14-Tb/s (140 x 111-Gb/s PDM/WDM) CSRZ-DQPSK Transmission over 160 km Using 7-THz Bandwidth Extended L-band EDFAs

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Abstract *Spectrally-efficient 111-Gb/s/ch WDM transmission is demonstrated using CSRZ-DQPSK format and extended L-band erbium-doped fiber amplifiers. Record total capacity of 14 Tb/s (2 b/s/Hz) is achieved in just a single amplifier gain bandwidth.*

Introduction

Recent developments in high speed electronics have accelerated research on 100 Gb/s-class optical transmission technologies for future 100G Ethernet transport over wide area networks [1-3]. 107 Gb/s binary transmission [1, 2] has been demonstrated based on electrical time division multiplexing (ETDM) transmitter/receiver. Differential quadrature phase shift keying (DQPSK) [3, 4] is attractive for high speed channel transmission because it can support line rates that are twice the operation speed of the electronics. Moreover, because of its narrow signal spectrum, high spectral efficiency (SE) is realized which can boost the total capacity of large-capacity WDM transmission systems. To date, several large capacity transmission experiments over 10 Tb/s have been reported using binary modulation and multi-gain-bandwidth optical amplification [5, 6] (Fig. 1). In this paper, we achieve the record total capacity of 14 Tb/s in just a single amplifier gain bandwidth. We adopt the following two key techniques: 1) a spectrally-efficient carrier-suppressed return-to-zero (CSRZ) DQPSK modulation technique that offers SE of 2 b/s/Hz with the aid of polarization-division multiplexing (PDM). 2) an extended L-band optical amplification technique that utilizes phosphorous co-doped silica fiber amplifiers (P-EDFAs) yielding 7 THz gain bandwidth (1.75 times as large as existing EDFAs). The line rate of our experiments is 111 Gb/s, which is sufficiently high for transparently transporting future 100G Ethernet channels and/or 10 x 10GbE LAN PHY channels while using forward error correction (FEC).

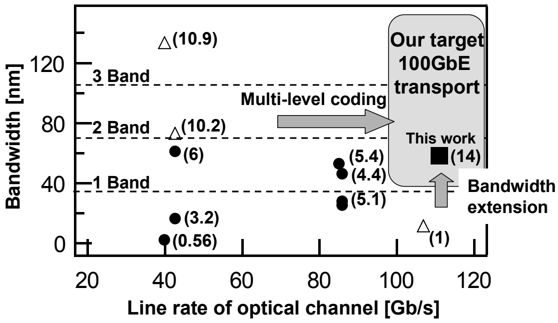

Fig. 1 Line rate and utilized bandwidth of recent large capacity transmission experiments. Triangles: binary modulation, Circles: quaternary modulation. Figures in parentheses show the total capacity in Tb/s.

Transmission Experiments

Fig. 2 shows the experimental setup. At the transmitter, 100-GHz spaced, 70 wavelengths (1561.42–1619.62 nm) were separated to even and odd channels, multiplexed, and individually modulated by PLC-LN hybrid DQPSK modulators [8] that have the nested Mach-Zehnder modulator (MZM) configuration with two parallel LN MZMs. In order to emulate a random data modulation, data signal was generated as follows: 1) Using InP HBT digital ICs [9], 55.5 Gb/s data was generated by multiplexing two

