Influence of Transmission Impairments on the OSMOSIS HPC Optical Interconnect Architecture

Fotini Karinou, Ioannis Roudas, Kyriakos G. Vlachos, B. Roe Hemenway, and Richard R. Grzybowski

Abstract—We examine the impact of transmission impairments on the performance of the optical supercomputer interconnect architecture, initially proposed in the context of the Optical Shared MemOry Supercomputer Interconnect System (OSMOSIS) project. We study two versions of the aforementioned optical interconnect that differ in terms of the number of semiconductor optical amplifiers (SOAs) used as on-off gates. For practical reasons related to packet arbitration, the size of the crossbar switch of the optical interconnect in this study is limited to 64 ports. The switch is based on a broadcast-and-select architecture and employs DWDM in conjunction with 10 Gb/s intensity modulation/direct detection (IM/DD) per wavelength channel. We show, both by experiment and by simulation, that the minimization of the number of SOAs in the optical switch by taking advantage of the cyclic routing capability of optical arrayed waveguide multiplexers/demultiplexers leads to negligible performance deterioration compared to conventional wavelength-space switches which are prohibitive slower and do not use any inherent gain properties like in OSMOSIS.

Index Terms—Optical interconnects, semiconductor optical amplifiers (SOAs), switching.

I. INTRODUCTION

SINCE the performance of high performance computing (HPC) systems (i.e., supercomputers and computer clusters) experiences a tenfold increase every four years [1], it is expected that exascale HPC systems will be developed by 2020 [2]–[3]. Until then, to satisfy the requirements of emerging, bandwidth-demanding applications for HPC systems, it is necessary to gradually replace the inefficient, conventional electronic interconnects with optical ones. For instance, two representative examples of state-of-the-art PetaFlops (PF) supercomputers (BlueWaters [4] and POWER7-IH [5]) use optical interconnects for inter-rack communication.

The Optical Shared MemOry Supercomputer Interconnect System (OSMOSIS) project [6] proposed an optical interconnect architecture for high bandwidth, low latency, cost-effectiveness and scalability. The OSMOSIS optical interconnect uses electronics for scheduling and routing and optics for switching and transmission. Its basic building block is a two-stage, broadcast-and-select, 64×64 optical crossbar switch fabric for synchronous, fixed-size optical cell switching. The latter is accomplished through semiconductor optical amplifiers (SOAs), acting as on-off gates [6]. The main advantage of the OSMOSIS architecture is that it performs ns-scale switching, as opposed to active optical cables, which are used for dedicated point-to-point links between pairs of nodes. In this sense, OSMOSIS is superior to the currently used optical active cable technology in terms of sharing resources. Nevertheless, the cost of the OSMOSIS architecture is still prohibitive for commercial HPC systems, due to the large number of on-off gates. The problem is exacerbated as the throughput of the interconnect must eventually grow to accommodate exascale traffic.

An economically-viable, multi-stage alternative design of the original two-stage OSMOSIS [6] crossbar switch fabric architecture, targeted at the minimization of the number of SOAs, was recently proposed [7]. More specifically, the multi-stage \( N \times N \) optimum interconnect alternative design proposed in [7] can reduce the number of on-off gates from \( 2N\sqrt{N} \), that are required in the original two-stage OSMOSIS architecture [6], down to asymptotically \( N \ln N \), where \( N \) is the number of nodes to be interconnected.

In a preliminary study [8], we experimentally investigated the performance of the multi-stage optimized crossbar switch fabric employing polarization division multiplexing (PDM) quadrature phase shift keying (QPSK) modulation and coherent intradyne detection. In a more recent publication [9], we showed that the economically-viable optimized optical switch fabric performs almost equally well to the original one when using conventional intensity modulation/direct detection (IM/DD).

Elaborating on the work of [9], in this paper, we assess the physical layer performance of the optimized 64×64 three-stage, OSMOSIS optical switch fabric and compare it to its two-stage original counterpart, both experimentally and by simulation. In particular, we evaluate the impact of SOA nonlinearities, optical filter concatenation and amplified spontaneous emission (ASE) noise accumulation, on the performance of both interconnect architectures, using 10 Gb/s IM/DD serial optical transmission. Simulation and experiment show that the optimized, cost-efficient OSMOSIS crossbar switch fabric performs almost as well as the original one, despite the fact that, in the former, optical signals travel through more concatenated SOAs.

