# Phase shift keyed systems based on a gain switched laser transmitter

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**Abstract:** Return-to-Zero (RZ) and Non-Return-to-Zero (NRZ) Differential Phase Shift Keyed (DPSK) systems require cheap and optimal transmitters for widespread implementation. The authors report on a gain switched Discrete Mode (DM) laser that can be employed as a cost efficient transmitter in a 10.7 Gb/s RZ DPSK system and compare its performance to that of a gain switched Distributed Feed-Back (DFB) laser. Experimental results show that the gain switched DM laser readily provides error free performance and a receiver sensitivity of −33.1 dBm in the 10.7 Gbit/s RZ DPSK system. The standard DFB laser on the other hand displays an error floor at $10^{-1}$ in the same RZ DPSK system. The difference in performance, between the two types of gain switched transmitters, is analysed by investigating their linewidths. We also demonstrate, for the first time, the generation of a highly coherent gain switched pulse train which displays a spectral comb of approximately 13 sidebands spaced by the 10.7 GHz modulation frequency. The filtered side-bands are then employed as narrow linewidth Continuous Wave (CW) sources in a 10.7 Gb/s NRZ DPSK system.

**OCIS codes:** (060.0060) Fiber optics and optical communications; (250.5960) Optoelectronics and semiconductor lasers; (320.5550) Ultrafast optics and pulses.

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#110879 - $15.00 USD Received 1 May 2009; revised 2 Jun 2009; accepted 24 Jun 2009; published 10 Jul 2009

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## 1. Introduction

The introduction of Wavelength Division Multiplexing (WDM) by telecommunication operators provided a new direction for dealing with increased data transmission requirements. However, the extensive increase in bandwidth usage shows no sign of abating in the coming decade and is pushing service providers to deploy optical backbone transmission with increased capacity and reach. With this continued push for higher capacities and longer reach, carriers are resorting to upgrade the WDM systems by deploying higher wave counts (at 10 Gb/s) or higher capacities per wavelength. One of the factors that has been attracting a lot of attention, with the move to higher line rates, is the coding used at the transmitter. Most of the current systems have tended to employ conventional On-Off-Keyed (OOK) signals in the Non-Return-to-Zero (NRZ) format. However, in order to achieve large line rates, it may become necessary to use Return-to-Zero (RZ) coding [1,2]. RZ (pulse) modulation formats offer a number of advantages over NRZ modulation schemes (especially in long haul transmission), such as higher Signal-to-Noise Ratio (SNR) and lower system Bit Error Rate (BER), translating to better overall system performance. Hence, the development of picosecond optical pulse sources with excellent temporal and spectral properties is vital for future implementation of high capacity optical communications systems [3].

As mentioned earlier, another way of increasing the capacity of optical communication systems involves increasing the number of WDM channels. However, this effectively causes

#110879 - $15.00 USD Received 1 May 2009; revised 2 Jun 2009; accepted 24 Jun 2009; published 10 Jul 2009

the WDM channel spacing to decrease, thereby placing added emphasis on the impact of dispersion as well as intra- and inter-channel nonlinearities. The use of advanced modulation formats is one technology that can improve system performance by offering better immunity to dispersion and/or nonlinear impairments [4–6]. Moreover, the use of such formats also yields better spectral efficiency or higher information spectral density. Many of these formats involve the use of Phase Shift Keying (PSK), where the information is mapped on to the phase of the optical signal [7]. Since the conventional direct detection receivers lack an absolute phase reference, the phase of the preceding bit is used as a relative reference for modulation. This results in a Differential Phase Shift Keyed (DPSK) format, which carries information in optical phase changes between bits, offers high receiver sensitivity, high tolerance to major nonlinear effects in high-speed transmissions and high tolerance to coherent crosstalk [8,9]. Depending on the coding used, the optical power can appear in an entire bit slot (NRZ DPSK) or appear as an optical pulse (RZ DPSK). In terms of performance and tolerance to nonlinearity, RZ DPSK has been reported to be better [10,11]. A vital requirement for such RZ DPSK systems is an optical RZ transmitter that exhibits high levels of performance in terms of pulse width, phase noise, pulse to pulse stability and wavelength stability [11].

