10 Gbps NRZ-DPSK Modulation in SOA-based Optical Packet Switching Networks

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Abstract *Differential phase-shift keying transmission in optical packet switching networks can reduce pattern-induced distortion incurred in the semiconductor optical amplifier based switching elements, but phase noise becomes the performance limitation of the physical layer network scalability.*

Introduction

Optical packet switched (OPS) networks are a promising means of delivering high bandwidth data communication with the fine granularity enabled by individual packet routing. In most OPS network architectures, semiconductor optical amplifiers (SOA) are the predominant technology used in switching elements due to their fast switching time, broad gain bandwidth and potential for hybrid integration with optical and electrical devices.

Conventionally, the payload channels are modulated with on-off keying modulation (OOK). In such systems, the physical layer scalability is primarily limited by the ASE noise accumulation from the SOAs [1]. When multiple WDM channels are propagated, additional effects such as cross-gain modulation can become problematic. Recently, phase modulation has regained interest in optical communication systems due to the lower power requirement at the receiver and immunity to cross-gain modulation [2]. When phase modulation is used, the power remains constant over each bit period reducing the carrier-lifetime effects in SOA-based systems. It has also been demonstrated, however that phase noise becomes a key limitation to system performance when differential phase-shift keying (DPSK) encoding is used [3].

In this paper, a re-circulating loop is used to investigate the role DPSK modulated payload channels could potentially play in the context of optical packet switching networks. Optical packets are propagated in the re-circulating loop to model a cascade of SOA-based switching elements. Comparisons with NRZ-OOK modulation are done through power penalty and phase noise measurements.

Experimental setup

The experimental testbed is shown in Figure 1. A tunable laser operating at 1550 nm is followed by a polarization controller (PC) and modulated with a $LiNbO_3$ phase modulator at 10 Gbps to create NRZ-DPSK modulated data. The optical modulator is driven by an NRZ pseudo-random bit sequence (PRBS) of length 2^9-1 produced by a fast pattern generator (PPG1) and amplified to 5V_{p-p} (V_π). A bit '0' corresponds to a phase of 0° and a bit '1' corresponds to a phase change of 180°. A packet length of 25.6 ns is created using a separate SOA to gate the continuous data stream. The optical signal-to-noise ratio at the input of the loop was maintained above 35 dB (0.1 nm resolution bandwidth).

A single packet is injected once every 40 roundtrips into a 115 ns long re-circulating loop. Packets ingress through switching node 1 and either propagate back into the loop or exit from switching node 2 [4]. Both nodes are controlled by a separately programmed signal generated by PPG2. To avoid the accumulation of noise in the loop, the device labeled 'Loop SOA' in node 2 is turned off while the packet is dropped out of the loop through 'Out SOA'. The SOAs are commercial devices (Kamelian OPB-10-10-X-C-FA) specified with a noise figure of 6.5 dB, an unsaturated gain of 10 dB, and a saturation input power of approximately 0 dBm. The devices have a transparency current of about 18 mA, and their ASE spectrum is concentrated near 1465 nm. In each node, the SOA gain compensates for approximately 5.5 dB of loss due to the couplers and connectors.

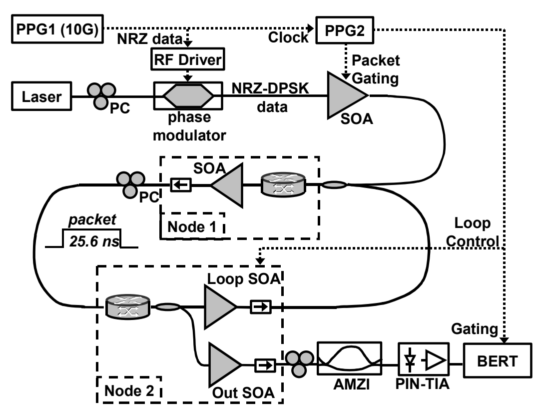

Fig. 1: Re-circulating loop testbed. PC: Polarization controller. PPG: Programmable pattern generator. AMZI: Asymmetric Mach-Zehnder interferometer.

At the output of the re-circulating loop, a simple asymmetric Mach-Zehnder interferometer (AMZI) with a differential time delay of one bit period to demodulate the NRZ-DPSK follows a polarization controller. The AMZI is quite sensitive to the signal state-of-polarization (SOP) which is adjusted prior to the AMZI demodulator. A slight difference in the path length between the two polarizations is manifested as a frequency offset and leads to non-optimal demodulation of the signal [2]. A single p-i-n directly detects the demodulated signal generated from constructive or destructive interference depending on the relative phase of two consecutive bits.

