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System-Performance Analysis of Optimized Gain-Switched Pulse Source Employed in 40- and 80-Gb/s OTDM Systems

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***Abstract*—The development of ultrashort optical pulse sources, exhibiting excellent temporal and spectral profiles, will play a crucial role in the performance of future optical time division multiplexed (OTDM) systems. In this paper, we demonstrate the difference in performance in 40- and 80-Gb/s OTDM systems between optical pulse sources based on a gain-switched laser whose pulses are compressed by a nonlinearly and linearly chirped fiber Bragg grating. The results achieved show that nonlinear chirp in the wings of the pulse leads to temporal pedestals formed on either side of the pulse when using the linearly chirped grating, whereas with the nonlinearly chirped grating, pedestals are essentially eliminated. In an OTDM system, these pedestals cause coherent interaction between neighboring channels, resulting in intensity fluctuations that lead to a power penalty of 1.5 dB (40 Gb/s) and 3.5 dB (80 Gb/s) in comparison to the case where the nonlinearly chirped grating is used. Simulations carried out with the aid of Virtual Photonics Inc. verify the results achieved.**

***Index Terms*—Grating, optical communication, optical pulse generation, pulse compression.**

I. INTRODUCTION

ENHANCING the capacity of long-haul and metro-network photonic communication systems, without increasing the cost (by avoiding high-speed electronics), can be achieved by the use of optical time division multiplexing (OTDM) or hybrid wavelength division multiplexing/OTDM [1]. A key requirement in such high-capacity systems is a stable, compact, and low-cost source of picosecond optical pulses. However, the increased line rate and the reduced channel spacing place stringent requirements, such as a high repetition rate, narrow pulsewidth, low jitter, high side mode suppression ratio (SMSR), high temporal pedestal suppression ratio (TPSR), and small chirp, on the pulse source. For instance, a return-to-zero (RZ) optical transmitter designed to achieve satisfactory performance in a $\geq$ 40-Gb/s photonic communication system needs to be capable of generating pulses with repetition rates of at least 10 GHz [2], pulsewidths of $<$ 8 ps (duty cycle of $\sim$1/3) [3], SMSR of at least 30 dB [4], TPSR $>$ 30 dB [5], and a negligible chirp (transform-limited) [6]. Therefore, the design of an optical transmitter has to be optimized, in that it has to be capable of generating pulses with adequate temporal and spectral purity, for acceptable operation in high-speed lightwave communication systems.

The main types of picosecond optical pulse sources that have been used in recent OTDM-system demonstrations are mode-locked fiber ring lasers [7], tunable mode-locked semiconductor lasers (TMLL) [8], pulse shaping using external modulators [9], and gain-switched semiconductor laser diodes [10]. Relative to the rest of the aforementioned techniques, gain switching of a DFB laser is readily recognized to be an uncomplicated, robust, and reliable technique [11], [12]. Furthermore, the inherent simplicity brought about by being a direct modulation technique results in the gain-switched pulse source being cost-efficient, which proves to be of great practical significance with regard to market adoption. While the advantages in employing this method are numerous, it suffers from a few drawbacks such as a degraded SMSR and a relatively large temporal jitter exhibited by the generated pulses. However, these shortcomings could be overcome by externally injecting into a gain-switched laser [13], [14]. Yet, another problem associated with this technique is the spectral purity portrayed by the generated pulses. The large signal modulation applied directly to the laser diode causes a time varying carrier density in the active region of the device, which in turn causes a variation in the output wavelength from the laser during the emission of the optical pulse. This results in a frequency chirp across the pulse, which degrades the performance of these pulses when used in practical optical communication systems [15]. It has been reported how this chirp can be used to compress the pulses using dispersion compensating fiber [16] or linearly chirped fiber Bragg gratings (LC FBGs) [17] to obtain near transform-limited pulses. However, due to the chirp being nonlinear in the wings of the pulse, this compression typically results in pedestal formation on either side of the pulse [18]. By using more elaborate arrangements involving nonlinear amplifying loop mirrors [19], [20], external modulators [21], spectral windowing [22], or semiconductor optical amplifiers in conjunction with shifted

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filtering [23] after the linearly compressed pulse, it is possible to greatly reduce the pedestal. The above-listed methods, to optimize the TPSR of the pulse source, leads to the source becoming more complex, bulky, and expensive. In previous work, we reported a simple, yet systematic approach to design a pulse source exhibiting excellent temporal and spectral purity with the aid of a nonlinearly chirped FBG (NC FBG) placed after an externally injected gain-switched laser diode [24]. This approach of using a tailor-made grating has an additional bonus in that it has the potential to be integrated with the gain-switched laser diode [25].

