Available online at www.sciencedirect.com

ScienceDirect

Optics Communications 277 (2007) 150–155

OPTICS COMMUNICATIONS

www.elsevier.com/locate/optcom

Experimental investigation of the impact of optical injection on vital parameters of a gain-switched pulse source

C. Guignard, P.M. Anandarajah *, A. Clarke, L.P. Barry, O. Vaudel, P. Besnard

Research Institute for Network and Communications Engineering, School of Electronic Engineering, DCU, Dublin 9, Ireland

Received 9 January 2007; received in revised form 27 April 2007; accepted 30 April 2007

Abstract

An analysis of optical injection on a gain-switched distributed feedback (DFB) laser and its impact on pulse parameters that influence the performance of the pulse source in high-speed optical communication systems is presented in this paper. A range of 10 GHz in detuning and 5 dB in injected power has been experimentally identified to attain pulses, from an optically injected gain-switched DFB laser, with durations below 10 ps and pedestal suppression higher than 35 dB. These pulse features are associated with a side mode suppression ratio of about 30 dB and a timing jitter of less than 1 ps. This demonstrates the feasibility of using optical injection in conjunction with appropriate pulse compression schemes for developing an optimized and cost-efficient pulse source, based on a gain-switched DFB laser, for high-speed photonic systems.

Keywords: Semiconductor lasers; Pulse generation; Optical injection; Frequency resolved optical gating; Optical pulse measurement

1. Introduction

Semiconductor lasers are key components to develop short optical pulse sources suitable for applications such as optical return-to-zero (RZ) transmitters (used at its base repetition rate or temporally multiplexed in the optical domain to achieve higher capacities), optical signal processing, optical clock recovery and signal regeneration, high bit rate optical sampling, optical impulse response investigations, optical analogue–digital (A–D) conversions, high-speed optical interconnects etc. The most common, amongst the given range of applications, is its use as an RZ transmitter to achieve terabit per second photonic communication systems by exploiting the technique of OTDM [1] to form hybrid WDM/OTDM [2]. However, one of the major problems associated with the reduced channel spacing and increased line rate is the more stringent characteristics that are imposed on the transmitter performance in terms of repetition rate, pulsewidth, jitter, side mode suppression ratio (SMSR), temporal pedestal suppression ratio (TPSR or extinction ratio) and chirp. For instance, a return-to-zero (RZ) optical transmitter designed to achieve satisfactory performance in a $\geqslant$40 Gb/s photonic communication system, needs to be capable of generating pulses with repetition rates of at least 10 GHz [3], pulsewidths of <8 ps (duty-cycle of ~1/3) [4], SMSR of at least 30 dB [5], TPSR greater than 30 dB [6] and a negligible chirp (transform-limited) [7]. Therefore, the design of an optimum optical transmitter is crucial, in that it has to be capable of generating pulses with adequate temporal and spectral purity for acceptable operation in high-speed optical communication systems.

Picosecond pulse generation can be accomplished with many different techniques such as external modulation of a continuous-wave light signal [9], gain-switching [8], and mode-locking [10–12]. In comparison to gain-switching, active mode-locking requires expensive and complex techniques, but is superior concerning the amplitude and timing

* Corresponding author. Tel.: +353 17007537; fax: +353 17005508.
E-mail addresses: anandara@eeng.dcu.ie (P.M. Anandarajah), liam.barry@dcu.ie (L.P. Barry).

