Impact of Cumulative Polarization-Dependent Gain on SOA-Based Optical Packet Switching Networks

Odile Liboiron-Ladouceur, *Student Member, IEEE*, Keren Bergman, *Member, IEEE*, Misha Boroditsky, *Senior Member, IEEE*, and Misha Brodsky, *Member, IEEE*

***Abstract*—The physical layer scalability of multistage interconnection networks is determined by the maximum number of internal switching nodes that packets can traverse error-free. We show that for nodes based on commercial semiconductor optical amplifier switches with polarization-dependent gain of less than 0.35 dB, the maximum number of cascaded nodes could vary by as much as 20 nodes, depending both on the packet wavelength and its state of polarization. We explain such a dramatic effect by optical signal-to-noise ratio degradation due to accumulated amplified spontaneous emission noise with the number of nodes.**

***Index Terms*—Optical packet switching (OPS), polarization-sensitive devices, semiconductor optical amplifier (SOA).**

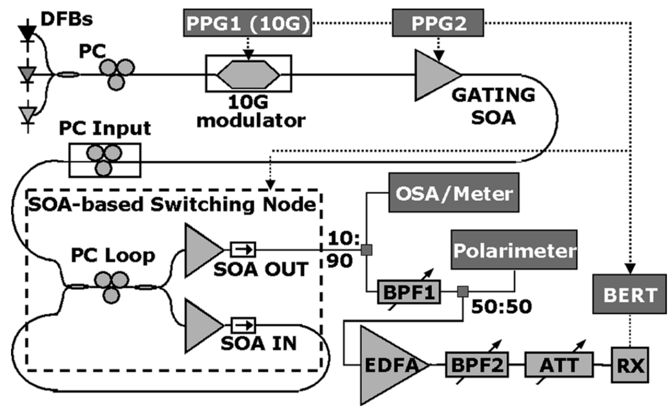

Fig. 1. Testbed. Optical and electrical paths (solid and dashed lines).

I. Introduction

OPTICAL packet switched (OPS) interconnection networks are a promising means of routing high bandwidth optical packets with low communication latency [1]. Depending on the network size, the possible applications range from local area and storage networks to high-performance computing [2]. The data vortex network architecture has been shown to be a particularly attractive candidate for the latter application, as it allows scaling in both the network size and packet bandwidth [3].

In most OPS networks, the predominant switching element is the commercially available semiconductor optical amplifier (SOA) due to its broad gain bandwidth, fast switching, and potential for integration [3]–[7]. In the data vortex architecture, SOAs are used to transparently route individual packets containing multiple wavelength-division-multiplexing payload channels. Besides acting as a gate, the SOA compensates for small optical power losses from the passive optical components of the node structure such as couplers, delay lines, and connectors. The inherent polarization-dependent gain (PDG) of the SOA used in the switch element, albeit very small in modern devices, could potentially accumulate as the packets propagate through a cascade of SOA-based nodes and affect the overall system performance when the launched packets are at certain polarizations. In fact, in our previous studies, we observed that the packet polarization influenced the node cascadability [8].

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O. Liboiron-Ladouceur and K. Bergman are with the Department of Electrical Engineering at Columbia University, New York, NY 10027 USA (e-mail: ol2007@columbia.edu; bergman@ee.columbia.edu).

M. Boroditsky and M. Brodsky are with AT&T Laboratories Research, Middletown, NJ 07748 USA (e-mail: boroditsky@research.att.com; brodsky@research.att.com).

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In this letter, we report a detailed study of the impact of such cumulative PDG on the size of SOA-based OPS networks. Using a recirculating loop, we send the packets through a virtual cascade of SOA-based nodes. By setting two polarization controllers, one inside and one at the input of the loop, we control both the input state of polarization (SOP) into the recirculating loop and the PDG accumulation with the number of traversed loops. We characterize the performance by taking the bit-error-rate (BER) measurements as a function of number of cascaded nodes for three difference wavelengths (1531, 1543, and 1553 nm). For two extreme cases of maximum and minimum cumulative PDG, we observe the wavelength-dependent variations in the number of nodes that packets could travel error-free can be as large as 20 nodes. Further, we show that in all cases, increases in the BER arise from the optical signal-to-noise ratio (OSNR) degradation due to accumulated amplified spontaneous emission (ASE) noise.

