Extinction Ratio Improvement by Strong External Light Injection and SPM in an SOA for OTDM Pulse Source Using a DBR Laser Diode

Zhaoyang Hu, Marcelo Davanco, and Daniel J. Blumenthal, *Fellow, IEEE*

***Abstract*—We demonstrate above 6-dB extinction ratio (ER) improvement by strong external light injection for 20-GHz optical pulses generated from a gain-switched high-speed distributed Bragg reflector (DBR) laser diode. The pulses also exhibit a reduced chirp accompanied with a reduced total root-mean square noise. Above 12-dB pulse ER improvement was further obtained with self-phase modulation (SPM) effect in a semiconductor optical amplifier (SOA) followed by an optical bandpass filter. Stable 40-GHz pulses were demonstrated through passively multiplexing the pulses with 6-ps pulsewidth.**

***Index Terms*—Extinction ratio, optical pulse generation, gain-switched lasers, optical time-division multiplexing (OTDM), optical sampling.**

I. Introduction

OPTICAL pulse sources with a repetition rate above 10 GHz are extremely important for high speed optical time-division multiplexing (OTDM) systems that transmit at rates of 40 Gb/s and greater [1] and also for high-speed optical sampling applications [2]. In these systems, a high-pulse extinction ratio (ER) is required to avoid interference noise between passively multiplexed adjacent pulses. The pulse ER is here defined as P_1/P_0, where P_1 is the pulse peak power level and P_0 is the maximum unwanted background signal power level between the pulses. Mode-locked semiconductor lasers and pulsed electroabsorption modulators (EAMs) have shown high pulse ER. However, the mode-locked lasers are difficult to maintain, and an EAM's large loss restricts its practical applications in OTDM systems. External injection seeding of a gain-switched laser diode (LD) has been used to produce very low-jitter optical pulses [3] and enhance the modulation bandwidth of a gain-switched Fabry–Pérot (FP) LD [4]. These techniques demonstrate a gain-switched LD to be a potential compact and simple solution as a high bit rate OTDM pulse source. However, inherent low-pulse ER characteristics limits its application in OTDM systems. An additional EAM has been used to increase pulse ER but introduced above 7-dB insertion loss [3].

Manuscript received January 2, 2003; revised May 28, 2003. This work was supported in part by the DARPA COAST program Grant 442530-23056 and in part by the DARPA MURI Multidisciplinary Center for Optical Switching Technology Grant 442530-25358.

The authors are with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, Santa Barbara, CA 93106-9560 USA (e-mail: huby@ece.ucsb.edu).

Digital Object Identifier 10.1109/LPT.2003.818258

In this letter, we demonstrate how strong external light injection improved ER better than 6 dB for 20-GHz optical pulses generated from a gain-switched high-speed distributed Bragg reflector (DBR) LD. The pulsewidth was reduced from 15 to 10 ps accompanied with reduced total root-mean square (rms) noise. Above 12-dB pulse ER improvement further was obtained with self-phase modulation (SPM) effect in a semiconductor optical amplifier (SOA) followed by an optical bandpass filter (OBPF). Stable 40-GHz operation was demonstrated by passively multiplexing the 20-GHz pulses with 6-ps pulsewidth.

II. Basic Principles and Experimental Setup

In a gain-switched LD with strong external light injection, coherent addition of the injection optical field with the LD optical field depends on their phase offset, which varies during modulation due to the dependence of refractive index on the carrier density. This results in increased coupling between the carriers and photons. Thus, an effectively higher differential gain is given. Higher differential gain of the laser indicates the enhanced modulation efficiency, i.e., enhanced pulse ER. Detailed analysis can be obtained through numerically solving a set of standard single-mode rate equations for injection-locking LD [5]. It is known that dispersion compensating fiber (DCF) for gain-switched pulse compression only compensates the linear chirp which locates at the central part of the pulses. The rest of the of the pulses corresponding to the nonlinear chirp remains to form the pulse pedestals and leads to poor ER [6]. However, the pedestals could be removed through using the SPM effect in an SOA [7]. Due to the gain-saturation-induced SPM, the spectrum corresponding to the leading edge of the optical pulses shifts toward the long-wavelength side (the red side) and the rest of the parts stay at the position of the input wavelength. Thus, filtering out the red-shifted part of the spectrum, the pulse pedestals and the DC offset can potentially be removed and substantially increase the pulse ER.

