Relative phase noise induced impairment in M-ary phase-shift-keying coherent optical communication system using distributed fiber Raman amplifier

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We show for the first time, to the best of our knowledge, that, in a coherent communication system that employs a phase-shift-keying signal and Raman amplification, besides the pump relative intensity noise (RIN) transfer to the amplitude, the signal's phase will also be affected by pump RIN through the pump–signal cross-phase modulation. Although the average pump power induced linear phase change can be compensated for by the phase-correction algorithm, a relative phase noise (RPN) parameter has been found to characterize pump RIN induced stochastic phase noise. This extra phase noise brings non-negligible system impairments in terms of the Q-factor penalty. The calculation shows that copumping leads to much more stringent requirements to pump RIN, and relatively larger fiber dispersion helps to suppress the RPN induced impairment. A higher-order phase-shift keying (PSK) signal is less tolerant to noise than a lower-order PSK.

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Although linear impairments, such as chromatic dispersion (CD) and polarization mode dispersion can be compensated for in the post-signal-processing stage of coherent optical communication system, the spectral efficiency of a multilevel modulated signal is ultimately limited by the fiber nonlinearity, especially for a data rate of 400 Gb/s and beyond. The distributed fiber Raman amplifier (DFRA) has been recognized to be useful to suppress nonlinear noise accumulation in the fiber link [1]. In traditional intensity-modulation direct-detection systems with DFRA, pump relative intensity noise (RIN) induced system impairment has been intensively studied [2]. However, the effect of pump RIN transfer to the complex electromagnetic field (i.e., amplitude and phase) of a multilevel modulated signal has not been explored, to the best of our knowledge.

In this Letter, by establishing an analytical model, we demonstrate that, in a coherent communication system employing a phase-modulated signal, such as phase-shift keying (PSK) and quadrature-amplitude modulation (QAM), the RIN of the Raman pump transfers to the signal phase component through a pump–signal cross-phase modulation (XPM) effect together with the amplitude RIN transfer behavior. This extra relative phase noise (RPN) has not yet been considered in the traditional digital signal-processing phase estimation (PE) algorithm, thus introducing non-negligible system impairments in terms of the Q-factor penalty.

In order to fully assess the complex signal field in phase-modulated coherent optical system, we propose the following coupled amplitude equations to describe the evolution of both the amplitude and phase of a Raman-amplified optical signal field [3]:

$$\pm\frac{\partial A_p^{\pm}}{\partial z}+\frac{\alpha_p}{2}A_p^{\pm}=i\gamma_p|A_p^{\pm}|^2A_p^{\pm}, \quad (1)$$

$$\frac{\partial A_s}{\partial z}-d\frac{\partial A_s}{\partial T}+\frac{\alpha_s}{2}A_s=i\gamma_s(2-f_R)|A_p^{\pm}|^2A_s+\frac{g_s}{2}|A_p^{\pm}|^2A_s, \quad (2)$$

where A_p and A_s are the slowly varying envelopes associated with the pump and signal, $\pm$ represents copumping and counterpumping schemes, respectively, f_R is the fractional Raman contribution, g_s is the effective Raman gain coefficient, $d=\pm v_{gp}^{-1}-v_{gs}^{-1}$ is the walk-off parameter, v_{gj} is the group velocity, γ_j is the nonlinear parameter, and α_j is fiber attenuation with $j=p$ or s. In the copumping scheme, $T=t-z/v_{gp}$, while in the counterpumping scheme, $T=t-(L-z)/v_{gp}$. The walk-off parameter d accounts for the group-velocity mismatch between the pump and signal. Since $|A_s|^2\ll|A_p|^2$, we thus neglect the XPM from the signal to the pump and the self-phase modulation of the signal. By assuming a nondepletion regime of pump power, $A_s(z,T)$ could be solved as follows:

$$A_s(z,T)=A_s(0,T+zd)\exp\left(-\frac{\alpha_s}{2}z\right)\cdot\exp\left\{\left[i\gamma_s(2-f_R)+\frac{g_s}{2}\right]\Psi^{\pm}(z,T)\right\}. \quad (3)$$

Here,

$$\Psi^{+}(z,T)=\int_0^z|A_p^{+}(0,T+zd-z'd)|^2\exp(-\alpha_p z')\mathrm{d}z', \quad (4)$$

$$\Psi^{-}(z,T)=\int_0^z|A_p^{-}(L,T+zd-z'd)|^2\exp[-\alpha_p(L-z')]\mathrm{d}z'. \quad (5)$$

