Coherent 40 Gb/s SP-16QAM and 80 Gb/s PDM-16QAM in an Optimal Supercomputer Optical Switch Fabric

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Abstract: We demonstrate, for the first time, the feasibility of using 40 Gb/s SP-16QAM and 80 Gb/s PDM-16QAM in an optimized cell switching supercomputer optical interconnect architecture based on semiconductor optical amplifiers as ON/OFF gates.

OCIS codes: (200.4650) Optical interconnects; (200.6715) Switching; (250.5980) Semiconductor optical amplifiers

1. Introduction

High-performance computing (HPC) systems currently use optical interconnects for rack-to-rack communication. This is achieved using point-to-point links based on vertical-cavity surface emitting laser diodes (VCSELs), multimode fibers (MMFs) and intensity modulation /direct detection (IM/DD) [1]. Looking forward, more advanced modulation formats have been proposed for increasing capacity [2]. In addition, optical interconnects based on different flavors of optical packet switching have been actively investigated. For instance, the Optical Shared MemOry Supercomputer Interconnect System (OSMOSIS) project, proposed a N×N crossbar optical cell switch fabric based in a broadcast-and-select architecture using semiconductor optical amplifiers (SOAs) as on-off gates [3]−[4].

In the past, we studied the transmission effects limiting the performance of the OSMOSIS 64×64 optical switch fabric [5] and its optimized version in terms of cost-efficiency [6]. We also explored the feasibility of the optimized OSMOSIS 64×64 optical switch fabric when using coherent polarization division multiplexed (PDM), quadrature phase shift keying (QPSK) transmission [7]. In this paper, in order to increase further the capacity of the optimized 64×64 OSMOSIS interconnect architecture, we investigate a futuristic scenario of employing 40 Gb/s single polarization (SP) and 80 Gb/s (PDM) 16-quadrature amplitude modulation (QAM) with coherent detection. We extensively study the transmission performance of the two aforementioned formats in OSMOSIS and we compare it to IM/DD [7]. Bit error rate (BER) is measured for all implemented wavelengths in both cases, showing a higher BER variation in the PDM-16QAM case. SOA-induced phase-noise nonlinearities arising in the OSMOSIS switch limit the performance in both cases, while PDM-16QAM proves also to be more vulnerable to polarization crosstalk. Employing 16-QAM modulation format instead of IM/DD, increases the spectral efficiency, while still using the same 10-GHz electrical components. In addition, digital signal processing enables equalization and mitigation of transmission impairments arising in short-range links.

2. Experimental setup

The experimental setup for the investigation of the performance of SP- and PDM-16QAM through the OSMOSIS optical interconnect architecture is shown in Fig. 1(a). The optimized OSMOSIS 64×64 optical switch fabric uses 16 wavelengths, organized in four wavebands [6]. In our experimental study, only eight standard telecom DFB lasers are used to represent the first two wavebands and a single laser is used to represent the remaining two wavebands, due to lack of resources. The wavelength allocation is shown in Fig. 1(b). We choose λ_0=1546.897 nm and channel spacing within a waveband Δf=100 GHz. Empty wavelength slots between wavebands serve as guard bands, in order to facilitate the fabrication of arrayed waveguide (AWG) MUX/DMUXs. AWGs' periodic transfer function plays a significant role in the last stage (wavelength selection) of the OSMOSIS switch architecture [5]−[6]. Given the strict linewidth requirements for coherent intradyne detection of 16-QAM modulation format, the performance of each wavelength channel is measured after substituting it with an external-cavity laser (ECL) source with a narrow 3-dB linewidth of 100 kHz.