Picosecond pulse sources have been demonstrated using several different techniques such as pulse carving [12], mode-locking of fibre ring lasers [13], modelocking of semiconductor lasers [14] and gain-switching [15], all of which have unattractive attributes for the applications concerned. For example, pulse carving is achieved by gating Continuous Wave (CW) light with a sinusoidally driven electro-absorption modulator or Mach-Zehnder Modulator (MZM). While this method offers short pulse generation over a wide wavelength range, it suffers from large insertion losses and requires the use of expensive components including post amplification. Similarly, mode-locking has the ability to generate very short pulses at fixed frequencies, however cavity complexity, wavelength instability and limited repetition rate tunability are major disadvantages associated with this technique.

The simplest and most robust pulse generation technique involves gain-switching of single mode Distributed Feed-Back (DFB) laser diodes [15]. The inherent simplicity of direct modulation, results in the gain-switched pulse source being cost-efficient, which proves to be of great practical significance with regard to market adoption. Unfortunately, while low cost and simplicity are among the numerous advantages of this technique, it does suffer from some drawbacks, such as Side Mode Suppression Ratio (SMSR) degradation and relatively large temporal jitter. While these shortcomings have been overcome by self seeding [16] or external light injection [17], such corrective measures not only increase the cost and complexity of the pulse generation technique but also can lead to unstable operation.

In this paper, we investigate the gain switching of Discrete Mode (DM) laser diodes [18] and demonstrate the use of the generated picosecond pulses in a 10.7 Gb/s RZ DPSK system. We also compare the performance of the gain switched DM laser pulses with that of conventional DFB laser diode pulses in the same 10.7 Gb/s RZ DPSK system. The results show that the DFB laser cannot be used in such PSK systems thereby demonstrating that the cost efficient DM laser outperforms the standard DFB laser by exhibiting superior phase noise characteristics. The low phase noise and and high level of phase stability exhibited by the gain switched DM laser should allow this laser to be used as a frequency comb generator, which enables the generation of lightwaves with the precisely controlled channel spacing required for high information spectral densities. Hence, in order to verify whether the gain switched DM laser can be used successfully as a frequency comb generator, individual sidebands are filtered and phase modulated. This characterization is carried out on the gain switched DFB laser as well. The difference in performance between the two laser transmitters is mainly attributed to the linewidth. Hence, the linewidth of the two types of lasers is characterized, using the Delayed Self-Heterodyne (DS-H) method when the lasers are gain switched.

#110879 - $15.00 USD Received 1 May 2009; revised 2 Jun 2009; accepted 24 Jun 2009; published 10 Jul 2009

## 2. Pulse Source and DPSK System Performance

### *2.1 Experimental Set-up*

Figure 1 shows the experimental set-up used to realize the optical pulse source. As illustrated in Fig. 1, the pulse generation set-up involves using the technique of gain switching on two different types of lasers (DM and DFB). Gain switching is achieved by combining an amplifed 10.7 GHz sinusoid RF signal (25 dBm) with a DC bias (~4$I_{th}$) via a bias tee and then applying this combined signal to the laser. The characterization of the generated pulses is carried out by using a high resolution (20 MHz) Optical Spectrum Analyzer (OSA) and a high-speed oscilloscope (>65 GHz) in conjunction with a 50 GHz pin detector.

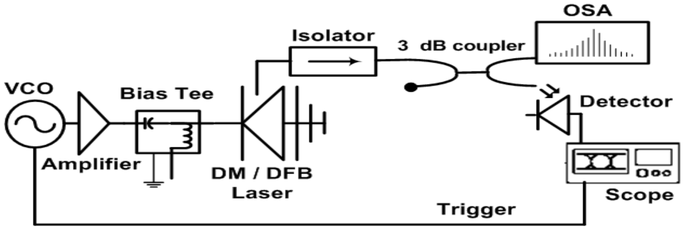

Fig. 1. Optical pulse source based on gain switched DM and DFB lasers.

