Time Resolved Bit Error Rate Analysis of a Fast Switching Tunable Laser for Use in Optically Switched Networks

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***Abstract*—We investigate the use of different direct detection modulation formats in a wavelength switched optical network. We find the minimum time it takes a tunable sampled grating distributed Bragg reflector laser to recover after switching from one wavelength channel to another for different modulation formats. The recovery time is investigated utilizing a field programmable gate array which operates as a time resolved bit error rate detector. The detector offers 93 ps resolution operating at 10.7 Gb/s and allows for all the data received to contribute to the measurement, allowing low bit error rates to be measured at high speed. The recovery times for 10.7 Gb/s non-return-to-zero on–off keyed modulation, 10.7 Gb/s differentially phase shift keyed signal and 21.4 Gb/s differentially quadrature phase shift keyed formats can be as low as 4 ns, 7 ns and 40 ns, respectively. The time resolved phase noise associated with laser settling is simultaneously measured for 21.4 Gb/s differentially quadrature phase shift keyed data and it shows that the phase noise coupled with frequency error is the primary limitation on transmitting immediately after a laser switching event.**

***Index Terms*—Packet switching; Time resolved error detector; Tunable laser; Wavelength switching.**

I. Introduction

Current projections for Internet backbone network growth suggest that traffic could increase by a factor of 30 in the next 10 years [1]. This increase in bandwidth will necessitate changes in network architecture as we approach the limit on the amount of data that can be transmitted over our current Internet long haul backbone [2]. In order to increase the utilization of the available bandwidth, increased network flexibility is essential, as this allows for a reduction in the amount of optical–electrical–optical conversions at different network nodes [3]. As a result of this requirement for network flexibility there has been an increasing interest in optical transmission systems that are capable of operating in burst mode with special interest recently in transmitters with tunable lasers used for routing in wavelength routed networks [4]. An important requirement for such burst mode systems is the ability to start transmitting data as quickly as possible after the network requests that a burst begin in order to minimize latency and maximize network utilization. Different modulation formats vary in their tolerance to the frequency error and phase noise associated with a tunable laser tuning between wavelength channels. The impact of frequency error can be associated with a mismatch between the laser's frequency and the passband of the receiver filters and/or the impact of the one bit delay interferometer (ODI) being optimized for a slightly different frequency in the case of formats such as differential phase shift keying (DPSK). It is important to trade off the need for high speed tuning and the associated increased level of frequency drift and phase noise associated with the noise added by allowing the electronics tuning the laser to have high bandwidth, as this results in additional optical noise being added to the output of the laser and also not allowing the laser as much time to settle at its destination wavelength with the need for a high level of information spectral density as well as tolerance to the myriad of transmission impairments, i.e., dispersion and optical signal to noise ratio (OSNR).

In this paper we characterize the amount of time it takes for a sampled grating distributed Bragg reflector (SGDBR) laser to transition from error free performance on one wavelength channel to error free performance on a different wavelength channel. The transition times associated with the SGDBR laser modulated with different direct detection modulation formats are investigated. The transition time is characterized using a time resolved bit error rate (TRBER) detector utilizing a field programmable gate array (FPGA) which is capable of carrying out TRBER analysis on data transmitted at 10.7 Gb/s and return bit error rate (BER) data with 93 ps resolution (corresponding to one bit slot) [5]. Unlike a gated error detection technique [6,7], which suffers from only measuring the BER in a small window, this FPGA based TRBER detector allows for all received data to contribute to the TRBER, allowing for measurements to be made much more quickly [5].

