U-Band Transmission of Real-Time 200-Gb/s Signal Co-Propagating with C+L-Band WDM Signal

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Abstract: We propose a U-band transmission added to the C+L-band that can mitigate large loss at long wavelength by inter-channel SRS. The benefit is demonstrated in 80-km SSMF transmission of real-time 200-Gb/s DP-QPSK signal. © 2022 The Author(s)

1. Introduction

Efficient use of wavelength bands is important to support explosive growth in communications demand while suppressing deployment of new fiber cables by efficiently using existing ones. Multi-band WDM transmission utilizing an extended wavelength band within a broad fiber transparent window is an attractive solution for rapidly and continuously increasing the transmission capacity in existing fibers. Therefore, in recent years, a capacity increase by extending the wavelength band beyond the C+L-band has attracted renew attention [1-5]. The S- and U-band are the next bands that enjoys lower fiber attenuation. In addition to linear losses, we must consider nonlinear losses induced by inter-channel stimulated Raman scattering (SRS), which is prominent in multi-band WDM transmission bundling many channels over a wavelength range greater than 100 nm. U-band channels that propagate simultaneously with short wavelength channels such as in the S-, C-, and L-band benefit from reduced optical power attenuation due to inter-channel SRS. This results in power transfer from the short wavelength channel to the long wavelength channel, reducing the potential high loss due to bending in some cable. In the C+L-band system in which distributed Raman amplification is introduced, the additional channel in the U-band can be freely arranged since there is no wavelength overlap with Raman pump.

However, transceivers and optical amplifiers for U-band transmission are still challenge. As an extension of the technology introduced in the C- and L- bands, there is a concern that the performance of transceivers deteriorates in the long wavelength region. Laser performance at longer wavelengths may degrade because internal absorption and refractive index change in the semiconductor begin to impair the laser linewidth [6]. High-speed photodiodes, typically based on InGaAs or Ge materials, exhibit a sharp drop in absorption at these wavelengths [7]. For U-band optical amplification, there is a lack of effective rare-earth ions that can be doped in the fiber [8].

In this paper, we propose a multi-band WDM transmission system adding U-band to C+L-band. A wavelength converter [9,10] that allow new wavelength band transmission without using a transceiver for a new wavelength band where performance degradation is a concern, and discrete Raman amplifiers that are a highly competitive solution for U-band amplification [11] are introduced to overcome above issues. We demonstrate single channel U-band transmission of 200-Gb/s DP-QPSK signal in an 80-km standard single-mode fiber (SSMF) co-propagating with C+L-band WDM signal.

2. Experimental Setup and Characteristics of Wavelength Converters and Distributed Raman Amplifiers

Figure 1 shows an experimental setup of U-band transmission. A U-band test channel was prepared by a first wavelength converter from the C-band transceiver output. The U-band test channel was launched into the transmission fiber after a first discrete Raman amplifier booster. After transmission, the U-band test channel was amplified by a second discrete Raman amplifier, reverted to C-band by a second wavelength converter, and received by a C-band real-time transceiver after amplification by an Erbium-doped fiber amplifier (EDFA). C+L-band WDM signal was additionally prepared to verify the effect of inter-channel SRS on the U-band channel. C- and L-band WDM signals within the range of 191.375–196.100 THz and 186.175–190.900 THz was generated by combing transceiver output at 193.4 THz and 188.5 THz and 63 channels of 75-GHz spaced 60-GHz bandwidth spectrally shaped amplified spontaneous emission (ASE) by a wavelength-selective switch (WSS). The C-, L-, and U-band channels were combined before an 80-km SSMF compliant with G.652.D. Channels in each band after transmission were detected by receiver for each band. To construct such a transmission system, a C-to-U converter, a U-to-C converter, two discrete Raman amplifiers were evaluated.

Two wavelength converters based on four-wave mixing [12] consisted of a continuous-wave (CW) parametric pump source, a signal-pump coupler, a polarization diversity looped idler generator including a polarization beam splitter (PBS) and a highly nonlinear fiber (HNLF), and an optical filter to extract the converted signal. 75-m

