Multiple Beat-Noise Suppression in Polarization-Multiplexed Pump Light for Forward-Pumped Raman Amplifier

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Abstract *We show that orthogonally polarized pump light emitted from two different laser sources in a forward-pumped Raman amplifier system induces beat noise on amplified signal light. Utilizing our proposed noise suppression technique, we improved the SNR of a 36-QAM signal after a 1,920-km transmission.*

Introduction

A distributed Raman amplifier system is very useful for high-capacity optical transmission systems due to its wide gain spectrum and its applicability to field-installed fibers[1]. In forward-pumped Raman amplifier systems (fwd-Raman amp) in particular, the relative intensity noise (RIN) induced inside and/or outside of the light source should be suppressed because of the fast response of the Raman amplifier[2–4]. In fact, a fwd-Raman amp with an improper pump light has been reported to degrade amplified signal light quality[5]. A multimode laser diode (LD) with a fiber Bragg grating (FBG) is widely used as a pump light source for Raman amplifiers. Depolarization and noise reduction are essential for a pump unit because the pump light emitted from the LD is linearly polarized and the Raman gain is strongly dependent on polarization. Two approaches have achieved depolarization. One uses a depolarizer constructed by optical delay[6–8]. In our previous work, we showed that the additional RIN induced by synthesized polarization[7–8] can be suppressed by fine-tuning the optical delay with our depolarizer[8]. The other approach uses polarization-combined LDs[3–4]. This approach easily double the optical power density of pump light. However, Martinelli et al. showed that the amplified signal light degrades substantially when the optical spectra of the two orthogonally polarized longitudinal modes of pump light overlap[3–4].

This paper theoretically and experimentally demonstrates how the orthogonally polarized longitudinal modes of pump light induce multiple beat noise in amplified signal light. We also propose a technique of suppressing these beat noise. Finally, we present the signal-to-noise ratio (SNR) measurement of the demodulated 96-Gbaud probabilistically shaped (PS) 36-QAM signal after 1,920-km transmission. Our technique improved the SNR by 0.5 dB using the fwd-Raman amp (5-dB On/Off gain) compared with the SNR without using the fwd-Raman amp.

Proposed pumping technique

Figure 1 shows our pump unit and the experimental setup to evaluate it. Two multimode LDs, LD #1 and LD #2, were used for the pump light and not have FBG. Their output of was emitted into a polarization maintaining variable optical attenuators (VOAs) to cancel out the power imbalance between them. Electrical optical fields at the output of these VOAs were denoted as E_X and E_Y, and were combined orthogonally in the polarization beam combiner (PBC). We define the spacing between each longitudinal mode emitted from one LD as Δf. The Δf of LD #1 and LD #2 must be nearly the same. In this study, Δf was 44 GHz. We define the spacing between orthogonally polarized longitudinal modes as Δf_1 and Δf_2. Here, $\Delta f = \Delta f_1 + \Delta f_2$ (see Fig. 2(b)). Δf_1 and Δf_2 should be set to different values and should be greater than 1 GHz, so Δf_1 and Δf_2 were 16 GHz and 28 GHz, respectively. The technical meanings of these settings are explained in a later section. We set Δf_1 and Δf_2 by changing the LD current with the controller. Note that changing the LD current also changes the output power of LD #1 and LD #2. However, the induced power imbalance can easily be canceled out by the VOAs. If necessary, these VOAs can modify total pump power and

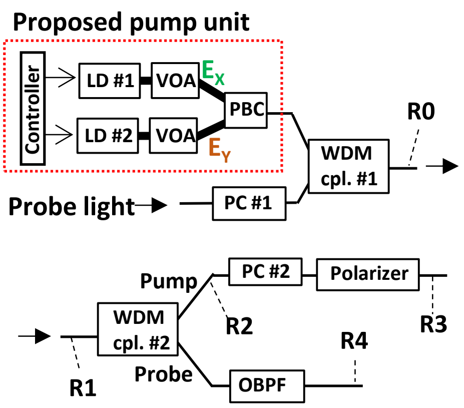

Fig. 1: Proposed pump unit and experimental setup.

Raman gain without changing Δf_1 and Δf_2. The generated pump light was multiplexed into probe light (1563 nm) by wavelength division multiplexing coupler (WDM cpl.) #1. The polarization of the probe light was controlled by polarization controller (PC) #1. The optical spectra of the pump light ($|E_X|^2$, $|E_Y|^2$) measured at reference point 0 (R0) is shown in Fig. 2 (a) and (b). Figure 2 (b) scales up the horizontal axis though the resolution is the same as Fig. 2 (a), 0.01 nm. Because LD #1 and LD #2 had no FBG, the spectra envelope was broad, and each longitudinal mode was narrow. For comparison, Fig. 2 (c) and (d) shows the output of a commercially available pump unit. The envelopes of the spectra were narrow due to the FBG, but each longitudinal mode was broadened by fine structures[3–4], so Δf_1 and Δf_2 can not be defined clearly in Fig. 2 (d).

