZ format with 10 Gb/s data rate. All modulated signals were then fed into the multiplexer and launched inside different lengths of optical fiber. The optical fiber had a 0.25 dB/km attenuation and 16.75 ps/nm/km dispersion. Next, the signal from the optical fiber was split accordingly upon entering the developed SOI-based AWG demultiplexer. At the receiver (R_x) part, the signal was detected by a PIN detector with responsivity of 1 A/W, and later went through a filter that displayed the resulting data in the form of a Bessel shape. The performance of the system was analysed using a BER analyzer. The signal sensitivity that arrived at the BER analyzer was determined using the size of the maximum eye opening for each wavelength. The same procedure was carried out for different data rate of 40 Gb/s.

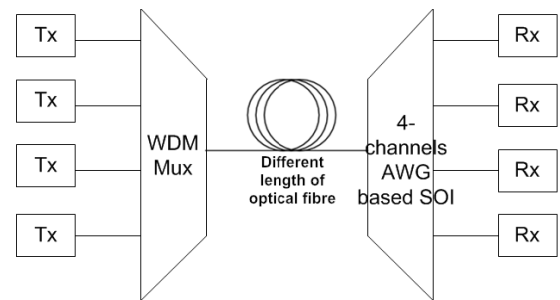


Figure 2. The schematic design of the 4 channel AWG demultiplexer based on SOI that was applied into the CWDM system.

III. RESULTS AND DISCUSSION

A. Simulation Results and Discussion

At the device level, a 4-channel AWG based on SOI had been successfully transmitted to the output port covering C and L band. Figure 3 shows the transmission spectrum for the 4-channel AWG. Average insertion loss and adjacent crosstalk for all channels are 5.04 dB and -17.05 dB respectively, while the bandwidth at 3 dB is 14.5 nm and non-uniformity for each channel is below 1.3 dB. When being compared with the theoretical data from Table 1, it can be seen that the simulation data for non-uniformity and crosstalk gives a higher value. Comparison with the existing work [6-7] shows that this device produces higher value of insertion loss. In the case of adjacent crosstalk, comparable values [8] are exhibited especially for waveguide that has a cross section of 1.2 μm in width and 200 nm etch depth. However, when comparing the overall transmission spectrum with the standard ITU-T CWDM wavelength grid, we found that the central peak wavelength of 1551 nm from the simulation result almost perfectly fits the wavelength grid.

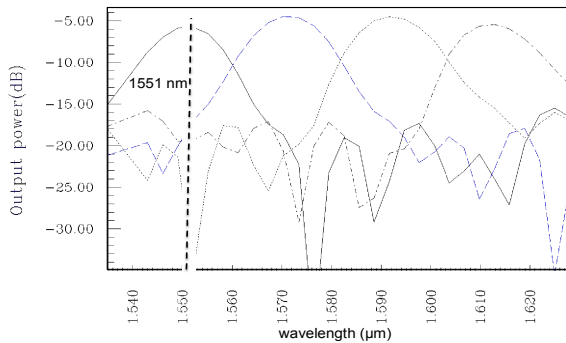


Figure 3. The simulation result for 4-channels AWG based on SOI.

B. Experimental Results and Discussion

Figure 4 shows the transmission spectrum of the 4-channel AWG obtained from procedure B. Before the DUT is measured, losses between two connectors for each wavelength are measured. The peak power for wavelength 1551 nm, 1571 nm, 1691 nm and 1611 nm are -2.99 dBm, -2.96 dBm, -4.14 dBm, -4.32 dBm respectively. Thus, the throughput loss for each wavelength is 26.20 dB, 29.77 dB, 27.73 dB and 27.15 dB. At first attempt, we launched single wavelength (1551 nm and 1571 nm) from TLS and 1591 and 1611 from FP laser source towards for each output port. As the result, we obtained a gabled spectrum line representing each window as shown in Figure 4. However, when compared between simulation and fabrication results, indicated that the 20 nm channel spacing for each window was not obtained. The same experimental procedure was repeated with the scanning range from 1480 nm to 1580 nm with scanning steps of 0.01 nm and the result is shown in Figure 5. It was observed that 20 nm slightly achieved at output 3 and 4, however, when the same input power was launched at different output port, indicated that there is no specific trend represented that each wavelength was split accordingly. From the fabrication perspective, we

believe that the light source that carry different wavelength was coupled at the second star coupler due to fabrication tolerance. Therefore, as the result, all the wavelengths were combined at each port and each wavelength that representing for each window has been seen at each port. As comparison between simulation data and experimental data observed from Figure 4, experimental result for 3 dB level bandwidth gives equal values of 4 nm as tabulated in Table 2.