In this paper, we advance on our previous work by characterizing the performances of 40- and 80-Gb/s OTDM systems employing two gain-switched pulse sources: one compressed with an NC FBG that achieves an excellent TPSR (> 40 dB) and the other with an LC FBG that achieves a poor TPSR ($\sim$20 dB). The degraded performance, in the case of the latter (power penalty of 1.5 dB in 40-Gb/s system and 3.5 dB in 80-Gb/s system), even though both sources generate pulses that are transform-limited, exhibit widths $< 30\%$ of the 80-Gb/s bit slot and portray SMSRs of > 30 dB, is attributed to the presence of pulse pedestals which cause coherent interactions between individual OTDM channels, thereby resulting in severe intensity fluctuations [19]. We define the TPSR (P_1/P_2) as the difference in power between the peak of the pulse (P_1) and the peak of the next highest pedestal (P_2). A commercially available TMLL pulse source was also used to benchmark the experimental system-performance characterization.

This paper is organized as follows. Section II describes the experimental realization of the two different pulse sources used in this paper. Section III focuses on the experimental performance characterization of 40- and 80-Gb/s OTDM test bed by employing the externally injected gain-switched pulse source followed by the NC FBG/LC FBG. In Section IV, we concentrate on the verification of the obtained experimental results by looking at simulations that were performed using a photonic design automation tool called Virtual Photonics Inc. (VPI). Finally, Section V presents a brief discussion on the achieved results.

II. PULSE GENERATION AND COMPRESSION

The essential element in our proposed pulse source is an externally injected gain-switched DFB laser diode (EI GSLD). With the aid of the frequency-resolved optical gating (FROG) technique [26], [27], an accurate characterization of the intensity and chirp profile across the optical pulses generated from the EI GSLD is carried out. Fig. 1 shows that the generated pulses have a duration [full-width-half-maximum (FWHM)] of about 10.5 ps and that the frequency chirp (dashed line in the figure) becomes nonlinear in the wings, due to the gain-switching mechanism. The measured spectral width of the signal is about 140 GHz, yielding a time bandwidth product (TBP) of 1.5. We subsequently use the measured nonlinear chirp across the pulse to design and fabricate an NC FBG. This process involves the initial creation of the group-delay response for the FBG based on the group-delay data derived from the FROG measurements of the externally injected gain-switched pulse.

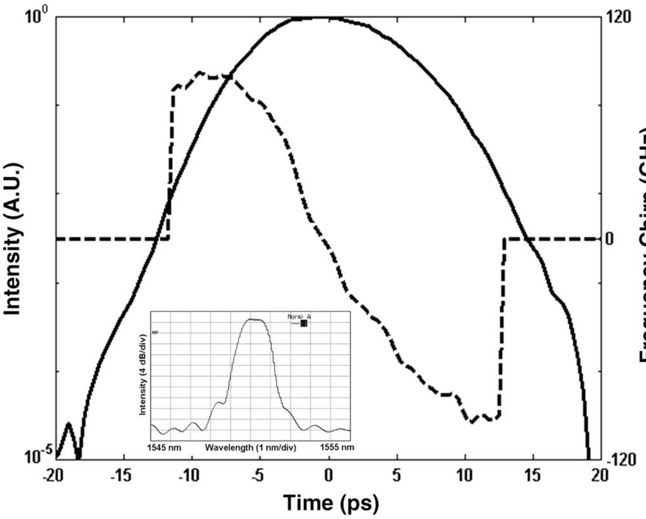

Fig. 1. Intensity (solid line) and chirp (dashed line) of optical pulses from the externally injected gain-switched laser. Inset: Corresponding pulse spectrum.

The FBG target group-delay response is simply selected as the inverse to the pulse group-delay response, which should result in the pulse having a constant group-delay profile over the pulse bandwidth after it has been reflected from the FBG. In addition to a constant group-delay profile across the pulse bandwidth, for an optimized pulse source, we also require the pulse to exhibit a Gaussian spectrum. Generally, gain-switched spectra tend to be more rectangular than Gaussian in shape. The reflection profile of the NC FBG is constructed as the difference between the spectral amplitude of the gain-switched output and a Gaussian profile, which should result in the compressed pulse portraying a Gaussian spectrum. Fig. 2 shows the reflection and group-delay profiles of the fabricated NC FBG. Since we aim to alter the group-delay profile only over the spectral range of the pulse, the group delay outside this spectral range rapidly falls off to zero.

Once the FBG target spectrum and group-delay profile are obtained, it is relatively straightforward to calculate an FBG design that can be implemented into the optical fiber by using an inverse scattering algorithm [28]–[30]. We also fabricated an LC FBG which had a chirp profile that was opposite to a linear approximation of the chirp across the gain-switched pulse. By employing the tailor-made NC FBG/LC FBG after the externally injected gain-switched laser (as shown schematically in Fig. 3), we achieve direct compression of the gain-switched pulses.