Experimental results

In the first experiment, the penalty induced by packet propagation through one loop consisting of two SOA-based switching nodes is measured for both NRZ-DPSK and NRZ-OOK modulated payloads. For NRZ-OOK modulation, the AMZI was bypassed and an intensity modulator was used instead of a phase modulator. The bit error rate (BER) was taken on a received alternative bit sequence to factor out power penalty due to pattern dependence distortion; only the effect of ASE noise in the amplification process of the nodes is observed. The power penalties following one loop for each of the two modulation formats are shown in figure 2. The average input signal power of the payload channel for both cases is –13 dBm. A power penalty of approximately 0.15 dB at a BER of 10^{-9} was measured for NRZ-OOK modulation and a corresponding power penalty of 0.08 dB was measured in the case of NRZ-DPSK modulation.

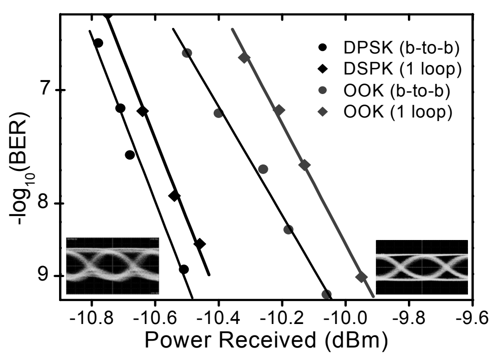

Fig. 2: Penalty induced by one re-circulating loop for NRZ-OOK and NRZ-DPSK modulation format

In the re-circulating loop configuration, packets with NRZ-DPSK modulated payload data experience a lower power penalty than the NRZ-OOK encoded packets after one loop propagation. This improvement can be attributed to the constant power seen by the SOA in DPSK modulation case. Moreover, ASE noise accumulates in the '0' bits power level of the NRZ-OOK payload, which lowers the extinction ratio of the received signal.

The second experiment is performed to investigate the propagation of packets through a larger cascade of SOA-based switching nodes when the payload data is phase modulated. Phase noise is generated by SOAs in addition to ASE intensity noise through carrier density fluctuations [5]. In the demodulation process of the NRZ-DPSK payload, the AZMI is adjusted to achieve constructive and destructive interference for consecutive bits and is thus highly phase sensitive. In the presence of phase noise, the position of the rise and fall edges of the received optical signal will fluctuate in time. These fluctuations can be measured as the increase in the rise time jitter of the electrical received signal (inset of fig. 3). An increase of approximately 10% in the standard deviation of the jitter following each loop propagation was measured for the NRZ-OOK case and a 30% increase was measured for the NRZ-DPSK modulated data. The accumulating timing jitter for phase modulated packets can clearly become the limiting performance factor as packets propagate through multiple SOA-based switching nodes in large-scale OPS networks.

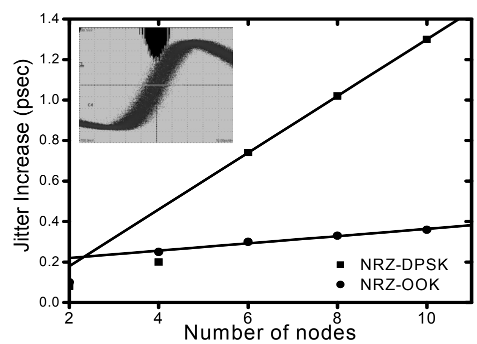

Fig. 3: Increase in time jitter as a function of the number of cascaded SOA-based switching nodes.

Conclusions

The propagation of optical packets through a cascade of SOA based switch elements is investigated with NRZ-DPSK modulated payload data. It is shown that NRZ-DPSK encoded packets incur a lower power penalty compared with conventional NRZ-OOK modulated packets after a cascade of two switching nodes. For larger numbers of cascaded nodes however, phase noise generated by the SOAs leads to increased timing jitter in the demodulated DPSK data packets. This significant increase in timing jitter at the rise and fall edges of the received signal becomes the limiting factor on the scalability of OPS networks with phase modulated data payloads.

References

1. O. Liboiron-Ladouceur et al., WM3, LEOS 2004.
2. P.S. Cho et al., Photonics. Techn. Lett., 15, 2003.
3. H. Kim et al., Photonics. Techn. Lett., 15, 2003.
4. B.A. Small et al., Photonics Techn. Lett., 17, 2005.
5. K. Kikuchi et al., Journal Quant. Elec., 27, 1991.