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Nonlinearity Mitigation of PDM-16QAM Signals Using Multiple CSI-OPCs in Ultra-Long-Haul Transmission without Excess Penalty

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SUMMARY We developed a polarization-independent and reserved-band-less complementary spectral inverted optical phase conjugation (CSI-OPC) device using dual-band difference frequency generation based on highly efficient periodically poled $LiNbO_3$ waveguide technologies. To examine the nonlinearity mitigation in a long-haul transmission using a large number of OPCs, we installed a CSI-OPC device in the middle of a pure silica core fiber-based recirculating loop transmission line with a length of 320 km. First, we examined the fiber-input power tolerance after 5,120-km and 6,400-km transmission using 22.5-Gbaud PDM-16QAM 10-channel DWDM signals and found a Q-factor improvement of over 1.3 dB along with enhanced power tolerance thanks to mitigating the fiber nonlinearity. We then demonstrated transmission distance extension using the CSI-OPC device. The use of multiple CSI-OPCs enables an obvious performance improvements attained by extending the transmission distance from 6,400 km to 8,960 km, which corresponds to applying the CSI-OPC device 28 times. Moreover, there was no Q-factor degradation for the link in a linear regime after applying the CSI-OPC device more than 16 times. These results demonstrate that the CSI-OPC device can improve the nonlinear tolerance of PDM-16QAM signals without an excess penalty.
key words: *optical signal processing techniques for optical communications, optical phase conjugation, nonlinear optics, periodically poled $LiNbO_3$ waveguide*

1. Introduction

Recent digital coherent technologies have dramatically increased the capacity and transmission distance in optical fiber transmission systems [1], [2]. However, the mitigation of fiber nonlinearity is still a major issue to overcome if we are to cope with the ever-increasing demand for transmission capacity in optical transport networks [3]. To mitigate or compensate for fiber nonlinearity, not only digital signal processing (DSP) approaches such as digital back-propagation [4] but also optical signal processing techniques have been investigated [5], [6]. The use of an optical phase conjugation (OPC) is a particularly promising technique to mitigate nonlinear distortion because it features modulation format transparency and can mitigate the nonlinear impairments in wavelength division multiplexing (WDM) signals simultaneously [7]. Following the first proposal of an OPC for compensation of chromatic dispersion [8], the advantages of mitigating nonlinear impairments that result from the Kerr effect have also been revealed [9], [10]. However, a conventional OPC based on (single) spectral inversion requires more than twice the bandwidth because a reserved band for the wavelength band conversion is needed. To overcome the limitation of losing half the bandwidth, reserved-band-less OPC techniques, namely dual-band OPC or complementary spectrally inverted (CSI)-OPC, have been proposed [11]–[13]. Following these, there have been successful demonstrations of the transmission reach enhancement of super-channels [14], the simultaneous nonlinearity mitigation of a large number of WDM signals [15], and the applicability of OPC to installed fiber links [16]. Recently, the mitigation of the intra-channel nonlinearity of a high-baud-rate single-carrier signal with a 100-GHz optical bandwidth has also been experimentally demonstrated by using CSI-OPC [17]. First experiment combining dual-band OPC and commercially available real-time transceivers in a standard-single-mode-fiber link has also been demonstrated [18]. These results suggest the possibility of utilizing an OPC device without any reduction in spectral efficiency stemming from wavelength conversion. Moreover, reserved-band-less OPC enables an OPC device to be installed multiple times into a transmission link because it is possible to retain the original WDM bandwidth. With ideal OPC-based nonlinearity compensation, which fully compensates for deterministic nonlinear interactions, the system becomes limited by nondeterministic nonlinear noise with either the polarization mode dispersion (PMD)-induced reduction of compensation efficiency [19] or ultimately nonlinear signal-noise interactions [20]. In such systems, the deployment of multiple OPCs is expected to provide a significant performance enhancement. However, if OPC systems have any impairment, such as a large intrinsic loss, low conversion efficiency,

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and large polarization-dependent loss (PDL), increasing the number of OPCs may degrade the performance due to additional linear noise.

