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Relative phase noise induced impairment in CO-OFDM optical communication system with distributed fiber Raman amplifier

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In this Letter, we demonstrate that the interplay between Raman pump relative intensity noise and cross-phase modulation leads to a relative phase noise (RPN) that brings non-negligible performance degradation to coherent optical orthogonal frequency-division multiplexing (CO-OFDM) transmission systems with co-pumped Raman amplification. By theoretical analysis and numerical simulation, we proved that RPN brings more system impairment in terms of Q-factor penalty than the single carrier system, and relatively larger walk-off between pump and signal helps to suppress the RPN induced impairment. A higher-order modulated signal is less tolerant to RPN than a lower-order signal. With the same spectral efficiency, the quadrature-amplitude modulation format shows better tolerance to RPN than phase-shift keying. The reported findings will be useful for the design and optimization of Raman amplified CO-OFDM multi-carrier transmission systems.

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The combination of coherent detection, advanced modulation formats, and digital signal processing has led to an enormous increase in the capacity of the optical fiber communication system [1]. However, the capacity of the system is ultimately limited by the fiber nonlinearity, and the distributed fiber Raman amplifier (DFRA) has been widely adopted to suppress the nonlinear noise accumulation by maintaining relatively flat and low signal power distribution in the fiber link [2]. Recently, Cheng *et al.* have shown that in a single-carrier coherent optical communication system with DFRA employing a phase-modulated signal, such as phase-shift keying (PSK) and quadrature-amplitude modulation (QAM), an extra phase noise will be generated through a pump–signal cross-phase modulation (XPM) effect [3]. This extra phase noise, defined as relative phase noise (RPN), brings non-negligible system impairments of 0.9 dB in terms of the Q-factor in single carrier system with the fiber length of 100 km when the pump relative intensity noise (RIN) is −100 dB employing QPSK modulation format [3]. However, to the best of our knowledge, the impact of RPN on a multi-carrier system has not been studied yet. In this Letter, we perform the theoretical analysis and numerical simulations on the RPN induced impairments in coherent optical orthogonal frequency-division multiplexing (CO-OFDM) systems and compare the result with the single-carrier counterpart.

CO-OFDM is one of the most promising technologies for next-generation optical long-haul transmission systems [4]. Two fundamental advantages of OFDM are its robustness against channel dispersion and its ease of phase and channel estimation in a time-varying environment [5,6]. OFDM belongs to a broader class of multicarrier modulation (MCM) systems in which data are transmitted in parallel on a number of different frequencies [6]. As a result, the symbol rate in each subcarrier is very low.

The signal's RPN transferred from the pump RIN can be defined by $\mathrm{RPN}_s(f) = \langle \Delta\theta^2 \rangle / \langle \theta \rangle^2$, and its analytical expressions can be obtained as follows by assuming a non-depletion regime of pump power and neglecting the XPM from the signal to the pump and the self-phase modulation of the signal itself [3]. In the co-pumping case, after further simplifying the equations, we have

$$\mathrm{RPN}_s(f) = \frac{\mathrm{RIN}_p(f) \times \alpha_p^2}{[\alpha_p^2 + (2\pi f d)^2]} \times \frac{1 + \exp(-2\alpha_p z) - 2\cos(2\pi f d z) \times \exp(-\alpha_p z)}{[1 - \exp(-2\alpha_p z)]^2}, \tag{1}$$

where $\mathrm{RIN}_p(f)$ is the RIN of pump power, f represents frequency, z is the distance along the fiber, $d = V_{gp}^{-1} - V_{gs}^{-1}$ is the walk-off parameter in co-pumping schemes, accounting for the group-velocity (V_{gj}) mismatch between the pump and the signal, and α_j is the attenuation with $j = s$ or p that is associated with the signal and pump. The RPN can be treated as a zero-mean Gaussian random variable with the variance given by [3]:

$$\sigma_{\mathrm{RPN}}^2 = \int_{v_1}^{v_2} \mathrm{RPN}_s(f) * \langle \theta \rangle^2 \mathrm{d}f. \tag{2}$$

In the above equation, $\langle \theta \rangle$ is the average phase noise induced by RIN, while ν_1 and ν_2 are the lower and upper frequencies of the receiver, respectively. The RPN transfer function, referring to Eq. (1), which determines the power spectral density (PSD) shape of the RPN for both co-pumping and counter-pumping Raman amplifier, is illustrated in Fig. 1 [7,8].

