Ultra-Wideband WDM Transmission Technologies for >100-Tb/s Optical Transport Network Systems

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***Abstract*—This paper reviews trends in optical transmission with ultra-wideband WDM systems. It also presents our recent ultra-wideband WDM transmission demonstration of >100-Tb/s transmission capacity with the bandwidth of >10 THz in a triple-band WDM configuration.**

Keywords—digital coherent, wavelength division multiplexed transmission, digital signal processor

I. Introduction

To cope with the rapid growth in communication traffic, the capacity of optical transmission systems has continued to increase, aided by breakthroughs such as wavelength-division multiplexing (WDM) and digital coherent technologies that fully utilize the capability of light waves through powerful digital signal processing (DSP) [1]. Digital coherent technologies with DSP application-specific integrated circuits (ASICs) support multi-rate and multi-modulation formats to meet the demands of multiple applications including long-haul, metro, and short-reach networks. For example, the technology generation in DSP ASICs for up to 200 Gb/s/carrier could handle polarization-division multiplexed (PDM) quadrature amplitude modulation (QAM) formats at the symbol rate of ~32-GBaud with modulation orders of between 4, 8, and 16 for 100, 150, and 200 Gb/s/carrier, respectively [2, 3]. Using higher-order modulation formats, 600-Gb/s/carrier transmission experiments using 64QAM have been reported with real-time transponders incorporating 64-GBaud-class DSP-ASICs [4–6]. We have demonstrated net data-rate 1-Tb/s transmission with dual 500-Gb/s PDM-32QAM signals over 1122 km and net data-rate 1.2-Tb/s transmission with dual 600-Tb/s PDM-64QAM signals over 336.6 km through field-deployed G.654.E fiber [5, 7]. Furthermore, a cutting-edge DSP for supporting up to 1.2 Tb/s/carrier with 140-GBuad-class coded 64QAM for digital coherent systems has been announced [8]. In addition to technical approaches to increase channel capacity, multiple-band WDM technologies have been intensively studied to enlarge the capacity of optical transport network systems [9]. Many high-capacity optical transmissions of over 100 Tb/s have been reported for single-mode fiber (SMF) transmission experiments with offline DSP in dual- and triple-band WDM configurations (e.g., [10–14]). Recently, we reached over 100-Tb/s capacity with DSP-ASIC-integrated real-time optical transponders under triple-band configuration with a WDM bandwidth of 16.95 THz [15].

This paper provides an overview of the trends in capacity growth in digital coherent experiments with DSP-ASIC-integrated optical transponders. We also present our recent research results on >100-Tb/s real-time transmission with triple-band WDM configuration.

II. Trends in Capacity Growth

Figure 1 shows the trends in capacity growth in digital coherent experiments for real-time transmission with DSP-ASIC integrated optical transponders. In real-time transmission experiments, 20-Tb/s-class WDM signals have been transmitted in the C band using optical transponders with DSP ASICs [16–21]. To further enlarge the capacity per optical fiber, ultra-wideband WDM transmission technologies using multiple bands are essential while increasing the capacity per WDM channel with higher symbol rates and modulation order formats [9]. WDM-bandwidth-extension techniques have been applied and demonstrated for real-time transmissions in the super-C band [22], dual-band (the C and L bands) [23, 24], and triple-band (the S, C, and L bands) [15, 25, 26].

Recently, we successfully demonstrated 112.8-Tb/s real-time transmission under the 16.95-THz triple-band 226-channel WDM condition with DSP-ASIC-based optical transponders for S-, C-, and L-band signals; we achieved the first-ever >100-Tb/s single-mode fiber capacity with the highest WDM bandwidth in real-time transmission experiments [15]. Forward (FW) and backward (BW) pumped distributed Raman amplifiers (DRAs) were applied to compensate for the excess transmission loss for the S-band caused by inter-band stimulated Raman Scattering (SRS).

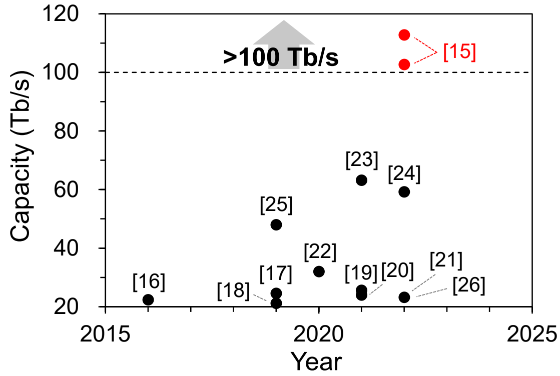

Fig. 1. Trends in capacity growth in digital coherent experiments for real-time transmission with DSP-ASIC-integrated optical transponders.

III. >100-Tb/s REAL-TIME TRANSMISSION

We have demonstrated a single mode capacity of 112.8-Tb/s with 16.95-THz triple-band WDM transmission using DSP-ASIC-integrated optical transponders [15]. This section briefly describes the experimental setup and discusses the results.

