DWDM 40G transmission over trans-Pacific distance (10,000 km) using CSRZ-DPSK, enhanced FEC and all-Raman amplified 100 km UltraWave™ fiber spans

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Abstract—**We demonstrate error-free DWDM transmission of forty 40 Gbit/s channels with 100 GHz spacing over 10,000 km dispersion-managed fiber using CSRZ-DPSK, enhanced FEC and all-Raman amplified spans with 100 km terrestrial length.**

Index Terms—40 Gbit/s, Differential phase shift keying, Dispersion mapping, Forward error correction, Optical fiber dispersion, Optical transmitters, Optical receivers, Precoding, Raman amplification, Ultra long distance transmission

I. INTRODUCTION

The many recent impressive DWDM 40G transmission demonstrations over distances up to about 9000 km [1-12] clearly show the rapidly improving performance of 40G transmission equipment and techniques, and in the present paper we present error-free transmission of 40x40 Gbit/s over a new record distance of 10,000 km with 100 km spans [13].

The trans-Pacific transmission distance of 10,000 km was achieved by combining for the first time, to our knowledge, CSRZ-DPSK, enhanced FEC (EFEC), distributed Raman amplification, and dispersion-managed fiber spans. An additional key factor in achieving this distance is the implementation of a transmitter/receiver pair with a back-to-back OSNR sensitivity of 11.3 dB at a BER of $10^{?12}$. This is only 1 dB from the theoretical limit and we believe it is the best reported result at 40G. It should also be emphasized that DPSK precoding is done at 40G using 50G logic (an AND gate and a T-flip-flop) and that EFEC decoding is fully implemented.

II. EXPERIMENTAL SET-UP

A. Transmitter

Figure 1 shows the CSRZ-DPSK transmitter. The transmitter takes a 2^{31} ? 1 PRBS at 9.95 Gbit/s from a pattern generator and performs EFEC encoding to generate a 10.7 Gbit/s data signal which is multiplexed to get a 42.8 Gbit/s data signal. This signal is sent to the 40G DPSK precoder built from 50G logic, more precisely an AND gate and a T-flip-flop rather than the conventional XOR/one-bit-delay solution [14]. The output signal from the precoder is amplified in a high power driver delivering about 10 V_{pp} (?$2V_p$) voltage swing to the single drive x-cut (zero chirp) $LiNbO_3$ Mach-Zehnder modulator (MZM) biased at transmission minimum. Using an x-cut modulator to generate the DPSK phase modulation contributes to the good transmitter performance by virtually eliminating unwanted chirp. A z-cut $LiNbO_3$ Mach-Zehnder modulator also biased at transmission minimum and push-pull driven by a 21.4G clock subsequently carves CSRZ pulses to generate the CSRZ-DPSK signal. Two transmitters are used to modulate the 20 even and 20 odd channels that are interleaved with arbitrary polarizations to get forty 100 GHz spaced channels in the C-band from 1530.33 nm to 1561.42 nm. The average launch power into the transmission fiber is –11 dBm per channel.

B. Transmission link, dispersion map, and amplification

Figure 2 shows the optical link used in this transmission demonstration. 20 odd channels from one CSRZ-DPSK transmitter are combined with 20 even channels from the other CSRZ-DPSK transmitter in an interleaver. The resulting 40 channel WDM signal is then sent through –1100 ps/nm of precompensation before it is launched in the loop which is

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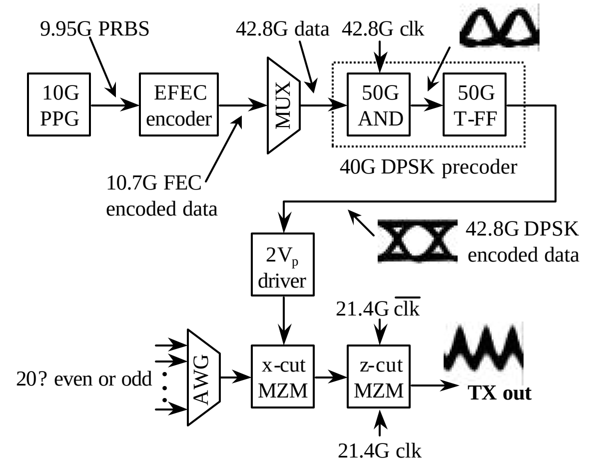

Fig. 1. Schematic of the CSRZ-DPSK transmitter including the 40G DPSK precoder. “PPG”: pattern generator.

