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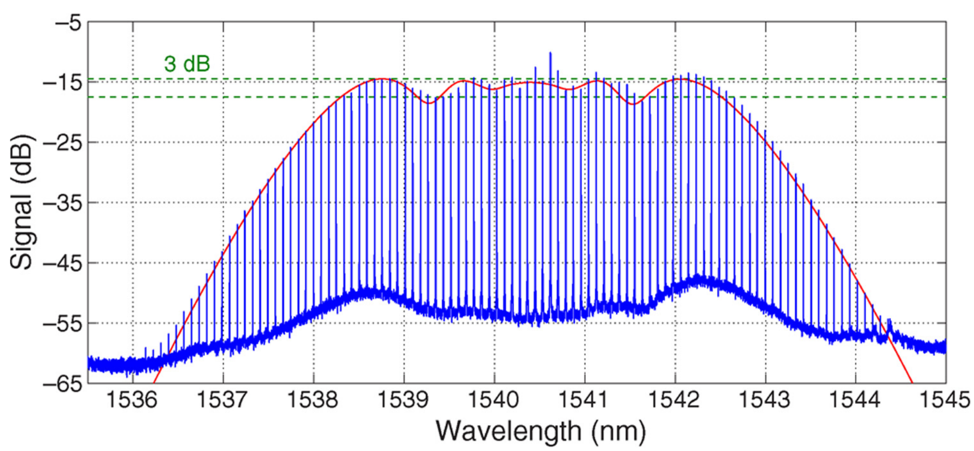

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Generation of Coherent Multicarrier Signals by Gain Switching of Discrete Mode Lasers

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Abstract: The authors demonstrate the generation of a highly coherent multicarrier signal that consists of eight clearly resolved 10.7-GHz coherent sidebands generated within 3 dB of the spectral envelope peak and with an extinction ratio in excess of 45 dB by gain switching a discrete mode (DM) laser. The generated spectral comb displays a corresponding picosecond pulse train at a repetition rate of 10.7 GHz with a pulse duration of 24 ps and a temporal jitter of ~450 fs. The optical spectra and associated pulses of the gain-switched DM laser are subsequently compared with a gain-switched distributed feedback (DFB) laser that generates a spectrum with no discernible sidebands and corresponding pulses with ~3 ps of temporal jitter. By means of external injection, the temporal jitter of the gain-switched DFB laser is then reduced to < 1 ps, resulting in visible tones on the output spectrum. Finally, a nonlinear scheme is employed and initially tailored to compress the optical pulses, after which, the setup is slightly altered to expand the original frequency comb from the gain-switched DM laser.

Index Terms: Frequency combs, injection locked lasers, pulse compression, optical communications.

1. Introduction

The extensive increase in bandwidth usage shows no sign of abating and is pushing service providers to deploy long-haul, metro, and access networks with increased capacity. With this continued push for higher capacities, carriers are resorting to upgrade the wavelength division multiplexing (WDM) systems by deploying higher wave counts or higher capacities per wavelength. One of the factors that have been attracting a lot of attention, with the move to higher line rates, is the information spectral density achieved at the transmitter. A promising approach entails the use of multicarrier spectrally efficient transmission techniques with the subchannel spacing equal to the symbol rate of each subchannel [1]–[4]. This can be achieved by electrically generated orthogonal frequency division multiplexing (OFDM) [1], all optically generated OFDM [2], the combination of both electrical and optical OFDM [3] or coherent WDM (CoWDM) [4]. A vital component that enables CoWDM is the optical frequency comb source (OFCS), which generates the coherent optical multicarrier signal. The

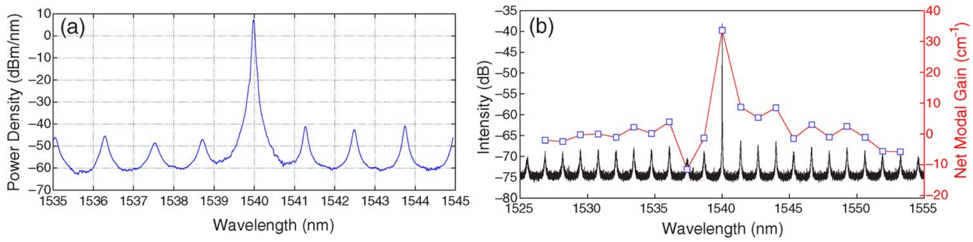

Fig. 1. (a) Optical spectrum of DM laser operating in CW mode. (b) Amplified spontaneous emission (ASE) spectrum with modal gain.

cost and simplicity of these sources are vital factors that will determine the applicability of this technology, especially in the price sensitive metro and access networks.