The DFB used is a commercial device in a temperature controlled hermetically sealed high speed butterfly package with a bandwidth of about 18 GHz at a bias current of 60 mA and has an inbuilt isolator. It has a room temperature emission wavelength of 1545 nm and a threshold current of 15 mA. The DM laser is also a commercially available ridge waveguide Fabry-Perot laser diode constrained to lase in a single mode. 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 [18]. The DM laser used in this study is hermetically sealed in a high speed package, contains an optical isolator and is temperature controlled. It displays a room temperature bandwidth of about 10 GHz at a bias of about 55 mA. The emission wavelength at room temperature is 1539 nm and the threshold current is about 16 mA.

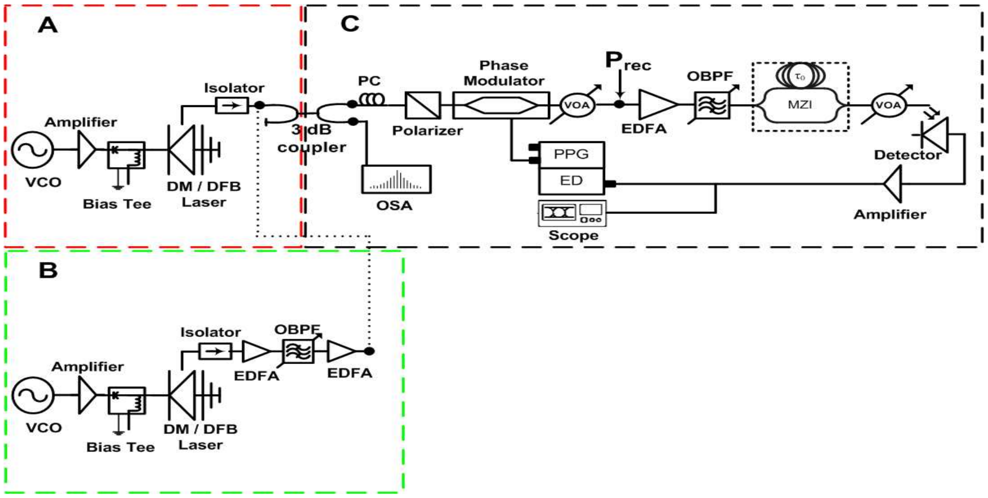

Fig. 2. Experimental set-up for (C) 10.7 Gb/s DPSK system (A) with RZ transmitter and (B) filtered line transmitter.

Figure 2 shows the DPSK system set-up with 2 different transmitter configurations. Section A (red dashed square), in the Fig., shows the case when the gain switched laser (same set-up as in Fig. 1) is used as the transmitter in the system performance analysis. Section C (black dashed rectangle), in the Fig., illustrates the DPSK system. The output of the gain switched laser is connected to a Polarization Controller (PC) and a polarizer which is then followed by a Phase Modulator (PM). The polarizer is set to match the polarization axis of the PM after which the PC is then adjusted to maximize the power at the output of the polarizer. A 10.7 Gb/s Pseudo Random Binary Sequence (PRBS) of length $2^7$-1 from a Pulse Pattern Generator (PPG) is used to modulate the 10.7 GHz pulse train with the aid of the PM. The phase of the pulses from the gain switched laser is modulated with a $\pi$ phase shift between "0" and "1" bits. At the receiver, the average power ($P_{rec}$) is recorded after the first Variable Optical Attenuator (VOA) subsequent to which the signal is amplified using an Erbium Doped Fiber Amplifier (EDFA) and passed into an Optical Band Pass Filter (OBPF). The EDFA used had a gain of 45 dB and a noise figure of 4 dB while the OBPF used had a FWHM of 5 nm. A Mach-Zehnder Delay-Interferometer (MZDI), with a differential delay equal to the bit period, is used for demodulation of the DPSK signal (In DPSK formats, the phase of the proceeding bit is used as a relative phase reference [4]). The demodulated optical signal from the constructive port of the MZDI is then detected (>50 GHz single ended pin detector), amplified and passed to the Error Detector (ED) for BER measurements. Section B (green dashed rectangle), in Fig. 2, exhibits the configuration when the gain switched laser is used as a comb generator. In this case, one of the generated side-bands from the modulated laser is filtered out using a Fabry Perot filter, with a 3 dB bandwidth of about 3 GHz, providing approximately 20 dB suppression of unwanted sidebands. The filtered (CW) signal is then passed into the same DPSK set-up as described above for performance evaluation.

