Fast Wavelength Switching 6 GBd Dual Polarization 16QAM Digital Coherent Burst Mode Receiver

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***Abstract*—A commercially available digital supermode distributed Bragg reflector tunable laser is employed as a fast wavelength switching local oscillator (LO) in a dual polarization (DP) 16-quadrature amplitude modulation (16QAM) coherent burst mode receiver. A digital coherence enhancement technique is used to compensate both the Lorentzian and non-Lorentzian distributed phase noise of the tunable LO laser. It is shown that differential decoding is not sufficient to overcome the substantial bit errors caused by the LO laser phase noise. However, the coherence enhancement technique enables the reception of low symbol rate DP-16QAM bursts, with an average optical signal to noise ratio penalty of 3.5 dB observed relative to theory at the forward error correction threshold (1.5 × 10^{-2}).**

***Index Terms*—Tunable lasers, coherent communications, wavelength switching.**

I. INTRODUCTION

FAST wavelength switching tunable lasers, coherent detection and digital signal processing (DSP) provide the potential to vastly improve the bandwidth utilisation and energy efficiency of inter-data centre networks, by dynamically allocating bandwidth with sub-wavelength granularity. Burst reception is achieved by exploiting the frequency selectivity of coherent detection, combined with the fast wavelength switching of a tunable LO laser. By performing burst switching in the optical domain, the physical network can be virtualized through a distributed optical layer 2 switch. The key advantage of collapsing the network layers stems from the significant reduction in power consumption that can be achieved relative to legacy architectures [1].

The spectral efficiency of a distributed optical burst switched network can also be improved by utilizing higher order modulation formats. However, the inherent phase sensitivity of such formats (e.g. M-QAM and OFDM) places stringent requirements on the phase noise and low frequency noise performance of the fast switching tunable laser, at both the transmitter and within the digital coherent receiver [2]. Differential decoding is a pre-requisite to overcome the high probability of cycle slips introduced by semiconductor tunable lasers [3]; however significant performance penalties are still incurred as the modulation order increases and as the symbol rate decreases (assuming T/2 sample spacing).

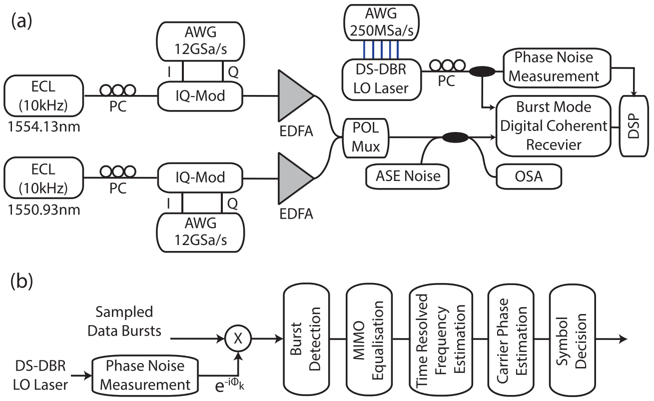

Fig. 1. (a) Fast wavelength switching digital coherent receiver and (b) offline receiver DSP.

Several techniques for transmitter laser phase noise reduction have previously been demonstrated [4], [5], while Secondini *et al.*, demonstrated a ten-fold phase noise reduction of a LO laser in a digital coherent receiver [6]. In this letter, the digital coherence enhancement technique proposed in [6] was adapted [7] and applied to a fast wavelength switching DS-DBR LO laser. It is the first demonstration, to the best of our knowledge, of a fast wavelength switching DP-16QAM digital coherent burst mode receiver, that utilizes a commercially available DBR based tunable laser as the LO. This letter improves upon our previous work that focused on high symbol rate DP-QPSK modulation [3] and shows that the receiver based digital coherence enhancement technique is a pre-requisite in order to detect DP-16QAM bursts at low symbol rates.

