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S+C+L-Band WDM Transmission Using 400-Gb/s Real-Time Transceivers Extended by PPLN-Based Wavelength Converter

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Abstract *Extended utilization of S-band based on common-band transceivers employing PPLN-based wavelength converters and distributed Raman amplification was investigated to achieve S+C+L-band WDM transmission above 14 THz. We demonstrated 100-km SSMF transmission of 64-ch 400-Gb/s DP-16QAM real-time signal in the S-band co-propagating with the C+L-band. ©2022 The Author(s)*

Introduction

Efficient use of transmission media is important to support the explosive growth of communications demand while maintaining sustainability. Multi-band WDM transmission is an attractive solution for rapidly and continuously enhancing transmission capacity in deployed optical fibres with greater use of fibre transparent window. In recent years, the capacity enhancement by the extension of the optical bandwidth beyond the C+L-band has attracted renewed attention [1–7]. One of the challenges of multi-band WDM transmission is that every single optical component must be available in the new wavelength bands. Although existing components can be reused in new wavelength bands, performance degradation is inevitable [8]. Wavelength conversion technology is promising to overcome such wavelength constraints. Therefore, as schematically shown in Fig. 1, we have proposed a scheme that enables multi-band WDM transmission without using a new transceiver supporting a new wavelength [9].

However, a concern in realizing multi-band WDM transmission using a wavelength converter is deterioration in transmission performance due to an increase in linear and nonlinear noise induced by the wavelength converter. Among the nonlinear optical media comprising the wavelength converter, a periodically poled lithium niobate (PPLN) waveguide provides highly efficient idler generation over a wide wavelength range covering the entire C-band [10-13]. A PPLN-based wavelength converter (PPLN-WC) was then evaluated and demonstrated to be usable for S-band transmission [14]. In addition to the performance of the wavelength converter, a challenge in the additional use of new wavelength bands is the reduction of transmission distance due to larger transmission losses. When the S-band is used together with

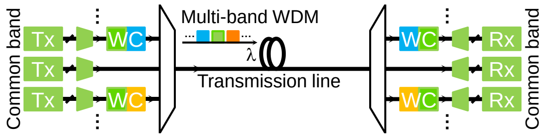

Fig. 1: Schematic of multi-band WDM system using wavelength converter and common band transceivers.

the C- and L-band, the S-band optical signal suffers a much larger attenuation than that of the C- and L-band due to the optical power transition by stimulated Raman scattering (SRS), in addition to the larger linear fibre attenuation.

In this paper, we evaluate a triple-band WDM transmission using a 400-Gb/s real-time transceiver in which an S-band WDM signal generated by wavelength conversion is added to a C+L-band WDM signal. To achieve the generation and reception of the S-band WDM signal based on real-time transceivers, we use PPLN-WC designed and fabricated in NTT labs [11,12]. In addition, we extend the transmission distance by employing distributed Raman amplification to compensate for large fibre attenuation in the S-band and demonstrate 100-km standard single-mode fibre (SSMF) transmission of WDM signal across the S+C+L band over 14 THz.

Experiments

Using the experimental setup shown in Fig. 2, a triple-band WDM transmission was conducted using 400-Gb/s real-time transceiver output as a test channel. 75-GHz spaced 64-ch WDM signals with a C-band range of 191.375–196.100 THz and an L-band range of 186.175–190.900 THz were generated by combining the test channel with other channels of 60-GHz bandwidth-shaping amplified spontaneous emission (ASE) to provide a transceiver output mimic with uniform optical power for each channel. An S-band WDM signal in the range of 196.300–201.025 THz was generated by spectral inversion of the C-band

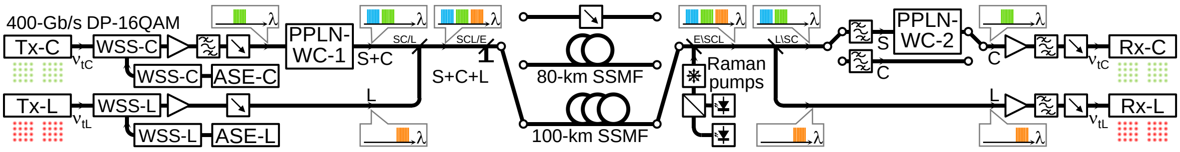

Fig. 2: Experimental setup of triple-band WDM transmission in S+C+L-band.

