A Method to Separate the Penalties Caused by Various Nonlinear Signal-Pump Impairments in Raman Amplified System

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Abstract: We separate various nonlinear impairments caused by pump laser RIN in Raman amplified system. Experiment shows that nonlinear polarization scattering has more impact than phase noise does, and the gain fluctuation has the least impact. © 2020 The Author(s)

1. Introduction

Compared with lumped Erbium-doped fiber amplifier (EDFA) amplified systems, distributed Raman amplified systems have more ability to improve the reach and capacity of optical fiber communication system [1]. The backward (BW) pump configuration with multiple wavelength pumps is widely used in many systems [2]. In some cases, the BW pump associated with the forward (FW) pump is an attractive scheme to achieve larger Raman gain to extend span length and reach [1]. However, Raman amplified systems have several nonlinear impairments caused by relative intensity noise (RIN) of pump lasers. The impairments are gain fluctuation caused by pump to signal RIN transfer [3], cross phase modulation (XPM) phase noise and nonlinear polarization (Pol) scattering caused by pump RIN [4,5]. The system performance degradation is caused by the combined effects of those impairments. For deeper understanding of system degradation and better system design, it is necessary to separate those impairments and to answer which impairment causes how much penalty.

In this paper, we propose and verify a behavior model to separately describe each nonlinear impairment caused by pump laser RIN. Based on the proposed model, we could turn on or off each impairment and separate the system degradation caused by each impairment. Experiments show that nonlinear polarization scattering induced penalty is more than phase noise induced penalty and the penalty caused by gain fluctuation can be ignored.

2. Impairments Separated Model

The proposed model, as shown in Fig. 1, includes three nonlinear impairments. The first one is Raman gain fluctuation caused by the pump to signal RIN transfer [3]. It is modelled by the time-varying relative gain $\Delta(t)$. The next two are caused by XPM between pump laser RIN and the signal. Based on the XPM model in [6], the XPM impairment is split into nonlinear polarization scattering which is modeled as a time-varying Jones matrix and a common phase noise for both polarizations. In the proposed model, the nonlinear polarization scattering is described by the combination of 45 degree retarder with angle $\delta(t)/2$ and rotator with angle $\theta(t)$. The phase noise is described by the time-varying phase $\varphi_{xpm}(t)$. The linear chromatic dispersion (CD) and the amplified spontaneous emission (ASE) noise are added in the end.

$$\begin{bmatrix} E_{x,in}(t) \\ E_{y,in}(t) \end{bmatrix} \rightarrow \text{Raman amplified system} \rightarrow \begin{bmatrix} E_{x,out}(t) \\ E_{y,out}(t) \end{bmatrix}$$

$$\underbrace{\begin{bmatrix} 1+\Delta(t) & 0 \\ 0 & 1+\Delta(t) \end{bmatrix}}_{\text{Raman gain fluctuation}} \rightarrow \underbrace{\underbrace{\begin{bmatrix} cos(\delta(t)/2) & -jsin(\delta(t)/2) \\ -jsin(\delta(t)/2) & cos(\delta(t)/2) \end{bmatrix}}_{\text{45 degree Retarder}} \rightarrow \underbrace{\begin{bmatrix} cos(\theta(t)) & -sin(\theta(t)) \\ sin(\theta(t)) & cos(\theta(t)) \end{bmatrix}}_{\text{Rotator}}}_{\text{Nonlinear polarization scattering}} \rightarrow \underbrace{\begin{bmatrix} e^{j\varphi_{xpm}(t)} & 0 \\ 0 & e^{j\varphi_{xpm}(t)} \end{bmatrix}}_{\text{Phase noise}} \xrightarrow{FFT} \underbrace{G(D,z,\omega)}_{\text{CD}} \xrightarrow{IFFT} + \underbrace{\begin{bmatrix} n_x(t) \\ n_y(t) \end{bmatrix}}_{\text{ASE noise}}$$

Fig. 1. The proposed impairments separated model for nonlinear impairments caused by pump laser RIN.

To obtain the detailed model, we use continuous wave (CW) laser as the probe signal, and record the received optical field through coherent receiver (Rx) and digital storage oscilloscope (DSO). Based on the captured optical field $[E_x, E_y]^T$, the received probe signal is converted to Stokes space and the Stokes vector $[S_0, S_1, S_2, S_3]^T$ is obtained. Due to nonlinear polarization scattering, the received signal diffuses to a cloud. We select the Stokes coordinate system so that the center of the cloud is $[1,0,0]^T$. We calculate the spectrums of $S_0 - \langle S_0 \rangle$, S_2 and S_3 and the spectrums with relative amplitudes are shown in Fig. 2(a). We can obtain the model coefficients from those spectrums.

For Raman gain fluctuation: S_0 is the optical intensity which is not affected by polarization scattering and phase noise. Due to the walk-off effect, the Raman gain fluctuation only has low frequency [3], and the high frequency part is caused by ASE noise only. Since ASE noise is white, we simply remove the flat bottom of the spectrum to obtain the spectrum of gain fluctuation. At last, we generate the time-varying relative gain $\Delta(t)$ according to this spectrum.

