

1.6 Tbit/s (40×42.7 Gbit/s) transmission over 3600 km UltraWave™ fiber with all-Raman amplified 100 km terrestrial spans using ETDM transmitter and receiver

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Abstract: We demonstrate error free transmission of 40×40 Gbit/s over a record distance of 36×100 km UltraWave™ dispersion managed fiber with all-Raman amplification and 100 GHz channel spacing. CS-RZ modulation and 43 Gbit/s ETDM transmitter and receiver are used.

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Introduction

Lower cost per transmitted bit and emerging 40 Gbit/s router interfaces are the main drivers for 40 Gbit/s transport. Today, cost effective 40Gbit/s terminal equipment is becoming available whereas ultra-long haul 40 Gbit/s transport is still very challenging. However, new techniques such as carrier-suppressed RZ (CS-RZ) modulation format, distributed Raman amplification and new fiber types continue to increase the achievable transmission distance for 40 Gbit/s [1-6]. For systems with terrestrial span length, actual demonstration of error free transmission has been made for up to 2000 km (20×100 km) in an experiment using ETDM transmitter [1]. It should, however, be noted that most long distance 40 Gbit/s transmission demonstrations are performed with either optical time demultiplexing receivers or without actually demonstrating error-free performance (i.e., FEC assumed but not implemented).

In this paper we demonstrate error-free transmission of 40 channels at 40 Gbit/s over a record distance of 3600 km UltraWave™ fiber with a terrestrial span length of 100 km. The dispersion managed fiber spans are symmetrical so that the fiber can be used equally well for transmission in both directions which is very important for terrestrial systems. The fiber loss is compensated by distributed Raman amplification only. Importantly, the record distance is obtained with ETDM transmitter and ETDM receiver and without using polarization interleaving.

Experimental set-up

The 36×100 km transmission distance is demonstrated in a 400 km loop setup which is shown schematically in figure 1. The transmitter generates 40 channels in the C-band at ITU wavelengths from 1530.33 nm to 1561.42 nm with a spacing of 100 GHz. Odd and even channels are modulated separately by two transmitter boards with two cascaded LiNbO₃ Mach-Zehnder modulators. The first modulator impresses NRZ data modulation at 42.657 Gbit/s and the second modulator driven by 21.329 GHz clock converts the NRZ signal into a CS-RZ signal with approximately 50% duty cycle. Odd and even channels are modulated with data and delayed inverted data, respectively. The 42.657 Gbit/s data signal is formed by electrically multiplexing four 10.664 Gbit/s 2³¹-1 PRBS. A RS(255,239) FEC encoding can be enabled or disabled. The even and the odd channels are finally combined with

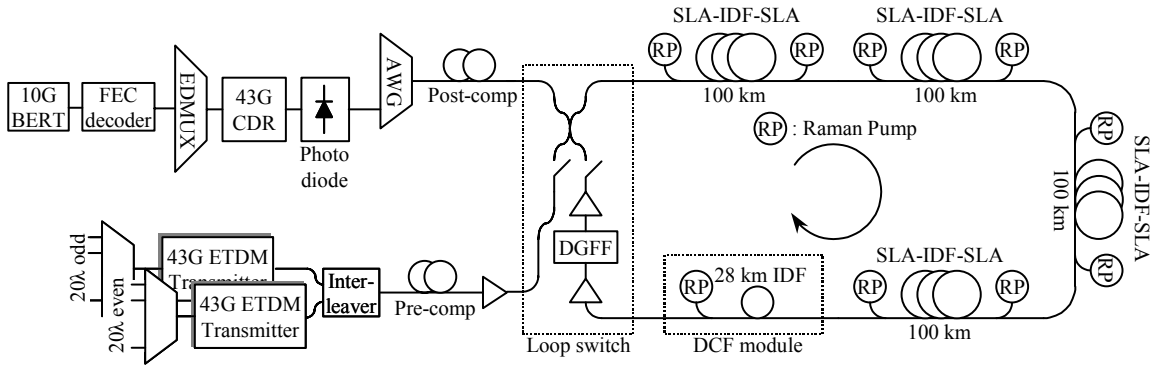


Fig. 1. Experimental set-up. (BERT: Bit Error Rate Test-set, CDR: Clock & Data recovery, DGFF: Dynamic gain flattening filter, EMUX: Electrical Demultiplexer, GFF: Gain flattening filter, IDF: Inverse dispersion fiber, RP: Raman Pump, SLA: Super large effective area fiber)

arbitrary polarizations in a wavelength interleaver and sent through a dispersion compensating fiber to obtain the desired -160 ps/nm of pre-compensation. The average channel power into the transmission fiber is -7 dBm.