From Fig. 1, we find that the RPN is a low-frequency noise in nature and the −3 dB frequency of co-pumping is several MHz and several kHz in the counter-pumping

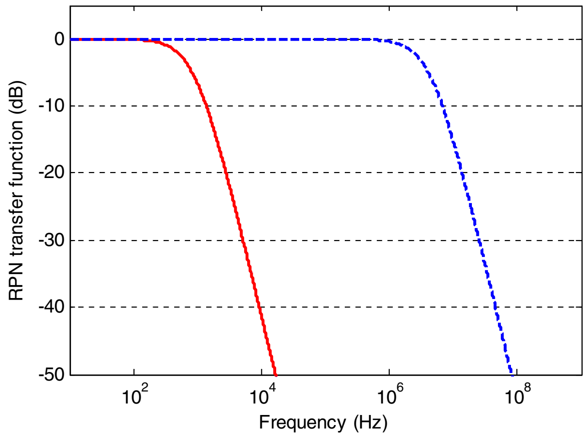

Fig. 1. RPN transfer function for Raman amplifier with walk-off is 2 ps/m, pump at 1450 nm, and signal at 1550 nm. The pump attenuation is 0.25 dB/km, the signal attenuation is 0.2 dB/km, and the length is 100 km for the co-pumping case (dotted line) and the counter-pumping case (solid line).

case. Because of its low −3 dB cut-off frequency, RPN induced impairments in the counter-pumped Raman system can be neglected compared with that in the co-pumped system [3]. Therefore, only the co-pumping Raman amplified CO-OFDM system is being evaluated.

Figure 2 compares the phase samples during 1 μs of one subcarrier of the OFDM and the RPN in the co-pumping case. Clearly, we see that the changing speed of RPN is at a similar level to the OFDM subcarrier symbol rate. As is well-known, in OFDM symbols, each subcarrier's data rate is quite lower than that in the single carrier system with the same total data. In addition, the OFDM symbol is sensitive to phase noise. Hence, it is reasonable to infer that the RPN will cause more performance degradation in an OFDM system than in a single-carrier system, in which the symbol rate is much faster.

To investigate the impact of the RPN on the CO-OFDM multicarrier system, the simulation has been carried out in a 40 GSam/s 8PSK-CO-OFDM system which is built in a MATLAB environment.

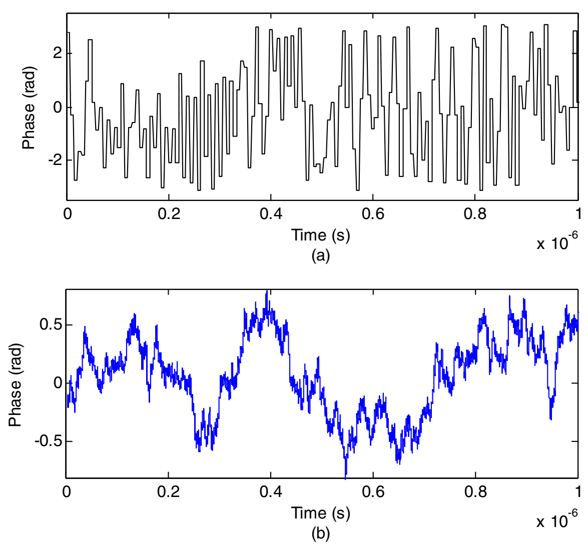

Fig. 2. Phase samples of (a) one subcarrier of the OFDM employing 8PSK and (b) the RPN in the co-pumping case (with RPN variance 0.34 rad^2). Both are in 1 μs.

