Gain Instability in Forward-Pumped Raman Amplifier and Its Suppression Utilizing a Dual-Arm Depolarizer for Pump Light

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Abstract *The requirements for the depolarizer of the pump light used in a forward-pumped Raman amplifier were clarified. Management of the optical phases is strongly required to enable stable gain. Utilizing a dual-arm depolarizer, we successfully improved the 16-QAM transmission specifications.*

Introduction

Raman amplifiers for high-capacity optical transmission systems are being extensively explored because of their wide gain spectrum. In particular, distributed Raman amplifiers have an advantage over lumped Raman amplifiers (or Er-doped fiber amplifiers) in that they reduce loss in the transmission fiber[1]–[3]. In the Raman amplifier system, the gain stability is strongly affected by the relative intensity noise (RIN) and/or degree of polarization (DOP) of the pump lights[4]–[6]. These restrictions are relaxed in the backward-pumped Raman amplifier (bwd-Raman amp) because of its slower response than the forward-pumped Raman amplifier (fwd-Raman amp). Therefore, backward pumping has been widely used in the conventional Raman amplifier system[1]. However, a combination of fwd- and bwd-Raman amplifiers is required to further extend the distance of high capacity transmission systems[2]. To address the aforementioned restrictions, Kobayashi et al. utilized incoherent pump lights for the fwd-Raman amp, though conventional coherent pump lights were also used to boost the incoherent pump lights[3]. Generally, depolarization is performed to reduce the DOP when utilizing a coherent pump light. In a bwd-Raman amp, depolarization can be achieved using the two polarization-multiplexed laser sources or depolarizer connected to a laser source[5]–[6]. However, Martinelli et al. reported that a classical depolarizer (a variant of the Lyot depolarizer) in a fwd-Raman amp could result in unstable gain[4].

In this paper, we show that if the optical phases are not properly managed, depolarized pump light can induce gain instability in the fwd-Raman amp. We clarify the requirements for the pump lights to suppress this instability. We also show that fine tuning of the optical phases can be enabled using a dual-arm depolarizer that we proposed for the bwd-Raman amp in our previous work[6]. Finally, we present the measurement of the Q factor of the 16-QAM signal after 35-km transmission, with and without the fwd-Raman amp. The Q factor improved by 0.5 dB, and gain instability was not observed when the depolarizer was optimized and when the on-off gain was 3.2 dB.

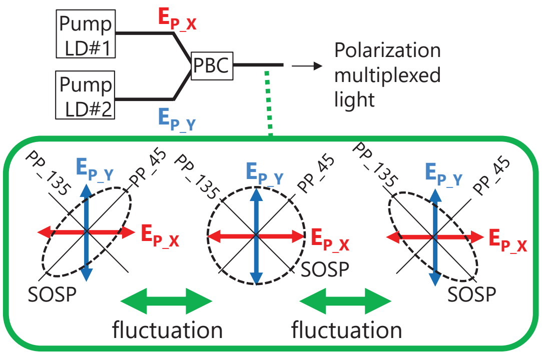

Fig. 1: Synthesized polarization generated using a two-pump light source.

DOP of the polarization-multiplexed pump lights

First, let's assume that the two polarization-multiplexed laser sources were utilized for pump light. Figure 1 schematically shows the typical setup. Optical electric fields generated using pump laser diode #1 (LD#1) and #2 are denoted as E_{P_X} and E_{P_Y}, respectively. These lights were coupled orthogonally using a polarization beam combiner (PBC). If LD#1 and #2 are single mode LDs and if their wavelengths are almost identical, then the sum of E_{P_X} and E_{P_Y} can synthesize a new polarization, as shown schematically at the bottom of Fig. 1. In this paper, the state of this synthesized polarization is denoted as the SOSP. Because of the finite coherency of LD lights, the SOSP was unstable, and the time-averaged DOP was low. However, in the fwd-Raman amp, fluctuation in the SOSP could induce gain instability because of the fast response of the amplifier. When the signal light was linearly polarized, and its plane of polarization was aligned at 45 or 135 degrees with respect to the E_{P_X} (denoted as PP_45 and PP_135 in Fig. 1.), this instability was maximized. This is because the Raman gain is decided by the square of the inner product of the signal and pump electric fields[5]. Note that this gain instability could occur even if no RIN occurred on LD#1 and #2. On the other hand, if the wavelengths of LD#1 and #2 differed, synthesized polarization could not be generated. In this case, E_{P_X} and E_{P_Y} may have suffered from different polarization rotations in the optical fiber as the gain medium because polarization rotation depends on the birefringence in the fiber and wavelength. This means that their orthogonality was not guaranteed[6]. Thus, the depolarizer described in the next section was required.