In Fig. 1(a), the seven wavelength channels (λ_1-λ_{11}) are multiplexed using a 100-GHz AWG MUX and then they are combined with the wavelength under test (λ_0) through a 3-dB coupler. The WDM signal is then modulated on an I/Q modulator using four-level electrical waveforms, generated using a pulse pattern generator (PPG) operating at a symbol rate of 10 Gb/s as shown in Fig 1(c). Four uncorrelated binary pseudo-random bit sequences (PRBSs) of length $2^{15}-1$ are first amplified by four identical microwave amplifiers and then each pair is attenuated by 10 dB and

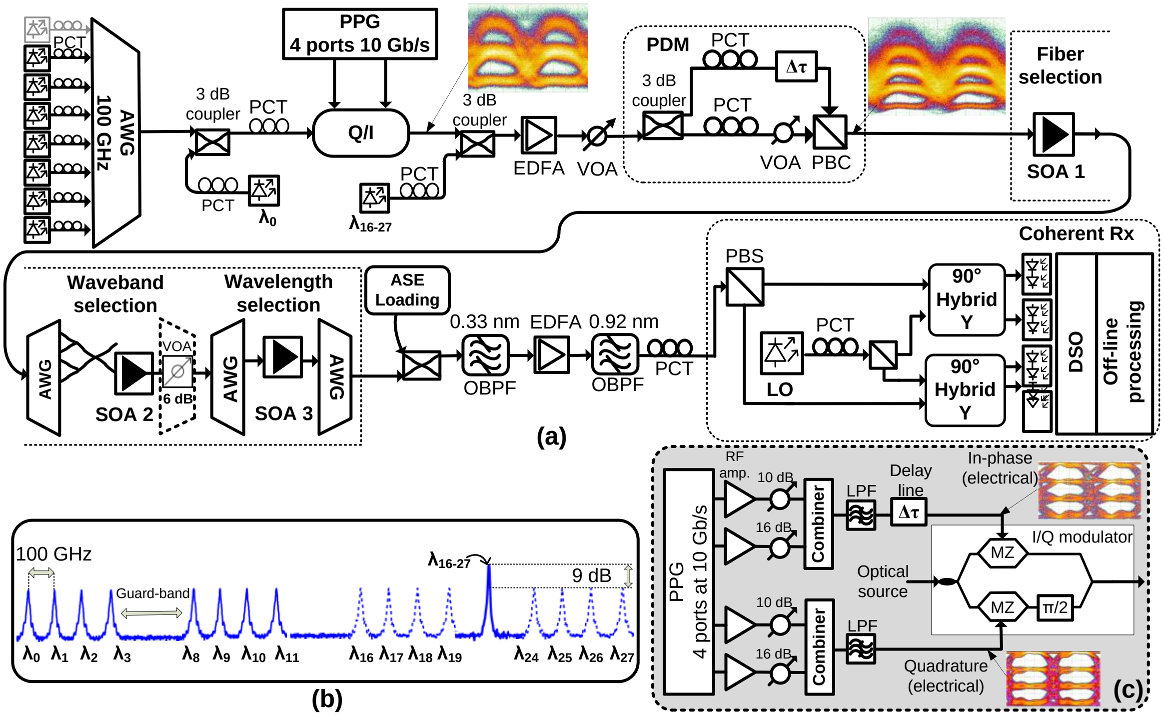

Fig. 1 (a): Experimental setup; (b): Nominal (λ_0-λ_{27}) and implemented (blue solid line) wavelength allocation scheme and (c): 16-QAM transmitter configuration.