0030-4018/$ - see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.optcom.2007.04.058

jitter and the minimum width of the obtainable pulses. Relative to the rest of the techniques mentioned above, gain-switching of a DFB laser is readily recognized to be an uncomplicated, robust and reliable technique [13,14]. While the advantages in employing the gain-switching technique are numerous, it suffers from a few drawbacks such as a degraded SMSR and a relatively large temporal jitter exhibited by the generated pulses. The significant reduction of the SMSR under gain-switching conditions is due to the large fluctuations in the photon density (caused by the laser being pulled below threshold), which result in the side modes of the laser being strongly excited. As a consequence, the SMSR of a GS DFB laser can be 25 dB lower in comparison to the usual SMSR (>30 dB) exhibited by DFB laser under continuous operation. The temporal jitter, on the other hand, could be mainly attributed to spontaneous noise and pulse turn on dynamics [15,16]. Self-seeding [17] and external optical injection [18–21] have been demonstrated to be the most effective solutions to improve both the poor timing jitter and the SMSR of the generated pulses. However, external injection is advantageous in comparison to self-seeding, in that it does not require any adjustment of the repetition frequency or external cavity length. Furthermore, the possibility of improving the laser bandwidth, reducing the chirp and the possibility of using it in applications involving interferometry has resulted in injection locking of semiconductor lasers being actively investigated over the past decade [22–25].

In this paper, we propose to extend on the different works that have been published on the use of external optical injection to enhance the modulation bandwidth, reduce the chirp and optimize the timing jitter and the SMSR of GS DFB pulse sources by presenting an experimental study of the impact of optical injection on the other key parameters (pulsewidth, TPSR and frequency chirp shape) for high-speed optical communications. To the best of our knowledge, this is the first time that the effects of external injection on a gain-switched pulse source has been characterized as regards the evolution of pulsewidth, height of pedestals and shape and magnitude of the chirp.

2. Experiments

2.1. Experimental set-up

The experimental setup used for this study is shown in Fig. 1. All of the components, up to the output of the circulator, are pigtailed and the fiber used is polarization-maintaining (PM) so that the polarization of the injected field is controlled to ensure a constant coupling. However, since the coupling fiber of the packaged slave laser is not PM, a polarization controller is used to align the polarization of the injected light onto the polarization of the laser field. The set-up used permits excellent reproducibility of the results.

The illustrated experimental set-up essentially consists of a master–slave laser configuration of two lasers: the optical output signal of the first laser, known as the master laser (ML), is injected into the second gain-switched laser, called the slave laser (SL). The ML used is a commercially

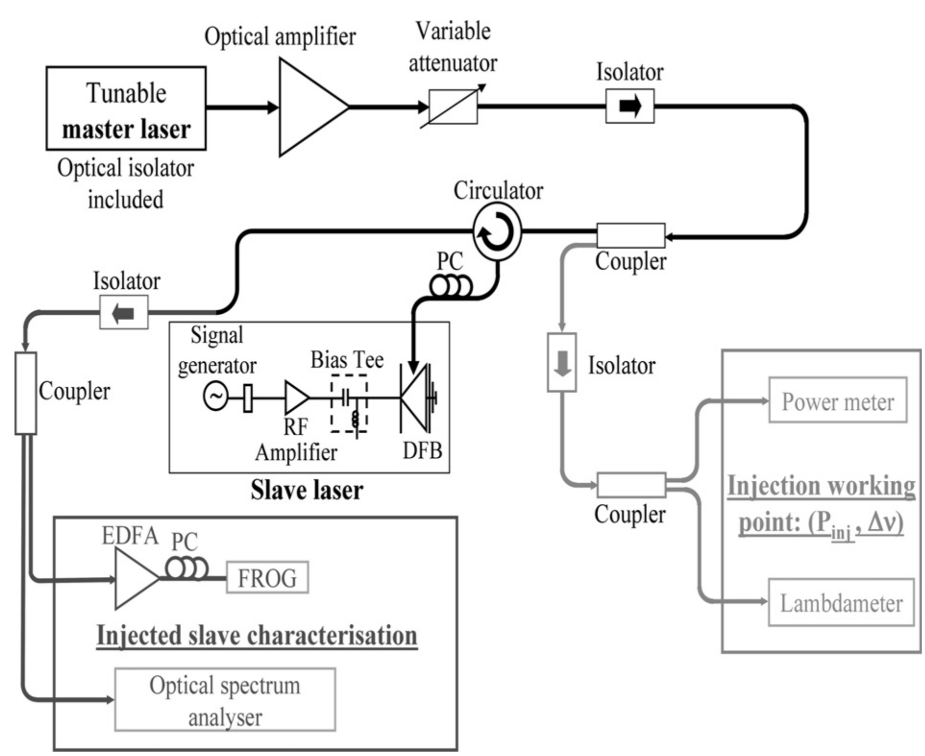

Fig. 1. Experimental setup.