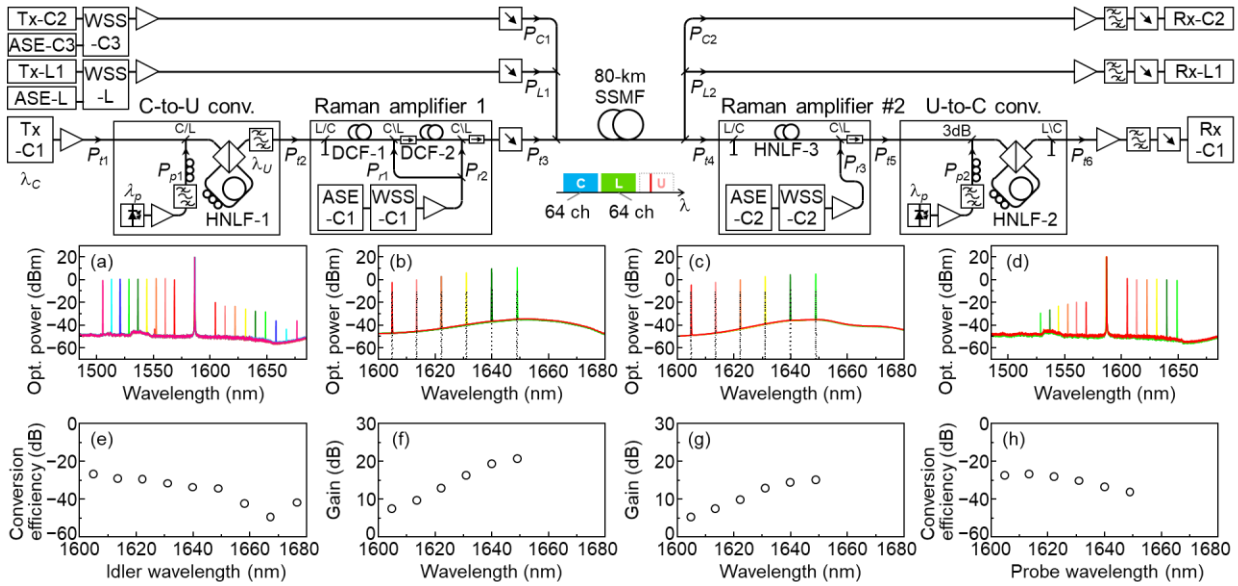

Fig.1 Experimental setup, output optical spectra (0.1-nm resolution) of (a) C-to-U converter, (b) the first discrete Raman amplifier, (c) the second discrete Raman amplifier, and (d) U-to-C converter, conversion efficiency of (e) C-to-U converter and (h) U-to-C converter, and gain of (f) the first discrete Raman amplifier and (g) the second discrete Raman amplifier

HNLF-1 and HNLF-2 having γ ~ 20 /W/km and λ_0 ~ 1587 nm and parametric pump at 188.950 THz (λ_p ~ 1586.62 nm) was used to generate idlers. The parametric pump with optical power of about and linewidth of < 100 kHz was input to the PBS by adjusting the polarization to equally divide to each polarization diversity path. The optical power of the CW parametric pump was adjusted high enough to ignore the effect of the stimulated Brillouin scattering occurring at the HNLFs, then P_{p1} = +24.5 dBm and P_{p2} = +25.1 dBm. The signal-pump couplers were a C/L WDM coupler for the C-to-U converter and a 3-dB coupler for the U-to-C converter. The polarization controller in the loop was adjusted to maximize the converted signal output. Reversible spectral inversion was measured at +10 dBm CW laser output at frequencies of 191.1 to 199.1 THz with the 1-THz interval in the C-to-U converter (Fig. 1 (a)) and 181.8 to 186.8 THz with the 1-THz interval in the U-to-C converter (Fig. 1 (d)), respectively. From the measured optical spectra, the conversion efficiencies of the C-to-U converter and the U-to-C converter was calculated as plotted in Figs. 1 (e) and 1 (h), respectively. It was confirmed that the relatively flat conversion of about −30 dB was obtained in the conversion to and from a wavelength range 1625 to 1650 nm.

Two discrete Raman amplifier were prepared by backward pumping based on ASE from C-band EDF. A dual-stage discrete Raman amplifier with 6-km and 3-km dispersion compensating fibers (DCF-1 and DCF-2) was used for the booster amplifier before the transmission fiber, and a single-stage discrete Raman amplifier with 2-km HNLF having γ ~ 20 /W/km and *D* ~ −50 ps/nm/km @1550 nm was used for the pre-amplifier before the U-to-C converter. As a result of extracting ASE at 1530 nm and 1560 nm with 0.8-nm bandwidth using WSS and amplifying it by a high-power EDFA, the Raman fiber launched power of each wavelength was set to the same, and total $P_{r1} = P_{r2}$ = 28.5 dBm and P_{r3} = 29.0 dBm was launched into DCF-1, DCF-2, and HNLF-3, respectively. As shown in Figs. 1 (b) and 1 (c), the gain of the discrete Raman amplifiers was measured by −10 dBm CW laser output at frequencies of 181.8 to 186.8 THz with the 1-THz interval. The gain of the first discrete Raman amplifier was about 20 dB (Fig. 1 (f)) and that of the second discrete Raman amplifier was about 15 dB (Fig. 1 (g)) at a wavelength range 1625 to 1650 nm. Two different types of discrete Raman amplifiers were used in the experiments, basically due to the limitation of the components available.

