80-Gb/s OTDM System Analysis of a Vertical Microcavity-Based Saturable Absorber for the Enhancement of Pulse Pedestal Suppression

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***Abstract*—In future high-speed optical time-division-multiplexed (OTDM) systems, an important factor that needs to be considered for optical pulse generation schemes is the impact of pulse pedestals on the overall system performance. The results presented in this letter are two-fold; first, the impact due to the height of pulse pedestals in an 80-Gb/s OTDM system are established. Second, a solution is provided to overcome these high pedestal levels through the use of a vertical microcavity saturable absorber, which can significantly reduce the pulse pedestal level and give enhanced system performance.**

***Index Terms*—Optical pulse shaping, optical time-division multiplexing (OTDM), pulse generation, saturable absorber (SA).**

I. Introduction

FUTURE high-speed communications systems are likely to employ optical time-division multiplexing (OTDM) due to simpler system configuration at increasing bit rates, relating to more cost-efficient systems [1]. One of the key components in such high-capacity OTDM systems is the picosecond optical pulse source, which should exhibit excellent temporal and spectral purity. One particular parameter of the optical pulse source which is important in OTDM systems is the extinction ratio (ER) [or temporal pedestal suppression ratio (TPSR)]. It has been shown in previous work that a 40-Gb/s OTDM system requires a TPSR of 30 dB [2] to prevent power penalties due to coherent interactions between the individual OTDM channels. The actual ER or TPSR required to prevent degradation of system performance will depend on the number of return-to-zero channels multiplexed together to obtain the overall OTDM signal, which in turn will be determined by the pulsewidth and repetition rate of the optical pulse source employed at the transmitter.

Considering the main pulse generation techniques available, namely, mode-locking, gain-switching, and use of electroabsorption modulators (EAMs), it is extremely difficult to achieve a TPSR in excess of 30 dB. In order to overcome this limitation of these sources, a number of techniques have been developed to improve the TPSR of optical pulses. These techniques include the use of an EAM [3], a nonlinear amplifying loop mirror (NALM) [4], or self-phase modulation in a semiconductor optical amplifier (SOA) in conjunction with shifted filtering [5]. The EAM can provide high TPSR values; however, it is an active and expensive component which may significantly increase the cost of the pulse source. The NALM is fiber-based, which makes it bulky, and suffers from instability problems, and the SOA scheme exhibits limited TPSR improvement ($\sim$7 dB). The limitation of these three ER enhancement techniques may be overcome by the use of a vertical microcavity-based saturable absorber (SA). This is a passive device that can be monolithically integrated with semiconductor laser sources. The SA is very efficient for ER enhancement and "space" noise attenuation. Furthermore, the efficiency of SA coupled with fiber or semiconductor techniques allowing "mark" fluctuations reduction has been demonstrated at 10 and 40 Gb/s [6], [7]. In [8], the authors have shown the enhancement of the ER of a 160-GHz optical pulse train by employing the microcavity-based SA. This improvement in ER is vital for OTDM systems. In this letter, we simulate and experimentally characterize the power penalties introduced by optical pulses with varying levels of TPSR in an 80-Gb/s OTDM system. We then present the TPSR improvement obtained using the SA ($>$15 dB) for different input TPSR levels, and subsequently demonstrate the improvement in system performance (3.3 dB), which is obtained as a result of the increased TPSR, in an 80-Gb/s OTDM system using bit-error-rate (BER) measurements.

II. Experimental Setup

A. Characterization of the Pulses Before and After the SA

The experimental setup used to introduce the pulse pedestals with varying levels, and subsequently reduce the pedestal height using the SA, is shown in Fig. 1. An actively mode-locked semiconductor laser that generates 2.1-ps pulses with a time-bandwidth-product (TBP) of 0.35. These pulses were split by a 3-dB coupler; one arm (for pedestal generation) was delayed by around 8 ps with respect to the main pulse, and attenuated via a variable optical attenuator (VOA). The pedestal delay of 8 ps was chosen as this delay corresponded to the point where the penalty due to the introduced pedestal level becomes significant. As the delay is increased, the penalty correspondingly increases for the same TPSR as the power

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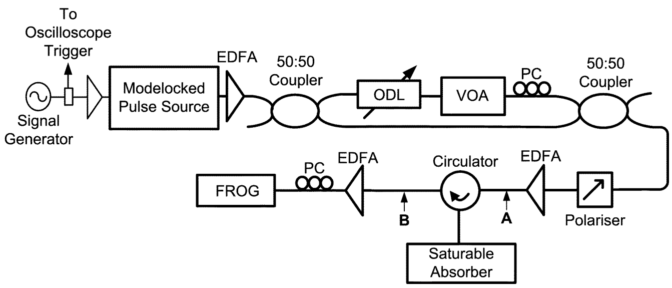

Fig. 1. Experimental setup used to introduce pedestals and SA to the pulse source.