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II. Experimental Setup

The experimental setup is shown in Fig. 1. The optical signal was generated by a SGDBR laser. The laser consisted of four sections; three of the sections were controlled using DC supplies (front, phase, gain) and the fourth (back) was controlled by a square wave switching signal. The switching signal was generated by a Stanford Research Systems function generator (FG) (CG635) and the switching signal was selected so that the laser was continuously switching between two channels which were at 1547.6 nm and 1560.4 nm, respectively. The tuning response of the back section is shown in Fig. 2. The period of the switching signal was set to be the same as the period of 1600 bit slots (1 bit slot = 93.45 ps, switching period = 149.53 ns). The FG also provided a 10 MHz clock which was used to synchronize the 10 Gb/s pattern generator (PG, Anritsu MU181020A) to the FG. The FPGA clock was synchronized with the FG via a 668 MHz clock from the PG. The output of the laser was passed through a manual polarization controller before being modulated using a dual parallel Mach–Zehnder modulator (DPMZ). By changing a combination of the modulator bias and the electrical drive amplitudes it was possible to use the DPMZ to generate different modulation formats allowing for the investigation of the performance of different modulation formats. The formats investigated were non-return-to-zero on–off keying (NRZ-OOK), DPSK and differential quadrature phase shift keying (DQPSK). The modulated output was then passed into the receiver first stage optical amplifier with the optical power kept constant at 0 dBm using a variable optical attenuator (VOA) followed by an optical power monitor (PM). This optical signal was amplified using an erbium doped fiber amplifier (EDFA) and filtered by a 2.0 nm bandpass filter (BPF), which reduced the amount of out of band amplified spontaneous emission noise. The output of the BPF was then re-amplified using a second EDFA and filtered again with a 0.2 nm tunable optical BPF, which acted as a channel selection filter. Both BPFs were centered on the channel for which the TRBER was to be measured. The DPSK and DQPSK modulation formats were converted to intensity modulation using an ODI. For detection of NRZ-OOK this ODI was bypassed. The optical signal was then split using a 3 dB optical splitter before being incident on two 10 GHz photodiodes (Nortel Networks PP-10G, single ended direct detection). The time averaged signal power input onto the receiver photodiodes was kept constant at 0 dBm. For DQPSK the in-phase and quadrature components were not simultaneously detected and only the results for the in-phase are reported in this paper. Both the in-phase and the quadrature detected signals showed similar performance.

The output of the first photodiode was split using a 6 dB electrical splitter and the outputs were sent to both a 12.5 Gb/s GHz error rate detector and a 80 GHz bandwidth sampling oscilloscope. The standard BER detector was only used for initial system verification and not used for any of the TRBER measurements. The output of the second photodiode was passed to the TRBER detector. The electrical signal passed to the TRBER detector was XOR'd with a PRBS (pseudo-random binary sequence) 2^7-1 (generated by the FPGA) using an Inphi 50 Gb/s XOR (XOR1). This scrambling operation ensured the input of the FPGA did not see long periods of 0s when the received signal was a long sequence of 0s (as is the case between bursts), overcoming the high pass response of the FPGA board used. The XOR device had differential inputs, allowing an input to be connected to a precision voltage source to allow decision threshold adjustment for the incoming data. Thus this XOR also made the decision on whether the received datum was a 1 or a 0 and the FPGA was then used to carry out data analysis and generate error statistics. The transitions of the received data were lined up with those of the FPGA generated PRBS pattern using an electrical delay (ΔT).

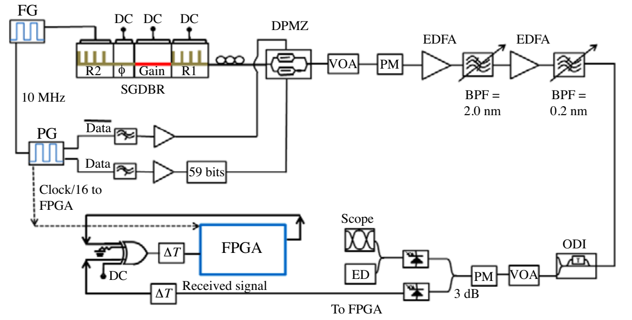

Fig. 1. (Color online) Experimental setup. SGDBR = sampled grating distributed Bragg reflector; PG = 10.7 Gb/s pattern generator; ΔT = variable electrical delay; ODI = one bit delay interferometer; ED = 10.7 Gb/s bit error rate detector; FPGA = field programmable gate array; R1, R2 and Φ are the SGDBR front, back and phase sections, respectively.

