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Efficient evaluation of impairment induced by distributed fiber Raman amplifier using error vector magnitude techniques in unrepeated coherent communication system

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ABSTRACT

We investigate the impairment induced by relative intensity noise (RIN) of Raman pump in an ultra-long unrepeated multi-level modulated coherent optical communication system. By adopting error vector magnitude (EVM) techniques, we proposed a simple and high efficient numerical method to calculate and analyze the impact of Raman pump RIN on the coherent receiver system. Both intensity and phase noise are taken into consideration in our numerical simulations when choosing Raman pump lasers with different RIN and using different signals. Our simulation result shows that higher-order phase-modulated signal is more sensitive to RIN of the Raman pump. Comparing to the phase noise, intensity noise induced by RIN of the Raman pump can generally be ignored. Apart from the well-known walk-off parameter, nonlinear parameters and Raman-gain coefficient also play important roles in the complex noise transfer process. Our calculation makes it possible to quickly and accurately evaluate the hybrid distributed fiber Raman amplification (DFRA) along with remotely-pumped erbium-doped fiber amplification (EDFA) in ultra-long unrepeated transmission systems.

1. Introduction

Due to the growing demand for terrestrial links in rural or not easily accessible areas, there is an increasing interest in unrepeated transmission technologies [1]. DFRA is a widely used technology for supporting high bit rate data transmission over long fiber spans due to the optical signal-to-noise ratio (OSNR) benefit it provides. In traditional intensity modulated unrepeated ultra-long applications, impairment induced by pump RIN has been widely studied [2]. With the increasing demand for higher data transmission capacity, higher-order phase-modulated signal is adopted in more and more unrepeated ultra-long communication systems. However, attention to the phase noise induced by pump RIN is not enough before *Cheng* and *Tang*'s work [3–5]. In [3–5], they focused on the extra relative phase noise (RPN) induced by RIN of Raman pump in coherent receiver system. The RPN can be calculated by $RPN_s = \left\langle \delta\theta^2 \right\rangle / \langle\theta\rangle^2$, where θ is the phase shift induced by pump-signal XPM, $\delta\theta^2$ is the variance of θ, $\langle\theta\rangle$ is the average of θ. In order to analyze the property of RPN, offline digital signal processing (DSP) is employed in [3–5]. However, analytical expression is needed to generate vast amounts of data required in their calculation. As a result, it is difficult to evaluate the hybrid DFRA and EDFA in ultra-long unrepeated transmission system directly using the results in [3–5].

In this paper, we further studied the performance of DFRA under different Raman pump RIN, gain coefficient, signal powers, and modulation formats. Both depletion regime and non-depletion regime are considered in our simulations. Besides, self-phase modulation (SPM) of signal is included as well. EVM [6] is employed to quickly and reliably evaluate the quality of received signal in our simulations. Unlike the offline DSP, not too much data is required in our simulations. Therefore, we can easily assess the performance of hybrid DFRA/EDFA amplification in transmission system using numerical solution.

2. Principle

The coupled amplitude equations which are used to describe the evolution of both amplitude and phase of a Raman-amplified optical signal field can be written as follows [7]:

$$\pm\frac{\partial A_p^{\pm}}{\partial z} + \frac{\alpha_p}{2}A_p^{\pm} = i\gamma_p\left(\left|A_p^{\pm}\right|^2 + (2 - f_R)\left|A_s\right|^2\right)A_p^{\pm} - \frac{g_p}{2}\left|A_s\right|^2 A_p^{\pm} \tag{1}$$

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

where A_s and A_p are slowly varying envelopes of signal and pump. ± Represents co-pumping and counter-pumping scheme respectively. α_s and α_p are the attenuation constant of signal and Raman pump. f_R is the fractional Raman contribution, which is set to 0.18 [8]. z is the coordinate variable along the fiber. Inco-pumping configuration, $T = t - z/v_{gp}$, while in counter-pumping approach, $T = t - (S - z)/v_{gp}$. S is the whole length of DFRA. The walk-off parameter d, $d = \pm v_{gp}^{-1} - v_{gs}^{-1}$, accounts for the group-velocity mismatch between signal and Raman pump. Its typical value is 2 ps/km. v_{gp} and v_{gs} are the group velocity of Raman pump and signal. The nonlinearity parameter γ_j, and Raman-gain coefficient g_j (j=s or p) are slightly different for signal and pump due to the Raman shift of about 13 THz between their carrier frequencies. λ_s and λ_p account for the wavelength of signal and Raman pump. In terms of the wavelength ratio λ_p/λ_s, these parameters for signal and Raman pump are related as [7]

$$\gamma_s = \frac{\lambda_p}{\lambda_s}\gamma_p,\ g_s = \frac{\lambda_p}{\lambda_s}g_p \tag{3}$$

