# 10-Gb/s RZ-DPSK Transmitter Using a Saturated SOA as a Power Booster and Limiting Amplifier

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***Abstract*—The performance of a semiconductor optical amplifier (SOA) in the deep saturation regime is studied for single-channel return-to-zero (RZ) and nonreturn-to-zero differential phase-shift keying (DPSK) and ON–OFF keying signals at 10 Gb/s. It is found that saturated SOAs can be used as power boosters and limiting amplifiers for RZ-DPSK transmitters with almost no compromise of performance.**

***Index Terms*—Differential phase-shift keying (DPSK), modulation format, semiconductor optical amplifier (SOA).**

## I. INTRODUCTION

THE semiconductor optical amplifier (SOA) is of great interest not only for fast all-optical signal processing but also for its potential as a low-cost substitute to replace erbium-doped fiber amplifiers (EDFAs) as power boosters in transmitters [1], [2], in-line amplifiers, and receiver preamplifiers. However, despite the many advantages of SOAs such as large wavelength range, small form factor, and low power consumption, the use of SOAs in commercial optical transmission systems is very limited. Besides issues of high noise figure, limited output power, and polarization sensitivity, the fast gain dynamics which leads to waveform distortion and cross-gain modulation (XGM) poses serious challenges to employing SOAs in the saturation regime. Many techniques, including gain clamping [3], polarimetric filtering [4], and optical equalization [5], have been used to reduce this effect. However, most of these techniques have added complexity to the devices.

Novel modulation schemes have also been considered to improve the performance of saturated SOAs. One example is wavelength-shift keying to maintain a constant input power [6]. Recently, significant reduction of XGM in the SOA was successfully demonstrated for wavelength-division-multiplexed transmission with return-to-zero differential phase-shift keying (RZ-DPSK) [7], and RZ-DPSK was also used to effectively mitigate the pattern-induced degradation in all-optical time-division multiplexing demultiplexers based on SOAs [8]. In this letter, we investigate the performance of a highly saturated SOA for a 10-Gb/s single-channel RZ-DPSK signal and compare with other modulation formats. Similar to a saturated EDFA, the SOA here serves not only as an efficient power booster but also as a limiting amplifier to regulate the channel power. To our knowledge, the performance of the SOA in such a deep saturation regime has not been reported before. We find that highly saturated SOAs are well suited for RZ-DPSK transmitters. This is because, unlike ON–OFF keying (OOK) modulation and nonreturn-to-zero (NRZ) DPSK modulation, RZ-DPSK has a data-independent intensity profile and completely removes the pattern effect.

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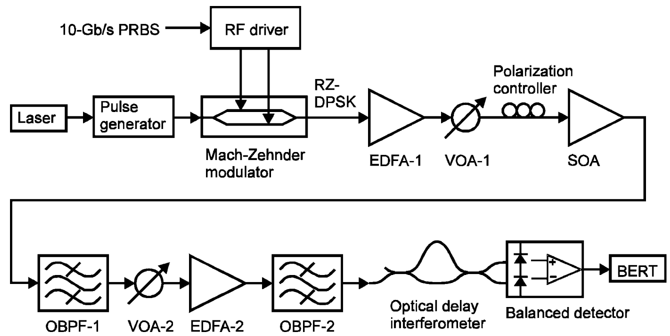


Fig. 1. Schematic diagram of the experimental setup for RZ-DPSK. For NRZ-DPSK and NRZ-OOK, the pulse generator is bypassed. For OOK, the driver voltage and bias of the Mach–Zehnder modulator need to be adjusted and the optical delay interferometer and balanced detector are replaced with a regular detector.

