Over 100-Tbit/s Ultra-wideband Wavelength Division Multiplexed Transmission Technologies for Future Optical Transport Network Systems

Fukutaro Hamaoka, Kohei Saito, Akira Masuda, Hiroki Taniguchi, Takeo Sasai, Masanori Nakamura, Takayuki Kobayashi, and Yoshiaki Kisaka

Abstract

This article reviews trends in ultra-wideband wavelength-division multiplexing (WDM) transmission techniques for expanding the capacity of optical transmission systems. It also presents NTT's recent research and development results on ultra-wideband WDM transmission for over 100-Tbit/s transmission capacities in a triple-band (S, C, and L bands) WDM configuration.

Keywords: digital coherent, wavelength division multiplexing, digital signal processing

1. Introduction

To cope with the rapid increase in communication traffic, it is necessary to increase the transmission capacity per optical fiber while reducing the cost per bit of optical transmission systems. Innovative technologies, such as wavelength-division multiplexing (WDM) transmission with optical amplifiers and digital coherent technology with digital signal processing (DSP) [1], have continuously been expanding the system capacities for optical transmission. DSP application-specific integrated circuits (ASICs) for digital coherent technology support multi-rate and multi-modulation formats to meet the demand for multiple applications: long-haul, metro, and short-reach (particularly datacenter interconnects) networks. For example, a DSP-ASIC can execute ~32-GBaud polarization-division multiplexed (PDM) quadrature amplitude modulation (QAM) formats with modulation orders from 4 to 16 for from 100 to 200 Gbit/s/carrier [2]. Up to 600-Gbit/s/carrier with 64QAM transmission experiments have also been reported with a real-time transponder including a 64-GBaud-class DSP-ASIC [3]. NTT has recently developed a cutting-edge DSP and an optical device supporting 1.2 Tbit/s/carrier with 140-GBuad-class coded 64QAM for digital coherent systems [4].

To further increase system capacity, expanding the WDM bandwidth is effective along with high spectral efficiency (SE) signals with digital coherent technology using high-order QAM formats. A transmission of 102.3-Tbit/s with PDM-64QAM signals has been demonstrated under the 11.2-THz dual-band (C and L bands) WDM condition with an SE of 9.1 bit/s/Hz [5]. NTT has also successfully demonstrated the first ever greater than 150-Tbit/s transmission with 272-channel PDM-128QAM signals under the 13.6-THz triple-band (S, C, and L bands) WDM condition with an SE of 11.05 bit/s/Hz [6]. Both experiments were conducted using the offline evaluation technique in which DSP is carried out on workstations for transmitted and captured received signals. The offline evaluation enables detailed signal analysis of DSP methods toward ASIC implementation.

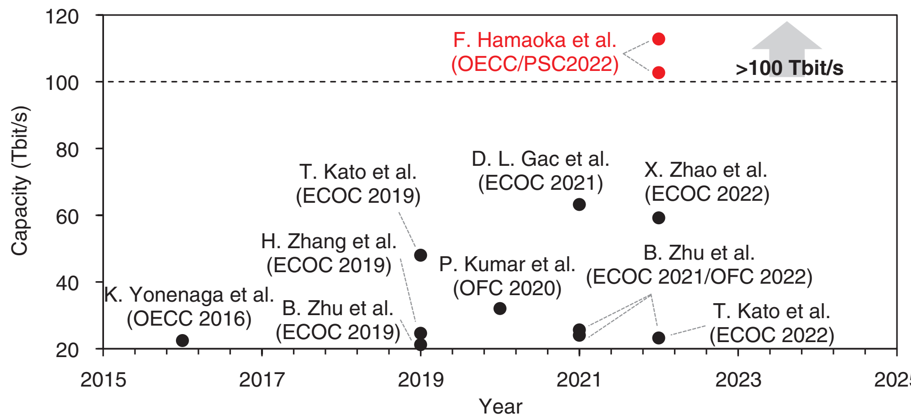

Fig. 1. Trends in capacity growth in digital coherent experiments for real-time transmission with DSP-ASIC-integrated optical transponders.