II. FAST WAVELENGTH SWITCHING DIGITAL COHERENT RECEIVER

The fast wavelength switching digital coherent receiver experimental configuration is illustrated in Fig. 1(a). Two low linewidth (10kHz) external cavity lasers (ECL) generated two wavelength channels at 1550.93nm (CH1) and 1554.13nm (CH2) respectively. Each laser was individually modulated with a nested IQ modulator, which was driven with

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TABLE I

DSP ALGORITHMS USED FOR EACH MODULATION FORMAT

Format	EQ	EQ Taps	CPE	CPE Taps
BPSK	CMA (A-CMA)	7	V-V	32
QPSK	CMA	7	V-V	32
16QAM	CMA & RDE	7	DD	32

6GBd binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) or 16QAM electrical signals generated using two 12GSa/s (2Sa/symbol) arbitrary waveform generators (AWG). The two channels were optically amplified before being passively coupled and simultaneously polarization multiplexed to generate two optical DP-M-QAM signals. The subsequent dual polarization data signal was passed into the signal port of the burst mode digital coherent receiver.

A commercially available Oclaro DS-DBR laser [8], which exhibited a Lorentzian phase noise of 1.4MHz (measured as in [9]), was employed as the LO in the coherent receiver. A 250MSa/s AWG generated the switching signals for the tunable laser. The output of the DS-DBR LO laser was split at a 3dB coupler and one arm was passed directly into the LO port of the coherent receiver. The second arm was passed into the differential phase noise measurement setup, which consisted of a 90° optical hybrid, balanced receivers and a two channel optical sampling oscilloscope. An additional delay (τ) was added to one of the optical hybrid arms to create an interferometer, with the maximum frequency ($1/\tau$) of the measurement technique inversely proportional to the delay, as described in [7]. Finally, a noise loading stage was employed to vary the received OSNR for BER measurements.

III. DIGITAL SIGNAL PROCESSING

The digitally estimated phase noise for the LO laser was applied to the received signal offline in Matlab, as illustrated in Fig. 1(b). Burst detection was subsequently carried out before equalization. The equalizer and phase recovery algorithms utilized in this letter were slightly different for each modulation format and are therefore treated separately, as shown in Table I. The intermediate frequency (IF) offset was estimated and removed from the signal using the Viterbi-Viterbi algorithm prior to equalization for each modulation format. The estimator was block based, where the data was removed from the X and Y polarization signals by raising to the fourth power and then the peak frequency was identified using a fast Fourier transform (FFT) over a window of length 1024 samples. To improve the frequency estimate, a quadratic interpolation technique was used to find the maximum of the FFT [10].

A constant modulus algorithm (CMA) based equalizer with 7 T/2 spaced taps was employed to equalize both the dual polarization BPSK and QPSK bursts and the least mean squares (LMS) algorithm was used to update the taps of the multiple input multiple output (MIMO) equalizer. Carrier phase estimation (CPE) was performed for each polarization using the Viterbi-Viterbi (V-V) algorithm [13] and the complex field was averaged over a 32 T spaced sliding window to improve the robustness of the estimate. In the case of BPSK, joint equalization and phase recovery was employed, as in [11]. However, improved performance for DP-BPSK was realized for the uncompensated differentially symbol decoded case (Fig. 4), when an adapted constant modulus algorithm (A-CMA), proposed by Yan *et al.* was employed for equalization [12]. The performance enhancement was due to improved symbol decisions, as carrier recovery was not required for this algorithm.

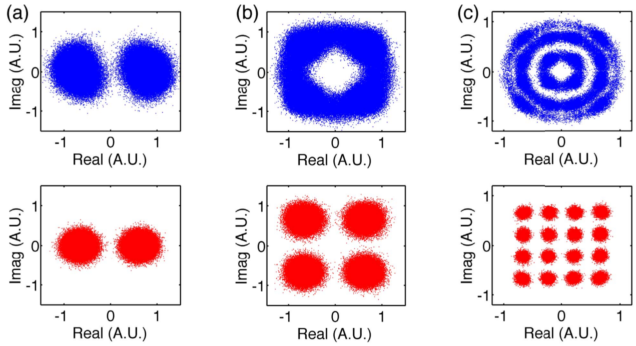

Fig. 2. Constellation diagrams for 6GBd (a) BPSK, (b) QPSK and (c) 16QAM, with (bottom) and without (top) digital phase noise compensation.

