16x40 Gb/s over 800km of SSMF using mid-link spectral inversion

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 (nonreturn-to-zero, return-to-zero, differential phase-shift keying, etc.) and different channel data rates (10 Gb/s, 40 Gb/s, etc.) can be used on the same link. Another advantage of MLSI systems is that they are realized without using DCF, which results in a simplified and cost-efficient amplifier design.

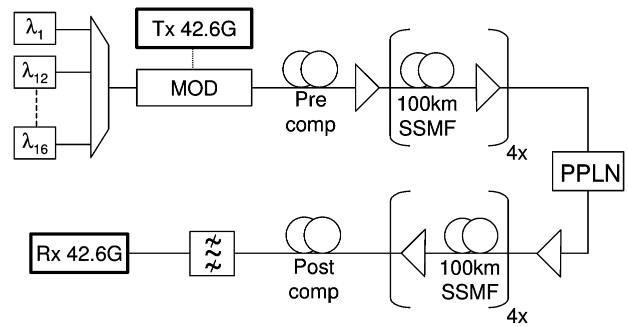

Fig. 1. Experimental setup.

In this letter, we show successful transmission of 640 Gb/s (16×40 Gb/s) over 8×100 km SSMF at 100-GHz channel spacing. In [3], five 40-Gb/s channels are transmitted over 105 km of SSMF using highly nonlinear fiber as spectral inverter. All other experiments reported so far at 40-Gb/s channel data rate (or higher) using MLSI were single-channel experiments [4]–[7]. To the best of our knowledge, 640 Gb/s is the highest total data rate reported using a phase conjugator as chromatic-dispersion compensator.

II. EXPERIMENTAL SETUP

Fig. 1 shows the experimental setup of the straight line transmission link. The WDM transmitter consisted of 16 distributed feedback lasers with wavelengths ranging from 1548.5 to 1560.6 nm (100-GHz spacing). The 16 continuous wave channels were multiplexed in an arrayed-waveguide grating multiplexer and modulated at 42.6 Gb/s.

Each channel was generated using a $2^{31} - 1$ pseudorandom bit sequence (PRBS). After modulation, the data was sent into the transmission link, consisting of eight spans of 100 km of SSMF (SMF-28) with each span loss varying between 21 and 24 dB. The noise figure of the in-line erbium-doped fiber amplifiers (EDFAs) was 4.5 dB. No DCF was used in the transmission link for in-line dispersion compensation. Instead, a polarization-diverse phase (PDL < 0.5 dB) conjugator subsystem, utilizing Magnesium-oxide-doped periodically poled lithium niobate (MgO : PPLN), was placed after four spans in the middle of the link. Quasi-phase matching inside the PPLN was realized with a phase matching period of 17.1 μm and a temperature

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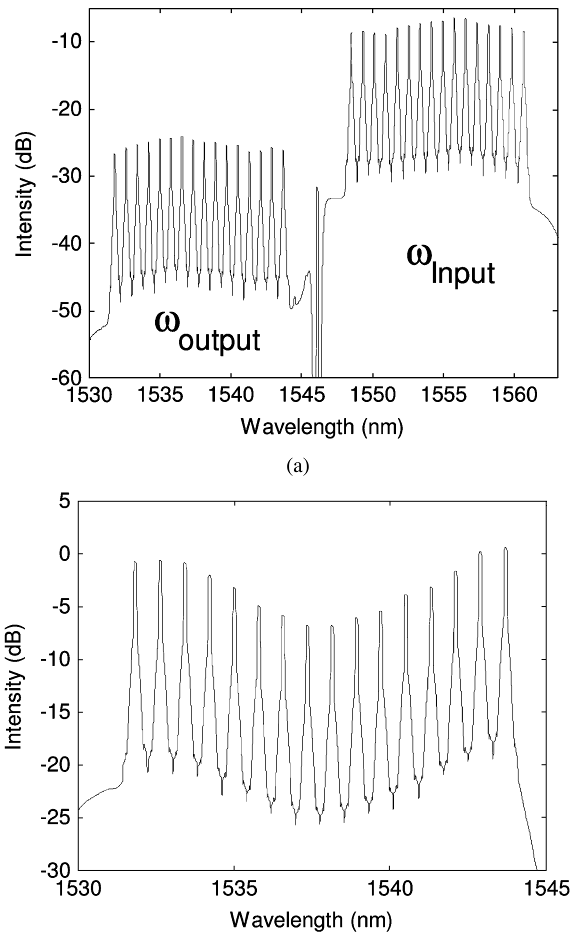


