Optimized Pulse Source for 40-Gb/s Systems Based on a Gain-Switched Laser Diode in Conjunction With a Nonlinearly Chirped Grating

A. Clarke, P. M. Anandarajah, D. Reid, G. Edvell, L. P. Barry, and J. D. Harvey

***Abstract*—The authors demonstrate the generation of short optical pulses, which display spectral sidemode suppression ratio, and temporal pedestal suppression ratio, well in excess of 30 dB. The exceptional spectral and temporal characteristics exhibited by these pulses are attained by employing a novel technology, based on an externally injected gain-switched laser in conjunction with a nonlinearly chirped grating. Using this technique, near transform limited 7-ps optical pulses, exhibiting a time bandwidth product of 0.49, are generated.**

***Index Terms*—Gratings, optical fiber communication, optical pulse compression, optical pulse generation, semiconductor lasers.**

I. Introduction

WITH THE massive growth in demand for bandwidth showing no sign of declining in the coming decade, it will be necessary to further increase the overall capacity of the existing telecommunication networks. This goal of developing future terabit all-optical communication systems may be achieved by a reduction in channel spacing of wavelength-division-multiplexed (WDM) systems, an increase in the per-channel data rate by exploiting optical time-division multiplexing (OTDM) or by using a combination of these two methods as in hybrid WDM/OTDM systems.

The base data rate in high-speed optical networks for several years has been 10 Gb/s. Generally, such systems have tended to employ nonreturn-to-zero (NRZ) coding at the transmitter. However, current research has brought tremendous advances in the development of optical systems operating at 40 Gb/s and beyond [1]. In order to achieve line rates of 40 Gb/s and higher, it may become necessary to use return-to-zero (RZ) coding. RZ (pulse) modulation formats offer a number of advantages over NRZ modulation schemes [2]. First, for high-speed long-haul systems, RZ modulation maintains signal integrity over longer distances as it travels through the network. Moreover, RZ formatting has a lower bit-error rate and is far less susceptible to nonlinearity and dispersion effects in the transmission fiber that can cause the signal to spread (thus, rendering it unintelligible at the receiver) [3].

One of the major problems associated with the reduced channel spacing and increased line rate is the more stringent measures that are imposed on the transmitter performance. Hence, the design of an optical transmitter capable of generating pulses with adequate temporal and spectral purity for acceptable operation in high-speed optical communication systems is crucial. There are many techniques available to generate picosecond optical pulses [4], and it is readily recognized that the gain-switching technique is among the simplest of these. While the advantages in employing this technique are numerous, one of its major drawbacks is the spectral purity of the generated pulses. The direct modulation of 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. It has been reported how this chirp can be used to compress the pulses using dispersion-compensating fiber [5] or linearly chirped gratings [6] to obtain near transform limited pulses. However, due to the chirp being nonlinear across the pulse, this compression typically results in pedestals on either side of the pulses that make them unsuitable for use in practical systems. By using more complex arrangements involving nonlinear loop mirrors or external modulators, after the linearly compressed pulse, it is possible to greatly reduce the pedestal [7].

In this letter, we report a simple yet systematic approach to design an optimized source of picosecond optical pulses, which exhibit excellent temporal and spectral purity. The procedure is based on an initial complete intensity and chirp characterization of pulses, from an externally injected gain-switched laser, using the technique of frequency-resolved optical gating (FROG). This characterization yields the parameters that are required for the design of a nonlinearly chirped fiber Bragg grating (NC FBG) with a chirp profile that is opposite to that measured across the pulse. By employing the tailor-made NC FBG after the gain-switched laser, we can achieve direct compression of the gain-switched pulses to obtain pedestal-free, near transform-limited, 7-ps pulses.

II. Experimental Setup

The experimental setup employed in this work is shown in Fig. 1. A 2.5-GHz sine wave is amplified with the aid of

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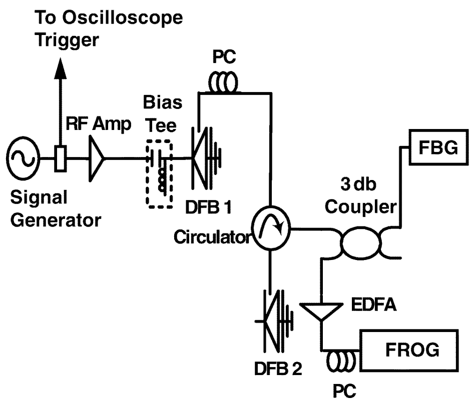

Fig. 1. Experimental setup for the generation of compressed externally injected gain-switched optical pulses.