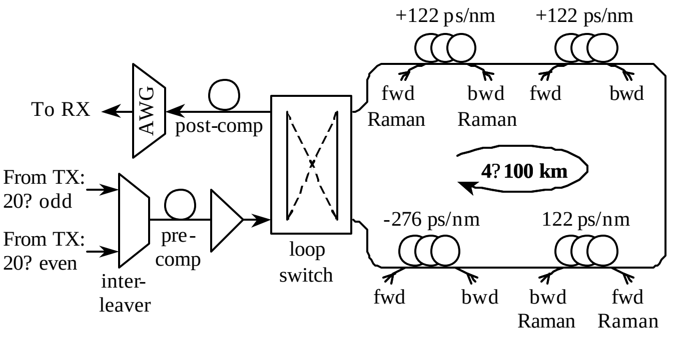

Fig. 2. Schematic of the loop set-up including the four 100 km spans of Raman amplified dispersion managed fiber. The first three spans have a dispersion of 122 ps/nm, and the fourth span has a dispersion of ?276 ps/nm. ?1100 ps/nm of precompensation is used.

composed of four spans of 100 km Raman amplified UltraWave™ dispersion-managed fiber [6,15]. Each span consists of two identical sections of large effective area fiber with an effective area of 107 µm^2 and a dispersion of 20 ps/nm/km separated by a section of fiber with an effective area of 31 µm^2 and a dispersion of ?45 ps/nm/km. The lengths of the three sections are adjusted to give the desired net dispersion per span. The first three spans in the loop have a net dispersion of ?122 ps/nm and the fourth span has a dispersion of ?276 ps/nm giving a loop round-trip dispersion of ?90 ps/nm; all values refer to the center of the C-band. Extensive numerical simulations were carried out to find this dispersion map that optimizes CSRZ-DPSK transmission over distances in the 10,000 km region. It was found that the transmission penalty generally decreases with increasing absolute value of the net dispersion per loop round-trip. A high loop round-trip dispersion means, however, that the dispersion accumulated in many loop round-trips becomes very high, and it was found that a positive loop round-trip dispersion of about 100 ps/nm is a good compromise between transmission performance and the practical issues related to compensation of the accumulated dispersion. For a given net dispersion per loop roundtrip, it was furthermore found that the transmission performance generally improves slightly if the four spans in the loop are not identical leading to the employed “3+1” dispersion map. Figure 3 shows an example of the results of the transmission penalty simulations. The figure shows the simulated eye opening penalty after 25 loop round-trips (=10,000 km) as a function of the precompensation and the dispersion of the first three 100 km spans; the dispersion of the fourth span is always adjusted to give a loop round-trip dispersion of 90 ps/nm. The dot in the figure shows the dispersion map used in this transmission demonstration. The optimum precompensation of about –1100 ps/nm is approximately the value that gives a transform limited pulse (corresponding to an accumulated dispersion of 0) in the middle of the considered nonlinear link, i.e. after 12.5 loop round-trips: ?12.5·90 ? ?1100 ps/nm in agreement with [16]. Since the transmission penalty increases sharply if the precompensation becomes too negative as shown in figure 3, we decided to operate near the left border of the low penalty valley shown in the figure.

The loss of the transmission link is compensated by forward and backward distributed Raman amplification. Each span has a fiber loss of 21 dB and an additional total loss of 1.2 dB in the two Raman pump couplers. Moreover, and not shown in figure 2, is a wavelength dependent loss of a fixed gain flattening filter inserted between the second and third fiber span. Semiconductor lasers with low RIN provide depolarized co-propagating pump waves at 1418, 1438 and 1465 nm giving approximately 6dB of forward gain. The rest of the required Raman gain is provided by counter-propagating pump waves at 1427 and 1455 nm from Raman lasers. WDM couplers are used to couple the co-propagating Raman pump waves to the transmission fiber, and circulators are used for the counter-propagating Raman pump waves. These circulators furthermore prevent the backward traveling spontaneous emission from one 100 km fiber span to propagate into the preceding 100 km fiber span.