### *2.2 Results and Discussion*

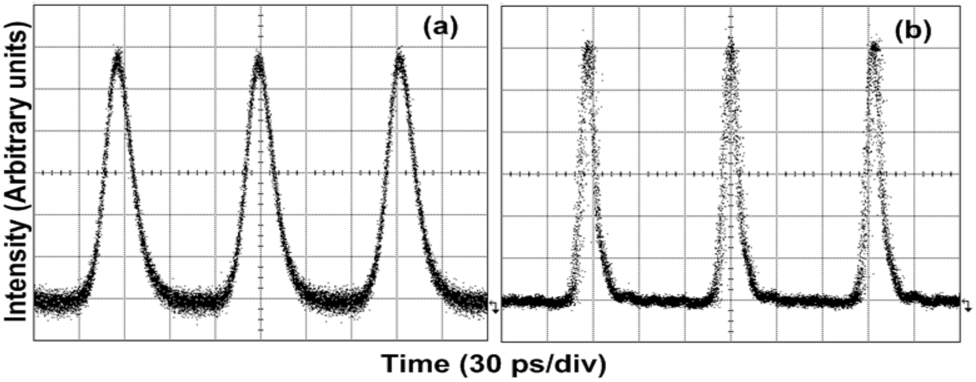

Fig. 3. Gain switched pulses (a) DM (b) DFB.

The gain switched pulses at a repetition rate of 10.7 GHz from both the DM and the DFB lasers are shown in Figs. 3(a) and (b) respectively. The pulsewidth of the gain switched DM laser is measured to be 22.3 ps while the pulsewidth of the gain switched DFB laser is 10.3 ps. We attribute the lower pulsewidth of the DFB pulses to the higher bandwidth of the DFB device. More importantly the rms jitter of the gain switched DM pulses is measured to be ~800 fs, while that of the DFB is measured to be ~3 ps [19]. The average output power of the gain switched pulse train from the DM and DFB lasers are measured to be 1.9 mW and 2.5mW, respectively.

Figure 4 shows the measured spectra of the gain switched lasers. Figure 4(a) shows the spectrum of the DM laser under gain-switched modulation and clearly illustrates the efficient sideband generation in the lasing mode. The envelope has a FWHM spectral width of about 0.3 nm. Approximately seven sidebands, spaced by 10.7 GHz, are generated within 10 dB of the spectral envelope peak and are clearly resolved by the high resolution OSA. The high modulation depth of about 50 dB indicates the excellent pulse to pulse phase stability and co-relation of the emitted pulses [11]. This property alludes to the fact that such a gain switched DM laser can be employed as a cost efficient transmitter (by filtering individual sidebands) in systems emplying advanced modulation formats and also in Coherent WDM (CoWDM)

#110879 - $15.00 USD Received 1 May 2009; revised 2 Jun 2009; accepted 24 Jun 2009; published 10 Jul 2009

transmission systems [20,21]. It is important to note that the frequency spacing of the comb corresponds to the modulation frequency and can be tuned precisely with the RF signal generator within a range of about 8 GHz (5-13 GHz). The two small equidistant features on either side of the spectrum corresponding to the sub-threshold Fabry-Pérot (FP) cavity modes match the measured chip length of $L_{cav}$ = 350 µm. A key point is that the SMSR (~68 dB) is preserved under the high speed, high contrast modulation. This high SMSR portrayed by the pulses is vital when they are employed in hybrid WDM/OTDM systems [22]. The inset in Fig. 4(a) represents the DM emission spectrum obtained when the laser is operated CW at a bias of 55 mA. The measured SMSR is 70 dB.

