# Demonstration of Dispersion-Enhanced Phase Noise in RGI CO-OFDM Systems

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***Abstract*— We report the first experimental demonstration of dispersion-enhanced phase noise (DEPN) in reduced-guard-interval (RGI) coherent optical orthogonal frequency-division multiplexing (CO-OFDM) systems. It is first shown that channel estimation enhances DEPN. Then we experimentally demonstrate that for 28 Gbaud dual-polarization QPSK (112 Gb/s) RGI CO-OFDM systems with different inverse fast Fourier transform sizes, the transmission distance at a bit error rate = $3.8 \times 10^{-3}$ is limited to 1830–2550 km by DEPN when a distributed feedback laser with a 2.6-MHz linewidth is employed as the local oscillator. We also, however, show that using DEPN compensation can increase the distance to 3320–4400 km.**

***Index Terms*— Dispersion-enhanced phase noise (DEPN), orthogonal frequency-division multiplexing (OFDM), phase estimation.**

## I. Introduction

BECAUSE of high attainable spectral efficiencies, reduced-guard-interval (RGI) coherent optical orthogonal frequency-division multiplexing (CO-OFDM) systems are considered as a potential candidate for next generation optical transport [1]. In RGI CO-OFDM systems, an overlapped frequency domain equalizer (OFDE) is employed to compensate for chromatic dispersion (CD) followed by OFDM demodulation with a much shorter cyclic prefix (CP) to accommodate for the residual inter-symbol interference. However, dispersion-enhanced phase noise (DEPN) is an impairment that occurs in such systems when a large linewidth laser is employed as the local oscillator (LO) [2].

In this letter, we report the first experimental demonstration of DEPN and its compensation in RGI CO-OFDM systems. We first numerically illustrate that DEPN will be enhanced by channel estimation. In the experiments, 28 Gbaud dual-polarization (DP) QPSK (112 Gb/s) RGI CO-OFDM systems with inverse fast Fourier transform (IFFT) sizes of 64, 128 and 256 were evaluated. With external cavity lasers (ECLs) employed at both the transmitter and receiver sides, the three systems can achieve transmission distances of up to 4900,

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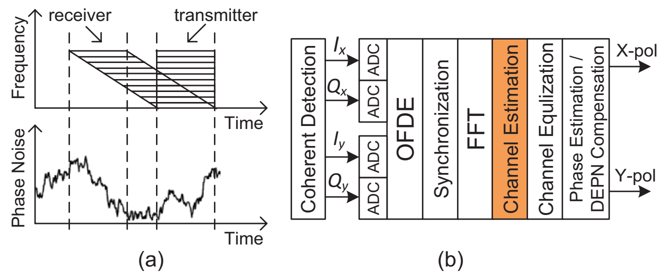


Fig. 1. (a) Origin of DEPN. (b) Block diagram of RGI OFDM receiver.

4940 and 4640 km, respectively. However, the distance is reduced to 1830, 2550 and 2400 km, respectively, with a 2.6 MHz linewidth distributed feedback (DFB) laser employed as the LO due to DEPN. We also demonstrate that by compensating DEPN using the algorithm proposed in [2], [3] the distances are increased to 4400, 4070 and 3320 km with the DFB laser used as the LO, respectively.

## II. Dispersion-Enhanced Phase Noise

The interaction between CD and laser phase noise was first shown in single carrier [4], [5] and direct-detection OFDM systems [6]. It also occurs in RGI CO-OFDM and is referred to as DEPN, of which the origin is illustrated in Fig. 1(a). Due to the walk-off between subcarriers caused by CD after transmission, different subcarriers will experience different phase noise from the LO laser. Therefore, the phase shifts of subcarriers within one symbol will no longer be identical [2]. Thus, conventional common phase error (CPE) compensation which estimates only one phase for all subcarriers [7] will degrade the performance when DEPN is non-negligible.

