Heterogeneous SISCAP Microring Modulator for High-Speed Optical Communication

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Abstract *We present a semiconductor-insulator-semiconductor capacitor (SISCAP) microring modulator in the O-band suitable for integration with lasers and photodetectors on the heterogeneous silicon platform. We show data modulation up to 28 Gb/s without any pre or post cursor intersymbol interference (ISI) cancellation.*

Introduction

High speed data communication is the quintessential backbone of modern internet. With ever growing demand for connectivity there is increased stress in improving network efficiency. In an era where application is king, disaggregation of the underlying compute and storage hardware resources is required to improve utilization, which can be made possible with an optical fabric that connects the various network components, viz. CPU, GPU and storage, to form a pool of resources rather than a stack of nodes like in a direct attach storage (DAS) architecture. The optical interconnect needs to be scalable, energy efficient and support high bandwidth density. Wavelength division multiplexing (WDM) is a simple scheme by which we can achieve large data throughput through a single fiber and later scale up by either adding more channels or increasing the data rate per channel. A WDM transmitter commonly consists of a laser and a modulator for each channel and a combiner to funnel the different wavelength channels to a single fiber output. More recently, a new kind of comb laser source[1] has gathered interest, which generates a plurality of wavelengths at once. The wavelength spacing between the channels remain fixed and therefore complex wavelength monitoring and control circuits are not required. It also obviates the need for guard bands and allows tight packing of the wavelength channels thereby increasing spectral efficiency. Having the laser source integrated on silicon provides further benefit as the output can be efficiently coupled to silicon photonic circuits that have demonstrably low loss and high yield[2].

In this summary, we demonstrate the operation of a novel microring modulator structure that integrates seamlessly with the heterogeneous comb laser. We take advantage of the strong plasma dispersion effect in GaAs compared to silicon, due to a lower electron effective mass, to improve the modulation efficiency. We observe an open eye diagram at 28 Gb/s operation with an extinction ratio in excess of 7 dB. Three devices with different radii were measured and they all showed similar performance. The microring design allows for cascading many devices on a single bus waveguide, one for each laser channel, thereby avoiding the need for complex splitter or combiner.

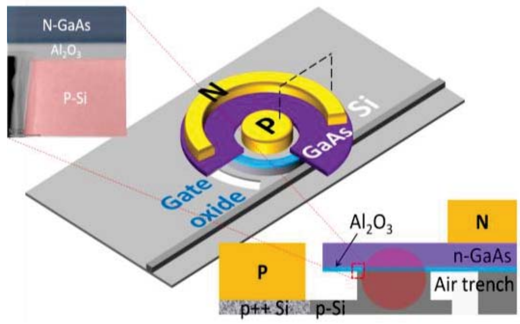

Fig. 1: Schematic cross-section of the modulator with an approximate optical guided mode shape showing the overlap with SISCAP junction. Inset: TEM image showing ~20 nm interface oxide layer

Modulator design

The modulators are fabricated on a silicon-on-insulator (SOI) substrate with 2 μm buried oxide and 300 nm top silicon. The top silicon is uniformly p-doped with a boron concentration of 2×10^{18} cm^{-3}, except for regions where contacts need to be made. Quantum dot layers incorporated within an inverted p-i-n structure grown on a GaAs substrate is wafer bonded to the SOI substrate to fabricate both lasers and modulators on the same die. The detailed process flow can be found here[3]. The bonding process introduces a thin oxide layer between n-GaAs and top silicon forming a SISCAP junction. We use aluminium oxide, instead of silicon dioxide, to increase the charge density accumulated across the capacitor for a given voltage. The n-GaAs contact layer is 150 nm thick which is half the thickness of the top silicon, hence the mode is predominantly guided in the silicon layer. Lateral confinement of the mode is achieved by a silicon rib etch, ~170 nm deep. Fig. 1 shows the cross-section of the device with an air trench which is needed to reduce extraneous capacitance. The bus and the ring waveguide are 500 nm wide separated by 200 nm at the coupling section. The p-contact is placed inside the ring which is one of two possible configurations. We will next discuss the test and measurement results.

