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Semiconductor Optical Amplifier Pattern Effect Suppression Using a Birefringent Fiber Loop

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Abstract—The capability of a birefringent fiber loop to suppress the pattern effect in a semiconductor optical amplifier is experimentally demonstrated. The results verify that compared to direct signal amplification this scheme achieves reduced amplitude modulation, enhanced eye diagram extinction ratio, pulse reshaping, tolerance to long string of spaces, low power penalty, and extended input power dynamic range.

Index Terms—Birefringent fiber loop (BFL), optical comb filter, pattern effect, semiconductor optical amplifier (SOA).

I. INTRODUCTION

DUE to their multifunctional capability, low power consumption, compactness, broad gain bandwidth, and ability to be integrated with affordable cost, semiconductor optical amplifiers (SOAs) are showing great promise for use in evolving optical communication systems and networks [1]. In their classical role, they are deployed as gain units for post-, in-line, and preamplification purposes, where ideally the profile of the output signal should be an amplified replica of the original one. In practice, however, the combination of the power and duration of the input data signal can cause heavy saturation of the SOA, whose recovery time is finite. When a random data stream is launched into the SOA, the variations of its binary content result in an amplified output that is not uniform leading to performance degradation [1]. One solution that has been proposed to allow for direct amplification of digitally coded pulses consists of the fact that the strong gain saturation responsible for the problem also incurs self-phase modulation (SPM) and subsequently spectral broadening of the data carrier to longer wavelengths (red shift) [2], [3]. This means that a good way for reducing the pattern-dependent distortion is to suppress these undesirable spectral components by means of optical filtering [2], [3]. In this letter, we propose to apply this spectral elimination technique by using a birefringent fiber loop (BFL). The technique is used to compensate for the pattern effect on a 10-Gb/s return-to-zero (RZ) pseudorandom binary sequence (PRBS) amplified by an SOA. So far this configuration has been exploited for optical pulse generation [4], repetition rate multiplication [5], development of multi-wavelength laser sources [6], [7], differential phase shift-keying demodulation [8], and all-optical clock recovery [9], but to our

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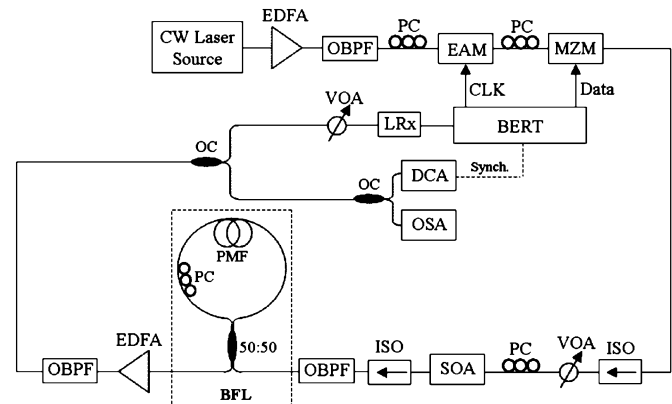


Fig. 1. Experimental setup.

knowledge, not for pattern effect cancellation. Because of its simplicity, potential robustness to environmental perturbations, polarization independence, good channel isolation, and flexibly tunable transmission characteristics, it is an attractive scheme for combating the deleterious consequences of the pattern effect.

II. EXPERIMENTAL SETUP AND DATA FOR BFL OPERATION

The experimental setup is illustrated in Fig. 1. A 1550-nm tunable laser source is amplified by an erbium-doped fiber amplifier (EDFA) and subsequently modulated by an electroabsorption modulator (EAM) and a LiNbO₃ Mach-Zehnder modulator (MZM) driven by the internally synchronized clock (CLK) and data output of a bit-error-rate tester (BERT), respectively, to obtain a 10-Gb/s RZ 2⁷ - 1 PRBS having full-width at half-maximum (FWHM) pulsewidth of 27 ps. This signal is amplified by an SOA, which is a 1-mm-long, bulk InGaAsP-InP device (Kamelian, model OPA-20-N-C-FA) with a fiber-to-fiber small-signal gain of 23 dB that drops by 3 dB when the input power is -7 dBm, a gain polarization dependence of 0.5 dB, and a gain recovery time of about 75 ps at 1550 nm, when biased at 270 mA and thermally stabilized at 20 °C. The SOA input optical power is controlled by a variable optical attenuator (VOA). The SOA output is fed to the BFL, which comprises of a polarization maintaining 3-dB coupler, a polarization controller (PC), and a segment of polarization-maintaining fiber (PMF) resulting in a total PMF length $L = 8.5$ m with birefringence $B = 3.1 \times 10^{-4}$ at 1550 nm. It is then equally split into two counterpropagating beams and by setting the PC to generate a rotation of 90° to light coming from both directions their orthogonal polarization states to which they are decomposed are aligned and travel along different axes of the PMF. Due to their relative propagation delay, [7] $(BL)/c$, where c is the speed of light in vacuum, equals 8.8 ps; these