The pulse source consists of a commercially available high-speed 1550-nm DFB (1) laser that is gain-switched at a repetition rate of 10 GHz. External injection, from a second DFB (2) laser operating in continuous wave (CW) mode, is carried out to improve the SMSR and the temporal jitter of the gain-switched laser via a circulator. The temporal jitter is measured (with the aid of an oscilloscope characterized by a temporal resolution of 1 ps) to be < 1 ps, and the SMSR is improved from 15 to 30 dB. The generated pulses are then spectrally shaped and temporally compressed by the specially fabricated gratings via another circulator.

Fig. 4 shows the compressed pulses after the NC FBG (bold black line) and the LC FBG (faint gray line). The measured

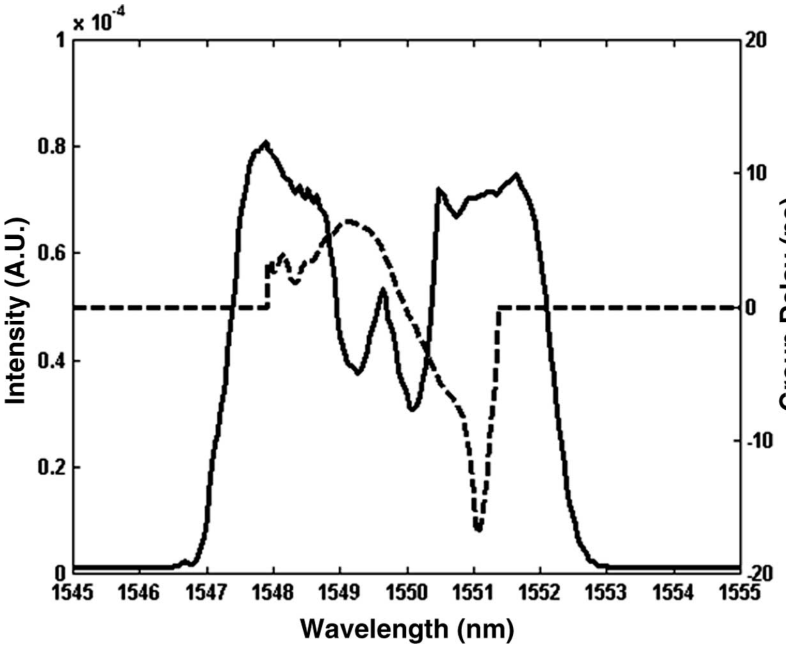

Fig. 2. Reflection (solid line) and group-delay (dashed line) profiles of the NC FBG.

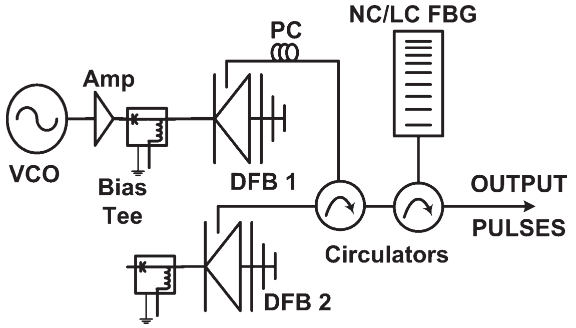

Fig. 3. Experimental setup for pulse generation.

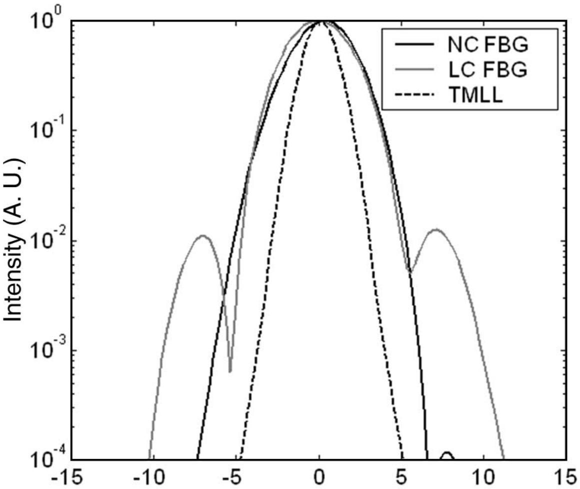

Fig. 4. Intensity of externally injected gain-switched pulses after (bold) NC FBG, (faint) LC FBG, and (dotted line) TMLL.

