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Dual-Carrier 1-Tb/s Transmission Over Field-Deployed G.654.E Fiber Link Using Real-Time Transponder

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SUMMARY We demonstrated 1-Tb/s-class transmissions of field-deployed large-core low-loss fiber links, which is compliant with ITU-T G.654.E, using our newly developed real-time transponder consisting of a state-of-the-art 16-nm complementary metal-oxide-semiconductor (CMOS) based digital signal processing application-specific integrated circuit (DSP-ASIC) and an indium phosphide (InP) based high-bandwidth coherent driver modulator (HB-CDM). In this field experiment, we have achieved record transmission distances of 1122 km for net data-rate 1-Tb/s transmission with dual polarization-division multiplexed (PDM) 32 quadrature amplitude modulation (QAM) signals, and of 336.6 km for net data-rate 1.2-Tb/s transmission with dual PDM-64QAM signals. This is the first demonstration of applying hybrid erbium-doped fiber amplifier (EDFA) and backward-distributed Raman amplifier were applied to terrestrial G.654.E fiber links. We also confirmed the stability of signal performance over field fiber transmission in wavelength division multiplexed (WDM) condition. The Q-factor fluctuations respectively were only less than or equal to 0.052 dB and 0.07 dB for PDM-32QAM and PDM-64QAM signals within continuous measurements for 60 minutes.

key words: *optical fiber communication, digital coherent transmission, real-time transmission, field transmission*

1. Introduction

Digital signal processing (DSP) and digital coherent techniques have driven an increase in the transmission capacity of optical communication systems. Digital coherent technology has been applied not only to long-haul and metro networks but also to short-reach networks, particularly data-center interconnects. To meet the demand for multiple applications, DSP supports multi-rate and multi-modulation formats. For example, in [1] and [2], DSP application-specific integrated circuits (ASICs) could treat ~32-GBaud polarization-division multiplexed (PDM) quadrature amplitude modulation (QAM) formats with the modulation orders of 4, 8, and 16 for 100, 150, and 200 Gb/s/carrier, respectively. In addition, up to 600-Gb/s/carrier transmission experiments have recently been reported with real-time transponder including 64-GBaud-class DSP-ASIC [3]–[5].

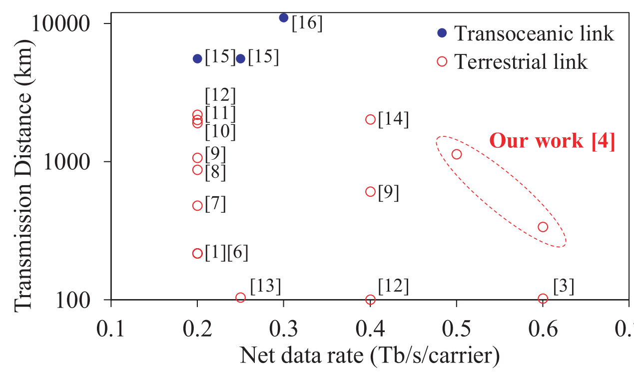

Fig. 1 Recent field experiments using DSP-ASIC-integrated real-time optical transponders.

Field experiments using DSP-ASIC-integrated real-time optical transponders over terrestrial [1], [3], [4], [6]–[14] and transoceanic [15], [16] links are shown in Fig. 1. To expand transmission distance with high-order QAM signals, which require a high optical signal-to-noise ratio (OSNR) and low fiber nonlinearity, large-core low-loss fiber has been deployed in terrestrial links (ITU-T G.654.E, effective area (Aeff): 110 μm^2) [8]–[11], [14] and transoceanic links (ITU-T G.654.D, Aeff: 130 μm^2) [15]. 1-Tb/s-class transmissions of field-deployed G.654.E fiber links have recently been demonstrated using our newly developed real-time transponder [4]; we have demonstrated net data-rate 1-Tb/s transmission with dual 0.5-Tb/s PDM-32QAM signals over 1122 km, and net data-rate 1.2-Tb/s transmission with dual 0.6-Tb/s PDM-64QAM signals over 336.6 km. Shown in Fig. 1, these transmission distances of 1122 and 336.6 km are, to the best of our knowledge, the longest in field experiments using DSP-ASIC-integrated real-time optical transponders with net data-rate > 0.4 Tb/s/carrier. The signals are generated and detected with our newly developed transponder that integrates a DSP-ASIC based on 16-nm complementary metal-oxide-semiconductor (CMOS) technology [17] and a high-bandwidth coherent driver modulator (HB-CDM) based on indium phosphide (InP) technology [18]. The modulation order must be higher than 16 to realize a capacity of >0.4 Tb/s/carrier with the symbol rate of ~64 GBaud. Thus, techniques, e.g., a distributed Raman