The experimental setup (Fig. 1) and the high-speed DBR-LD was fabricated at KTH, Sweden [8]. It has the threshold current of 12 mA and the output power of 4 dBm at 60-mA bias current. A 20-GHz sinusoidal modulation signal was generated from a synthesizer at 10 GHz, a radio frequency (RF) frequency doubler, an RF filter, and an RF amplifier. External light injection to the gain-switched DBR-LD was realized by using a wavelength tunable laser via an isolator and an optical circulator. A polarization controller (PC) was used to optimize the light injection

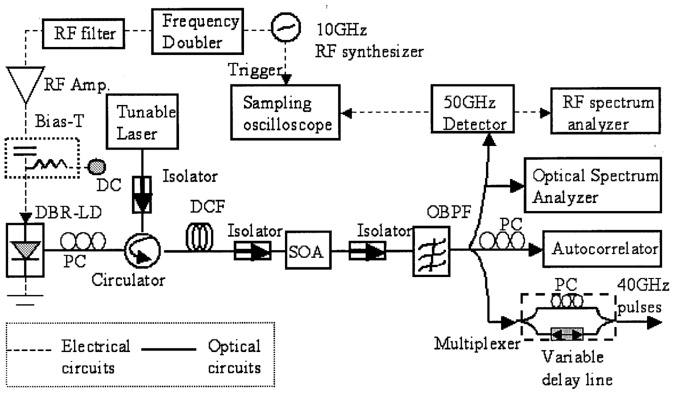


Fig. 1. Experimental setup.

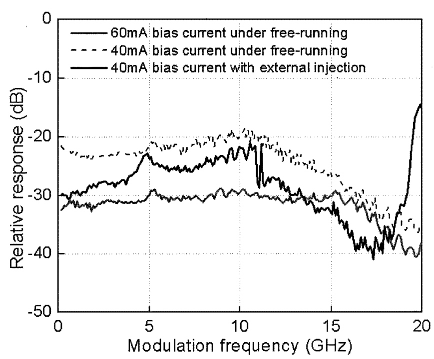


Fig. 2. DBR-LD frequency response under free-running and external injection.

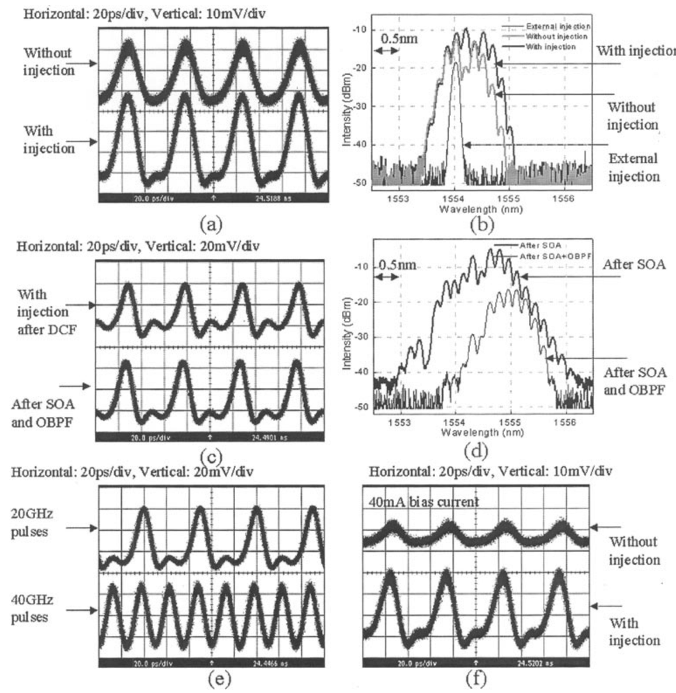


Fig. 3. (a) 20-GHz pulse outputs without injection (upper) and with injection (lower) at 60-mA bias current. (b) Corresponding optical spectra without and with injection, respectively. (c) 20-GHz pulses before entering SOA (upper) and after SOA+OBPF (lower). (d) Corresponding optical spectra after SOA and after OBPF, respectively. (e) 40-GHz pulses after a multiplexer (lower). (f) At 40-mA bias current, 20-GHz pulse outputs without injection (upper) and with injection (lower). Persistence time of the sampling oscilloscope was set to 10 s.

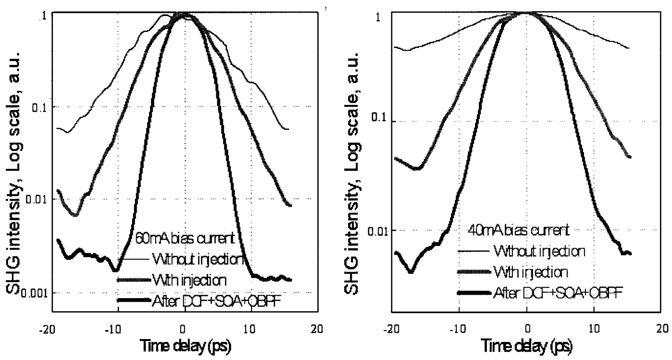
from the tunable laser. A 50 –GHz sampling oscilloscope and an RF spectrum analyzer in conjunction with a 50-GHz photodetector were used to measure the temporal behavior and RF spectrum of the output pulses, respectively.