In the transmitter, the MATLAB is performed to generate the OFDM baseband signals. The processing sequence is shown in Fig. 3(b). The pseudo-random bit sequence (PRBS) with a length of $2^{21} - 1$ as the transmitted data stream is mapped into 8PSK, which adds 8 subcarriers as pilot information used for phase noise estimation to fill the middle 240 subcarriers and 8 null subcarriers in the end. Two training symbols are subsequently inserted at the beginning of each OFDM frame, in which one training symbol stands for OFDM symbol synchronization and the other stands for channel estimation and frequency offset estimation (FOE). The time domain signal is generated by an IFFT operation of size 256. Before parallel-to-serial conversion (P/S), 27 cyclic prefixes (CPs) as the guard interval are inserted for eliminating inter-symbol interference (ISI) because of channel dispersion, resulting in an OFDM symbol size of 283. Each OFDM frame includes two training and 126 payload OFDM symbols, as shown in Fig. 3(a). Afterward, the real and imaginary parts of the OFDM signal are uploaded into the DAC operated at 40 GSam/s to generate IQ analog signals, and are fed into the I/Q modulator to generate an 8PSK-OFDM signal in optical domain. In the end, the 8PSK-OFDM signal is obtained with a 100 Gb/s $(= 3 \times 40\ \text{GSam/s} \times 240/256 \times 256/283 \times 126/128)$ date rate and 156.3 MHz (= 40 GHz/256) subcarrier spacing, respectively.

The fiber link in the simulation is comprised of single-mode fiber (SMF) and because of the assumption of RPN's theoretical analysis, only the fiber attenuation, additive white Gaussian noise (AWGN), group velocity dispersion (GVD), and RPN are considered, while other

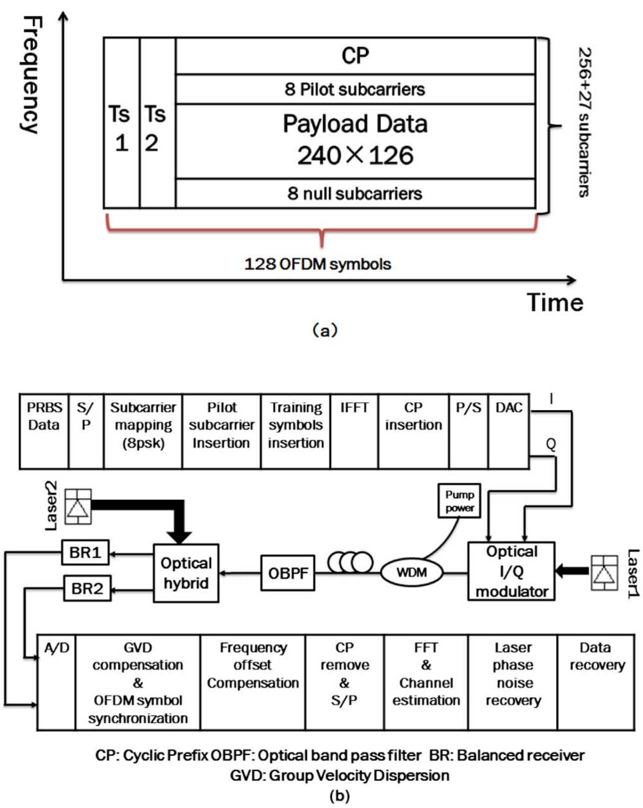

Fig. 3. (a) OFDM frame structure and (b) the schematics of the transmitter, fiber link, and receiver.

nonlinear noise are beyond our studies in this Letter. Here, signal-to-noise ratio (SNR) can be adjusted by changing the noise power of the AWGN.