In this paper, we demonstrate the feasibility of installing a large number of multiple OPCs in a transmission line using a polarization-diversity CSI-OPC device. In a linear regime, the low-loss configuration enables WDM signal transmission using polarization-division multiplexing (PDM)-16QAM signals without Q-factor degradation after utilizing the CSI-OPC device over 16 times in a non-dispersion-managed transmission link with all-Raman amplification. In a nonlinear regime, the transmission distance was clearly increased from 6,400 to 8,960 km by increasing the optimal fiber input power of 4 dB with a Q-factor improvement of 1.3 dB.

Section 2 describes the configuration and schematic diagrams of our polarization-independent CSI-OPC device. We also present the experimental setup of Raman amplifier-based multi-span transmission to examine the nonlinearity mitigation in a long-haul transmission using a large number of multiple OPCs. Section 3 reports the experimental results for ultra-long-haul transmission using multiple OPCs. First, we compare the optical signal to noise ratio (OSNR) for the link without and with our CSI-OPC device. Next, we show the fiber-input power tolerance for the link with and without the CSI-OPC device. We then show the experimental results for transmission distance extension by using the CSI-OPC device.

2. Concept and Configuration of CSI-OPC and Experimental Setup of Multi-Span Transmission

2.1 Polarization-Diversity CSI-OPC Device Based on PPLN Waveguides

Figure 1 shows the configuration and schematic diagrams of a polarization-independent CSI-OPC device. First, input wavelength division multiplexed and polarization-division multiplexed signals were split into two frequency bands, which have a shorter or longer wavelength than a center wavelength, using a short/long pass filter (S/LPF). In the path for each wavelength band, the WDM signals were simultaneously converted into phase-conjugated idlers by a second-harmonic pumped difference frequency generation (DFG) process. We utilized eight periodically poled lithium niobate (PPLN) ridge waveguide modules [21]. Four PPLN modules were utilized for the phase-conjugated signal generation by DFG. The other four modules used second-harmonic generation (SHG) to generate pump lights for DFG. We used an external-cavity laser (ECL) as a local light source whose wavelength was the same as the center wavelength of the S/LPF with an ultra-narrow linewidth