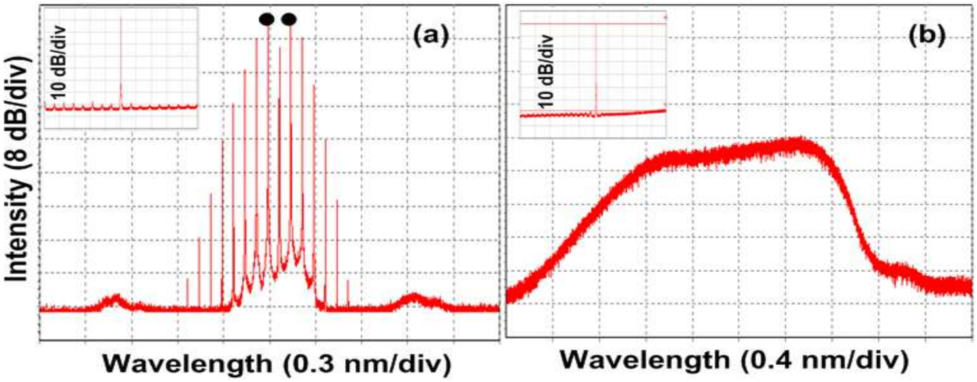

Fig. 4. Spectra (a) DM gain switched, inset (CW) (b) DFB gain switched, inset (CW).

Figure 4(b) shows the spectrum of the gain switched DFB laser. In contrast to the gain switching of the DM laser, the modulation of the DFB laser results in a significantly broadened spectrum [15]. In addition, the peak to background spectral contrast reduces to about 30 dB. The inset in Fig. 4(b) presents the DFB emission spectrum obtained when the laser is operated CW at a bias of 55 mA. The SMSR under CW conditions is measured to be 68 dB. Note that at lower RF drive levels (producing broader temporal pulses similar to those produced by the DM laser) the individual sidebands of the emission spectrum remain indistinct.

After the characterization of the pulses, both sets of gain switched pulses (as in Fig. 2 – section A) were employed in the DPSK system and their performance characterized by measuring the BER as a function of the received optical power. Achieved results are shown in Fig. 5. The RZ DPSK back-to-back (B2B) performance employing the DM laser is illustrated by the open triangles. As can be seen error free performance is readily achieved. The receiver sensitivity (defined at a BER of $10^{-9}$) is −33.1 dBm. Meanwhile the RZ DPSK B2B performance employing the DFB laser resulted in an error floor around $10^{-1}$ (open circles). As mentioned earlier, in addition to the RZ DPSK system performance, sidebands of the gain switched lasers are filtered using an optical FP filter with a FWHM of 3 GHz, phase modulated and characterized in the 10.7 Gb/s DPSK system. In the case of the DM laser, two different spectral lines (marked by black dots in Fig. 4 (a)) are filtered. Their performance (BER vs received power) is also shown in Fig. 5 with one of the filtered lines of the gain switched DM laser represented by the filled green triangle (upper sideband), the other filtered line by the filled black triangle (lower sideband). A filtered signal from the gain switched DFB laser was also employed in the same NRZ DPSK system. Here again, the DM laser yielded error free performance and the receiver sensitivity is measured to be −28.4 dBm. There is a negligbile variation in performance between the two filtered lines. The standard difference in performance between a 10 Gb/s RZ and NRZ DPSK system is about 1.5-2 dB [23]. In this case, we incur a 4.7 dB penalty between the performance of the RZ and NRZ DPSK system, respectively. The additional penalty can be attributed to the degraded OSNR, which occurs as a result of the narrowband optical filtering of 1 sideband and subsequent

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optical amplification. However, in the case of the DFB laser, the optical filter selects a large spectral portion of the broadened gain switched spectrum, shown in Fig. 4(b), resulting in poor system performance. Filtration from the broadend gain switched spectrum results in the signal occupying the filter bandwidth and thereby portraying the filter transfer characteristic. Performance measurements resulted in an error floor around $10^{-1}$ and are depicted by the filled black circles.

