S+C+L WDM Coherent Transmission with >1-Tb/s/λ Signals

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Abstract: Ultra-wideband wavelength-division-multiplexed (WDM) transmission is an essential technology to achieve >100-Tb/s single-mode-fiber (SMF) capacity. This paper overviews the status of high-capacity SMF transmission and provides our research results using high-symbol-rate coherent channels under a triple-band WDM configuration.

1. Introduction

Wavelength division multiplexed (WDM) transmission with digital coherent channels has helped increase system capacity per fiber to handle the rapid growth of communication traffic [1]. Increasing the capacity per wavelength to accommodate next-generation high-speed client signals is also necessary to develop a cost-effective optical transmission system. Applying high-symbol-rate quadrature-amplitude-modulation (QAM) signals is an effective way to decrease the number of transceivers needed to fill the WDM band, thereby reducing system complexity [2, 3]. The high-symbol-rate approach can increase the bitrate per channel with high-order QAM signals. However, the improvement in spectral efficiency (SE) with high-order QAM is limited by noise and nonlinear distortion in optical transmission links. Therefore, ultra-wideband (multiple-band) WDM transmission technologies are also essential to further increase the capacity per single-mode fiber (SMF).

This paper reviews trends in ultra-wideband WDM transmission with an SMF capacity exceeding 100-Tb/s. We also introduce our recent research results on combining ultra-wideband WDM optical transmission technology with >1-Tbps/λ-class high-symbol-rate technology [4].

2. Trends in capacity growth of SMF transmission

Since the research on digital coherent technology started strongly, many experiments have been reported under ultra-wideband WDM configurations in dual [5–8], triple [4, 9–17], quad [18, 19], and five [20, 21] bands. As Fig. 1(a) shows, >100-Tb/s SMF capacity with 128QAM [5] and 64QAM [6] signals were demonstrated using all-Raman amplification in the C+L bands. A net bitrate of 115-Tb/s was then reported applying 100-nm-bandwidth semiconductor optical amplifiers in the S+C+L bands [9]. We applied an ITU-T G.652.D compliant fiber with low-water peak characteristics to a 13.6-THz triple-band transmission to effectively amplify S-band signals by using a backward-distributed Raman amplifier (DRA) [10], achieving a net bitrate of 150.3-Tb/s with WDM power optimization considering inter-band stimulated Raman scattering (SRS) [22]. We demonstrated, for the first time, >100-Tb/s real-time SMF transmission using 70-GBaud-class optical transponders under a 16.95-THz triple-band WDM configuration [15]. Recently, the highest net bitrate of 244.3 Tb/s in the S+C+L bands [14] and 285 Tb/s in the E+S+C+L bands have been demonstrated using 19.825- and 27.425-THz WDM bandwidth, respectively.

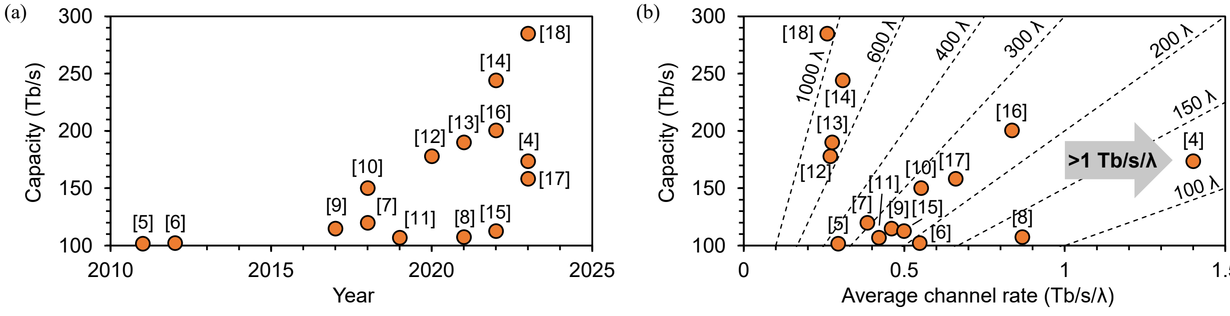

Fig. 1. Trends in ultra-wideband WDM transmission experiments: (a) capacity growth of >100-Tb/s SMF transmission and (b) capacity versus average channel rate per wavelength in which contours indicate the number of WDM channels. Capacity and average channel rate were estimated after FEC decoding for [4, 5–7, 9–11, 13–15, 18] and were estimated from GMI for [8, 12, 16, 17].