For DP-16QAM, each burst was equalized using a 7 tap (T/2 spaced) radius directed equalizer (RDE) [14], with the CMA equalizer used for pre-convergence. The carrier phase was estimated per polarization using a decision directed (DD) phase estimation algorithm [15].

IV. STATIC OPERATION

The performance of the burst mode digital coherent receiver was initially characterized when the DS-DBR LO laser was not switching (static mode). The modulation format was varied between, BPSK, QPSK and 16QAM, all of which were polarization multiplexed and operated at a symbol rate of 6GBd. Fig. 2 illustrates the constellation diagrams of each modulation format for a received OSNR of 8.15, 11.33 and 20.2dB for BSPK, QPSK and 16QAM respectively (corresponding to a BER of $1e^{-5}$). The top figures demonstrate the performance when no digital phase noise compensation was applied to the DS-DBR LO tunable laser, while the bottom figures illustrate the performance when the compensation was applied.

The large Lorentzian phase noise of the DS-DBR tunable laser causes the constellation points to depart from a Gaussian distribution (top of Fig. 2) and manifests as a fixed penalty for BPSK and cycle slips for QPSK and 16QAM. As the order of the M-ary modulation format increases, the required linewidth-symbol time product to achieve an acceptable cycle slip probability of 10^{-18} reduces [16], therefore more cycle slips are experienced for QPSK and 16QAM, resulting in catastrophic bit errors. By applying digital phase noise compensation to the LO laser, the phase noise is dramatically reduced, which is evident from the compensated constellations shown bottom of Fig. 2.

The bit error rate performance of the coherent receiver, when employing digital laser phase noise compensation, is illustrated in Fig. 3. The BER was recorded as a

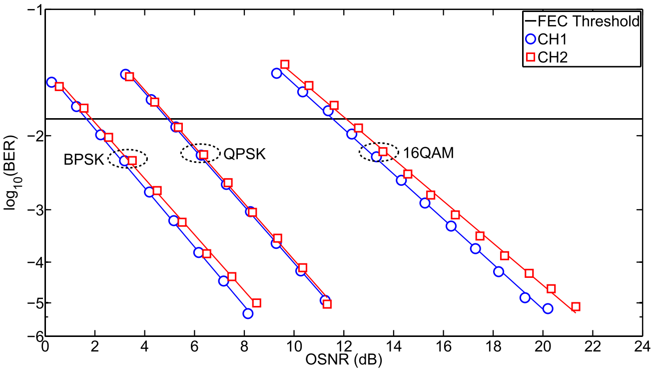

Fig. 3. **Static LO operation:** BER as a function of received OSNR for 6GBd DP-BPSK, DP-QPSK and DP-16QAM for both wavelength channels.

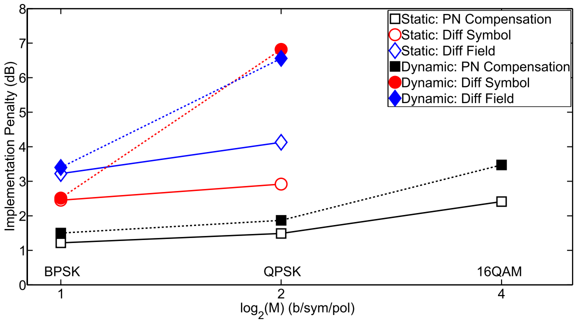

Fig. 4. Implementation penalty (relative to theory) at the FEC threshold of 1.5×10^{-2}, for 6GBd M-ary (M = 2, 4 and 16) modulation formats, when the burst mode receiver operated in static mode (solid lines) and dynamic switching mode (dashed lines).

function of the received OSNR for both wavelength channels (CH1 and CH2) and for three modulation formats. Consistent BER performance was demonstrated for both channels under BPSK modulation, with an average required OSNR of 1.8dB observed at the FEC threshold (1.5×10^{-2}), which increased to 5dB for QPSK. Similar performance was demonstrated for DP-16QAM, with an OSNR of 11.5dB and 12.1dB at the FEC threshold for CH1 and CH2 respectively.