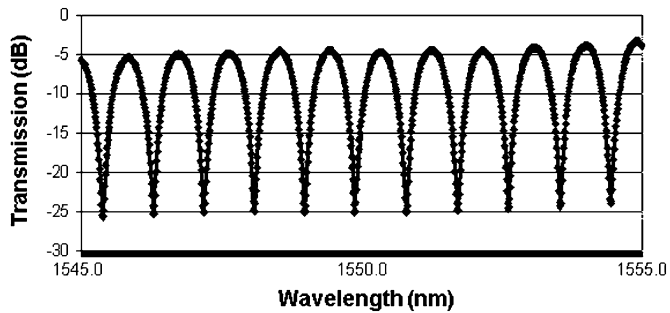


Fig. 2. Measured spectral response of BFL.

components acquire a phase difference directly proportional to the birefringence and hence wavelength-dependent. Thus, when they recombine at the coupler they interfere either constructively or destructively, which results in the spectral response shown in Fig. 2. This was obtained by injecting a *C*-band amplified spontaneous emission source and monitoring the output with an optical spectrum analyzer (OSA) with a resolution bandwidth of 0.06 nm. It exhibits a periodic comb-like profile with the null points being situated midway between adjacent peaks whose wavelength spacing or free spectral range (FSR) is approximately 0.91 nm. This value is well matched with that predicted from [7] $FSR = \lambda^2/(BL)$ for the operating wavelength $\lambda = 1550$ nm and the employed PMF parameter values. Furthermore, the peak-to-notch contrast ratio is over 19.9 dB in the entire tuning range and reaches 20.4 dB in the region around 1550 nm where additionally the flatness variation of the notches is 0.2 dB. These transfer function characteristics can be further improved by using a 3-dB coupler with a splitting ratio as symmetric as possible and, more importantly, an electrically instead of manually actuated PC [8] so that, according to its principle of operation, the BFL exercises its filtering action on the amplified data in the most efficient way. As the insertion loss was measured to be ~ 8.5 dB, an EDFA was placed at the BFL exit to enhance the transmitted signal before going into the diagnostic equipment. Finally, PCs, optical bandpass filters (OBPFs), and isolators (ISOs) are used where necessary to ensure best coupling of light, block the out-of-band noise, and prevent back reflections, respectively.

III. EXPERIMENTAL RESULTS

Fig. 3 shows the experimental results obtained in the time domain using a digital communications analyzer (DCA) with 65-GHz optical bandwidth. For visual purposes a representative 20-bit-long segment of 11000110100101110111 inside the 10-Gb/s RZ $2^7 - 1$ PRBS has been used (Fig. 3(a) left column). The logical “1”s have an amplitude modulation (AM) defined in [3] of 0.35 dB with a symmetrical pulse shape (Fig. 3(a) middle column), whereas the corresponding eye diagram (Fig. 3(a) right column) has an extinction ratio (ER) of 20 dB. The average input power to the SOA is set at -2 dBm, which is capable of bringing it into deep saturation. The difference between the repetition period of the injected pulses and their FWHM is smaller than the SOA gain recovery time. This leads to a pronounced pattern effect after the SOA and to the poor performance observed in Fig. 3(b). In effect, the amplified marks suffer from intense peak fluctuations, which results in an AM of 1.71 dB. Also their individual pulse shape becomes

