50 Gb/s Silicon Photonics Receiver with Low Insertion Loss

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Abstract - Optical (de)multiplexers which can provide low insertion loss, low cross-talk, high thermal stability and insensitivity to fabrication tolerances are essential components for silicon photonics integration. In this paper we demonstrate the integration of an angled multimode interferometer coarse wavelength division multiplexer with germanium *p-i-n* photodetectors to form a 50 Gb/s receiver with a low insertion loss of < -0.5 dB and cross-talk of < -15 dB. The angled multimode interferometer has the flexibility to be designed on a platform with a wide range of waveguide thicknesses with little variation in performance, which allows for the optimisation of other optical components in the photonics integrated circuit.

Index Terms - Germanium, Integrated Optoelectronics, Lithography, Loss Measurement, Multimode Waveguides, Optical Waveguide Components, Photodetectors, Silicon in Insulator Technology, Waveguide Theory, Wavelength Division Multiplexing

I. INTRODUCTION

The demonstration of a 4-channel angled multimode interferometer (AMMI) [1] and an interleaved 8-channel AMMI [2] on the silicon-on-insulator (SOI) platform offers a convenient way to build a silicon wavelength division multiplexing (WDM) optical transceiver. The AMMI based transceivers could have the distinct advantages of both low insertion loss (hence, low input power for transmitter and high responsivity for receiver) and ease of fabrication (single lithography and etch step on the WDM part) at the same time. The AMMIs we reported previously were based on the SOI platform with a 400 nm thick top silicon layer and an etch depth of 220 nm. These structural parameters were designed for the optimization of surface grating couplers in connection with the AMMIs, as well as other active silicon components to be integrated with the AMMIs, e.g. modulators and detectors. Fortunately, the AMMI has the flexibility to be designed on a platform with a wide range of waveguide thicknesses with little variation in performance, which is superior to WDMs based on single-mode waveguides, e.g. arrayed waveguide gratings (AWGs) and planar concave gratings (PCGs). When designing an AMMI based photonic integrated circuit (PIC), for the best performance, one may firstly optimize the waveguide thickness and etch depth (if rib waveguides are to be used) for the other optical components and use those parameters as the condition for the design of the AMMI.

Previously, a large variety of silicon photonic devices and PICs have been built on the 220 nm SOI platform [3-5], where commercial fabrication technology is available for both passive and active silicon photonic components, e.g. ePIXfab service. The design procedure for the AMMIs on the 220 nm platform is similar to that on the 400 nm platform [1] and can be tailored to the design of integrated devices incorporating AMMIs.

CMOS compatible photodetectors are another essential component for a silicon photonic IC. Since silicon is transparent at communication wavelengths another material, such as germanium, must be used. Germanium has a bandgap of 0.66 eV meaning the absorbing region extends slightly beyond 1.55 μm . Waveguide integrated photodetectors have been demonstrated by a number of groups with both vertical [6-15] and lateral [16-18] device designs.

Recently, a few high-performance integrated silicon photonics receivers targeting commercial application have been reported. In order to reduce the insertion loss, Feng *et al.* used an Echelle grating, with an insertion loss of 2.5 dB, as the WDM component [19]. However, the fabricated device has a large foot print of 16 mm $\times$ 11.5 mm. Hiraki *et al.* used a silica AWG as the WDM component for low-temperature-dependent operation but the insertion loss resulting from the AWG is relatively high (5.1 dB) [20].

Here, we report a silicon photonics receiver using an AMMI as the WDM structure integrated with lateral germanium photodetectors. The integrated receiver was fabricated on the 220 nm SOI platform using standardized epitaxy and implant processes provided by the ePIXfab service. It has an aggregate data rate of 50 Gb/s, an insertion loss of < -0.5 dB and a cross talk of < -15 dB coming from the WDM structure.

II. DEVICE DESIGN AND FABRICATION PROCESS

The integrated silicon photonics receiver is composed of a 4-channel AMMI and 4 germanium detectors in connection with the output waveguides of the AMMI. A schematic drawing of the device is shown in Fig. 1.