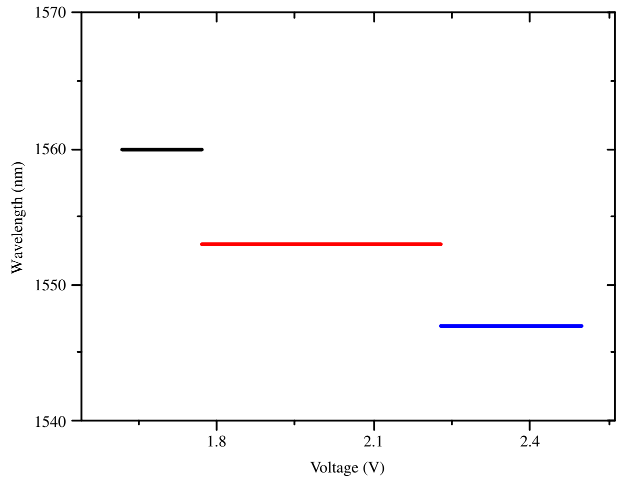

Fig. 2. (Color online) The tuning response of the back section of the SGDBR laser under test.

III. Time Resolved Bit Error Rate Detector

The structure of the FGPA logic is shown in Fig. 3. In order to recover the received data from the signal entering the FPGA, this input signal was again XOR'd with the same PRBS 2^7-1 pattern used to scramble the incoming data (appropriately delayed in FPGA memory by modifying delay 1) in the FPGA using XOR2. In order for the FPGA to carry out BER measurements, its data generator generated the same PRBS 2^7-1 repeating pattern as was generated by the PG. The FPGA then calculated the expected error free data patterns

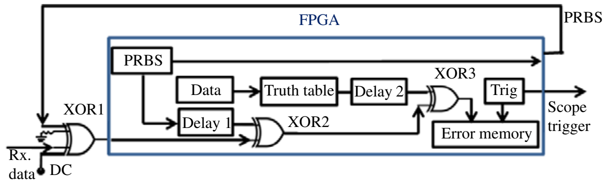

Fig. 3. (Color online) Schematic diagram of time resolved BER detector functionality. Delays 1 and 2 are controllable digital delays for aligning patterns.

that should be received for each of the three data modulation formats under test using the appropriate truth table for each of the different modulation formats. This expected data pattern was then appropriately delayed using delay 2 and XOR'd with the output of XOR2 using XOR3. The output of XOR3 was a digital 0 or 1 representing a bit received correctly or in error, respectively. These errors were then stored in error bins in the FPGA error memory. The number of error bins corresponded to the number of bits received by the FPGA between trigger events. The error memory was triggered at an integer sub-harmonic of the frequency of the laser switching signal. This triggering of the error memory meant that each error memory value corresponded to a particular time relative to the laser switching event. After the error memory was triggered, the next result output from XOR3 was placed in error bin 1 and so on for each subsequent value resulting from XOR3 until the error memory was once again triggered.

IV. Switching Laser TRBER Characterization

TRBER response curves were recorded initially for NRZ-OOK modulated data as shown in Fig. 4. The laser was set to switch between 1560.4 nm (source channel) and 1547.6 nm (destination channel). It was possible to access 1560.4 nm with a range of voltages (Fig. 2). In order to investigate the impact of switching from one cavity mode to various positions within another cavity mode TRBER curves for different destination voltages were recorded with the voltage of the source channel kept fixed. It was ensured for each combination of source and destination channels under test that the side mode suppression ratio of the channels was greater than 30 dB. Figure 4(a) shows the scope trace corresponding to the laser switching from the 1560.4 nm source channel (1.64 V) to the 1547.6 nm (2.25 V) destination channel, with the receiver filters aligned so as to transmit the destination channel (Rx = 1547.6 nm). The eye diagram shows that, once optical power starts to appear on the channel, within a few bit periods the eye starts to open. The TRBER curves for the same switching voltages are shown in Fig. 4(b). Each data point of the TRBER curves corresponds to the probability of receiving an error in a bit in a 93 ps long bit slot at a specific time delay after a trigger event. The data presented were recorded by receiving data for a large number of laser switching events (>1E9) and were calculated by comparing the number of recorded errors in each bin with the total number of trigger events (also recorded in a counter). In each case the decision threshold and electrical TRBER delays were optimized so as to minimize the BER after a laser switching event. From both these TRBER curves it was found that the average recovery time (T_{recovery}) between switching events (time it takes the transmission to go from having a BER of less than 1E−3 on the source channel to a BER of less than 1E−3 on the destination channel) for these two wavelengths for NRZ-OOK transmission was 6.1 ns for a destination voltage of 2.25 V. It is also seen that by changing the voltage associated with the destination channel the T_{recovery} for the laser during a switching event decreased to less than 4 ns. Each of the x-axes for the TRBER curves is set so as to have 0 ns as the time at which the BER of the source channel becomes greater than 1E−7, as this rising edge is well defined as the laser rapidly tunes away from the source channel.

