2nd-order forward-pumped distributed Raman amplification employing SOA-based incoherent light source in PDM-16QAM WDM transmission system

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Abstract:
We demonstrate 2nd-order forward-pumped distributed Raman amplification (DRA) in PDM-16QAM 25-GHz-spaced 11-channel WDM transmission system in L-band. Our forward-pumped DRA consists of semiconductor-optical-amplifier-based incoherent light source for signal amplification and two coherent light sources for incoherent light amplification. After 1,760 km single-mode-fiber transmission, 1.2-dB Q-improvement is experimentally achieved by our DRA scheme compared with that of in the case of amplification with EDFA only. And we also show the low RIN-transfer-induced Q-penalty of our pumping scheme at the Raman on/off gain of up to 10 dB.

Keywords: digital coherent transmission system, optical communication, forward-pumped Raman amplification

Classification: Fiber-Optic Transmission for Communications

References

[1] M. Nakamura, A. Matsushita, S. Okamoto, F. Hamaoka and Y. Kisaka, "Spectrally Efficient 800 Gbps/Carrier WDM Transmission with 100-GHz Spacing Using Probabilistically Shaped PDM-256QAM," Proc. European Conference on Optical Communication 2018, Rome, Italy, We3G.5, Sept. 2018. DOI: 10.1109/ECOC.2018.8535182

[2] A. Sano, T. Kobayashi, S. Yamanaka, A. Matsuura, H. Kawakami, Y. Miyamoto, K. Ishihara, and H. Masuda, "102.3-Tb/s (224 x 548-Gb/s) C- and Extended L-band All-Raman Transmission over 240 km Using PDM-64QAM Single Carrier FDM with Digital Pilot Tone," Proc. Optical Fiber
1 Introduction

In recent digital coherent transmission systems, advanced digital signal processing (DSP) such as highly-precise digital equalization, constellation shaping and forward error correction (FEC) achieve the channel capacity close to Shannon limit at given signal-to-noise ratio (SNR) [1]. For achieving higher channel capacity, it is necessary to improve the received SNR after fiber transmission while advancing the performance of transceivers and DSP algorithms. Distributed Raman amplifier (DRA) is well-known technique for improving the optical SNR, and especially backward-pumped DRA has been widely applied to high capacity digital coherent transmission systems [2, 3]. However, forward-pumped DRA application is very limited because relative intensity noise (RIN) of pumping light is transferred to optical signals in Raman amplification process as signals’ amplitude variation which is known as RIN transfer. So far, a digital coherent
transmission experiment with forward-pumped DRA has been reported with small Raman on/off gain [4]. The RIN mitigation techniques utilizing incoherent pumping scheme have been reported and demonstrated in digital coherent transmission system [5, 6]. The incoherent-light source candidates are the fiber-based generator utilizing Rayleigh scattering [5] and semiconductor optical amplifier (SOA) [6]. The low RIN-transfer characteristics of 2nd-order forward-pumped DRA utilizing former one has been demonstrated in polarization-division-multiplexed (PDM) quadrature phase shift keying (QPSK) WDM transmission system [5]. On the other hand, we proposed 2nd-order incoherent forward-pumped DRA with SOA-based incoherent light source and demonstrated it in PDM 16-ary quadrature amplitude modulation (QAM) transmission in single channel [6] and WDM configuration [7]. However, they were conducted at specific Raman on/off gain and the dependence of transmission performance on the gain has not been reported yet.

In this paper, 2nd-order forward-pumped DRA utilizing incoherent-pump light source is demonstrated in PDM-16QAM L-band WDM transmission system. The DRA consists of SOA-based incoherent light source for signal amplification and two coherent light sources for incoherent light amplification. After 1,760-km SMF transmission, 1.2-dB Q-improvement is experimentally achieved by our DRA scheme compared with that of in the case of amplification with EDFA only. And we also show the Q-improvement of > 1 dB can be achieved at the Raman on/off gain of up to 10 dB without excess RIN-transfer-induced penalty.