available, single mode tunable external cavity semiconductor laser, with a precision of 1 pm (125 MHz at 1550 nm). Its maximum output power of about 3 mW can be enhanced via a PM optical amplifier that exhibits a gain of 23 dB. A high coefficient isolator (70 dB isolation) within this amplifier ensures unidirectional seeding from the master to the slave. The SL used is a commercially available NEL DFB laser contained within a hermetically sealed high-speed package that portrays a 3 dB bandwidth of approximately 20 GHz and emits a power of 4.7 dBm when biased at 3 I_{th}. Gain-switching of the SL is carried out by applying an amplified electrical RF signal (at 10 GHz) in conjunction with a DC bias (2.5 I_{th}). The resulting pulses were generated at a wavelength of 1551.54 nm.

During the experiment, the working point of the slave laser is considered to be fixed and the control parameters of interest are the power of the injected field, P_{inj}, and the frequency difference, or detuning $\Delta\nu = \nu_M - \nu_S$, between the slave ($\nu_S$) and the master ($\nu_M$) laser frequencies. Experimental results are obtained under two different scenarios: (i) by fixing the detuning and varying the injected power with the aid of a programmable attenuator or (ii) by fixing the injected power and varying the detuning by changing the frequency of the ML. Signal characterization of the injected signal is carried out by using an optical spectrum analyzer characterized by a resolution bandwidth (RBW) of 0.07 nm (8.75 GHz at 1550 nm), an oscilloscope in conjunction with a high-speed detector and the technique of frequency resolved optical gating (FROG) [26]. A short pulse erbium doped fiber amplifier (EDFA), specifically designed for the amplification of pulses with durations in the order of 2 ps (FWHM), is used before the FROG measurement set-up to improve the signal-to-noise ratio of the measurement. This type of measurement allows an accurate characterization of the intensity and the chirp profile across the optical pulses from the gain-switched laser with and without external injection.

2.2. Improvement of the SMSR

As explained in Section 1, the goal of this paper is not to focus on how the optical injection affects the SMSR of the GS pulse source, as it is a well-known result. However, in all experimental stages, the impact of optical injection on the pulsewidth, TPSR and the frequency chirp have been analyzed in an injection area where both the timing jitter and the SMSR of the pulse source matched the requirements (jitter <1 ps and SMSR >30 dB) of high-speed optical communications systems. Fig. 2 presents the range of injected power and detuning where the gain-switched pulse source exhibits an SMSR of at least 30 dB.

The timing jitter of this source also remains below 1 ps in this zone as illustrated by Fig. 3, which displays the non-averaged oscilloscope trace of the detected pulse. When there was no light injected, the optical bandwidth (FWHM) of the degraded (multimode) spectrum and the SMSR were 1.1 nm and around 5 dB, respectively. The

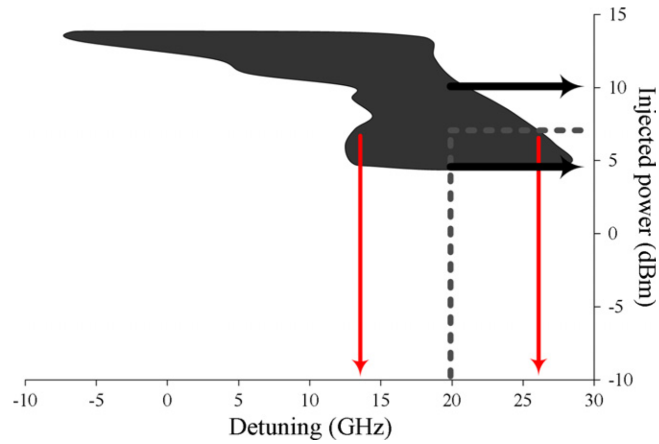

Fig. 2. Experimental map showing the area where an SMSR higher than 30 dB is achievable under optical injection.