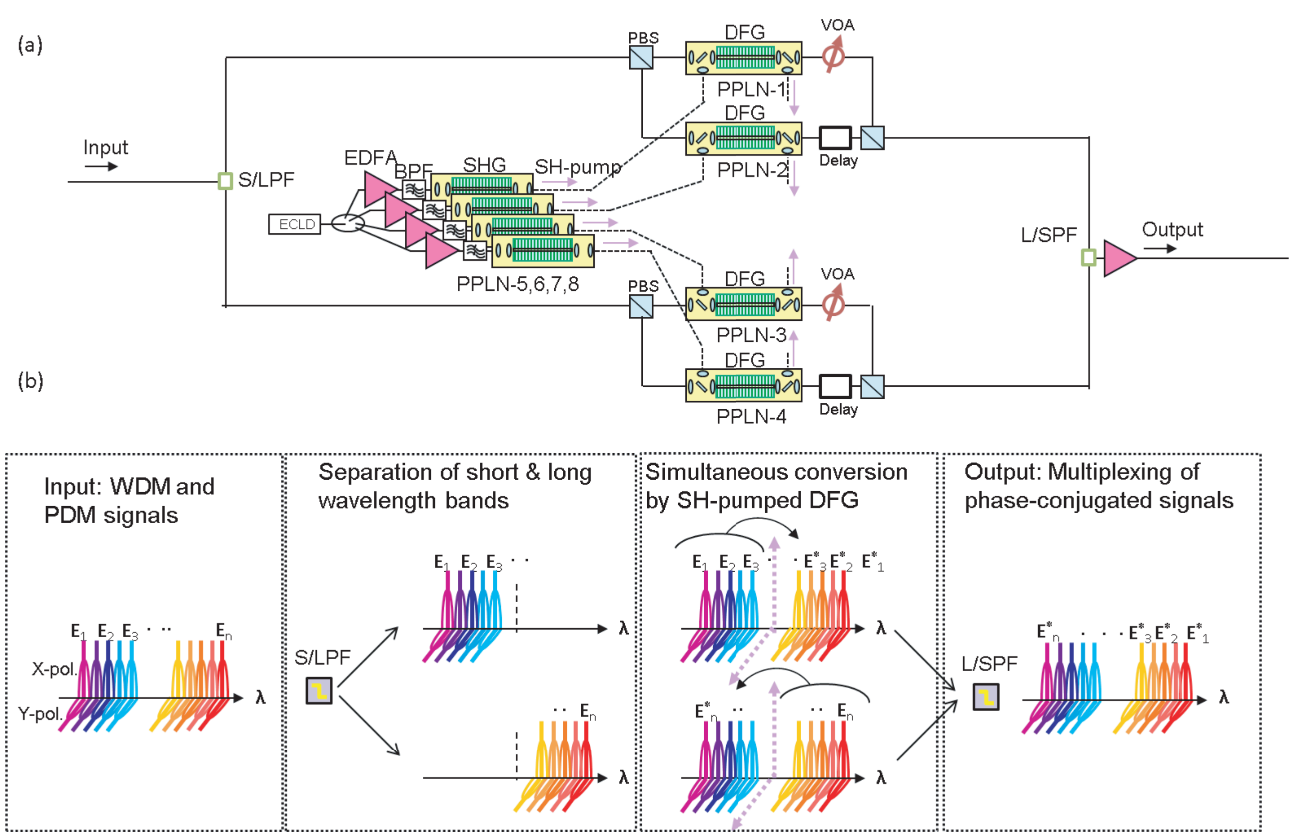

Fig. 1 (a) Configuration of polarization-diversity CSI-OPC device. (b) Schematic diagrams of complementary spectral inversion using SH-pumped DFG.

of 5 kHz to minimize the phase noise of the idler transferred from the SH pump. A polarization-diversity configuration was put into place by utilizing two independent SH-pumped DFG processes. Phase-conjugated signals for the polarization-division multiplexed signals were generated by utilizing these processes after dividing using a polarization beam splitter (PBS). The power imbalance between four tributaries was minimized with variable optical attenuators (VOAs) and path lengths were adjusted with optical delay lines. We used motorized variable optical delay lines to adjust the path lengths between X and Y arms to be less than 1 mm. Next, the phase-conjugated idlers of both polarization components were combined with a polarization beam combiner (PBC). Finally, a long/short pass filter (L/SPF) combined the phase-conjugated signals while rejecting the original input signals, and only the phase-conjugated signals were routed to the output.

2.2 Experimental Setup of Raman Amplifier-Based Multi-Span Transmission

To examine the nonlinearity mitigation in a long-haul transmission using a large number of multiple OPCs, we installed a CSI-OPC device in the middle of a transmission line so that it would operate as a standard mid-span OPC system. Figure 2(a) shows the experimental setup, which utilizes a recirculating loop configuration. Ten carriers on a 25-GHz grid consisting of a two-frequency band were prepared in the transmitter. Even and odd carriers were independently modulated to generate Nyquist-pulse-shaped 22.5-Gbaud PDM-16QAM signals with a roll-off factor of 0.1 using dual polarization IQ modulators driven by 56 GS/s digital-to-analog converters (DACs). The ten WDM channels were set at the signal band edge in relation to the fundamental center wavelength of 1536.6 nm. Figure 2(b) shows the arrangement of the wavelength of the ten WDM signals. We set two 5-channel WDM signals at the signal band edge to examine the effect of nonlinearity mitigation. The wavelength ranges for the shorter and longer bands are 1527.60–1528.38 nm and 1544.92–1545.72 nm, respectively. The measured test signal wavelength was 1545.32 nm. We used a test sequence of 2^{14} symbols by mapping and truncating a $2^{23} - 1$ PRBS. The recirculating loop consisted of four spans of pure silica core fiber (PSCF) with a length of 80 km with an average loss of 0.17 dB/km, an Aeff of 115 μm^2, and a dispersion of 20 ps/nm/km, a gain-equalizing filter (GE), and a loop-synchronous polarization scrambler (LSPS), which generates a step-wise change in polarization states with a round-trip time interval. We utilized distributed all-Raman amplification with pumping wavelengths in the 1422–1460 nm range. The test signal from the recirculating loop was passed through an optical filter and received by a digital coherent receiver, which consisted of an ECL as an LO with the linewidth of ~100 kHz, a polarization-diversity 90° optical hybrid, four balanced detectors, and 50-GS/s analog-to-digital converters (ADCs) in a real-time oscilloscope. The received signals were stored and equalized by using a fixed frequency-domain equalizer for chromatic dispersion (CD) compensation and an LMS-based adaptive filter through offline processing. Figure 2(c) shows an example of acquired constellation diagrams for a back-to-back signal of 22.5-Gbaud PDM-16QAM signals. Note that the residual CD, due to the dispersion slope of about 0.06 ps/nm^2/km, was reduced to less than 2.7% of the total dispersion of the PSCF-based transmission line. Thus, OPC also has the potential to significantly reduce the load imposed on the digital sig-