The remainder of the paper is organized as follows: In Section II, we compare the original and the optimized crossbar

 Manuscript received June 07, 2011.
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switch designs and describe the simulation block diagrams used to evaluate their performance. Their performance is also assessed through experimental measurements using the setup described in Section III. An itemized account of the penalties due to various transmission effects is presented in Section IV. Details of the simulation models are given in Appendix A. An analytical calculation to justify the results shown in IV, is presented in Appendix B.

II. OPTICAL INTERCONNECT ARCHITECTURES

In this Section, we describe the originally-proposed [6] and the optimized [7], 64×64 OSMOSIS optical interconnect architectures and their simplified simulation block diagrams. Both architectures use fixed-wavelength transmitters and discretely-tunable, direct-detection receivers. However, they differ in the organization of the transmitters into different multiplexing hierarchies and the number of stages in the discretely-tunable receivers that perform the selection of the desired channel.

A. Original OSMOSIS architecture

In the original OSMOSIS architecture [6], depicted in Fig. 1, the 64 transmitters are partitioned into eight sets. The transmitters of each set, are assigned eight equidistant carrier frequencies, $f_0, ..., f_7$. The frequency allocation plan for this scheme is shown as an inset in Fig. 1. Frequency reuse is employed among different transmitter sets. Each transmitter in Fig. 1, comprises a continuous wave (CW) laser. The output signal from each CW laser is first amplified by an erbium-doped fiber amplifier (EDFA) and then, is intensity modulated by a 10-Gb/s, non-return-to-zero (NRZ), pseudo-random Binary Sequence (PRBS), using a Mach-Zehnder modulator (MZM). All channels are synchronized in time. Each set of eight channels is wavelength division multiplexed (WDM) on a different fiber, the WDM signal is amplified by an EDFA, and is broadcasted to all 64 receiver cards, using 1:64 star couplers. The 64 discretely-tunable receivers consist of two selection stages, choosing a single set of eight wavelengths and a single wavelength channel, respectively. Each selection stage consists of eight SOAs, acting as ON/OFF gates.

For the simulation, the channel spacing $\Delta f$ is 100 GHz. More specifically, the carrier frequencies of the transmitted channels are 192.1 THz-192.8 THz (corresponding to wavelengths 1554.94-1560.60 nm). They are placed uniformly around the peak of the SOA gain, at 1557.77 nm, so they experience only a small gain variation due to the non-uniform SOA gain profile. The CW laser average power is set to -3 dBm per channel. The EDFA before the MZM has 17 dB gain to compensate for losses in the MZM and the consecutive MUX. The WDM signal reaches the second EDFA (acting as a booster amplifier) without any power variation among the eight channels. The maximum power variation of the channels at the output of the second EDFA is less than 1 dB, due to the spectral tilt in the EDFA gain profile. We assume that the SOA gain has a parabolic shape around the SOA gain peak. Uniform channel placement around the peak of the SOA’s gain curve minimizes power variation. More specifically, individual channels exhibit a maximum power variation of approximately ~1 dB, both at the input and at the output of the first SOA, as well as at input of the second SOA. The SOAs work in the linear regime, close to their saturation point. Their input saturation power is $P_{sat}^{in} = 4$ dBm (see Fig. 9 in Appendix A). Additional ASE noise is loaded to the signal to vary the optical signal-to-noise ratio (OSNR) and estimate the error probability. After the second selection stage, the desired wavelength is filtered by an optical Gaussian filter at the entrance of the optically-ramplified receiver, with an equivalent noise bandwidth $B_{eq}=34$ GHz [10].
B. Optimized OSMOSIS architecture

The proposed optimized 64×64 optical interconnect architecture is presented in Fig. 2. The 64 transmitters are partitioned into four sets. The transmitters of each set are assigned 16 carrier frequencies. Frequency reuse is employed among different transmitter sets. The frequency allocation plan is shown in the inset of Fig. 2. The sixteen carrier frequencies are grouped into four wavebands in sets of four, occupying an aggregate bandwidth of 2.7 THz. Guard bands facilitate waveband multiplexing/demultiplexing. The carrier frequencies span from 192.1 THz to 194.8 THz (corresponding to the wavelength range 1538.98 nm-1560.60 nm). The channel spacing within a waveband Δf is 100 GHz. The signals of each transmitter set are wavelength division multiplexed on a separate optical fiber and broadcasted to all 64 receiver cards using 1:64 star couplers. The discretely-tunable receivers use three selection stages for choosing a fiber, a waveband, and a wavelength channel, respectively. The wavelength allocation is done in a way that the periodicity of arrayed waveguide grating (AWG) MUX/DMUXs is exploited. More specifically, to reduce the number of SOAs in the proposed architecture, we use periodic MUX/DMUXs at the wavelength selection stage, with a free spectral range of FSR=8Δf. After the third selection stage, additional ASE noise is loaded to the signal in order to assess the transmission performance. At the entrance of the optical preamplified receiver, the desired wavelength is filtered by an optical Gaussian filter, similar to the one used in the original architecture.