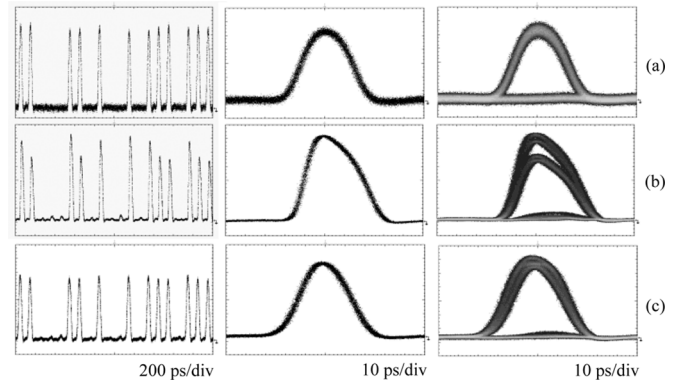


Fig. 3. Temporal waveforms at (a) SOA input, (b) SOA output, and (c) after BFL. Left column: PRBS sample of 20 bits. Middle column: Individual pulse shape. Right column: Eye diagram.

asymmetric and the eye diagram is deformed to the presence of subenvelopes having an ER of 10 dB. Nevertheless, with the use of the BFL the impact of the pattern effect can be alleviated and the signal’s quality be restored, as can be seen in Fig. 3(c). Indeed the peak excursions of the “1”s are balanced and the AM is dropped to 0.29 dB. Furthermore, the “1”s separated by the longest string of “0”s, i.e., six, in the PRBS, are flattened from 1.59 dB down to 0.24 dB. Moreover, the pulse profile is reshaped, resembling that before the SOA, and the eye diagram becomes clear and open having an ER of 18 dB. These improvements are feasible owing to the characteristics of the BFL transfer function, which enable it to be exploited as a spectral eliminating element to cancel the distortion of the SOA output signal. The first step towards this goal is to adjust the FSR by choosing the appropriate PMF length through a trial and error procedure that depends on the AM extent, the efficiency with which it must be reduced, and the particular operational characteristics of the setup. In practice, this process must be adapted to account for chromatic dispersion and the accompanying broadening of the pulses, which makes the SOA response to them slower and hence aggravates the pattern effect. Moreover, it can be facilitated by applying a programmable polarization differential delay line [6] to achieve the same effect as that of changing the PMF length. This allows the BFL to be tuned in a fast, precise, flexible, and continuous manner and also, owing to its periodic response, handle different wavelengths, for example with dense wavelength-division-multiplexing (DWDM) ITU grid spacing. Next, by rotating the plates of the intraloop PC, it is possible to move the maxima wavelengths and optimize the contrast ratio without affecting the channel spacing [6], [7]. If thus, the transmission peak wavelength position is negatively detuned relative to the optical carrier [3], the spectral components of the amplified pulses that have been spread towards the longer sideband due to SPM, as it can be seen in Fig. 4(b) versus before the SOA in Fig. 4(a), are pushed to fall around the sharp notches. Since the rejection of the latter is fairly uniform and over 20 dB at 1550 nm, they are attenuated in direct analogy to the degree of their shift. In this manner, the BFL can suppress the red-shifted spectral components, as depicted in Fig. 4(c), and smooth the peak amplitude variations. Its effectiveness was further verified through bit-error-rate (BER) measurements performed with a $2^{31} - 1$ PRBS and by varying with a VOA the power going into a lightwave receiver (LRx) before the