III. Experimental Results and Discussion

Before gain-switching the DBR-LD, we initially measured its frequency response using a 20-GHz lightwave component analyzer. The frequency response of the free-running DBR-LD exhibits a 3-dB bandwidth of 18 GHz at 60-mA bias current, shown as the gray line in Fig. 2. When we injected light from tunable laser into the DBR-LD, the relaxation frequency can be greatly enhanced to 20 GHz, shown as the dark line in Fig. 2. We gain-switched the DBR-LD at a frequency of 20 GHz without external injection under 60-mA bias current. The output 20-GHz pulses were shown as the upper waveform in Fig. 3(a) and the persistence time of the sampling oscilloscope was set to 10 s. The pulsewidth is 15 ps and the corresponding optical spectrum is shown as the gray line in Fig. 3(b). The corresponding time bandwidth product is about 0.93 and suggests the pulses were strongly chirped. No DC offset was directly observed from the pulse traces in the sampling oscilloscope.

We then injected the light into the gain-switched DBR-LD and the output power of the tunable laser was fixed to 4 dBm. The RF modulation power was fixed to 26 dBm. Considering the insertion loss of the circulator and the coupling loss between the lensed fiber and the DBR-LD, we estimate the external injection power into the DBR-LD to be above 0 dBm. We tuned the wavelength of the injected light to meet either one of the sideband peaks of the gain-switched DBR-LD for injection-locking operation. In the experiment, injection-locking operation with different injection wavelengths demonstrated almost the same ER improvement results but with different injection power. The thin dark line of Fig. 3(b) shows one injection wavelength of 1554 nm. The corresponding output pulses became strong due to enhanced modulation efficiency by the external light injection and also beats with the main modes when phase locked. The average output power was about 1.4 dBm, shown as the lower waveform of Fig. 3(a). The pulsewidth is 10 ps and the time bandwidth product is 0.74. We found that the lasing peak was about 0.3 nm red shifted due to the heating and reduced threshold carrier density by external light injection. When the tunable laser output power was below 0 dBm, the output pulses became almost the same as without injection. It indicates the enhanced modulation behavior only occurs at strong external light injection.

The 20-GHz pulses were subsequently compressed by 200-m-long DCF (dispersion of -67 ps/km/nm at 1550-nm wavelength), and the pulsewidth was reduced to 6 ps. The resulting time bandwidth product is 0.45, which is close to 0.44 for transform-limited Gaussian pulses. Afterward, the pulses went through an SOA (Alcatel 1901) followed by an OBPF with 0.6-nm bandwidth. Fig. 3(c) and (d) displays output optical pulses and their corresponding optical spectra. Compared with the spectrum before SOA, the spectrum after SOA was broadened and red shifted due to SPM effect in the SOA. The ER enhanced pulses were passively multiplexed, and stable



(a) (b)

Fig. 4. Autocorrelation traces for output pulses without injection, with injection and after SOA+OBPF at different bias current. (a) 60 mA. (b) 40 mA.

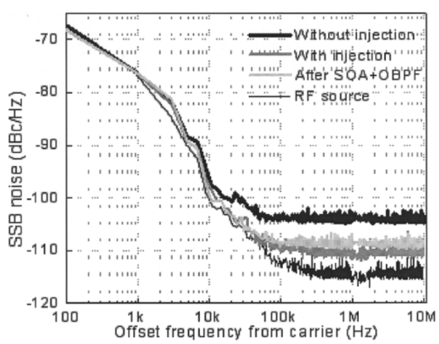


Fig. 5. SSB noise spectra measured for the RF source, 20-GHz pulses without injection, with injection, and after SOA+OBPF at 60-mA bias current of DBR-LD.

40-GHz pulses were obtained, as shown in the lower waveform of Fig. 3(e). Without the ER improvements, the multiplexed pulses fluctuated, leading to a noticeable interference between adjacent pulses over the 10-s persistence window. We also investigated that strong external light injection can improve high-frequency modulation behavior of the gain-switched LD with relatively low modulation bandwidth at 40-mA bias current displayed in Fig. 2. The pulse ER was greatly improved when we turned on the tunable laser with 4-dBm output power and tuned its wavelength to achieve injection-locking operation, shown as the lower waveform in Fig. 3(f).