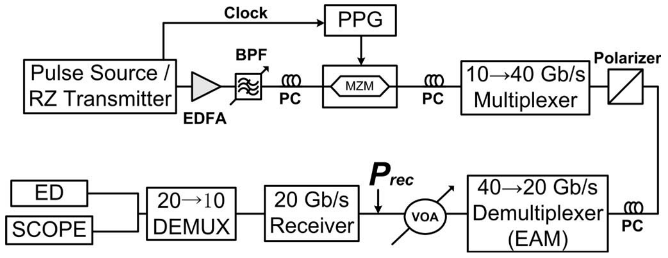

Fig. 5. The 40-Gb/s OTDM test bed.

pulse widths (FWHM), which are characterized using FROG, are 3.5 and 3.6 ps respectively, while their associated TBPs are 0.45 and 0.47, respectively. The same figure also shows the pulses generated by the TMLL (commercial pulse source) that exhibited widths of about 2.1 ps (FWHM). The associated TBP of this pulse source is about 0.35.

As can be seen, the pulses compressed by the NC FBG exhibits a TPSR > 40 dB, while that compressed by the LC FBG portray a TPSR of about 20 dB. The excellent TPSR, in the case of the NC FBG, is achieved by a combination of the fiber grating having the following: 1) a nonlinear group-delay profile that is the inverse of that across the gain-switched pulse directly from the laser and 2) a specially adapted reflection profile (transfer characteristic). However, when the LC FBG is used, the uncompensated nonlinear chirp directly from the gain-switched laser results in significant pedestals on the leading and trailing edges of the pulse.

III. PERFORMANCE CHARACTERIZATION OF 40- AND 80-Gb/s OTDM SYSTEMS

The experimental set-up employed to realize the 40-Gb/s OTDM test bed is shown in Fig. 5. Three different pulse sources were employed alternatively as the RZ transmitter block (as in Fig. 4) in the 40-Gb/s OTDM test bed. In the first instance of system-performance characterization, the EI GSLD employing an NC FBG was used, after which, it was replaced by the LC FBG. They both gave out near transform-limited

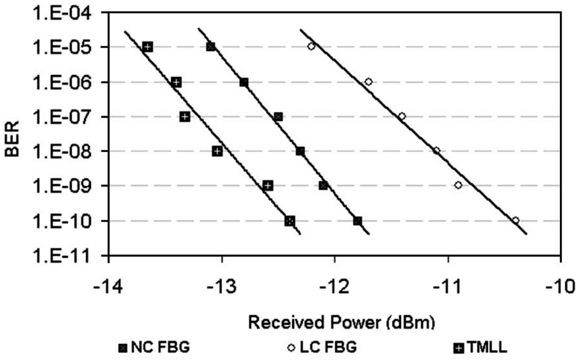

Fig. 6. BER versus received optical power for TMLL, NC FBG, and LC FBG employed in a 40-Gb/s OTDM test bed.

pulses with widths of 3.5 and 3.6 ps, depending on whether the NC FBG or LC FBG, respectively, is used for the compression. Once both versions of compression of the externally injected gain-switched pulses were characterized, the TMLL pulse source was used to replace them, mainly to act as a reference.

A pseudorandom binary sequence of length $2^7 - 1$ from a pulse pattern generator was used to modulate the 10-GHz pulse train with the aid of a Mach–Zehnder modulator. The resultant 10-Gb/s RZ optical signal is then passed into a passive fiber-based interleaver and multiplexed up to 40 Gb/s. The same state of polarization is maintained on all the tributaries by initially ensuring that the PC is optimized to maximize the amplitude of the 10-Gb/s signal passing through the multiplexer and the polarizer (all stages of the mux shut). Subsequently, as each stage of multiplexing is opened, the PC (available at each stage on the mux) is optimized to ensure copolarization by equalizing the power in all the tributaries.

In order to test the performance of the two sources when employed in the 40-Gb/s OTDM test bed, the signal is initially demultiplexed (stage 1) down to 20 Gb/s with the aid of an electroabsorption modulator (EAM) that is driven with a 20-GHz sinewave to yield an 8 ps switching window. The 20-Gb/s signal after the EAM is then optically preamplified prior to being received with the aid of a photodetector, after which, it is demultiplexed (stage 2) back down to 10 Gb/s using an electrical demultiplexer. Bit-error-rate (BER) measurements are performed for a range of received optical powers (P_{rec} measured before the 20-Gb/s preamplified receiver stage). Each of the four tributaries can be selected using electrical delay lines (EDLs) in the setup. The total variation in performance, between these channels, was observed to be about 0.4 dB. Signal analysis is carried out with the aid of an error detector (ED) and a high-speed oscilloscope.

Fig. 6 displays the BER versus received power plots for one of the demultiplexed channels. It can be observed that to achieve a BER of 10^{-9}, a power penalty of 1.5 dB is incurred when the pulse source with the LC FBG is employed, compared with the case where the NC FBG is used. This degraded performance is due to the presence of the pedestals about 20 dB below the peak of the pulse. These pedestals deteriorate the extinction between the adjacent timeslots of the temporally multiplexed signal, thereby leading to intensity fluctuations that cause the BER degradation.