The described distribution of forward and backward Raman gain was determined on the basis of simulations of the influence of the forward Raman gain on the optical signal to noise ratio (OSNR, referred to 0.1 nm) and the double Rayleigh backscatter (DRBS) relative to the signal. The result of these simulations is shown in figure 4 which displays the OSNR and the DRBS per 100 km span as a function of the forward Raman gain keeping the total Raman gain constant. To get a fair picture of the transmission improvement brought about by the forward Raman gain, the nonlinear distortion is kept approximately constant by adjusting the launch power for each value of the forward gain so that the time average nonlinear phase shift per span is 0.007 rad. This is the nonlinear phase shift experienced by the signal in our 10,000 km transmission demonstration where ?11 dBm per channel was launched into spans with 6 dB forward Raman gain. It was found experimentally that this launch power gives the lowest BER after transmission, i.e. the best tradeoff between OSNR (the higher the channel power, the better) and nonlinear transmission penalty (the lower the channel power, the better). Figure 4 shows that for fixed nonlinearity, the optimum OSNR is achieved with 6 dB of forward gain. The OSNR per span is 34.6 dB in this case corresponding to 14.6 dB after 100 spans (10,000 km). This is a 0.5 dB improvement compared to a purely backward pumped Raman amplified system with the same nonlinear distortion. Equally important, however, is the fact that the crosstalk from DRBS is 5 dB smaller in a system with 6 dB forward Raman gain than in a system that relies completely on backward Raman amplification. This can be seen from the DRBS curve in figure 4 that shows a reduction of the DRBS level from about ?40 dB (?20 dB after 100 spans) in the system with no forward Raman amplification to about ?45 dB (?25 dB after 100 spans) in the system with 6dB forward gain.

The results shown in figure 4 correspond as mentioned to a nonlinear phase shift per span of 0.007 rad. However, it should be noted that the main conclusion from the figure – that 6 dB forward gain maximizes the OSNR and gives at least 5 dB DRBS reduction compared to no forward gain – is the same for signal power levels up to a level roughly 10 times higher than what was used in figure 4, i.e. up to about 0.07 rad nonlinear phase shift per span.

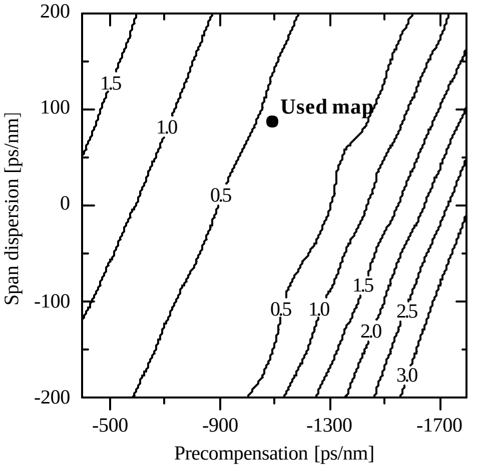

Fig. 3. Simulated eye opening penalty in dB after 10,000 km transmission as a function of the amount of precompensation and the per span dispersion of the first three 100 km spans in the loop. The dot shows the dispersion map used in this transmission demonstration.

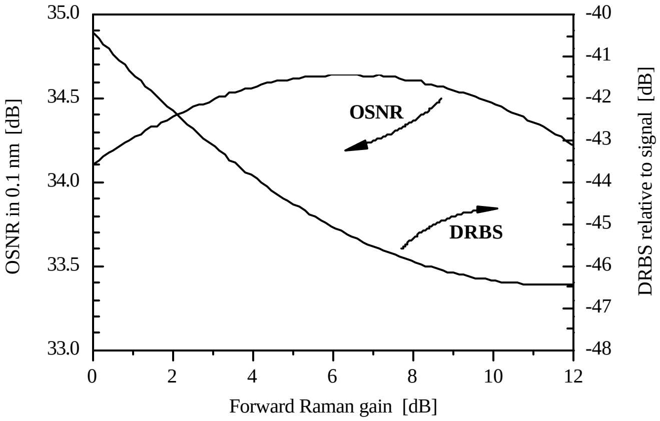

Fig. 4. OSNR and DRBS per span as a function of the forward Raman gain in the transmission fiber.