Fig. 4(a) and (b) shows the second-harmonic generation (SHG) autocorrelation traces for the 20-GHz pulses in logarithmic scale under the same measurement conditions but DBR-LD at 60- and 40-mA bias current, respectively. The lobes at the left side of the traces were subject to the pulse cross correlation due to the insufficient pulse ER. From autocorrelation traces, DC components of the pulses are small enough to be neglected. The pulse ER measured at ± 12.5 ps (corresponding to 2×20-Gb/s multiplexing) was improved by strong injection above 6 dB at 60-mA bias current and above 7 dB at 40-mA bias current, respectively [3]. SPM effect in the SOA results in above 12-dB pulse ER enhancement for the former and above 10 dB for the latter.

Fig. 5 depicts the single sideband (SSB) noise spectra of the 20-GHz gain-switched pulses at 60-mA bias current of DBR-LD. At 1-MHz offset frequency, a noise reduction is observed from -104 dBc/Hz without injection to -112 dBc/Hz with injection. The total rms noise is determined by integrating the noise spectrum $L(f)$ using the equation of $\sqrt{2\int_{f_1}^{f_2} 2L(f)df}$ from offset frequency f_1 of 100 Hz to f_2 of 10 MHz. The total rms noise has been effectively suppressed from 0.479 to 0.0715 rad due to strong injection. It indicates strong injection results in the suppressed statistical fluctuations of the carrier density during optical pulse generation. Our experiment has been carried out with a DBR-LD, but also applies to DFB-LDs and FP-LDs [9].

IV. Conclusion

We have experimentally demonstrated above 18-dB pulse ER improvement for 20-GHz pulses generated from a gain-switched DBR-LD by using strong external light injection and SPM effect in a SOA followed by an OBPF. The ER improved 20-Gb/s pulses with 6-ps pulsewidth were passively multiplexed to obtain stable 40-GHz pulses. Strong injection also results in the reductions of the pulsewidth, the chirp, and the total rms noise. This technique shows promising for compact high bit rate sources in OTDM systems.

Acknowledgment

The authors would like to thank Drs. O. Kjebon and L. Thylen from KTH, Sweden, for the DBR-LDs.

References

[1] S. Kawanishi, "Ultrahigh-speed optical time-division-multiplexed transmission technology based on optical signal processing," *IEEE J. Quantum Electron.*, vol. 34, pp. 2064–2079, Nov. 1998.

[2] F. Coppinger, A. S. Bhushan, and B. Jalali, "Photonic time stretch and its application to analog-to-digital conversion," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 1309–1314, July 1999.

[3] P. Gunning, J. K. Lucek, D. G. Moodie, K. Smith, R. P. Davey, S. V. Chernikov, M. J. Guy, J. R. Taylor, and A. S. Siddiqui, "Gainswitched DFB laser diode pulse source using continous wave light injection for jitter suppression and an electroabsorption modulator for pedestal suppression," *Electron. Lett.*, vol. 32, pp. 1010–1011, 1996.

[4] L. P. Barry, P. Anandarajah, and A. Kaszubowska, "Optical pulse generation at frequencies up to 20 GHz using external-injection seeding of a gain-switched commercial Fabry-Perot laser," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 1014–1016, Sept. 2001.

[5] J. Wang, M. K. Haldar, L. Li, and F. V. C. Mendis, "Enhancement of modulation bandwidth of laser diodes by injection locking," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 34–36, Jan. 1996.

[6] L. P. Barry, B. C. Thomsen, J. M. Dudley, and J. D. Harvey, "Optimized design of fiber-based pulse compressor for gain-switched DFB laser pulses at 1.5 μm," *Electron. Lett.*, vol. 35, pp. 1166–1168, 1999.

[7] M. L. Nielsen, B. E. Olsson, and D. J. Blumenthal, "Pulse extinction ratio improvement using SPM in an SOA for OTDM systems applications," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 245–247, Feb. 2002.

[8] O. Kjebon, R. Schatz, S. Lourdudoss, S. Nilsson, B. Stalnacke, and L. Backbom, "30 GHz direct modulation bandwidth in detuned loaded InGaAsP DBR lasers at 1.55 um wavelength," *Electron. Lett.*, vol. 33, pp. 488–489, 1997.

[9] G. Yabre, "Effect of relatively strong light injection on the chirp-to-power ratio and the 3 dB bandwidth of directly modulated semiconductor lasers," *J. Lightwave Technol.*, vol. 14, pp. 2367–2373, 1996.