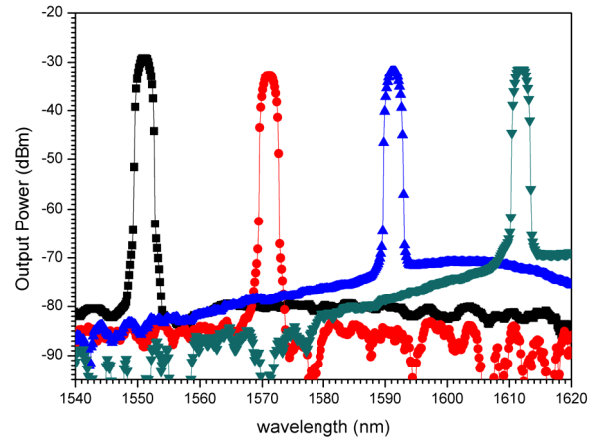


Figure 4. The transmission spectrum from each output port.

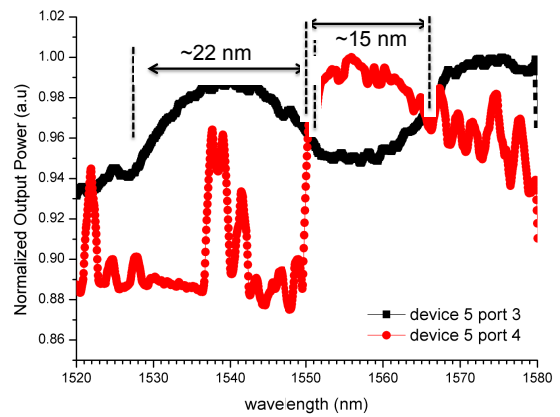


Figure 5. The transmission spectrum from each port 3 and port 4.

TABLE 2. COMPARISON DATA BETWEEN SIMULATION AND FABRICATED AWG DEVICE COVERING C AND L BAND

Standard ITU-T CWDM wavelength grid	Central wavelength (nm); simulation	Central wavelength (nm); experiment	-3dB bandwidth (nm); simulation	-3dB bandwidth (nm); experiment
1551	1551	1551.04	6.75	4.0
1571	1572	1571.04	20.00	4.0
1591	1593	1591.36	14.50	4.0
1611	1611	1611.84	11.15	4.0

D. Simulation and Discussion for Application AWG Device in CWDM-System using 10 Gb/s and 40 Gb/s Data Rate

At the system level, SOI-based AWG was adopted into the CWDM system using 10 Gb/s and 40 Gb/s data rate. To

produce a good link system, the power budget must be larger than the power sensitivity. In our system, this terminology can be simplified by means of the received power which must be greater than the minimum power at BER <10⁻¹². Calculation of the power sensitivity for PIN and avalanche (APD) photodiode in this system is shown in Figure 5. However, for this system we only used PIN photodiode as the receiver. From the power budget stated in equation (1), P_{RX} is the received power, Σ losses= summation of connector loss (l_c) + splice loss (l_s) + insertion loss of AWG based SOI & WDM Mux (l_{AWG}) + attenuation fiber × Length (αL) and G_{MARGIN}=6 dB. Assuming that the connector loss =0.2 dB, splice loss =0.1 dB and α=0.25 dB/km [9], then the received power can be determined. Simulation result at the device level for SOI-based AWG demonstrates an insertion loss of 5.04 dB. From the parameter given, calculation of the theoretical power budget and simulation data in accordance to the fiber length increment is summarized in Table 3 and Table 4.

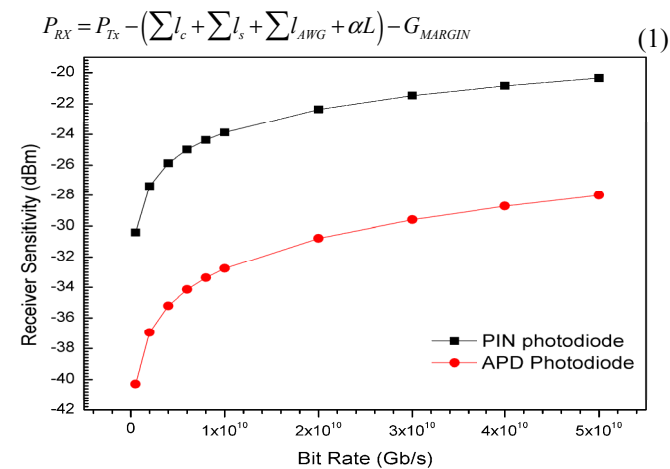


Figure 6. The theoretical value of power sensitivity for different bit rate.

Table 3 shows that the theoretical power sensitivity at 10 Gb/s gives the value of -23.87 dB. This data is observed for the wavelength at 1551 nm. At the fiber distance of 55 km, power budget drops to -25.49 dB and causes the link to fall under a bad condition. However, based on the simulation data, it can be observed that the eye diagram gives the BER=10⁻¹² until the fiber reaches 65 km. This indicates that the link can be operated as far as 65 km with reference to the simulation data. However, due to fiber dispersion at 1551 nm, we estimated that the maximum working length of the fiber is 56.10 km before the system fails to transmit. Due to this condition, we decided to limit the maximum fiber length for this system to be below 55 km to ensure a proper transmission. The same situation occurs for the AWG device working under 40 Gb/s data rate. Fiber dispersion limited the maximum reach of the fiber distance to 3.66 km although the calculated power budget shows that the link can be operated until 5 km. However, the BER analyzer shows that the calculated power budget is erred since the BER increased to 0.005 dB. Hence, we have decided that for 40 Gb/s data rates,

the system can perform in good condition when the fiber length is below 4 km.

