Reduction of Nonlinear Distortion From a Semiconductor Optical Amplifier Using an Optical Equalizer

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***Abstract*—We demonstrate significant improvement in the measured bit-error rates of 40-Gb/s signals distorted after passing through a saturated semiconductor optical amplifier (SOA) by using a simple colorless general optical equalizer. The optical equalizer reduces the overshoots arising from the nonlinear gain dynamics of the SOA and improves the opening of the eye. We study the improvement in receiver sensitivity by using the equalizer while varying the optical power and wavelength at the input of the SOA.**

***Index Terms*—Nonlinear distortion, optical equalizers, semiconductor optical amplifiers (SOAs).**

I. INTRODUCTION

OPTICAL equalizers have been proposed and demonstrated recently for the mitigation of intersymbol interference (ISI) [1] arising from impairments such as chromatic dispersion and polarization-mode dispersion. However, these previously studied impairments are linear in nature. In this letter, we investigate the improvement in the bit-error rates (BERs) by using the equalizer to mitigate the intrachannel distortions arising from ultrafast nonlinear gain dynamics of a semiconductor optical amplifier (SOA). It is well known that the nonlinearities in an SOA, primarily interband transitions (where the recovery time of the carriers is of the order of a nanosecond) can cause a significant power penalty to amplitude-shift-keyed signals passing through the SOA, with the penalty worsening the closer the SOA is to saturation [5]. We investigate the interesting property that a linear device, the optical equalizer, can significantly reduce this penalty. We explain the degradation in the BER by looking at the eye diagrams and at some specific patterns and show how the optical equalizer helps in mitigating the distortions on the signal. The use of such optical equalizers could enhance the performance of SOAs in a variety of applications: as power boosters on the transmitter side [2], in-line amplifiers [3], and preamplifiers on the receiver side [4]. Because the response of the equalizer is periodic on a 50-GHz grid, a single device can equalize many wavelength-division-multiplexed channels with intrachannel SOA-induced distortion simultaneously. Note that we are not considering the case of *inter*channel SOA-induced crosstalk in this letter.

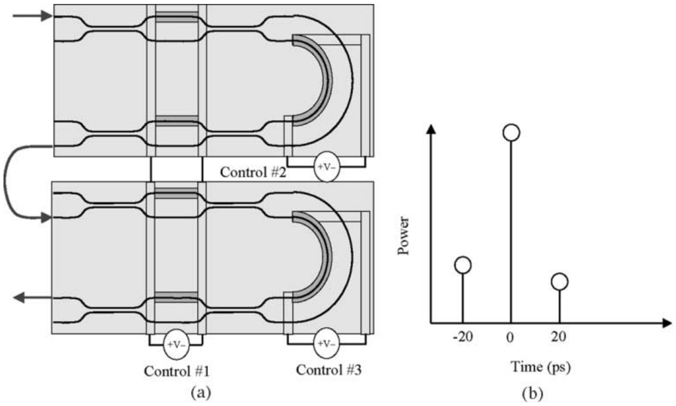

Fig. 1. (a) Schematic of the optical equalizer and (b) representative time response of the optical equalizer.

II. OPTICAL EQUALIZER

The optical equalizer consists of two single-mode-connected Mach–Zehnder interferometers (MZIs) each with a relative optical path delay of 20 ps, as shown in Fig. 1(a) [1]. At each instant of time, the optical equalizer takes a controllable portion of the energy present and adds it at ±20 ps with a controllable phase, as shown in Fig. 1(b). Each MZI is on a separate silica waveguide chip, but both are mounted on a single thermoelectric cooler. The waveguides have a 0.8% index contrast and are on a silicon substrate. The fiber-to-fiber insertion loss for both MZIs in series is 4.2 dB, and the polarization-dependent loss is less than 0.5 dB.

Each MZI has two tunable couplers and a thermooptic phase shifter in one arm. Each tunable coupler consists of a small MZI with a thermooptic phase shifter in one arm and a quarter-wavelength length increase in the other arm. Both couplers in each MZI are adjusted to be at the same value for minimum insertion loss, so the coupler drives within an MZI are wired together. The coupler drives control the impulse response satellite amplitudes, and the phase shifters control the satellite phases.