II. Experimental Setup

A schematic of the recirculating loop setup used in this investigation is shown in Fig. 1. The loop contains an SOA-based switching node such as the one used in the data vortex OPS interconnection network [3]. Three cooled distributed feedback lasers emitting at 1531, 1543, and 1553 nm are used to quantify the PDG over the SOA gain bandwidth. The channels are multiplexed into a single fiber and simultaneously modulated with a dual-drive Mach–Zehnder modulator at 10 Gb/s. The modulator is driven by a nonreturn-to-zero pseudorandom bit sequence of length $2^9 - 1$ produced by the fast pattern generator (PPG1). A short packet of 25.6 ns is created using a separate SOA to gate the continuous data stream. Packets are launched with a period of 3.22 μs to ensure that there is at most one packet in the loop at a time. The launched SOP of the payload channels is

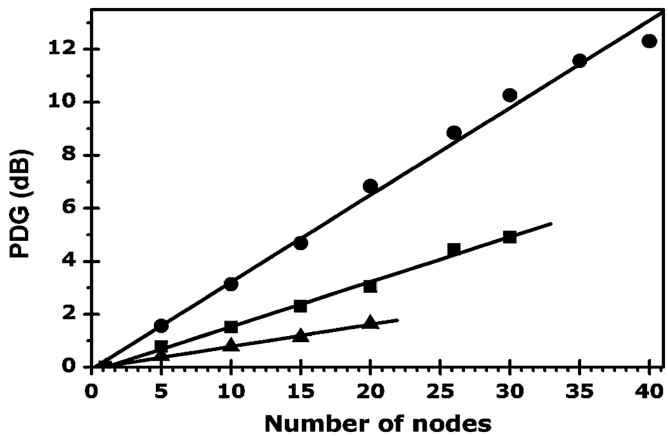

Fig. 2. Maximum PDG increasing linearly for channels at 1531 (circles), 1543 (squares), and 1553 nm (triangles).

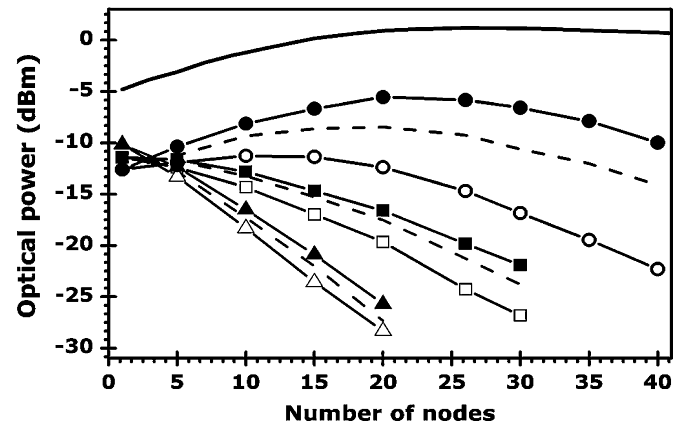

Fig. 3. Optical power as a function of the number of cascaded nodes for "High Gain" (solid symbols), "Low Gain" (open symbols), and "No PDG" (dashed lines) at 1531 (circles), 1543 (squares), and 1553 nm (triangles). The plain line represents the total power of the packet.

set using a polarization controller (PC Input). The SOAs in the node are commercial devices (Kamelian OPB-10-10-X-C-FA) with a noise figure of 6.5 dB, an unsaturated gain of 8 dB, and a saturation input power of approximately 0 dBm for an operating current of 40 mA. The SOA gain is 6.5 dB compensating for the node loss.

The recirculating loop is constructed by connecting one of the node outputs to its input using a deflection fiber. Packets are either routed back to the same node through a 40-ns-long loop or out of the loop. A programmable pattern generator (PPG2) sends a switching signal after a predetermined number of loops that corresponds to the desired number of cascaded nodes. Two polarization controllers adjust the PDG of concatenated loops (PC Loop) and the input SOP (PC Input). The details of the recirculating loop synchronization and the packets' payloads BER measurements methodology can be found in [8] and [3], respectively. The front-end receiver has been optimized to a sensitivity of -35 dBm (BER $< 10^{-9}$) by adding a bandpass filter (BPF1). An optical spectrum analyzer measures the optical signal-to-noise ratio (OSNR).