Test and Measurement

Individual test structure for each modulator is designed with grating couplers on the bus waveguide for input and output coupling. The wafer is tested on a copper stage held at 20 °C. The grating coupler loss is measured to be ~6 dB at peak transmission. A commercial tunable laser is used as the input to the device-under-test (DUT). The optical power is set to 0 dBm to avoid any non-linear effects[4]. The output of the DUT is amplified using a Praseodymium-Doped Fiber Amplifier (PDFA) and later filtered to remove spontaneous emission noise from the amplifier. The eye diagram is measured using a digital sampling oscilloscope. The DC bias and the high speed signal are combined with a bias-tee and applied to the DUT using a G-S-G probe. The block diagram of the setup is shown in Fig. 2.

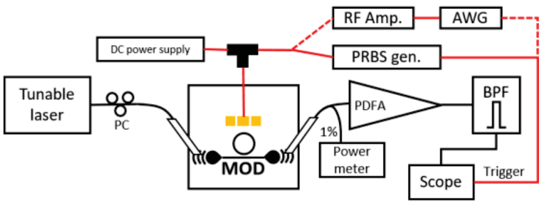

Fig. 2: Block diagram of the test setup with demarcated paths for optical (black) and electrical (red) signals.

With the high speed signal turned off, we measured the optical transmission as a function of wavelength for different DC bias values. The results are plotted in Fig. 3. The raw data is normalized to remove the loss from the two grating couplers. We observe a blue shift of the resonance wavelength and reduction in quality factor (Q) with increasing bias, due to plasma dispersion and increased loss from free carrier absorption (FCA) respectively. Next, we used a pattern generator to apply a high speed signal to

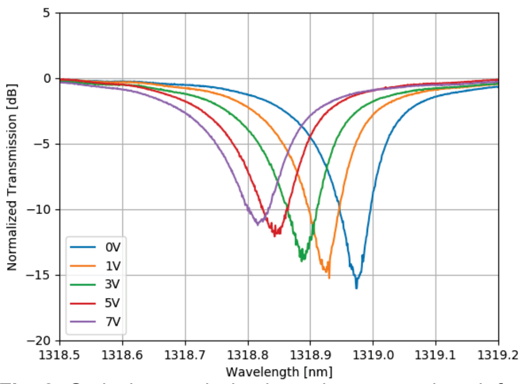

Fig. 3: Optical transmission intensity vs. wavelength for various applied voltages across the modulator.

the modulator. Fig. 4 shows a clear open eye at 10 Gb/s with an extinction ratio of 5.5dB using 2 V peak-to-peak swing. The extinction ratio reduces to 3 dB at 16 Gb/s. Hence, we

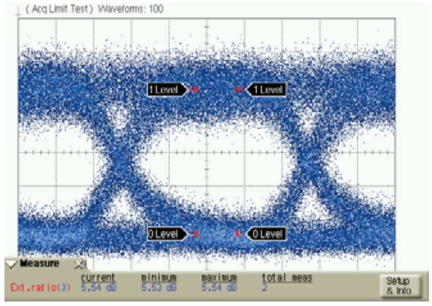

Fig. 4: 10 Gb/s eye diagram for a 10 µm radius modulator using 2 V peak-to-peak swing and a PRBS15 pattern. X span 2 UI, Y scale: 86 µW/div.

increased the voltage swing to 3.5 V. Fig. 5 shows the 20 Gb/s eye diagrams from three modulators with different radii. They show similar rise/fall time. The extinction ratio in each case is greater than 7 dB. The photon lifetime for the three devices vary from 22 GHz to 30 GHz which implies the eye closure is caused by the RC time constant limited bandwidth. This is also consistent with the rise/fall time