III. EXPERIMENTAL SETUP

The experimental setup used to measure the performance of the aforementioned, optimized 64×64 optical switch fabric is depicted in Fig. 3. Due to lack of resources, nine semiconductor lasers on the transmitters’ side emulate all 16 wavelength channels per fiber shown in Fig. 2. For the same reason, the wavelength channel distribution with reference to the SOA’s gain peak is not the same in the simulation and in the experiment. More specifically, eight DFB lasers, with carrier frequencies spaced by 100 GHz, are used to represent the first two wavebands, W1-W2. The carrier frequencies span from 192.469 THz to 193.563 THz (corresponding to the wavelength range 1548.808 nm-1557.608 nm). A ninth (tunable) semiconductor laser, with eight times the nominal average power of a single WDM channel, located at the frequency slot f21,s=192.164 THz (λ21,s=1566.008 nm), is used to represent the remaining two wavebands W3-W4 (Fig. 3(a)). The nominal and the experimentally implemented frequency allocation plans are shown in Fig. 3(b), (grey and blue arrows, respectively). The CW optical signals from all nine lasers are initially combined and preamplified by an EDFA. Then, the WDM signal is modulated using a single MZM modulator by a 10-Gb/s, non-return-to-zero (NRZ), Amplitude Shift Keying (ASK), 2^7-1 pseudo-random binary sequence (PRBS). This way, time-aligned, identical wavelength channel bit sequences are generated. This corresponds to the worst-case scenario for studying the impact of cross-gain modulation (XGM) due to SOAs. Subsequently, the signal is first amplified again using a booster EDFA, and then it goes through a variable optical attenuator (VOA) with 18 dB loss, that emulates the 1:64 star...
On the receiver waveband before amplification - SMOSIS, despite the frequencies n while Wλ. Almost equally to the implemented i.e., λ implemented.FWM) connected arms 1 experiment, respectively. Blue and green color represents simulation and experimental results, respectively. A second experimental set-up, described in detail in [6], is used for evaluating the performance of the original OSMOSIS optical switch fabric. Its description is omitted here for brevity. Only, the implemented frequency allocation plan for that experiment is shown in Fig. 3(b). The carrier frequencies span from 192.866 THz to 193.563 THz (corresponding to the wavelength range 1548.808 nm-1554.408 nm (Fig. 3(b)). Another laser with three times the nominal average power of a single WDM channel, located at the frequency slot f3=193.015 THz (λ3=1553.208 nm), is used to represent the lasers sources not available in the lab (Fig. 3(b)).

IV. SIMULATION AND EXPERIMENTAL RESULTS

In this Section, we evaluate the performance of both optical interconnect architectures using the raw BER as a criterion. In practice, the raw BER is reduced by using additional forward error correction (FEC) coding and/or automatic repeat re-quest (ARQ) protocol. We investigate the impact of SOA nonlinear effects, such as self-gain modulation (SGM), XGM, and four wave mixing (FWM), optical bandwidth narrowing due to AWG concatenation, and ASE noise accumulation on the performance of the optical interconnect. We show that the optimized architecture performs well, almost equally to the original one, despite the stricter limitations imposed by the additional stage of SOAs.
We define here three reference systems used in the following subsections for performance comparison: i) by the term ‘ideal system’ we refer to the one described in [11], where optical signal is assumed to be distortionless and the ASE noise is filtered at the IM/DD receiver by a brickwall optical BPF and an integrate-and-dump LPF (in the absence of a polarizer); ii) the term ‘back-to-back’ refers to a hypothetical scenario where the selection stages of the receiver (i.e., grey boxes in Fig. 3(a)) are omitted; and iii) the term ‘single-channel transmission’ refers to the hypothetical case where only one wavelength, i.e., the one that experiences the best or worst performance, is transmitted through the OSMOSIS architecture. A commercially-available software tool (VPI TransmissionMaker) enhanced with custom-made modules in Matlab for OSNR measurements, was used for carrying out the simulations shown [12]. Moreover, Mathematica software was also used to validate the SOA model.

A. Overview

The BER is assessed as a function of the received OSNR for each of the transmitted wavelengths, both by experiment and simulation. The final results are shown in Fig. 4 and Fig. 5, for the original and the optimized architecture, respectively. The hatched areas between two consecutive curves in both figures represent families of closely spaced BER curves corresponding to different wavelength channels.