III. Results

By controlling the polarization in the recirculating loop, we investigate three different cases of the impact of PDG on each of the three payload channels. For the first two cases, the loop polarization controller (PC Loop) is adjusted such that the channel's polarization returns to the same state after one loop trip. In this setting, the PDG effect is maximized and it accumulates in a linear fashion as the packet traverse through consecutive loops (Fig. 2). Depending on its input SOP, each channel will experience gain that falls between a certain range of the total gain. The channel's input SOP corresponding to the lowest gain monitored is referred as the "Low Gain" Case 1, while the one corresponding to the highest gain is referred as the "High Gain" Case 2. The last and third case corresponds to the "No PDG" Case 3, where the loop polarization controller (PC Loop) is set to change the packet's polarization to the orthogonal one as it travels through one loop so that PDG of consecutive loops cancel each other and practically no cumulative effect is observed. Due to small but finite polarization-mode dispersion in the deflection fiber, these three PC Loop settings are channel-specific. PDG is measured by monitoring the channel power at the output of the loop while the input polarization controller (PC Input) operates in scrambling mode covering the entire Pointcaré sphere using the polarimeter at a sampling rate faster than the scrambling speed.

In Fig. 3, the measured optical power of each of the three payload channels at the receiver front-end is plotted as a function of the number of nodes propagated for all three cases described above. The input power of each channel is compensated with more power for the shortest channels to minimize the effect of the wavelength gain dependence of the SOA device [9]. For some channels, the node transparency is broken by the combined effects of PDG, polarization-dependent loss, and the wavelength-dependent gain of the node's components. When this occurs, as shown in Fig. 3 for channels at 1543 nm and at 1531 nm, the packet experiences a net loss traveling through the cascade of nodes. Concurrently, the minimum and maximum powers change in a nonlinear fashion for the channel at 1531 nm and saturate after an initial linear increase. The total optical power of the multiwavelength packet at the output of the loop indicates a shift in the SOA operation regime from linear to saturation after 20 nodes. There is a delicate balance between ensuring adequate gain for the longer wavelength channels while maintaining the SOA in the linear regime with low gain settings to prevent the accumulated ASE noise from quenching the available gain.

The methodology of concatenating multiple nodes allows for accurate measurements of relatively small polarization dependences of one node when the cumulative PDG is maximized (Fig. 2). The node PDG corresponds to the rate of increase in the power differences between the "High Gain" and "Low Gain" cases in Fig. 3. Clearly, the measured node PDG is wavelength-dependent with 0.33 dB at 1531 nm, 0.17 dB at 1543 nm, and 0.09 dB at 1553 nm for a gain set to 6.5 dB. The SOA device specifications show similar wavelength dependence with 0.52 dB at 1528 nm and 0.10 dB at 1550 nm at a gain set to 13 dB. Higher PDG is associated with higher gain as the balance achieved between the difference in confinement factors and the strain in the SOA [10] is more difficult to maintain at high gain.

We now turn to the investigation of the impact of cumulative PDG on the network size scalability. For each channel. three BER curves (corresponding to the three cases of "High Gain,"

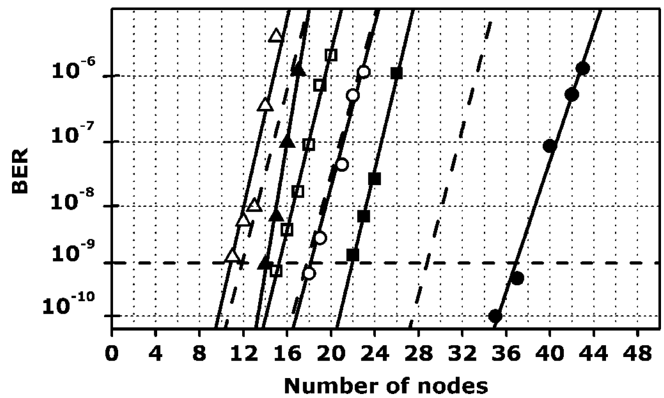

Fig. 4. BER measurements for the three channels (circles: 1531 nm; squares: 1543 nm; triangles: 1553 nm) for "High Gain" (solid symbols), "Low Gain" (empty symbols), and "No PDG" cases (dashed lines).

