Lossless Scalable Optical Switch Design in a SiP/InP Hybrid Platform

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Abstract: *Lossless and distortion-free experimental operation of an 8×8 SiP/InP hybrid optical switch is demonstrated. The design employs an 8-channel InP gain block added to a SiP switch to compensate for its high insertion loss.*

Keywords: *Optical interconnects, optical switches, photonic integrated circuits, hybrid integrated circuits, silicon photonics, indium phosphide*

I. INTRODUCTION

Ever increasing internet traffic calls for higher capacity data centers operating at lower power consumption per bit [1]. Currently deployed electronic switches do not scale well due to their high power consumption and latency. Alternatively, one may consider optical switches as a possible solution for the realization of wider bandwidth capacity, lower data transfer latency, and potentially lower power consumption data communication [2]. Advanced data center applications require optical switches with the large port count. Silicon Photonics (SiP) based optical switches offer compatibility with the ubiquitous complementary metal oxide semiconductor (CMOS) technology offering low-cost fabrication, wafer scale testing, high level of integration, and long-term reliability [3]. These attributes make SiP an influential choice for optically interconnected large data centers. However, high radix SiP optical switches have a high insertion loss challenging their deployment in next-generation data centers. Reducing the fiber-to-fiber insertion loss of the SiP based optical switch would make a difference, enabling for the manufacturing of large scale as well as low-loss – or even lossless – optical switch fabrics.

Integrated switches fabricated in an III-V semiconductor platform, such as Indium Phosphide (InP), can perform active functions such as high-speed optical switching while offering inherent gain on-chip. Benefiting from the gain of the active elements, the lossless operation of an active-passive 4×4 semiconductor optical amplifier (SOA)-based switch has been demonstrated [4]. However, the proposed switch suffers from the large insertion loss of 3.5 dB per splitter or combiner [4]. InP Mach-Zehnder Interferometer (MZI) structures as switches eliminate the considerable loss generated by passive elements. Due to fabrication process variations, the crosstalk in MZI-based switches in InP platform is often poor. For example, an 8×8 MZI switch fabricated in an InP platform exhibits -11 dB crosstalk for the propagation of a transverse electric (TE) mode [5].

Despite the great advantages offered by SiP technology, the indirect energy bandgap of silicon is constitutionally prohibiting light amplification. Combining the respective optical attributes of Si and InP semiconductor materials, SiP/InP hybrid integrated switches have been recently introduced [6-9]. In such a technology platform, routing the optical signal from a specific input port to the desired output port is performed in the SiP chip. SiP technology upholds superior switching merits, while the InP active gain block boosts the optical power of the routed payload signal. The SiP/InP hybrid scheme suffers from coupling loss between the two different materials used for the switching part and the gain part in addition to relatively higher cost and complexity of packaging. When all considered, the hybrid approach provides a more sustainable solution for realizing scalable large port count optical switches with multiple cascaded stages for non-blocking operation, achievable in neither SiP nor InP technologies.

In this paper, we proposed the lossless operation of an 8×8 SiP MZI-based Banyan optical switch with thermal phase shifters coupled to an 8-channel single stage InP gain block. The SOAs configured as a single stage have been experimentally validated to compensate for the inherently large insertion loss of the SiP switch with eight ports. The SOAs provide more than 25 dB of gain while maintaining sufficient optical signal to noise ratio (OSNR) at the output of the gain block for distortion-free 12.5 Gb/s optical data transfer.

II. HYBRID SWITCH DESIGN AND FABRICATION

In this work, the proposed SiP/InP hybrid optical switch is following the configuration presented in the schematic view of Figure 1. An 8×8 thermo-optic Banyan SiP switch is edge-coupled to an 8-channel InP gain block. The gain block is

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an array of eight 1300 µm long SOAs. The input light to the SiP chip and the output from the InP gain block are also edge-coupled. Table 1 indicates the loss and gain of the passive and active elements used in the hybrid switch.

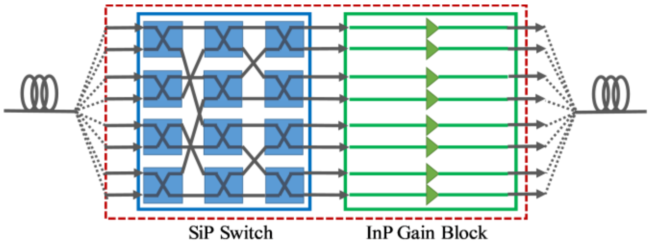

Fig. 1. Schematic view of the SiP/InP hybrid switch.