From Figure 1(b), we can identify the required channel rate and number of channels needed to achieve a capacity of >100 Tb/s in SMF. Approaches utilizing low-symbol rate with high-order QAM, such as ~25-GBaud 64/256/1024QAM, have achieved high capacity between 178 and 285 Tb/s in SMF transmission [12–14, 18] with a high SE between 10.3 and 12.3 b/s/Hz. However, they require a substantial number of more than 600 WDM channels with >250-Gb/s/λ channel rate. A higher symbol rate of 95 and 70 GBaud with probabilistically constellation-shaped (PCS) 64QAM respectively showed an SMF capacity, estimated from generalized mutual information (GMI), of 107.6 Tb/s using 124 channels with an average channel rate of 867.7 Gb/s/λ in the C+L bands [8] and a capacity of 200.5 Tb/s using 240 channels with 835.4 Gb/s/λ in the S+C+L bands [16]. We applied a high-symbol rate technology with the entropy and code-rate optimization scheme [23] to a triple-band WDM transmission. This enabled the highest average channel rate of 1.4 Tb/s/λ in the ultrawide-band transmission, achieving a 173.7-Tb/s SMF capacity using 124 WDM channels of high-symbol-rate 144-GBaud PCS-64QAM [4]. The next section briefly introduces this experiment.

3. Triple-band WDM transmission with high-symbol-rate channels

We transmitted a 173.7-Tb/s SMF capacity using 144-GBaud PCS-64QAM signals with an average net bitrate of 1.4 Tb/s in a triple-band (S, C, and extended L bands) configuration. The experimental results and setup are detailed in our previous study [4]. The main signal in the 150-GHz grid was swept from the center wavelength (frequency) of 1467.233–1524.304 nm (196.675–204.325 THz) in the S band, 1530.529–1566.518 nm (191.375–195.875 THz) in the C band, and 1570.211–1621.157 nm (184.925–190.925 THz) in the extended L band. The total WDM bandwidth is 18.6 THz with 124 channels, as shown in Fig. 2. The transmission line was a 101-km ITU-T G.654.E compliant fiber with large-core, low-loss characteristics having an effective area of 125 μm^2. Thulium-doped fiber amplifiers (TDFAs) for the S band and erbium-doped fiber amplifiers (EDFAs) for the C and extended L bands were used in this experiment. Due to inter-band SRS after triple-band WDM transmission, as shown in the orange line of Fig. 2 and 3, the signal power in the S-band was degraded, and excess power loss was observed in the S-band. Therefore, we selected a fiber with low-water-peak characteristics around 1383 nm [15] to effectively amplify the S-band signals using the forward-pumped DRA at 1370 nm and backward-pumped DRA at 1390 nm and 1430 nm. As seen in the blue line of Figs. 2 and 3, the transmission losses were reduced by the Raman amplifiers with sufficient Raman gain in the S band.

Figure 4 shows the experimental results after a 101-km SMF transmission under an 18.6-THz triple-band WDM configuration with 144-GBd PDM-64QAM signals. We measured normalized generalized mutual information

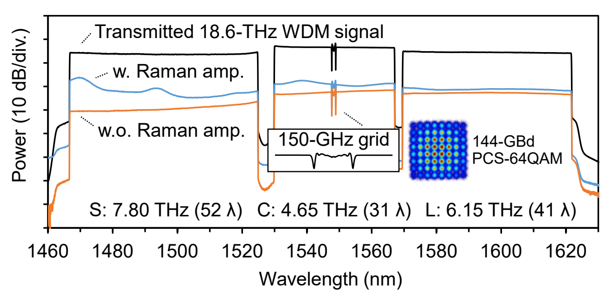

Fig. 2. Optical spectra of transmitted WDM signal and after 101-km transmission with and without Raman amplifiers.