For nonlinear polarization scattering: S_2 and S_3 describe the nonlinear polarization scattering and they are not affected by phase noise. Similar to that of S_0, we remove the ASE noise at first. Then, according to the geometric explanation of 45 degree retarder and rotator as shown in Fig. 2(b), we have the relationships of $S_2 \approx S_0 sin(2\theta)$ and $S_3 = S_0 sin(\delta)$. At last we generate $\delta(t)$ and $\theta(t)$ according to the spectrums of S_2 and S_3.

For phase noise: It is not straightforward because the laser phase noise and the nonlinear phase noise are hard to separate. According to [6], the common phase noise is the average of phase noise in polarization x and y. The retarder angle $\delta(t)$ is the phase difference between polarization y and x. The phase noises of two polarizations are assumed independent. Therefore, $\delta(t)/2$ and $\varphi_{xpm}(t)$ are independent and identical distribution.

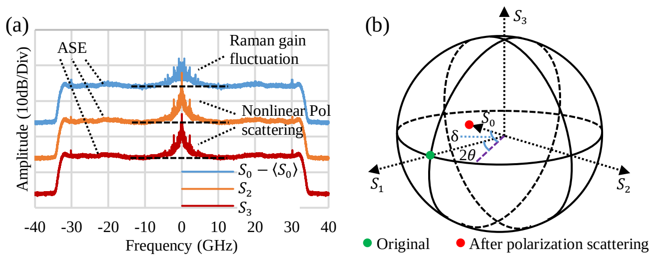

Fig. 2. (a) Experimental spectrums of $S_0 - \langle S_0 \rangle$, S_2 and S_3 with relative amplitudes and (b) polarization change on Poincare sphere.

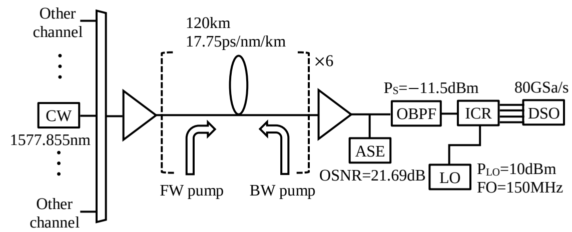

Fig. 3. The schematic diagram of CW experimental setup.

3. Experiment setup and model calculation

Figure 3 shows the experimental setup of Raman amplified system. The WDM channels are 80 and the wavelength of CW probe is 1577.855 nm. The Raman amplified system operates at BW pump or BW plus FW pump cases. Both BW and FW have 4 pump lasers at wavelength from 1450 nm to 1500 nm and the pump lights coupled into transmission link after depolarizer [7]. The span number is 6, each span has 120 km fiber with dispersion coefficient of 17.75 ps/nm/km. ASE noise is added in front of optical bandpass filter (OBPF). The optical signal-to-noise ratio (OSNR) and total optical power are fix to 21.7 dB and −11.5 dBm for two pump cases, respectively. The CW probe is detected by integrated coherent receiver (ICR) and the output signals are captured by DSO with sample rate of 80 GHz. The RIN of pump lasers, as shown in Fig. 4, is measured by photodetector and electrical spectrum analyzer. The RIN is in the range of −120 dBc/Hz which seem not so large. However, the absolute value of pump laser power is as high as 26 dBm, so that the pump laser intensity fluctuation is not small, and the nonlinear effect of pump laser RIN cannot be ignored. The frequency periodic nature of RIN may correspond to the Fabry-Perot design of pump laser.

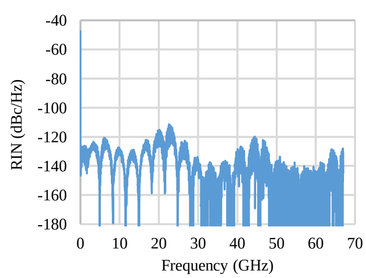

Fig. 4. Measured RIN of pump lasers.

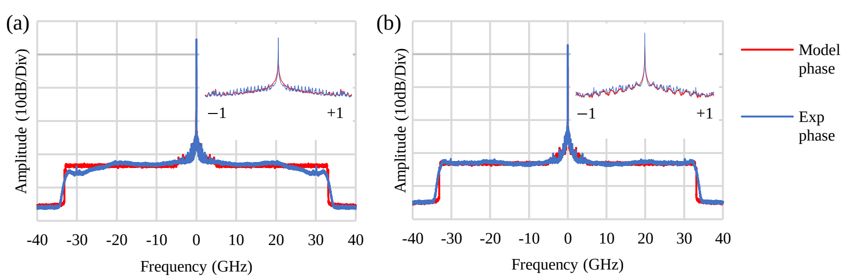

Fig. 5. CW phase spectrums comparison. (a) BW pump only and (b) BW plus FW pump.