The design strategy of the AMMI is the same as we reported in [1, 2]. The SOI strip waveguide structure with a silicon overlayer thickness of 220 nm and SiO_2 top and bottom cladding was used as the design condition of the AMMI. The design parameters of the AMMI are shown in Table I.

Fig. 1. Schematic of the AMMI receiver with enlarged Ge photodetector.

TABLE I. Designed structural parameters for the AMMI

$$W_{IO} = 10 \mu\text{m}, \theta = 16.6^\circ, W_{MW} = 25 \mu\text{m}$$

L_1 (μm)	L_2 (μm)	L_3 (μm)	L_4 (μm)
4129	4092	4055	4019

The AMMI has a channel spacing of 10 nm centered at 1560 nm. Simulation shows this structure has an insertion loss of -0.3 dB and a cross talk of -25 dB (Fig. 2). This optimized simulation data on the 220 nm strip waveguide platform is comparable with the 400/180nm rib waveguide platform [1, 2], showing the compatibility of AMMIs on different platforms.

Fig. 2. Simulated spectral response of a 4-channel AMMI.

There are two coupling schemes to consider for the integration of the germanium photodetectors with the silicon waveguides; evanescent coupling and butt coupling. We have designed a butt coupled device to improve the absorption efficiency and therefore allow a shorter device length which reduces the capacitance. The germanium detector is designed as a lateral *p-i-n* structure with an intrinsic absorbing area of $1.4 \mu\text{m} \times 14 \mu\text{m}$, as shown in Fig. 1.

The devices were fabricated at CEA-LETI on an 8-inch SOI wafer with a silicon overlayer thickness of 220 nm and a

buried oxide (BOX) thickness of 2 μm . The AMMI structure was fully etched to the BOX to form strip waveguides. Silicon recesses were etched at the end of each waveguide using a SiO_2 hard mask to allow butt coupling of light into the detector. Germanium was then deposited in these recesses using a selective reduced pressure chemical vapour deposition (RP-CVD) process. A chemical mechanical polishing step (CMP) was carried out to planarize the surface following germanium overgrowth which was necessary in order to prevent faceting in the recesses [17]. SiO_2 was then deposited and patterned to define the ion implantation windows needed to form the *p-i-n* junctions. After implantation the dopants were activated by thermal annealing and the electrodes formed by deposition of a titanium/titanium nitride/aluminum copper stack. A microscope image of the receiver is shown in Fig. 3.

Fig. 3. Microscope images of a 4-channel AMMI receiver showing: a) AMMI input, b) AMMI output coupling, c) truncated 4-channel AMMI integrated with Ge photodetectors.

III. EXPERIMENTAL AND RESULTS

Light from a tunable wavelength laser was coupled into the receiver device via an optical fibre and grating coupler. The resulting current from each of the 4 channels with no applied bias was measured and is plotted in Fig. 4. After removing the external losses such as coupling loss and waveguide loss by measuring the transmission through a straight waveguide, the responsivity of the detectors at 1550 nm with no applied bias is calculated to be approximately 0.5 A/W. This agrees with the ePIXfab quoted specification. It was found that the current had no dependence on the applied bias, similar to Vivien *et al.* [17] observed, which implies that all of the photogenerated carriers are collected by the strong built-in electric field.

By comparing the current from a standalone detector with the same configuration with the current from each channel of the AMMI receiver device, the transmission through the AMMI can be calculated and plotted, as shown in Fig. 5. A single AMMI has an insertion loss of < -0.5 dB and a cross-talk of approximately < -15 dB across the 4 channels. The channel spacing is 10 nm. The experimental results match reasonably well with the simulation data in Fig. 2 except that

the cross talk at channels 1, 3 and 4 is higher. It is shown that the main peaks of these channels coincide with the side peaks of the non-neighbouring channels, which is not seen in the simulation. This phenomenon is not that obvious on the 400 nm platform [1, 2], which can be explained by the increased phase noise in the process of self-imaging on the 220 nm platform. One may expect a thinner AMMI's spectral response to be more sensitive to the fabrication error, e.g. waveguide thickness variation.

Fig. 4. Measured current from the 4 detector channels and a standalone detector with the same configuration.

Fig. 5. Insertion loss of the 4-channel WDM device.