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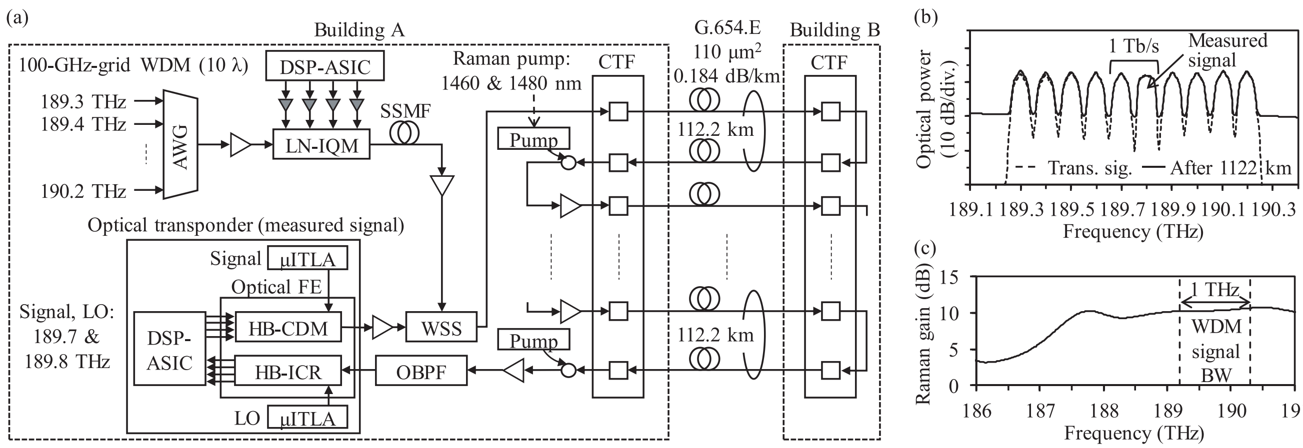

Fig. 2 (a) Setup for field experiments over large-core low-loss G.654.E link, (b) WDM signal spectra output from WSS and after 1122-km transmission, and (c) Raman gain spectra.

amplifier, should be considered to improve the OSNR of transmission links. We applied hybrid EDFA and backward-distributed Raman amplifier to terrestrial G.654.E links for the first time.

In this paper, we present the transmission experiments over field deployed G.654.E fiber links using hybrid EDFA and backward-distributed Raman amplifier. This field transmission using dual-carrier 1-Tb/s-class signal that logically consists of two wavelength signals was demonstrated with our newly developed transponder [4]. We used the dual-carrier signal in order to realize 1-Tb/s-class transmission using commercially available optical transmitter and receiver with the minimum number of sub-carriers. In Sect. 2, the experimental setup are shown for the field experiments. In Sect. 3, we show the results obtained. Record distances of 1122 and 336.6 km for dual-carrier 1- and 1.2-Tb/s transmissions were achieved using the real-time transponder and the hybrid EDFA and backward-distributed Raman amplifier for 112.2-km spans of field-deployed G.654.E fiber links.

2. Experimental Setup

Figure 2(a) shows the setup for our field experiments using NTT Group's terrestrial links. The experimental equipment was placed at building A; building B was only for directly connecting transmission lines. Our newly developed optical transponder consists of the DSP-ASIC based on 16-nm CMOS technology [17], an InP-based HB-CDM [18], high-bandwidth intradyne coherent receiver (HB-ICR), and micro-integrable tunable laser assemblies (μITLAs) for signal and local oscillator (LO) sources. The measured signal was generated in the optical transponder; the electrical signals output from the DSP-ASIC were modulated by the InP-based HB-CDM in the optical frontend (FE) with the optical carrier output from a μITLA. The dual-carrier 1- and 1.2-Tb/s signals logically consisted of two 500- and 600-Gb/s signals. The modulation formats of the net rate 500- and 600-Gb/s signals were Nyquist pulse shaped 66-GBaud PDM-32QAM and 69-GBaud PDM-64QAM, respectively.