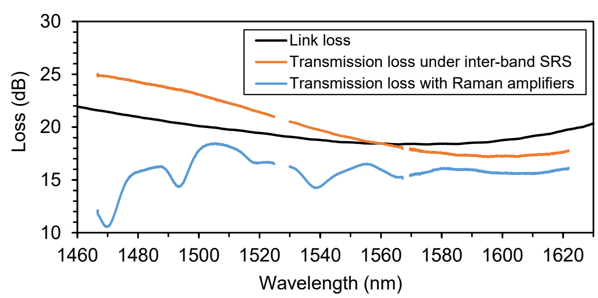

Fig. 3. Wavelength dependencies on (a) 101-km link loss, transmission loss under inter-band SRS, and that with Raman amplifiers.

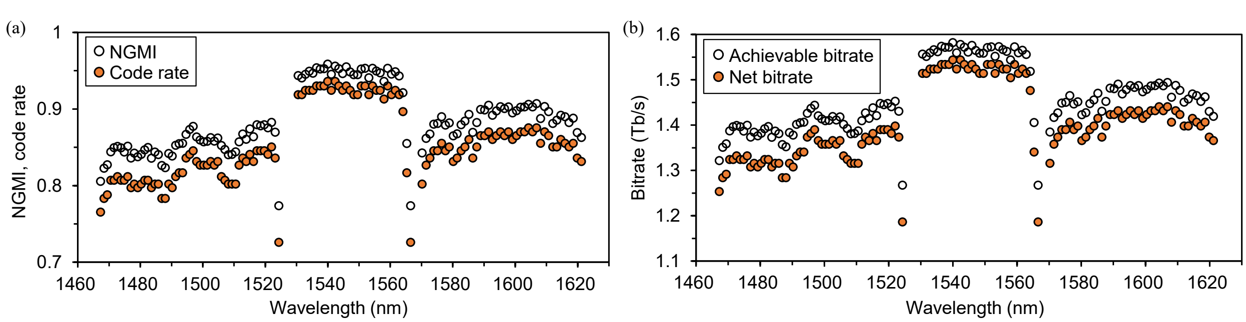

Fig. 4. Experimental results of wavelength dependencies on (a) NGMI and required code rate and (b) achievable and net bitrate after 101-km SMF transmission.

(NGMI) to estimate the achievable bitrate. The total achievable bitrate was 180.6 Tb/s from the NGMI of 124 WDM channels. As shown in Fig. 4(a), signal performance (NGMI) has wavelength dependencies. Thus, we calculated the required code rate on the basis of the rate-adaptive coding technique [23] to optimize the WDM transmission capacity. We estimated the net bitrate after forward error correction (FEC) decoding from the required code rate. The 124-WDM channels of net bitrates were between 1.18 and 1.54 Tb/s/λ; the average net bitrate was 1.4 Tb/s/λ. Therefore, we demonstrated a total net bitrate of 173.7 Tb/s with an SE of 9.33 b/s/Hz after the 101-km transmission.

4. Conclusion

We have reviewed the trends of more than 100-Tb/s SMF transmission using ultra-wideband WDM technologies. Since the research on digital coherent technology started strongly, many experiments have been conducted under dual-, triple-, and quad-band WDM configurations, achieving SMF capacities between 100 to 300 Tb/s. We also introduced our experimental demonstration of a 173.7-Tb/s SMF capacity under an 18.6-THz triple-band configuration in a 150-GHz-grid with 124 WDM channels based on high-symbol rate technology with 144-GBaud PCS-64QAM signals, resulting in an average net bitrate of 1.4 Tb/s/λ. The combination of >1-Tbps/λ-class high-symbol-rate technology and ultra-wideband WDM optical transmission technology is promising to reduce the complexity of future >100-Tb/s-class optical transport network systems.

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