In this paper, we assume the group velocity dispersion (GVD) can be compensated entirely by dispersion compensating fiber (DCF) in the receiving end and no additional penalty induced from the RIN and fiber nonlinearity. Thus, the GVD effects are ignored in Eq. (1) and Eq. (2). The solution of $A_s(z, T)$ can be expressed as follows:

$$A_s(z, T) = A_s(0, T + zd)\exp\left(-\frac{\alpha_s}{2}z\right)\exp\left(\frac{g_s}{2}\Phi^{\pm}(z, T)\right) \exp\left(i\gamma_s\Psi^{\pm}(z, T)\right) \tag{4}$$

where $\Phi^{\pm}(z, T)$ and $\Psi^{\pm}(z, T)$ are both function of $A_p(0, T)$. However, it is difficult to give their analytical expression unless some additional assumptions are made. In practical DFRA systems, Raman pump laser diodes exhibit RIN fluctuations. As a result, extra impairment will be induced to $A_s(z, T)$. According to [5,9], the RIN of Raman pump in our paper is not too large to violate the Gaussian noise assumption. If Raman pump depletion during stimulated Raman scattering (SRS) and SPM of signal are both neglected, we can rewrite the analytic solution in a simple form [7]. For the co-pumped DFRA in an ultra-long unrepeated system, it is necessary to consider both pump depletion during SRS and SPM of signal. Eqs. (1) and (2) can be solved numerically by finite difference method or split-step Fourier method. We focus on co-pumped DFRA in our simulations because in most ultra-long remotely-pump unrepeated system, power of signal is low enough to ignore pump depletion and SPM of signal in counter-pumping Raman scheme. Fig. 1 illustrates the MATLAB simulation set-up of co-pumped DFRA.

Signals of different modulation formats (e.g. QPSK, 8PSK and 16QAM) are generated by corresponding modulators. Raman pump is a typical high-power laser which is polarization multiplexed to minimize the polarization dependent gain. Wavelengths of signal and Raman pump are λ_s = 1550nm and λ_p = 1480nm respectively. Additive white Gaussian noise (AWGN) is added at the input side of the transmission system according to SNR of the original signal. RIN of Raman pump is modeled by a flat electrical noise spectrum and the noise bandwidth is set to be 1 GHz [10]. Transmission system is a standard single-mode fiber (SMF). Attenuation of signal and Raman pump are 0.2 dB/km and 0.22 dB/km respectively. The dispersion coefficient D_0 is set to 18 $ps/nm/km$ at 1550 nm. Digital optical modulation analyzer (OMA) is used to decode and evaluate the received signals.

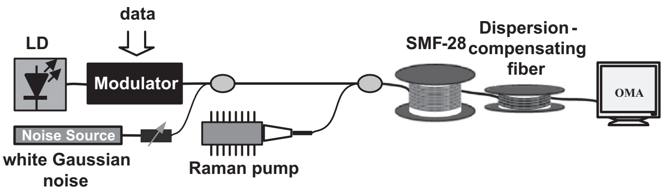

Fig. 1. Simulation set-up of co-pumped DFRA.

Fig. 2 compares constellation of signal before and after the transmission system. As shown in Fig. 2(b), non-ignorable impairment is induced to received signal comparing to the back-to-back signal. We assume both the laser in the transmitting end and local oscillator (LO) in the receiving end have zero linewidth. In addition, there is no frequency offset between them. Based on this, the laser phase noise compensation, frequency offset compensation and equalization are all neglected in our simulations. In other words, their impact on the penalty induced by RIN is not considered in this paper, because the impact varies when RIN is set to different values [5]. Of course, these assumptions are unrealistic as DSP has to be used in every practical coherent transmission systems and no ideal laser can be found in any practical systems. However, this method can help us to get a better understanding of the impairment induced by pump RIN and provide necessary theoretical guidance for the experiments or system design. In order to judge the quality of the encoded signals reliably and quickly, we employed EVM in our simulations. Apart from this, EVM can be easily associated to SNR or BER of signal [6].

In Fig. 3, the green dot stands for ideal signal and red cross is actually received signal. The relationship between error vector $E_{error,i}$, reference signal vector $E_{reference,i}$ and measurement signal vector $E_{measurement,i}$ is shown in Fig. 3.

The EVM can be obtained by the following formulas [6]:

$$EVM_m = \frac{\sigma_{err}}{|E_{reference,m}|},\ \sigma_{err}^2 = \frac{1}{I}\sum_{i=1}^{I}|E_{error,i}|^2,\ E_{error,i} = E_{measurement,i} - E_{reference,i} \tag{5}$$

where $E_{reference,m}$ represents the longest $E_{reference,i}$. I is the number of randomly transmitted data. For Gaussian channels, the relationship between BER and EVM can be described using the following expression

$$BER \approx \frac{1 - L^{-1}}{log_2 L}erfc\left[\frac{1}{kEVM_m}\sqrt{\frac{3log_2 L}{L^2 - 1}\frac{\sqrt{2}}{log_2 M}}\right] \tag{6}$$

where $erfc(x) = 2/\sqrt{\pi}\int_x^{\infty}e^{-z^2}dz$. L is the number of signal levels within each orthogonal direction of the constellation diagram. $\log_2 M$ is the amount of bits encoded into each QAM symbol, and format-dependent factor k can be found in [6].

3. Simulation results and discussions

In this section, we will evaluate the influences of key parameters (e.g. signal power and RIN of Raman pump) on transmission system. Most variables used in our simulation are assigned to typical values. Power of Raman pump and signal are set to 30 dBm and −20 dBm.

As shown in Fig. 4, maximum power of received signal is achieved when the length of DFRA is set around 40 km. According to the three solid lines, on–off gain of signal remains unchanged when length of DFRA is more than 80 km. Besides, higher g_s will strengthen the interaction between pump and signal. In order to ensure the accuracy, DFRA should be longer