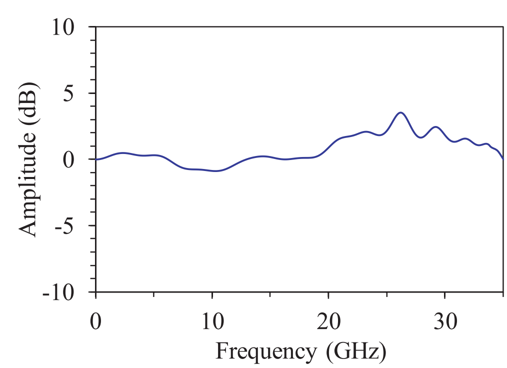

Fig. 3 Frequency response at transmitter side of optical transponder.

It should be noted that we prepared only one prototype of the optical transponder thus the carrier frequency was swept to measure the characteristics of the 1- and 1.2-Tb/s dual-carrier signals. The bit streams of the signals were sufficiently long pattern based on pseudo-random binary sequence. The HB-CDM package consists of an InP-based PDM IQ modulator (IQM), driver integrated circuits (ICs), RF package, and connection wires to achieve high E/O bandwidth and characteristics. The HB-CDM has a 3-dB E/O bandwidth of over 50 GHz [18]. Figure 3 shows the frequency response at the transmitter side of the optical transponder. The frequency amplitude and phase response at the transmitter side were compensated by using an optimized fixed equalizer based on a precise calibration scheme [19]. The carrier frequency of the measured signal was set to 189.7 and 189.8 THz. The 100-GHz-spaced ten optical carriers with frequencies from 189.3 to 190.2 THz were modulated by a lithium niobate (LN) IQM with electrical signals from a DSP-ASIC after being multiplexed by an arrayed-waveguide grating (AWG). The wavelength-division multiplexing (WDM) signal was input into an 11-km standard single mode fiber (SSMF) to decorrelate signals. The measured and WDM signals were multiplexed by a wavelength selective switch (WSS).

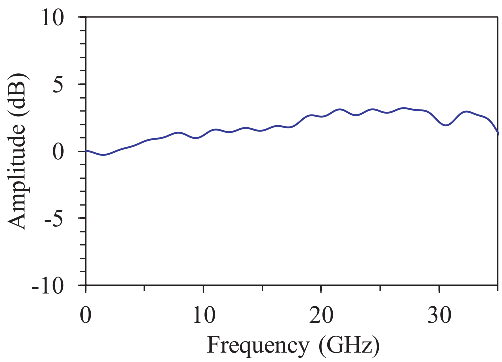

Fig. 4 Frequency response at receiver side of optical transponder.

The WDM signal (shown in dashed line of Fig. 2(b)) was input into field-deployed large-core low-loss G.654.E fiber (Aeff: 110 μm^2) between buildings A and B. In building B, the transmission lines were connected by only patch fiber cables. The average optical loss of the transmission link was 20.7 dB per 112.2-km span (0.184 dB/km) at 1580 nm, which includes losses of field-deployed G.654.E fiber, fusion splice points of the field-deployed fiber, cable termination frames (CTFs), and intra-building fibers. After WDM signal transmission for each 112.2-km span, the optical loss was compensated for by hybrid EDFA and backward-distributed Raman amplifier with pump lasers at 1460 and 1480 nm. As shown in Fig. 2(c), we confirmed wide-band Raman gain spectra with over 4 THz in L-band using the Raman pumps. The flat Raman gain was obtained in the tested WDM signal bandwidth of 1 THz. By adequately designing the pump wavelength, flat Raman gain spectra can be achieved for field-deployed G.654.E fiber.

