Digital Coherence Enhancement Enabling 6-GBd DP-64QAM Using a 1.4-MHz Linewidth Laser

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***Abstract*— This letter demonstrates the possibility of using digital coherence enhancement—a means of estimating and digitally compensating local oscillator laser phase noise using a secondary, low speed coherent receiver—to enable the reception of high order quadrature amplitude modulation (QAM) using a monolithically integrated tunable semiconductor laser as local oscillator. We show that this coherence enhancement technique compensates both the Lorentzian and non-Lorentzian distributed phase noise of this laser, enabling reception of DP-64QAM without differential decoding, and with a record (linewidth) × (symbol duration) product of 2.3×10^{-4}.**

***Index Terms*— Coherent receivers, quadrature amplitude modulation (QAM), laser linewidth, optical communications.**

I. Introduction

Digital coherent receivers translate the full optical field of a signal into the digital domain and are thus an ideal solution for high data rate optical communications employing advanced modulation formats, such as quadrature amplitude modulation (QAM). However, as the order of the modulation format increases (to meet a required information spectral density), the requirements of the laser phase noise become more stringent.

External cavity lasers (ECL) provide a low linewidth source ideal for the transmission of QAM, but suffer from issues of cavity stability [1], large form factor and cost, making them unsuitable for many applications. Additionally, they are outperformed by monolithically integrated semiconductor lasers in some applications, such as fast optical burst switching networks [2], even though these semiconductor lasers typically exhibit much greater phase noise.

Several techniques exist for reducing the impact of phase noise on coherent receivers such as digital carrier phase estimation (e.g. [3]), carrier assisted phase estimation [4] and optical tracking of carrier phase. In the first two scenarios, the combined phase noise of the signal and local oscillator (LO) lasers is estimated, and so the phase estimate is impaired by noise from the channel. The third technique, known as 'Coherence Enhancement', reduces the phase noise of a laser by directly measuring the laser phase with an interferometer and modulating the inverse of the phase onto the optical carrier itself [5], [6]. Although the resulting laser linewidth can be significantly reduced, it is a requirement of this technique that the phase measurement and the feedforward phase compensation must be synchronized. In [6], the phase compensation was estimated digitally and jointly applied with the modulation, meaning digitally applied timing skew can relax these synchronisation requirements.

In scenarios such as long-haul transmission systems [7] or coherent access networks [8], it is the linewidth of the local oscillator (LO) laser which dominates in the overall network performance. A method for independently measuring and digitally compensating the phase noise of the LO laser was first proposed in [9] and was also where the term 'Digital Coherence Enhancement' was first introduced. This technique was subsequently verified for long-haul transmission in [10]. In these works, the process was demonstrated for a standard Distributed Feedback (DFB) laser. Additionally, the experimental work considers only the use of differential QPSK. The key advantage of this technique comes from the fact that it is independent of modulation format, and that the phase noise being compensated does not follow any particular distribution.

In this letter, we describe a modified scheme for measuring, and compensating, the phase noise of an LO laser (with a non-Lorentzian frequency spectrum) in a digital coherent receiver, and experimentally demonstrate its performance using 6 GBd dual polarization (DP) 64QAM. Scaling these results for higher symbol rates, we show how a Terabit superchannel could be achieved using such high linewidth lasers.

II. Phase Noise Reduction Scheme

The LO laser phase noise mitigation scheme consists of an optical measurement of differential phase, followed by digital signal processing (DSP) to calculate the laser phase noise, as described in [9] and illustrated in Fig. 1. The output of a high linewidth LO laser is split into three paths. One path is sent to the LO port of a coherent receiver to provide a phase reference for a data carrying signal, while the remaining two paths are passed into a 90° optical hybrid, with the addition of an optical delay line in one of the arms. The delay line (time delay, τ) acts in a similar way to an interferometer, with the delay line length determining the maximum frequency, $1/\tau$, which can be discriminated between the two arms.