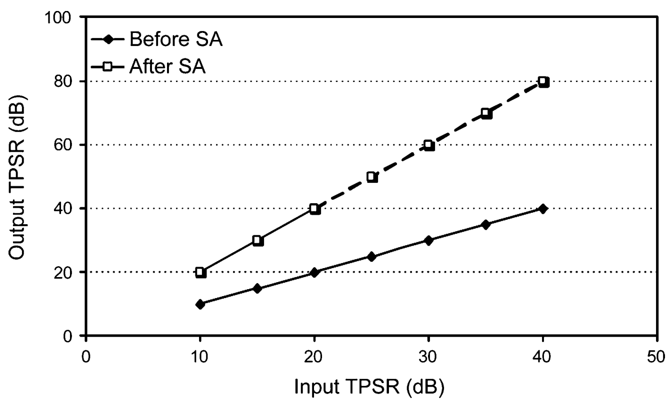

Fig. 2. Graph of input and output TPSR to the SA measured at Point A and B, respectively, by the FROG. The TPSR values are extrapolated at values greater than 40 dB (represented by a dashed line) as the FROG is limited by the noise floor of the system.

overlap between the next pulse and pedestal increases until it reaches the bit slot duration (12.5 ps). The increase in pulse and pedestal overlap leads to a larger generation of interferometric noise. The main pulse and pedestal were then recombined via a second coupler. A polarization controller and a polarizer were used to match the polarization of the main pulse with the pedestal so that an accurate measurement of the TPSR could be taken by using the technique of frequency-resolved optical gating (FROG) [9].

An SA was then introduced via a circulator. The SA used is a seven-quantum-well structure (InGaAs–InAlAs) in a resonant microcavity with a dielectric mirror (2x[TiO_2–SiO_2]) as the front mirror, and a broadband high-reflectivity metallic-based mirror (Ag+SiO_2) as the back mirror [10]. A heavy-ion-irradiation shortens the absorption recovery time down to 1.5 ps, which is short enough for the SAs to be employed in 160-Gb/s OTDM systems.

By varying the VOA, the height of the pedestal can be set to different values, and then measured using the FROG before (Point A) and after the SA (Point B), as shown in Fig. 2. The TPSR is improved by around 10 dB (to 20 dB) when its input value to the SA is 10 dB. As the input pedestal level decreases, the improvement in TPSR at the SA output increases due to the nonlinear transmission curve of the SA (Fig. 2). The FROG accurately measured TPSR values up to 40 dB for pulses with high signal-to-noise ratio (SNR). Thus, to demonstrate the nonlinear response of the SA, TPSR values greater than 40 dB were extrapolated and are represented by the dashed line in the figure.

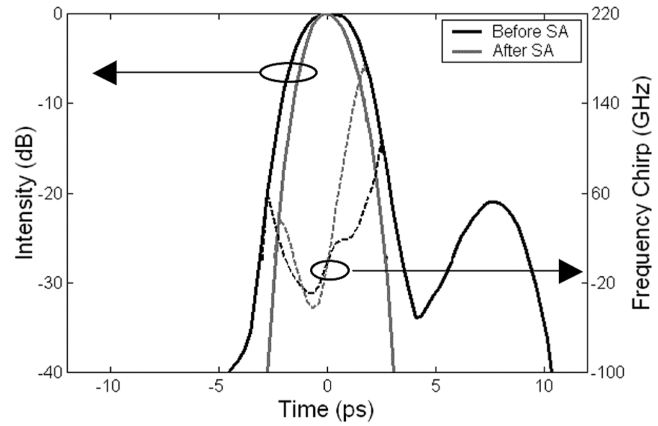

Fig. 3. Temporal and chirp profile of the pulse with 20-dB pedestal before and after the SA.

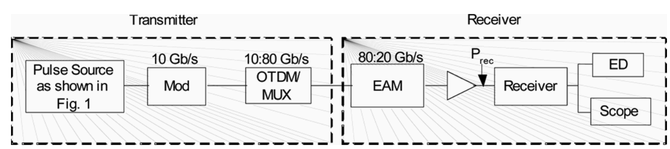

Fig. 4. An 80-Gb/s OTDM test-bed to characterize the performance of picosecond pulses with varying TPSR before and after the SA.

Fig. 3 displays the intensity and chirp profile of the pulse before and after the SA, with an input TPSR of 20 dB. This figure demonstrates that the SA reduces the pedestal level to greater than 40 dB, and also has very little effect on the frequency chirp of the pulse, an additional benefit of the device. Furthermore, it can be seen that the nonlinear response of the SA slightly compresses the pulse to 1.8 ps, with a corresponding TBP to 0.33.

