Mixed data rate and format transmission (40-Gbit/s non-return-to-zero, 40-Gbit/s duobinary, and 10-Gbit/s non-return-to-zero) by mid-link spectral inversion

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A polarization-diverse subsystem based on periodically poled lithium niobate waveguides is used as an optical phase conjugator for compensation for linear and nonlinear distortion. We show successful transmission formats of 13 × 40 Gbit/s non-return-to-zero mixed with 6 × 10 Gbit/s non-return-to-zero and 40-Gbit/s duobinary over 8 × 100 km of standard single-mode fiber. A single phase conjugator is used to conjugate all data formats, including the alternative duobinary format, simultaneously. © 2004 Optical Society of America

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Typically, today’s optical transmission systems require the use of dispersion-compensating fiber (DCF) to compensate for chromatic dispersion of the transmission fiber. Alternatively, one can compensate for transmission fiber dispersion by placing a spectral inverter in the middle of the transmission link. The spectral inverter inverts the frequency spectrum and conjugates the phase of the optical signals, which are distorted by chromatic dispersion and nonlinear effects.1–9 Because the in-line dispersion-compensation components are eliminated in a mid-link spectral inverter–based transmission system, the system costs are reduced. The dispersion map is simplified as well, which makes system design straightforward. Another advantage of using a mid-link spectral inverter is that, instead of two-stage amplifiers, single-stage amplifiers can be used for in-line amplification, which improves the optical signal-to-noise ratio (OSNR) of the received signal and relaxes the requirements of erbium-doped fiber amplifiers.7

In this Letter we show that, unlike in the DCF-based transmission systems, in which different dispersion maps are required for different data rates and data formats,9 mid-link spectral inverter–based and DCF-free transmission is transparent to data rates and modulation formats. This transparency is particularly appealing for network operators because existing networks can be upgraded without the need to replace the equipment or change the in-line settings of the transmission line. For the first time to our knowledge, we demonstrate that a single spectral inverter supporting multiple dense wavelength-division multiplexing channels can transparently restore signals with different data rates and modulation formats simultaneously by 10-Gbit/s non-return-to-zero (NRZ), 40-Gbit/s NRZ, and 40-Gbit/s duobinary transmission over the same link.

Figure 1 depicts the experimental setup. The NRZ channels were generated by distributed-feedback lasers and modulated with a Mach–Zehnder modulator. Thirteen distributed-feedback lasers were modulated at 42.7 Gbits/s and 6 were modulated at 10.7 Gbits/s. The duobinary transponder (from Stratalight Communications) operated at 42.7 Gbits/s. The pseudorandom bit sequence length was 231–1 for all data formats in this experiment. All channels were mixed together by a star coupler and launched copolarized to create a worst-case model for interchannel interactions. The OSNR per channel after the star coupler was larger than 43 dB for all channels. The optical spectrum of the transmitter is depicted in Figs. 2(a) and 2(b). After the transmitter, DCF with chromatic dispersion $D_{\text{dec}} = -170$ ps/nm was used to decorrelate the different channels in the fiber. The transmission link consisted of eight spans of 100 km of standard single-mode fiber (SSMF) with a loss that varied from 21 to 24 dB, an average chromatic dispersion of $\sim 16$ (ps/nm)/km, and an average dispersion slope of 0.048 (ps/nm²)/km. The SSMF input power was set to 0.8 dBm/channel for all 10-Gbit/s channels and to 2.8 dBm/channel.

Fig. 1. Experimental setup: Tx, transmitter; Rx, receiver; Mod, modulator.
for all 40-Gbit/s channels. A polarization-diverse spectral inverter subsystem, utilizing two 5-cm-long magnesium oxide–doped periodically poled lithium niobate (MgO:PPLN) waveguides, was placed after 400 km, at which point the channel polarizations were randomized by the transmission fiber. The polarization diversity scheme employed a polarization beam splitter (PBS) followed by a PPLN waveguide for each of the two output ports of the PBS. Then the signal was recombined by another PBS. The pump wavelength was launched at 45° with respect to the principal axes of the first PBS. The polarization-dependent loss was measured to be less than 0.5 dB. The use of MgO:PPLN resulted in a reduction of the photoeffect and allowed the device to be pumped with higher power and operated at lower temperature. The PPLN was quasi-phase-matched, with a phase-matching period of 17.1 μm and a temperature controller at 90°C. The optical power of the pump signal was set to 150 mW/PPLN waveguide. Spectral inversion in the waveguide was achieved by cascaded second-harmonic and difference-frequency generation. Because these processes are instantaneous and phase sensitive in their response, MgO:PPLN is transparent to data rate and data format. Another advantage of MgO:PPLN compared with other phase-conjugation materials is that it is broadband and wavelength-division multiplexing compatible, hence in this experiment a single phase conjugator was used to convert all channels. Because these processes are instantaneous and phase sensitive in their response, MgO:PPLN is transparent to data rate and data format. Another advantage of MgO:PPLN compared with other phase-conjugation materials is that it is broadband and wavelength-division multiplexing compatible, hence in this experiment a single phase conjugator was used to convert all channels. Because the experiment presented here no DCF modules were used at the in-line nodes to compensate for chromatic dispersion, single-stage amplifiers were used, which increased the OSNR after transmission by ~1 dB compared with that achieved with the two stage amplifiers that are needed in conventional systems. Instead of one preamplifier per span, one additional amplifier was needed to cover the loss of the phase conjugator, introducing an OSNR penalty of ~0.5 dB after transmission. Owing to the nonresonant nature of the PPLN, no extra noise was added in the conversion process. The measured insertion loss of the spectral inverter subsystem was 23 dB (input channel to output phase conjugate), including the filters used to remove the incoming data signal. At the end of the transmission link, a tunable dispersion compensator was used to optimize the residual chromatic dispersion at the receiver. Finally, the channels were filtered with 0.8-, 0.4-, and 0.2-nm (full width at half-maximum) optical bandpass filters for the 42.7-Gbit/s NRZ, the 42.7-Gbit/s duobinary, and the 10.7-Gbit/s NRZ channels, respectively.

