High Capacity (64 x 43 Gb/s) Unrepeatered Transmission over 440 km

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Abstract: We describe a 64 x 43 Gb/s unrepeatered transmission experiment over 440 km of ultra-low loss fiber with third-order Raman pumping. We then compare coherent transmission at 40 Gb/s and 100 Gb/s in unrepeatered conditions.

OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications

1. Introduction

Unrepeatered transmission systems aim at long distances without any in-line active elements, thus reducing the line complexity and the overall system cost. Since no underwater active electronics are required, all pumps have to be provided from the shore ends. Typical transmission lengths are a few hundred kilometers. Today, almost all such systems operate at bit rates of 10 Gb/s. However, the demand for increased capacity is rapidly moving interest toward 40 Gb/s and above. At these higher bit rates, polarization division multiplexed phase shift keying modulation format associated with a coherent receiver is seen as the preferred candidate because digital signal processing can compensate chromatic dispersion and PMD, thus enabling upgrade of already installed systems.

Two different trends can be seen: initially, unrepeatered systems aimed at the longest possible distances, even with only a few channels [1]. Recently, the trend is to increase the number of channels in order to provide capacities above 1 Tb/s. To date, experimental demonstrations of 64 x 40 Gb/s over 230km [2], 32 x 40 Gb/s over 402km [3], 26 x 100 Gb/s over 401 km [4] and 40 x 100 Gb/s over 365 km [5] have been achieved.

In this paper, we demonstrate the transmission of 64 Polarisation Division Multiplexed (PDM) RZ BPSK channels at 40 Gb/s over 440 km which is, to our knowledge, the longest high-capacity transmission experiment published to date. We apply a practical configuration consisting of only one type of fiber, over which both the signal and the pumps are propagated.

In the light of this 2.56 Tb/s experiment, we analyze the best configuration to achieve high capacity (more than 2 Tb/s) between 40 Gb/s or 100 Gb/s bit rates; we discuss the pros and cons of the two solutions based on our experimental results at 40 and 100 Gb/s.

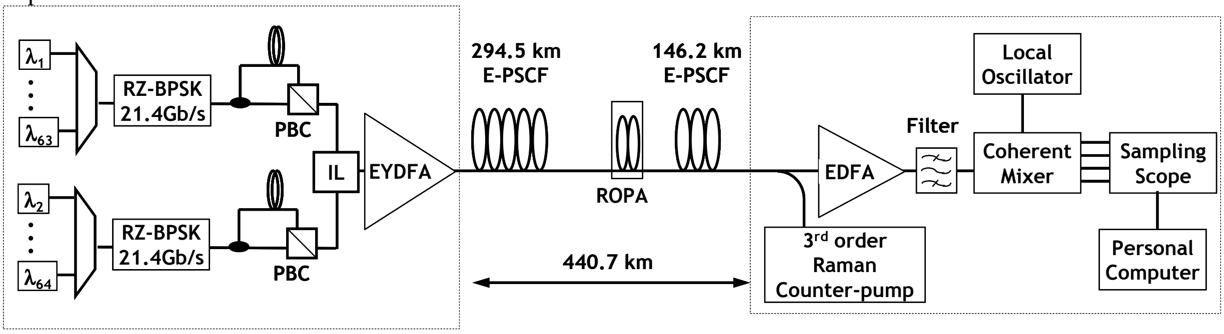


Figure 1: System configuration

2. System configuration

Figure 1 shows our experimental set-up: 64 DFB laser diodes with wavelengths ranging from 1536.61 to 1561.83 nm (50 GHz spacing) are combined two by two. The even and odd channels are modulated by separate RZ-BPSK modulators. Each modulator is fed with a 2^{31}-1 long PRBS sequence at 21.4 Gb/s. This bit-rate accounts for the 7% overhead of a concatenated BCH FEC, which corrects a BER of 4 10^{-3} (Q^2 =8.5 dB) to better than 10^{-13}. The output from the BPSK modulator is polarization multiplexed by splitting the signal, rotating the polarization state of one arm, decorrelating by hundreds of symbols with a relative delay, and combining with a Polarization Beam Combiner (PBC) to produce the PDM-RZ-BPSK signal at 43 Gb/s. The narrow spectrum of the RZ-BPSK format enables 50 GHz spacing without any special digital processing at the receiver. Finally, the even and odd channels are spectrally multiplexed by a 50-GHz Interleaver (IL) and amplified through a high-power Erbium-Ytterbium Doped Fiber booster Amplifier (EYDFA) providing up to 33dBm output power.