16 dB, respectively. The two pairs of signals are subsequently combined using microwave combiners. The two four-level signals at the outputs of the combiners are low-pass filtered (LPF). One of them is delayed with respect to the other by one symbol period, using an electrical delay line, so that the two quadrature components are completely de-correlated and synchronized, as shown in the inset of Fig. 1(c). The direct-detection eye-diagram of the generated 40 Gb/s SP-16QAM output optical signal is shown in the inset of Fig. 1(a). We can clearly distinguish the three intensity levels that correspond to the three concentric circles of the square 16QAM constellation. Next, a ninth CW laser source that has eight times the power of an individual wavelength channel and is placed in the middle of the remaining two wavebands, i.e., at the $\lambda_{21.5}$ slot, is added to the WDM signal in order to emulate the rest two wavebands, shown in Fig. 1(b) with the broken blue line. Afterwards, the WDM signal is boosted by an EDFA and it is attenuated using a 18 dB attenuator, which represents the 1:64 splitting losses of a star coupler used to broadcast the WDM signal to all 64 receiver cards [3]. For the PDM-16QAM case, the 80 Gb/s PDM-16QAM signal is generated as shown in Fig. 1(a). The PDM stage is omitted for the SP-16QAM experiment. Next, the signal enters the OSMOSIS switch fabric that consists of the fiber, the waveband and the wavelength selection stage. The fiber selection stage consists of a single SOA and selects one out of four fibers, each carrying 16 wavelengths [6]. The waveband selection stage employs a 100-GHz AWG MUX with interconnected arms to emulate a 400-GHz AWG MUX required in the proposed architecture [6] but was not available in the lab, a second SOA, and a 6 dB attenuator to emulate another 400-GHz AWG MUX. The third wavelength selection stage, which is comprised of a pair of conventional AWG MUX/DMUX with 100-GHz spacing and a single SOA performs the selection of the desired wavelength. Before the receiver, amplified spontaneous-emission (ASE) noise is loaded to the in order to vary the received OSNR. A 0.33-nm 3-dB bandwith optical bandpass filter (OBPF) is used to filter out the wavelength under test, which is then pre-amplified and filtered again by a 0.92-nm 3-dB bandwidth OBPF to remove out-of-band ASE noise. The signal is detected using a polarization- and phase-diversity coherent receiver. The local oscillator is an ECL with 100-kHz 3-dB linewidth. The outputs of the four balanced photodetector pairs are sampled using a real-time digital oscilloscope (DSO) and the stored data are processed off-line.

3. Results and Discussion

In order to quantify the signal degradation after the fiber, the waveband and the wavelength selection stages in the OSMOSIS switch, bit error rate (BER) vs OSNR measurements are carried out after each selection stage. Representative results are shown in Fig. 2 for λ_3. Taking as reference a hypothetical FEC limit BER=10^{-3}, we observe that the penalty between the 1^{st} and the 2^{nd} selection stage is less than 0.5 dB, in terms of required OSNR. In

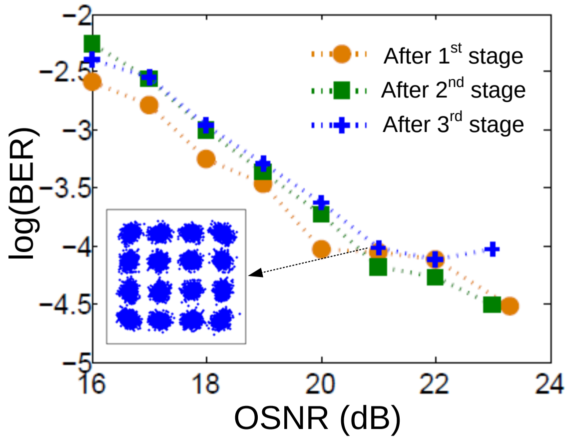

Fig. 2 BER vs OSNR (measured in RB=0.1 nm) for λ_3 after the 1st, the 2nd and the 3rd selection stage of the OSMOSIS switch fabric using SP-16QAM.