The experimental setup is shown in Fig. 2 for triple-band WDM transmission experiments with real-time optical transponders. We used three real-time optical transponders having DSP-ASICs [7] based on 16-nm complementary metal oxide semiconductor (CMOS) technology [27]. The transponders also have 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 (LD) sources were external cavity lasers for the S band and integrable tunable laser assemblies for the C and L bands. The carrier frequency of the main signal was set to 1467.233–1524.304 nm (196.675–204.325 THz) in the S band, 1530.529–1567.133 nm (191.300–195.875 THz) in the C band, and 1570.005–1607.897 nm (186.450–190.950 THz) in the L band. The modulation formats of the main signal were 67-GBaud PDM-16QAM with a net rate of 400 Gb/s and 66-GBaud PDM-32QAM with a net rate of 500 Gb/s, which were generated in the optical transponder for each WDM band. The WDM signals were emulated by amplified spontaneous emissions from the thulium-doped fiber amplifiers (TDFAs) for the S band and erbium-doped fiber amplifiers (EDFAs) for the C and L bands. The main signal from the real-time optical transponder and the WDM signal for each band were multiplexed assuming a 75-GHz WDM grid in an LCOS-based flexible-grid wavelength-selective switch (WSS). The S-, C-, and L-band WDM signals were then multiplexed in a WDM coupler. The triple-band WDM signal has a bandwidth of 16.95 THz with WDM signals of 226 channels (7.725, 4.650, and 4.575 THz with 103, 62, and 61 channels in the S, C, and L bands, respectively).

The ultra-wideband WDM signal was transmitted through the transmission line of a 101-km large-core low-loss fiber compliant with ITU-T G.654.E having an effective area (A_{eff}) of 125 μm^2. The fiber input power in the S, C, and L bands were 18.51, 19.47, and 19.52 dBm, respectively; the total fiber input power of the triple-band WDM signal was 23.96 dBm. We used a FW-pumped DRA at a wavelength of 1370 nm and a BW-pumped DRA at 1390 and 1430 nm. After 101-km optical fiber transmission, the triple-band WDM signal was divided into each S-, C-, and L-band WDM signal. 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 [7].

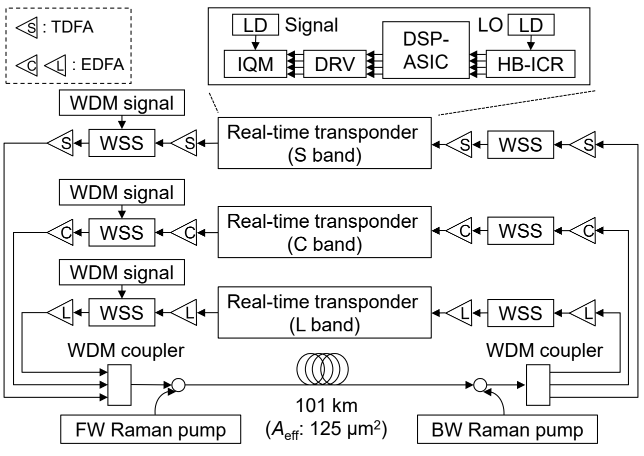

Fig. 2. Experimental setup for triple-band WDM transmission with DSP-ASIC-integrated real-time optical transponders.

The experimental results are shown in Fig. 3 over 101-km real-time triple-band WDM transmission. We applied the FW- and BW-pumped DRA for the transmission line to compensate for the excess power loss in the S band caused by the inter-band SRS. As shown in Fig. 3(a), the WDM signal power in the S band was well compensated by the Raman amplifiers with sufficient Raman amplification gain. We evaluated the signal performance using the pre-forward error collection (FEC) 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). As Fig. 5(b) shows, The pre-FEC Q margins of all measured 226-channel WDM signals showed more than zero. 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-Tb/s (= 500 Gb/s × 224 λ + 400 Gb/s × 2 λ) transmission using real-time optical transponders with the WDM bandwidth of 16.95 THz.

IV. CONCLUSION

We reviewed trends in capacity growth in ultra-wideband transmission technologies based on DSP-ASIC-integrated optical transponders. We also introduced our work on 112.8-Tb/s real-time transmission experiment over 101-km SMF with 16.95-THz triple-band WDM configuration. Ultra-wideband WDM technology with high-speed, high-capacity transponders is promising for future optical transport network systems toward over 100 Tb/s.

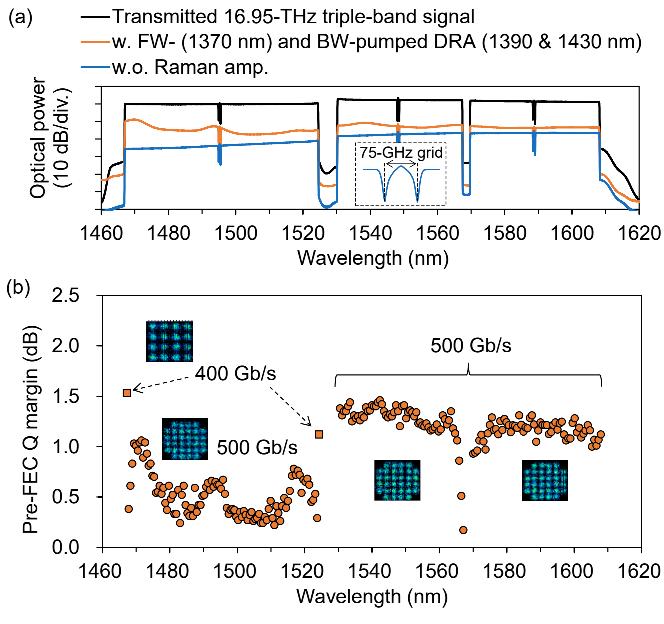

Fig. 3. Experimental results of 112.8-Tb/s real-time transmission: (a) WDM optical spectra of transmitted WDM signal and after 101-km transmission with and without FW- and BW-pumped DRA and (b) pre-FEC Q margin after 226-channel triple-band WDM transmission through 101-km fiber transmission with FW- and BW-pumped DRA.

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