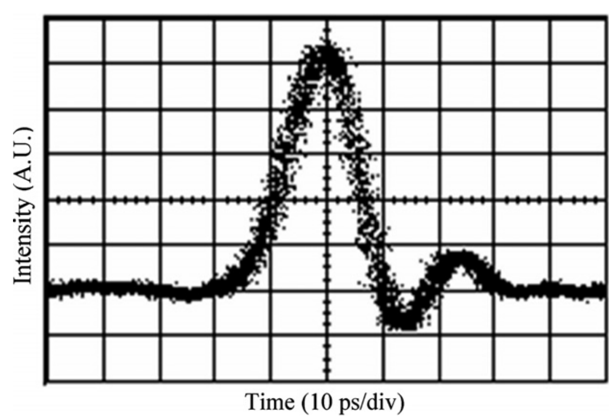

Fig. 3. Oscilloscope trace of the externally injected gain-switched pulse.

improvement of the SMSR is then observed for positive detuning and high injection power (>4 dBm). From a practical point of view, an injection power around 7 dBm associated with a detuning of 20 GHz will be the preferred operating point since it offers the best stability (allowance for deviation). In fact, a deviation range of 13 GHz in detuning (13 to 26 GHz) associated with a 6 dB range in injected power (4–10 dBm) is observed around this operating point. However, as previously reported for gain-switched Fabry–Pérot lasers under self-seeding [27] or optical injection [28], the SMSR improvement is accompanied by a narrowing of the optical spectrum. From Fig. 4, one may notice that the spectral width decreases as the injecting power increases. The origin of this reduction of the spectral width can be attributed to the reduced threshold gain induced by the optical injection field [9].

2.3. Pulsewidth and TPSR under optical injection

The evolution of the pulsewidth under external injection is important since the pulsewidth of the source is one of the main parameters that limits the maximum bit rate achievable in OTDM systems. As previously mentioned, another

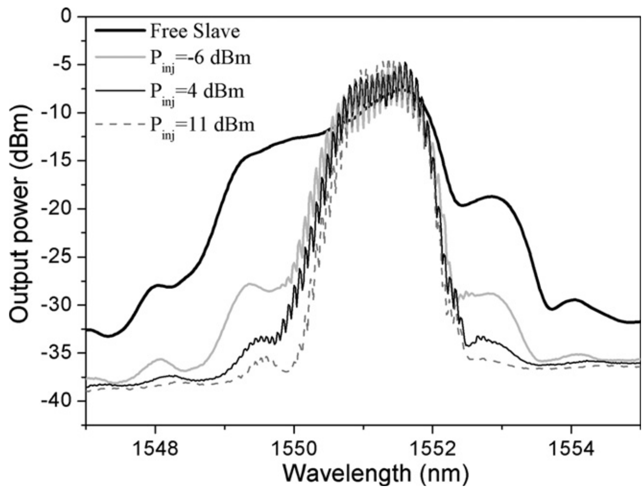

Fig. 4. Evolution of the optical spectrum of a gain-switched DFB pulse source subjected to optical injection.

vital parameter that may affect the usefulness of a short optical pulse source in a high-speed optical communication system is the TPSR. It has been demonstrated that a TPSR of at least 30 dB [6] is required to prevent coherent interference noise between individual channels in a 40 Gb/s OTDM system. Both the TPSR and the duration of the pulses are measured with the aid of the FROG. This equipment allows an accurate measurement of TPSR to beyond 30 dB if the signal-to-noise ratio is sufficient.