Most of the earlier reports on all optical implemented OFDM/CoWDM have used single or cascaded Mach–Zehnder modulators (MZM) to generate the phase correlated optical comb [5], [6]. Although this technique provides a relatively flat optical comb, the large insertion loss of the modulator coupled with the modulation efficiency can prove prohibitive. The extra optical component also adds to the cost and complexity of the transmitter, rendering this technique unsuitable for short reach applications. Another conventional technique entails the use of harmonic mode locking of a semiconductor laser, which subsequently generates an optical frequency comb with a comb spacing equal to the repetition rate of the pulse train [7], [8]. Although this technique can generate multicarrier signals spanning over a wide bandwidth, it inherently suffers from cavity complexity and fixed frequency spacing.

In this paper, we extend and improve previous work on gain switching of a discrete mode (DM) laser diode [9] to generate a highly coherent eight-carrier signal spaced by 10.7 GHz and compare the gain switching performance of DM lasers with that of conventional distributed feedback (DFB) laser diodes for the generation of an optical comb. The results show that the high SMSR and low jitter pulses, which exhibit a corresponding multitone spectrum, has potential to be employed as a frequency comb generator. Such a comb generator enables simple and cost efficient generation of lightwaves with the precisely controlled channel spacing required for high information spectral density communication systems. Conversely, previous results clearly show that the commonly used DFB laser cannot be used for efficient comb generation (coherent pulse generation), thereby demonstrating that the cost-efficient DM laser [10], [11] outperforms the standard DFB laser. This variation in performance can mainly be attributed to the superior phase noise characteristics that the DM laser exhibits. This characteristic is further validated, via experimental verification, by the improvement in the performance of the gain-switched DFB laser with external injection of light. In order to enhance the commercial applications and viability of the gain-switched DM laser as a comb source, we also carry out spectral comb expansion by employing a combination of linear and nonlinear pulse compression techniques.

2. Characterization of DM and DFB Laser Diodes

2.1. DC Characterization

The DM laser used is a commercially available ridge waveguide Fabry–Perot (FP) laser diode constrained to lase in a single mode of the FP cavity. This is achieved by introducing etched features onto the surface of the ridge to create topological refractive index perturbations that select a single mode of the cavity [10]. The device is hermetically sealed in a high-speed package, containing an optical isolator and is temperature controlled. The threshold current is characterized to be 16 mA, and the device displays a 3-dB electrical bandwidth of approximately 11 GHz at a bias of 55 mA. The emission wavelength when the laser is operated in continuous wave (CW) mode at a bias of 55 mA and at room temperature is 1540 nm, as shown in Fig. 1(a).

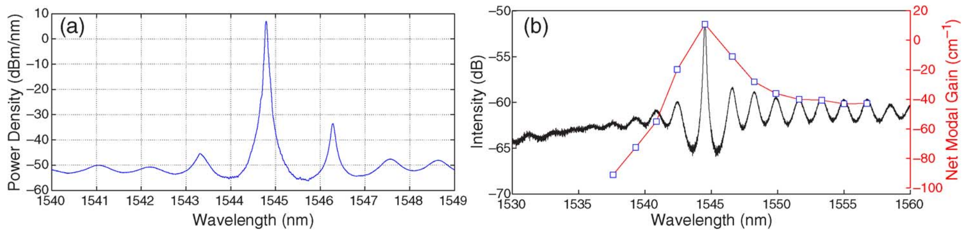

Fig. 2. (a) Optical spectrum of DFB laser operating in CW mode. (b) Amplified spontaneous emission (ASE) spectrum with modal gain.

The measured SMSR, in CW operation, is 48 dB, as indicated in Fig. 1(a). The suppressed subthreshold FP modes are visible and the mode spacing corresponds well to the measured chip length of 350 μm. The modal selectivity due to the etched features can be quantified using the Hakki–Paoli technique [12]. With this approach, the net modal gain (G) is related to the contrast ratio of the cavity resonances ρ in the below-threshold amplified spontaneous emission (ASE) spectrum using

$$G = \frac{1}{L_c}\ln\left(\frac{1}{r_1 r_2}\right) - \frac{1}{L_c}\ln\left(\frac{\sqrt{\rho}+1}{\sqrt{\rho}-1}\right). \tag{1}$$

Fig. 1(b) illustrates the ASE spectrum and the overlapped net modal gain (in cm^{-1}) for the DM laser. This figure clearly shows the gain difference between the lasing mode, and the next competing side mode is > 25 cm^{-1}, making it harder for competing modes to overcome this gain difference and lase. More importantly, this relatively large gain difference indicates that the coupling of ASE noise into the lasing mode is minimized.