The link consists of Enhanced -Pure Silica Core Fiber (EPSCF) with 115 μm^2 effective area and ultra low attenuation. This fiber is at an industrial stage, and can be cabled easily. The total loss of the 440.7 km-long link is 71.5 dB, which corresponds to a mean fiber attenuation of 0.163 dB/km including the splices. The cumulated chromatic dispersion is close to 9000 ps/nm.

A Remote Optically Pumped Amplifier (ROPA) is placed at 146 km from the receiver end. The ROPA is counter-directionally pumped by a Raman Fiber Laser (RFL) located at the receiver side. This RFL delivers 5.3 W at 1276 nm. Over the fiber, the energy is transferred from 1276 nm to a wavelength band around 1390 and then 1483 nm, through cascaded Raman amplification. More details can be found in [6]. Since the 1483 nm pump and the signal are propagated over the same fiber, the signal is also amplified by the Raman effect in the remote section. The total signal gain (Erbium and Raman) provided by the RFL is close to 40 dB.

At the receiver end, each channel is selected by a tunable filter and sent to the polarization-diversity coherent mixer. The mixer combines the selected channel with a CW (unlocked) local oscillator. The phase offset between each of its four output ports is 90° so as to supply the in-phase and quadrature components of the beat terms between the incoming signal and the local oscillator. These components are converted into electrical waveforms by four balanced photodiodes. The resulting electrical waveforms are digitized by analog-to-digital converters operating at 50Gsamples/s with 16-GHz electrical bandwidth and stored. They are then processed off-line in a personal computer to compensate for signal distortions induced by optical-fiber transmission. This is done by applying linear filters in the digital domain in five steps: re-sampling at twice the symbol rate, compensation of the cumulated chromatic dispersion, polarization demultiplexing by means of an adaptive equalizer in a butterfly structure, carrier phase estimation and subtraction using the Viterbi and Viterbi algorithm, and finally symbol identification. The total chromatic dispersion is digitally compensated, so that no optical chromatic dispersion compensation module is needed. Finally, the errored bits are counted, the BER is calculated, averaged over more than 1,000,000 bits, and converted into the Q^2 factor.

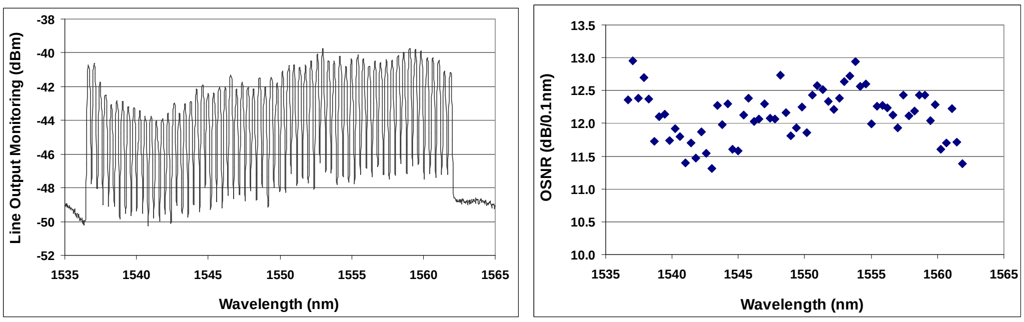


Figure 2: WDM spectrum at the output of the line (right) and estimated OSNR (dB/0.1nm) (left)