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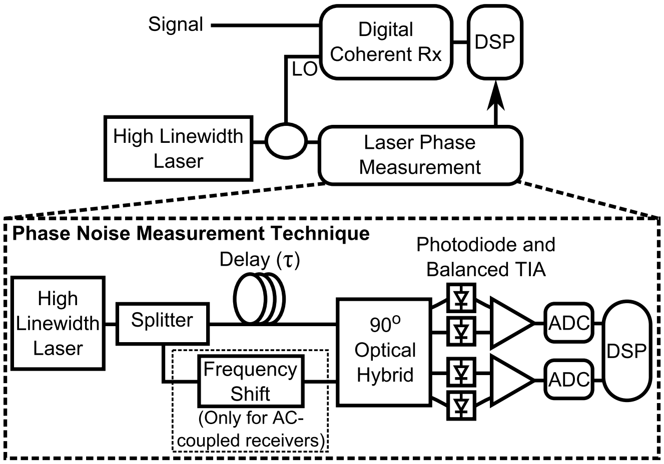

Fig. 1. Schematic for local oscillator phase noise measurement and digital compensation in a coherent transmission system. The experimental implementation of phase measurement technique is shown inset.

The signal received on each photodiode pair after the 90° optical hybrid is defined as

$$\begin{pmatrix} I_I(t) \\ I_Q(t) \end{pmatrix} \propto \begin{pmatrix} \mathrm{Re}\{E(t)E^*(t-\tau)\} \\ \mathrm{Im}\{E(t)E^*(t-\tau)\} \end{pmatrix} \tag{1}$$

where $I_{I,Q}(t)$ are the photodiode currents (in-phase and quadrature) and $E(t)$ is the electric field of the LO laser. Direct detection terms are minimised by using balanced detection. Assuming constant optical intensity (and small τ), the instantaneous frequency can be calculated from the received signal.

$$\frac{d\phi(t)}{dt} \approx \frac{1}{\tau}\left[\phi(t) - \phi(t-\tau)\right] = \frac{1}{\tau}\arg\left(E(t)E^*(t-\tau)\right) \tag{2}$$

The phase, $\phi(t)$, is then obtained by numerical integration[1]

$$\phi(t) = \frac{1}{\tau}\int_0^t \arg\left(E(x)E^*(x-\tau)\right)\, dx \quad (\mathrm{mod}\ 2\pi) \tag{3}$$

This analysis is independent of spectral shape. The measured phase can be used to digitally compensate the coherent beat signal (combined signal and LO) received using a separate digital coherent receiver. This removes the phase noise contribution of the LO laser from the data carrying signal[2].

III. FM Noise Spectrum and Linewidth Reduction

To quantify the possible linewidth reduction using this technique, a high linewidth laser was first emulated by modulating phase noise onto CW light from an ECL (intrinsic linewidth 10 kHz) as in [11]. Phase noise was applied to the CW light using a triple Mach-Zehnder modulator ('IQ' modulator) driven by an arbitrary waveform generator (ArbWG) operating at 12 GSa/s. The modulated phase was then compared with the phase estimated using this technique (Fig. 2). For the phase noise compensation stage, the interferometer bandwidth was set to 550 MHz, allowing a practical implementation with 1.1 GSa/s analogue-to-digital converters (ADC). A 35 MHz frequency shift was applied to one arm using an acousto-optic modulator to overcome AC-coupling from balanced transimpedance amplifiers (TIA); this shift was later removed digitally. Note that the frequency shift would not be required if DC-coupled balanced photodiodes were used, as demonstrated in section IV. The signal from the photodiodes was digitized and resampled to 12 GSa/s. The performance of the linewidth measurement is principally limited by the interferometer bandwidth, the receiver bandwidth and the photodetector noise [10].

[1] Assuming a time step at the Nyquist limit, this integration can be computed in hardware using a cumulative sum updating a fixed resolution buffer.

[2] Temporal misalignment between receivers reduces the effective compensation bandwidth. However, for the results presented herein, ±1 sample skew had no measurable impact on performance.