The DFB laser with a cavity length of $\sim$320 μm is also a commercially available high-speed device contained within a temperature controlled hermetically sealed butterfly package. The threshold current was measured to be 15 mA and the bandwidth characterized to be 16 GHz at a bias current of 55 mA. Fig. 2(a) shows the CW DFB room temperature emission wavelength of 1545 nm at a bias current of 55 mA when measured using an optical spectrum analyzer (OSA). The measured SMSR is 40 dB. Fig. 2(b) shows the ASE spectrum and the overlapped net modal gain spectrum (in cm^{-1}) of the DFB laser. The DFB has a quarter-wave shifted grating as the Bragg mode is in the center of the stop band. The gain difference between the Bragg mode and the next competing mode is $\sim$20 cm^{-1}. This is 20% lower than that exhibited by the DM laser diode, which, as opposed to the DM laser, allows more coupling of ASE noise into the lasing mode [13].

The origin of the linewidth broadening in a semiconductor laser stems from the fact that the phase of the electric field within the laser cavity is perturbed by inherent spontaneous emission noise [13], [14]. In addition, the ASE noise also induces a photon number fluctuation in the cavity that manifests as amplitude noise, which causes a corresponding frequency noise through the change in refractive index with carrier density. Therefore, the overall linewidth (phase noise) can be decomposed into the sum of two contributions from the spontaneous emission noise and the frequency noise induced by amplitude variations through refractive index change. Hence, to further outline the differences between the two types of laser transmitters used in this work, in terms of their phase noise properties, we also characterized the linewidth of each device. It is important to note that both the DM and DFB lasers used in this experiment were chosen based on possessing similar high-speed characteristics and closely matched parameters.

2.2. Linewidth Characterization

Fig. 3 shows the experimental setup used to realize the delayed self-heterodyne (DS-H) linewidth characterization [15]. The fiber delay length in one arm of the setup is 12 km (corresponding to a linewidth measurement resolution of $\sim$10 kHz). Light propagating in the short arm of the setup is modulated using a $LiNbO_3$ phase modulator to frequency shift the detected heterodyne beat signal to 2 GHz, thereby enhancing the measurement accuracy. The laser linewidth is then deduced from

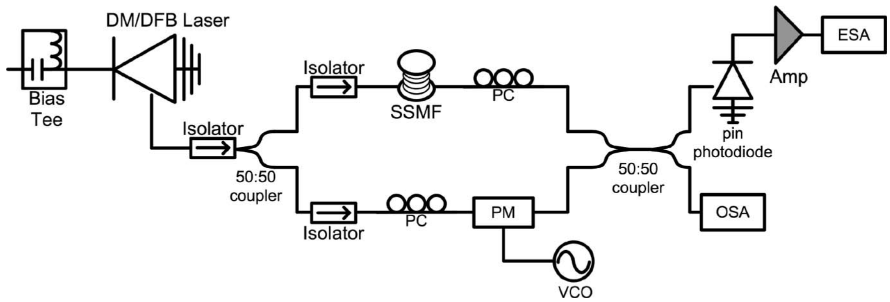

Fig. 3. Experimental setup for linewidth characterization.

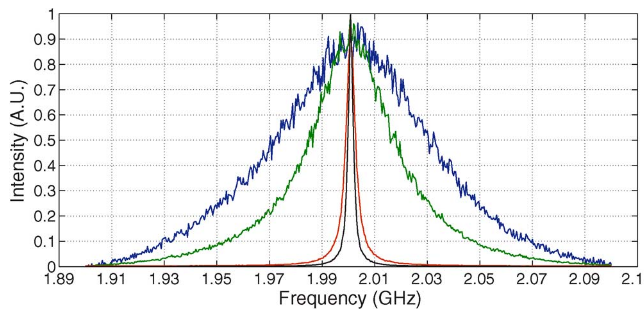

Fig. 4. Linewidths measured using the DS-H method. Black line: CW DM @ 1 mW. Red line: CW DM @ 2 mW. Green line: CW DFB @ 1 mW. Blue line: CW DFB @ 2 mW.

the beat frequency spectrum between the delayed and the nondelayed light measured using an electrical spectrum analyzer (ESA).

The linewidth of the two lasers (DM and DFB) in CW mode is characterized when they emit fiber coupled output powers of 1 and 2 mW, and the measured results are shown in Fig. 4. The CW linewidth of the DM laser at output powers (bias currents) of 1 mW (34 mA) and 2 mW (55 mA) is measured to be 2 and 1.2 MHz, respectively. The CW linewidth of the DFB laser at output powers (bias current) of 1 mW (28 mA) and 2 mW (48 mA) is measured to be 31.8 and 17.8 MHz, respectively. This large variation in linewidth between the two types of lasers, when running in CW mode, shows that the DM laser exhibits superior phase noise characteristics.