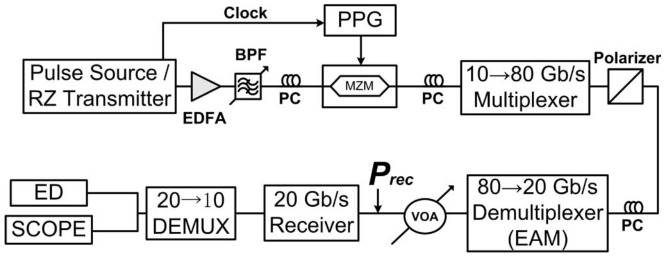

Fig. 7. The 80-Gb/s OTDM test bed.

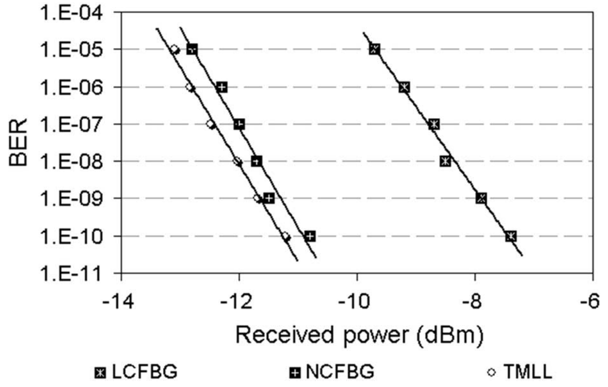

Fig. 8. BER versus received optical power for TMLL, NC FBG, and LC FBG employed in an 80-Gb/s OTDM test bed.

A difference of 0.5 dB was noticed in the case of the commercial TMLL and the optimized gain-switched pulse source employing an NC FBG. This variation could be attributed to the difference in pulsewidth, with the narrower pulsewidth leading to a slightly better sensitivity at the receiver.

The experimental setup used to realize the 80-Gb/s OTDM test bed is also shown in Fig. 7. Essentially, the setup and the sequence of performance characterization were the same as in the 40-Gb/s OTDM-system characterization. However, in this case, the modulated data at a base rate of 10 Gb/s were passively multiplexed up to an aggregate bit rate of 80 Gb/s. The demultiplexing was carried out in the same manner as described with the EAM used to demultiplex from 80 to 20 Gb/s prior to employing an electrical demultiplexer to go from 20 to the base rate of 10 Gb/s. Using the EDLs attached to the demux drive, each of the eight tributaries is selected (one at a time), and signal analysis is carried out with the aid of an ED and a high-speed oscilloscope.

Fig. 8 displays the BER versus received power curves for one of the demultiplexed channels. It can be observed that to achieve a BER of 10^{-9}, a power penalty of 3.5 dB is incurred in the case of the LC FBG when compared to the NC FBG. The degraded performance is once again due to the presence of the pedestals (poor TPSR), which results in ISI between the adjacent channels. Yet again, a difference of 0.5 dB was noticed in the case of the commercial TMLL and the optimized gain-switched pulse source employing an NC FBG. The slight difference in pulsewidth, as explained earlier, causes the marginal difference in the sensitivity at the receiver (shorter pulse exhibits better sensitivity).

The detected eye diagrams (shown at 20 Gb/s after the EAM demux stage) corresponding to received powers of −30.8

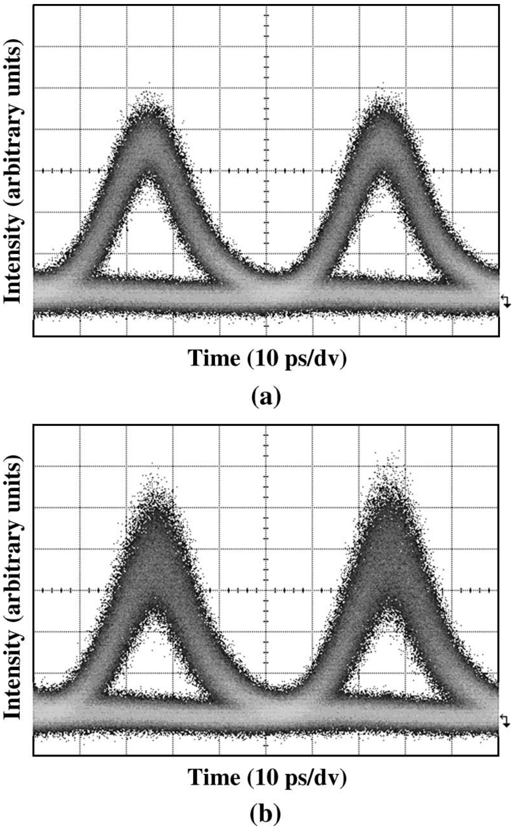

Fig. 9. Received eye diagrams at 20 Gb/s corresponding to the EI GSLD pulses compressed with the (a) NC FBG and (b) LC FBG when employed in an 80-Gb/s OTDM test bed.

