Assessment of an O-band 4x4 InP Monolithic Photonic Switch at 100 Gbit/s PAM-4

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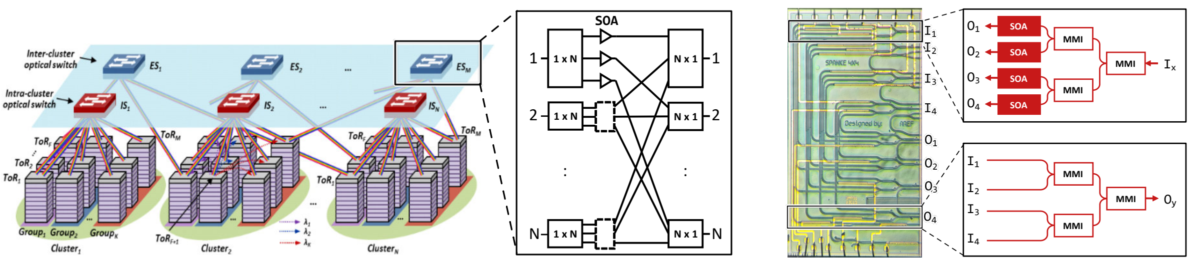
Abstract: We assess the performance of an O-band integrated optical 4x4 switch using the broadcast and select architecture with 100 Gbit/s PAM-4 signals. We measured a power penalty of <1 dB at the FEC-limit for multiple optical paths.

1. Introduction

Since the release of publicly accessible artificial intelligence (AI) services, the world has become dependent on large-scale models. New applications are emerging in quick succession and the models double yearly in scale [1]. These developments require a highly efficient and scalable compute infrastructure, often consisting of a distributed network of highly specialized accelerators equipped with multi-Tb interfaces. Today's network interconnects are identified as the bottleneck, limiting network throughput and affecting the communication time between accelerators [2, 3]. This problem can be solved by bringing the optics closer to the core using co-packaged optics (CPO) and combining them with a flat, all-optical network such as OPSquare [4] (Fig. 1a) as an example or other similar architectures. An important component in such network are the optical switches, which allow optical traffic flows to be redirected dynamically. Transparent optical operation allow the network to be upgraded in terms of data rate, modulation format and wavelength grid without having to replace the switches. Furthermore, the lack of an O/E/O conversion reduces power consumption compared to the electronic counterparts and reduces the amount of costly optical transceivers. A great variety of optical switches have been proposed: Ranging from expensive, high port-count, and slow MEMS based switches [5] down to small footprint photonic integrated devices, providing a full optical system on a small scale.

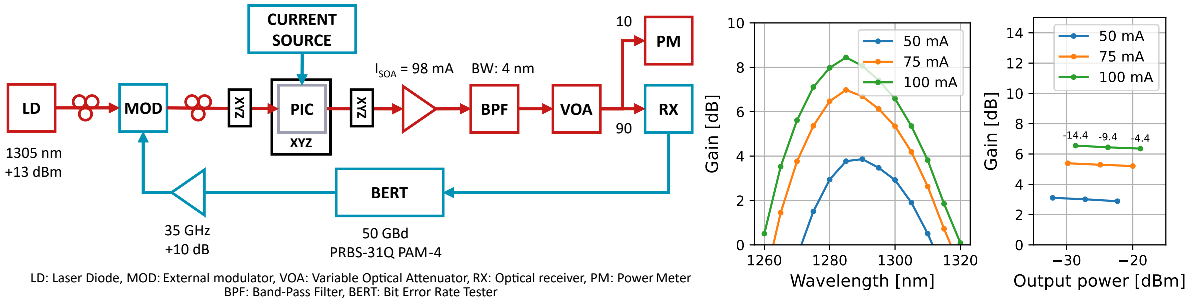
Previously, we have demonstrated the first O-band InP, 4x4 integrated photonic space switch with nanosecond switching time based on the broadcast and select (B&S) architecture [6]. By using the InP platform in combination with the B&S architecture, optical losses can be compensated using an semiconductor optical amplifier (SOA) as a switching and amplification component, whilst minimizing the added noise due to the architecture as compared to SOAs in Beneš or Banyan [7] based multi-stage switches. Alternative platforms using e.g., SiPh [8, 9] or SiN [10] cannot monolithically compensate for the circuit losses. Furthermore, the demonstrated data rates remain below 50 Gb/s.