In Fig. 4, measurements for the original architecture show that the spread among all eight channels is approximately 1 dB, both in simulation and experiment.

Experimental results in Fig. 5 reveal that there is a spread of 1.2 dB, in terms of required OSNR, among the eight channels of waveband W_1 and W_2 for BER = 10^{-9}. In close agreement with the experiment, simulation results indicate that there is an OSNR spread of approximately 1.45 dB among the eight channels of wavebands W_1 and W_2. However, simulation also shows that there is a spread of approximately 2 dB between all 16 simulated channels of the optimized architecture for BER = 10^{-9}. The BER curve for an ideal system [11] is also shown for comparison. For qualitative comparison, experimental eye diagrams are also shown as insets in Fig. 4-5, for the best and the worst channels, for both architectures.

Finally, the performance of both architectures is also tested without in-line SOAs, in a back-to-back configuration (squares in Fig. 4 and Fig. 5), as well as for single-channel transmission, after the three selection stages of the optimized configuration (triangles in Fig. 5). We observe that the penalty difference is negligible among the back-to-back, the single-channel, and the best case transmission scenario (i.e., \lambda_{27}) for the optimized architecture (Fig. 5). Similarly, the curves corresponding to the back-to-back and the best case transmission scenario (i.e., \lambda_3) for the original architecture (Fig. 4) are indistinguishable.

It is worth noting that the measured performance, in both architectures, is worse than the one predicted by simulation by approximately 1 dB (e.g., compare the back-to-back cases for the simulation and the experiment, respectively). This small difference is attributed to the following parameter mismatch between simulation and experiment: i) the use of narrower optical filters in the simulation; ii) the use of the same data pattern for modulating all wavelength channels in the experiment, in contrast to the simulation, where each laser is independently modulated with a different bit sequence (a 4 dB degradation is observed using the same data patterns); and iii) the omission of polarization dependent gain (PDG) from the SOA simulation model [13]. Despite this small discrepancy, from Fig. 4-5, we can safely conclude that the performance of the optimized architecture is slightly worse than the performance of the original one for the worst channel (whereas it is identical for best channel). We point out here, that the experimental results shown in Fig. 4 and Fig. 5 are optimized compared to the ones reports in [9] by 1.4 dB, a penalty found to be due to the low extinction ratio (ER) that holds in the experiment [14]. The ER in [9] was 8 dB, while in the present work the ER was optimized by 5 dB to avoid penalty due to a reduced modulation ER.

In Fig. 6, the OSNR (measured in a resolution bandwidth of 0.08 nm and expressed in dB) required for BER = 10^{-9} for all channels: (a) original and (b) optimized optical interconnect architecture. (Symbols: W_1-W_4 wavebands used in the optimized architecture; Open and filled circles: simulated and experimental results, respectively).

![Fig. 6 OSNR](Image)

**Fig. 6** OSNR (measured in a resolution bandwidth RB=0.08 nm) required for BER=10^{-9} for all channels: (a) original and (b) optimized optical interconnect architecture. (Symbols: W_1-W_4 wavebands used in the optimized architecture; Open and filled circles: simulated and experimental results, respectively).
Influence of transmission impairments on the OSMOSIS HPC optical interconnect architecture

Fig. 7 BER vs OSNR (measured in RB=0.08 nm) (a) for the worst channel of the original OSMOSIS architecture and (b) for the worst channel of the optimized OSMOSIS architecture. (Symbols: ideal system [11]; red line; Back-to-back: blue circles; Single-channel transmission through the actual interconnect: red squares; WDM transmission through the actual interconnect after the substitution of SOAs and EDFAs by ideal, flat-gain amplifiers: black crosses; WDM transmission through the actual interconnect i.e., a concatenation of two and three SOAs, for the original and the optimized scheme, respectively: dash-dotted curve with stars.

from longer to shorter wavelengths (i.e., a higher OSNR value is needed for the same BER moving from longer to shorter wavelengths). This is partially attributed to the noise figure (NF) of the SOAs, which increases for shorter wavelengths [17].

No FWM [18]–[19] products were observed in the recorded spectrum for the specific operating conditions and the wavelengths under test, in the experiment. This indicates that FWM is not a major factor to the observed signal.

From the above, we conclude that the optimized architecture provides a good trade-off between SOA count reduction and performance degradation. Its relatively small penalty in required OSNR compared to the original architecture justifies its use.

In the following subsections B to D, using simulation, we quantify the contribution of different transmission effects in the performance degradation of both architectures.