The measured signal in the WDM signals (shown in solid line of Fig. 2(b)) was filtered by an optical band-pass filter (OBPF) after transmitting the field-deployed optical fiber link. We individually measured the characteristics of the dual-carrier signals at 189.7 and 189.8 THz by sweeping the carrier frequency. Then, the measured signal was coherently detected by an ICR in the optical FE with the optical LO output from a μITLA. Finally, the received signal was equalized, demodulated, and decoded in the DSP-ASIC consisting of blocks of the fixed equalizer for the precise calibration of the received signal, an adaptive equalizer for linear equalization and polarization de-multiplexing, a carrier phase recovery, and an LDPC-based soft-decision FEC. Figure 4 shows the frequency response at the receiver side of the optical transponder. An optimized fixed equalizer based on the precise calibration scheme [19] also compensated the frequency amplitude and phase response at the receiver side. As shown in Figs. 3 and 4, the optical transmitter and receiver had sufficient bandwidth for the 66- and 69-GBaud signals. Since the frequency ripples occurred, we applied the precise calibration scheme to equalize the frequency ripples.

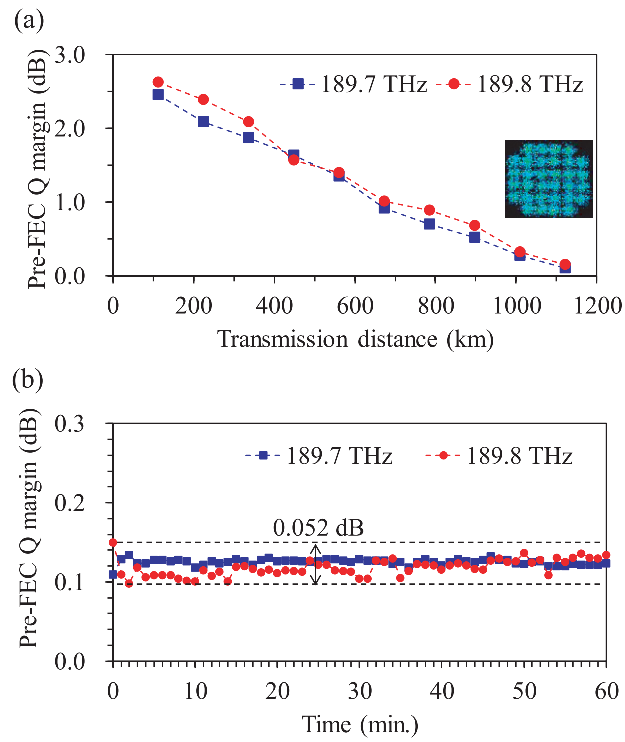

Fig. 5 (a) Experimental result of dual-carrier 1-Tb/s transmission over field-deployed G.654.E fiber links and (b) stability measurements of dual-carrier 1-Tb/s signal performances at 189.7 and 189.8 THz in WDM conditions after 1122-km transmission.

3. Results and Discussion

The net data-rate 1-Tb/s (dual-carrier PDM-32QAM) transmission performances at the center carrier frequencies of 189.7 and 189.8 THz of the WDM signals are shown in Fig. 5(a). In these transmission experiments, the average fiber input power was 2.5 dBm/carrier, and the gain of the backward-distributed Raman amplifier was set to 11 dB for each 112-km span. Note that the pre-forward error correction (FEC) Q margin in the results shown in all of the figures is equivalent to the difference between the pre-FEC Q factor and pre-FEC Q limit; that is, the pre-FEC Q margin of zero corresponds to the pre-FEC Q limit. As shown in Fig. 5(a), pre-FEC Q-factor showed better than the pre-FEC Q limit and confirmed that the post-FEC bit error rate (BER) was error-free for each channel and transmission distance. Thus, we achieved dual-carrier 1-Tb/s transmission over 1122-km (10 spans × 112.2 km) and 1.2-Tb/s transmission over 336.6-km (3 spans × 112.2 km) field-deployed G.654.E fiber links. Figure 5(b) shows the variations over time of the dual-carrier 1-Tb/s signal performances after 1122-km transmission. The carrier frequencies of the signals are 189.7 and 189.8 THz, which are the center of the WDM signal. The signal performances were continuously measured for 60 minutes with an interval of one minute. The pre-FEC Q margin showed more than zero, and we also confirmed that the post-FEC BER was error-free for each inter-