III. MEASUREMENT SETUP

The SOA used in this study was a commercially available SOA with a fiber-to-fiber small-signal gain of 18 dB at 1550 nm at a bias current of 200 mA. Nonreturn-to-zero (NRZ) data at 40 Gb/s was modulated on light from an external cavity laser at 193.4 THz (1550.12 nm) using a chirp-free $LiNbO_3$ modulator and launched into the SOA. The input power to the SOA

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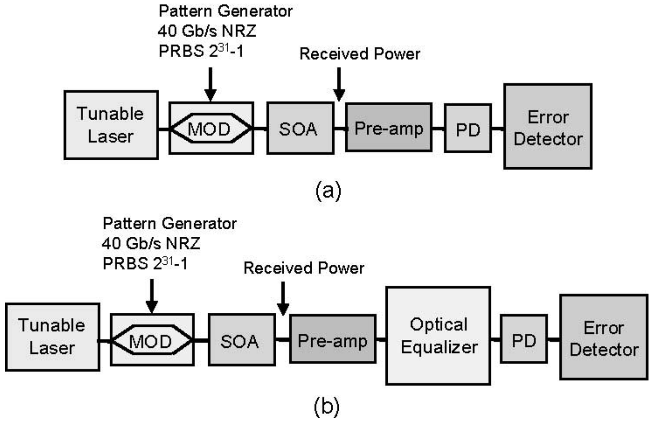


Fig. 2. Measurement setup (a) without and (b) with the optical equalizer. PD: photodetector. In both cases, the received optical power is measured at the input to the preamplified receiver.

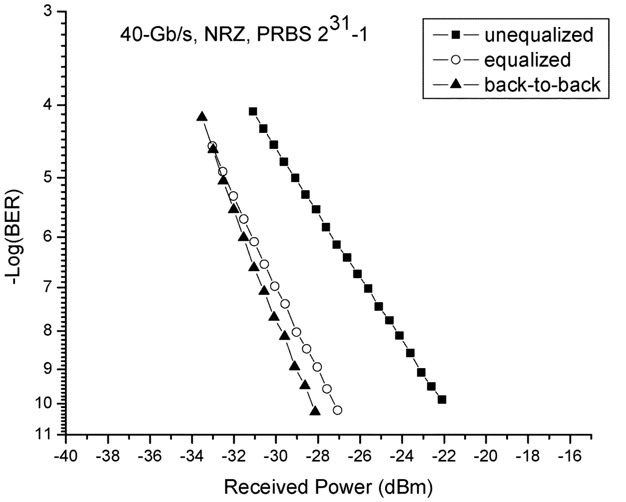


Fig. 3. Measured BER after transmission through the SOA both without and with the equalizer used after the SOA. Input power to the SOA is −3 dBm.

was varied from −3 to −12 dBm to study the degradation of the BER resulting from the nonlinearity of the SOA. The BER versus received power is measured after the SOA without any equalization, as in the setup shown in Fig. 2(a). The BER versus received power is also measured after equalization, as in the setup shown in Fig. 2(b). In both cases, the received power is measured at the input to the preamplified receiver. The equalizer is put after the preamplifier, as shown in Fig. 2(b). This is done primarily for convenience, allowing us to optimize the equalizer settings without affecting the received optical power. However, for applications where the SOA is used for in-line amplification, the equalizer would be put directly after the SOA, where it may work even more effectively due to the higher optical signal-to-noise ratio at the SOA output.

IV. RESULTS AND DISCUSSIONS

Fig. 3 shows the measured BER after transmission through the SOA both with and without equalization. The input power to the SOA is −3 dBm. The SOA penalizes the sensitivity in the BER at the receiver. The equalizer substantially reduces this penalty. For a BER of 10^{-9}, an improvement of nearly 5 dB is observed in the receiver sensitivity for a pseudorandom bit stream of length $2^{31} - 1$.

