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Abstract: We investigate the effects of different phase noise processes of SGDBR laser on coherent systems. The SGDBR device operated well with QPSK modulation at 5 Gbaud, while the performance of 16-QAM was significantly degraded due to excess noise. The white FM noise mainly defines the ultimate performance of coherent reception, but the low frequency excess noise can potentially degrade the performance of systems that employ 16-QAM format at 5 Gbaud.

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1. Introduction

Multi-level modulation has been identified as one of the key technologies to address the capacity increase in Dense Wavelength Division Multiplexing (DWDM) optical networks [1,2]. Higher order quadrature amplitude modulation (QAM) schemes such as 16-QAM [1] and 64-QAM [2] with digital coherent receivers have attracted research attention recently as the potential candidates for next generation optical networks. One of the key elements in these systems will be the laser transmitter, and phase noise of the laser sources has been

identified as a crucial characteristic that affects the ultimate performance of these coherent systems.

Widely tunable lasers (TLs) have become the key transmitter technology for the operation of WDM systems, as they greatly reduce inventory and sparing costs. In addition, as carriers deal with changing traffic patterns and increased bandwidth requirements the need for reconfigurable and agile optical networks has become more apparent, and the TLs can be used for the development of fast reconfigurable optical networks based on optical burst or packet switching technologies [3]. Sampled Grating DBR (SGDBR) lasers have been proven to be a suitable candidate for use in WDM networks offering stable wavelength operation at over ninety 50GHz spaced ITU channels, with side-mode suppression ratio (SMSR) greater than 40dB, and output power greater than 10mW [4,5]. If these lasers are to be employed in the transmitters of future WDM systems that employ higher order QAM, then it is necessary to accurately assess how the phase noise in these devices will affect the performance. The 3-dB linewidth from the delayed self-heterodyne (DSH) measurement has typically been the metric for determining whether the laser will work in a specific coherent system with a certain baud rate and modulation format. However, the observed DSH linewidth, which can be broadened due to excess low frequency noise, has been shown to be an incomplete measure of the laser phase noise [6, 7].

In this paper, we accurately characterized the different phase noise processes of SGDBR laser with the delayed self-heterodyne phase modulation detection (DSH-PM) method [6], and investigated their effects on a coherent transmission system. Experimental results show that the system performance was well maintained with QPSK at 5Gbaud while the performance with 16-QAM at the same baudrate was significantly affected by the large excess noise of the SGDBR device.

2. Experiment setup

The experimental setup is depicted in Fig. 1(a). The transmitter employed two DFB lasers and one SGDBR laser, all with different phase noise characteristics, while the receiver local oscillator (LO) was a narrow linewidth external cavity laser (ECL). The 16-QAM driving signal was generated by an arbitrary waveform generator (AWG) whose outputs were followed by a pair of anti-aliased low-pass filters and amplified to drive the I & Q arms of a dual parallel Mach-Zehnder modulator. The driving signals, shown in the upper inset of Fig. 1(a), were optimized for the nonlinearity of the electrical amplifiers and the I/Q modulator. The variable optical attenuator (VOA) adjusts the received power into the low-noise EDFA that served as the pre-amplifier for the receiver front-end. The EDFA output was further amplified by a second EDFA, with the optical filters (2 nm bandwidth) reducing the ASE noise. The second VOA maintained an input optical power of −14 dBm into the 90° optical hybrid. The lower inset of Fig. 1(a) shows the optical eye of the 16-QAM signal. The polarization of the received optical field was manually adjusted to match with the polarization of the LO optical field whose power was kept at + 3 dBm.