There are two fundamentally inherent mechanisms that contribute to the narrow linewidth exhibited by the DM laser. First, the FP cavity mirror loss strongly enhances one FP mode relative to all other modes that are simultaneously suppressed. This differentially increases the loss for nonlasing cavity modes and reduces the noise amplitude coupled into the lasing mode. Second, an important feature of the DM laser is that the multiple quantum well active region is fabricated in the InGaAlAs material which has a high differential gain. This high differential gain results in a linewidth enhancement (alpha) factor of approximately 2–3 [16]. As mentioned, the laser linewidth induced by the amplitude noise arises from the spontaneous emission noise through the linewidth enhancement factor [13]. Therefore, the linewidth of the DM laser can be maintained at a low value (1–2 MHz), relative to that exhibited by the DFB laser (18–32 MHz), which typically has an alpha factor of approximately 5.

3. Gain Switching of DM and DFB Laser Diodes

3.1. Experimental Setup

Fig. 5 shows the experimental setup used to realize the gain switching of the DM and DFB lasers characterized in the previous sections. Gain switching is achieved by applying an amplified

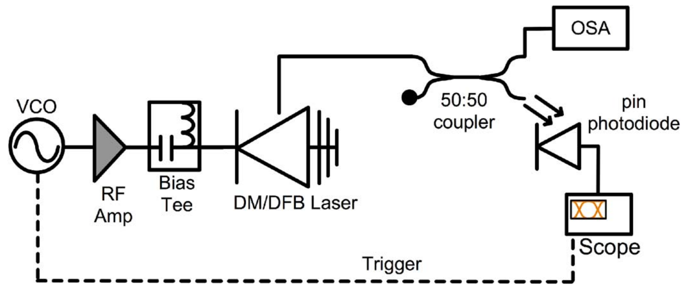

Fig. 5. Experimental setup for gain-switched DM and DFB lasers.

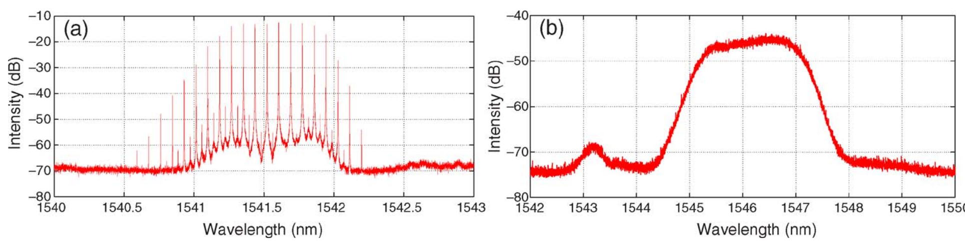

Fig. 6. (a) Optical gain-switched spectra for DM laser. (b) Optical gain-switched spectra for DFB laser.

10.7-GHz sinusoidal RF signal (24 dBm) in combination with a dc bias ($\sim 4I_{th}$) to the laser via a bias tee. The optical output of the laser source is split using a 3-dB fiber coupler to enable simultaneous temporal and spectral measurements. The characterization of the multicarrier signal is carried out by using a high-resolution (20-MHz) OSA and a high-speed oscilloscope ($>$ 65 GHz) in conjunction with a 50-GHz pin detector.

3.2. Results and Discussion

Fig. 6(a) shows the spectrum of the gain-switched DM laser where the spectral envelope has a full-width at half-maximum (FWHM) of approximately 0.5 nm. The SMSR is preserved under the high-speed modulation and is greater than 45 dB, which is highly advantageous in hybrid WDM/OTDM systems [17]. This modulated spectrum also shows efficient sideband generation in the lasing mode (approximately eight, 10.7-GHz sidebands are generated within 3 dB of the spectral envelope peak) and two small equidistant features on either side of the spectrum corresponding to the subthreshold FP cavity modes. The high modulation depth of $>$ 45 dB indicates the excellent pulse-to-pulse phase stability, as well as the phase co-relation of the emitted pulses [18]. Fig. 6(b) displays the corresponding spectrum of the gain-switched DFB laser. In contrast to the gain-switched DM laser, modulation of the DFB laser results in a significantly broadened spectrum [8]. In addition, the peak to background spectral contrast reduces to 32 dB, which would result in degraded performance if the DFB based transmitter is implemented in a hybrid WDM/OTDM system [17]. The degradation in performance is due to an effect that is known as mode partition noise. This effect is basically a fluctuation of the energy in each laser mode with time, due to a constant transfer of energy between the modes. For a single-mode laser with a large SMSR, the power in the side modes is negligible; thus, the power fluctuation of the main mode is negligible. However, as the SMSR decreases the power fluctuation of the main mode, and the side modes may become nonnegligible.