2 Transmission experiment with incoherent-pumped DRA

Schematic diagram of our 2nd-order incoherent-pumped DRA [6] is shown in Fig.1.(a). Our scheme requires the incoherent light which has broadband spectra as 1st-order pumping light for reducing the RIN-transfer in Raman amplification process [8]. And coherent light for 2nd-order pumping is added at about 100-nm shorter wavelength of incoherent light. Because incoherent light is amplified by coherent light while maintaining the wide optical spectra, RIN-transfer can be mitigated in 1st-order Raman amplification process all over the transmission fiber. Optical spectra of pump lights employed in this experiment is shown in Fig.1 (b). We employed SOA-based incoherent light source with the center wavelength of 1500 nm [9]. Coherent light sources were Fabry-Perot Laser Diodes (FP-LDs) with fiber Bragg grating (FBG) and the wavelengths were 1422 nm and 1430 nm. The experimental setup is shown in Fig. 2. Eleven lasers were operated at a 25-GHz-spaced WDM grid from 1604.9 nm to 1607.1 nm. We used a tunable external-cavity laser (ECL) with a linewidth of about < 100 kHz for the test channel (1605.96 nm) at the center wavelength of WDM signal; the remaining lasers were DFB lasers with the linewidth of ~2 MHz. The odd/even optical carriers were separately multiplexed and modulated by a dual polarization IQ-modulator (DP-IQM) to 22.5-Gbaud Nyquist-pulse-shaped PDM-16QAM signals. The roll-off factor was 0.01. Modulator driving signals were generated with digital-to-analog converters (DACs). 16QAM symbols were generated from bit sequence derived from DC-balanced pseudo random binary sequence with a
length of $2^{23}$. Then, even-/odd- PDM-16QAM signals were combined by an optical 25-GHz/50-GHz interleaver (IL), resulting in 11-ch PDM-16QAM WDM signal with 25-GHz spacing. The net rate per channel is 150 Gb/s after subtracting 20% FEC overhead.

The transmission line consisted of a 80-km SMF re-circulating loop containing single 80-km span of standard SMF, an optical band pass filter (OBPF) with 3-nm bandwidth for filtering ASE noise, an optical gain equalizer (GEQ) and a loop-synchronous polarization scrambler (LSPS). The loss of the 80-km span was 16.9 dB. The losses of optical components for re-circulating loop were compensated by Erbium-doped fiber amplifiers (EDFAs).

The optical powers of pump lights and signals were measured at the input of SMF. In all measurements, the optical power of incoherent pump was set to 80 mW which was maximum output power of our incoherent-light source. Raman on/off gain was varied from 4 dB to 10 dB by changing the optical powers of two coherent-pump lights of 1422 nm and 1430 nm. For comparison, we also investigated the transmission performance utilizing conventional coherent-pumped DRA with 1505-nm FP-LD.

At the receiver side, the received signal was detected by a polarization-diversity coherent receiver. A free-running ECL with linewidth $< 100$ kHz was employed as a local oscillator. The received signal was digitized at 50 GS/s with 16-GHz electrical bandwidth and then post-processed off-line.

![Fig. 1.](image1)

(a) Schematic diagram of 2nd-order incoherent-pumped DRA
(b) Optical spectra of pump lights.

![Fig. 2.](image2)

Experimental setup.
3 Results

Optical spectrum of pumping lights and WDM signal after 80-km SMF transmission in the case of 10-dB Raman on/off gain were shown in Fig. 3(a) and (b). Incoherent-pump, 1422-nm and 1430-nm c-pumps had the pumping powers of 80 mW, 370 mW and 390 mW, respectively. Raman on/off gain of 10 dB over all 11-channel WDM signals was achieved while two c-pumps amplified incoherent-pump lights with its gain peak around 1530-nm wavelength. On the other hand, Raman on/off gain with incoherent-pumping only was 1.8 dB. For comparison, utilizing conventional FP-LD pump with 1505-nm wavelength can also achieved the 10-dB Raman on/off gain as also shown in Fig. 3(b). Next we investigated the dependence of signal quality on Raman on/off gain in long-haul transmission. The Raman on/off gain was varied from 4 dB to 10 dB by optimizing the power of coherent pump lights (1422 nm and 1430 nm). Fig.3(c) and (d) show Q-factor of the test channel (1605.96 nm) as a function of the fiber input power after 1,720-km SMF transmission. With 2nd-order forward-pumped DRA with incoherent light source, optimal fiber input power was shifted to lower power region as Raman gain increased as shown in Fig.3 (c). Q-factor was improved by 1.2 dB compared with in the case of EDFA only amplification. This result shows that OSNR improvement by our forward-incoherent-pumped DRA was much larger than RIN-transfer-induced penalty. On the other hand, with the conventional 1505-nm FP-LD, Q-factors were drastically degraded as Raman on/off gain increased as shown in Fig.3 (d). At the 10-dB Raman on/off gain, the optimal Q-factor was decreased to 4.6 dB which equaled to that of with EDFA only amplification. It would be most likely due to RIN-transfer and fiber nonlinearities because the optical peak power in the link which is larger than that of 2nd-order incoherent-pumped DRA. These results confirmed that 2nd-order incoherent-pumped DRA can improve the transmission performance of PDM-16QAM signal with negligible RIN-transfer-induced penalty.
4 Conclusion

2nd-order forward-pumped DRA utilizing SOA-based incoherent pump light was demonstrated in PDM-16QAM L-band WDM transmission system. After 1,760-km SMF transmission, 1.2-dB Q-improvement is experimentally achieved by utilizing our DRA compared with that of in the case of amplification with EDFA only. And the Q-improvement of > 1 dB can be achieved at the Raman on/off gain of from 4 dB to 10 dB without excess RIN-transfer-induced penalty. By utilizing not only backward-pumped DRA but also our low noise forward-pumped DRA, it would enable more flexible power-profile desing of transmission link as well as the OSNR improvement.