A pair of balanced photo-detectors detected the output signals from the optical hybrid. An Agilent real-time scope captured the detector output signals at 40 GSa/s, and they were then fed into a computer for off-line DSP processing, as illustrated in Fig. 1(b). The digital samples were firstly normalized by their root mean square (rms) values and the I/Q components were balanced. The non-data-aided frequency correction removed the frequency offset between the lasers [8] and a 20-symbol training sequence was employed to achieve symbol synchronization. Many algorithms have been developed for carrier phase recovery in digital coherent receiver including the least mean-squared (LMS) algorithm [1], decision-directed phase-locked loop [9,10], decision-aided maximum likelihood phase estimation [11], blind phase search technique [12], and QPSK partitioning algorithm [13]. In this work, we developed a first order decision-directed phase-locked loop (DD-PLL) [9] as shown by the block diagram in Fig. 1(c). The performance of the DD-PLL was verified against the LMS algorithm and showed a slight improvement; primarily because the LMS algorithm is subjected to both amplitude and phase corrections. As a result, we employed the first-order

DD-PLL as the referenced scheme to evaluate the system performance with the DFB and SGDBR lasers. Gray coding was also employed for symbol mapping prior to transmission. Both error vector magnitude (EVM) and bit-error rate (BER) calculations were carried out to evaluate the system performance. The EVM of the decoded symbols can be calculated according to:

$$EVM_{RMS}[\%] = \sqrt{\frac{\frac{1}{N}\sum_{n=1}^{N}\left|S_{Rx,n} - S_{Tx,n}\right|^2}{\frac{1}{N}\sum_{n=1}^{N}\left|S_{Tx,n}\right|^2}} \times 100\%$$

Here $S_{Tx,n}$ and $S_{Rx,n}$ are the nth transmitted and received symbols, respectively, and N is the number of symbols.
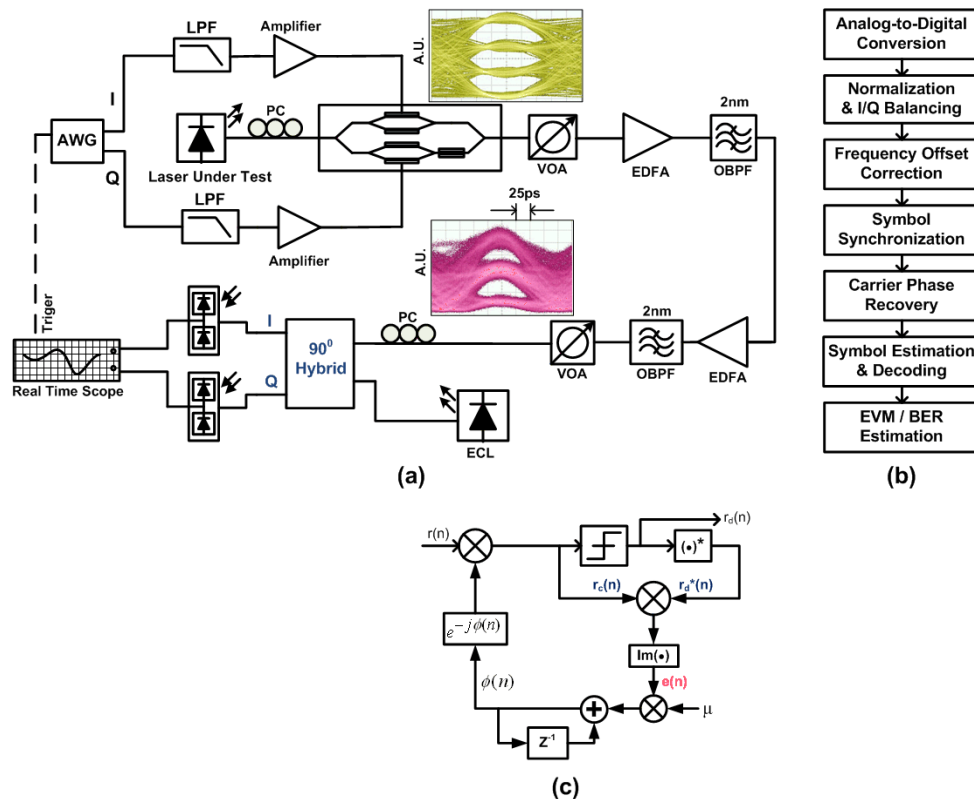

Fig. 1. Experiment setup for coherent communication system (a), block diagram for signal processing offline (b), and decision-directed phase-locked loop carrier phase recovery (c).