B. Penalty due to SGM

As its name indicates, SGM is gain modulation due to instantaneous channel power variation at the SOA input [20]. In this subsection, we focus on the penalty due to SOA SGM in both optical interconnect architectures under study. To distinguish between the penalty due to SGM and the total system penalty, we perform simulations using a single channel, i.e., the worst and the best channel, in both architectures. The results for the worst channel are shown in Fig. 7 (red squares). The curves for the ideal system (red line), the back-to-back case (blue circles), and the case of WDM transmission through the interconnect (dash-dotted curve with stars), are also included for comparison. An additional curve corresponding to the WDM case, obtained by substituting all SOAs and EDFAs by ideal, flat-gain amplifiers, is also shown (black crosses).

Comparing the back-to-back case with the single-channel transmission, we conclude that the penalty is negligible in the original architecture (Fig. 7(a)) and 1.5 dB in the optimized one (Fig. 7(b)) at an error probability of $10^{-9}$. In contrast, for the best channels, the penalty is negligible in both architectures (not shown here to avoid clutter). The difference of 1.5 dB in performance between the worst and the best channel of the optimized interconnect is explained as follows: the worst channel reaches higher power levels, due to its allocation closer to the gain peak of the SOAs, and therefore, is more affected by SGM. As expected, SGM is more severe in the optimized architecture than in the original one because the signal passes through one more SOA in the former case.

C. Penalty due to XGM

SOAs are subject to XGM [21] that results into data pattern-dependent crosstalk among WDM signals when ASK is used [22]–[23]. The use of quasi-constant envelope modulation formats, such as return-to-zero (RZ) differential phase-shift keying (DPSK) [15], [22], RZ differential quadrature phase-shift keying (RZ-DQPSK) [16], or PDM-QPSK [8]–[9], has been proposed to counteract this effect. We can assess the penalty due to XGM from Fig. 7, by comparing the results for WDM transmission through the optical interconnect after substitution of SOAs and EDFAs by ideal, flat-gain amplifiers.

The penalty due to XGM is negligible for the best channel in both architectures. Plots of the best channel performance are not shown in Fig. 7 to avoid clutter. In contrast, the XGM penalty is equal to 1 dB, for the worst channel of the original architecture (Fig. 7(a)), and 2 dB, for the worst channel of the optimized architecture (Fig. 7(b)), respectively.
In the original architecture, the WDM signal bandwidth is smaller so channels are less affected by the SOA gain non-uniformity. More specifically, the eight channels are located uniformly around the SOA’s gain peak and occupy a bandwidth of 800 GHz (inset in Fig. 1). In particular, the eight channels exit the first SOA with negligible difference in power. On the other hand, in the optimized architecture, the 16 channels occupy a bandwidth of 2.7 THz (inset of Fig. 2) around the SOA’s gain peak, and, consequently, they experience a larger power variation. In addition, power variation as a function of wavelength, due to the gain non-uniformity of the EDFAs and the SOAs, and the insertion loss non-uniformity of the cascaded AWGs exacerbates the power variation among channels. This leads to a different behavior among channels with respect to XGM and to higher penalties compared to the original architecture.

Fig. 8(a),(b) show the Q-factor as a function of transmitted power per channel, for the best ($\lambda_6$ and $\lambda_{27}$) and the worst ($\lambda_1$ and $\lambda_{10}$) channels of the original and the optimized architecture.

In both architectures, the performance reaches an optimum and remains at a constant level. The ceiling of the Q-factor for higher power levels is analytically explained in Appendix B.

D. Penalty due to the concatenation of optical MUX/DMUXs

AWG MUX/DMUX concatenation leads to narrowing of the optical bandwidth, which, in turn, results in signal attenuation and distortion [10]. In this subsection, we evaluate, by simulation, the penalty due to the narrowing of the optical bandwidth of the aggregate transfer function of the cascaded AWGs, in both interconnect architectures under study.

We consider conventional AWGs with Gaussian amplitude transfer function and linear phase transfer function. To focus on filter-induced distortion exclusively, we substitute all EDFAs and SOAs, in Fig. 1 and Fig. 2, with ideal (flat-gain) amplifiers. In this way, we neglect all transmission effects related to optical amplifiers.

Plots of BER as a function of OSNR are shown in Fig. 7, for the worst case transmission scenario, for both architectures. Comparing the curve for the back-to-back case to the one for the ideal flat-gain EDFAs, we conclude that this penalty is negligible in both cases. These results can be easily explained by the following analysis.