The dark current of the detectors is measured to be 60 pA with no applied bias and 10-20 nA at -1 V. IV curves for a 4 channel receiver and stand-alone detector are shown in Fig. 6 where a current limit of 250 μ A has been set in order to prevent damage to the devices.

In order to characterise the high-speed performance of the 4-channel receiver a 12.5 Gb/s modulated optical signal was generated using an electrical pseudo-random binary sequence (PRBS) source, driver amplifier and commercial LiNbO₃ modulator. This signal was amplified using an erbium doped fibre amplifier (EDFA) and coupled to the device using an optical fibre and a grating coupler. A -1 V reverse bias was applied to the devices. The electrical signal from each channel

was measured using a high-speed ground-signal-ground (GSG) probe and digital communications analyser (DCA). The resulting open eye-diagrams for each channel at its peak wavelength are shown in Fig. 7 giving an aggregate data rate of 50 Gb/s. The difference in amplitude for each channel can be attributed to the non-uniform gain of the EDFA.

Fig. 6. IV curves for the 4-channel detectors and standalone detector showing a dark current of 60 pA at 0 V and 10-20 nA at -1 V.

Fig. 7. 12.5 Gb/s eye diagrams of detectors operating at -1 V showing a) channel 1 at 1545 nm, b) channel 2 at 1555 nm, c) channel 3 at 1565 nm, d) channel 4 at 1575 nm and e) modulator eye diagram.

The data rate from each channel could be further improved by integration with the Vivien *et al.* [17] 40 Gb/s photodetectors also fabricated at LETI. These devices have a narrower intrinsic width of 500 nm which decreases the carrier transportation time. Furthermore, the aggregate data rate for these integrated receivers can be extrapolated for additional channels and could indeed reach 320 Gb/s by integration of the 40 Gb/s photodetectors with our recently demonstrated eight channel interleaved AMMI demultiplexers [2].

IV. SUMMARY

We have reported on the design, fabrication and characterisation of a 4-channel AMMI structure integrated with germanium *p-i-n* photodetectors to form a silicon photonics receiver. Light detection at 50 Gb/s has been demonstrated with a low dark current of < 20 nA at -1 V bias. The AMMI structure exhibits a low insertion loss of < -0.5 dB and cross-talk of < -15 dB across the 4 channels.