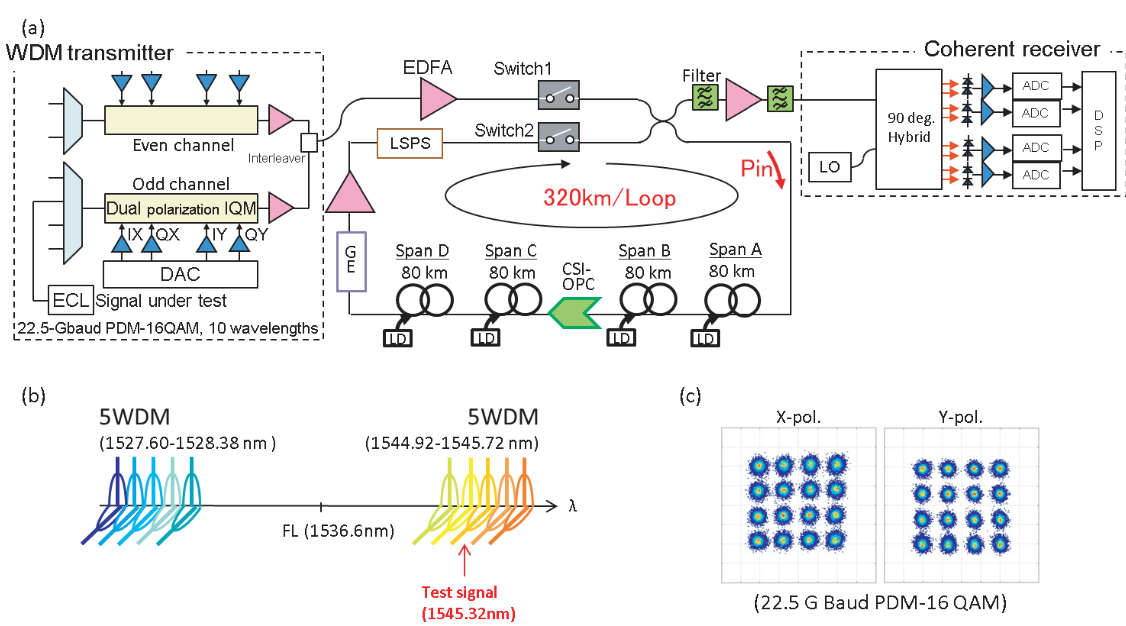

Fig. 2 (a) Experimental setup for multi-span transmission using distributed all-Raman amplification while applying CSI-OPC to mid-span spectral inversion. (b) Arrangement of wavelength of ten WDM signals. (c) Constellation diagrams for a back-to-back signal.

nal processor with regard to chromatic dispersion compensation.

3. Experimental Results for Ultra-Long-Haul Transmission Using Multiple OPCs

3.1 Effect of Loss by Installing CSI-OPC Device in Terms of OSNR

First, we investigated the degradation by installing the CSI-OPC device in a linear regime. If multiple OPC processes impose an excess penalty in the linear regime by installing the OPC devices, the effect of mitigation by the OPC will be largely degraded. We measured the optical signal to noise ratio (OSNR) of the recirculating loop by using a continuous wave (CW) for the signal light with the launched power of −7 dBm/ch. Figure 3 shows the OSNRs for the link without and with the CSI-OPC device as a function of transmission distance from 1920 km to 9600 km, which correspond to applying the CSI-OPC device from 6 to 30 times. Both OSNRs for without and with the CSI-OPC device were similarly degraded as a function of transmission distance. There was no OSNR penalty if we applied a large number of OPCs This result indicates that the effect of nonlinear mitigation allows higher transmission power and hence directly increases the SNR at the receiver, as our polarization-diversity CSI-OPC device has no excess penalty in the linear regime after applying the device over 30 times. Note that not only OSNR but also the effect of phase noise is important because the phase fluctuation of the pump light is instantaneously imposed on the idler through DFG process. In this experiment, we utilized an ECLD with an ultra-narrow linewidth of 5 kHz to minimize the phase noise of the idler.