According to the method in section 2, we obtain the model firstly. Then, we simulate received CW signal and compared it with the experimentally measured one. Since the model is fitted from the Stokes space signal, a good agreement of S_0, S_2, S_3 is nature. We verify the model in Jones space and mainly focus on the phase part. We obtain the spectrum of phase of E_x for both experiment and model. Figure 5(a) shows that comparison for BW pump only case, and (b) shows that of BW plus FW pump case. The insets are the detailed figures of low frequency range. The good agreement is obtained.

4. Impairment penalty analysis

The penalty caused by the pump laser RIN is also experimentally evaluated by replacing the CW probe with 33.47 GBaud dual-polarization (DP) 16 quadrature amplitude modulation (QAM) Nyquist signal with 1/32 quadrature phase shift keying (QPSK) pilot. After data recovery by CD compensation, QPSK-assisted constant modulus algorithm (CMA), frequency offset (FO) compensation and QPSK-assisted carrier phase recovery (CPR), the experimental Q factor under BW pump only and BW plus FW pump cases are 8.52 dB and 7.06 dB, respectively. Since the OSNR of both cases are adjusted to be same (21.7 dB), the difference between them is caused by the additional nonlinear impairment of FW pump. Experiment shows FW pump induces extra penalty of 1.46 dB.

The same DP-16QAM Nyquist signal with 1/32 QPSK pilot is also sent to the proposed model in simulation. In order to obtain reasonable penalty for each impairment, the appropriate noise is added at transmitter side to emulate the impairments in the transmitter. Then, the model has the same base Q factor of 8.52 dB in BW pump only case at optimal CPR block size of 17, as shown in Fig 6(a). Under such Tx configuration and CPR block size, the Q factor is 7.21 dB in BW plus FW pump case as shown in Fig. 6(b). Simulation shows FW pump induces extra penalty of 1.31 dB, the deviation from experimental Q factor is only 0.15 dB, which also verifies proposed model.

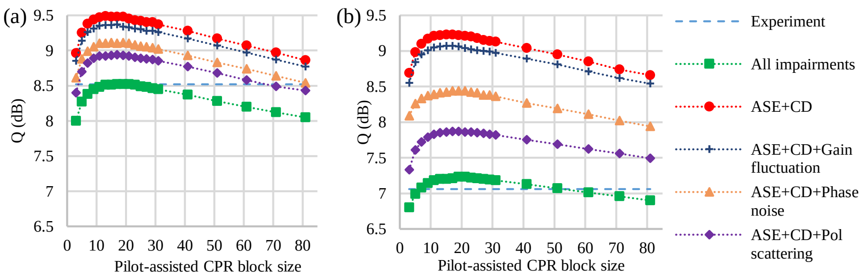

Fig. 6. Q factors under different cases. (a) BW pump only and (b) BW plus FW pump.

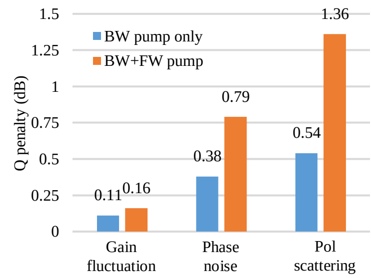

Fig. 7. Q penalties of each nonlinear impairment.

The most significant advantage of the proposed model is that we could switch on or off each impairment and calculate the Q penalty of it. Since we focus on nonlinear impairments, we always include ASE and CD impairments in following and set it as the reference Q factor. Figure 6 shows the Q factor as a function of CPR block size under various impairments. For the impairment of ASE plus CD, there are slight difference (~0.2 dB) between Fig. 6(a) and (b). It is caused by slight OSNR and transceiver condition differences between the two measurements in the experiment. It's found that the optimal CPR block size is almost the same for all cases, i.e., ~17 pilot symbols. Thus, we select the Q factor at 17 block size as the Q factor under each impairments.

Figure 7 shows the Q penalty of each nonlinear impairment. The Q penalty of gain fluctuation is 0.11 dB for BW pump only and 0.16 dB for BW plus FW pump. It has least impact among the three nonlinear impairments. In the case of BW plus FW pump, the phase noise causes 0.79 dB penalty and the nonlinear polarization scattering causes 1.36 dB penalty. This shows that nonlinear polarization scattering has more significant impact than phase noise. In the case of BW pump only, the penalty of phase noise is 0.38 dB and the penalty of nonlinear polarization scattering is 0.54 dB. The nonlinear polarization scattering also has larger impact. If we compare the penalty between BW pump only and BW plus FW pump, the penalty of BW plus FW pump is always larger. This is consistence with that in [4]. Anyway, the FW pump have larger pump gain and extends the transmission reach. In the actual FW pumping system design, it is necessary to balance the benefit of more gain and the penalty of more nonlinear impairment.

5. Conclusion

We propose a method to separate various nonlinear impairments caused by pump laser RIN in Raman amplified system. Based on the CW probe experiment, we obtain the model for BW pump only and BW plus FW pump cases. We turn on or off each impairment in the model and find that compared with phase noise, nonlinear polarization scattering has more degradation and gain fluctuation induced penalty is the least.

6. References

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