Transmission of 40×42.7 Gbit/s over 5200 km UltraWave® fiber with terrestrial 100 km spans using turn-key ETDM transmitter and receiver

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Abstract: We demonstrate error free transmission of 40×42.7 Gbit/s over 5200 km UltraWave® fiber with 100 km span length and 100 GHz channel spacing using turn-key ETDM transmitter and receiver, CS-RZ modulation, enhanced FEC and all-Raman amplification.

Introduction

The price per bit per km is a decisive figure of merit for optical transport systems. This means that long unregenerated transmission distances are very important. The possible transmission distance at 40G continues to increase thanks to advances in forward error correction (FEC), modulation formats, fiber types and amplification schemes. Recent impressive WDM transmission demonstrations include [1-8].

In this paper we report record 40G transmission over 5200 km UltraWave fiber with 100 km spans using turn-key electronic time division multiplexing (ETDM) transmitter and receiver. We used the robust and practical CS-RZ modulation format, all-Raman amplification and enhanced FEC (EFEC). FEC with higher coding gain is a key to increasing transmission distances without adding complexity to the transmitter and receiver. However, especially for 40G ETDM systems, it is important to limit the overhead to avoid penalties due to limited component bandwidth. The EFEC used in our demonstration has 8.7 dB coding gain with 7% overhead. Our demonstration shows that even for terrestrial span lengths, the achievable WDM transmission distance at 40G is approaching transatlantic distances.

Experimental set-up

The 5200 km transmission was demonstrated in a re-circulating loop with 400 km UltraWave fiber. The set-up is very similar to the one used in [1]. Figure 1 shows the ETDM transmitter used in the experiment. It generates 40 CS-RZ channels with 100 GHz spacing in the C-band. Even and odd channels are modulated separately by two 43G transponders in loop-back configuration. The transponders are driven by differently delayed versions of a 42.7 Gbit/s data signal. This signal is formed by electrical multiplexing of four 10.7 Gbit/s signals generated by EFEC encoding a 2^{31}-1 PRBS from a pattern generator (PG). An interleaver combines even and odd channels and dispersion compensating fiber gives -160 ps/nm pre-compensation. The launch power into the transmission fiber is –6.5 dBm per channel. Figure 1 also shows the ETDM receiver together with the post dispersion compensation and the optical DMUX. The receiver is also a 43G transponder in loop-back configuration. It delivers a 42.7 Gbit/s electrical data signal which is demultiplexed into its four 10.7 Gbit/s tributaries that are subsequently FEC decoded and sent to the error counter (EC). The measured BER is the average of the four tributaries.

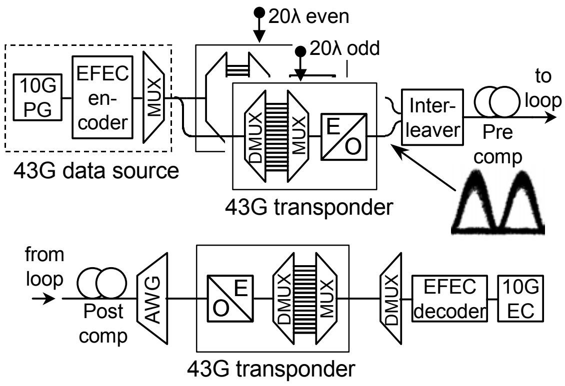

Figure 1: *40G transmitter (top) and receiver (bottom).*

The loop contains four identical, symmetrical 100 km UltraWave spans as shown in figure 2. Each span has a dispersion of 254 ps/nm. 28 km dispersion compensating fiber ("IDF") after the fourth UltraWave spans leads to a net dispersion per loop round-trip of -100 ps/nm. The dispersion map is described in [1].

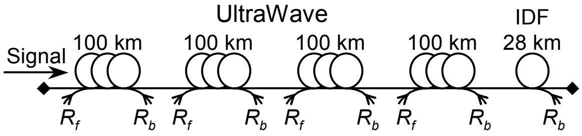

***Figure 2:** The loop: 4×100 km UltraWave + 28 km IDF. R_f: forward Raman pumps. R_b: backward pumps.*

Forward and backward Raman gain compensates the loss in UltraWave spans, couplers and gain flattening filters. Three co-propagating pump waves from semiconductor lasers give a forward gain of 4 dB and two counter-propagating pump waves from fiber lasers provide a backward gain of 22 dB. A gain flattening filter after each UltraWave span reduces the gain variation to ±0.3 dB per span.

The set-up used in this experiment is similar to the one in [1] except for the following improvements that enabled the significant increase of transmission distance: i) EFEC, ii) Smaller rise/fall time of the MUX in the 43G transponder, iii) Inclusion of control loops for the modulators in the E/O part of the transponder giving excellent long term stability, and iv) Reduction of the forward Raman gain to reduce intensity noise transfer from the forward pump (the associated OSNR reduction is only about 0.3 dB).