The Gaussian transfer function of each of the four AWGs is given by the formula

$$H_i(f) = A_i e^{\frac{1}{2} \left( \frac{f-f_{oi}}{f_{ci}} \right)^2}$$  \hspace{1cm} (1)

where, $A_i$ is the amplitude, $f_{oi}$ is the center frequency and $f_{ci}$ is the cut-off frequency of the $i$-th AWG ($i = 1,...,4$).

Assuming that all center frequencies are perfectly aligned to the channel carrier frequency $f_{ck}$, the aggregate transfer function $H_{tot}(f)$ of the four concatenated AWGs is

$$H_{tot}(f) = \prod_{i=1}^{4} H_i(f) = A e^{\frac{1}{2} \left( \frac{f-f_{ch}}{f_{c}} \right)^2}$$ \hspace{1cm} (2)

where $f_{ch}$ is the overall cut-off frequency

$$f_{ch} = \left( \sum_{i=1}^{4} f_{ci}^{-2} \right)^{-\frac{1}{2}}$$ \hspace{1cm} (3)

By substituting $f_{c1} = f_{c2} = 200$ GHz and $f_{c3} = f_{c4} = 20$ GHz, for the cut-off frequencies of the AWG pairs of the discretely-tunable Rx in the OSMOSIS optimized interconnect, we find that $f_{c} = 14$ GHz. The equivalent noise bandwidth of the
aggregate transfer function is \( B_c = \sqrt{\pi f_c} = 25 \text{GHz} \) [10].

Given that the 95% of the power of an ideal 10 Gb/s NRZ ASK signal occupies 30 GHz [24] we conclude that the signal distortion due to the bandwidth narrowing arising from MUX/DMUX concatenation would be negligible, as indicated by the simulation results shown in Fig. 7(b).

The above analysis does not take into account the increased filtering of AWG MUX/DMUXs in the presence of spectral broadening due to SPM and XPM in SOAs. This is taken indirectly into account in Fig. 7(a), (b) (dash-dotted curves with stars).

**V. SUMMARY**

In this paper, we assessed the performance of a recently-proposed, economically-viable, broadcast-and-select, 64×64, optical interconnect architecture [7] using a minimum number of SOA-based on-off gates. We compared its performance to its originally proposed counterpart [6], both by experiment and by simulation. We showed that both interconnect architectures perform almost equally well, while the optimized one is advantageous in terms of the number of SOAs required to perform permutation switching.

To examine the impact of SOA nonlinearities and ASE noise accumulation on the performance of the optical interconnect architectures under consideration, each effect was studied separately. The proposed optimized architecture proved to be tolerant in SOA’s nonlinearities. SGM and XGM worsen the performance of the optimized architecture in terms of required OSNR for error free operation only by about 1 dB for the worst case scenario, when compared to the corresponding performance of the original configuration. FWM and the bandwidth narrowing imparted by the concatenation of AWGs in the architecture proved to have negligible impact on the degradation of the performance of the optimized interconnect. ASE noise accumulation and WDM channel power variation due to the wavelength dependent gain of the SOAs affect the performance of the optical interconnect too, resulting both in unequal accumulation of ASE noise for each channel, as well as in channel power variations at the receiver. Finally, we experimentally studied the performance of both optical interconnect architectures. Experimental and theoretical results were in good qualitative agreement.

**APPENDIX A**

In this Appendix, we briefly describe: i) the SOA model used in the simulation and its simulation parameters, and ii) the formula used for the error probability for the ideal system.

**A. SOA model validation**

For the simulation of the SOAs, the Transmission Line Model (TLM) was used [13]. In the simulation, we assumed that the SOAs in the simulation have 1-mm length and a 90-nm 3-dB gain bandwidth. The other parameters used in the SOA model are extracted by least squares fitting of experimental data for the SOA gain and output power as a function of input SOA power (Fig. 9) [25]. The most important SOA parameters are shown in Table 1.

**B. Error probability evaluation of the ideal system**

As a reference, in Fig. 4, 5 and 7 we plot the error probability of an IM/DD receiver with a brickwall optical BPF and an integrate-and-dump LPF, in the absence of a polarizer [11]. As a sanity check, the accuracy of the semi-analytical method used in simulation [12], [26] for the calculation of error probability, was compared to the accurate analytical

**TABLE I**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Description</th>
<th>Value</th>
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<tr>
<td>( \Gamma )</td>
<td>-</td>
<td>Confinement factor</td>
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</tr>
<tr>
<td>( \alpha_0 )</td>
<td>m(^2)</td>
<td>Differential gain coefficient</td>
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<tr>
<td>( N_w )</td>
<td>m(^3)</td>
<td>Carrier density at transparency</td>
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<td>( \alpha_i )</td>
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<td>Internal loss</td>
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</tr>
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<td>( L )</td>
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<td>( w )</td>
<td>m</td>
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<td>Auger recombination coefficient</td>
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Fig. 9 Fitting experimental data for the SOA gain (blue) and for the output power (green), as a function of input power using the TLM simulation model. (Symbols: P\(_{in}\)=Input SOA power, P\(_{out}\)=Output SOA power, Solid line: Simulation, Crosses: Experimental values).
method of [11]. The two methods were found to be in good agreement.