The free-running gain-switched laser is characterized by a pulse duration of around 7.5 ps without pedestals. But under optical injection, this pulsewidth increases with the augmentation of either the injected power or the detuning. From Fig. 5a, we can say that, for an injected power of 5 dBm, a detuning under 20 GHz has low impact on both the TPSR and the duration of the pulses since the pulsewidth remains under 8.2 ps and the TPSR remains higher than 30 dB. At detuning higher than 20 GHz, the pulsewidth increases linearly with the detuning, (~0.12 ps/GHz), whereas, the TPSR level decreases by −0.30 dB/GHz.

Fig. 5b shows that if the detuning is set to 19.4 GHz, for injected powers higher than 2 dBm, the pulsewidth starts increasing exponentially and the TPSR decreases linearly with a slope of −1.4 dB/dBm. However, if the injected power remains below 8 dBm, pulses characterized by a duration under 10 ps and TPSR of at least 31 dB, are achieved. Such TPSR levels should permit the use of this source in practical OTDM systems. But if the source is subjected to higher levels of injection, then coherent interference noise will be introduced between the different multiplexed channels due to the level of the pulse TPSR, which will result in the introduction of transmission penalties.

2.4. Chirp reduction

Another parameter that is vital as regards the transmission of RZ signals over fiber is the spectral quality of the

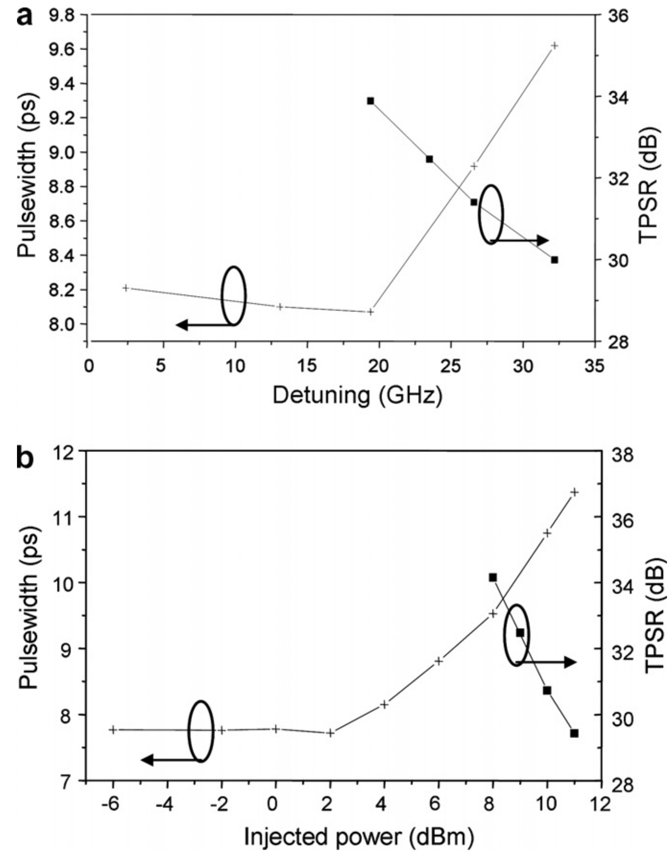

Fig. 5. (a) Pulsewidth and TPSR evolution when the detuning is varied ($P_{inj} = 5$ dBm) and (b) pulsewidth and TPSR evolution when the injected power is varied ($\Delta\nu = 19.4$ GHz).

pulse since frequency chirp across the pulse leads to the degradation of the performance of these pulses when used in practical optical communication systems [29]. Moreover, it is well known that the technique of gain-switching is associated with poor 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 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 generated pulses. It has been demonstrated in the literature how this chirp can be used to compress the pulse using dispersion-compensating fiber [30], linearly [31] and nonlinearly [32] chirped fiber Bragg grating to obtain near transform-limited pulses. However, these techniques, and in particular the latter, require a good knowledge of the shape and magnitude of the chirp. Chirp reduction under optical injection has been demonstrated in a transmission experiment by Mohrdiek et al. [33] via eye diagrams obtained with and without external optical injection. But these experiments give no indication on either the shape of the chirp or the sensitivity of this chirp to the variation of the injection conditions. We improve on this work by proposing a full characterization of this chirp reduction as a function of injection level and detuning, using FROG measurements.