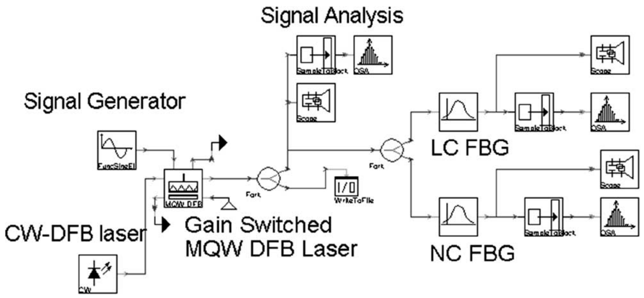

Fig. 10. Schematic of VPI simulation model used to realize EI GSLD pulse source.

and −29.7 dBm for the NC FBG and LC FBG are shown in Fig. 9(a) and (b), respectively. The increased level of noise (reflecting poorer performance) can be noticed in the case of the LC FBG [Fig. 9(b)], even though the received power level is higher than in the case where the NC FBG was used.

IV. SIMULATIONS

The system penalties introduced by a poor TPSR were characterized by carrying out simulations using VPI.

A. Pulse Generation and Compression

A schematic of the simulation model used to realize the externally injected gain-switched pulse source in conjunction with the NC FBG and LC FBG is shown in Fig. 10. A multiquantum-well DFB laser is gain-switched and subjected to external injection from another DFB laser that is operated in CW mode. The resulting pulses from the EI GSLD show widths (FWHM) of 9.8 ps, an SMSR of about 35 dB, and a TBP of about 1.27. The intensity and group-delay parameters are then extracted from the generated pulses and written to an output file.

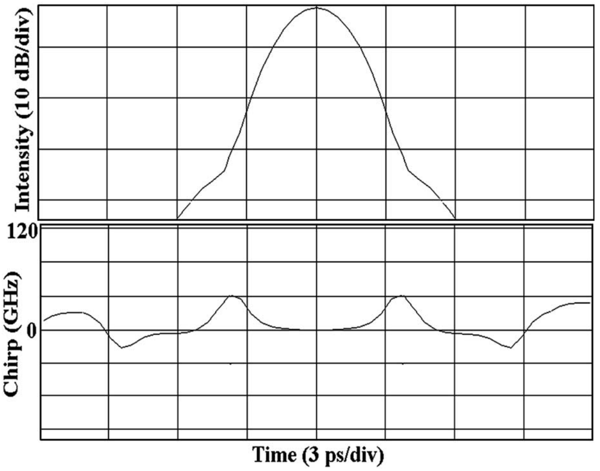

Fig. 11. Intensity and chirp profile of the EI GSLD pulse source employing an NC FBG for spectral shaping and temporal compression.

Temporal compressions using both the NC FBG and the LC FBG were simulated by using a measured optical filter in conjunction with the externally injected gain-switched laser. As in the experiment, the target reflection profile of these filters was set as the difference between the spectral amplitudes of a Gaussian profile and the EI GSLD output. Again, as in the experiment, the final group delay of the NC FBG and the LC FBG was obtained by selecting the following: 1) a group-delay response that is inverse to that measured across the EI GSLD pulse and 2) a group-delay profile opposite to a linear approximation of the pulse group-delay response, respectively.

Fig. 11 shows the pulse intensity and corresponding chirp when the EI GSLD pulses are compressed by the NC FBG. The resulting pulses portray a width of 2.9 ps (FWHM). Furthermore, it can be clearly seen that the resultant chirp has a negligible magnitude, thereby ensuing in an enhanced TPSR of about 35 dB. Fig. 12 shows the compressed pulses (3.1-ps width) and its corresponding chirp when the LC FBG is used. Here, the chirp in the central portion of the pulse can be seen to be flat and, hence, been compensated. However, the uncompensated nonlinear chirp in the wings of the pulse causes the formation of pedestals on the leading and trailing edges of the pulse and results in the pulses, exhibiting a TPSR of about 23 dB. The pulses from the TMLL pulse source were modeled by using a transform-limited Sech^2 pulse source that generated pulses with widths of 2.1 ps. The generated pulses and its equivalent chirp are shown in Fig. 13.

B. System-Performance Analysis of 80-Gb/s OTDM

Performance characterization of an 80-Gb/s OTDM system is carried out with each of these three different pulse sources employed alternatively.