3. Experimental results

3.1 Phase noise characteristics

We first characterize the phase noise of the lasers using the DSH-PM detection method with a 12 km fiber delay line that has been previously described [6]. The power spectral density (PSD) of the E-field, the phase-error variance and the FM-noise spectrum has been determined for the different devices under test. As shown in Fig. 2, the measurement results for the two different DFB lasers demonstrate the purely random walk in phase, or white FM noise, characteristics [6, 7] with 300 kHz and 6 MHz linewidths. The SGDBR laser operated

under different bias conditions resulted in different phase noise characteristics. The Gain section was constantly injected with 110mA current, while the temperature was kept stably at 20°C for all biasing points. The injected currents in to passive sections were then varied to chose different operating points for SGDBR laser. Figure 2(c) shows that the SGDBR laser has a high-frequency white FM-noise region above 200 MHz that corresponds to an intrinsic linewidth of 300 kHz. Below 200 MHz, the device exhibits excess $1/f$ or flicker FM noise when only the gain section was biased, and $1/f^2$ or random-walk FM noise when the bias was applied to both gain and tuning sections [14]. The excess noise resulted in a phase-error variance that increased quadratically, as shown in Fig. 2(b), in comparison with the 300 kHz DFB laser. The broadening of DSH linewidths of the SGDBR laser to 5.5 MHz and 19.5 MHz due to the excess noise can be observed with the E-field power spectral densities (PSDs) in Fig. 2(a) [7]. The results in Fig. 2 demonstrate in particular that the SGDBR laser has $1/f^2$ noise that can be attributed to biasing the passive sections; and therefore would benefit from the use of low-noise current sources.
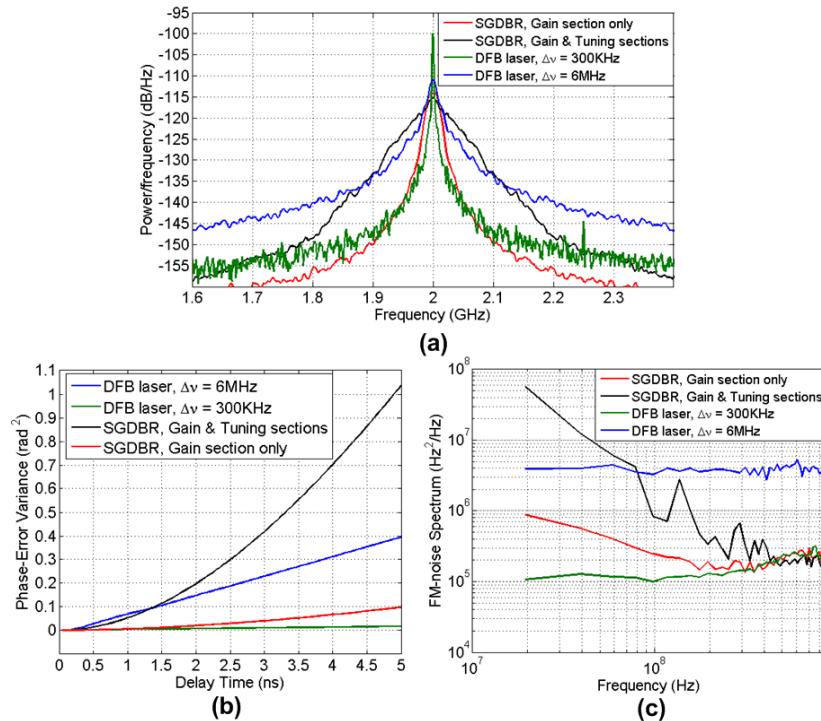

Fig. 2. Phase noise of DFB lasers and SGDBR laser: Power spectral density of received E-field (a), Phase-error variance (b), and FM-noise spectrum (c).