"Low Gain," and "No PDG") are taken as a function of the number of cascaded nodes through which a packet propagates (Fig. 4). The performance metric used to quantify the impact of node PDG on the multistage network size is the maximum number of cascaded nodes propagated by a packet while maintaining a BER below 10^{-9}. At 1531 nm, this number varies by almost 20 nodes from 18 cascaded nodes in the "Low Gain" case to 37 cascaded nodes in the "High Gain" case. These two limits deviate by about ten nodes from the case of "No PDG." Similarly, the performance of the channel at 1543 nm ranges from 15 to 22 nodes deviating by about four nodes from the "No PDG" case. Thus, large deviations in the maximum allowable cascaded nodes associated with the presence of even small individual node PDG can profoundly impact the network scalability when PDG is not carefully considered [8]. Appropriate channel placement in the region of lower PDG (1553 nm instead of 1531nm) could significantly improve the network performance uniformity. The lower gain associated with lower PDG makes this approach most applicable to smaller networks on the order of 100 ports or less.

For each point of the dataset in Fig. 4, the OSNR was measured in addition to the BER. These OSNR measurements are plotted as a function of the corresponding BER in Fig. 5. The back-to-back receiver sensitivity to the payload channel's OSNR is 17 ± 0.7 dB at a BER of 10^{-9} for all three wavelengths indicated by the gray line with error bars on the plot. Data points corresponding to the case of "Low Gain" lie within the sensitivity limitation of the receiver as well as data points corresponding to the case of "High Gain" for 24 loops or less. Hence, we conclude that the impact of cumulative PDG can be largely described as OSNR degradation for each wavelength. In presence of PDG, additional gain seen by some SOP could create some node gain overcompensation that extends the lifetime of the packet in the network. Alternatively, the gain reduction for some SOP could cause degradation of the channel OSNR due to spontaneous emission noise. Compensation techniques or better SOA design with regard to gain flatness and very low PDG should be considered for larger network sizes. The additional OSNR penalty for data points outside the OSNR receiver sensitivity is ascribed to nonlinear effects as the SOA reaches the saturation. These points (three black circles)

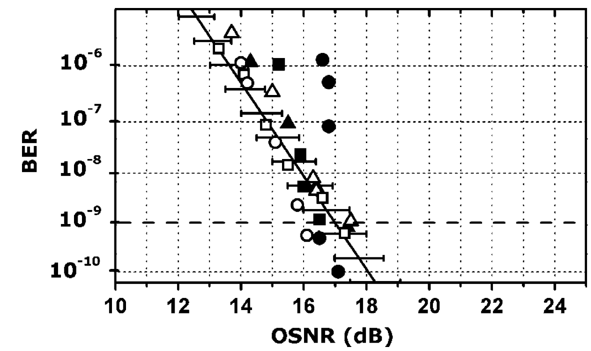

Fig. 5. OSNR versus BER measurements: back-to-back receiver sensitivity range (gray lines) and for the three payload channels for "High Gain" (solid symbols) and "Low Gain" (empty symbols).

correspond to 40, 42, and 43 node propagation by the shortest wavelength channel (1531 nm).

IV. Conclusion

The impact of cumulative PDG in an SOA-based OPS network is investigated in a recirculating loop test-bed environment that emulates the cascade of multiple switching nodes. We find that even small node PDG (0.33 dB at 1531 nm) can dramatically affect the OSNR degradation due to accumulated ASE noise. The maximum number of cascaded nodes was shown to vary by as many as 20 nodes, depending both on the packet wavelength and its input SOP. Large node variation could translate into considerably smaller network sizes than projected. The impact of PDG should, therefore, be addressed through optimum channel placements and improved SOA design.

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