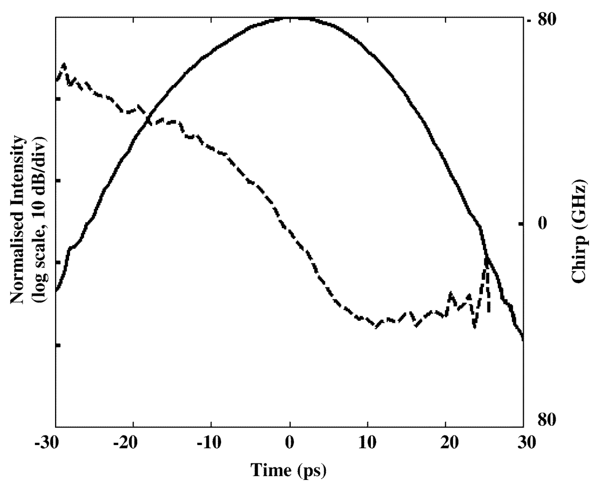

Fig. 2. Intensity and chirp of optical pulses from the externally injected gain-switched laser.

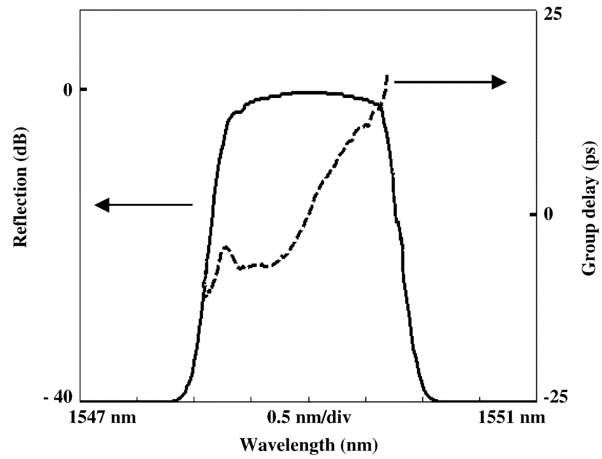

Fig. 3. Reflection and group delay profiles of nonlinearly chirped fiber grating.

a high-power radio-frequency amplifier. A bias tee was then used to combine the electrical signal ($\sim$25 dBm) with a dc bias (11.3 mA) to enable gain switching of a commercially available distributed feedback (DFB) laser contained within a hermetically sealed high-speed package. The resulting pulses generated were at a wavelength of 1549.35 nm. Wavelength tunablility of the laser mode could be achieved by temperature controlling the diode.

To overcome the poor sidemode suppression ratio (SMSR $\sim$15 dB) and timing jitter (4 ps) of the gain-switched pulses, we use external injection from a second DFB (2) laser (via an optical circulator) biased at 23.5 mA. A polarization controller was also used to ensure that the light being fed back was aligned with the optical axis of the laser. The injected power was measured to be about 13 dBm after taking into account the losses incurred in the optical injection path. The external light injection improves the SMSR to around 30 dB and reduces the timing jitter to $<$1 ps (as measured using an Agilent Digital Communications Analyzer). The generated pulses can then be characterized using an optical spectrum analyzer, a high-speed oscilloscope in conjunction with a 50-GHz p-i-n detector, and also a FROG measurement system [8]. From the FROG measurement, we can accurately characterize the intensity and chirp profile across the optical pulses from the gain-switched laser with external injection (as shown in Fig. 2). We can clearly see how the frequency chirp becomes nonlinear in the wings of the 16-ps pulse generated, due to the gain-switching mechanism.

We subsequently use the measured nonlinear chirp across the pulse to design and fabricate an NC FBG with a chirp profile opposite to that measured across the pulse. The reflective and group delay profiles of the fabricated filter are shown in Fig. 3. We also fabricated a linearly chirped fiber grating which had a chirp profile that was opposite to a linear approximation of the chirp across the gain-switched pulse. By placing the fiber gratings after the gain-switched laser (with external injection), we subsequently characterize the pulse compression in the fiber gratings using the FROG measurement technique.

III. Results and Discussion

Fig. 4(a) and (b), respectively, shows the measured intensity and chirp profile of the gain-switched optical pulses after compression with the linearly and nonlinearly chirped fiber gratings. In both cases, we can see that the gratings have eliminated any frequency chirp across the center of the pulses. However, when the linearly chirped grating is used, we can clearly see how the nonlinearity of the chirp directly from the gain-switched laser results in significant pedestals on the leading and trailing edge of the pulse. These pedestals, which are around 23 dB down from the peak of the pulse, would clearly pose significant problems (through intersymbol interference) for the use of these pulses in 40-Gb/s OTDM systems [9].