After fiber propagation, the received signals are processed offline. First, the step ADC is implemented. Subsequently, the GVD compensation, the OFDM symbol synchronization, and the frequency offset estimation (FOE) [9], channel estimation and laser phase noise compensation [10] are carried out one by one until the data are finally recovered.

The Q-factor parameter is connected to the BER by $\mathrm{BER} = \mathrm{erfc}(Q/\sqrt{2})/2$. The RPN induced impairments can be evaluated by Q-factor penalty, which is given as $Q_{\mathrm{Penalty}}(dB) = 20\,\log(Q_{\mathrm{without\ RPN}}/Q_{\mathrm{with\ RPN}})$[3].

For all simulations, the span length is 100 km, the attenuation of the signal and the pump is 0.20 and 0.25 dB/km, respectively, the fractional Raman contribution is 0.18, the nonlinear parameter is $1.3/(\mathrm{W}\cdot\mathrm{km})$ for the effective cross-sectional area of 80 $\mu\mathrm{m}^2$. The Raman gain coefficient is $0.35/(\mathrm{W}\cdot\mathrm{km})$. In addition to the fiber attenuation, an extra 2 dB power budget is added in our simulation system to take the components' insertion loss into consideration. At last, the on-off gain is 22 dB. The lower and upper frequencies of the receiver are 10 KHz and 20 GHz, respectively. The frequency offset employs 288 MHz (= 1.84 subcarrier spacing, including both fraction and integer parts of subcarrier spacing). The linewidths of the signal laser and the local oscillator (LO) are 100 KHz. The chromatic dispersion of fiber is 20 ps/nm/km. The SNR is set as 27 dB. Figure 4 shows the constellation of the received 8PSK-OFDM signal with/without the RPN. The performance degradation can be clearly observed.

We calculate Q-penalty at the pump RIN ranges from −140 dB/Hz to 100 dB/Hz. Figure 5 shows the estimated Q-penalty of the 8PSK signal because of the signal RPN versus pump RIN on the CO-OFDM co-pumping systems (the baseline $\mathrm{BER} = 1.87\times10^{-5}$). The walk-off parameters in the CO-OFDM configuration are 2.0, 3.0, and 4.0 ps/m by changing the dispersion parameter, respectively. We can see that the CO-OFDM configuration may tolerate nearly up to −107 dB/Hz pump RIN (with 2.0 ps/m walk-off) without suffering 1 dB Q-penalty. There is a 5 dB penalty of pump RIN compared with the single carrier case (dashed line) at the same baseline Q-factor that is calculated by using reported methodologies [3,11] (with the same walk-off, modulation format, symbol rate, and transmission length). In addition, from

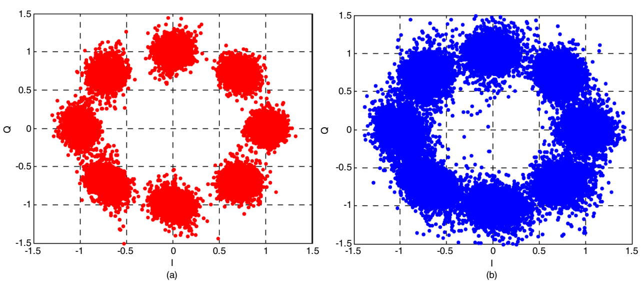

Fig. 4. Constellation of the received 8PSK-CO-OFDM signal (a) without RPN and (b) with RPN (with a variance equal to 0.34 rad^2).