## II. EXPERIMENT AND RESULTS

Fig. 1 shows the experimental setup that was used to test the performance of the SOA as a power booster for RZ-DPSK transmitter. The setup was also used to study NRZ-DPSK, RZ-OOK, and NRZ-OOK signals with modifications in the transmitter and the receiver. The laser was a tunable laser operating at 1550 nm. The pulse generator produced chirp-free optical pulses with a repetition rate of 10 GHz and a duty cycle of 50%. The Mach–Zehnder modulator was driven with a 10-Gb/s pseudorandom bit sequence of length $2^{31}-1$. EDFA-1 was used to amplify the signal power to reach the deep saturation region of the SOA. For each modulation format studied in this experiment, the optical signal-to-noise ratio (OSNR) at the SOA input was maintained above 35 dB (defined with 0.1-nm bandwidth for the noise power); therefore, the effect of the amplified spontaneous emission (ASE) noise produced by EDFA-1 can be neglected. The signal power at the SOA input was varied between $-28$ and 4 dBm by adjusting the variable optical attenuator VOA-1 in Fig. 1. The VOAs had built-in optical power meters to monitor the power levels. The SOA was a commercial polarization-maintaining booster amplifier (JDSU Model CQF871) with a gain recovery

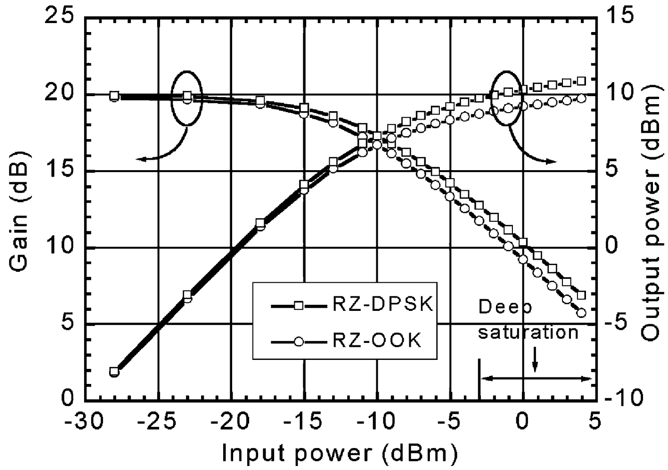


Fig. 2. Gain saturation characteristics of the SOA. The squares and circles were measured for RZ-DPSK and RZ-OOK, respectively.

time of approximately 200 ps. The driving current was set to 200 mA. A polarization controller was used to align the polarization of the optical signal entering the SOA. VOA-2 and EDFA-2 were used to measure the receiver sensitivity of the SOA output signals. The optical bandpass filters OBPF-1 and OBP-2 had 3-dB bandwidths of 0.6 and 0.8 nm, respectively. An optical delay interferometer with a 100-ps delay and a balanced detector were used to detect the DPSK signals. The electrical bandwidths of the DPSK balanced detector and the OOK regular detector were 12 and 11 GHz , respectively.

Fig. 2 shows the SOA gain saturation characteristics measured with RZ-DPSK and RZ-OOK. The gain of the SOA is 20 dB in the small-signal regime and drops by ~3 dB when the input power increases to $-10$ dBm. In the input power range from $-3$ to 4 dBm, the variation of SOA output power is only ~1 dB due to deep saturation. It is this deep saturation regime that is of interest here, because in this regime the SOA could be used as an optical power limiter to automatically suppress the power fluctuations at the input. The slightly higher output powers of RZ-DPSK than RZ-OOK in this regime can be attributed to the fact that with the same average input power, RZ-OOK has a higher peak power than RZ-DPSK, and hence, saturates more easily.

Fig. 3 shows the eye diagrams of the received signals of RZ-DPSK, NRZ-DPSK, RZ-OOK, and NRZ-OOK with four different power levels at the input of the SOA. To measure these eye diagrams, the power level at the input of EDFA-2 was set relatively high ($-20$ dBm) to avoid OSNR degradation. RZ-OOK and NRZ-OOK show strong pattern effect with high input powers. Note that the large "noise" on the zero rail of OOK is due to the fact that the "zeros" experience much higher gain than the "ones." In comparison, RZ-DPSK was found to have a distinct advantage in the deep saturation regime, showing almost no distortion in the received eye diagram. Some distortion was observed with NRZ-DPSK in the deep saturation regime because the intensity profile was pattern dependent. Note that the NRZ-DPSK signal is generated with a Mach–Zehnder modulator and the signal amplitude goes through zero when the phase is switched by $\pi$.