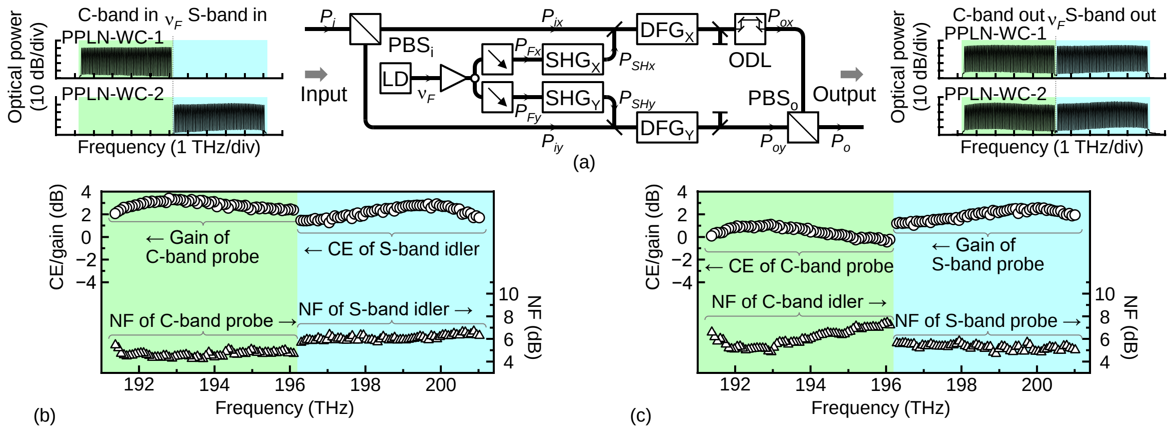

Fig. 3: (a) Configuration diagram of PPLN-WC and optical spectra of input and output signal, (b) CE/gain and NF for C-to-S conversion by PPLN-WC-1, and (c) CE/gain and NF for S-to-C conversion by PPLN-WC-2.

WDM signal by a first PPLN-based wavelength converter (PPLN-WC-1) having a fundamental pump frequency of ν_F = 196.200 THz. A triple-band WDM signal combining the S-, C-, and L-bands was launched into SSMF compliant with G.652.D and the transmitted triple-band WDM signal was divided into each band. The S-band WDM signal was received by the C-band real-time receiver after reverse conversion by a second PPLN-based wavelength converter (PPLN-WC-2). The C- and L-band WDM signals were received by the real-time receiver in each band. To compensate for the increased loss due to SRS, a configuration for distributed Raman amplification was prepared. The outputs of the two pump LDs having wavelengths of 1399 nm and 1410 nm after depolarization were connected to the transmission line to propagate in the opposite direction to the WDM signal. An optical filter with a transmittance of −2.2 dB was inserted prior to the PPLN-WC to eliminate ASE around the fundamental pump wavelength, which induces anomalous amplification. Since it is difficult to separate each band with a low-loss WDM coupler, a C-band WDM signal through PPLN-WC-1 was used for transmission. The additional use of an S-band optical amplifier could solve such a problem but avoided it to take advantage of the lossless conversion characteristics of the PPLN-WC.

The PPLN-WC had a polarization diversity configuration with two differential frequency generators (DFGs) and an optical delay line (ODL) sandwiched by two polarization beam splitters (PBSs) to operate on a polarization multiplexed signal as shown in Fig. 3 (a). The pump light input to the DFG, $\nu_{SH} = 2\nu_F$, was prepared using a 2-W amplified fundamental pump light and a thermally adjusted second harmonic generator (SHG) for maximum efficiency of about −3 dB. The spectral shape of the converted idler output from the DFG was thermally adjusted so that the optical power of the idler was the same between the far-edge and near-edge channels by inputting C-band ASE for the PPLN-WC-1 and S-band ASE extracted from the output of the PPLN-WC-1 for thePPLN-WC-2. The variable optical attenuator (VOA) in front of the SHG was tuned so that the conversion efficiency (CE), which is the optical power ratio of the output idler to the input probe, was unity for both polarizations. Then the optical power of the fundamental pump was P_{Fx} = 29.0 dBm and P_{Fy} = 28.2 dBm for PPLN-WC-1, which was set considering a gain saturation of 2 dB at a 20 dBm input [14], and P_{Fx} = 28.2 dBm and P_{Fy} = 27.4 dBm for PPLN-WC-2. The difference in optical power for each polarization path is mainly due to the loss difference of paths including ODL.

By modifying the method specified in IEC61290-3-1 to idler measurements, the CE and noise figure (NF) were measured using the input and output optical spectra of each PPLN-WC with a sufficiently low optical power input of 0 dBm (–18 dBm/ch) and a reduced bandwidth of 30 GHz, and the characteristics of the PPLN-WC-1 using C-band WDM signal input and the PPLN-WC-2 using S-band WDM signal input were plotted in Figs. 3 (b) and 3 (c). The inter-channel deviation of the CE of PPLN-WC-1 for C-to-S conversion and PPLN-WC-2 for S-to-C conversion was 1.3 dB and 1.0 dB, respectively. The difference in CE between two polarization diversity paths in each channel was less than 1.0 dB. The average