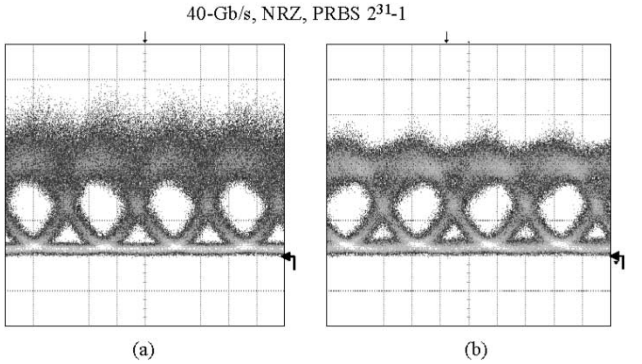
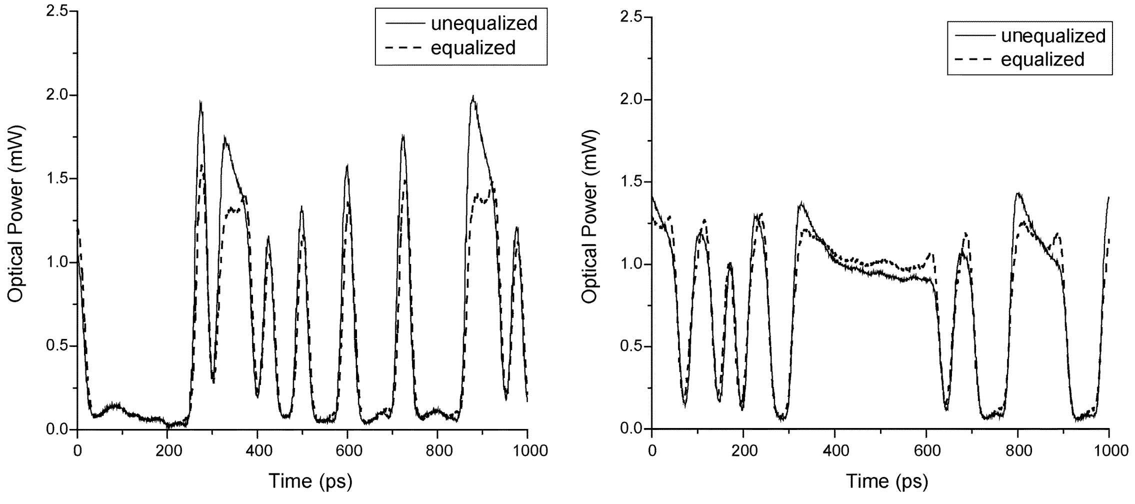


Fig. 4. Eye diagrams of the received signal at 40 Gb/s (a) without equalization and (b) with equalization. Input power to the SOA is −3 dBm. The arrow points to the reference level when no light is present.

Fig. 4(a) and (b) shows the eye diagrams of the received signal both with and without equalization using a fast photodetector with a bandwidth of 40 GHz. The input power to the SOA is −3dBm. It is seen that the equalizer reduces the overshoots on the "1" bits on the rising edges, i.e., the transitions from "0" to "1." In addition, the equalizer also increases the slope on the falling edges of the eye, i.e., it sharpens the transitions from "1" to "0." This can be more clearly seen in Fig. 5(a) and (b), which shows the effect of the equalizer on some distorted patterns after the SOA using the fast photodetector. Fig. 5(a) shows the impact of the nonlinear gain dynamics on isolated "1" bits. Large overshoots can occur on the "1" bits from the gain which builds up in the SOA over several "0" bits that occur together. In Fig. 5(b), one can see that the carrier recombination time in the SOA at this condition is ∼200 ps by observing the recovery of the overshoots over several "1" bits that occur together. The increase in the slope on the rising and the falling edges is a consequence of the fact that the equalizer takes some energy from a "1" bit and puts it in the "0" bit adjacent to it. The equalizer mitigates the overshoots in the "1" bits and can flatten a long string of "1" bits in the NRZ stream. The overshoots from the SOA lead to an increase in the average power of the data stream, resulting in a power penalty. However, this effect is small compared to the fact that the overshoots on the rising edges can cause a significant enhancement of ISI in the receiver [5]. [5] showed how an ideal integrate-and-dump receiver would be relatively immune to SOA-induced distortions, whereas, the usual filtered receiver exhibits significant eye closure from the overshoots. Although we did not study transmission performance, it is expected that such overshoots are detrimental to the transmission of NRZ data as well, as the nonlinearity of the transmission medium can add further distortions to the patterns.