Fig. 7(a) and (b) show the measured optical pulses from the gain-switched DM and DFB lasers, respectively. The pulse width for the gain-switched DM laser is 24 ps, while the pulse width for the gain-switched DFB laser is 13 ps. We attribute the shorter pulse width of the DFB laser to the relatively higher bandwidth $\sim$16 GHz (in comparison with the DM laser, which has a bandwidth of

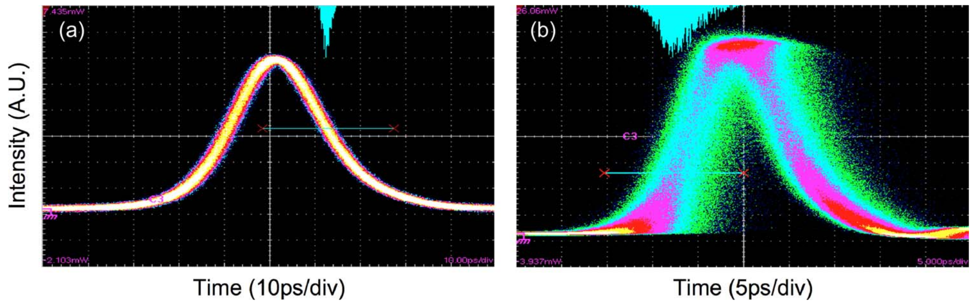

Fig. 7. Temporal jitter on gain-switched pulses (a) DM and (b) DFB.

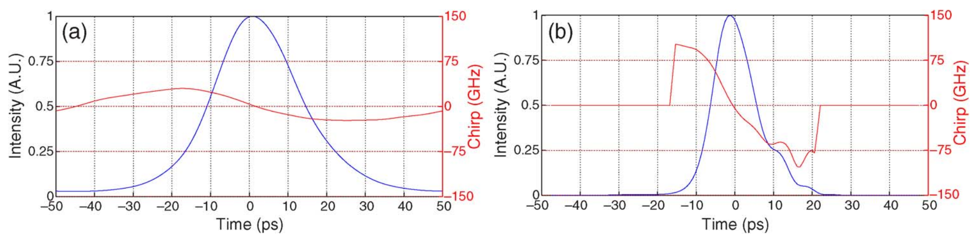

Fig. 8. Temporal intensity and chirp of gain-switched (a) DM laser pulse and (b) DFB laser pulse.

11 GHz). More importantly, the root mean squared (RMS) jitter of the gain-switched DM pulses is measured to be ∼450 fs, while that of the DFB is measured to be ∼3 ps. The reduced jitter on the generated pulses, in the case of the gain-switched DM laser, reflects the clearly resolvable sidebands in the corresponding spectrum.

The temporal jitter in gain-switched laser pulses stems from the fluctuation in the photon density during the buildup of the optical pulse, caused by the random nature of spontaneous emission [19]. Hence, the reduced level of jitter on the gain-switched DM laser pulses can be mainly attributed to the lower coupling of the ASE noise into the lasing mode. This principle is further substantiated by the minimization of the spontaneous emission contribution to the temporal jitter of the gain-switched DFB pulses by external injection [20], [21], which is experimentally verified in Section 4.

Further characterization of the gain-switched DM pulses is carried out using a stepped heterodyne measurement technique that is capable of recovering the amplitude and phase of a periodic optical signal [22]. Fig. 8(a) shows the intensity and the chirp profile of the gain-switched DM laser pulses obtained by using this technique. The pulse duration is 24 ps, and more importantly, the total magnitude of the chirp across the pulse is approximately 60 GHz. Fig. 8(b) shows the intensity and chirp profile of the gain-switched DFB laser. In this case, the stepped heterodyne could not be employed to characterize the amplitude and phase essentially due to the lack of discernible frequency tones. The amplitude and phase characterization, in this case, was performed by employing the Frequency Resolved Optical Gating (FROG) technique [23]. The pulse width is measured to be 13 ps, and the total magnitude of chirp across the pulse is approximately 200 GHz. The relatively small chirp across the gain-switched DM laser pulse (relative to the gain-switched DFB laser pulse) is testament to the previous studies that reported the linewidth enhancement factor of the DM laser to be approximately 2–3 [16].

4. Externally Injected Gain-Switched DFB Laser

4.1. Experimental Setup

Fig. 9 depicts the experimental setup employed to realize the externally injected gain-switched transmitter. The transmitter setup remains unchanged apart from the addition of a second DFB

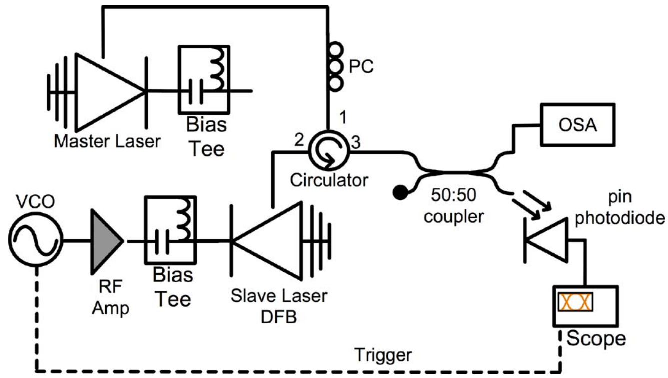

Fig. 9. Experimental setup for externally injected gain-switched DFB laser.