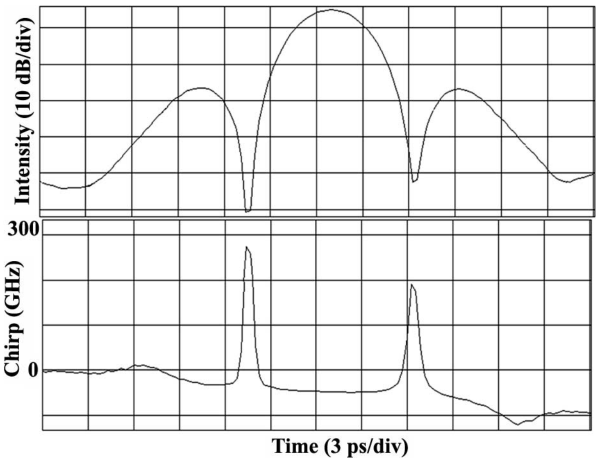

Fig. 12. Intensity and chirp profile of the EI GSLD pulse source employing an LC FBG for compression.

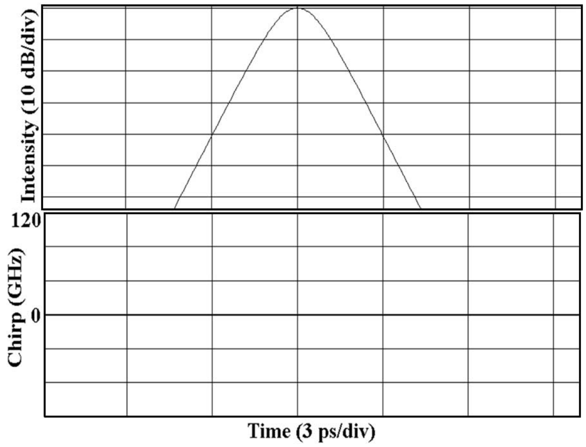

Fig. 13. Intensity and chirp profile of the TMLL pulse source.

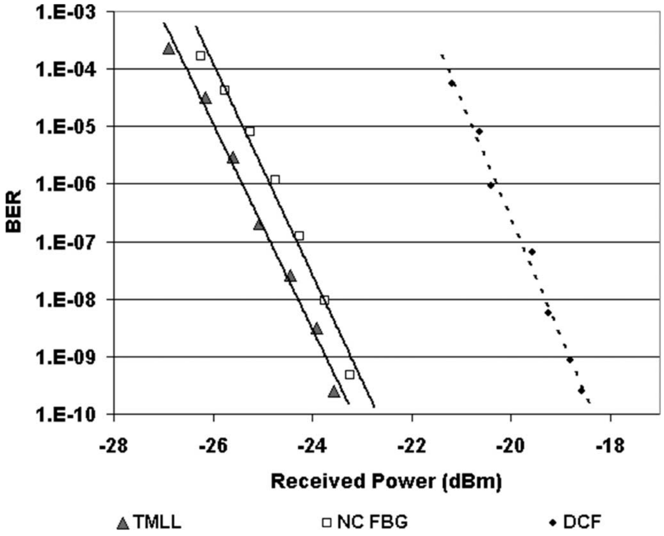

Fig. 14. BER versus received optical power for TMLL, NC FBG, and LC FBG employed in an 80-Gb/s OTDM test bed.