B. 80-Gb/s OTDM System Performance Experiment and Simulation

To test the back-to-back performance of the optical pulse source with and without the SA, and with varying TPSR levels, in an 80-Gb/s OTDM system, we used the experimental test-bed presented in Fig. 4. The pulses as generated in Fig. 1 are modulated using a 10-Gb/s modulator and passively multiplexed up to 80 Gb/s. BER measurements were taken by initially demultiplexing down to 20 Gb/s using an EAM, and then by electrically demultiplexing from 20 to 10 Gb/s.

We initially examined the effect of pulses with varying input TPSR values and measured the power penalties introduced, which are displayed in Fig. 5. This plot clearly displays the effect of TPSR on the performance of an 80-Gb/s OTDM system. TPSR values of 15 and 20 dB exhibit power penalties of 3 and 1 dB, respectively, at a BER $1e^{-9}$, compared to a TPSR of 30 dB (which results in negligible system degradation).

To verify the experimental results, we simulated the above system using Virtual Photonics Incorporated (VPI) software, and measured the power penalties as a function of varying TPSR values. In the simulation, a sech squared pulse source was used. The pedestal was introduced in a similar manner to the experimental setup as were the demultiplexing stages. As can be seen

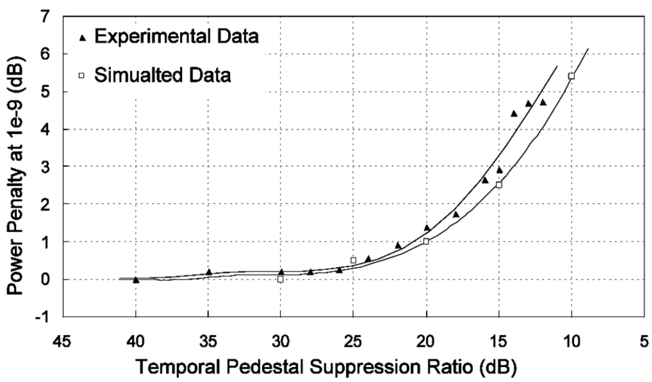

Fig. 5. Experimental and simulated results displaying induced power penalties by varying pulse TPSR values in an 80-Gb/s OTDM system.

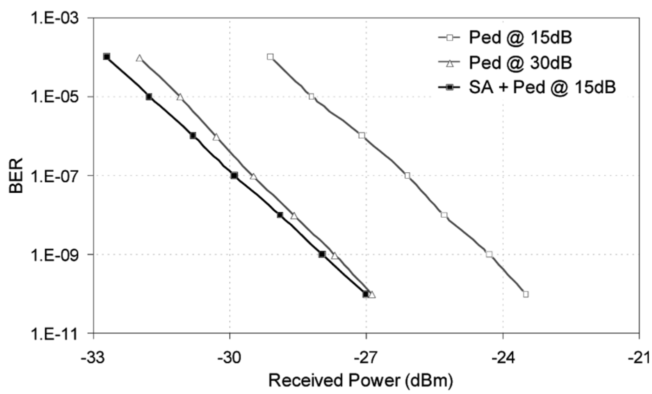

Fig. 6. BER versus received power for 1) pulse source with 15-dB TPSR, 2) this pulse source after the SA, showing TPSR improvement to 30 dB, and 3) a mode-locked pulse source.

from Fig. 5, the simulation results (grey line) match the experimental results reasonably well, confirming that pulse sources designed for high-speed OTDM systems require a high TPSR.

We then investigated how the introduction of the SA to increase the TPSR of the pulse source improved the performance of the 80-Gb/s OTDM system. For this work, we used a pulse source with an initial TPSR of 15 dB (which is improved to 30 dB after the SA). Fig. 6 displays the BER versus received power when using 1) the pulse source with TPSR of 15 dB, 2) this pulse source followed by SA, which improves TPSR to 30 dB, and 3) a mode-locked pulse source with TPSR set to 30 dB. Our results show how the SA improves the system performance by 3.3 dB. It is also important to note that the introduction of the SA improves the performance by 0.3 dB greater than what would be expected due to the increase in TPSR alone. This additional improvement is due to the narrowing of the main pulse which improves the overall sensitivity of the OTDM system.

III. Conclusion

We have presented the importance for pulse sources to have a high TPSR when used in high-speed OTDM systems. A 3-dB improvement in performance was obtained when the TPSR values were improved from 15 to 30 dB. For pulse sources that display poor pedestal suppression, the detrimental effects of poor TPSR values can be overcome by the introduction of a vertical microcavity-based SA, which has the potential to be integrated with a semiconductor-based pulse source. We demonstrated that with an initial TPSR of 15 dB, the SA can increase this level to 30 dB, and improve the overall system performance by 3.3 dB when these pulses are used in an 80-Gb/s OTDM system.

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