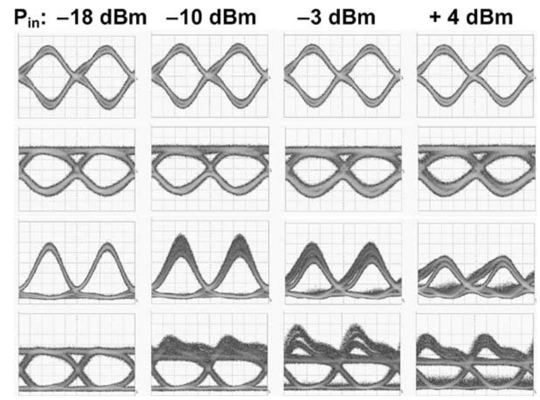


Fig. 3. Eye diagrams of the received (and demodulated) signals of different modulation formats. From top to bottom, the four rows of eye diagrams are for RZ-DPSK, NRZ-DPSK, RZ-OOK, and NRZ-OOK, respectively. The SOA input powers ($P_{\text{in}}$) are indicated above.

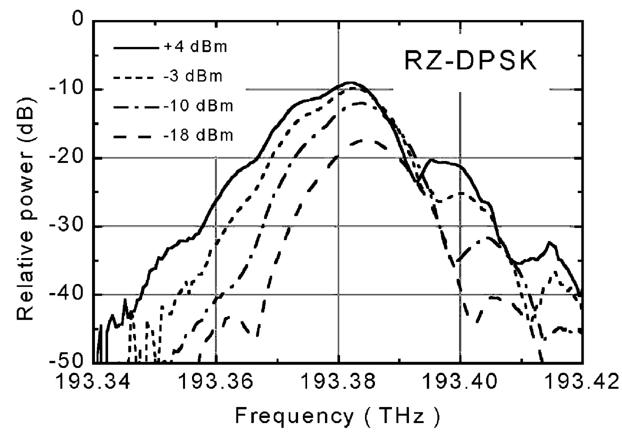


Fig. 4. Optical power spectra of RZ-DPSK at the output of the SOA with different SOA input power levels.

It may have come as a surprise that the RZ shape in the RZ-DPSK diagrams is unchanged even with deep saturation. This can be explained by the SOA gain recovery time (200 ps) that is longer than one bit period, and consequently, the gain does not change rapidly across one bit slot even though the SOA is highly saturated. The saturation does introduce some chirp to the pulses, as indicated by the broadening of the optical power spectra in Fig. 4. However, such chirp does not have a significant effect on the receiver sensitivity of the RZ-DPSK signal. It does not affect the optimal phase adjustment of the delay interferometer, either. This is because such chirp (or phase variation) is identical from pulse to pulse, and for DPSK, it is the phase difference between two adjacent pulses that matters.

Fig. 5 shows the measured receiver sensitivities (input power to EDFA-2) corresponding to the 16 conditions for the eye diagrams in Fig. 3. The bit-error rate (BER) was $10^{-9}$. The phase control of the DPSK delay interferometer was fixed for different SOA input power levels. The receiver sensitivity of RZ-DPSK appears to be independent of the degree of saturation of the SOA, whereas all other formats suffer significant degradation when the SOA is strongly saturated. This is consistent with the eye diagram observations and confirms that saturated SOAs can be used in RZ-DPSK transmitters with negligible degradation in performance.