The amplified signal amplitude and phase are:

$$A=A_s(0,T+zd)\exp\left(-\frac{\alpha_s}{2}z\right)\exp\left[\frac{g_s}{2}\Psi^{\pm}(z,T)\right], \quad (6)$$

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$$\theta = \gamma_s(2 - f_R)\Psi^{\pm}(z, T). \quad (7)$$

It is clearly seen that the phase term of the amplified signal experiences linear change originating from pump–signal XPM. In the coherent detection system, if the pump power of Raman amplification remains constant, the phase change is a predictable value and can be eliminated by the post-phase-correction algorithm. Unfortunately, in real DFRA systems, pump laser diodes exhibit RIN fluctuations. The RIN transferred to the complex signal field leads to uncertainty of signal phase that will directly impact the Q-factor of phase-modulated signal upon receiving.

If a small amount of modulation at frequency f is applied to the pump, the pump power at a certain time and distance along the fiber can be written as follows:

$$|A_p^+(z,T)|^2 = P_p^+(z,T) = P_{p0}\exp(-\alpha z)[1 + m\sin(2\pi fT + \varphi_0)], \quad (8)$$

$$|A_p^-(z,T)|^2 = P_p^-(z,T) = P_{p0}\exp[-\alpha(L - z)][1 + m\sin(2\pi fT + \varphi_0)], \quad (9)$$

where P_{p0} is the mean launched pump power, m is the modulation index, and φ_0 is the initial phase. Substituting Eqs. (8) and (9) into (4) and (5) gives

$$\Psi^+(z,T) = P_{p0}\frac{1 - e^{-\alpha_p z}}{\alpha_p} + mP_{p0}M(z)\frac{\cos(2\pi fT + 2\pi fzd + \varphi_0)}{\alpha_p^2 + (2\pi fd)^2} + mP_{p0}N(z)\frac{\sin(2\pi fT + 2\pi fzd + \varphi_0)}{\alpha_p^2 + (2\pi fd)^2}, \quad (10)$$

$$\Psi^-(z,T) = P_{p0}e^{-\alpha_p L}\frac{e^{\alpha_p z} - 1}{\alpha_p} + mP_{p0}e^{-\alpha_p L}M'(z)\frac{\cos[2\pi fT + 2\pi fzd + \varphi_0]}{\alpha_p^2 + (2\pi fd)^2} + mP_{p0}e^{-\alpha_p L}N'(z)\frac{\sin[2\pi fT + 2\pi fzd + \varphi_0]}{\alpha_p^2 + (2\pi fd)^2}, \quad (11)$$

where

$$M(z) = e^{-\alpha_p z}[\alpha_p\sin(2\pi fdz) + 2\pi fd\cos(2\pi fdz)] - 2\pi fd, \quad (12)$$

$$N(z) = e^{-\alpha_p z}[2\pi fd\sin(2\pi fdz) - \alpha_p\cos(2\pi fdz)] + \alpha_p, \quad (13)$$

$$M'(z) = e^{\alpha_p z}[-\alpha_p\sin(2\pi fdz) + 2\pi fd\cos(2\pi fdz)] - 2\pi fd, \quad (14)$$

$$N'(z) = e^{\alpha_p z}[2\pi fd\sin(2\pi fdz) + \alpha_p\cos(2\pi fdz)] - \alpha_p. \quad (15)$$

In Eqs. (10) and (11), the second and third terms are relevant to time and phase variables, corresponding to the fluctuation caused by pump RIN. The signal RIN transferred from the pump RIN can be obtained as follows:

$$\mathrm{RIN}_s(f)_{\mathrm{co}} = \frac{\langle \delta P^2\rangle}{\langle P\rangle^2} = \mathrm{RIN}_p(f)\frac{M^2(z) + N^2(z)}{[\alpha_p^2 + (2\pi fd)^2]^2}g_s^2P_{p0}^2, \quad (16)$$

$$\mathrm{RIN}_s(f)_{\mathrm{counter}} = \frac{\langle \delta P^2\rangle}{\langle P\rangle^2} = \mathrm{RIN}_p(f)\frac{M'^2(z) + N'^2(z)}{[\alpha_p^2 + (2\pi fd)^2]^2}g_s^2P_{p0}^2e^{-2\alpha_p L}. \quad (17)$$