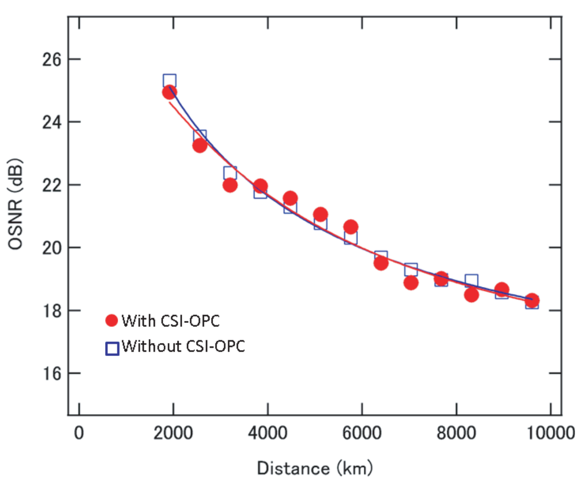

Fig. 3 OSNRs for the recirculating loop without and with the CSI-OPC device by using CW signals with launched power of −7 dBm/ch.

3.2 Fiber-Input Power Tolerance for Link with and without CSI-OPC Device

Next, we investigated the fiber-input power tolerance in a 10-channel WDM transmission. Figure 4(a), (b) shows the Q factor of the link with and without an OPC device after 5,120 km and 6,400 km transmission, respectively as a function of the launched signal power per channel. For the link without an OPC device, the optimal launched power of −7 dBm/ch was obtained with maximum Q factors of 5.9 and 5.3 dB after 5,120 km and 6,400 km transmission, respectively. These values were above the FEC limit (5.0 dB, dashed line) of the LDPC convolutional codes using a layered decoding algorithm with a 25.5% FEC overhead [22]. However, the signal quality degraded at a higher launch power due to large nonlinear impairments. In contrast, the Q-factor degradation was mitigated for the link with the OPC device. The signal quality remained high as the launched power increased, and maximum Q factors of 7.3 and 6.6 dB were obtained at powers of −3.5 and −3 dBm/ch. We clearly achieved a Q-factor improvement of over 1.3 dB and enhanced the power tolerance by mitigating the fiber nonlinearity. Figure 5 shows constellation diagrams for the signal with and without the CSI-OPC device for optimal launched powers of −3 and −7 dBm/ch, respectively. The

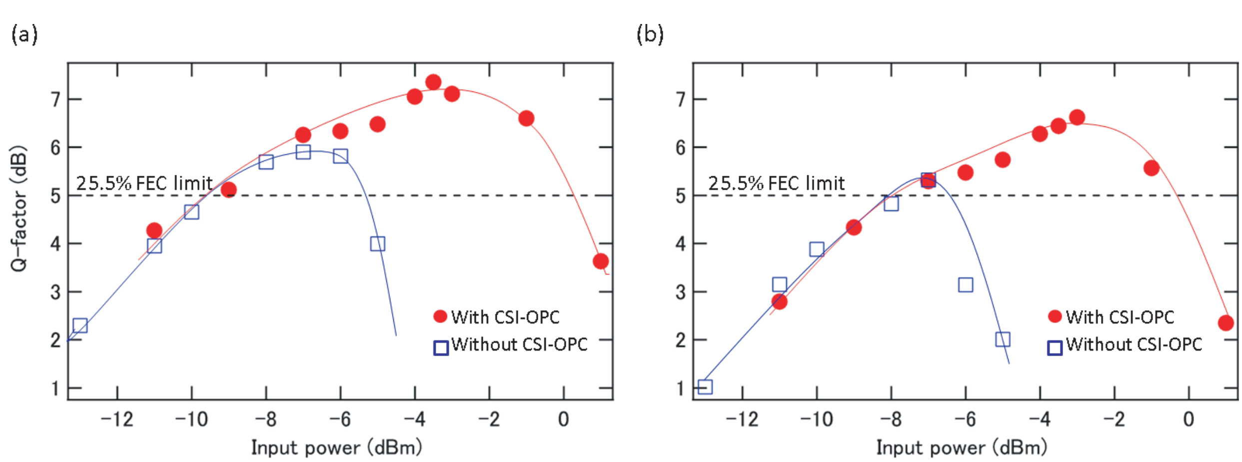

Fig. 4 Comparison of tolerance to nonlinear impairments with and without CSI-OPC device for test signal in ten WDMs after (a) 5,120 km and (b) 6,400 km transmission.