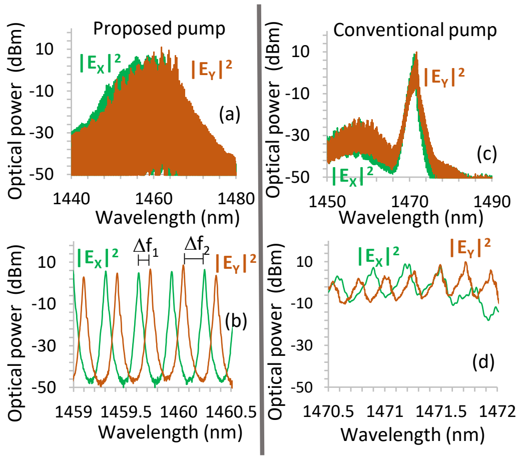

Fig. 2: The measured optical spectra of the pump light. (a) and (b) : proposed pump unit, (c) and (d) : commercially available pump unit, for comparison.

Simulated optical electric field

Now, let us consider the optical electric field of pump light at R0 generated by E_X and E_Y. It can be written as

$$E_X = \sum_{n=0}^{m} \{A_{xn} \sin(2\pi(f_0 + n \cdot \Delta f)t + \theta_{xn})\}$$
$$E_Y = \sum_{n=0}^{m} \{A_{yn} \sin\big(2\pi(f_0 + \Delta f_1 + n \cdot \Delta f)t + \theta_{yn}\big)\} \quad (1)$$

where f_0 is the minimum optical frequency of longitudinal mode, A_{Xn} and A_{Yn} are the amplitudes of n-th longitudinal mode, θ_{Xn} and θ_{Yn} are the optical phases of n-th longitudinal mode, t is the time, and m is the total number of longitudinal modes. Figure 3 shows the Lissajous figures calculated by Eq. 1. Here, we assume that f_0 / Δf was 5000 and Δf / Δf_1 was 4. In general, pump-LDs are not mode locked and each longitudinal mode has finite coherency, so it is difficult to accurately determine θ_{Xn} and θ_{Yn}. Therefore, we made these parameters be consistent with the measured waveform of the pump light. The initial value of t is also shown in each Lissajous figure. The time range that each Lissajous figure plots is $3/f_0$. In this short term (shorter than coherence time), these Lissajous figures can be regarded as the synthesized polarization introduced by ref [7–8]. This synthesized polarization was scrambled because $E_X + E_Y$ had frequency components Δf_1 and Δf_2. Though the polarization scrambling did not affect the total pump power, it could affect Raman gain, because Raman gain depends on the polarization of pump and signal light[7–8]. This means that this scrambling induces Δf_1 and Δf_2 beat noise in the amplified signal light.

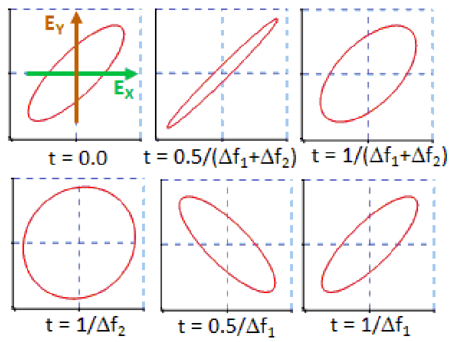

Fig. 3: Simulated Lissajous figures of E_X and E_Y of pump light before transmission.

Measured RIN of pump and probe light

We measured the RIN of the pump and probe light to confirm the simulation results (see experimental setup in Fig. 1). First, we directly connected R0 and R1 and measured the RIN of the pump light with and without a polarizer. We set the total pump power (two polarizations) at R0 to 220 mW. Figure 4 (a) shows the results with our pump unit. The black and red lines show the RIN measured at R2 (w/o polarizer) and at R3 (with polarizer), respectively. PC#2 was set to maximize the RIN after the polarizer. After the polarizer, the RIN of pump light dramatically increased at Δf_1 and Δf_2. This result was consistent with simulated predictions. Next, we connected a 35-km dispersion sift fiber (DSF) between R0 and R1 and measured the RIN of the amplified probe light at R4. We used an optical band-pass filter (OBPF) to reduce the effect of ASE caused by the fwd-Raman amp. The power of the probe light was -3 dBm at R0, and the On/Off gain was 10 dB. Figure 4 (b) shows the result with our pump unit. Three colors corresponded to the change of PC#1. The measured polarization dependence was almost negligible. The sharp peak at 10 GHz was induced by the stimulated Brillouin scattering. We observed small peaks at Δf_1 and Δf_2 due to the RIN transfer (close to the background noise level). The RIN transfer was well suppressed because Δf_1 and Δf_2 were set higher than 1 GHz[2,8]. We avoided concentration of the noise components at a specific frequency by setting Δf_1 and Δf_2 to different values. The results using the commercially available pump unit (see spectra in Fig. 2 (c) and (d)) are compared in Fig. 4 (c) and (d). The power of the pump and probe light at R0 were set to the same value as above. The RIN of the pump light without a polarizer (black) has a periodic spectrum induced by multiple reflections between the FBG and laser cavity[3–4]. The RIN of the pump light after the polarizer (red) increased drastically over a wide frequency range. It is considered that this is because the Δf_1 and Δf_2 of this pump light were not clearly determined. Because each longitudinal mode has fine structure, Δf_1 and Δf_2 can take values from almost zero to about 20 GHz. Figure 4 (d) shows that the RIN of the amplified probe light had a large polarization dependence, which was the result of the very irregular fluctuation of the synthesized polarization in the 35-km DSF.