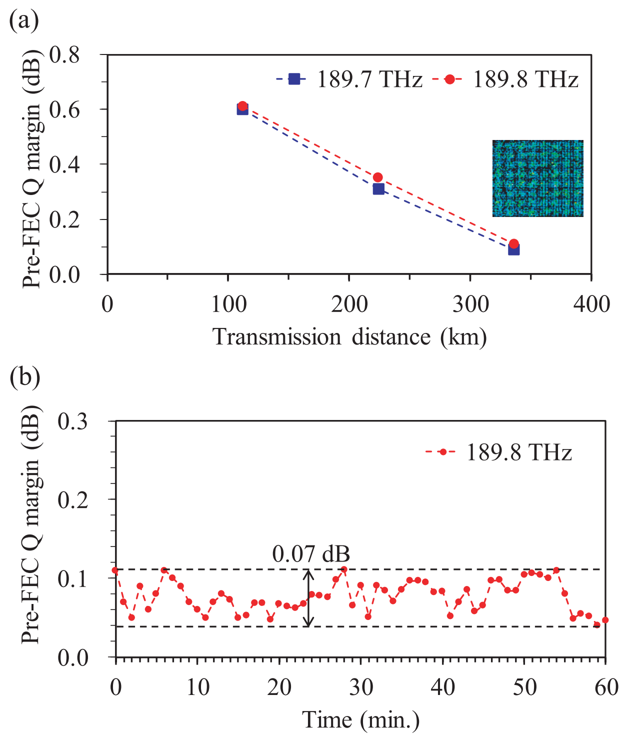

Fig. 6 (a) Experimental result of dual-carrier 1.2-Tb/s transmission over field-deployed G.654.E fiber links and (b) stability measurements of the PDM-64QAM signal performance at 189.8 THz in WDM conditions after 336.6-km transmission.

val measurement. The signals were stably transmitted over 1122 km with a Q-factor fluctuation of less than or equal to 0.052 dB within continuous measurements for 60 minutes.

The net data-rate 1.2-Tb/s (dual-carrier PDM-64QAM) transmission performances at the center carrier frequencies of 189.7 and 189.8 THz of the WDM signals obtained in the transmission experiments are also shown in Fig. 6(a). In these transmission experiments, the average fiber input power was 1.5 dBm/carrier, and the gain of the backward-distributed Raman amplifier was set to 14 dB for each 112-km span. We observed that the pre-FEC Q margin showed more than zero, and confirmed that the post-FEC BER was error-free for each channel and transmission distance. Thus, we achieved dual-carrier 1.2-Tb/s transmission over 336.6-km (3 spans × 112.2 km) field-deployed G.654.E fiber links. Figure 6(b) shows the variation over time of the PDM-64QAM signal performance after 336.6-km transmission. The carrier frequency of the signal is 189.8 THz, which is the center of the WDM signal. The signal performance was continuously measured for 60 minutes with an interval of one minute. The pre-FEC Q margin showed more than zero, and we also confirmed that the post-FEC BER was error-free for each interval measurement. The signals were stably transmitted over 336.6 km with a Q-factor fluctuation of less than or equal to 0.07 dB within continuous measurements for 60 minutes.

4. Conclusion

We demonstrated record transmission distances of 1122 km with a net data-rate of 1 Tb/s with dual-carrier PDM-32QAM signals and of 336.6 km with a net data-rate of 1.2 Tb/s with dual-carrier PDM-64QAM signals using our newly developed real-time transponder over 112.2-km spans of field-deployed large-core low-loss fiber, which is compliant with ITU-T G.654.E. Hybrid EDFA and backward-distributed Raman amplifier were applied to terrestrial G.654.E fiber links for the first time. The transponder integrates DSP-ASIC based on 16-nm CMOS technology and an optical frontend consisting of an HB-CDM based on InP technology and an HB-ICR. We also demonstrated stable signal performance over field fiber transmission in WDM conditions. The Q-factor fluctuation of the dual-carrier 1-Tb/s signal was less than or equal to 0.052 dB after 1122-km field-deployed G.654.E fiber transmission within continuous measurements for 60 minutes. We also confirmed that the Q-factor fluctuation of PDM-64QAM signal was less than or equal to 0.07 dB after 336.6-km transmission within continuous measurements for 60 minutes.

Acknowledgments

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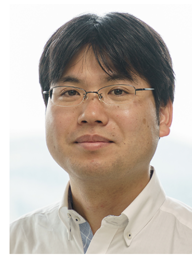

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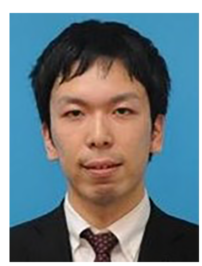

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