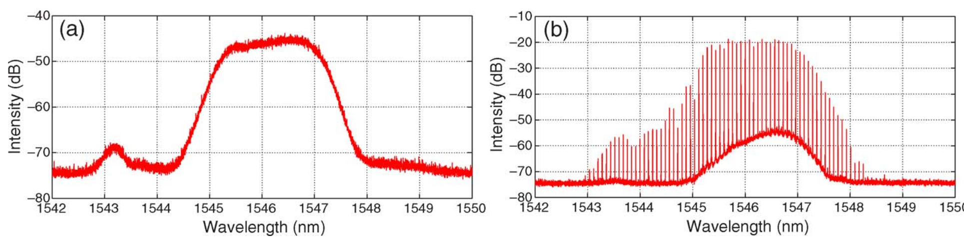

Fig. 10. (a) Optical spectra of gain-switched DFB without external injection. (b) With external injection.

laser for injection. External injection is achieved by employing a master-slave configuration and is realized by using an optical circulator to direct the light from the second DFB laser biased at 23.5 mA ($\sim$1.2I_{th}). A polarization controller (PC) is also used to ensure that the light being injected is aligned to the optical axis of the modulated (slave) laser. The wavelength of the master laser is matched to the slave (with the aid of temperature tuning), and the injected power is approximately 0 dBm (measured after port two of the circulator), which ensured low level injection of the slave laser. The generated optical signal is again characterized by using a high-resolution (20-MHz) OSA and a high-speed oscilloscope ($>$ 65 GHz) in conjunction with a 50-GHz pin detector.

4.2. Results and Discussion

Fig. 10(a) and (b) show the optical spectra from the gain-switched DFB without and with external optical injection. As can be seen in the free-running gain-switched DFB, modulation of the laser results in the same significantly broadened spectrum, as previously discussed in Section 3. However, by injecting light into the gain-switched DFB, we notice the generation of sidebands in the lasing mode. The external injection of light provides an excitation of the lasing mode to be well above the level of spontaneous emission, thereby reducing the relative fluctuations in the photon density, resulting in a corresponding reduction in timing jitter. The reduction in pulse-to-pulse timing jitter improves the coherence of the pulse train, thereby resulting in the presence of spectral sidebands. Fig. 10(b) illustrates that 19 tones are generated within 3 dB of the spectral envelope peak. This is approximately 2.5 times greater than the number of sidebands generated by the gain-switched DM laser; however, the modulation depth is limited to 30 dB, indicating that the phase co-relation of the emitted pulses and the pulse-to-pulse stability is still poorer than the gain-switched DM laser case.

Fig. 11(a) and (b) show the optical pulses without and with external optical injection. The free running gain-switched DFB pulses [see Fig. 10(a)] portray the same jitter ($\sim$3 ps), as mentioned previously in Section 3.2. In the case of the externally injected gain-switched DFB; the pulse width is

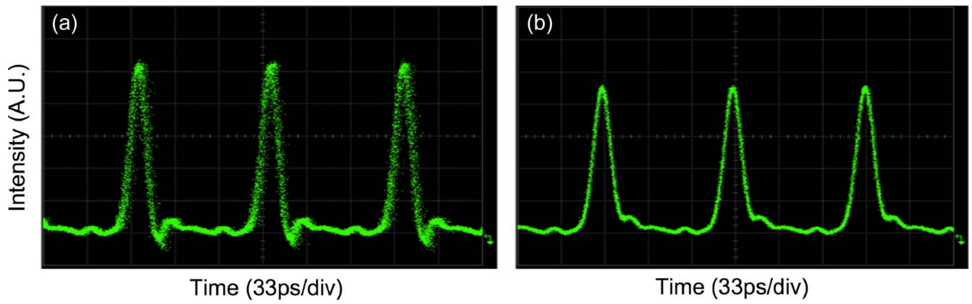

Fig. 11. (a) Pulses of gain-switched DFB without external injection. (b) With external injection.

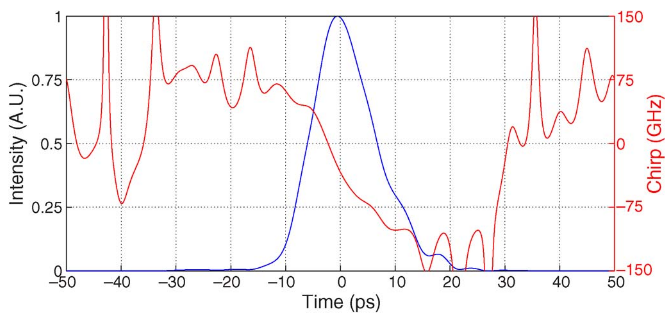

Fig. 12. Temporal intensity and chirp of externally injected gain-switched DFB laser.

measured to be 13 ps. More importantly, as shown in Fig. 11(b), the rms jitter is reduced to less than 1 ps (the Tektronix oscilloscope with the 250-fs jitter measurement option used earlier was not available at this time). As mentioned earlier, by injecting photons into the laser cavity, the differential gain of the longitudinal mode, whose frequency coincides with the frequency of the injected photons, will be increased, thereby suppressing the coupling of spontaneous emission. This prevents the random fluctuations of the photon density, thus exhibiting a smaller timing jitter in the output pulses.