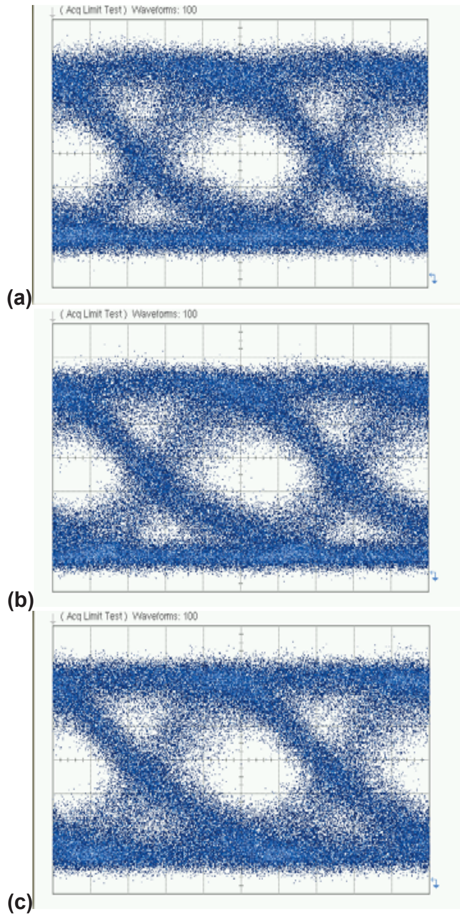

Fig. 5: 20 Gb/s eye diagrams for three device with radii (a) 10 µm, (b) 20 µm, and (c) 25 µm using 3.5 V peak-to-peak swing and PRBS15 pattern. X span: 2 UI, Y scale: (a) 55 µW/div, (b) and (c) 60 µW/div.

observation, as the RC time constant does not change strongly with radius. As the radius increases, the capacitance increases from the increased circumference but the resistance decreases proportionally due to the increased contact area. The long RF cable used in the experiment also introduced significant loss which caused further degradation from ISI. We then tried to compensate for the cable loss by using an AWG, instead of the pattern generator, to pre-distort the waveform. The sampling rate of the AWG is 65 GSa/s. We used an RF amplifier with 18 dB gain to increase the voltage swing as the output from the AWG was limited to 500 mV single ended. With the pre-distortion we were able to increase the data rate to 28 Gb/s (see Fig. 6).

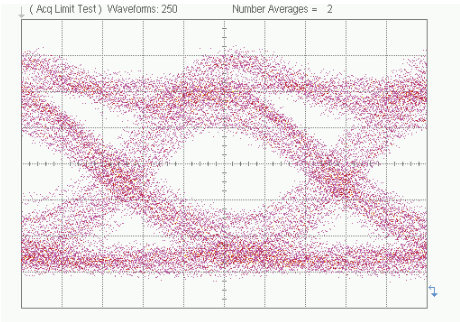

Fig. 6: 28 Gb/s eye diagram using 2.5 V peak-to-peak swing and PRBS9 pattern. The waveform has been averaged to make the rise/fall time more visible. X span: 2 UI, Y scale: 45 μW/div.

Discussion

The heterogeneous microring device presented is a versatile component. It can be either used as a modulator or a tunable filter. The latter functionality can be used to design a low power demultiplexer to filter out each channel at the receiver. When used as a modulator the speed is limited by the RC time constant and the photon lifetime. For a given voltage swing, resonant modulators show a trade-off between modulation bandwidth and optical modulation amplitude (OMA)[5]. In this fabrication run the RC limited bandwidth is smaller than the Q limited bandwidth and hence the maximum data rate is largely independent of the coupling condition (under, over or critically coupled). We believe that the RC bandwidth can be improved by further reducing parasitic capacitance and optimizing the bonding oxide thickness and/or silicon doping profile. Further testing to increase the data rate using post cursor cancellation is underway.

Conclusion

In conclusion, the heterogeneous modulator presented is capable of data modulation up to 28 Gb/s and does not require any different III-V materials or additional fabrication steps than required by the heterogeneous comb laser[1] and photodetectors. By cascading several such modulators at the output of a comb source we can design a transmitter with throughput in excess of 1 Tb/s, while occupying a small footprint.

Acknowledgements

We acknowledge the support from ARPA-E OPEN program under contract no. DE-AR00010391.

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