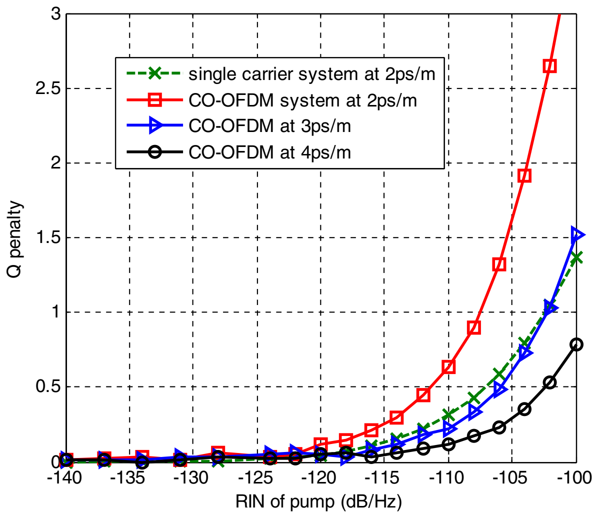

Fig. 5. Estimated Q-penalty versus pump RIN for 8PSK in the CO-OFDM system (solid line) at 2 ps/m, 3 ps/m, and 4 ps/m walk-off parameters and in a single carrier system (dashed line) at a 2 ps/m walk-off parameter. The symbol rate is 40 GSam/s, and the linewidth of the signal laser and the LO are 100 KHz.

the three separate curves (solid line) in the CO-OFDM case, we find that the larger walk-off helps to reduce the penalty because the pump RIN transfer is averaged to a greater degree.

In addition, the higher-order modulation formats suffer more impact because they have more stringent requirements of phase tolerance. The result is illustrated in Fig. 6. We fixed a BER value at 10^{-3} as the baseline BER for all high-order modulation OFDM signals by adjusting the SNR. A smaller Q-penalty is expected in the lower-order case. When the RIN is −102 dB/Hz, 16PSK suffers nearly 1.9 dB Q-penalty more than 8PSK and nearly 2.9 dB compared with QPSK. As for 16QAM, we find that it has a 1.8 dB improvement of Q-penalty compared with 16PSK at −102 dB/Hz pump RIN while maintaining the same spectral efficiency.

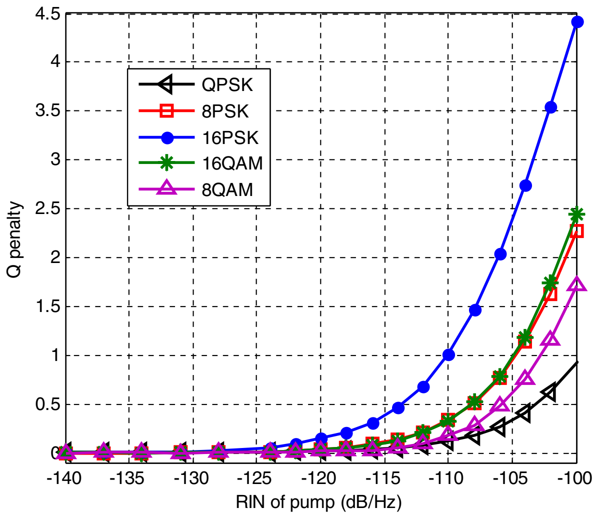

Fig. 6. Estimated Q-penalty versus pump RIN for different order PSK signals,16QAM, and 8QAM. The walk-off parameter is 2 ps/m for all, the symbol rate is 40 GSam/s, and the linewidths of the signal laser and the LO are 100 KHz.

In conclusion, we have shown for the first time to the best of our knowledge that a CO-OFDM system suffers more impairment induced by the RPN than that of a single carrier system. This was numerically confirmed in a 40 GSam/s-CO-OFDM system with 100 Gb/s effective data rate under an 8PSK modulation format. With 1 dB Q-penalty, 8PSK-CO-OFDM multi-carrier system introduces 5 dB more pump RIN penalty compared with single carrier system. A relatively larger walk-off effect helps to suppress the RPN induced impairment. Because of tighter phase tolerance, the higher-order modulation format suffers more impact from the RPN. In CO-OFDM system with the RPN, we found that the QAM modulation format has better performance than the PSK with the same spectral efficiency thus will be more suitable for future Raman amplified coherent communication systems. It is demonstrated that less than −120 dB/Hz pump RIN is compulsory to sufficiently suppress the RPN induced penalty.

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†These authors contributed equally to this work.

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