TABLE I
LOSS/GAIN DESIGN VALUES

loss/gain of active/passive elements	Value
SiP 8×8 switch: input fiber array coupling loss	-5.0 dB
SiP 8×8 switch: on-chip loss	-6.7 dB
SiP 8×8 switch to InP gain block coupling loss	-7.0 dB
InP gain block: on-chip loss	-2.9 dB
SOA net gain	+24.6 dB
InP gain block: output fiber array coupling loss	-3.0 dB

The input and output ports of the InP gain block consist of tapered waveguides with mode field dimensions of 2.8 µm in height and 0.96 µm in width. The front and back facets of the input and output ports are coated to reduce the reflectivity. To further reduce reflectivity and residual Fabry-Perot effects, the output ports of the InP gain block are tilted at 7 degrees. The SiP output ports to the InP gain block use a spot-size converter with a trident waveguide to optimize the mode overlap between the two chips [10].

Design and fabrication of the SiP part have been performed based on various designs of MZI-based thermo-optic switches previously fabricated and characterized by our research group [11]. The SiP switch is fabricated on a 220 nm thick silicon-on-insulator (SOI) wafer through Applied Nanotools [12]. The InP gain block is fabricated through SMART Photonics [13]. The switch lossless operation is for a minimum net gain of 24.6 dB per channel, provided by the inline SOA.

III. GAIN BLOCK EXPERIMENTAL VALIDATION

A set of experimental measurements is performed investigating the lossless operation of the 8×8 SiP/InP hybrid optical switch including high-speed payload transmission. A continuous wave (CW) optical signal at 1550 nm wavelength generated by a tunable C-band laser is TE polarized by a polarization controller (PC). This optical signal is edge-coupled to the InP gain block through an array of lensed fibers positioned by a six-axis nano-positioning stage. Each output of the InP gain block channels is monitored using an optical power meter (PM) through a similar set of lensed fibers. The fiber-to-fiber loss is calculated from the measured gain of the SOA gain block based on its generated current. As seen in Fig. 2, the fiber-to-fiber loss increases as the input optical power to the hybrid switch increases from 1.5 dBm to 12 dBm. This trend occurs as the SOA optical gain saturates. As such, the lossless operation of the hybrid switch is possible for lower optical input power. For an input optical power of 1.5 dBm, lossless operation requires an SOA bias current of 75 mA.

Amplified spontaneous emission (ASE) noise generated by the SOAs is an important concern about the proposed SiP/InP hybrid optical switches. In this study, the experimental setup in Fig. 3 performs payload data transmission. It evaluates the gain block performance at high bias current (i.e., up to 90 mA) to assess the impact of ASE noise. A pulse pattern generator (PPG) generates a 12.5 Gb/s nonreturn-to-zero (NRZ) PRBS-31 signal. The modulated input signal is edge-coupled to the InP chip. A PC maintains the polarization of the optical signal to a quasi-TE optical mode. A current source provides the electrical biased current to the SOAs. An erbium doped fiber amplifiers (EDFA) with a fixed optical output power of 8 dBm compensates for additional losses from the experimental setup. A 20 GHz photodetector (PD) detects the output signal. A 20 GHz clock synthesizer (CLK) provides the external clock to the PPG, and the trigger to the digital communication analyzer (DCA) for recording eye diagrams.

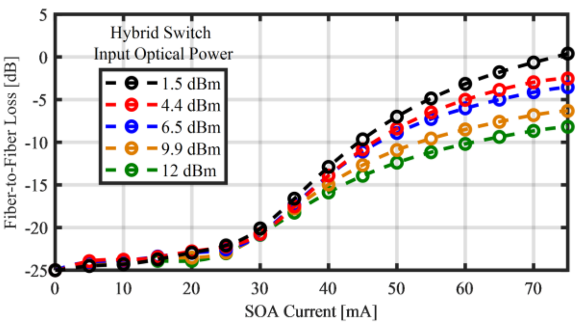

Fig. 2. Fiber-to-fiber loss as a function of SOA current.

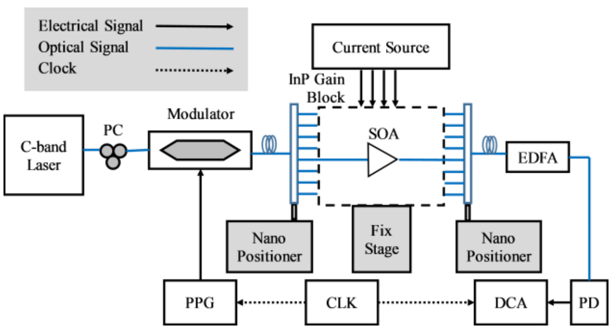

Fig. 3. Experimental setup for 12.5 Gb/sec payload transmission. One channel of the InP gain block is tested at a time.