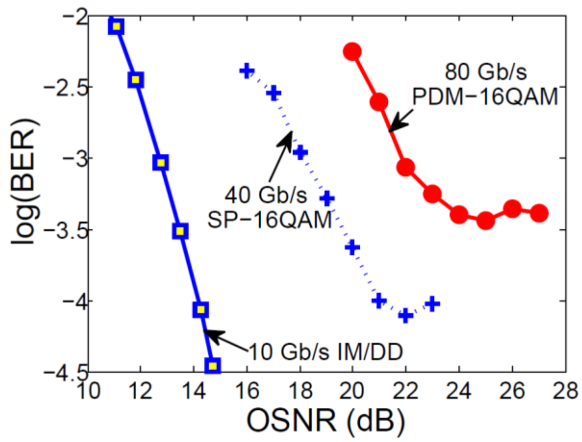

Fig. 3 BER vs OSNR (measured in RB=0.1 nm) for 10 Gb/s IM/DD (squares) [5], 40 Gb/s SP-16QAM (crosses) and 80 Gb/s PDM-16QAM (circles).

addition, there is no penalty between the 2nd and the 3rd selection stage. Error floors in the performance arise for all three cases, being more pronounced after the 3rd selection stage, indicating that the phase nonlinearities imposed by SOAs in the implemented architecture set a limit in the scalability of the interconnect.

Fig. 3 shows measurements of the BER vs OSNR for SP-16QAM (crosses) and PDM-16QAM (circles), after transmission through the OSMOSIS interconnect for λ_3. Results for 10 Gb/s IM/DD, previously reported [5] are also shown here for comparison (squares). SP- and PDM- 16QAM, increase the capacity by a factor of four and eight, respectively, compared to IM/DD using the same 10 GHz equipment as IM/DD, at the expense of 4 and 8 dB penalty in required OSNR at BER=10^{-3}, respectively. The penalty when employing 80 Gb/s PDM-16QAM instead of 40 Gb/s SP-16QAM in the optical interconnect architecture is around 4 dB at BER=10^{-3}. A penalty equal to 3 dB is expected from theory [8]. This implies that polarization crosstalk induces a 1 dB additionally penalty when PDM-16QAM is employed in OSMOSIS. A higher error floor occurs for the PDM-16-QAM compared to SP-16QAM and at higher OSNR values. Nevertheless, BER is well below the hypothetical FEC limit, i.e., BER=10^{-3} for both cases.

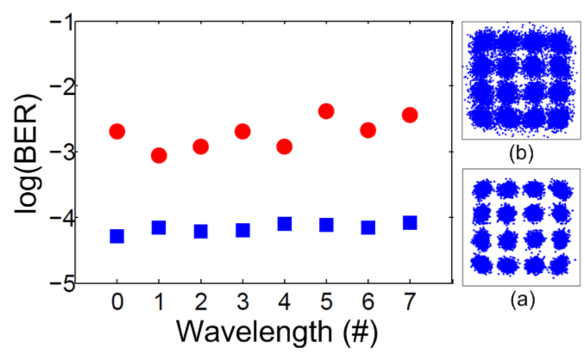

Fig. 4 BER for all implemented channels when employing SP-16QAM (squares) and PDM-16QAM (circles) at OSNR=23 dB (RB=0.1 nm). Constellation diagrams for the worst channel (a): SP-16QAM and (b) PDM-16QAM.

Fig. 4 shows the measured BER for each implemented channel, for the SP- and the PDM-16QAM case (squares and circles, respectively), at the same OSNR=23 dB. For the SP-16QAM experiment all eight measured channels exhibit approximately the same BER performance. On the other hand, the variation in BER performance among channels in the PDM-16QAM case is higher. This indicates that PDM-16QAM is more vulnerable to polarization crosstalk. Representative constellation diagrams for the worst channel are shown on the left of Fig. 4 both for SP-16-QAM (Fig. 4(a)) and PDM-16-QAM (Fig. 4(b)).

4. Conclusion

We have demonstrated the feasibility, and we have investigated experimentally, the performance of coherent SP- and PDM-16QAM when they are deployed in the optimal OSMOSIS 64×64 optical switch fabric. Phase-noise nonlinearities arising from the SOAs in the OSMOSIS switch are the dominant factor limiting the performance of the interconnect causing error floors. Polarization crosstalk is a second limiting factor when PDM-16QAM is used.

5. References

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