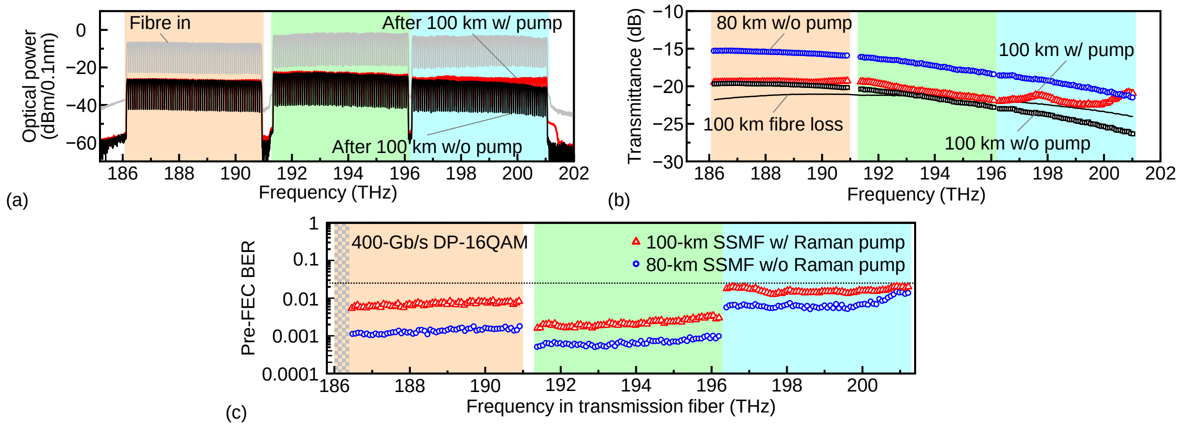

Fig. 4: (a) Optical spectra of triple-band WDM signal for 100-km SSMF transmission, (b) transmittance of each channel, and (c) pre-FEC BER of 400-Gb/s DP-16QAM signal within triple-band WDM signal.

NF of the C-to-S and S-to-C conversion was 7.0 dB and 6.0 dB, respectively. The C-band WDM signal output from the PPLN-WC-1 was amplified with an NF of 5.6 dB.

First, we evaluated 80-km SSMF transmission of the triple-band WDM signal without Raman pumping. The fibre launched optical power of the S-, C-, and L-band were 19.0, 20.6, and 16.0 dBm, respectively. The S-band and C-band WDM signals were output from the PPLN-WC-1 by inputting the C-band WDM signal having an optical power of 20.0 dBm, which is the maximum power in the setup. Under the condition, no significant increase in signal degradation due to nonlinear distortion in the transmission fibre is observed for S-band only transmission [14]. The optical power of the L-band WDM signal was set to reduce the SRS generated in the short wavelength range of the S-band while ensuring a sufficient signal-to-noise ratio. The bit error ratio (BER) before performing forward error collection (FEC) of the test channel when replacing the ASE dummy channel with the transceiver output was measured by counting uncorrected errors in the receiver digital signal processing. The measured pre-FEC BER was plotted as a circle in Fig. 5 (c). Unfortunately, the BER of five channels below 186.5 THz could not be measured because the transceiver does not support them, but there was no anomaly in the optical signal spectrum. In other channels, there was no error in every single plot after FEC-decoding. We confirmed that the increase in transmission loss due to SRS induced by triple-band WDM signal input, together with Rayleigh scattering, gradually degrades the transmission performance as the wavelength decreases in the S-band.

Next, we employed distributed Raman amplification to compensate for large losses in the short wavelength range of the S-band to extend the transmission distance. The fibre launched optical power of the two pumps was set to 220 mW for the 1399-nm pump and 60 mW for the 1410-nm pump to flatten the transmitted S-band WDM signal as shown in Figs. 4 (a) and 4 (b). The BER of 100-km SSMF transmission with the backward distributed Raman amplification was measured at the fibre launched optical power of the same WDM signal as in the previous experiment. The measured pre-FEC BER was plotted in Fig. 4 (c) as a triangle. There was no error in every single plot after FEC-decoding, even though the transmission distance was extended. Since the optical power after the transmission was flattened from 6.0 dB to 1.5 dB by the two Raman pumps, the BER variation in the S-band was reduced.

Conclusions

We demonstrated the tripe-band WDM transmission over 14-THz bandwidth, in which the S-band WDM signal generated and detected through the PPLN-WCs was transmitted after being combined with C- and L-band WDM signals. Using the PPLN-WC with uniform and unity conversion efficiency covering the whole C-band WDM channel, we demonstrated post-FEC error-free 80-km SSMF transmission of all 64 channels of real-time 400-Gb/s DP-16QAM at a 75-GHz spacing in the S-band that co-propagates the C+L-band WDM channels. In addition, enhanced transmission at 100-km SSMF was also demonstrated with no errors by additionally using backward Raman amplification to compensate for large losses in the S-band. It is expected that the transmission distance can be further extended by separately adjusting the optical power of the C-band and S-band WDM signal and increasing the Raman gain.

Acknowledgements

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