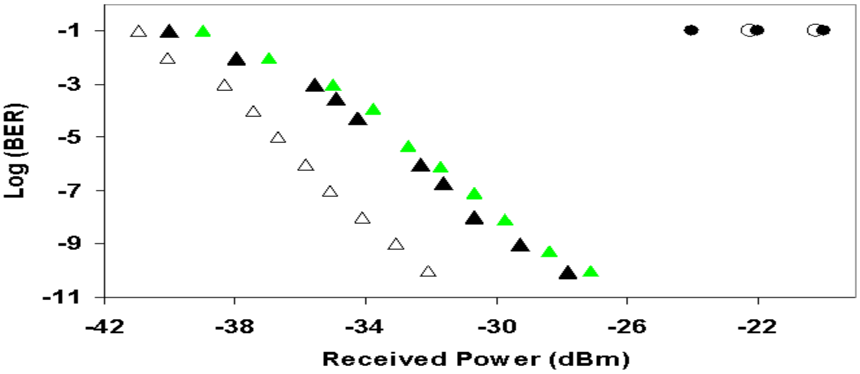

Fig. 5. BER versus received power for 10.7 Gb/s DPSK system. Open symbols: RZ DPSK format (open triangle – DM laser, open circle – DFB laser) and filled symbols: Single sideband filtered/NRZ DPSK (black triangle – lower sideband from DM laser, green triangle – upper sideband from DM laser and black circle – filtered DFB laser)

The received eye diagram from the 10.7 Gb/s RZ DPSK system experiment is plotted in Fig. 6. This eye diagram from the gain switched DM laser employed in the RZ DPSK system is taken at a received power level of –33.1 dBm. The open eye reflects the excellent performance achieved and agrees well with the RZ DPSK BER plot shown in Fig. 5.

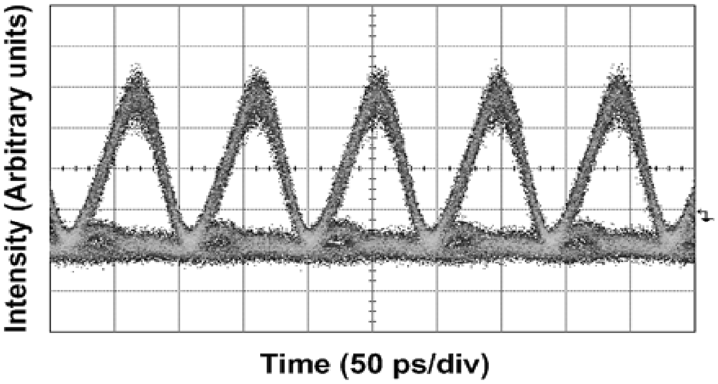

Fig. 6. Eye diagram for B2B RZ DPSK system employing gain switched DM laser @ –33.1 dBm

The eye diagram when the filtered sideband is employed, as a CW source, in the 10.7 Gb/s NRZ DPSK system is plotted in Fig. 7(a). The eye of the filtered sideband from the gain switched DM laser employed in the DPSK system is taken at a received power level of –29.4 dBm. Figure 7(b) shows the output optical spectrum when one sideband is filtered from the gain switched DM laser. This plot shows the selected sideband and also portrays the ~20 dB rejection of the other sidebands.

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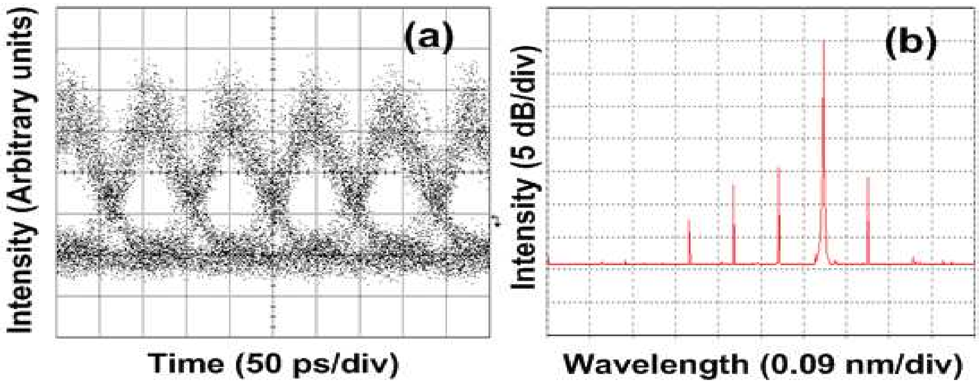