The 12.5 Gb/s eye diagrams (Fig. 4) are recorded for the payload data transmission over one single channel. All channels have similar performance. The input optical power of the signal to the InP chip is set to -17.5 dBm representing the weakened signal from propagating through the SiP chip. As observed in Fig. 4 for small SOA bias current (i.e., 30 mA), the eye diagram is degraded since the optical power of the signal at the receiver is smaller. When SOAs are biased at 50 mA, the gain is sufficient to compensate for the system losses. In this case, clear and open eye diagrams are observed, demonstrating distortion-free high-speed payload transmission. When the SOA bias current increases to 70 mA, the SOA's gain starts to saturate and exhibits self-gain modulation [14]. In other words, the sequences of payload bits with more binary ones see less gain than the sequences of bits with more binary zeros. For bias current above 90 mA toward deep gain saturation region, the effect of self-gain modulation fades away. Further from Fig. 4, the binary zero level of the eye diagrams increases with SOA bias current, which is due to an increase in the ASE level. Despite this added noise, the eye remains open even for SOA bias current as large as 90 mA.

The OSNR measurements as a function of the SOA bias current for different optical input power values are shown in Fig. 5. At first, the OSNR increases with SOA bias current as the SOA net gain increases. Then the OSNR saturates and slightly decreases as the SOA reaches the gain saturation region. A major source of OSNR degradation is the ASE generated in the gain block. Measurement of the OSNR at the output of the gain block provides a good estimation for the SiP/InP hybrid integrated optical switch. An important point is that the OSNR remains greater than 28 dB even at large values of SOA bias current despite the ASE noise. Along with the clear eye diagrams presented in Fig. 4, these results reveal that the gain block is capable of low noise transmission even when large SOA gain is required.

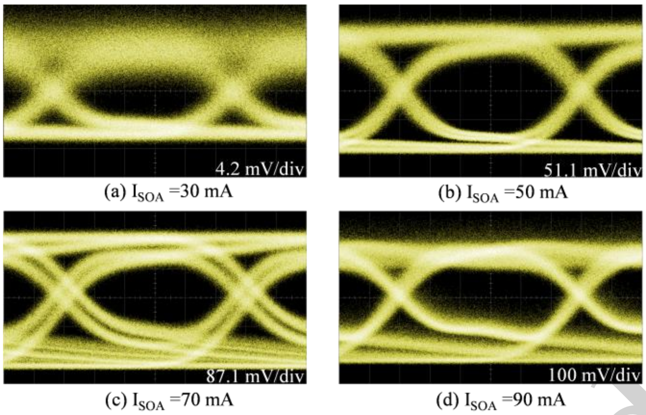

Fig. 4. Eye diagrams for 12.5 Gb/s payload transmission over a single channel of the InP gain block.

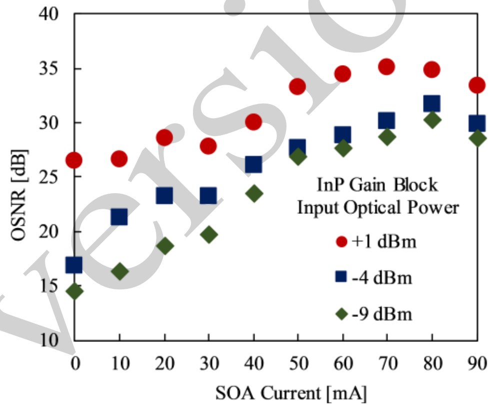

Fig. 5. OSNR as a function of SOA bias current.

IV. Conclusions

The lossless operation of an 8×8 SiP/InP hybrid integrated optical switch is experimentally demonstrated. The device consists of an 8×8 MZI-based Banyan optical switch in the SiP platform and the 8-channel gain block in InP. Zero fiber-to-fiber optical loss is achieved for a net gain of approximately 25 dB, provided by 1300 μm long SOAs biased at 75 mA. Wide open eye diagrams for 12.5 Gb/s NRZ PRBS-31 payload transmission and OSNR greater than 28 dB are demonstrated. These results confirm the suitability of hybrid integrated lossless switch for the distortion-free high-speed optical payload data transmission.

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