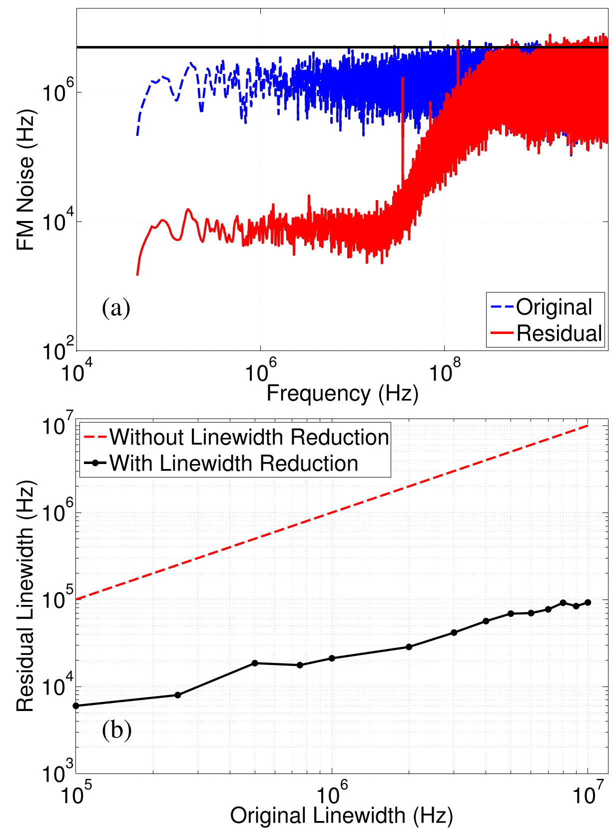

Fig. 2. (a) FM noise spectra (smoothed) before and after compensation of 10 MHz linewidth. (b) Residual linewidth after phase noise compensation (in compensation bandwidth).

Fig. 2(a) compares the spectrum of the applied frequency modulation (FM) noise with the spectrum of the phase noise after compensation (residual) for a 10 MHz laser linewidth. Though the interferometer bandwidth is 550 MHz, the phase noise compensation is flat only up to 30 MHz. Within the bandwidth DC-30 MHz, the phase noise is reduced significantly, with an estimate of the resulting linewidth shown in Fig. 2(b). For a 10 MHz input linewidth, the effective linewidth can be reduced to below 100 kHz.

In this letter, it is of primary interest to evaluate the possible phase noise reduction when using an LO laser with a non-Lorentzian frequency spectrum. The laser used in this letter was a tunable digital supermode distributed Bragg reflector (DS-DBR) laser, with an intrinsic linewidth of 500 kHz [12].

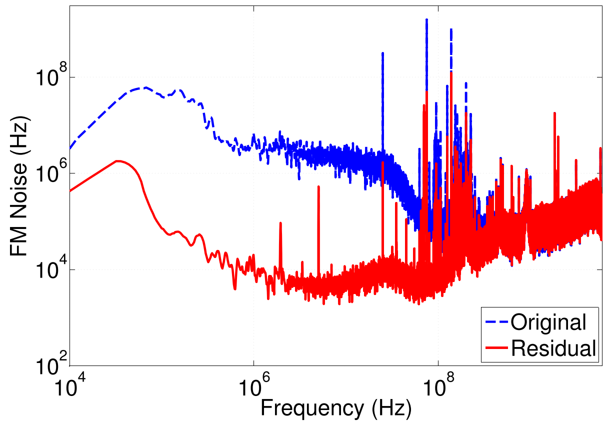

Fig. 3. FM noise spectra before and after compensation for a DS-DBR laser. Despite the non-Lorentizian frequency spectrum for this laser, the phase noise can still be compensated.

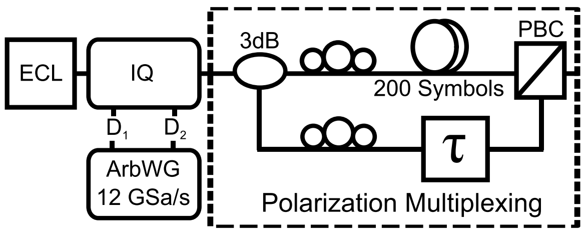

Fig. 4. Experimental generation of 6 GBd DP-64QAM.