Fig. 7. (a) Eye diagram for B2B DPSK system employing filtered sideband from gain switched DM laser @ −29.4 dBm (b) optical spectrum of filtered sideband from gain switched DM laser

## 3. Linewidth Characterization

The Delayed Self-Heterodyne (DS-H) method is used to measure the linewidth of the two types of lasers employed in this work, the DM and the DFB laser. This technique involves a relatively simple set-up, which is insensitive to slow wavelength drift and can be used for narrow linewidth lasers [24,25]. Initial linewidth characterization involved CW output from DM and DFB lasers, subsequent to which filtered sidebands from each of the gain switched lasers were characterized.

### *3.1 Experimental Set-up*

Figure 8 shows the experimental set-up used to realize the DS-H linewidth characterization.

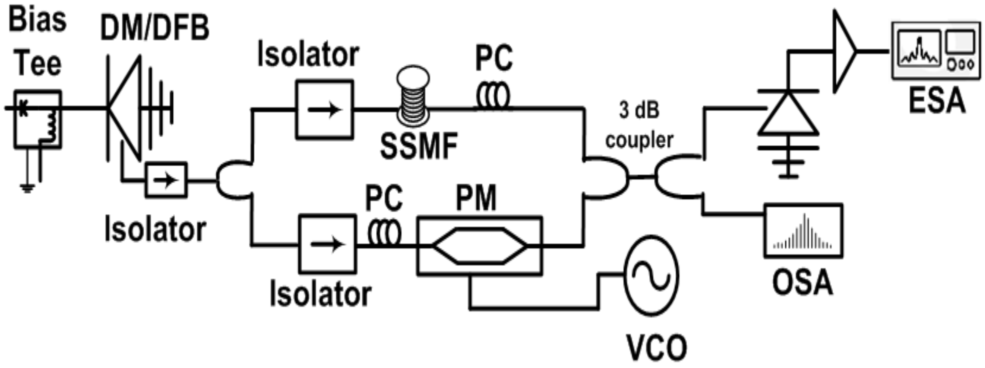

Fig. 8. Experimental set-up for linewidth characterization

The fibre delay length in one arm of the set-up is 12 km (corresponding to a linewidth measurement resolution of ~10 kHz). Light propagating in the short arm of the set-up is modulated using a LiNbO3 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 the beat frequency spectrum, measured using an Electrical Spectrum Analyser (ESA), between the delayed light and the non-delayed light.

Initally, the linewidth of the two lasers in CW mode is characterized when they emit a fibre coupled output power of 2 mW. In the case of the gain switched DM laser, the output signal is passed into a tunable narrowband optical filter (FP filter with a FWHM of 3 GHz) in order to filter out one of the sidebands. The linewidth of this individual mode is then characterized by using the same set-up as described in the case of the CW measurement.

### *3.2 Results and Discussion*

The measured laser linewidths shown in Fig. 9, highlight the reason for the differing levels of performance (BER vs received power in Fig. 5) obtained with the two different types of transmitters.

