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Ultra high capacity WDM transmission using CSRZ-DQPSK format and extended L-band optical amplifiers

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Abstract
WDM transmission system capacity has been dramatically increased to exceed 20 Tb/s. This paper describes high capacity transmission technologies focusing on high speed CSRZ-DQPSK modulation techniques and extended L-band amplification.

1 Introduction

Due to the rapid increase in IP data traffic, large capacity and cost-effective transmission systems are strongly required to construct future optical transport networks. In order to handle the increase in data traffic, future wavelength-division-multiplexing (WDM) systems are expected to achieve 10-Tb/s-class total capacity. High spectral efficiency (SE) modulation/demodulation schemes and wide band optical amplification technologies are indispensable to realize such high capacity transmission systems. Fig. 1 shows SE and signal bandwidth of recent large capacity WDM transmission experiments. High SE transmission has been demonstrated by using multi-level modulation techniques such as the differential quadrature phase-shift keying (DQPSK) format and polarization-multiplexing techniques. Broadband optical amplification is also indispensable to realize 10-Tb/s-class total capacity. Up to now, these techniques have been reported to realize total capacities of 25.6 Tb/s with dual gain-band amplifiers [1] and 20.4 Tb/s with single gain-band amplifiers [2].

In addition to the capacity requirement, future optical transport networks should support high speed client channels. Current commercial SONET/SDH interfaces offer the 40-Gb/s line rate, and 40 Gb/s/ch long-haul WDM transmission systems have been realized [3]. Moreover, higher speed interfaces such as 100 Gb/s Ethernet are expected in the near future. Therefore, the future large capacity WDM system is expected to transport 100-Gb/s-class high speed channels.

In this paper, we describe high capacity and high speed WDM transmission technologies focusing on high SE modulation techniques and broadband optical amplification techniques.

2 High SE modulation

Multi-level modulation schemes are very effective to improve SE. In particular, the DQPSK format has been extensively investigated over the last few years. The advantages of DQPSK format are summarized as follows: 1) Spectral width is half that of binary modulation, it can

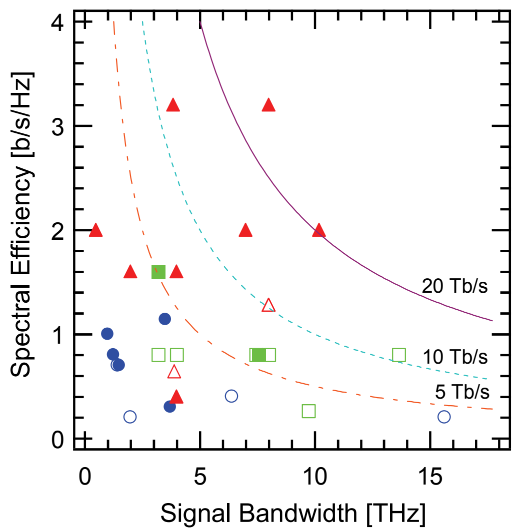

Fig. 1. Spectral efficiency and signal bandwidth of recent large capacity WDM transmission experiments.
Circles: single polarization. Squares: polarization interleaving. Triangles: polarization multiplexing. Open and filled symbols show binary and quaternary modulation, respectively.

double the SE. 2) it can support line rates that are twice the operation speed of the electronics. 3) Tolerances against chromatic dispersion (CD) and polarization mode dispersion (PMD) can be improved because of their narrow spectral width and wide symbol interval. The latter two merits are quite important in high speed transmission such as 100 Gb/s. On the other hand, its drawbacks are mainly transmitter/receiver complexity and tolerance to fiber nonlinearity and laser phase noise.

Return-to-zero (RZ) modulation has been widely used in phase-modulated signal transmission. Carrier-suppressed (CS) RZ modulation is promising because the spectral broadening is small compared to other RZ modulation schemes, and so it is suitable for high SE WDM transmission. We have conducted 111-Gb/s carrier-suppressed return-to-zero (CSRZ-) DQPSK transmission by employing high-speed InP HBT digital ICs, DQPSK modulators based on the hybrid integration of a planar lightwave circuit (PLC) and $LiNbO_3$ (LN) lightwave circuit, and an InP balanced detector [4-6]. Fig. 2 shows measured and calculated CD and PMD tolerances of 111-Gb/s DQPSK format. The calculated performance of conventional non-return-to-zero on-off keying (NRZ-OOK) are also shown for comparison. The measured CD and PMD tolerances at 1-dB OSNR penalty are 30 ps/nm and 9 ps, respectively, and we can confirm that CSRZ-DQPSK format effectively improves both CD and PMD tolerances.

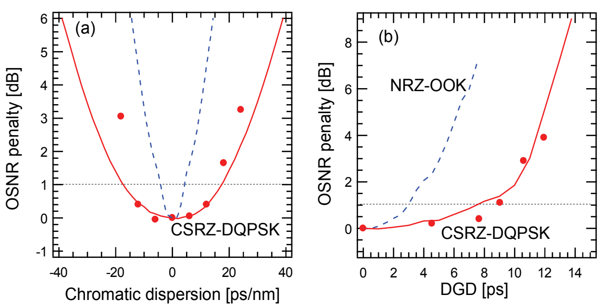

Fig. 1. CD (a) and DGD (b) tolerances of 111-Gb/s CSRZ-DQPSK and NRZ-OOK formats.
Circles: CSRZ-DQPSK, measured. Solid lines: CSRZ-DQPSK, calculated. Dashed lines: NRZ-OOK, calculated. OSNR penalties are evaluated at the bit error rate of 10^{-3}.

3 Broadband optical amplification techniques

One approach toward bandwidth-extension is the parallel configuration of optical fiber amplifiers with different gain bandwidth. 13.7-THz signal bandwidth has been obtained over the S-, C-, and L-bands by using three types of fiber amplifiers, and a 10.9 Tb/s transmission experiment has been demonstrated [7]. In order to realize cost-effective WDM systems, on the other hand, extending the gain bandwidth of single optical amplifiers is an attractive approach. Extended L-band amplifiers such as phosphorous co-doped silicate EDFA (P-EDFA), bismuth-oxide-based EDFA and tellurite-based EDFA offer continuous wide gain bands. We have realized 7-THz bandwidth and demonstrated 14-Tb/s transmission by using a P-EDFA. Moreover, 10.2-THz bandwidth, 20.4-Tb/s transmission has demonstrated by using hybrid amplification technique of P-EDFA and Raman amplifiers. All Raman amplification is also attractive to obtain continuous wide gain bandwidth. 12.2-THz bandwidth has been obtained by using silica fiber Raman amplifiers [8], and hybrid silica/tellurite fiber Raman amplifiers have attained 15.7-THz bandwidth [9]. Further extension of total capacity will be expected by employing these Raman amplification technologies and high SE modulation techniques.

4 Conclusion

We have discussed high capacity and high speed WDM transmission technologies focusing on high SE modulation and broadband optical amplification. CSRZ-DQPSK modulation and extended L-band amplification techniques are promising to realize cost-effective WDM systems.

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