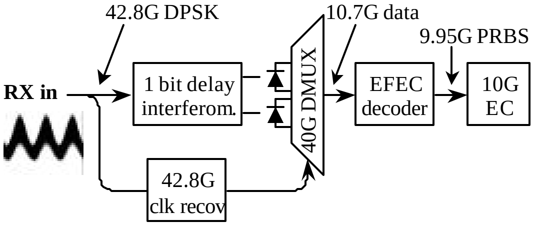

Fig.5. Schematic of the DPSK receiver. “EC”: error counter.

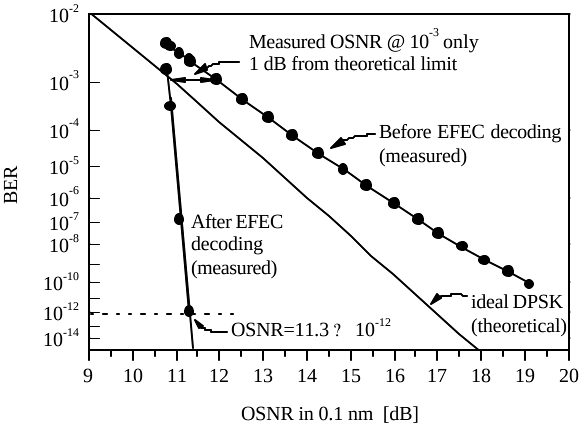

Fig. 6. BER before and after EFEC decoding versus the OSNR. A BER of $10^{?12}$ requires and OSNR of only 11.3 dB.

Finally in the discussion of the transmission link, it should be mentioned that the loop switch in figure 2 includes a dynamic gain flattening filter as well as an EDFA that compensates the loop switch related loss.

C. *Receiver*

After 25 loop round-trips corresponding to 10,000 km, the 40 channel WDM signals is coupled out of the loop by the loop switch and subsequently post dispersion compensated. After demultiplexing by a Gaussian AWG with a 3 dB bandwidth of 50 GHz, a selected channel is sent to the receiver for error counting.

The receiver is shown in figure 5. The core of the receiver is a commercial all-fiber one bit delay interferometer with 23.4 ps differential delay. Light from its two outputs is sent to photo diodes connected directly to the non-inverting and inverting inputs of a 40G 1:4 electrical DMUX. A fraction of the incoming CSRZ-DPSK signal is used to recover a 40G clock for the DMUX. One of the DMUX’s 10G outputs is connected to the EFEC decoder whose output is sent to a 10G error counter. Since the measurements were made in a re-circulating loop, the measured error rate is an average for the four 10G tributaries.

D. *Comparison with previous experiment*

In comparison with our previous 5200 km transmission demonstration [8], the most important improvement of the transmission system used for the current transmission is the introduction of CSRZ-DPSK. However, also lower span loss, lower PMD, improved forward Raman pumps and an optimized dispersion map contribute to the significant increase of the transmission distance.

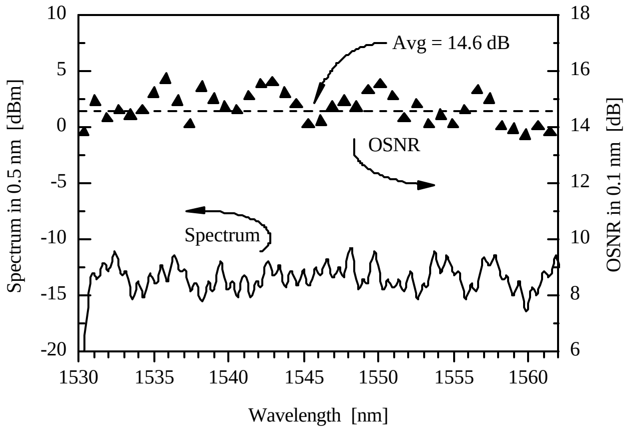

Fig. 7. Received spectrum in 0.5 nm and OSNR, referred to 0.1 nm, after 10,000 km transmission.

