Long-haul transmission using counter-pumped distributed Raman ring laser amplification

Akihide Sano\textsuperscript{1, a)} and Katsuya Ura\textsuperscript{1}

\textsuperscript{1}Graduate School of Science and Engineering, Ritsumeikan University,
1–1–1 Noji-Higashi, Kusatsu, Shiga 525–8577, Japan
\textsuperscript{a)}ak-sano@fc.ritsumei.ac.jp

Abstract: This paper proposes a novel distributed Raman amplification (DRA) scheme for long-haul optical fiber transmission systems. The scheme utilizes two fibers for the bidirectional transmission links, and each fiber is counter-pumped by a second-order pump source. The first-order pump lights are generated in the ring cavity consisting of two fibers, and amplify the optical signal. This scheme enables both co-pumping and counter-pumping from the generated first-order pump lights by using only second-order counter-pumping. The amplification performance of the proposed scheme is examined in the long-haul transmission experiments using dual-polarization QPSK signal, and the proposed scheme is confirmed to improve the transmission performance compared with the conventional first-order counter-pumping DRA.

Keywords: optical fiber communication, distributed Raman amplification, second-order pumping

Classification: Transmission Systems and Transmission Equipment for Communications

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1 Introduction

Data traffic in backbone optical transport networks is continuously increasing due to the emerging novel communication services. Thus there is a strong demand for the extension of the per-fiber transmission capacity of long-haul optical transmission systems based on coherent reception and polarization division multiplexing (PDM). Distributed Raman amplification (DRA) is a powerful technique to improve the transmission performance. In particular, a first-order counter-pumping scheme has been widely deployed in commercial networks to improve the received optical signal to noise ratio (OSNR) without increasing nonlinear impairments [1, 2].

Higher order pumping and co-pumping are the key to further improve the performance of the conventional first-order counter-pumping DRA. By employing these techniques, the signal power variation along the fiber can be effectively suppressed, and thus we can expect excellent noise performance while maintaining low signal power to suppress nonlinear impairments. However, these techniques are associated with the following additional hurdles: The use of higher order pumps in addition to the first-order pumps complicates the configuration and control of DRA systems. Moreover, pump-to-signal relative intensity noise (RIN) transfer, which caused by the power fluctuation of the co-propagating pump, degrades the signal transmission performance severely [3].

Thus advanced pumping schemes have been proposed to overcome such hurdles. Forward Raman amplification using low RIN incoherent co-propagating pump sources has been proposed [4]. In this scheme, additional second-order co-propagating pump sources are used to obtain sufficient forward DRA gain. Ultra-long Raman fiber laser has been demonstrated [5]. This scheme utilizes second-order co-pumping and counter-pumping to pump the long cavity consisting of a transmission fiber and fiber Bragg gratings.

We have recently proposed a distributed Raman ring laser amplification (DRRLA) scheme [6]. This scheme also utilizes second-order co-pumping and counter-pumping, and the first-order pump light is generated in the ring cavity consisting of two fibers for bidirectional transmission. In this scheme, however, OSNR improvement is restricted because the generated first-order pump propagates in the fiber with a opposite direction to the signal, and thus the signal is mainly amplified near the output end of the fiber. In addition, the RIN of the second-order co-pumps causes small degradation in the signal transmission performance.

In this paper, we propose a novel DRRLA configuration based on only counter-pumping. The proposed scheme generates both co-propagating and counter-propagating first-order pump, and thus the signal power variation along the fiber can be suppressed. The performance of the proposed counter-pumped DRRLA is verified in the dual polarization-QPSK (DP-QPSK) long-haul transmission experiment.
2 Counter-pumped DRRLA

Fig. 1 shows the proposed system configuration of the second-order counter-pumped DRRLA. This scheme utilizes both eastbound (W to E) and westbound (E to W) links to form a ring cavity that generates first-order pump lights. Transmission fibers for both directions are pumped from the output ends by second-order pump sources via signal/second-order pump WDM couplers (WDM2). The transmission fibers are further connected with signal/first-order-pump WDM couplers (WDM1) at the input and output ends, and the pump ports of WDM1 for both directions are connected each other. Thus the fibers for both directions create a ring cavity for the radiation at the first-order pump wavelength.

When the two fibers are pumped by the second-order pump sources, the first-order pump light is generated in the transmission fiber due to the Raman scattering, and propagates along the ring cavity in both directions, as shown in Fig. 1. If the second-order pumping power is above the threshold necessary to overcome the round-trip attenuation of the first-order pump, a stable first order pump is generated in the ring cavity and propagates in the fibers with both directions. Therefore, the signal is amplified by the generated co-propagating and counter-propagating first order pump.

![Fig. 1. Proposed system configuration.](image)

Compared with the previous version of our DRRLA configuration [6], the novel configuration has the following advantages: First, since the novel configuration pumps the signal bidirectionally by the first-order pumps, signal power variation along the fiber is smaller than that of the previous version. Thus the OSNR improvement can be expected. Moreover, the novel configuration does not use the high-power co-propagating second-order pumps. Therefore nonlinear impairments due to the RIN of the second-order co-pumps can be suppressed.