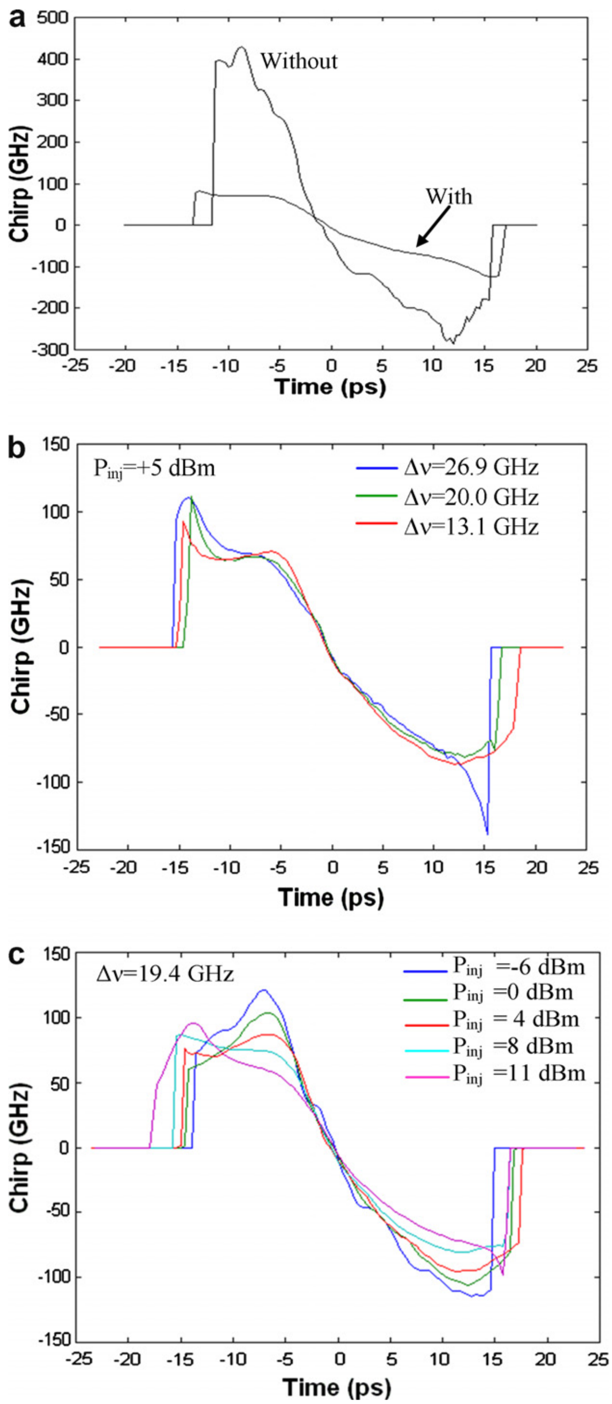

Fig. 6. (a) Chirp reduction induced by optical injection ($P_{inj} = 5$ dBm and $\Delta\nu = 32.2$ GHz), (b) evolution of the chirp when the detuning is varied (the injection power is fixed around 5 dBm) and (c) evolution of the chirp when the injected power is varied (the detuning is fixed around 19.4 GHz).

Fig. 6a presents the evolution of the frequency chirp when the laser is free-running and under optical injection. From this figure, we can notice that the pulse obtained from the free-running gain-switched laser is characterized by a chirp becoming nonlinear in its wings, and a chirp magnitude of around 700 GHz. Under optical injection Fig. 6b where a detuning of 32.2 GHz and a seeding power of 5 dBm have been considered, the chirp magnitude is reduced to only 200 GHz but the chirp remains nonlinear in the wings of the pulse.