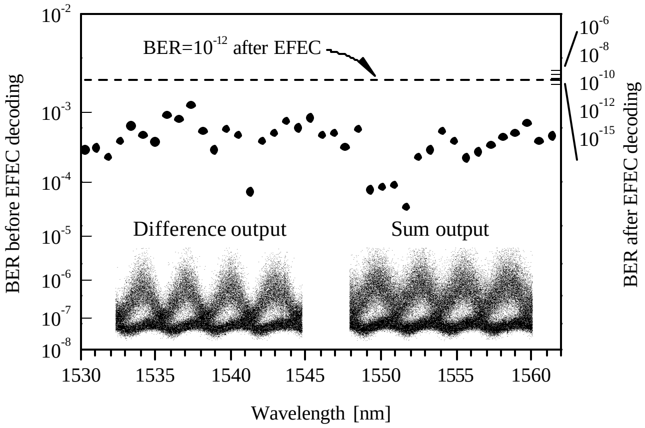

Fig. 8. BER after 10,000 km transmission. The left and right axes show, respectively, the BER before and after EFEC decoding. The two insets show the optical eye diagrams after 10,000 km at the two demodulator outputs (difference output: zero transmission at the signal carrier frequency, sum output: full transmission at the signal carrier frequency).

III. RESULTS

Figure 6 displays the measured back-to-back BER before and after EFEC decoding as a function of the OSNR. An OSNR of only 11.3 dB ensures a BER of $10^{?12}$ after EFEC decoding which we believe is the best reported sensitivity at 40G. The error rate before decoding is $2.3?10^{?3}$ in this case corresponding to 7.8 dB coding gain at $10^{?12}$. This is exactly the same coding gain as we measured for CSRZ transmission [8]. Also shown in figure 6 is the theoretical result

$$\mathrm{BER}\ ?\ 0.5\,?\exp(?2\,?\mathrm{OSNR}\ ??\,B/B)\,?(1\,?\,0.5\,?\mathrm{OSNR}\ ??\,B/B),$$

where $?B/B$ is the ratio of the OSNR bandwidth to the bit rate, for the ideal case of a matched optical filter and no electrical post filtering [17]. The measured sensitivity is 2.6 dB away from this theoretical limit at a BER of $10^{?9}$. However, at a BER of $10^{?3}$, i.e. near the EFEC threshold which is the important BER region in systems with EFEC, the difference is only 1 dB.

The performance after 10,000 km transmission appears from figures 7 and 8. Figure 7 shows the OSNR and the received spectrum. The average OSNR is 14.6 dB in perfect agreement with the simulation. This OSNR corresponds to an effective Raman amplification noise figure of $?8.6$ dB given the $?11$ dBm launch power and 21 dB fiber loss. The channel power variation after 10,000 km is about 5 dB.

Figure 8 shows the BER after transmission. The BER before EFEC decoding is less than $10^{?3}$ for all channels except channel 10 which has a BER of $1.2?10^{?3}$. This corresponds to a BER after decoding much lower than $10^{?12}$ for all 40 channels. To ensure that even the worst channel is indeed error-free after 10,000 km transmission, we measured the BER after EFEC decoding for an extended period of 1.5 hours. In this measurement interval, which corresponds to 10^{12} bits taking the loop duty cycle into account, we detected no errors.

Since a BER of about $10^{?3}$ before EFEC decoding requires an OSNR of about 12 dB back-to-back, the average OSNR of 14.6 dB after transmission corresponds to a transmission penalty of less than 3 dB. We found that this penalty is mainly due to single channel effects since a channel only experienced minor transmission improvements when its neighbors were turned off.

The two insets in figure 8 show the measured optical eyes at the two outputs of the one bit delay interferometer for an arbitrary channel. The eyes are very noisy because of the low OSNR but the shape is still good without obvious signs of PMD.

IV. CONCLUSION

We have demonstrated error-free transmission of forty 100 GHz spaced 40 Gbit/s channels over a trans-Pacific distance of 10,000 km despite a terrestrial span length of 100 km. This record result was achieved using CSRZ-DPSK, all-Raman amplified dispersion-managed fiber spans and enhanced FEC. Our transmitter performs DPSK precoding at 40G and it uses an x-cut Mach-Zehnder modulator for the DPSK phase modulation to eliminate unwanted chirp. The performance of the transmitter/receiver pair is excellent, requiring an OSNR of only 11.3 dB to get a BER of $10^{?12}$. This is only 1 dB from the theoretical limit.

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