Fig. 1(b) depicts the receiver diagram of a RGI CO-OFDM system. The channel estimation as highlighted in Fig. 1(b) was omitted from the previous studies of DEPN [2]. However, it is noted that training symbols also suffer from DEPN, which will introduce undesired phase shifts for the estimated channel transfer function. Since those phase shifts will be applied to the following data symbols in the process of channel equalization, the total DEPN of data symbols will be enhanced. Fig. 2 shows the evaluation of such an enhancement. By comparing the constellations without and with channel estimation shown in inset (a) and (b), respectively, it is apparent that the phase variance of subcarriers is increased by channel estimation. The optical signal-to-noise ratio (OSNR) penalty (at a bit error rate (BER) = $3.8\times10^{-3}$) versus the LO laser linewidth

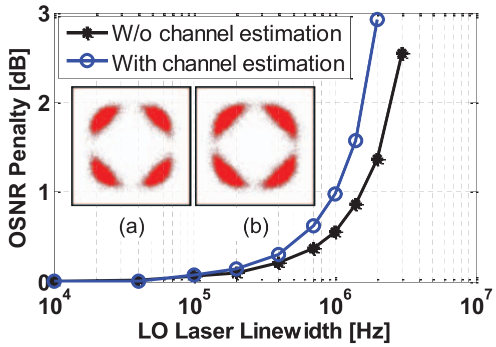


Fig. 2. Simulated OSNR penalty at BER = $3.8 \times 10^{-3}$ versus LO laser linewidth. System parameters: 28 Gbaud, 112 subcarriers, and 3200-km distance. Insets: the constellation (a) without and (b) with channel estimation with a 2-MHz linewidth LO laser and no noise loading.

of the two scenarios is also compared. The required OSNR without LO phase noise is used as a reference. In particular, channel estimation enhances DEPN and thus increases the OSNR penalty by 0.4 and 1.6 dB for 1 MHz and 2 MHz linewidths, respectively. It should be noted that the enhancement can be removed by employing more training symbols and averaging over transfer functions obtained from them for a single estimation, and then the amount of DEPN will stay the same as shown in our previous study where channel estimation was omitted [2].

## III. Experimental Setup and Results

Fig. 3 shows the experimental setup. The OFDM samples were generated offline and uploaded to the memory of two field-programmable gate array (FPGA) boards, which drove two 32 GS/s Micram digital-to-analog converters (DACs) with 6 bit resolution for the generation of the analog inphase and quadrature signals. The modulated optical signal was then passed through a DP emulator with one branch delayed by 24.8 ns (6 OFDM symbols) for de-correlation. The DP signal was fed into an optical re-circulating loop, which consisted of 4 spans of 80 km standard single mode fiber (SMF-28e+) and 4 erbium doped fiber amplifiers (EDFAs) (5 dB noise figure). The output signal was filtered, amplified and filtered again before being coherently detected and digitized for offline processing, of which the flow diagram is shown in Fig. 1(b). For the OFDM signal, the IFFT size $N_{IFFT}$ is 128, if not otherwise specified, filled with 108 data subcarriers, 4 pilot subcarriers and 1 unfilled DC subcarrier, leading to a baud rate of 28 Gbaud with an oversampling ratio of 1.14%. The CP overhead was 3.13%. One pair of correlated dual-polarization (CDP) training symbols [8] was sent for each 412.5 ns period data signal (100 symbols for $N_{IFFT} = 128$). The CPE compensation in [7] was employed for phase estimation, if not otherwise specified. In the following results, we denote the system with different lasers by 'transmitter laser/ LO laser', e.g. ECL/ECL for the system with ECLs at both transmitter and receiver sides. The linewidth of the ECL we used was ~100 kHz. For the DFB laser we used, the linewidth was 2.6 MHz calculated from the phase variance which was measured using the coherent detection method proposed in [9].

Fig. 4 shows the BER performance as a function of OSNR for the back-to-back configuration. Compared with the theoretical limit, a 2 dB OSNR penalty is observed for the ECL/ECL system at a BER of $3.8\times10^{-3}$. Such a penalty is partially caused by the low effective number of bits (ENOB) of the DACs at high frequencies. The ECL/DFB and DFB/DFB systems achieve identical performance, but slightly worse than that of the ECL/ECL system due to the DFB laser phase noise induced inter-carrier interference (ICI).