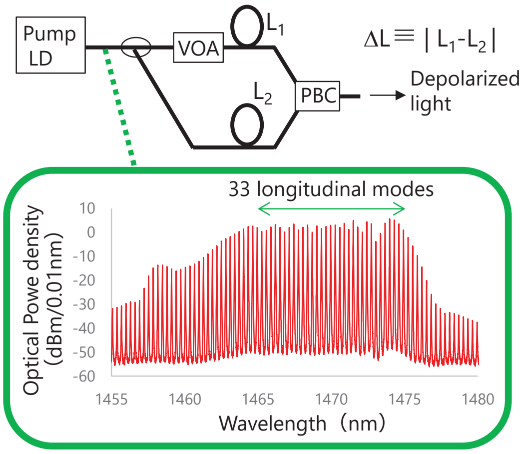

Fig. 2: Construction of the dual-arm depolarizer and optical spectrum of the pump light.

Construction of the dual-arm depolarizer

Figure 2 shows the construction of the dual-arm depolarizer used in this study. It was almost the same as the one proposed in our previous work[6], though the second pump LD was omitted. In this depolarizer, all optical components were polarization maintained. Linearly polarized pump light from the pump LD (Fabli-Perot type) was emitted into the 3 dB coupler. One of the divided pump lights was emitted into a variable optical attenuator (VOA) and the delay line denoted as L_1. Another divided pump light was emitted into another delay line denoted as L_2. The power imbalance induced by the L_1 and L_2 was cancelled out by the VOA. Finally, the two pump lights were combined orthogonally in the PBC. The difference in length between the two arms (including the VOA) is defined as ΔL, and the generated differential group delay (DGD) is defined as Δt. In this study, the typical ΔL and Δt were about 2 m and 10 nsec, respectively. These delay lines could be replaced to adjust the DGD. This replacement was easy because the required lengths of the L_1 and L_2 were only a few meters. Figure 2 also shows the spectrum of the pump light used in this study. There were 33 longitudinal modes from 1465 to 1475 nm. The spacing between each mode, Δf, was 43 GHz. In this paper, the SOSP generated by the Nth longitudinal mode is denoted as SOSP(N). The best depolarization was achieved when

$$\Delta t = (M + 0.5)/\Delta f, \quad M \text{ is an integer} \tag{1}$$

because in this case,

$$2\pi(N \cdot \Delta f)\Delta t = (2N \cdot M + N)\pi = N\pi \,(rad), \tag{2}$$

so then SOSP(N) and SOSP(N ± 1) were orthogonal. Note that their frequency slightly differed. In the optical fiber as the gain medium, SOSP(1) and SOSP(33) may have suffered from different polarization rotations as mentioned. However, because the wavelengths of the adjacent longitudinal modes were very close, SOSP(N) and SOSP(N ± 1) were still almost orthogonal. Thus, the overall DOP maintained a low value at any moment. On the contrary, when

$$\Delta t = M/\Delta f, \quad M \text{ is an integer}, \tag{3}$$

depolarization failed because SOSP(N) and SOSP(N ± 1) were identical[5]. In practice, the finite coherency of the 33 longitudinal modes and 10 nsec DGD decreased the time average of the overall DOP[5]–[6]. However, in the short term, linear polarization could be regenerated, as we will show experimentally.

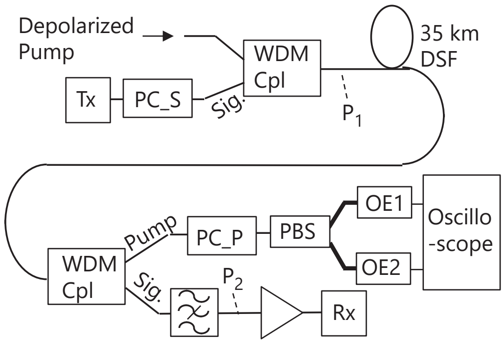

Fig. 3: Experimental setup.

Experimental setup

Figure 3 shows the experimental setup. We used a 35-km dispersion shift fiber (DSF) for the transmission line and the gain medium of the fwd-Raman amp. The signal light generated by the transmitter (TX) was dual polarization (DP) 32-Gbaud 16-QAM, and its wavelength was 1563 nm. Before being emitted to the DSF, the signal light passed through the polarization controller denoted as PC_S. The signal light and the pump light from the mentioned dual-arm depolarizer were coupled using a wavelength division multiplexing coupler (WDM Cpl), and the light was then emitted to the DSF. The signal power at P_1 (see Fig. 3) was −15.4 dBm. After transmission, another WDM Cpl divided the signal light and the pump light. The signal was input to a receiver (RX) after passing through the optical bandpass filter and lumped amplifier. Transmitted pump light was input to a polarization beam splitter (PBS) to monitor the overall DOP.

Two orthogonal polarization components were input to two O/E converters (OE1 and OE2). These components could be selected by another polarization controller, denoted as PC_P. The output of the OE1 and 2 were simultaneously measured using an oscilloscope.