The loop contains four identical 100 km spans of UltraWave™ Terrestrial dispersion managed fiber [1]. The spans are symmetrical and consist of 35.5 km super large effective area fiber (SLA, dispersion 20 ps/nm/km, effective area $107 \mu\text{m}^2$) followed by 29 km perfectly slope matched dispersion compensating fiber (“Inverse dispersion fiber”, IDF, dispersion -40 ps/nm/km, effective area $31 \mu\text{m}^2$) followed by additional 35.5 km SLA leading to a span net dispersion of 254 ps/nm. After the four SLA/IDF spans follows additional 28 km IDF to get a net dispersion per loop round trip of about -100 ps/nm corresponding to the dispersion map shown in figure 2a. It was found in computer simulations that this semi-periodic dispersion map has far better transmission properties than traditional dispersion maps where the same basic span is repeated in a completely periodic fashion.

Distributed Raman amplification is used to compensate the loss of the four SLA/IDF spans. Semiconductor lasers provide three depolarized Raman pump waves (1440, 1455 and 1487 nm) co-propagating with the signal to give a forward gain of about 7.5 dB and two counter-propagating Raman pump waves (1427 and 1455 nm) provided by fiber lasers give about 18.5 dB of backward gain. The counter-propagating pump waves are coupled to the transmission fibers by circulators to eliminate possible reflections. A fixed gain flattening filter after each SLA/IDF span reduces the peak-to-peak gain ripple per span to less than 1 dB. The net gain of a SLA/IDF span is 3.5 dB to accommodate the losses in the couplers/circulators for the Raman pumps and the gain flattening filters. Figure 2b

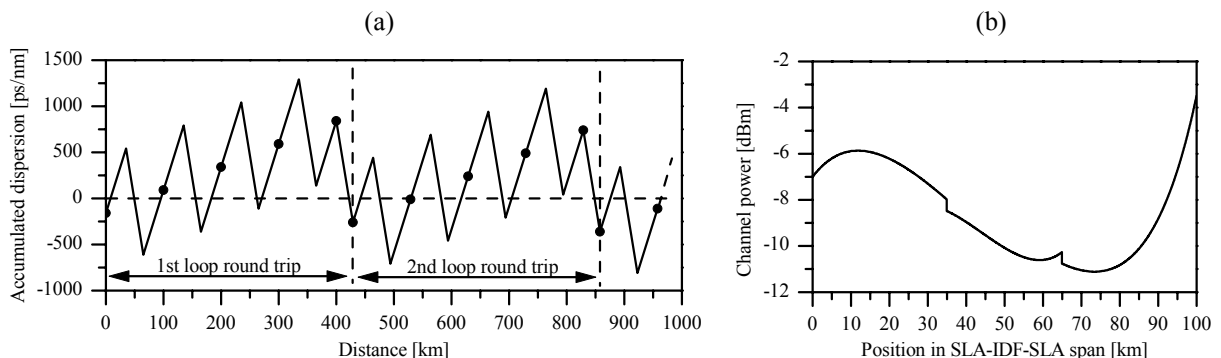


Fig. 2a. The first 1000 km of the dispersion map (the dots indicate start/end points of SLA/IDF spans).

Fig. 2b. The evolution of the channel power throughout a single SLA-IDF-SLA span.

shows the evolution of the channel power in a SLA/IDF span. The path average power is 5.8 dB higher than without the Raman amplification. Distributed Raman amplification is also used to compensate the loss of the 28 km IDF.

In addition to the transmission fiber, the loop contains a dynamic gain flattening filter and two EDFAs to compensate for the loss in the loop switch and the dynamic gain flattening filter.

The WDM signal at the output of the loop switch is post dispersion compensated and then demultiplexed in an AWG so that the selected channel can be sent to the receiver for BER measurement.