Fig. 6c presents the evolution of the frequency chirp when the detuning is equal to 26.9, 20 and 13.1 GHz, while the injected power is fixed to 5 dBm. Slight modifications of the nonlinear chirp across the pulse can be observed. If the injected power is varied, then important variations in the nonlinear chirp across the pulse appear, as illustrated by Fig. 6c. These observations demonstrate that for pulse compression of an externally injected GS pulse source using one of the compression techniques previously mentioned, it will be necessary to keep the injected power level reasonably constant to avoid fluctuations of the frequency chirp, and thus fluctuations of the resulting compressed pulse duration.

3. Discussion and conclusions

The increase of bit rate in all-optical communications systems relies on the development of cost-efficient short optical pulse sources with high spectral and temporal purity. Due to the simplicity and the reliability of the gain-switching technique, pulse sources based on GS DFB lasers are an attractive solution. Moreover, optical injection has been demonstrated to be an ideal technique to overcome the major drawbacks associated with the GS technique, which are principally a degradation of the SMSR and a high timing jitter. As a consequence, we can find in the literature, numerous papers on the impact of optical injection on SMSR and timing jitter improvement. However, pulsewidth, TPSR and frequency chirp also play a considerable role in the performance/usefulness of these sources when used in practical OTDM systems. The impact of external optical injection on these key parameters has been investigated in this paper.

The experimental analysis presented is realized within an injection area where the injected pulse source is characterized by an SMSR in excess of 30 dB and a timing jitter of approximately <1 ps. Our results show that we can achieve a pulsewidth below 10 ps and TPSR better than 30 dB for a detuning between 15 and 25 GHz and an injection level ranging from 4 to 8 dBm. The external injection is also shown to greatly reduce the level of frequency variation across the pulse from 700 to 200 GHz. The remaining chirp across the pulse, and its low sensitivity to reasonable variations of optical injection conditions ensure the possibility to successfully compress the pulse. For example, in previous work [32], we demonstrated the generation of 3.5 ps optical pulses that exhibited a time-bandwidth product of 0.45 by employing a tailor-made nonlinearly chirped fiber Bragg grating after an optically injected gain-switched laser. These features ensure that if such a compression scheme (or one equivalent) is used in conjunction with the appropriate optical injection regime, then these optically injected GS DFB pulse sources could be optimized for use in high-speed OTDM systems with bit rates in excess of 80 Gbit/s.

In conclusion, we provided a complete analysis of optically injected gain-switched sources, which is important in the development of picosecond pulse sources used for high-speed communications systems.