3.2 Performance evaluation

The back to back performance of the system set up in Fig. 1 was determined with the SGDBR laser biased at different operating points: gain section only, gain and back sections, then all sections. The operating wavelength was then also changed by re-adjusting the back section bias. Figure 3 presents the system performance for QPSK in terms of the EVM and symbol constellations. The EVM plots in Fig. 3(a) are within less than 10% of one another under all bias conditions, and indicate that the biasing effects are small but observable. The symbol constellations in Figs. 3(b) and 3(c) at −28dBm received power also show slight degradation from biasing all sections: 14.5% vs. 16% EVM, which corresponds to a BER less than 10^{-9} [15]. The results demonstrate excellent tolerance of QPSK modulation format to laser phase

noise. The phase-error variance plots suggest that the effects of excess noise or linewidth broadening would become negligible at shorter time intervals as the line rates increase.

As the Euclidean distance between QAM constellation symbols grows shorter for higher order modulation formats, the laser phase noise requirement becomes more stringent compared to QPSK. The performance of the 16-QAM coherent system in Fig. 1 was evaluated with the characterized DFB and SGDBR lasers in the transmitter. We note for the tunable SGDBR laser that in order to achieve operation on a specific ITU channel, it is normally necessary to bias all sections (gain and tuning) of the device. Figure 4(a) displays the BER versus received power for the two DFB lasers. The plots verify that the BER improves slightly with the DD-PLL, and the system performance is limited by the phase noise of the DFB laser with a 6 MHz linewidth in comparison to the narrow linewidth laser. The inset in Fig. 4(a) depicts the example symbol constellation for the 300 kHz DFB laser at −28 dBm received power.
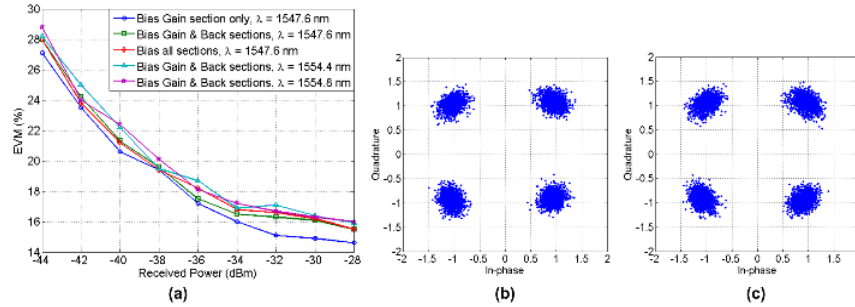

Fig. 3. Receiver sensitivity for SGDBR laser with QPSK at 5Gbaud (a) and received symbol constellations when biasing gain section only (b), biasing all sections (c) at same received power (−28dBm).

The system performance was further analyzed with the time-resolved BER measurements as shown in Fig. 4(b). These measurements were performed by capturing the output signals from the balanced photo-detectors in data blocks of 2 µs long for offline processing. The BER for each of the 2 µs data blocks was then computed (received power at −20 dBm). The time-resolved BER plots for the DFB devices again show that the laser with a 300 kHz linewidth could operate consistently at around 10^{-3} BER, whereas the laser with a 6 MHz linewidth cannot be used for the 16-QAM transmitter at 5 Gbaud.

The time-resolved BER plots in Fig. 4(b) for the SGDBR laser show intermittent performance degradation when biasing the gain section only; and the degradation became more prevalent when both the gain and tuning sections were biased. The overall comparison of the results in Fig. 4 would suggest that the performance of the SGDBR laser is closer to the narrow linewidth DFB laser. This is consistent with the previous observation that the SGDBR laser has the intrinsic, white-FM linewidth that is similar to the narrow linewidth DFB laser at 300 kHz. The intermittent degradation worsened subject to the bias conditions, and is consistent with the increase in the phase-error variances in Fig. 2(b), and in the low-frequency FM noises from $1/f$ to $1/f^2$ in Fig. 2(c). The time-resolved BER plots also indicate that the SGDBR laser performance remains largely bounded between the two DFB lasers, even though its DSH linewith broadening exceeded both and was as much as 19.5 MHz.