In this paper we assess the performance of the O-band 4x4 B&S photonic switch at 100 Gbit/s PAM-4 data signal. Results confirm <1 dB power penalty at the FEC limit with a maximum optical signal-to-noise ratio (OSNR) of 35.4 dB and an on/off ratio of at least 40 dB at 1305 nm. This demonstration paves the way to supporting high-speed commercial interconnects technologies for integrated optical devices.



(a) (b)

Fig. 1. (a) The flat all-optical network OPSquare, the inset shows the principle of operation of the Broadcast and Select switching architecture. (b) Photograph of the fabricated 4x4 optical space switch. The insets show the optical components used in each optical path between input I_x and output O_y.



(a) (b) (c)

Fig. 2. (a) The transmission setup. (b) SOA gain vs. wavelength for various drive currents. (c) SOA gain vs. fiber coupled output power for various drive currents. Both gain measurements show the SOA only gain, by subtracting the splitting and coupling losses and are taken using a fiber coupled input power of -14.3 dBm.

2. Design and fabrication

The B&S topology of the switch is shown in the insets of Figs. 1a and 1b. The input signal is split by two cascaded 2x2 multimode interference (MMI) couplers to four paths. Each path consists of an SOA to block or pass the optical signal. All signals are combined in a second cascaded MMI structure to the output ports and is coupled out of the chip using edge couplers. The SOA lengths vary between 350 and 650 µm, to evaluate the impact on its optical characteristics.

The chip is fabricated using the open-access O-band PDK of SMART Photonics. It uses an active-passive integration platform to integrate the quantum well SOAs, the MMIs and the waveguide structures. The epitaxial growth of the layer stacks and the processing steps are performed at SMART Photonics. The fabricated chip is shown in Fig. 1b.

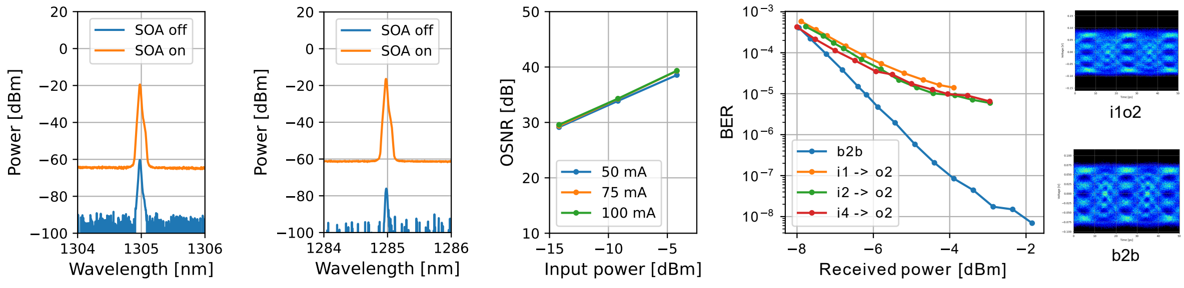
3. Experimental setup and results

The 2 x 4.6 mm^2 photonic integrated circuit (PIC) is glued onto a water-cooled aluminium chuck which is set to 20 °C. Light is coupled using two lensed fibers. For the steady state optical characterizations, the setup consist of a tunable, 0 dBm O-band laser source, a variable optical attenuator to control the laser power into the chip, a polarization controller to rotate the signal to the quasi-TE mode. Via a 90/10 splitter, the results are recorded using either an optical power meter or spectrum analyzer. A constant current source drives the SOAs. For all measurements, the results are compensated for the measured insertion losses of the components. This includes a 2.3 dB loss per edge coupler and an added loss of 0.8 dB per MMI. All characterization results are measured using the SOA between input 1 and output 2 (i1o2), which has a length of 550 µm.