Results of data transmission

Finally, we show the measured power tolerance after 1,920-km transmissions with and without the fwd-Raman amp. We compared our pump unit and the above-mentioned commercially available pump unit. The experimental setup will be explained only in outline due to word limit. We transmitted a 10-channel WDM signal (1557 - 1564 nm, 100 GHz spacing) using the recirculating loop. We used a polarization multiplexed 96-Gbaud PS-36QAM signal format[9]. Figure 5 shows a schematic of the recirculating loop. Transmission loss of the G.652.D fiber (80 km) and insertion loss of the acoustic optical modulator (AOM) was compensated by an erbium-doped fiber amplifier (EDFA) and a fwd-Raman amp. When we used the fwd-Raman amp, we also used the EDFA (see red hatching). When we did not use the fwd-Raman amp, we used the EDFA shown by blue hatching. The Raman pump power was 220 mW, and the On/Off gain was about 5 dB (slightly depending on wavelength; fiber used was not DSF, unlike previous chapter). After the 1,920-km transmission, the signal was detected by a coherent receiver (RX), and the SNR was measured as the function of the fiber-launched

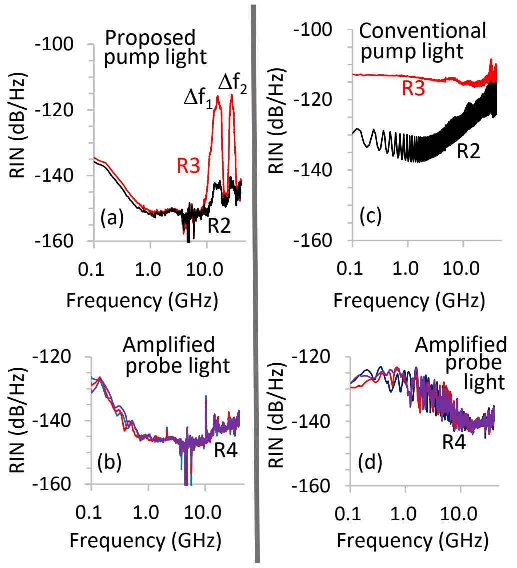

Fig. 4: Measured RIN. (a), (b): proposed pump light at R2-R3, amplified probe light at R4. (c), (d): conventional pump light at R2-R3, amplified light at R4

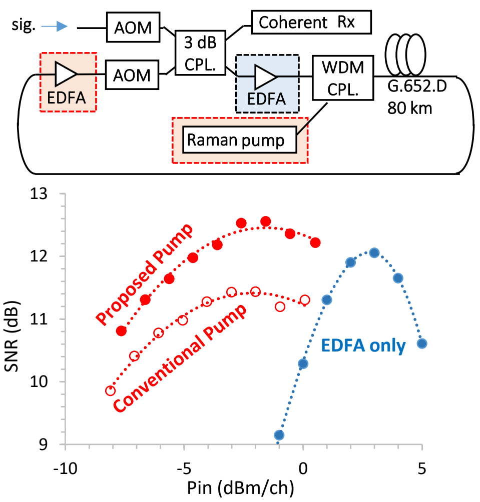

Fig. 5: Experimental setup for data transmission (only main components) and measured power tolerance. Red: fwd pumped Raman used, Blue: only EDFA used.

power per channel, Pin. Figure 5 shows the results. The fwd-Raman amp with our pump unit improved the maximum SNR by 0.5 dB, compared with the maximum SNR without using the fwd-Raman amp (EDFA only). However, the fwd-Raman amp with the commercially available pump unit deteriorated signal quality[5].

Conclusions

We discussed multiple beat noise induced by orthogonally polarized pump light. We improved the SNR of the PS-36QAM signal by 0.5 dB after a 1,920-km transmission, by utilizing the fwd-Raman amp with our pumping technique (5-dB On/Off gain).

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