Figure 5 further illustrates the example time-resolved measurements from Fig. 4 at points t = 12 µs and 18 µs for the SGDBR laser with only the gain section biased. Figures 5(a,b) and 5(c,d) display the symbol constellation and the error vector magnitude, respectively. In comparison to Figs. 5(a) and 5(c), the noisy constellation of Fig. 5(b) corresponds to the sudden increase of the error vector magnitude in Fig. 5(d) from the loss of carrier phase tracking due to the $1/f$ noise. The low-frequency excess FM noise of the semiconductor laser generally induces a slow fluctuation of the instantaneous carrier frequency [7], and the effect of this random frequency drift for the SGDBR laser can be observed by comparing the

symbol constellations in Figs. 5(a) and 5(b) and note that the entire constellation has also been slightly rotated.

To overcome the problems caused by the excess noise in these coherent systems we are looking to (i) use low noise current sources with low-pass filtering to reduce the noise from the biasing circuits, and (ii) develop improved carrier phase recovery algorithm that would achieve better phase tracking under large excess phase noise. For example, instead of the first-order DD-PLL in this work, a second-order DD-PLL can be employed for tracking both the phase and frequency drifts, together with more frequent symbol re-timings along the data blocks.
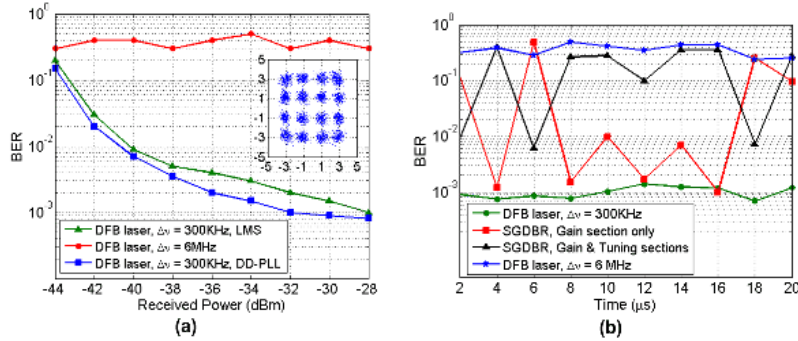

Fig. 4. Performance of DFB lasers for 16-QAM system at 5 Gbaud (a) and time-resolved BER of 16-QAM with SGDBR (2-μs long data blocks) (b).
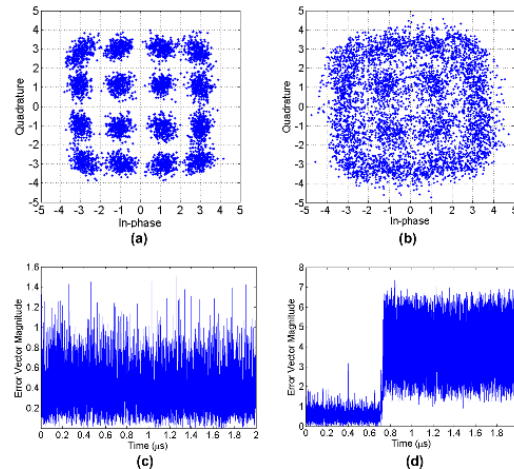

Fig. 5. Examples of constellations at point t = 12μs (a), at point t = 18μs (b); and error vector magnitudes at point t = 12μs (c), at point t = 18μs (d) from Fig. 4 for SGDBR laser with only gain section biased

4. Conclusion

In this paper, we have examined the performance of an SGDBR laser in a coherent optical communication system. We characterize the phase noise processes of the SGDBR device under different bias conditions and showed that the laser performs well at 5Gbaud with QPSK modulation. The performance, however, is significantly reduced with 16-QAM due to excess noise. We confirmed that while the white FM noise has been determined to largely define the overall system performance, the system operation could potentially be impaired by excess laser phase noise. The experimental results show the importance of distinguishing different phase noise processes of laser sources and developing the means to cope with excess noise of SGDBR lasers in future WDM systems that employ high order modulation formats.