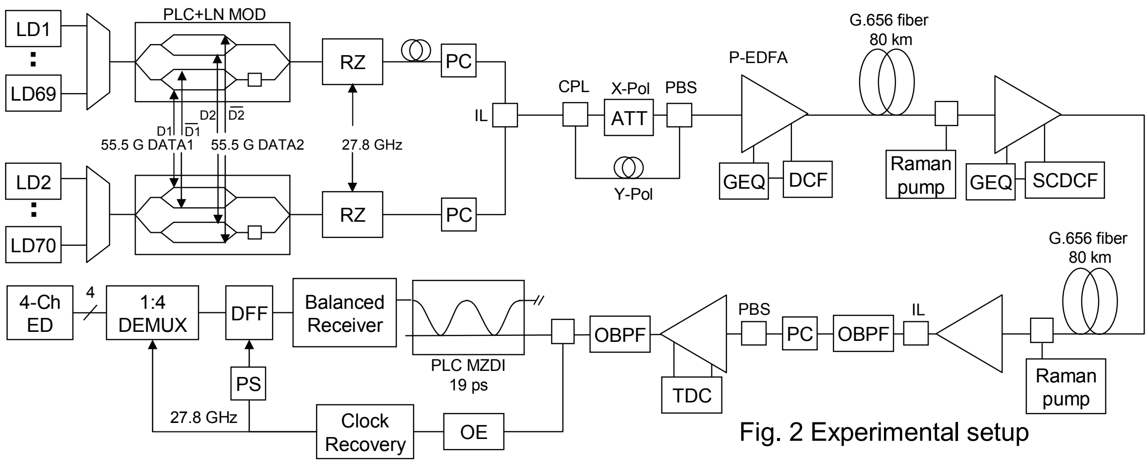

Fig. 2 Experimental setup

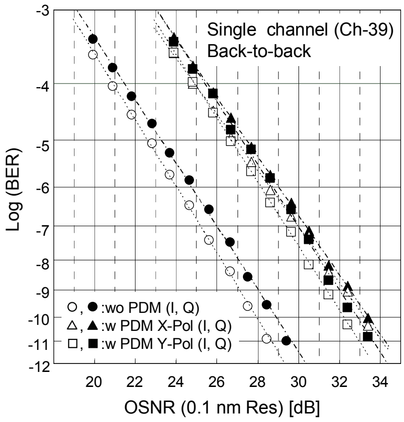

Fig. 3 BER performance as a function of OSNR

27.8 Gb/s data: one was a true 2^9-1 pseudo-random binary sequence (PRBS), and the other was the complement of the first but delayed by 88 bits. 2) The DQPSK modulators were driven in push-pull operation by two 55.5 Gb/s signals (DATA1/2), where DATA2 was the same data pattern as DATA1, but delayed by 118 bits. After DQPSK modulation, the signals were modulated by X-cut LN modulators to realize CS-RZ intensity modulation [10]. Odd channels were delayed by about 7.5 nsec, and multiplexed by using an interleaver. The signals were then separated into two paths, one signal was delayed by about 5 ns, and combined with orthogonal polarization. The transmission line consisted of two spans of 80-km ITU-T G.656 dispersion-flattening fibers (DFF) with the dispersion of 6 ps/nm/km and an in-line P-EDFA. The average fiber input power per channel was about -2.5 dBm/ch. We also employed distributed Raman amplification to improve the received OSNR. We used three pump wavelengths per span (ranging from 1470 to 1510 nm), and the spectrally averaged on-off gain was around 13 dB. At the receiver side, the transmitted signal was wavelength/polarization-demultiplexed, and the residual dispersion was compensated by a tunable dispersion compensator (TDC). The signal was then demodulated by a PLC MZ delay interferometer (MZDI) and received by the 50-GHz balanced receiver module that we have developed. The demodulated 55.5 Gb/s data was demultiplexed to 6.9 Gb/s by using a DFF and a 1:4 demultiplexer, and the BER was measured by a 4-Ch error detector programmed with the expected demodulated data

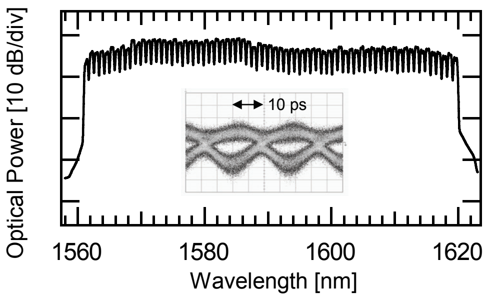

Fig. 4 Optical spectra and eye pattern

patterns. We measured the BER of all tributaries by selecting the demultiplexed channel at the DFF, and the BERs of the worst channel are shown in the followings.

Fig. 3 shows the measured BER performance as a function of OSNR in single-channel back-to-back transmission. In PDM transmission, although the OSNR penalties of 4.3 (Y-Pol.) to 5.1 dB (X-Pol.) were observed, no error floors were seen down to the BER of 10^{-11}. Taking account of the 3 dB power decrease due to PDM, the excess penalties due to PDM were 1.3 to 2.1 dB; they are attributed to the polarization crosstalk caused by the misalignment of the polarization controller. Fig. 4 shows the optical spectra and the demodulated eye pattern (Ch-39, I-Ch) after 160-km transmission. We can confirm that good eye opening is maintained even after 160-km transmission. Fig. 5 shows the OSNR (measured in CW transmission) and Q-factors of all channels (X/Y-Pol., I/Q) after 160-km transmission. All 2(X/Y) x 2(I/Q) x 70 channels had Q-factors better than 9.9 dB, which exceeds the Q-limit of 9.1 dB (shown by the dashed line in Fig. 5) yielding BERs below 1 x 10^{-12} with the use of ITU-T G.975.1 enhanced FEC.

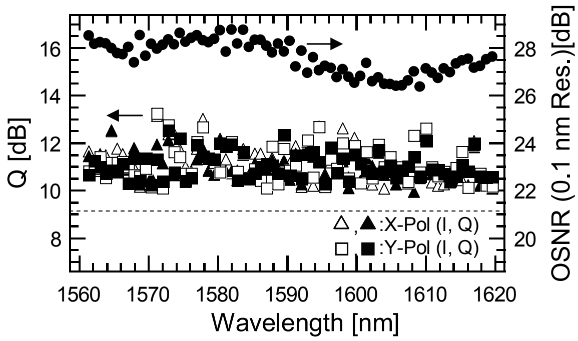

Fig. 5 OSNR and Q after transmission

Conclusions

We have successfully demonstrated spectrally-efficient 111 Gb/s/ch WDM transmission over 160 km of fiber by using the CSRZ-DQPSK modulation format and P-EDFAs. High SE of 2 b/s/Hz and the largest single amplifier gain bandwidth of 7 THz realized the total capacity of 14 Tb/s for the first time.

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