The analytical model of [11] takes into account the non-Gaussian ASE noise statistics at the receiver but neglects any signal distortion due to filter-induced intersymbol interference. The analytical expression of the error probability \( P_e \) for the receiver of [11], in the absence of a polarizer, is:

\[
P_e = \frac{1}{2} \left( 1 + 2 N_{ph} d \right) e^{-2 \sigma_P^2} + \frac{1}{2} \left[ 1 - Q_2(2 \sqrt{N_{ph}} d) \right]
\]  

where \( N_{ph} \) is the average number of photons at the receiver. The latter is related to the OSNR, calculated in both polarizations, through the equation, \( \text{OSNR} = P_s/(2h\nu\Delta\nu) = N_{ph}/2 \). The last equality holds for a resolution bandwidth \( \Delta\nu = 2B_e \), a LPF equivalent noise bandwidth \( B_e = 1/(2T_b) \) where \( T_b \) is the bit period, a spontaneous emission factor \( nsp = 1 \), and an infinite extinction ratio. In (4), \( d \) is the normalized optimum threshold, \( 0 \leq d \leq 1 \), and \( Q_m \) is the generalized Marcum’s function [27]

\[
Q_m(a,b) = \int_{b}^{\infty} x^{m-1} e^{-x^2/2} I_{m-1}(ax) dx
\]

where \( I_m(x) \) is the \( m \)-th order modified Bessel function of the first kind.

The deterministic semi-analytical method [26] for error probability estimation is used in the simulations. When the deterministic approach is used, the BER is calculated from the deterministic signal and statistical properties of the optical, thermal and shot noises. The module finds the exact (nongaussian) moment generating function (MGF) of the detected signal, taking into account the optical noise spectral shape, relations between the signal and noise polarization states, thermal and shot noises of the receiver and correlations due to postdetection filtering. The bit error rate is then calculated from the MGF using the saddle-point approximation technique [12].

APPENDIX B

In this Appendix, using small-signal analysis, we interpret the Q-factor ceiling observed in Fig. 8, when the launched power per channel is high. We assume \( N \) amplitude shift keying (ASK) signals of equal average power at the SOA input. Let \( G \) be the instantaneous SOA gain, \( G_i \) the SOA small-signal gain, \( P_{soa} \) the instantaneous total input power, and \( P_i \) the SOA input saturation power. From the SOA rate equation for the optical power [28], assuming zero internal loss and constant carrier concentration, yields

\[
G = G_i e^{-\left(G-1\right) P_{soa}}
\]

Assume that the total input power to the SOA is \( P_{tot} = P_i + \delta P \), where \( P_i \) is the sum of average powers of all channels and \( \delta P \) is a small perturbation \( (\delta P \ll P_i) \) due to the sum of the instantaneous power variation of all channels. Substituting in (6), the amplifier gain is

\[
G_i + \delta G = G_i e^{\frac{(G_i + \delta G - (G_i + P_{soa} + \delta P))}{P_i}}
\]

Expanding the terms in parentheses and ignoring the second-order term \( \delta G \delta P \) yields

\[
\delta G = - \frac{G_i(G_i - 1)\delta P}{P_i + G_i P_0}
\]

The instantaneous power per channel at the output of the SOA amplifier is

\[
P_{out} + \delta P_{out} = (G_i + \delta G)(\bar{P} + \delta P) \]

where \( \bar{P} \) is the average input power per channel and \( \delta P \) is the instantaneous power variation per channel \( (\delta P \ll \bar{P}) \). Given that \( P_{out} = G_i \bar{P} \) and neglecting \( \delta G \delta P \), we get

\[
\delta P_{out} = \bar{P} \delta G + G_i \delta P_i = \frac{G_i(G_i - 1)}{P_i + G_i P_0} \bar{P} \delta P + G_i \delta P_i
\]

Because \( \delta P \), \( \delta P_i \) are independent random variables with zero mean value and variances \( \sigma_{\delta P}^2 \) and \( \sigma_{\delta P_i}^2 \), respectively, \( \delta P_{out} \) is also a random variable with zero mean value and variance

\[
\sigma_{\delta P_{out}}^2 = \left( \frac{G_i(G_i - 1)}{P_i + G_i P_0} \bar{P} \right)^2 \sigma_{\delta P}^2 + G_i^2 \sigma_{\delta P_i}^2
\]

For each transmitted channel the instantaneous input power, \( P_i \) can be explicitly written as

\[
P_i = \bar{P} + b_i \Delta
\]

where \( b_i \) is a binary random variable taking values in the set \( \{-1,1\} \), and \( \Delta \) is the fraction of power added to or subtracted from the average input power to yield a logical ONE or ZERO.