Fig. 2. (a) Optical spectrum at the output of the optical phase conjugator (spectral resolution of 0.1 nm). (b) Optical spectrum at the end of 800 km (spectral resolution of 0.1 nm).

controller at 90 °C. Inside the PPLN, the incoming data signals ($\omega_{\rm input}$) were mirrored with respect to the pump frequency at 1546.12 nm ($\omega_{\rm pump}$) according to

$$\omega_{\rm output} = 2\omega_{\rm pump} - \omega_{\rm input}. \qquad (1)$$

Hence, the array of wavelengths of the data signals were converted from 1548.5–1560.6 to 1543.7–1531.9 nm, as can be seen in the optical spectrum depicted in Fig. 2(a). For the PPLN itself, no optical signal-to-noise ratio (OSNR) degredation was measured. One can see this in Fig. 2(a), since the OSNR for 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.

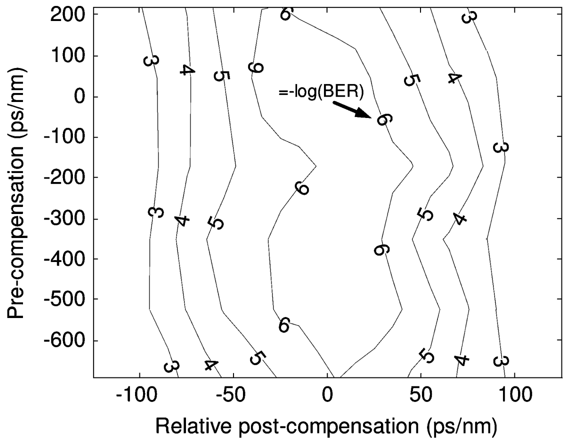
III. Results

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.

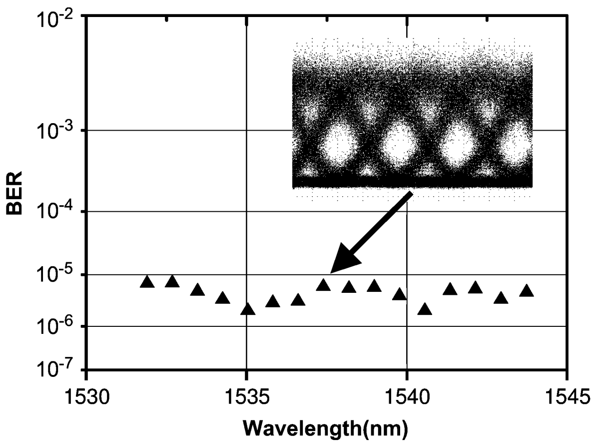
In the optical spectrum, after transmission Fig. 2(b), a ripple is clearly visible. This ripple, created by unequal gain of the EDFAs in the system, introduced a nonuniform channel performance. In DCF-based transmission systems, channel equalization is classically done by designing the two-stage amplifiers 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 ($3.5 * 10^{-6}$) 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 $2.1 * 10^{-6}$ and $7.1 * 10^{-6}$, respectively. These BER rates are more than two decades below the FEC threshold of the concatenated code $\mathrm{RS}(255, 247) + \mathrm{RS}(247, 239)$ with a 7% redundancy, for which a BER of $2.3 * 10^{-3}$ corresponds to error-free transmission after



(a)



(b)

Fig. 3. (a) Measured contour plot of the BER as a function of the precompensation and postcompensation. (b) BER performance for all 16 WDM channels.

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.

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