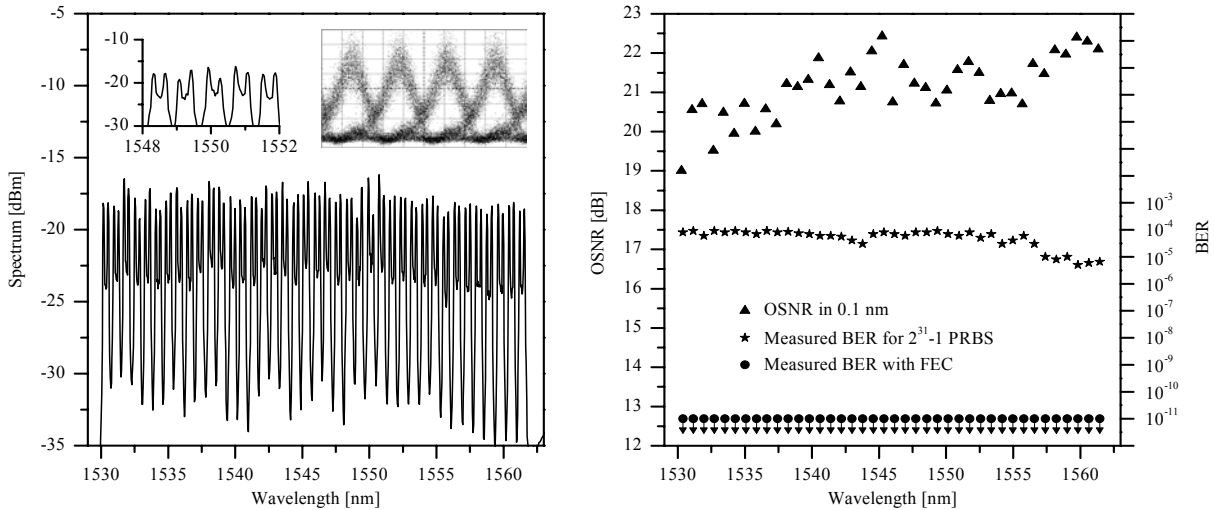


Fig. 3. Transmission performance after 3600 km. To the left: The received optical spectrum and the eye diagram for the channel at 1549.32 nm (the worst channel). The insert shows more clearly the shape of the individual WDM channels. To the right: The OSNR, the BER for a 2^{31} -1 PRBS and the BER when FEC is used.

A 43 Gbit/s ETDM receiver was used in the experiment. It consists of a photo diode and a 43 Gbit/s clock and data recovery that extracts the 42.657 Gbit/s electrical data signal. This signal is demultiplexed into the four 10.664 Gbit/s tributaries which are subsequently FEC decoded to get the 9.953 Gbit/s PRBS. The measured BER is the average of the four tributaries.

Results

The optical spectrum after 3600 km transmission is shown in figure 3 together with the eye diagram for a selected channel (the channel with the highest BER). The eye indicates a good pulse shape even after 3600 km and there are no signs of PMD. The spectrum shows that the channel power variation after 3600 km is as low as 3 dB proving very tight control of the combined gain shape of the Raman amplification and the gain flattening filters.

The optical signal to noise ratio (OSNR) in 0.1 nm bandwidth is also shown in figure 3. Values vary from 19.0 dB to 22.4 dB. An OSNR of 21 dB after 36 spans corresponds to an effective noise figure of -8.1 dB for the considered span loss of 22.5 dB. However, the distributed Raman amplification increases the path average power with 5.8 dB in our system so to have the same influence from nonlinearities as in a non-Raman system, the input power must be reduced by approximately 5.8 dB. This means that the performance of our system is comparable to a hypothetical non-Raman system using amplifiers with a noise figure of -2.3 dB.

Finally, figure 3 shows the BER for transmission of a 2^{31} -1 PRBS (i.e. without FEC) and the BER when FEC is used. The BER without FEC is between $6 \cdot 10^{-6}$ and $9 \cdot 10^{-5}$ for all channels. This remarkably small variation in channel performance is partly due to the employment of up to 2 dB pre-emphasis. When FEC is used, all channels have a BER smaller than 10^{-11} . This was verified by measuring each channel for more than $3\frac{1}{2}$ minutes without counting any errors; $3\frac{1}{2}$ minutes corresponds to 10^{11} bits taking into account the duty cycle of the loop and the fact that error counting is done at 9.953 Gbit/s.

The match between the dispersion slopes of the positive and the negative dispersion fibers used in this experiment is excellent meaning that the total dispersion after 3600 km (including post-compensation) changed by only 200 ps/nm over the C-band.

Conclusion

We have demonstrated error free transmission of 1.6 Tbit/s (40×40 Gbit/s, 100 GHz channel spacing) over a record distance of 3600 km UltraWave™ dispersion managed fiber with a terrestrial span length of 100 km. The fiber spans are symmetrical which is important for terrestrial systems. The fiber loss is compensated by distributed Raman



amplification only. The 43 Gbit/s transmitter and the receiver are of the ETDM type. All channels were measured to be error free when FEC is used. The results were obtained without using polarization interleaving.

Acknowledgement

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