TABLE 3. PERFORMANCE OF THE CWDM SYSTEM FOR 10 Gb/s DATA RATE AND OBSERVED AT 1551 NM WAVELENGTH

Fibre Length (km)	Max. fibre length due to dispersion (km)	Calculated Power Budget (dB)	Calculated Power Sensitivity for 10 Gb/s bit rate	Simulation data when BER<10 ⁻¹²	Condition of the system
35	56.10	-20.85	-23.87	3.02 ×10 ⁻⁵³	Good
45		-22.99		1.31×10 ⁻⁵⁴	Good
55		-25.49		2.39×10 ⁻²⁴	Good
65		-27.99		2.82×10 ⁻¹²	Good
75		-30.49		3.95×10 ⁻⁶	Bad

TABLE 4. PERFORMANCE OF THE CWDM SYSTEM FOR 40 Gb/s DATA RATE AND OBSERVED AT 1551 NM WAVELENGTH

Fibre Length (km)	Max. fibre length due to dispersion (km)	Calculated Power Budget (dB)	Calculated Power Sensitivity for 40 Gb/s bit rate	Simulation data when BER<10 ⁻¹²	Condition of the system
1	3.66	-11.99	-20.83	9.59 ×10 ⁻⁷⁶	Good
2		-12.24		2.27×10 ⁻⁴⁰	Good
3		-12.49		2.52×10 ⁻⁴⁰	Good
4		-12.74		6.67×10 ⁻²³	Good
5		-12.99		0.005	Bad

IV.CONCLUSIONS

We have successfully designed and fabricated a SOI-based AWG that covers the wavelength range of 1551 nm to 1611 nm for an approximate 2500 GHz channel spacing. Based on central channel of each wavelength, an almost perfect fit with the standard ITU-T CWDM wavelength grid is achieved, proving our device reliability as a demultiplexer. One of the concerns for the fabricated AWG device is the higher insertion losses which can be overcome by using tapered fiber. Fabricated device need to be improved since the wavelength at star coupler was coupled and increased the optical crosstalk for each adjacent waveguide and apparently makes the respective wavelength that represented CWDM wavelength grid were combined.

At the system level, the device has successfully operates under good condition for a distance below 55 km when 10 Gb/s data rate is used, and below 4 km when 40 Gb/s data rate is used. Increasing the data rate will decrease the maximum fiber length as well as fiber dispersion. Using APD

photodiode and dispersion shifted fibre (DSF) will possibly increase the maximum fiber reach and improve the whole system.

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Nurjuliana Juhari obtained her B.Sc and M.Sc from University of Malaya (UM) under the physics department in the years 2003 and 2007. She is currently pursuing a PhD degree at Photonics Technology Laboratory, IMEN, UKM. Her research interests revolve around the design, fabrication and characterization of passive devices in sub-micron level SOI based Arrayed Waveguide Grating (AWG) for the application in CWDM system.

P Susthitha Menon (M'09) received her B.Eng. degree in Electrical, Electronics and System Engineering from The National University of Malaysia (Universiti Kebangsaan Malaysia - UKM) in 1999 and the M.Sc. degree in optoelectronics from UKM in 2005. She obtained a Ph.D. degree with distinction in Optoelectronics and Nanophotonics from the Institute of Microengineering and Nanoelectronics (IMEN), UKM in 2008. She is currently a senior research fellow at IMEN and her current research interests are in the field of nanophotonic optical waveguides, surface plasmon resonance (SPR), optoelectronics and optical fiber based sensors, which are all geared towards bio-sensing.

Abang Annuar Ehsan received a B.E. degree in Electrical Engineering from University of New South Wales, Australia in 1996, and a M.Sc. degree in Microelectronics from UKM, in 2002. He received a Ph.D degree in Applied

Science from Universiti Teknologi MARA, Malaysia in 2010 and a Ph.D in Microengineering and Nanoelectronics from UKM, in 2012. His research interests include plastic optical fiber devices, planar optical waveguides, optical design and modeling, and rapid manufacturing of optical devices.

Sahbudin Shaari received the M.Sc degree (Quantum Electronics) from University of Essex and Ph.D degree (Microelectronics) from University of Wales in 1980 and 1989 respectively. From 1978 to 2003 he was a lecturer at the Department of Electrical, Electronics and System Engineering, UKM. In 1982, he introduced optical fiber communications into the country. He became a full-fledged professor in microelectronics/photonics in 2002. In 2003, he joined IMEN, UKM as the head of Photonics and Nanophotonics Research Group. Currently his research interest is in the field of silicon photonics.