Figure 2 depicts the optical spectra of the data signals at several points in the transmission line. The 20 data channels at the transmitter are shown in Fig. 2(a). A more detailed plot of the positioning of the 40-Gbit/s duobinary channel and the six 10-Gbit/s channels can be seen in Fig. 2(b). The optical spectra after the phase conjugator and after the 800-km transmission link are shown in Figs. 2(c) and 2(d), respectively.

The 40-Gbit/s duobinary data channel is launched at 1555.8 nm (before the spectral inverter). At 50-GHz spacing, three 25-GHz spaced 10-Gbit/s data channels are placed on each side of the duobinary channel. These 10-Gbit/s data channels are surrounded by thirteen 40-Gbit/s channels placed on a 100-GHz grid. All channels together cover the red subband of the C band ranging from 1548.5 to 1560.6 nm. Figure 2(c) depicts the optical spectrum after it has passed through the optical phase conjugator but before the filters used to suppress the original input channels. From this plot we can see that all data channels are converted from the red subband of the C band to the blue subband. In the middle of the plot, at 1546.1 nm, the residual of the suppressed

![Image of optical spectra](image_url)
pump can be seen. The optical spectrum at the end of the 800-km SSMF link is shown in Fig. 2(d). The OSNR after transmission was greater than 20.5 and 22.3 dB for all 10-Gbit/s and 40-Gbit/s NRZ channels, respectively. The 40-Gbit/s duobinary channel had an OSNR of 23.6 dB. The OSNR per channel is shown in Fig. 3(a).

Figure 3(b) depicts the bit-error rate (BER) performance before forward-error correction (FEC) of all 20 channels. Errors were counted for several minutes for each data point. The straight line at a BER of $2.3 \times 10^{-3}$ corresponds to the correction limit of the FEC decoder to achieve a BER of $1 \times 10^{-14}$ after correction. The BER of the thirteen 40-Gbit/s NRZ data channels (plotted as diamonds in Fig. 3) varied from $2 \times 10^{-5}$ to $4 \times 10^{-9}$. The performance variation correlates with the (small) OSNR variations shown in Fig. 3(a). The performance is OSNR limited because the BER performance is similar to the BER $(3.5 \times 10^9)$ measured in a back-to-back configuration at the OSNR of 23.5 dB. The 10-Gbit/s NRZ channels (plotted as crosses in Fig. 3) had a BER performance before FEC that varied from $1 \times 10^{-10}$ and $2 \times 10^{-9}$. Because of the narrow channel spacing of 25 GHz there is an OSNR penalty of $\sim 1$ dB from cross-phase modulation. For the 40-Gbit/s duobinary channel (plotted as triangles in Fig. 3) a BER of $7.2 \times 10^{-5}$ was measured, which is higher than the BER of all the 40-Gbit/s NRZ channels; still, the BER of the duobinary channel is more than a decade below the FEC threshold. The 40-Gbit/s duobinary channel is OSNR limited, as the BER performance after 800-km equals the back-to-back performance at the same OSNR. To ensure that this worst channel was error free, we measured the BER after FEC for 6 h. In this measurement interval, no errors were detected.

We have successfully shown that using mid-link spectral inversion for linear and nonlinear distortion compensation can eliminate DCF in the transmission system and support different data rates and modulation formats simultaneously. With a single polarization-diverse MgO:PPLN-based spectral inverter, we successfully completed 40-Gbit/s NRZ, 10-Gbit/s NRZ, and 40-Gbit/s duobinary transmission over 800 km. Even for the worst channel the BER was more than a decade below the FEC threshold, and stable error-free transmission was measured after FEC for several hours. This technology provides functionality, transparency, and performance that can be advantageous in designing upgradable transmission systems, which potentially can reduce capital and operating costs for carriers.

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References