Fig. 6 shows the receiver sensitivity both with and without equalization for a BER of 10^{-9} at different input powers to the SOA. The equalizer settings were readjusted for each power lever. The penalty between the unequalized and equalized data streams is reduced as the input power to the SOA is lowered. This is expected since the SOA operates in a linear regime at low input optical powers, further from gain saturation, and the distortion induced due to the nonlinearity is reduced. The equalizer actually makes the performance better than the back-to-back case at lower SOA input powers.

Fig. 7 shows the receiver sensitivity for a BER of 10^{-9}, both with and without equalization for different International



(a)

(b)

Fig. 5. Measured patterns with and without equalization. (a) Impact of the nonlinear gain dynamics on isolated “1” bits can be seen and (b) carrier recombination time ~200 ps can be seen by observing the recovery of the overshoots over several “1” bits that occur together. Input power to the SOA is −3 dBm in all cases.

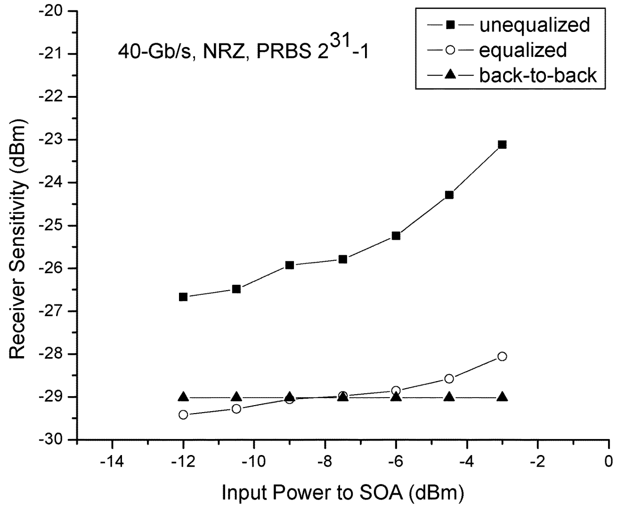


Fig. 6. Receiver sensitivity for a BER of 10^{-9} versus input power to the SOA measured with and without equalization at 1550.12 nm.

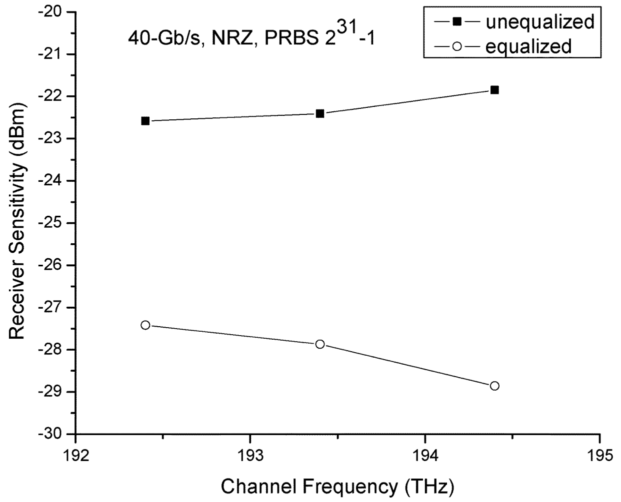


Fig. 7. Receiver sensitivity for a BER of 10^{-9} at different ITU grid frequencies (192.4, 193.4, and 194.4 THz) measured with and without equalization for an input power of −3 dBm to the SOA. The control settings were not changed on the equalizer during this measurement.

Telecommunications Union (ITU) channel frequencies. The input power to the SOA is −3 dBm in all cases. The control settings on the equalizer were optimized at 193.4 THz (1550.12 nm) and were not changed during this measurement. This shows that one equalizer can function effectively for different channel frequencies on the ITU grid if the input power to the SOA remains unchanged.

V. CONCLUSION

We have shown that an optical equalizer can be used to significantly reduce the power penalty in the measured BER for NRZ data at 40 Gb/s due to the fast nonlinear gain saturation of an SOA. Significant improvements in the receiver sensitivity for a BER of 10^{-9} are observed with the use of the equalizer after the SOA. The equalizer can function effectively at different wavelengths for the same control settings if the input power to the SOA remains unchanged. Though the measurements were performed at 40 Gb/s, such equalizers can be used at different bit rates. Optical equalizers could significantly enhance the performance of SOAs in transmission networks.

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