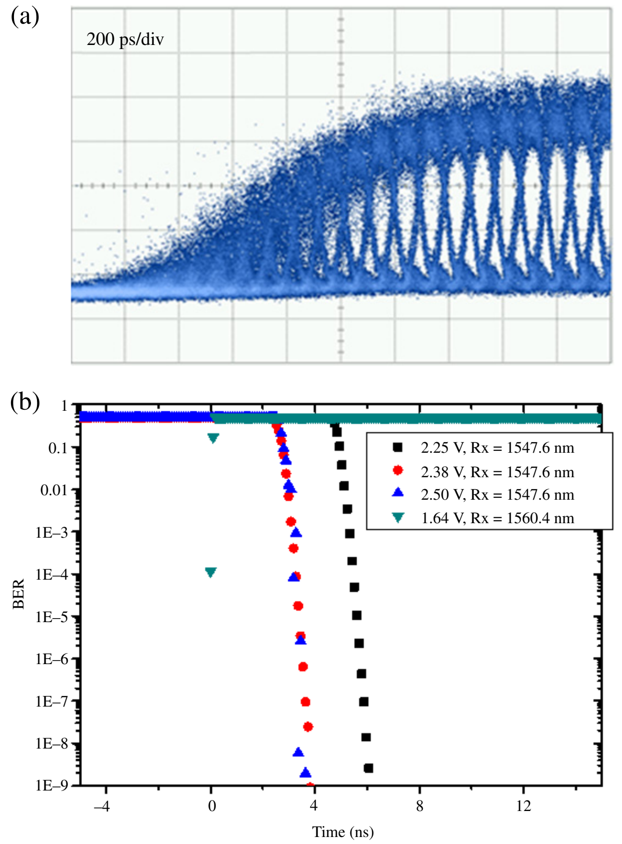

Fig. 4. (Color online) NRZ-OOK signal switching from 1560.4 nm to 1547.6 nm. (a) Scope trace corresponding to switching from 1.64 V to 2.25 V, Rx = 1547.6 nm. (b) TRBER traces for different switching combinations, with the voltage of the destination channel and the wavelength transmitted through receiver filters shown in the legend.

The same laser switching voltages were characterized for DPSK and DQPSK modulated data (see Figs. 5 and 6, respectively). The eye diagram for DPSK is less open than is the case for NRZ-OOK, but the TRBER curves show that it is possible to have T_{recovery} values between switching events as low as 6 ns, which are similar to the results for NRZ-OOK; see Fig. 5(b). The ODI was optimized for each switching combination in order to minimize the BER on the wavelength under test. The worst case T_{recovery} shown for DPSK is 11.8 ns. For DQPSK it can be seen that the upper and lower rails of the eye diagram flip around a number of times resulting in a large number of deterministic errors as the laser settles at its destination wavelength. These flips in the rails are caused by frequency oscillations as the laser settles on the frequency for