The transmission performance is shown in Fig. 5. The ECL/ECL system achieves a 4940 km distance at the $3.8 \times10^{-3}$ BER threshold. However, with the DFB laser used as the LO the achievable distance is significantly reduced to 2550 km due to both DEPN and ICI. But by comparing to the DFB/ECL system which only suffers from ICI and therefore reaches 4070 km, it is clear that DEPN is more significant than ICI in terms of the performance degradation. The DEPN-induced residual phase shift is illustrated in the constellation (inset).

However, DEPN can be compensated using the grouped maximum-likelihood (GML) algorithm proposed in [2], [3]. In GML, all the subcarriers are virtually divided into two groups with the same amount of subcarriers. The pilot subcarriers in each group are used to compensate for the common phase of the subcarriers in that group, in order to partially mitigate DEPN. Next, standard maximum-likelihood phase estimation is implemented for each subcarrier using a moving averaging filter. Using GML the distance is increased to 4070 km for the ECL/DFB system as shown in Fig. 6.

It has been analytically and numerically demonstrated that ICI scales with $N_{IFFT}$, whereas DEPN increases as the $N_{IFFT}$ decreases [2]. Here, we conducted the experimental investigation of the relationship between DEPN and $N_{IFFT}$ with a fixed oversampling ratio for the RGI CO-OFDM system. In order to do so, we measured the transmission performance of the system with $N_{IFFT} = 64$ and $N_{IFFT} = 256$, which is shown in Fig. 6 and Fig. 7, respectively. The number of pilot subcarriers, CP overhead, and training period was the same as the system with $N_{IFFT} = 128$. The achieved transmission distance with different $N_{IFFT}$ for the ECL/ECL and ECL/DFB systems with only CPE compensation, and the ECL/DFB system with the DEPN compensation using GML are summarized in Table I. First, with the ECL/ECL configuration, the system with $N_{IFFT} = 256$ performs slightly worse than the other two systems. This is caused by the reduced tolerance to fiber nonlinearities since for symbols with a larger $N_{IFFT}$ the peak-to-average power ratio (PAPR) increases and the de-correlation between subcarriers resulting from the CD-induced walk-off is reduced [10]. In the ECL/DFB configuration with CPE compensation, the system with $N_{IFFT} = 64$ has the worst performance due to the largest DEPN. The systems with $N_{IFFT} = 128$ and $N_{IFFT} = 256$ perform similarly because the former has a larger DEPN but a smaller ICI, whereas the latter suffers from LO laser phase noise in an opposite manner. The relationship between DEPN and $N_{IFFT}$ is much clearer when we compare the performance of the ECL/DFB systems with and without GML. In particular, applying GML for DEPN compensation increases the

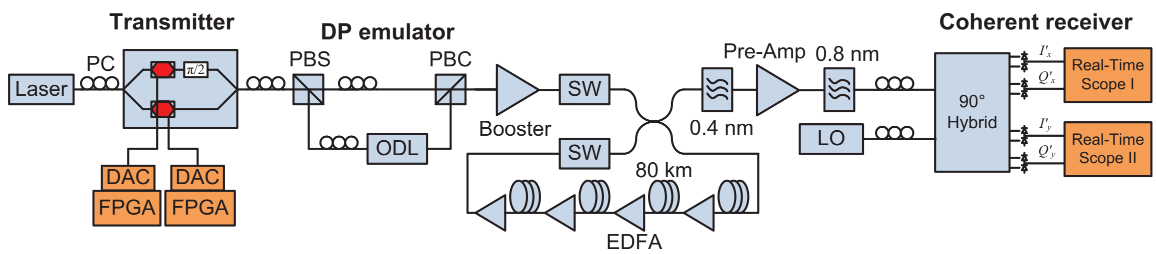


Fig. 3. Experimental setup. ODL: optical delay line. PBS: polarization beam splitter. PBC: polarization beam combiner. PC: polarization controller. SW: switch.