3. Experimental Results

We tested U-band transmission by using the evaluated wavelength converters and discrete Raman amplifiers. U-band transmission through 80-km SSMF was evaluated by using real-time 200-Gb/s DP-QPSK signal. +20 dBm amplified single channel C-band transceiver output at 193.1, 194.1, 195.1, and 196.1 THz was converted to 184.8, 183.8, 1821.8 and 181.8 THz by the C-to-U converter, respectively. U-band Fiber launched power of each channel in C-, L- and U-band was set to 0 dBm/ch. The optical spectra before and after the transmission was measured as shown in Fig. 2 (a). By adjusting the fiber launched power of C+L-band WDM channel while keeping the U-band channel power, the transmission loss for each channel was changed as shown in Fig. 2 (b). The reduced loss of 1.5–

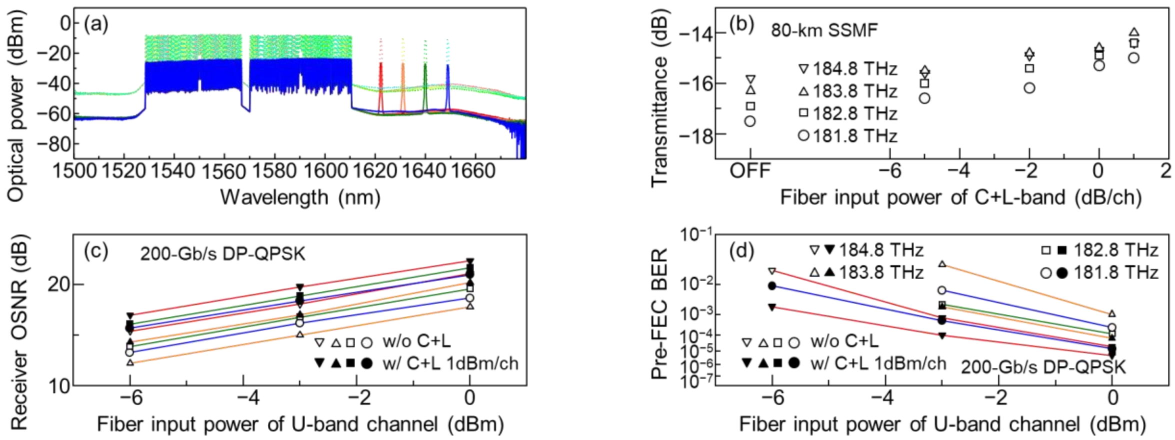

Fig.2. (a) optical spectra before (dotted) and after (solid) 80-km SSMF transmission, (b) transmission loss dependent on C+L-band channel power, (c) receiver OSNR for U-band channels, and (d) pre-FEC BER of U-band channel after 80-km SSMF transmission.

2.5 dB was observed in the large C+L-band fiber launched power of +1 dBm/ch. Then optical signal-to-noise ratio (OSNR) at the receiver of test channel in U-band was measured and pre-FEC bit-error ratio were counted by uncorrected error at the receiver digital signal processing. Comparing the U-band channel was only transmitted, the receiver OSNR was improved approximately 2.0 dB by adding the C+L-band channels as shown in Fig. 2 (c). BER was also improved by adding the C+L-band channels as shown in Fig. 2 (d). No error after FEC decoding was observed in each plot in Fig. 2 (d). OSNR penalty between with and without U-band channel was not observed in the C- and L-band test channels.

4. Conclusions

We proposed and demonstrated U-band transmission co-propagating with C+L-band WDM signal. Using the wavelength converters and discrete Raman amplifiers, post-FEC error-free 80-km SSMF transmission of single channel real-time 200-Gb/s DP-QPSK signal in the U-band was achieved. Furthermore, it was confirmed that co-propagation with the C+L-band WDM channel improves the U-band transmission performance. In this experiment, it is considered that the gain in the U band by inter-channel SRS was high because of the U-band single-channel transmission due to the limitation of the performance of the wavelength converter, but there is no doubt that the gain can be obtained even by multi-channel transmission. By using a wavelength converter capable of high-efficiency conversion such as periodically poled lithium niobate waveguide [10] to be designed to U-band conversion, it is expected that the transmission distance can be extended, and the characteristics of each channel can be flattened due to the relaxed level diagram. The U-band transmission in addition to C+L-band is promising because the degradation on C+L-band channels can be improved by introducing distributed Raman amplification.

5. Acknowledgements

This paper is partly based on results obtained from a project carried out by Fujitsu Limited, JPNP20017, commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

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