The average implementation penalty (relative to theory) at the FEC threshold for the two wavelength channels, are displayed in Fig. 4 for all three modulation formats. The performance of the receiver when utilizing differential symbol decoding and differential field detection, but without applying digital phase noise compensation, are also shown. When digital phase noise compensation was applied to the LO laser, the implementation penalty for the three formats ranged from 1.2dB for BPSK to 2.4dB for 16QAM. Without digital phase noise compensation, but with differential symbol decoding, the OSNR penalty increased to 2.5dB and 2.9dB for BPSK and QPSK respectively. It is important to note that a BER below the FEC threshold was not obtainable for differentially decoded DP-16QAM. An implementation penalty of 3.2dB and 4.1dB was experienced for BPSK and QPSK when differential field detection was employed.

Therefore, digital LO laser phase noise compensation provides an OSNR gain of approximately 1.4dB over differential symbol decoding for both BPSK and QPSK, while the compensation technique provides a larger gain of 2-2.5dB over differential field detection. As a result, the extra receiver complexity may not be warranted for the BPSK or QPSK modulation formats when operating the receiver in static mode; as differential symbol decoding avoids catastrophic bit errors caused by laser phase noise induced cycle slips, at the cost of an additional 1.4dB OSNR penalty. However, digital phase noise compensation of a DS-DBR tunable LO laser is a pre-requisite when using the DP-16QAM modulation format, as differential decoding is not sufficient to overcome the substantial bit errors caused by the LO laser phase noise.

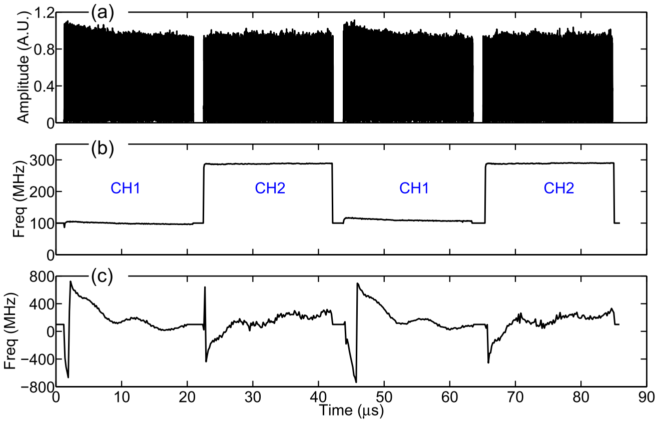

Fig. 5. (a) Amplitude of two burst channels, (b) instantaneous IF of beat note between transmitted channels and fast switching DS-DBR LO laser, when digital phase noise compensation was employed and (c) IF without digital phase noise compensation.

V. DYNAMIC SWITCHING OPERATION

Under burst switched operation, both the Lorentzian phase noise and the low frequency (non-Lorentzian) 1/f noise must be tracked and compensated. The low frequency fluctuations experienced after a LO switching event are the key difference between static and dynamic operation and pose significant challenges to the offset frequency estimator within the receiver DSP. The digital laser phase noise compensation technique inherently compensates low frequency fluctuations of up to ±550MHz, with the upper limit on the frequency compensation determined by the interferometer delay in the phase noise measurement setup.