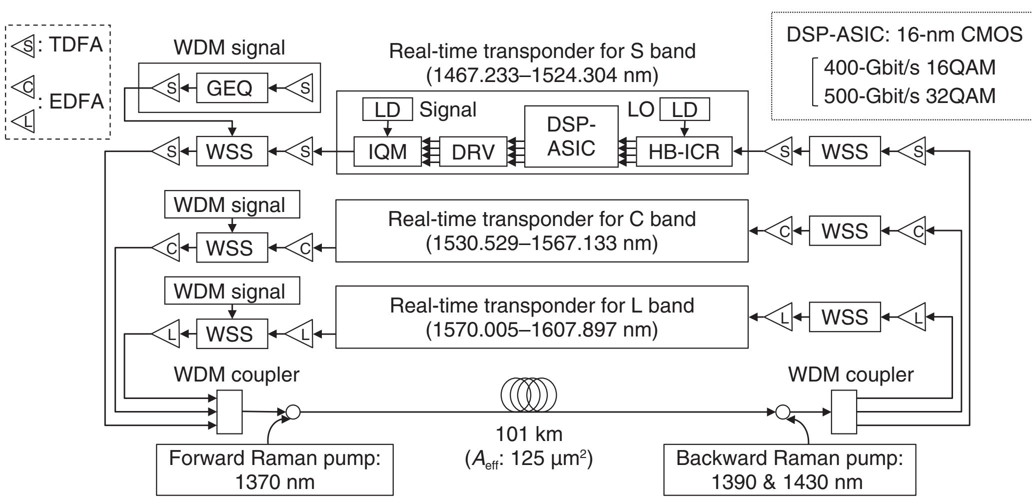

Fig. 2. Experimental setup for triple-band WDM transmission with DSP-ASIC-integrated real-time optical transponders.

In this article, we present real-time triple-band transmission with a WDM bandwidth of 16.95 THz using DSP-ASIC-integrated optical transponders. We transmitted total capacities of 102.7 and 112.8 Tbit/s using 226-channel WDM signals with 400-Gbit/s PDM-16QAM and 500-Gbit/s PDM-32QAM [7]. As can be seen in **Fig. 1**, we achieved, for the first time, over 100-Tbit/s capacity in real-time transmission experiments.

2. Experimental setup for ultra-wideband WDM transmission using DSP-ASIC-integrated optical transponders

Figure 2 shows the setup for triple-band WDM transmission experiments with real-time optical transponders. We used three real-time optical transponders having DSP-ASICs based on 16-nm complementary metal oxide semiconductor (CMOS) technology [3, 8]. The transponders were also implemented driver (DRV) amplifiers, a lithium niobate in-phase and quadrature modulator (LN-IQM), and a high-bandwidth intradyne coherent receiver (HB-ICR). Signal and local oscillator (LO) laser diodes

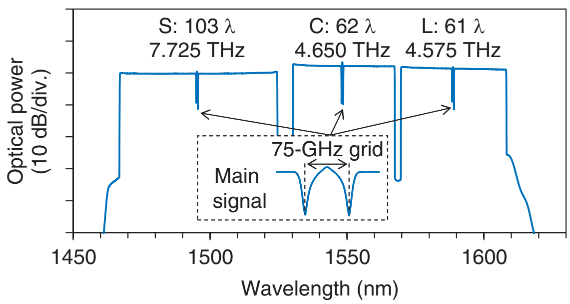

Fig. 3. WDM signal spectra of 16.95-THz bandwidth.

(LD) sources were external cavity lasers for the S band and integrable tunable laser assemblies for the C and L bands. The modulation formats of the main signal were 67-GBaud PDM-16QAM with a net rate of 400 Gbit/s and 66-GBaud PDM-32QAM with a net rate of 500 Gbit/s, which were generated in the optical transponder for each WDM band. The carrier frequency of the main signal was set to 1467.233–1524.304 nm in the S band, 1530.529–1567.133 nm in the C band, and 1570.005–1607.897 nm in the L band.