3 Experimental setup

The performance of the proposed counter-pumped DRRLA was examined in the long-haul DP-QPSK transmission experiment. Fig. 2 shows the experimental setup, which utilizes a recirculating loop setup with a simplified single-direction configuration.
Fig. 2. Experimental setup. Inset (a) shows the measured signal power evolution along the fiber.

A 1557.36-nm CW light was modulated by an IQ modulator to create a 9.6-Gbaud Nyquist-pulse-shaped QPSK signal with a roll-off factor of 0.1. The modulated signal was then polarization division multiplexed by a PDM emulator with a 260-symbol delay between the two polarization tributaries, and launched into a recirculating loop.

The recirculating loop consisted of an 80-km standard single-mode fiber (SMF) with an average loss of 0.20 dB/km, a dynamic gain-equalizing filter (DGE), an EDFA, and an acousto-optic switch (SW). The SMF was pumped by a second-order counter-pump consisting of a fiber Raman laser (FRL). The wavelength of the FRL was 1360 nm and the fiber input power was 1.07 W. Unlike the proposed DRRLA configuration with a bidirectional link shown in Fig. 1, we employed simplified configuration with a unidirectional link in this experiment. We also utilized a loop-synchronous polarization scrambler (LPS) to minimize the polarization dependence in the loop.

The output signal from the recirculating loop was received by a polarization-diversity integrated coherent receiver (ICR) and sampled by a 25-GS/s digital storage oscilloscope (DSO) with an analog bandwidth of 6 GHz. The digitized signals were stored, and processed offline with standard DSP algorithms: First, chromatic dispersion (CD) was compensated by a frequency-domain fixed equalizer, and then polarization-demultiplexing and equalization was done by 31-tap adaptive FIR filters controlled by the decision-directed LMS algorithm with a step-size parameter of $1 \times 10^{-3}$. After carrier-phase recovery, Q factors were calculated from the result of bit error counting over one million bits.

4 Results and discussion

The signal power evolution measured using a modified optical time-domain reflectometer is shown in the inset of Fig. 2. When the pump power was off, the signal power was exponentially decreased with a loss coefficient of 0.2 dB/km. In the case
of the proposed counter-pumped DRRLA, the signal power variation is effectively reduced, and the on-off Raman gain of 12 dB was obtained. Since the proposed scheme generates both co-propagating and counter-propagating first-order pump, the signal light experiences both the forward-Raman and the backward-Raman gain. We also measured the power evolution for the conventional first-order counter-pumping with the same on-off Raman gain. The minimum signal power of the proposed scheme was 2.8 dB higher than that of the conventional scheme, and thus the higher received OSNR can be obtained.

Next, we evaluated the performance of DP-QPSK long-haul transmission. Fig. 3(a) shows the Q-factors as a function of the fiber input power after 8,320-km transmission. In both proposed and conventional schemes, the Q-factor increases as the fiber input power increases due to the OSNR improvement at low input power condition, and decreases at high input power due to nonlinear signal distortion. In the proposed scheme, the maximum Q-factor was 9.7 dB at the fiber input power of −8 dBm. In the conventional scheme, on the other hand, the maximum Q-factor was 8.2 dB at the fiber input power of −7 dBm. The optimum fiber input power of the conventional scheme was slightly higher because of the lower path-averaged signal power. Despite the lower optimum input power, however, the proposed configuration was confirmed to exhibit higher Q-factor by 1.5 dB compared with the conventional configuration.

![Fig. 3](image-url)

**Fig. 3.** Q-factor as a function of fiber input power (a), Q-factor as a function of transmission distance (b), and constellation diagrams after 8,320-km transmission (c–f). (c) DRRLA (x-pol.). (d) DRRLA (y-pol.). (e) 1st-order counter-pump (x-pol.). (f) 1st-order counter-pump (y-pol.).

Fig. 3(b) shows the measured Q-factor as a function of transmission distance for the proposed and the conventional schemes. In this measurement, the fiber input power was set to the optimum shown in Fig. 3(a). We can confirm that the Q-factors for the proposed scheme are 1.3 to 1.8 dB higher than the conventional scheme at the transmission distance over 4,000 km. Taking account of the Q-limit of 9.1 dB
for standard hard decision FEC (shown by the dashed line), the attainable distance of the proposed scheme was around 9,200 km, which was extended by 2,000 km compared with the conventional scheme.

Fig. 3(c) and (d) show the constellation diagrams after 8,320-km transmission with the proposed DRRLA for x- and y-polarization, respectively, and Fig. 3(e) and (f) show the results with the conventional first-order counter-pumping. We can confirm that the broadening of the signal distribution observed in the conventional case is successfully suppressed by the proposed scheme.

5 Conclusion

We have proposed the novel counter-pumped DRRLA for the long-haul optical fiber transmission with DRA. The proposed scheme generates co-propagating and counter-propagating first-order pumps in a ring cavity consisting of two fibers for bidirectional transmission link. Thus the proposed scheme enables both forward-Raman and backward-Raman amplification as well as second-order Raman amplification by using only second-order counter-pumping. The performance of the proposed DRRLA was examined in the 9.6-Gbaud DP-QPSK long-haul transmission experiment. It was confirmed that the proposed DRRLA effectively improved the received Q-factor by 1.3 to 1.8 dB compared with the conventional first-order counter-pumping scheme.

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