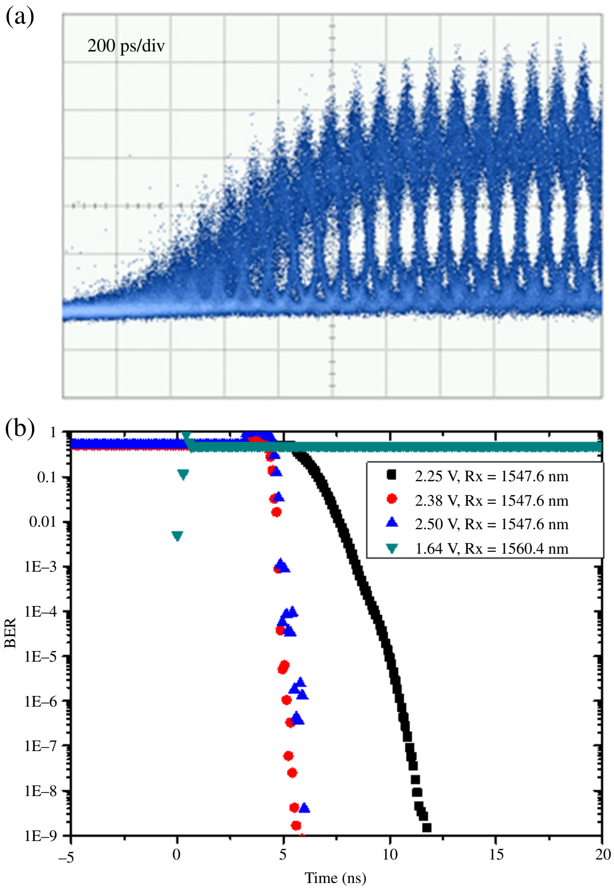

Fig. 5. (Color online) DPSK signal switching from 1560.4 nm to 1547.6 nm. (a) Scope trace corresponding to switching from 1.64 V to 2.25 V, Rx = 1547.6 nm. (b) TRBER traces for different switching combinations.

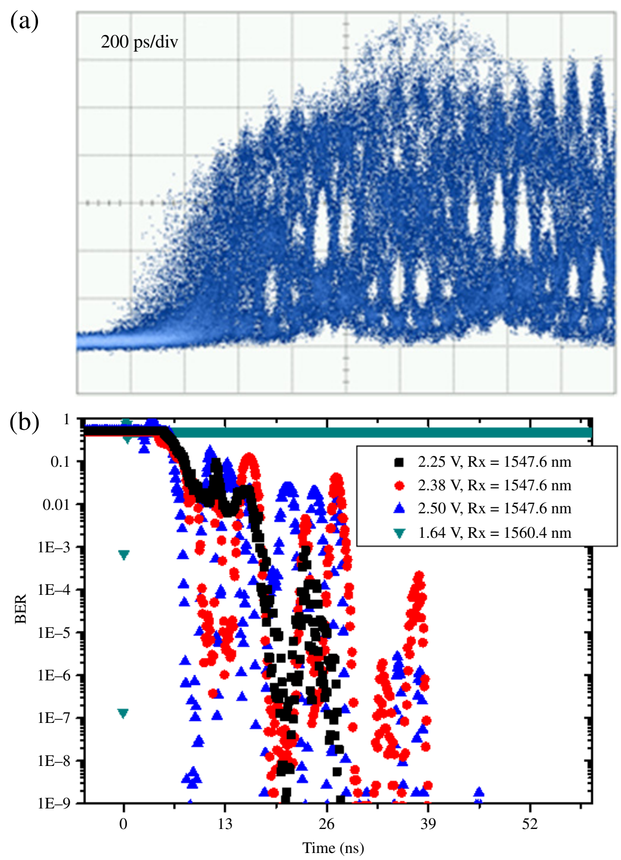

Fig. 6. (Color online) DQPSK signal switching from 1560.4 nm to 1547.6 nm. (a) Scope trace corresponding to switching from 1.64 V to 2.25 V, Rx = 1547.6 nm. (b) TRBER traces for different switching combinations.

which the ODI has been tuned to operate. These transients are more visible for DQPSK than the other formats investigated due to the higher penalty associated with frequency error (offset from ODI optimized frequency) for DQPSK [8]. The $T_{recovery}$ values for DQPSK were consequently significantly longer than for DPSK with it taking up to 46 ns with a destination voltage of 2.50 V with a minimum $T_{recovery}$ of 28 ns for a destination voltage of 2.25 V.

Note that for NRZ and DPSK, the relative bias point within the super-mode boundary has little impact on the BER recovery time due to their relatively high tolerance to small frequency offsets [8]. For NRZ and DPSK larger switching amplitudes generally resulted in reduced switching times [9]. However, for DQPSK signals, the increased sensitivity to small frequency errors [8] results in substantial variability. We believe that in this experiment the sensitivity of DQPSK to small frequency offsets magnifies small distortions in the rectangular electrical switching signal.