The WDM signals in the S, C, and L bands were generated using amplified spontaneous emissions from the thulium-doped fiber amplifiers (TDFAs) and erbium-doped fiber amplifiers (EDFAs). The power level of the WDM signal was equaled using a gain equalizer (GEQ) on the basis of flexible-grid wavelength selective switches (WSSs) with liquid crystal on silicon (LCOS). TDFAs for the S band and EDFAs for the C and L bands were used in this experiment. The main signal from the real-time optical transponder and WDM signal for each band were multiplexed in a LCOS-based flexible-grid WSS. The WDM grid in this experiment was set to 75 GHz. The WDM signals in the S, C, and L bands were then multiplexed in a WDM coupler with a total bandwidth of 16.95 THz (7.725, 4.650, 4.575 in the S, C, and L bands, respectively), as shown in **Fig. 3**. The total number of WDM signals was 226 channels (103, 62, and 61 channels in the S, C, and L bands, respectively). The triple-band WDM signal was transmitted through the transmission line of a 101-km large-core low-loss fiber, which is compliant with ITU-T (International Telecommunication Union - Telecommunication Standardization Sector) G.654.E, with an effective area (A_{eff}) of 125 μm^2. We used a forward (FW)-pumped distributed Raman amplifier (DRA) at a wavelength of 1370 nm and a backward (BW)-pumped DRA at 1390 and 1430 nm.

The triple-band WDM signal was divided into each S-, C-, and L-band WDM signal after 101-km optical fiber transmission. The WDM signals were then amplified using a TDFA for the S band and EDFAs for the C and L bands at the receiver side to compensate for the transmission losses. After filtering the main signal for each S, C, and L band using a LCOS-based flexible grid WSS, the signal was coherently detected with the HB-ICR with the optical LO. Finally, the received signal was equalized, demodulated, and decoded in the DSP-ASIC [3].

3. Experimental results of over 100-Tbit/s real-time transmission

In the ultra-wideband WDM configuration, inter-band stimulated Raman scattering (SRS) affects the WDM signals. A nonlinear interaction is caused by inter-band SRS in bands with a gap of around 100 nm for ultra-wideband transmission systems; inter-band SRS causes a signal power transition from S- to L-band signals in triple-band transmissions [6]. Therefore, we evaluated the effect of inter-band SRS with the 16.95-THz triple-band WDM configuration. The fiber loss at 101 km and transmission loss with inter-band SRS are shown in **Fig. 4**. The signal-power transition was mainly observed from the S band to the L band.

Figure 5 shows the experimental results in 101-km real-time triple-band WDM transmission. The FW- and BW-pumped DRA were applied for the transmission line to compensate for the excess power loss in the S band caused by the inter-band SRS. As Fig. 5(a) shows, the WDM signal power in the S band was drastically increased by the Raman amplifiers with sufficient Raman amplification gain. To evaluate the signal performance, we used the pre-forward error collection (FEC) quality (Q) margin, which is defined by the difference between the measured pre-FEC Q factor in the experiments and the required pre-FEC Q factor to achieve an error-free post-FEC bit error rate (BER). We observed that the pre-FEC Q margins of all measured 226-channel WDM signals showed more than zero, as shown in Fig. 5(b). We also confirmed that the post-FEC BER of all signals were error-free in this case. That is, in this setup, we achieved 112.8-Tbit/s (= 500 Gbit/s × 224 λ + 400 Gbit/s × 2 λ) transmission using real-time optical transponders.

The long-term signal performance under the 16.95-THz triple-band WDM condition was evaluated

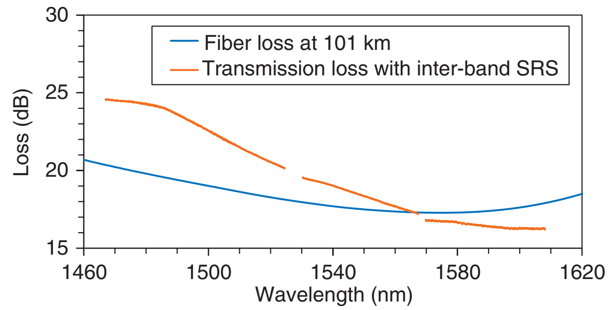

Fig. 4. 101-km fiber loss and transmission loss with inter-band SRS.

