16 × 40 Gb/s Over 800 km of SSMF Using Mid-Link Spectral Inversion

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Abstract—We demonstrate the feasibility of a cost-effective 640 Gb/s (16 × 40 Gb/s) wavelength-division-multiplexed (WDM) transmission system over 800 km of conventional standard single-mode fiber (SSMF) without using in-line dispersion management. Instead for chromatic-dispersion compensation, a Magnesium-oxide-doped periodically poled lithium niobate (MgO: PPLN)-based polarization-diverse subsystem is used to phase conjugate all 16 channels. The transmission line uses all erbium-doped fiber amplifiers and has an amplifier spacing of 100 km. All channels launched were copolarized. To the best of our knowledge, this is the first WDM transmission experiment with a channel data rate of 40 Gb/s using a PPLN as chromatic-dispersion compensator.

Index Terms—Fiber nonlinearity, fiber-optics communications, mid-link spectral inversion (MLSI), optical phase conjugation, optical transmission.

I. INTRODUCTION

In high bit-rate wavelength-division-multiplexed (WDM) systems using dispersion compensating fiber (DCF) as chromatic-dispersion compensation, the dispersion management has a great impact on the system performance. Many studies have been conducted to maximize system performance by optimizing the dispersion map [1], [2]. Still the optimal dispersion map is dependent on many aspects of the system including the total transmission length, the span length, the number of channels, the channel spacing, the channel data rate, etc.; hence, every link needs its own custom dispersion map.

A more cost-effective solution would be to use mid-link spectral inversion (MLSI). In a system based on MLSI, no in-line dispersion compensation is needed. Instead in the middle of the link, an optical phase conjugator inverts the frequency spectrum and phase of the distorted signals caused by chromatic dispersion. As the signals propagate to the end of the link, the accumulated spectral phase distortions are reverted back to the value at the beginning of the link if perfect symmetry of the link is assumed. The great advantage of using MLSI is that in such a system no custom dispersion map needs to be designed for each specific link; also, different modulation formats (nonre-

Manuscript received January 21, 2004; revised March 25, 2004. This work was supported by the University of Technology Eindhoven, The Netherlands, by Siemens AG, Munich, Germany, and by Lightbit, Mountain View, CA.

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Digital Object Identifier 10.1109/LPT.2004.828546

Fig. 1. Experimental setup.

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C. Inside the PPLN, the incoming data signals measured in a back-to-back according to 170, 40, and 220 ps/nm. Please note that for this measurement, the input and the output data signals is equal. The noise output of the phase conjugator unit, with no input signals, was measured at less than -65 dBm per 0.1-nm bandwidth. For further transmission, the input channels were filtered out. The net loss of the phase conjugator plus filters was 23 dB which equals the loss of one SSMF span. However, this loss does not represent a fundamental limitation of the PPLN’s conversion efficiency and can be further reduced. Since in this setup no in-line DCF was needed, one-stage amplifiers were used for in-line amplification. Hence, instead of one preamplifier per span for the PPLN, only one extra amplifier is required for the whole link. At the receiver, the chromatic dispersion was optimized for each channel using a variable dispersion compensator. Accordingly, the signal was properly amplified, filtered with a 0.8-nm (full-width at half-maximum) tunable bandpass filter, and detected using a bit-error-rate (BER) detector.

III. RESULTS

Fig. 2(a) depicts the optical spectrum of all channels after they are spectrally inverted by the PPLN. On the right part of the plot, the 16 input channels can be seen (1548.5–1560.6 nm), and the left part shows the 16 output channels (1531.9–1543.7 nm). In the middle (at 1546.12 nm), the residual of the suppressed pump can be seen (for illustration purposes). Fig. 2(b) depicts the spectrum of the WDM signals at the receiver. The measured OSNR at the receiver was larger than 23.5 dB for all 16 channels, which is in good agreement with what would be expected from launch power, loss, and amplifier noise considerations.