To analyze the performance of the fast wavelength switching digital coherent receiver, the DS-DBR LO laser was dynamically switched to reside at each of the two wavelength channels in 20μs bursts. Fig. 5(a) displays the amplitude of the burst channels (CH1 and CH2), which are repeated twice. The corresponding instantaneous intermediate frequency of the beat note between the transmitted channels and the fast switching LO laser is shown in Fig. 5(b). The IF was ∼100MHz for CH1 and ∼300MHz for CH2, and remained relatively constant for each channel for the duration of the burst. The frequency only varied by approximately ±5MHz from the mean, which represents a fraction of the low frequency drift that is typical for this type of semiconductor tunable laser. The reason for this is that the digital phase noise compensation technique also reduces the magnitude of the non-Lorentzian frequency

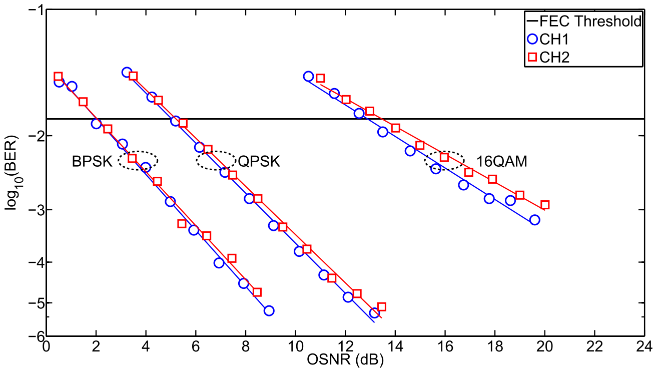

Fig. 6. **Dynamic LO operation:** BER as a function of received OSNR for 6GBd DP-BPSK, DP-QPSK and DP-16QAM for both wavelength channels.

variations that are caused by the electrical drive signals applied to the passive tuning sections of the tunable laser.

Fig. 5(c) illustrates the instantaneous IF when no digital phase noise compensation was applied to the LO laser. The frequency varies significantly over the duration of each burst. For burst CH1, the IF exceeded the limits (±750MHz) of the digital offset frequency estimator at the beginning of each burst, which results in significant bit errors.

The BER as a function of the received OSNR for each burst channel is shown in Fig. 6. An average required OSNR of 2dB was observed at the FEC threshold for both wavelength channels under burst switched DP-BPSK operation. This demonstrates excellent performance relative to the the static case, with a slight increase in implementation penalty of 0.2dB. The QPSK format incurred an additional average implementation penalty of 0.4dB relative to the static case, as shown in Fig. 4, which demonstrates consistent performance for both the BPSK and QPSK formats.

When utilizing the DP-16QAM modulation format, an additional implementation penalty of 1dB was incurred at the FEC threshold, relative to the static case. This corresponds to a 3.5dB OSNR penalty relative to theory at a BER of 1.5×10^{-2}. The additional implementation penalty experienced for the DP-16QAM case is attributed to the un-compensated high frequency phase noise that resides outside the measurement bandwidth (±550MHz) of the digital phase noise compensation technique. The additional high frequency phase noise has a larger impact on the DP-16QAM format, when compared to BPSK or QPSK, resulting in a fixed OSNR penalty and a difference in the slope of the OSNR vs BER curve, as seen in Fig. 6.

It is evident from Fig. 4 that differential symbol decoding and differential field detection incur minimal additional OSNR penalties for the BPSK modulation format when the receiver is operated in dynamic burst switching mode. However, the differential symbol decoded QPSK format incurs an additional OSNR penalty of 4dB relative to the static case, which is larger than the additional penalty observed for differential field detection. This is expected, as differential field detection is inherently more tolerant to large phase and frequency fluctuations.

VI. CONCLUSION

We have validated the performance of a fast wavelength switching DS-DBR tunable LO laser, which exhibited a Lorentzian phase noise of 1.4MHz and a linewidth-symbol time product of 2.33×10^{-4}, in a burst mode digital coherent receiver. A digital phase noise compensation technique was employed to significantly reduce both the Lorentzian and non-Lorentzian phase noise of the tunable laser. An average OSNR penalty of 3.5dB was incurred, relative to theory, for two 20μs 6GBd DP-16QAM burst channels.

It was demonstrated that the digital coherence enhancement technique is a pre-requisite when utilizing a fast wavelength switching DBR based tunable LO laser in a 6GBd QPSK or 16QAM digital coherent burst mode receiver.

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