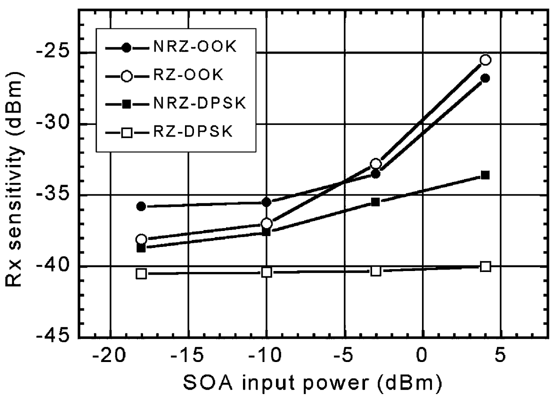


Fig. 5. Measured receiver sensitivities of different modulation formats at various SOA input power levels. The corresponding BER was $10^{-9}$.

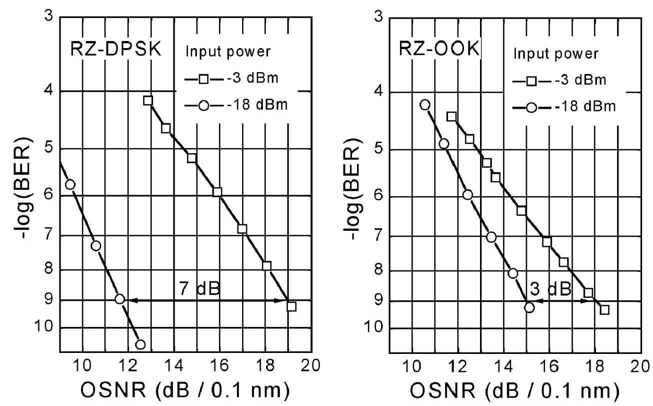


Fig. 6. Measured BER against the SOA input OSNR for RZ-DPSK (left) and RZ-OOK (right) with two SOA input powers −18 and −3 dBm.

The chirp induced by the saturated SOA in the RZ-DPSK signal is expected to affect the dispersion tolerance of the signal to some extent. However, we found in our experiment that the impact was relatively small. Details of the study will be published elsewhere.

## III. Discussion

Although saturated SOAs perform very well for RZ-DPSK transmitters as power boosters and limiting amplifiers, they may not be suitable as in-line amplifiers because the input optical signals to these amplifiers usually have much lower OSNR than the signals at the transmitters. When the SOA is highly saturated, the intensity noise at the input of the SOA can be transferred to phase noise at the output. This effect was mentioned in [7] but not studied in detail.

In our experiment, we measured this effect by loading the ASE noise at the input of the SOA. We moved VOA-2 and EDFA-2 in Fig. 1 to the place immediately after the Mach–Zehnder modulator and moved OBPF-1 to the place right in front of EDFA-1. The OSNR was controlled with VOA-2 and measured at the output of EDFA-2 with an optical spectral analyzer. We also added another OBPF (with a 3-dB bandwidth of ∼1 nm) after EDFA-1 to prevent the out-of-band ASE noise from entering the SOA, otherwise the SOA would not provide enough gain for the true signal because of the ASE background. To avoid receiver thermal noise effects, the SOA output signal was further amplified with an EDFA (if needed) to ∼6 dBm before entering the delay interferometer (the estimated power received by each photodiode of the balanced detector was ∼0 dBm).

Fig. 6 shows the measured BER as a function of the SOA input OSNR for both RZ-DPSK and RZ-OOK. In the linear regime with low input power (−18 dBm), the required OSNR for RZ-DPSK to achieve a BER of $10^{-9}$ is approximately 3-dB lower than that of RZ-OOK. However, as the SOA input power increased to a higher level of −3 dBm, a very large penalty (∼7 dB) was observed for RZ-DPSK due to the extra phase noise produced by the SOA. In comparison, the corresponding penalty for RZ-OOK was much smaller (∼3 dB). If SOAs are used for in-line amplification in RZ-DPSK transmission, caution should be made to keep the SOAs in the small-signal regime to avoid saturation-induced phase noise, which would inevitably sacrifice the output power.

## IV. Conclusion

We have experimentally demonstrated the feasibility of employing highly saturated SOAs in RZ-DPSK transmitters as power boosters and limiting amplifiers. We also identified the saturation-induced phase noise as a limitation for using saturated SOAs as in-line amplifiers.

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