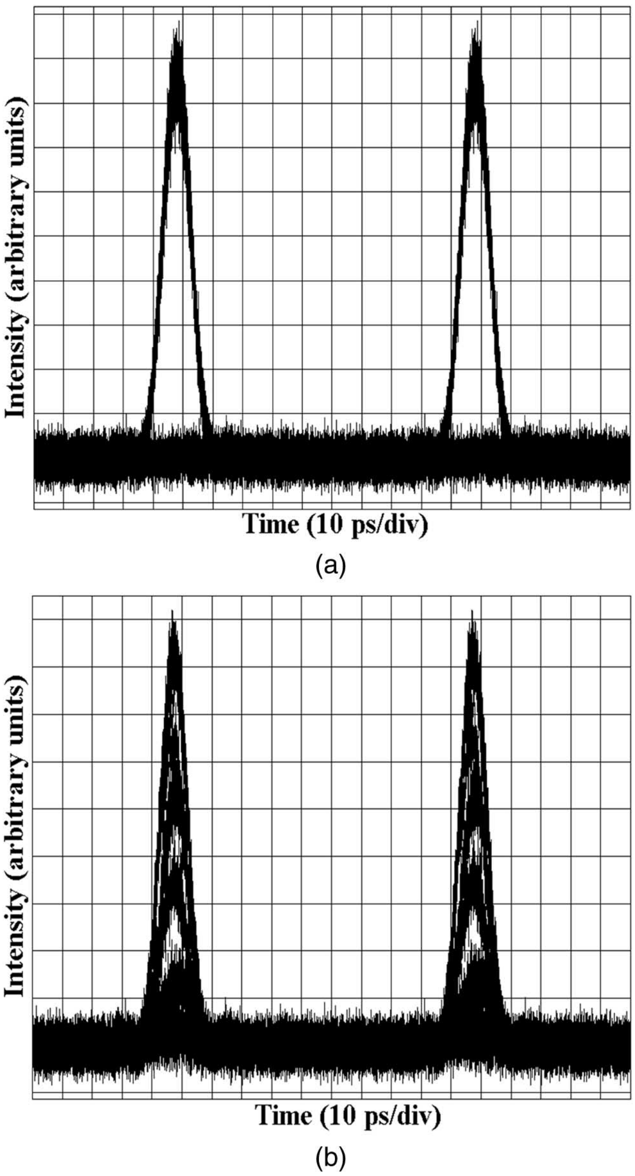

Fig. 15. Received eye diagrams at 10 Gb/s corresponding to the EI GSLD pulses compressed with the (a) NC FBG and (b) LC FBG when employed in an 80-Gb/s OTDM test bed.

Fig. 14 displays the BER versus received power plots for one of the demultiplexed channels. It can be observed that to achieve a BER of 10^{-9}, a power penalty of 4 dB is incurred when the pulse source with the LC FBG is employed in comparison to the case where the NC FBG is used. This degraded performance is due to the presence of the pedestals about 23 dB below the peak of the pulse, as previously explained in the experimental case. In terms of the power penalty incurred, these simulation results achieved show a very good agreement with the experimental 80-Gb/s OTDM-system-performance characterization. The small difference in pulse width could be attributed to the minor difference (0.5 dB) in the sensitivities between the gain-switched pulses compressed by the NC FBG and the sech^2 pulses, as was noticed in the experimental section.

The 10-Gb/s eye diagrams, corresponding to a power level of -23.24 dBm, are shown (Fig. 15) for the case of the EI GSLD pulses compressed by the NC FBG [Fig. 15(a)] and LC FBG [Fig. 15(b)]. The error free performance achieved by the pulses compressed by the NC FBG is reflected by the clean and open eye in the case of Fig. 15(a). On the other hand, the closed eye

[Fig. 15(b)] shows the degraded BER in the case of the pulses compressed by the LC FBG.

V. DISCUSSION AND CONCLUSION

OTDM is one of the techniques that could be used to realize high-capacity photonic communication systems. However, the fundamental component required to build such high-capacity OTDM systems is a cost-efficient source of short optical pulses that exhibits excellent temporal and spectral purity. An attractive solution to build such sources involves the use of a technique known as gain switching essentially due to its simplicity and reliability. The disadvantages that this technique suffers from could easily be overcome by employing external injection. The possibility of integrating the device used for external injection with a DFB laser [31] reduces the cost and footprint of the chosen solution.

Experiments performed show that pulses from an externally injected gain-switched source compressed by an LC FBG results in the formation of pedestals at a level of about 23 dB below the peak of the pulse. These pedestals occur as a result of the uncompensated nonlinear chirp in the wings of externally injected gain-switched pulse. BER measurements carried out show that these pedestals have a detrimental impact on the performance (1.5 dB) of a 40-Gb/s OTDM system. The penalty incurred goes up to 3.5 dB as the aggregate bit rate is doubled from 40 to 80 Gb/s. The increased interleaved bit rate leads to a reduction of the temporal slot allocated to each bit (25 ps for 40 Gb/s and 12.5 ps for 80 Gb/s). Hence, the coherent interactions between the adjacent OTDM channels (with poor TPSR) result in severe intensity fluctuations which in turn lead to the worsening system performance. Optimum system performance can be achieved by employing the tailor-made NC FBC. This grating not only portrays a nonlinear group delay (to compensate for the group delay of the gain-switched pulse) but also exhibits a nonlinear reflective profile (to compensate for the asymmetry of the pulse spectrum). These characteristics enable the compensation of the entire chirp across the pulse, thereby suppressing the pedestals to a level of about 40 dB below the peak of the pulse. The experimental results achieved demonstrate the importance of optimizing all the vital parameters of a gain-switched pulse source to yield pulses with excellent temporal and spectral purity. The simulations carried out with the aid of VPI transmission maker software verify the experimental result achieved.

In conclusion, we have presented a cost-efficient technique of generating pulses and provided a simple yet systematic way of optimizing such a source. We have also demonstrated its excellent performance in 40- and 80-Gb/s OTDM systems.

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