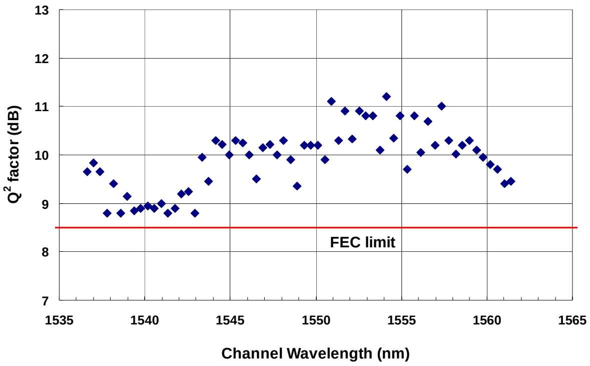
3. Transmission results

Figure 2 (right) shows the spectrum at the output of the line: all channels are roughly equalized. Their OSNRs cannot be measured directly since the noise level cannot be accessed. The noise level is estimated by switching off a few channels, measuring the noise, and interpolating these results. The OSNR is estimated from the channel level and the interpolated noise. The resulting OSNR levels vary from 11.3 to 13 dB/0.1nm between the channels. The BER of all the 64 channels is measured by off-line processing and the resulting Q^2 factor is plotted in Figure 3. The average Q^2-factor is 9.9dB, while the worst channel is at 8.8 dB: all channels are above FEC limit of 8.5 dB and would yield a BER below 10^{-13} after correction by today's commercial FEC with 7% overhead. The transmission distance is limited by the channels in the low wavelength region (around 1540 nm).

4. Discussion

We can now compare this experiment to our previous one at 100 Gb/s: in both, the same line equipment is applied, namely a high-power booster and a third order ROPA and EPSCF fiber. The fiber's effective areas are the same too, even if the fiber's attenuation is reduced in the present experiment (see Figure 3). In both, a capacity of 2.6 Tb/s is achieved with 50 GHz spacing, using either 26 x 100 Gb/s PDM QPSK channels or 64 x 40 Gb/s PDM-RZ-BPSK channels. The transmission at 100 Gb/s needs fewer channels and it therefore benefits from reduced Cross

Polarization Modulation and Stimulated Raman Scattering between the channels. It covers an optical bandwidth of only 10 nm and can thus take advantage of the regions of lowest fiber attenuation and lowest Raman and ROPA noise factors (1550-1560 nm). Comparing the wavelengths of 1536 and 1555 nm, the difference in fiber attenuation and ROPA noise figure totals more than 2.5 dB. On the other hand, the transmission at 40 Gb/s benefits from a better OSNR sensitivity (while the theoretical difference is 4.0 dB, an improvement of 4.7 dB is measured in back-to-back), and slightly better non-linear power limit (1- 2 dB) due to the BPSK format [7].



	This paper	Ref [4]
Format	PDM-BPSK	PDM-QPSK
Bit rate	40 Gb/s	100 Gb/s
Nb of channels	64	26
Bandwidth	25 nm	10 nm
Fibre effective area	115 μm^2	115 μm^2
Fiber attenuation	0.163 dB/km	0.167 dB/km
Link length	440 km	401 km
Link loss	71.5 dB	67 dB
Average Q	9.9 dB	9.1 dB

Figure 3: Q^2 -factor of the 64 channels after 440 km calculated from the BER (left); comparison of 100 Gb/s and 40 Gb/s experiments (right)

We clearly obtain better results with the 40 Gb/s bit-rate in spite of the larger bandwidth required: the achievable link loss is 4.5 dB higher than with 100 Gb/s channels. This corresponds to 28 km of fiber. An additional improvement of 2 dB (12 km of fiber) is obtained thanks to the ultra-low fiber attenuation, so that the total distance is increased by 40 km (or 6.5 dB) compared to our previous experiment at 100 Gb/s using the currently available PDM-QPSK transmitters and receivers. However, for even higher capacities above 5 Tb/s, it is expected that the 100 Gb/s bit-rate will yield better results, because the spacing of the 40 Gb/s channels then has to be reduced.

5. Conclusion

High capacity unrepeatered WDM transmission is investigated at 40 Gb/s, with the best available technology, i.e., PDM-RZ-BPSK transmitters and coherent receivers, third order Raman pumping, and ultra low loss fiber. A record transmission length of 440 km and a record optical budget of 71.5 dB are demonstrated for a transmitted capacity of 2.6 Tb/s, with Q^2 factors above the 8.5 dB FEC limit. This experiment demonstrates an improvement of more than 4 dB over our previous experiment at 100 Gb/s with the same capacity.

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