More importantly, an RPN term representing the extra phase noise initiated by pump RIN transfer on the received signal can be given by $\mathrm{RPN}_s(f) = \langle \delta\theta^2\rangle / \langle\theta\rangle^2$. It turns out to be as follows:

$$\mathrm{RPN}_s(f)_{\mathrm{co}} = \mathrm{RIN}_p(f)\frac{M^2(z) + N^2(z)}{[\alpha_p^2 + (2\pi fd)^2]^2}\frac{\alpha_p^2}{(1 - e^{-\alpha_p z})^2}, \quad (18)$$

$$\mathrm{RPN}_s(f)_{\mathrm{counter}} = \mathrm{RIN}_p(f)\frac{M'^2(z) + N'^2(z)}{[\alpha_p^2 + (2\pi fd)^2]^2}\frac{\alpha_p^2}{(e^{\alpha_p z} - 1)^2}. \quad (19)$$

Because pump RIN transfer through pump–signal XPM adds additional stochastic phase noise on the signal complex field in addition to the linear phase change determined by the averaged pump power, a coherent communication system employing the phase-modulation format will suffer performance degradation. In this Letter we focus on the specifically M-ary PSK modulated signal. The impact on M-ary QAM modulated signal can be analyzed in a similar manner.

In a digital coherent receiving system, the carrier phase is recovered by the PE algorithm. Due to the limited linewidth of the local oscillator (LO) and the signal laser, and also the existence of additive noise, such as amplified spontaneous emission noise induced by an optical amplifier, thermal noise in an electric circuit, and RPN induced by pump RIN, a phase error $\Delta\theta$, which can be treated as a zero-mean Gaussian random variable with variance $\sigma_{\Delta\theta}^2$, would be induced to degrade the system performance. In the presence of phase error, the bit-error rate (BER) of M-ary PSK signal can be numerically evaluated as

$$P_b(e) = \int_{-\pi}^{\pi} P_b(e|\Delta\theta)p(\Delta\theta)\mathrm{d}\Delta\theta, \quad (20)$$

where $P_b(e|\Delta\theta)$ is the BER conditioned on a fixed value of the phase error $\Delta\theta$, and $p(\Delta\theta)$ is the probability density function of the phase error. The expression $P_b(e|\Delta\theta)$ of QPSK, 8PSK, and 16PSK can be found in [4]. Using the decision-aided maximum likelihood PE algorithm, the variance of phase error in M-ary PSK considering the impact of RPN can be given as

$$\sigma_{\Delta\theta}^2 \approx \frac{2L^2+3L+1}{6L}\sigma_p^2 + \frac{1}{2L}(\sigma_n^2+\sigma_{\mathrm{RPN}}^2). \quad (21)$$

In Eq. (21), L is the memory length used in the PE algorithm, $\sigma_p^2 = 2\pi(2\Delta\nu)T_s$ is the variance of laser phase noise, T_s and $\Delta\nu$ are the symbol duration and linewidth of each laser, respectively (the same linewidth is assumed for the transmitter and LO laser), $\sigma_n^2 = 1/\gamma_s$ is the variance of additive white Gaussian noise (AWGN) without RPN, $\gamma_s = (\log_2 M)\gamma_b$ is the signal-to-noise ratio (SNR) per symbol, γ_b is the SNR per bit, $\sigma_{\mathrm{RPN}}^2 = \langle\theta_{\mathrm{RPN}}^2(t)\rangle = \int_{\nu_1}^{\nu_2}\mathrm{RPN}_s(f)\cdot\langle\theta\rangle^2\mathrm{d}f$ is the variance of RPN, and ν_1 and ν_2 are the lower and upper frequency of the receiver, respectively. We assume that the phase-noise components of AWGN and RPN have similar properties, based on the fact that they both decrease with larger L; thus those variances can be directly added.

In order to get the minimum $\sigma_{\Delta\theta}^2$, L needs to be optimized. After that, the BER can be calculated using Eq. (20). With the traditional PE algorithm, σ_{RPN}^2 included in Eq. (21) leads to non-negligible system impairments even after optimization. Note that the Q-factor parameter is connected to BER by $P_b(e) = 1/2\,\mathrm{erfc}(Q/\sqrt{2})$. RPN induced impairment can be evaluated by Q-factor penalty, which is given by $\mathrm{Penalty(dB}Q) = 10\lg(Q_{\text{without RPN}}/Q_{\text{with RPN}})$.