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REFERENCES

- [1] Y. Hu, R. M. Jenkins, F. Y. Gardes, E. D. Finlayson, G. Z. Mashanovich, and G. T. Reed, "Wavelength division (de)multiplexing based on dispersive self-imaging," *Optics Letters*, vol. 36, pp. 4488-4490, 2011.
- [2] Y. Hu, F. Y. Gardes, D. J. Thomson, G. Z. Mashanovich, and G. T. Reed, "Coarse wavelength division (de)multiplexer using an interleaved angled multimode interferometer structure," *Applied Physics Letters*, vol. 102, 2013.
- [3] W. Bogaerts, P. Dumon, D. V. Thourhout, D. Taillaert, P. Jaenen, J. Wouters, *et al.*, "Compact Wavelength-Selective Functions in Silicon-on-Insulator Photonic Wires," *Selected Topics in Quantum Electronics, IEEE Journal of*, vol. 12, pp. 1394-1401, 2006.
- [4] J. Brouckaert, W. Bogaerts, P. Dumon, D. Van Thourhout, and R. Baets, "Planar Concave Grating Demultiplexer Fabricated on a Nanophotonic Silicon-on-Insulator Platform," *Journal of Lightwave Technology*, vol. 25, pp. 1269-1275, 2007.
- [5] P. Dong, W. Qian, H. Liang, R. Shafiiha, N.-N. Feng, D. Feng, *et al.*, "Low power and compact reconfigurable multiplexing devices based on silicon microring resonators," *Optics Express*, vol. 18, pp. 9852-9858, 2010.
- [6] J. F. Liu, D. Pan, S. Jongthammanurak, D. Ahn, C. Y. Hong, M. Beals, *et al.*, "Waveguide-Integrated Ge *p-i-n* Photodetectors on SOI Platform," in *Group IV Photonics, 2006. 3rd IEEE International Conference on*, 2006, pp. 173-175.
- [7] D. Ahn, C.-y. Hong, J. Liu, W. Giziewicz, M. Beals, L. C. Kimerling, *et al.*, "High performance, waveguide integrated Ge photodetectors," *Opt. Express*, vol. 15, pp. 3916-3921, 2007.
- [8] T. Yin, R. Cohen, M. M. Morse, G. Sarid, Y. Chetrit, D. Rubin, *et al.*, "31 GHz Ge *n-i-p* waveguide photodetectors on Silicon-on-Insulator substrate," *Opt. Express*, vol. 15, pp. 13965-13971, 2007.
- [9] M. Beals, J. Michel, J. F. Liu, D. H. Ahn, D. Sparacin, R. Sun, *et al.*, "Process flow innovations for photonic device integration in CMOS," San Jose, CA, USA, 2008, pp. 689804-14.
- [10] Y. Tao, C. Rami, M. Mike, S. Gadi, C. Yoel, R. Doron, *et al.*, "40Gb/s Ge-on-SOI Waveguide Photodetectors by Selective Ge Growth," 2008, p. OMK2.
- [11] L. Vivien, J. Osmond, J.-M. Fédéli, D. Marris-Morini, P. Crozat, J.-F. Damlencourt, *et al.*, "42 GHz *p-i-n* Germanium photodetector integrated in a silicon-on-insulator waveguide," *Opt. Express*, vol. 17, pp. 6252-6257, 2009.
- [12] S. Klinger, M. Berroth, M. Kaschel, M. Oehme, and E. Kasper, "Ge-on-Si *p-i-n* Photodiodes With a 3-dB Bandwidth of 49 GHz," *Photonics Technology Letters, IEEE*, vol. 21, pp. 920-922, 2009.
- [13] N.-N. Feng, S. Liao, P. Dong, D. Zheng, H. Liang, C.-C. Kung, *et al.*, "A compact high-performance germanium photodetector integrated on 0.25 μ m thick silicon-on-insulator waveguide," San Francisco, California, USA, 2010, pp. 760704-6.
- [14] S. Liao, N.-N. Feng, D. Feng, P. Dong, R. Shafiiha, C.-C. Kung, *et al.*, "36 GHz submicron silicon waveguide germanium photodetector," *Opt. Express*, vol. 19, pp. 10967-10972, 2011.
- [15] C. T. DeRose, D. C. Trotter, W. A. Zortman, A. L. Starbuck, M. Fisher, M. R. Watts, *et al.*, "Ultra compact 45 GHz CMOS compatible Germanium waveguide photodiode with low dark current," *Opt. Express*, vol. 19, pp. 24897-24904, 2011.
- [16] D. Feng, S. Liao, P. Dong, N.-N. Feng, H. Liang, D. Zheng, *et al.*, "High-speed Ge photodetector monolithically integrated with large cross-section silicon-on-insulator waveguide," *Applied Physics Letters*, vol. 95, pp. 261105-3, 2009.
- [17] L. Vivien, A. Polzer, D. Marris-Morini, J. Osmond, J. M. Hartmann, P. Crozat, *et al.*, "Zero-bias 40Gbit/s germanium waveguide photodetector on silicon," *Opt. Express*, vol. 20, pp. 1096-1101, 2012.
- [18] J. Van Campenhout, M. Pantouvaki, P. Verheyen, H. Yu, P. De Heyn, G. Lepage, *et al.*, "Silicon-Photonics Devices for Low-Power, High-Bandwidth Optical I/O," 2012, p. ITu2B.1.
- [19] D. Feng, W. Qian, H. Liang, B. J. Luff, and M. Asghari, "High-Speed Receiver Technology on the SOI Platform," *Selected Topics in Quantum Electronics, IEEE Journal of*, vol. 19, pp. 3800108-3800108, 2013.
- [20] T. Hiraki, H. Nishi, T. Tsuchizawa, K. Rai, H. Fukuda, K. Takeda, *et al.*, "Si-Ge-Silica Monolithic Integration Platform and Its Application to a 22-Gb/s x 16-ch WDM Receiver," *Photonics Journal, IEEE*, vol. 5, pp. 4500407-4500407, 2013.