If \( r \) is the extinction ratio, defined as \( r = \frac{P_{ZERO}}{P_{ONE}} \) [23], where \( P_{ZERO} \cdot P_{ONE} \) are the instant powers for the ZEROS and ONES, respectively, \( \Delta \) can be expressed as

\[
\Delta = \frac{\bar{P}}{1 + r}(1 - r)
\]
The variance of \( \delta P \) is
\[
\sigma^2_{\delta P} = \bar{P}^2 \left( \frac{1-r}{1+r} \right)^2
\]  \hspace{1cm} (14)

Due to channel independence, the variance of the total instant power variation \( \delta P \) is
\[
\sigma^2_{\delta P} = N \sigma^2_{\delta P}
\]  \hspace{1cm} (15)

At the limit \( \bar{P} \to \infty \), the SOA ASE noise is negligible and the OSNR at the output of the SOA is calculated by the formula
\[
\text{OSNR} = \frac{\bar{P}_{\text{out}}}{\sigma_{\delta \bar{P}}}
\]  \hspace{1cm} (16)

or, equivalently,
\[
\text{OSNR} = \frac{G_0}{\left[ \frac{\left( (G_0 - \delta G) \bar{P} + \delta P \right)^2}{G_0 N \bar{P} + P} \right]^{1/2} \left( \frac{1-r}{1+r} \right)}
\]  \hspace{1cm} (17)

where \( G_0 = G_0(P_s) = G_0(N \bar{P}) \).

It is observed that as \( \bar{P} \to \infty \), the OSNR reaches a ceiling. The same is true for the Q-factor given by [14]
\[
Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}
\]  \hspace{1cm} (18)

where
\[
\mu_1 = (G_0 + \delta G)(\bar{P} + \delta P)
\]
\[
\mu_0 = (G_0 - \delta G)(\bar{P} - \delta P)
\]
\[
\sigma^2_1 = 4 \left( G_0 + \delta G \right) (\bar{P} + \delta P) h v \Delta \nu \cdot n_{sp} (G_0 + \delta G - 1)
\]
\[
\sigma^2_0 = 4 \left( G_0 - \delta G \right) (\bar{P} - \delta P) h v \Delta \nu \cdot n_{sp} (G_0 - \delta G - 1)
\]  \hspace{1cm} (19)

We set
\[
G_0 \pm \delta G - 1 = G_0 \pm \delta G
\]  \hspace{1cm} (20)

which is valid for \( G_0 \gg 1 \), we use the 2nd order Taylor series to get
\[
\left( \bar{P} + \delta P \right)^{\gamma} = \bar{P} \pm \frac{1}{2} \delta P
\]  \hspace{1cm} (21)

and we assume that for XGM, the average error probability is equal to the error probability of the innermost traces in the eye diagram corresponding to all ONES and ZEROS [23]. By substitution of (19)-(21) in (18) we get
\[
Q \approx \frac{1}{2 \sqrt{a}} \left( \frac{1-r}{1+r} \right) G_0 (N \bar{P}) N \bar{P} + P
\]  \hspace{1cm} (22)

where \( a = h v \Delta \nu \cdot n_{sp} \). As \( \bar{P} \to \infty \), \( Q \) reaches a ceiling similar to the one observed in Fig. 8 for large-signal modulation which is
\[
Q \approx \frac{1}{2 \sqrt{a}} \left( \frac{1-r}{1+r} \right)
\]  \hspace{1cm} (23)

It is worth noting here that the curves in Fig. 8 do not assume the bell shape shown in [29] (Chapter 14, Fig. 15), i.e., the optical interconnect performance does not degrade at high SOA input power levels but reaches a ceiling. This apparent contradiction is due to the fact that, in our simulations, the input power to the photodiode is unlimited, whereas, in practice, there is a maximum optical power that can be received by the photodiode. In [29], there is an attenuator before the photodiode that keeps the optical power below a certain level.

REFERENCES

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