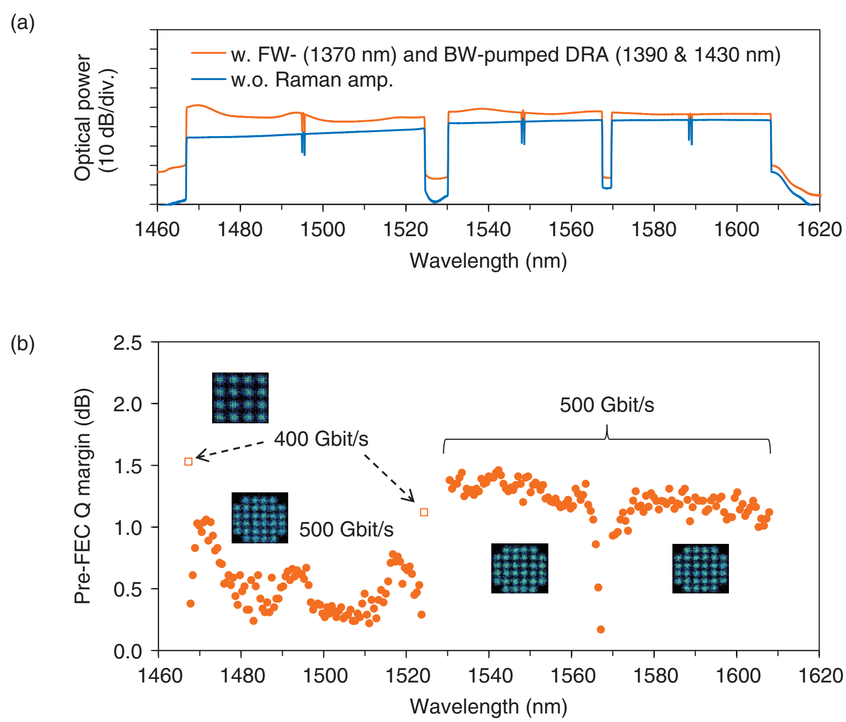

Fig. 5. Experimental results: (a) WDM optical spectra with and without FW- and BW-pumped DRA and (b) pre-FEC Q margin after 226-channel triple-band WDM transmission through 101-km fiber transmission with FW- and BW-pumped DRA.

during transmission in 101-km fiber when applying the FW- and BW-pumped DRA. As shown in **Fig. 6**, we obtained stable signal-transmission performance at the center channels of S-, C-, and L-band signals with small pre-FEC Q-factor fluctuations of less than or equal to 0.036, 0.025, and 0.037 dB, respectively, within continuous measurements for 60 min. During the stability test, we also confirmed error-free operation after FEC decoding.

4. Conclusion

We reviewed trends in ultra-wideband WDM transmission techniques to expand the capacity of optical transmission systems and NTT's latest R&D in the field. With the combination of ultra-wideband WDM transmission and digital coherent technology using the state-of-the-art DSP-ASIC, we successfully demonstrated the first ever over 100-Tbit/s real-time transmission. This technology is promising for use in

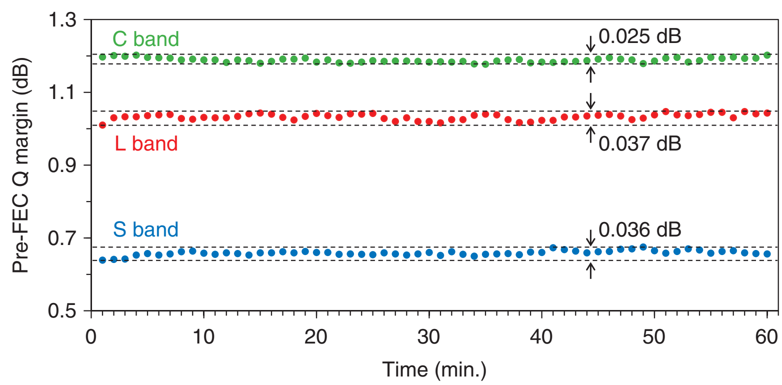

Fig. 6. Stability test for signal performance at center channels of S-, C-, and L-band signals with FW- and BW-pumped DRA during 101-km fiber transmission under 16.95-THz triple-band WDM condition within continuous measurements for 60 min.

future optical transport network systems.

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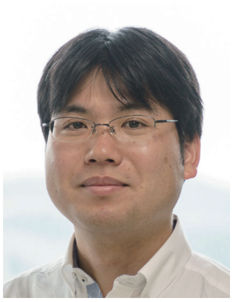

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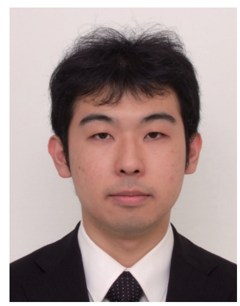

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