Further characterization of the externally injected gain-switched DFB laser pulses in terms of the intensity and chirp profiles was carried out using the stepped-heterodyne measurement technique and is depicted in Fig. 12. It can be clearly seen that the total magnitude of chirp has been reduced from 200 GHz to approximately 140 GHz by employing external light injection. This reduction in chirp is due to the inherent suppression in carrier density fluctuations due to external injection and the effects of this suppression is also clearly visible from the coherent comb depicted in Fig. 10(b).

5. Pulse Compression/Comb Expansion Through Self Phase Modulation

The special property of a gain-switched DM laser yielding low jitter pulses and a corresponding frequency comb alludes to the fact that it can be employed as a cost efficient transmitter (by filtering individual sidebands) in networks utilizing advanced modulation formats, as well as in CoWDM transmission systems [24], [25]. The viability of such a source would be vastly improved if the number of generated sidebands could be increased. This may be achieved by exploiting the nonlinear effects in standard single mode fiber. If the peak power of the generated pulses is sufficient, self phase modulation (SPM) effects in the fiber may be induced, and when combined with anomalous dispersion, pulse compression occurs. A consequence of pulse compression is a broader spectral envelope. Therefore, this technique is employed to multiply the number of frequency tones present in the gain-switched comb spectrum.

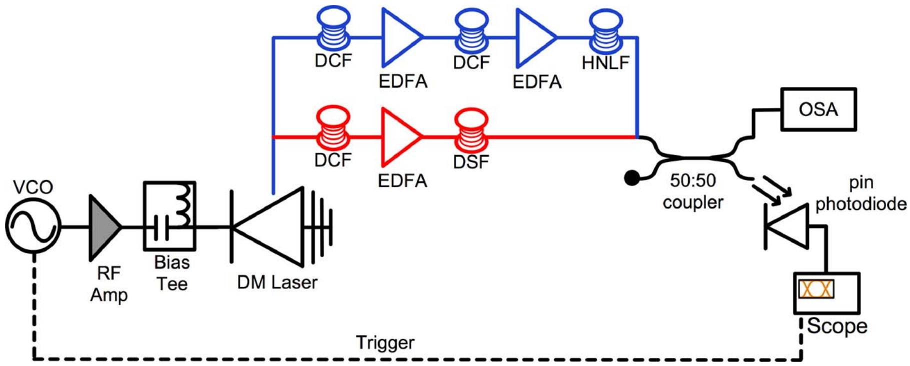

Fig. 13. Experimental setup used to perform. Compression of the gain-switched pulses (red line) and the expansion of the frequency comb (blue line).

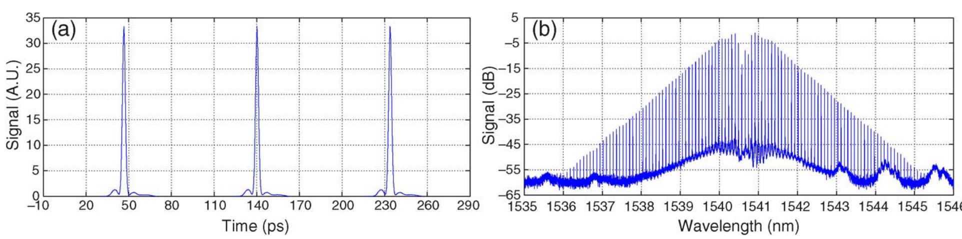

Fig. 14. (a) Compressed gain-switched pulse. (b) Corresponding expanded frequency comb spectrum.

5.1. Experimental Setup

Fig. 13 shows the experimental setup used to compress the generated pulses (red line) and to generate an expanded a low-ripple frequency comb (blue line) from the gain-switched DM laser. The transmitter setup is unchanged, and the optical pulses are passed directly into a dispersion compensating fiber (DCF). As shown in Fig. 8, the gain-switched DM pulses exhibit a predominantly linear chirp with a negative slope across the central part of the pulse; therefore normal dispersion can be employed for compression. The first compression technique (see the red section in Fig. 13) employed a 600-m span of DCF with a dispersion of -99 ps/nm/km at 1540 nm. The pulses are further compressed by the nonlinear technique of higher order soliton compression in a dispersion shifted fiber (DSF) [26]. A 4.8-km span of dispersion shifted fiber is used for the soliton compression, and it exhibited a dispersion parameter of 4.5 ps/nm/km at 1540 nm. For the second scenario (see the blue section in Fig. 13), the linearly compressed pulses are amplified and passed through a second 200 m length of DCF followed by a second EDFA and a 950-m length of highly nonlinear fiber (HNLF, dispersion -0.5 ps/nm/km) to produce an optical frequency comb optimized for low spectral-ripple. For both compression stages, the output signal is split using a passive 3-dB optical coupler before being analyzed with a high-resolution OSA and a commercially available optical sampling oscilloscope with a sampling bandwidth of 500 GHz.