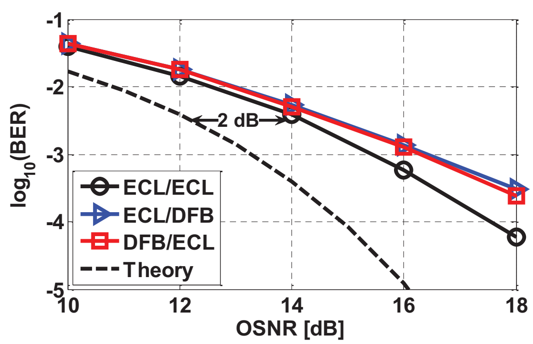


Fig. 4. Back-to-back BER versus OSNR.

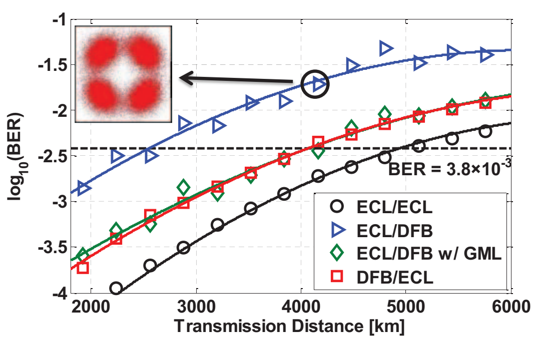


Fig. 5. BER versus transmission distance for the system with $N_{IFFT} = 128$.

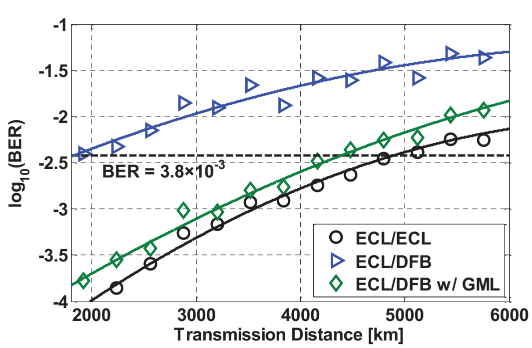


Fig. 6. BER versus transmission distance for the system with $N_{IFFT} = 64$.

transmission distance by 140%, 60% and 38% for the system with $N_{IFFT} = 64$, 128 and 256, respectively. It indicates that the DEPN impairment increases rapidly when $N_{IFFT}$ decreases. However, with the DEPN compensation the system with $N_{IFFT} = 64$ achieves the longest transmission distance, demonstrating the good performance of the proposed GML algorithm for compensating DEPN.

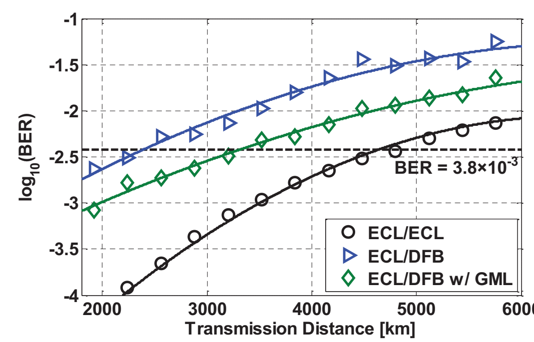


Fig. 7. BER versus transmission distance for the system with $N_{IFFT} = 256$.

TABLE I

PERFORMANCE COMPARISON OF VARIOUS RGI CO-OFDM SYSTEMS

| | ECL/ECL | ECL/DFB | ECL/DFB (GML) |
|---|---|---|---|
| $N_{IFFT} = 64$ | 4900 km | 1830 km | 4400 km |
| $N_{IFFT} = 128$ | 4940 km | 2550 km | 4070 km |
| $N_{IFFT} = 256$ | 4640 km | 2400 km | 3320 km |

## IV. CONCLUSION

We experimentally demonstrated dispersion-enhanced phase noise (DEPN) in reduced-guard-interval (RGI) CO-OFDM systems in this letter. We first numerically showed that DEPN will be enhanced by channel estimation. In 28 Gbaud dual-polarization (DP) QPSK (112 Gb/s) RGI CO-OFDM experiments with different IFFT sizes, DEPN caused by a 2.6 MHz distributed feedback (DFB) laser employed as the local oscillator (LO) reduces the transmission distance to 1830–2550 km depending on the FFT size. However, we also demonstrated that by compensating for DEPN the transmission distance can be increased to 3320–4400km.

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