As this laser was originally developed prior to the re-emergence of coherent detection, it exhibits an excess low frequency noise as well as a broadened Lorentzian linewidth of 1.4 MHz due to noise translated from the electrical driving circuitry (for direct detection applications, a linewidth below approximately 5 MHz is appropriate). To estimate the uncompensated FM noise spectrum, a coherent heterodyne technique was employed as described in [13], using a 10 kHz linewidth reference laser, Fig. 3. The compensated spectrum was estimated by comparing the phase noise measured using the heterodyne technique, and the phase noise measured using digital coherence enhancement. The resulting FM noise spectrum is also shown in Fig. 3. Note that the bandwidth of the interferometer is sufficient to compensate the laser's low frequency noise, which is reduced by an order of magnitude.

IV. Experiment and Simulation

When applying phase noise compensation, the high frequency FM noise is uncompensated as it falls outside the interferometer bandwidth. To evaluate the impact of these frequency components, a DP-64QAM signal was generated and detected (Fig. 4). The transmitter laser was an ECL (wavelength 1554 nm, linewidth 10 kHz), and the LO was a DS-DBR laser (1.4 MHz estimated Lorentzian linewidth). 6 GBd 64QAM was generated using an ArbWG operating at 12 GSa/s (2 Sa/symbol), driving an 'IQ' modulator. Polarization multiplexing was emulated by splitting the signal into two arms of a delay line stage (200 symbols delay) before recombination using a polarization beam combiner (PBC).

At the receiver, the signals were detected using a phase- and polarization-diverse coherent receiver, and digitally sampled using a digital storage oscilloscope, before being resampled to 2 Sa/symbol. At this point the phase noise compensation was applied to the received signal. The channel was estimated using the constant modulus algorithm, which initialized a decision directed equalizer stage [14] interleaved with decision directed carrier phase estimation [3].

The DP-64QAM transceiver structure was also studied in simulation. Here, a variable Lorentzian linewidth was added to the LO in order to quantify the penalty expected for a particular (linewidth) × (symbol duration) product ($\Delta\nu \cdot \mathrm{T}$). The phase noise compensation scheme was simulated to quantify the impact of residual high frequency phase noise. Additionally, the impact of receiver AC-coupling was investigated (modelled as a 100 kHz high pass filter), in order to investigate the requirement for an optical frequency shift when using AC-coupled receivers.

V. Results and Discussion

The simulation results are shown in Figs. 5(a), (b). Fig. 5(a) shows that for uncompensated LO laser phase noise, the sensitivity penalty is 1 dB when $\Delta\nu \cdot \mathrm{T} = 3.1 \times 10^{-5}$. Using the phase noise compensation scheme (with a 550 MHz interferometer bandwidth), the penalty is 1 dB for $\Delta\nu \cdot \mathrm{T} = 3 \times 10^{-4}$. Further, Fig. 5(b) shows the relationship between the interferometer bandwidth and the required OSNR penalty (assuming negligible contribution from receiver noise sources). From these results it is clear that a 550 MHz interferometer bandwidth is sufficient to maintain a required OSNR penalty below 1 dB for the experimental configuration considered herein.

The simulations confirm the experimental results shown in Fig. 5(c), where $\Delta\nu \cdot \mathrm{T} = 2.3 \times 10^{-4}$. For this experimental configuration, phase noise compensation is required in order to recover the data. When applying phase noise compensation, the sensitivity penalty against using the ECL as LO laser is 0.6 dB, which is due to uncompensated high frequency phase noise. To the best of our knowledge, this represents 64QAM data recovery with a record $\Delta\nu \cdot \mathrm{T} = 2.3 \times 10^{-4}$ compared with the previous highest reported results $\Delta\nu \cdot \mathrm{T} = 1.2 \times 10^{-5}$ [15].

Consider, now, the implication for higher order QAM. The linewidth requirements for 256QAM are approximately a factor of 5 more stringent than those for 64QAM [3], meaning that 75 GBd DP-256QAM, achieving 1.2 Tbit/s, has a linewidth requirement of 500 kHz for a 1 dB penalty. Using this scheme, the LO laser linewidth could be increased to 5 MHz, enabling the use of fast tunable lasers for this application.