Figure 1 shows the estimated Q penalty of the QPSK signal due to signal RPN for both co- and counterpumping systems. For all calculations, the polarization multiplexing scheme is considered; the span length is 80 km, the fiber attenuation of the signal and the pump is 0.21 and 0.25 dB/km, respectively, the Raman gain coefficient is 0.35 $\mathrm{W}^{-1}\,\mathrm{km}^{-1}$, and the on–off gain is 16.8 dB. The lower and upper frequencies of the receiver are 10 kHz and 20 GHz, respectively. We can see that the counterpumping scheme may tolerate pump RIN up to −70 dB/Hz without suffering 0.1 dBQ penalty. There is a 47 dB margin of pump RIN compared to the copumping case (with 2 ps/m walk-off). We should note that RPN will accumulate as the number of spans increases. Ten spans of copumping DFRAs with a pump RIN −117 dB/Hz will produce 1 dBQ penalty. From the three

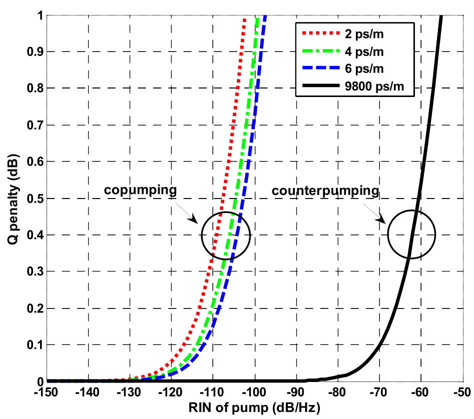

Fig. 1. (Color online) Estimated Q penalty of QPSK signal versus pump RIN on the copumping and counterpumping configuration. The walk-off parameters in the copumping configuration are 2, 4, and 6 ps/m, respectively, and in the counterpumping configuration is 9800 ps/m. The bit rate is 100 Gb/s, the linewidth of the signal laser and the LO is 300 kHz, and $\gamma_s = 20$ dB.

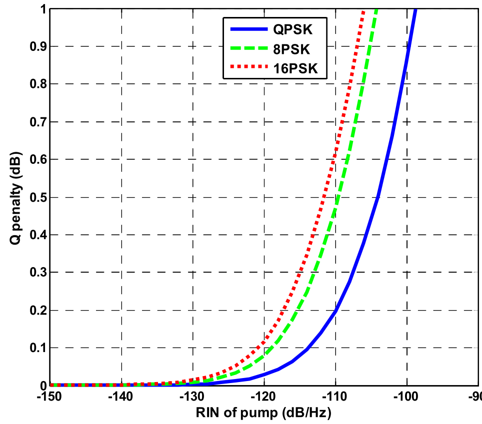

Fig. 2. (Color online) Estimated Q penalty versus pump RIN for different order PSK signal. The walk-off parameter is 2 ps/m for all, the bit rate is 100 Gb/s, the linewidth of the signal laser and the LO is 300 kHz, and $\gamma_b = 15$ dB.

separate curves in the copumping case, we can find that larger walk-off helps to reduce the penalty, because pump RIN transfer is averaged to a greater degree.

We also compared the estimated Q penalty for different order PSK, i.e., QPSK, 8PSK, and 16PSK. The result is illustrated in Fig. 2. A larger Q penalty is expected with higher-order PSK, because of the more stringent phase-noise tolerance. Under 0.1 dBQ penalty, 8PSK will introduce 5 dB pump RIN penalty compared to QPSK, which has a pump RIN tolerance of about −114 dB/Hz, while 16PSK will introduce 6 dB penalty.

In conclusion, we have presented, for the first time, to the best of our knowledge, an analytical model to analyze the pump-to-signal RIN/RPN transfer in the Raman-amplified coherent communication system. The RPN parameter has been found to characterize pump RIN induced phase noise in the complex field of the phase-modulated signal. By calculating the Q penalty in a typical QPSK modulated system, the pump RIN is suggested to be no more than −117 dB/Hz in copumping and −70 dB/Hz in counterpumping. With the CD equalized coherent receiver, a relatively larger fiber dispersion helps to suppress the RPN induced impairment. In terms of RPN, higher-order PSK signal is less tolerant to pump RIN. Our findings provide a useful guideline to design Raman amplification for a multilevel modulated coherent optical communication system.

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