5.2. Results and Discussion

After propagating through the 600 m of DCF, the pulse duration of the gain-switched DM laser is reduced from 24 ps to 11 ps. This compressed pulse has a time-bandwidth product of 0.5, which is close to the optimum value of 0.44 for a Gaussian pulse. For the higher order soliton compression, this pulse is then amplified to 46 mW average power (peak power 0.42 W, soliton number $N \sim 4$) and propagated through 4.8 km of DSF. The temporal profile and spectrum of the pulse at the output of the DSF is shown in Fig. 14. The pulse width after this compression is 2.3 ps, and the

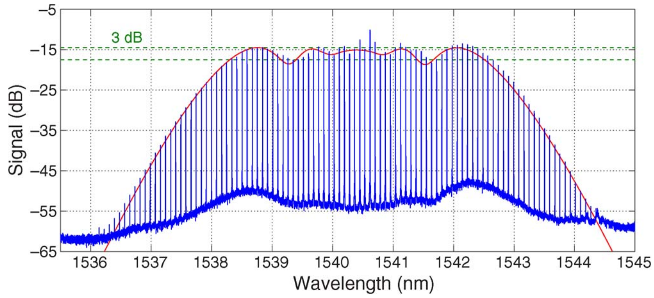

Fig. 15. Expanded comb spectrum of the gain-switched DM laser. Measured spectrum (blue trace). Numerical simulation (red trace).

temporal profile of the pulse is clean, apart from the small pedestals on either side of the main pulse, which are characteristic of higher order soliton compression [26]. As can be seen in Fig. 14(b), the number of frequency tones in the spectrum of the compressed pulse is considerably increased, compared with the input pulse. For many applications, it is desirable that this expanded frequency comb also possesses a relatively flat spectral profile rather than the peaked spectrum seen in Fig. 14(b).

This can be achieved using the second configuration shown in Fig. 13 (blue line). The fiber lengths and the pump powers used in this setup have been optimized for low spectral ripple using a full simulation of the generalized nonlinear Schrodinger equation, including the effects of third-order dispersion and the complex Raman susceptibility [26]. After the linear compression stage, the pulse is amplified to 100 mW average power and passed though a second 200 m length of DCF in order to pre-chirp the pulse. The pulse is then amplified to 83 mW average power and passed through 950 m of highly nonlinear fiber. The spectrum at the output of the HNLF is shown in Fig. 15(a) (blue trace) and exhibits excellent flatness and enhanced spectral width. The frequency spacing and 3-dB spectral width of the expanded comb were 10.7 GHz and $>$ 500 GHz, respectively. The number of spectral tones within a 3-dB spectral ripple is approximately 50. Also plotted is the result of the nonlinear Schrodinger equation simulation (red trace) used to optimize the comb expansion. The two curves show an excellent agreement. Importantly, the frequency tones are still clearly resolvable with a large modulation depth, indicating that the phase co-relation and pulse-to-pulse stability remains high, demonstrating improved performance over the externally injected DFB laser. The optimum expansion of the frequency comb is significant as it would allow such a source to act as a multiwavelength transmitter for implementation in DWDM applications. Additionally, the low linewidth portrayed by each of the individual sidebands [9] implies that such a transmitter could be used in optical networks that employ spectrally efficient advanced modulation formats, such as m-PSK on each tone. Also, as previously alluded to, the high coherence between the spectral frequency tones enables the use of this transmitter in CoWDM systems [25].

6. Conclusion

We have demonstrated an optimized, cost-efficient technique of gain switching a DM laser transmitter to generate a coherent optical multicarrier signal. The gain-switched DM laser spectrum portrays efficient sideband generation in the lasing mode with eight 10.7-GHz sidebands generated within 3 dB of the spectral envelope peak and an extinction ratio in excess of 45 dB that signifies excellent coherence properties. The corresponding optical pulses exhibit pulse widths of about 24 ps and display extremely small temporal jitter of $\sim$450 fs without the additional complexity of external injection seeding. By incorporating additional linear and nonlinear compression schemes, we have also shown that this transmitter can be considered as a potential candidate for high-speed multicarrier transmission systems targeting Terabit per second applications and beyond.

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