Before the transmission of data, we present the characteristics of the optical path. More details on the performance of SOAs can be found in [6]. To illustrate the optical path bandwidth, the isolated SOA gain is measured for various wavelengths, and shown in Fig. 2b. The gain peaks at 1285 nm and has a 3 dB bandwidth of 35 nm. The peak shows a blue-shift with increasing current due to the band filling effect in the SOA. Similarly, the gain at 1305 nm for the 550 µm SOA is shown in Fig. 2c, with no gain saturation visible. At last, the on/off ratio or the crosstalk of the switch is evaluated. Fig. 3a shows the difference of a blocked or active optical path by setting the SOA to 0 and 100 mA respectively. At this wavelength, 40 dB isolation is achieved. Operating the switch at the peak gain point further increases the isolation towards 60 dB as demonstrated in Fig. 3b.

For the transmission experiment, a high-power 1305 nm laser diode is used, with no other wavelengths being available at the time of measuring. The signal is modulated onto the 13 dBm carrier using a 40 GHz MZI-modulator. A PRBS-31Q 100 Gbit/s PAM-4 modulated signal is generated and analyzed using an EXFO BA4000 bit error rate tester (BERT). The RF output signal is amplified using a 35 GHz differential to single-ended amplifier. The optical signal is amplified at the output using a discrete, polarization insensitive ($<$ 0.5 dB), O-band SOA and received using a 42 GHz photodetector. The eye-diagram is generated using the same photodetector and a 63 GHz electrical sampler.

First, the OSNR is measured. Fig. 3c shows a linearly increasing OSNR with respect to the fiber coupled input power. With the tunable laser limited to 0 dBm, the OSNR is expected to increase further with increasing input power, exceeding 40 dB. The OSNR is invariant to the current and hence gain, meaning that the noise and peak signal power are proportionally increasing in the measured range. The high OSNR is beneficial for multi-level transmission such as PAM-4 modulation, as is demonstrated in Fig. 3d. The transmission performance is measured for three different optical paths. The optical back-to-back path is taken as a reference. The OSNR for



(a) (b) (c) (d)

Fig. 3. On and off spectrum at (a) 1305 nm and (b) 1285 nm with 100 and 0 mA, respectively. (c) OSNR for various drive currents and SOA referred optical input powers. (d) BER curve of 3 different optical paths and an optical back-to-back reference. The eye diagrams show the back-to-back and the i1o2 signal.

the paths are 35.4, 34.0 and 31.4 dB for i1o2, i2o2 and i4o2 respectively. Assuming a KP4, RS(544, 514) forward error correction (FEC) with a minimal pre-FEC bit error rate (BER) of 2.4×10^{-4}, a received power of -7 dBm is sufficient for error-free transmission. At the pre-FEC level, the power penalty is within 1 dB. The addition of a second SOA decreases the OSNR, causing the BER curves to saturate. The eye-diagram of the back-to-back and i1o2 path are shown in the inset, showing little to no signal distortion.

These results demonstrate that optical switches are not limited to low data rates and OOK modulation. A performance improvement is expected at wavelengths closer to the SOA's gain peak, but error-free transmission achieved at the gain edge is a good indication that the switch can operate with multiple WDM channels which will be assessed in future experiments. The on-chip gain is not sufficient to cover all losses, and an additional external SOA is required to close the optical link budget by boosting the signal with 10 dB. Increasing the length of the gate SOAs will increase the gain and a second pre-amplifier can be added on chip to boost the output signals. The OSNR penalty will be limited, as the total amount of cascaded SOAs is still limited to two. Regardless, these results shows the potential compatibility of a photonic integrated circuit with data center interconnects running at high speeds by successfully carrying a multi-level modulated high-baud rate signal.

4. Conclusions

In this work we have for the first time demonstrated an O-band InP monolithically integrated 4x4 photonic space switch using the broadcast and select topology at 100 Gbit/s PAM-4 data signal. The BER is well below the FEC limit and shows a power penalty of less than 1 dB with a maximum OSNR of 35.4 dB. On/off ratios up to 60 dB show the blocking capabilities of SOAs. This demonstration is a great step towards full compatibility with existing high-capacity data center interconnection technologies.

Acknowledgements

This work has been partially supported by the EU research and innovation program ADOPTION grant agreement 101070178 and ALLEGRO grant agreement 101092766.

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