Results

The EFEC used in this experiment has a coding gain of 8.7 dB at a BER of 10^{-15} – corresponding to 7.8 dB at 10^{-12} – when the receiver noise is Gaussian. It is not obvious that the same coding gain can be obtained after long distance optical transmission since the noise statistics in the receiver might be different. However, the measured results in figure 3 show that an uncorrected BER of $2.3 \cdot 10^{-3}$ is converted into 10^{-12} corresponding to a coding gain of 7.8 dB even after transmission.

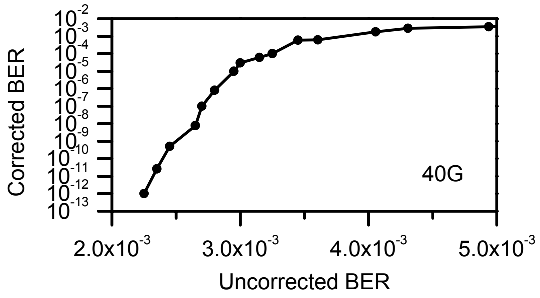

***Figure 3:** Corrected –v– uncorrected BER after transmission.*

The decisive figure of merit for FEC in optical systems is the reduction of the required optical signal to noise ratio (OSNR) at the receiver to get a certain corrected BER. This number is typically greater than the coding gain as illustrated in figure 4. The figure shows measured BER with and without EFEC as a function of the OSNR for the back-to-back case. The use of EFEC reduces the required OSNR by more than 10 dB at a BER of 10^{-12}.

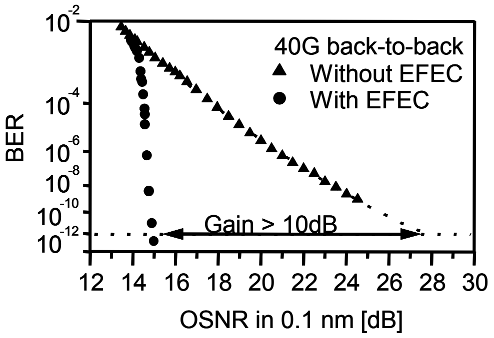

***Figure 4:** BER –v– OSNR with and without EFEC.*

The transmission performance after 5200 km is illustrated in figure 5. The upper graph shows the received spectrum and the OSNR for the 40 channels. The channel power variation is about 4.5 dB indicating very good gain flattening. The OSNR is around 18 dB which is 3 dB higher than the OSNR required for a BER of 10^{-12} back-to-back.

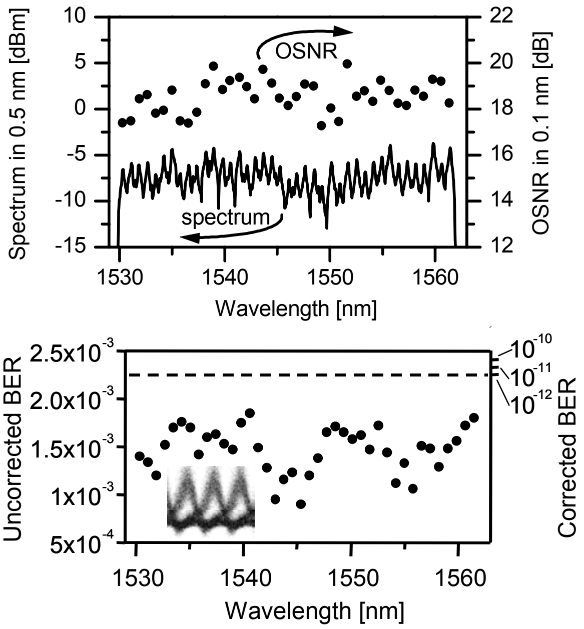

***Figure 5:** 40G transmission performance after 5200 km. Upper graph: the received spectrum and the OSNR. Lower graph: uncorrected and corrected BER. Insert: the received eye of a typical channel.*

The lower graph shows uncorrected and corrected BER after 5200 km. All channels have a BER less than 10^{-12} when EFEC is used. As it can be seen from the eye diagram inserted in the lower graph, the pulse shape is still good after transmission. The limiting effects in this transmission demonstration are mainly single channel effects: ASE noise, self-phase modulation and some PMD. The fact that WDM effects are quite small means that it is straightforward to add additional channels without sacrificing transmission distance.

Conclusions

We have demonstrated error free transmission of 1.6 Tbit/s (40×40 Gbit/s) over a record distance of 5200 km UltraWave fiber with 100 km span length. We used enhanced FEC with 7% overhead and 8.7 dB coding gain, practical CS-RZ modulation and turn-key 40G ETDM transmitter and receiver. The fiber loss was overcome with all-Raman amplification. In conclusion, we have shown that even for terrestrial span lengths, WDM transmission at 40G is possible over distances approaching transatlantic distances.

Acknowledgement

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