References

[1] J.P. Turkiewicz, E. Tangdiongga, G. Lehmann, H. Rohde, W. Schairer, Y.R. Zhou, E.S.R. Sikora, A. Lord, D.B. Payne, G.-D. Khoe, H. de Waardt, IEEE J. Lightw. Technol. 23 (2005) 225.
[2] M. Saruwatari, IEEE J. Sel. Topics Quantum Electron. 6 (2000) 1363.
[3] V. Mikhailov, P. Bayvel, I. Lealman, R. Wyatt, in: Proc. Eur. Conf. Optical Communications, 2001, p. 336.
[4] D.M. Spirit, A.D. Ellis, P.E. Barnsley, IEEE Comm. Mag. (1994) 56.
[5] P. Anandarajah, L.P. Barry, A. Kaszubowska, IEEE Photon. Technol. Lett. 14 (2002) 1202.
[6] P.L. Mason, A. Wonfor, D.D. Marcenac, D.G. Moodie, M.C. Brierley, R.V. Penty, I.H. White, S. Bouchoule, in: Proc. LEOS, 1997, p. 289.
[7] L.P. Barry, P. Guignard, J. Debeau, R. Boittin, M. Bernard, IEEE J. Select. Areas in Commun. 14 (1996) 1030.
[8] M. Suzuki, H. Tanaka, K. Utaka, N. Edagawa, Y. Matsushita, Electron. Lett. 28 (1992) 1007.
[9] K.Y. Lau, Appl. Phys. Lett. 52 (1988) 257.
[10] J.M. Wiesenfeld, M. Kuznetsov, A.S. Hou, IEEE Photon. Technol. Lett. 2 (1990) 319.
[11] P.B. Hansen, G. Raybon, U. Koren, B.I. Miller, M.G. Young, M. Chien, C.A. Burrus, R.C. Alferness, IEEE Photon. Technol. Lett. 4 (1992) 215.
[12] R. Kaiser, B. Huttl, H. Heidrich, S. Fidorra, W. Rehbein, H. Stolpe, R. Stenzel, W. Ebert, G. Sahin, IEEE Photon. Technol. Lett. 15 (2003) 634.
[13] H.F. Liu, S. Oshiba, Y. Ogawa, Y. Kawai, Opt. Lett. 17 (1992) 64.
[14] L.P. Barry, R.F. O'Dowd, J. Debeau, R. Boittin, IEEE Photon. Technol. Lett. 5 (1993) 1132.
[15] E.H. Bottcher, K. Ketterer, D. Bimberg, J. Appl. Phys. 63 (1988) 2469.
[16] M. Jinno, IEEE Photon. Technol. Lett. 5 (1993) 1140.
[17] L.P. Barry, J. Debeau, R. Boittin, Electron. Lett. 30 (1994) 2143.
[18] M.R.H. Daza, C.A. Saloma, IEEE J. Quantum Electron. 37 (2001) 254.
[19] P. Gunning, J.K. Lucek, D.G. Moodie, K. Smith, R.P. Davey, S.V. Chernikov, M.J. Guy, J.R. Taylor, A.S. Siddiqui, Electron. Lett. 32 (1996) 1010.
[20] D.-S. Seo, D.Y. Kim, H.-F. Liu, Electron. Lett. 32 (1996) 44.
[21] S. Nogiwa, Y. Kawaguchi, H. Ohta, Y. Endo, Electron. Lett. 36 (2000) 235.
[22] J.M. Liu, H.F. Chen, X.J. Meng, T.B. Simpson, IEEE Photon. Technol. Lett. 9 (1997) 1325.
[23] V. Annovazzi-Lodi, A. Scire, M. Sorel, S. Donati, IEEE J. Quantum Electron. 34 (1998) 2350.
[24] L.P. Barry, P. Anandarajah, A. Kaszubowska, IEEE Photon. Technol. Lett. 13 (2001) 1014.
[25] L. Chrostowski, X. Zhao, C.J. Chang-Hasnain, R. hau, M. Ortsiefer, M.-C. Amann, IEEE Photon. Technol. Lett. 18 (2006) 367.
[26] R. Trebino, K.W. DeLong, D.N. Fittinghoff, J.N. Sweetser, M.A. Krumbugel, B.A. Richman, Rev. Sci. Instrum. 68 (1997) 3277.
[27] L.P. Barry, B.C. Thomsen, J.M. Dudley, J.D. Harvey, IEEE Photon. Technol. Lett. 10 (1998) 935.
[28] Y. Matsui, S. Kutsuzawa, S. Arahira, Y. Ogawa, IEEE Photon. Technol. Lett. 9 (1997) 1087.
[29] J.M. Dudley, L.P. Barry, J.D. Harvey, M.D. Thomson, B.C. Thomsen, P.G. Bollond, R. Leonhardt, IEEE J. Quantum Electron. 35 (1999) 441.
[30] K.A. Ahmed, H.F. Liu, N. Onodera, P. Lee, R.S. Tucker, Y. Ogawa, Electron. Lett. 29 (1993) 54.
[31] B.J. Eggleton, P.A. Krug, L. Poladian, K.A. Ahmed, H.F. Liu, Opt. Lett. 19 (1994) 877.
[32] P.M. Anandarajah, C. Guignard, A. Clarke, D. Reid, M. Rensing, L.P. Barry, G. Edvell, J.D. Harvey, IEEE J. Sel. Topics Quantum Electron. 12 (2006) 255.
[33] S. Mohrdiek, H. Burkhard, H. Walter, IEEE J. Lightw. Technol. 12 (1994) 418.