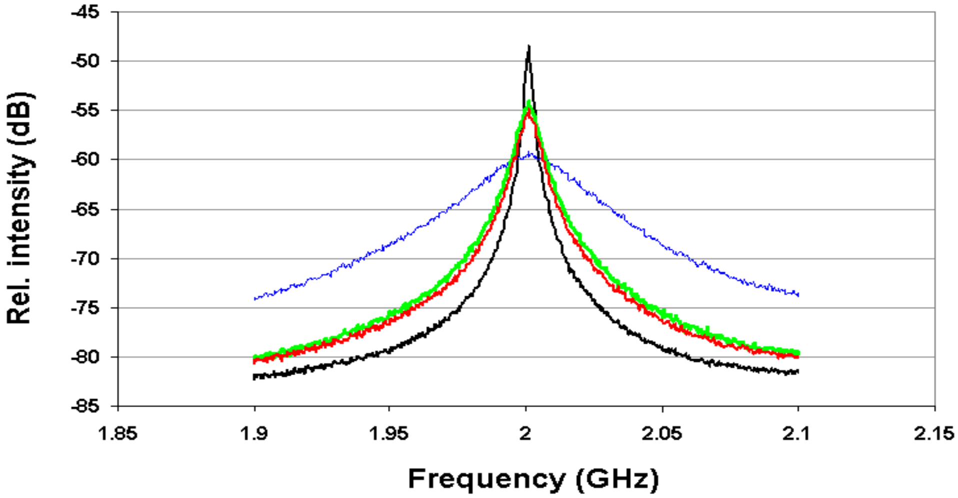

Fig. 9. Linewidths measured using the DS-H method, Blue line – CW DFB, green line – gain switched DM filtered lower sideband, red line – gain switched DM filtered upper sideband, black line – CW DM

The CW linewidth of the DM laser at an output power (bias current) of 2 mW (55 mA) is measured to be 1.2 MHz. The CW linewidth of the DFB laser, on the other hand, at an output power (bias current) of 2 mW (48.05 mA) is measured to be 17.8 MHz. 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. When the DM laser is subjected to high contrast modulation (gain switched), the linewidth of of the filtered upper sideband is measured to be about 3.5 MHz while the filtered lower sideband is measured to have a linewidth of 3.8 MHz. In the case of the gain switched DFB laser, the resultant linewidth of the filtered signal is about 3 GHz (3 dB bandwidth of the filter).

The variation in the linewidth confirms the BER performance of the two different transmitters. The low linewidth of the DM laser under modulation enables this transmitter to deliver error free performance in the 10.7 Gb/s RZ DPSK system. Moreover, the fact that the filtered lines exhibit a very small increase in linewidth in comparison to the CW case clearly outlines the excellent phase noise characteristics of this type of laser. Hence, such a laser would be an ideal candidate to serve as a transmitter in phase shift keyed systems. The DFB laser, on the other hand, portrays an inherently large linewidth when running in CW mode. When gain switched, in contrast to the DM laser, the DFB laser loses coherence and displays a broadened spectrum that is an order larger in linewidth than the CW case. This makes such a laser an unsuitable transmitter for PSK systems.

## 4. Conclusions

We have investigated the performance of a cost efficient pulse source, comprising of a gain switched discrete mode laser in a 10.7 Gb/s RZ and NRZ DPSK transmission system. It has been demonstrated that the modulated DM laser can readily achieve error free performance in the RZ DPSK system and exhibits a receiver sensitivity of –33.1 dBm. Performance comparison to a conventional DFB laser has been also shown. The difference in performance is then explained by characterization of linewidths of both types of transmitters. This shows

Received 1 May 2009; revised 2 Jun 2009; accepted 24 Jun 2009; published 10 Jul 2009

that it is imperative for the employed transmitter to portray excellent phase noise properties. We also show for the first time, to the best of our knowledge, that the gain switched DM laser can be used as a frequency comb generator. The 50 dB modulation depth exhibited by the gain switched spectrum indicates the excellent pulse to pulse phase stability and co-relation of the emitted pulses. This property makes such a source suitable not only for high order modulation formats but also for coherent WDM systems. The filtered lines, from the gain switched DM laser, employed as low linewidth CW sources also show excellent performance in a 10.7 Gb/s NRZ DPSK system.

## Acknowledgements

This work is supported in part by the Enterprise Ireland Commercialization Fund Techology Development Phase (EI CFTD/2008/324), Science Foundation Ireland (SFI) Industrial Supplement and also by the Higher Education Authority Program for Research in Third Level Institutions (2007-2011) via the INSPIRE programme.

Received 1 May 2009; revised 2 Jun 2009; accepted 24 Jun 2009; published 10 Jul 2009