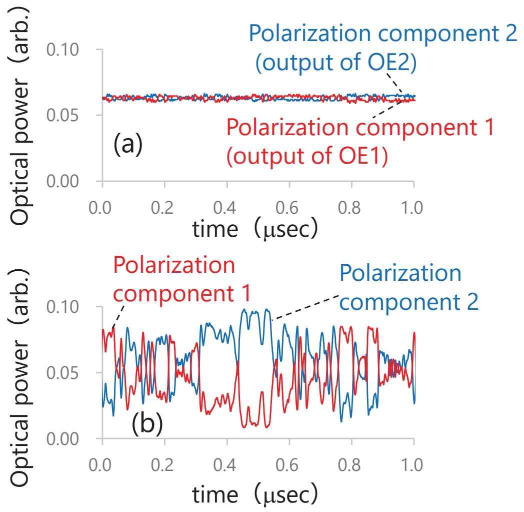

Fig. 4: Polarization components of the pump light measured at OE1 and OE2: (a) ΔL was optimized, (b) ΔL was not optimized.

Results and discussion

Figure 4 shows the measured output of OE1 and 2. In this measurement, the root mean square (RMS) of the voltage output from OE1 and 2 out were monitored using the oscilloscope, and the PC_P was set to make the highest RMS value. In other words, most noisy polarization components (corresponding to the PP_45 and 135 in Fig. 1) were selected. Fig. 4 (a) shows the results with optimized ΔL. The measured outputs of OE1 and 2 were almost identical and stable. Thus, depolarization was achieved. For comparison, Fig. 4 (b) shows the results without optimizing the ΔL. The output of the OE1 and 2 fluctuated complementarily, and in the center of the graph, OE2 made the highest output, though the output of OE1 almost vanished. This means that all of the SOSPs were temporarily close to linear polarization. Therefore, the two channels of the DP-16-QAM signal temporarily experienced unequal gains, though the RIN of the pump source was not changed.

Figure 5 (a) shows the power of the signal (total of the two channels) measured at P_2 (see Fig. 3), as a function of the pump power. Because of the restrictions in the experimental setup, the highest pump power at P_1 was 79.4 mW. The maximum on-off gain was 3.2 dB thanks to the small mode field diameter of the DSF. Figure 5 (b) shows the Q factor measured at the RX as a function of the pump power. In this experiment, the polarization of the signal light was set to the maximum and the minimum Q factor, utilizing a PC_S. Without pump light, the Q factor was between 8.46 dB and 8.41 dB. When ΔL was optimized (fill symbol), the Q factor at the maximum pump power was between 9.00 dB and 8.90 dB. This means that the Q factor improved by 0.5 dB and that the dependence on the signal polarization of the Q factor was negligible. When the pump power at P_1 exceeded 65 mW, the Q factor was saturated. This is because the optical signal to noise ratio was saturated after the lumped amplifier. For comparison, we also measured the Q factor with the worst ΔL (null symbol). When the pump power at P_1 was 20.4 mW, the Q factor slightly improved. However, when the pump power at P_1 was 53.7 mW, the Q factor was drastically degraded, and the signal polarization dependence was increased. This can be explained from the aforementioned gain instability.

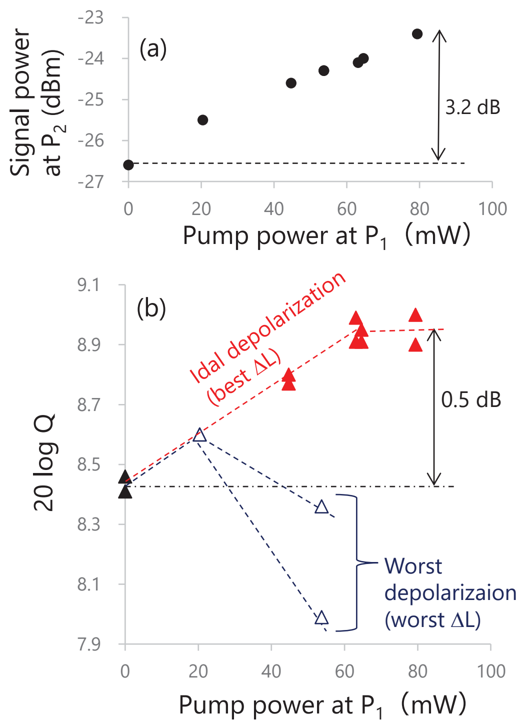

Fig. 5: Transmitted signal at various pump powers: (a) measured signal power at P_2, (b) measured Q factor.

Conclusions

We clarified the requirements for DGD inside the depolarizer to suppress the gain instability in a fwd-Raman amp. Utilizing a dual-arm depolarizer with optimal tuning, we experimentally showed that DP-16-QAM signals (32 Gbaud) were successfully amplified. The Q factor after 35-km transmission was improved by 0.5 dB when the on-off gain was 3.2 dB.

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