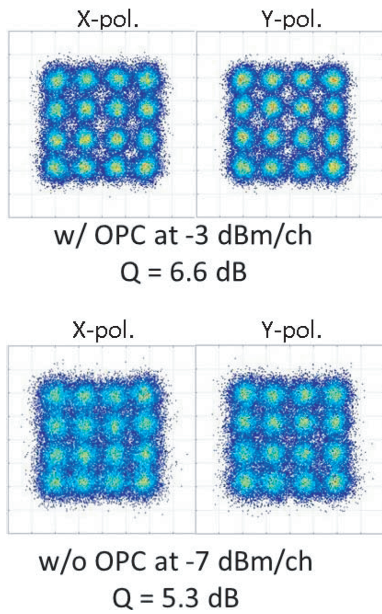

Fig. 5 Constellation diagrams for signal with and without CSI-OPC device after 6,400 km transmission for launched powers of −3 and −7 dBm/ch, respectively.

difference in signal quality between the signals with and without the CSI-OPC device was clearly observed. Improved symbol separation was observed in the measured constellation diagrams for the signal with OPC.

3.3 Transmission Distance Extension by Using CSI-OPC Device

Next, we demonstrated transmission distance extension by using the CSI-OPC device. Figure 6 shows Q factors as a function of transmission distance without and with CSI-OPC for optimal fiber launched powers of −7 and −3.5 dBm/ch, respectively. The Q factors both with and without the CSI-OPC device for a fiber-launched power of −11 dBm are also plotted for a comparison of the performance in a linear regime. This figure shows clear performance improvements by OPC thanks to nonlinearity mitigation. After 8,960 km, which corresponds to applying the CSI-OPC device 28 times, the Q factor with OPC was above the Q limit of 5.0 dB (dashed line). The optimal fiber launched power was increased from −7 to −3.5 dBm/ch so that the transmission distance was extended from 6,400 to 8,960 km. Moreover, there was almost no Q-factor degradation for the link with an input power of −11 dBm/ch after applying the CSI-OPC device more than 16 times. These results demonstrate that the CSI-OPC device can improve the nonlinear tolerance of PDM-16QAM signals without an excess penalty.

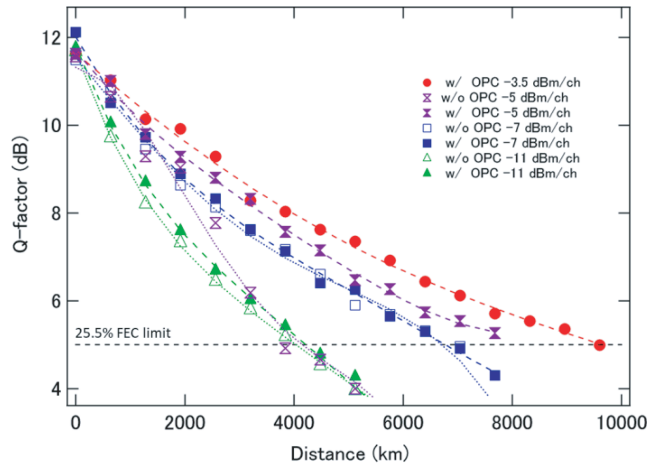

Fig. 6 Q-factors as a function of transmission distance without and with CSI-OPC for launched powers of −11, −7, −5, and −3.5 dBm/ch, respectively.

4. Conclusion

We developed a polarization-independent and reserved-band-less complementary spectral inverted optical phase conjugation device based on a dual-band SH-pumped DFG process using highly efficient PPLN waveguide modules. We demonstrated an enhanced transmission reach from 6,400 to 8,960 km through nonlinearity mitigation and increased the optimal fiber input power of 4 dB using the CSI-OPC device multiple times in a Raman amplifier-based transmission link using 22.5-Gbaud PDM-16QAM 10-channel DWDM signals.

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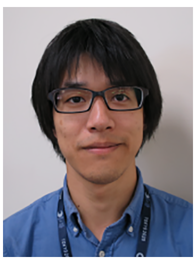

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