Finally, Fig. 5(d) confirms that receiver AC-coupling impairs the phase estimate due to high pass filtering of the measured differential phase. Further simulations (not shown) indicate that the minimum required frequency shift is exactly twice the AC-coupling high pass filter bandwidth. Therefore, the frequency shift used in the phase measurement technique, Fig. 1, could be removed for DC-coupled receivers. Note that some information about the high frequency phase noise is lost through AC-coupling however, as the frequency shift increases, the information loss tends asymptotically to zero.

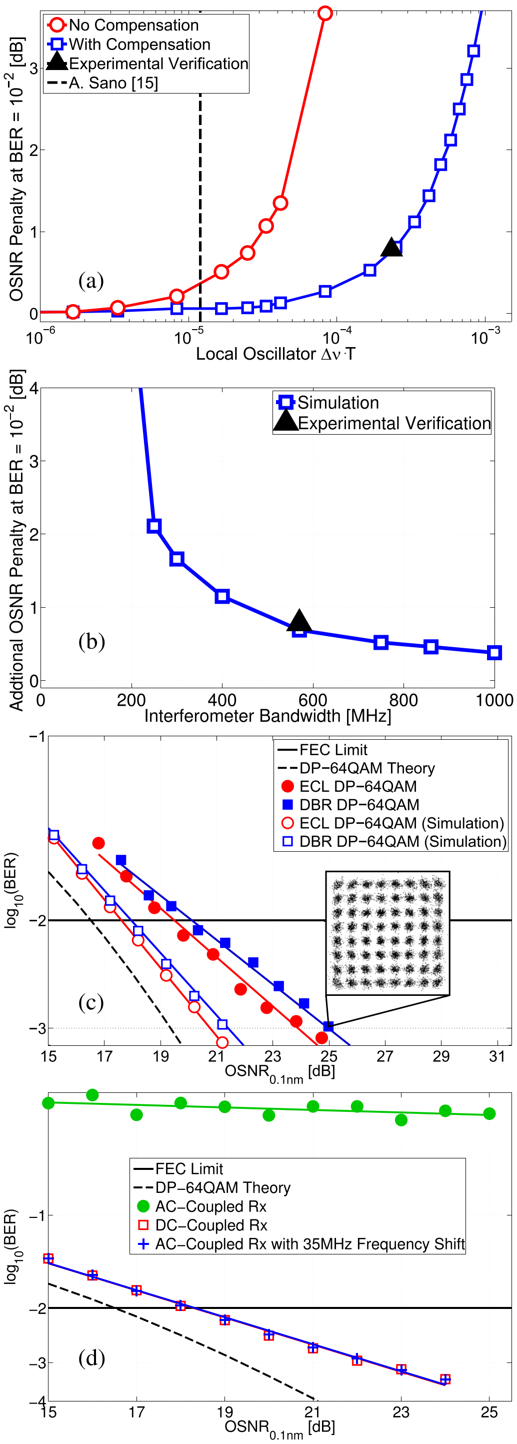

Fig. 5. (a) Simulation showing penalty due to LO laser linewidth (c.f. [3]). The previous highest LO $\Delta\nu \cdot T$ is indicated [15]. (b) Simulation of required OSNR penalty versus interferometer bandwidth for $\Delta\nu \cdot T = 2.3 \times 10^{-4}$. (c) Experimental results showing DP-64QAM performance both with an ECL and with a phase noise compensated DBR laser as the LO. (When using the DS-DBR laser without phase compensation, the data cannot be recovered.) (d) Simulations showing the effect of AC-coupling when measuring and compensating 1.4 MHz LO laser linewidth.

VI. Summary and Conclusion

A self-coherent detection method was used to measure, and digitally compensate, the phase noise from a LO laser in a coherent receiver. Experimental investigations show that low frequency noise from a DS-DBR laser can be compensated sufficiently to enable the reception of DP-64QAM. Further, simulation and experimental results show the potential for the measurement technique to enable the use of a high linewidth LO with high order modulation formats, such as DP-64QAM. The additional penalty for 6 GBd DP-64QAM was 0.6 dB at a BER 10^{-2} when the LO has a 1.4 MHz linewidth. This letter has particular significance for coherent transmission systems where integrated semiconductor tunable local oscillator lasers are required for frequency selectivity, for example coherent burst switched networks.

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