In the optical spectrum, after transmission Fig. 2(b), a ripple is clearly visible. This ripple, created by unequal gain of the EDFAs in the system, introduced a nonuniform channel performance. In DCF-based transmission systems, channel equalization is classically done by designing the two-stage amplifiers to result in a flat gain spectrum. Since this MLSI system is built up with single-stage amplifiers only and without a channel equalizer, no active channel equalization was conducted. The ripple after transmission was reduced to 7 dB by lowering the output power of the boosters. Instead of the optimal input power of 4 dBm we measured in single-channel performance, 3 dBm per channel (15 dBm total power) was the setting with the most equal channel performance.

The optimal channel power in this experiment is higher than the optimal channel power used for the 10-Gb/s/channel dense WDM experiment (1 dBm) we reported earlier [8]. Even though the spectral efficiency of both experiments is equal (0.4 b/s/Hz), the 10-Gb/s experiment was cross-phase modulation (XPM)-limited due to the narrow channel spacing of 25 GHz. In the case of the 40-Gb/s/channel transmission, the XPM effect is not the limiting factor. Instead the performance is OSNR-limited, since the BER performance after transmission [Fig. 3(b)] is very similar to the BER (3.5 \times 10^{-6}) measured in a back-to-back configuration at the same OSNR of 23.5 dB.

In order to see the effect of precompensation, the dispersion tolerance of Channel 8 (1537.4 nm after spectral inversion) was assessed for the following precompensations -640, -510, -340, -170, 40, and 220 ps/nm. Please note that for this measurement, the PRBS length used was 2^{7} - 1. Fig. 3(a) shows the contour plot of the BER as a function of the precompensation and postcompensation. From Fig. 3, it can be seen that the BER performance is not seriously affected as long as the precompensation is smaller than 220 ps/nm and larger than -640 ps/nm.

The best result, e.g., the lowest BER, was obtained at a precompensation of -510 ps/nm. Fig. 3(b) depicts the BER of all 16 channels before forward-error correction (FEC) [PRBS 2^{31} - 1]. The precompensation in this configuration was -510 ps/nm. The BER of the best and the worst channel were 2.1 \times 10^{-6} and 7.1 \times 10^{-6}, respectively. These BER rates are more than two decades below the FEC threshold of the concatenated code RS(255, 247) + RS(247, 239) with a 7% redundancy, for which a BER of 2.3 \times 10^{-3} corresponds to error-free transmission after...
FEC (BER after FEC < 10^{-13}) [9]. For all measured channels, the post dispersion was optimized. The inlay of Fig. 3(b) depicts the eye pattern obtained for Channel 8 (1537.4 nm after transmission).

The PPLN inverts the chromatic dispersion of the data signal. What it does not compensate for is the slope of the fiber. For a 40-Gb/s channel, the slope has almost no influence on the performance since the optical spectrum is small (>0.8 nm), however, due to the slope, the effective accumulated dispersion before the postcompensation unit varies for different channels, which results in different optimal postcompensations. Based on a typical dispersion slope of 0.057 ps/nm for SSMF, the computed difference in optimal dispersion between the first and the 16th channel is 551 ps/nm for the 800-km link. This is in excellent agreement with the measured value of 560 ps/nm.

In this experiment, a dispersion compensator was used to maximize the BER performance per channel. Alternatively, a slope compensator could be used instead of the channel dispersion compensator at any point of the transmission link. In a similar but different experiment at 10 Gb/s, the PPLN optical phase conjugator with a slope compensator adequately and effectively compensated for chromatic dispersion and dispersion slope. The main advantage of the slope compensator is that it compensates the slope for all channels at once.

IV. CONCLUSION

Using a polarization-diverse MgO: PPLN optical phase conjugator, we have shown successful transmission of 16 40-Gb/s channels over 800 km of SSMF. By using this technique, we eliminated the need for in-line dispersion compensation in the transmission link.

REFERENCES