V. Limitations on BER Recovery After Laser Switching

After a laser switching event the laser takes a period of time which can be ≫100 ns for the frequency to fully stabilize. In [8] it was found that DQPSK is six times more sensitive to frequency offsets than DPSK. NRZ-OOK, on the other hand, is largely unaffected by these frequency offsets as long as they are not large enough for the laser channel to be blocked by the receiver filters. In order to verify the cause of the errors associated with laser switching, another set of measurements was taken, where the phase noise associated with a laser switching was simultaneously measured along with the TRBER. The laser phase noise was found experimentally by determining a complementary cumulative distribution function of the laser's differential phase as a function of time after a switching event. The time resolved phase noise was measured by taking a tap of the optical signal after the 2.0 nm BPF and passing it and a low linewidth local oscillator (133 kHz) external cavity laser into a 90° optical hybrid, which allowed the time resolved differential phase of the laser's complex field to be found. The acquired differential phase distributions contained all information pertaining to deterministic (frequency drift) and non-deterministic (phase noise, white noise, etc.) variations and allowed direct BER prediction without inferring parameters such as frequency drift or linewidth. The four outputs were detected using balanced detectors and electrically sampled at 20 GS/s using a real time oscilloscope. The external cavity laser was kept static at a frequency <10 GHz away from the destination wavelength of the tunable laser under test. Using the external

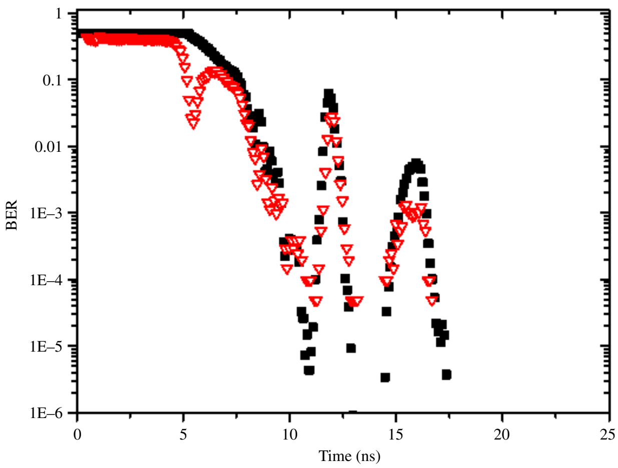

Fig. 7. (Color online) Measured TRBER (black squares) and BER determined from laser phase noise analysis (red triangles). DQPSK signal switching from 1547.6 nm (2.25 V) to 1560.4 nm (1.64 V), Rx = 1547.6 nm.

cavity laser as a low phase noise reference it was possible to calculate the phase evolution of the switching tunable laser as it arrived at its destination channel and from this determine the expected BER which comes from the time resolved CCDF of the absolute corrected differential phase, which was measured and explained in detail in [10]. The BER determined from the phase noise analysis is shown to predict the experiment TRBER measurement extremely well (Fig. 7). The time resolved phase noise measurements cannot be used to measure extremely low BER values (BER < 1E−7) due to the amount of data that would be necessary. Subtle differences between Figs. 6 and 7 resulted from slight differences in the operating point of the ODI, the receiver decision threshold and the receiver analogue electrical delays. While both deterministic and non-deterministic phase noise were taken into account in this work, and while both deterministic and non-deterministic characteristics had an effect on the BER, it was deterministic phase noise which dominated the DQPSK switching response.

VI. Conclusion

We have demonstrated the tolerance of three different formats to the frequency error and phase noise associated with a tunable laser as it is switching between different wavelength channels. We have demonstrated a means of effectively investigating the suitability of different modulation formats for use in optically switched flexible networks which employ differential detection. The recovery times for 10.7 Gb/s non-return-to-zero on–off keyed modulation, 10.7 Gb/s differentially phase shift keyed signal and 21.4 Gb/s differentially quadrature phase shift keyed formats were found to be as low as 4 ns, 7 ns and 40 ns, respectively.

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