When the nonlinearly chirped fiber grating is employed, the pedestal is completely eliminated on one side of the pulse and reduced to around 32 dB down from the peak of the pulse on the other side. The slight imperfection in the compression can be attributed to the fabricated nonlinearly chirped grating not being a perfect match to compensate the chirp of the gain-switched pulse. In both cases (linear and nonlinear grating), the duration of the compressed pulse is around 7 ps, compared with 16-ps pulsewidth directly from the gain-switched source. However, the nonlinearly chirped grating is vital for ensuring a high level of pedestal suppression.

The spectrum of the generated optical pulses as measured using an optical spectrum analyzer, in addition to the nonaveraged oscilloscope trace of the detected pulse (after the nonlinear

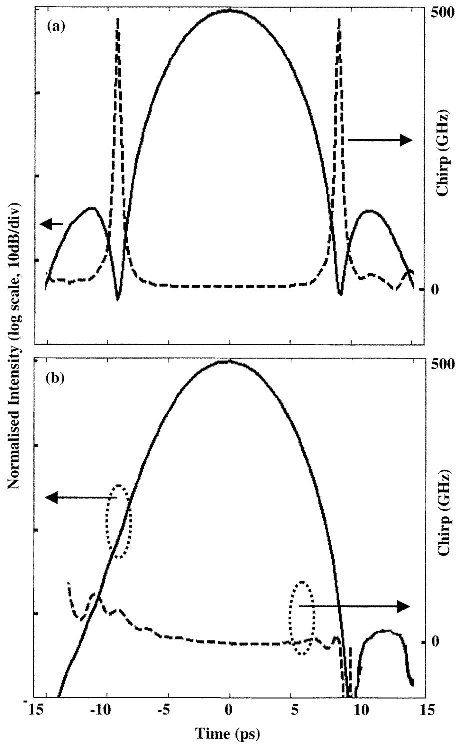

Fig. 4. Intensity and chirp of externally injected gain-switched pulses after (a) linearly chirped and (b) nonlinearly chirped gratings.

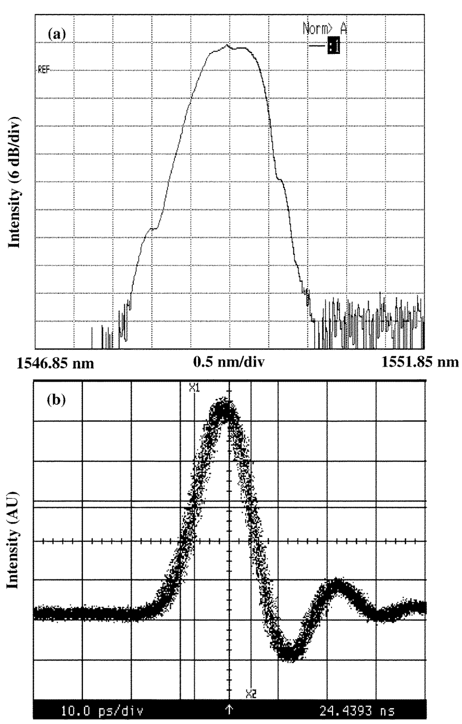

Fig. 5. (a) Optical spectrum and (b) oscilloscope trace of compressed pulse after nonlinearly chirped gratings.

grating), are shown in Fig. 5(a) and (b), respectively. The spectrum, which is in excellent agreement with the pulse spectrum obtained from the FROG measurement, shows that the spectral width is around 0.56 nm (70 GHz), thus giving a time bandwidth product of around 0.49. The low temporal jitter on the generated pulses is clear from the nonaveraged oscilloscope trace, and the ringing in the detected pulse is due to the pulse duration being a lot shorter than the response time of the detector ($\sim$10 ps).

This pulse generation/compression scheme exhibits excellent repeatability and stability over long periods of time, within laboratory conditions. This could be mainly attributed to the bias current and temperature of the two DFB (modulated and seeding) lasers being controlled with the aid of profile current/temperature controllers. Hence, drifts in wavelength of the lasers, due to current or temperature variations, were negligible. Furthermore the wavelength variation with temperature of the fabricated FBGs being relatively small ($\sim$0.009 nm/°C) also leads to the stable generation of optimized pulses over very long periods in time.

IV. Conclusion

We have demonstrated the use of nonlinearly chirped fiber gratings for optimum compression of optical pulses generated from a gain-switched laser diode. A nonlinearly chirped fiber grating is required to correctly compensate for the nonlinear chirp across the gain-switched pulse. This is vital for ensuring sufficient temporal pedestal suppression of the compressed gain-switched pulses. The resulting 7-ps pulse source comprising of gain-switched laser followed by nonlinearly chirped fiber grating would be suitable for use in 40-Gb/s transmission systems.

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