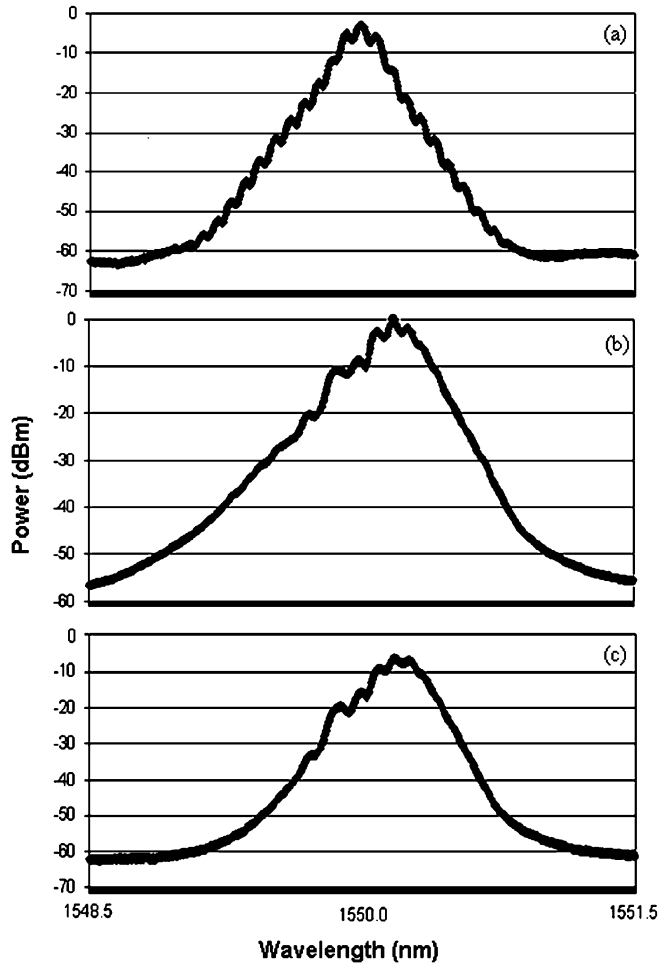


Fig. 4. Optical spectra at (a) SOA input, (b) SOA output, and (c) after BFL.

BERT. The results plotted in Fig. 5 show that at $\text{BER} = 10^{-9}$, a power penalty of 2 dB with respect to the back-to-back case is incurred after the SOA due to the pattern effect. However, with the use of the BFL, the BER curve is moved close to that before the SOA and the power penalty is reduced to only 0.7 dB, which according to the SOA characterization data and the level of its driving signal is achieved for an input power dynamic range that has been extended by 5 dB. This residual power penalty is not fundamental to this technique since it is possible to be reduced further by a more optimal implementation using better as well as more appropriate constructing components and the exact margin for this improvement can be found only through simulation analysis. Also it must be noted that the cause of the error floor indication at a BER of 10^{-10} is not due to the BFL itself but to the SOA saturation at a relatively low input power, which degrades the optical signal-to-noise ratio at the receiver end. On the other hand and after accounting for the BFL insertion loss, the data sequence receives a peak amplification of about 2.28 dB less than compared to the SOA only because due to the filtering action a portion of information contained in the suppressed red-shifted spectral components is inevitably lost. Furthermore, the BFL may be affected by changes in temperature, which can cause a slow drift of the peak transmission wavelengths [8]. Thus, a thermoelectric cooler is required for temperature stabilization [8] but it is also

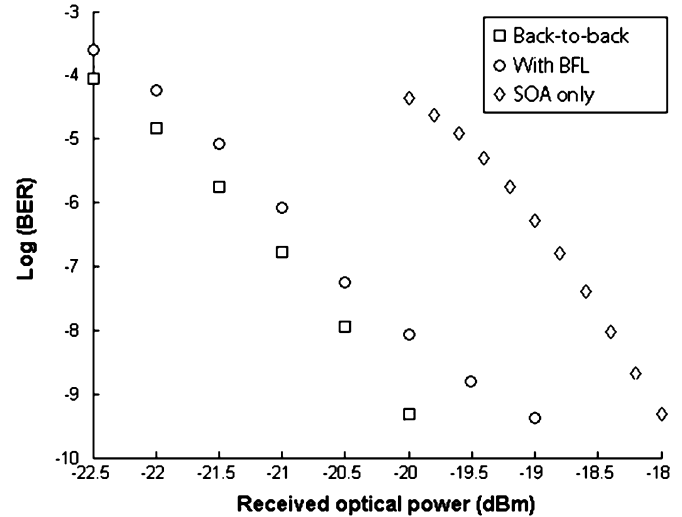


Fig. 5. Measured BER against received optical power (PRBS $2^{31} - 1$).

possible to make the BFL insensitive to this condition in a more compact manner by using a PM photonic crystal fiber [8]. Finally, the scheme is bit-rate transparent [8] and its specified inserted delay can serve as the starting point for extending its operation to higher rates.

IV. CONCLUSION

The feasibility of employing a BFL as a comb filter to compensate for the pattern-induced degradation in an SOA driven by 10-Gb/s RZ data has been experimentally demonstrated. This suggests that it is an efficient method for greatly reducing SOA pattern effects and their negative effects on system performance.

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