Record 500 km unrepeatered 1 Tbit/s (10x100G) transmission over an ultra-low loss fiber

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Abstract: In this work we experimentally demonstrate 1 Tbit/s (10 x 100 Gbit/s) unrepeatered transmission over 500.5 km using dual polarization quadrature phase shift keyed (DP-QPSK) format and real-time processing. Such ultra-long distance is enabled by the use of high-performance 100G DP-QPSK transponders (the required optical signal-to-noise ratio is 12 dB), ultra-low loss Corning SMF-28 ULL fiber (the average attenuation of the spools used in this experiment <0.160 dB/km), and optimization of remotely-pumped optical amplifiers. To the best of our knowledge this is the longest unrepeatered 100G-based 1 Tb/s WDM transmission distance reported to date.

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

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1. Introduction

Ultra-long-distance unrepeatered optical fiber transmission systems are essential in connecting islands to the mainland, providing connectivity to offshore oil and gas rigs, and deploying coastal networks linking a large number of landing points (festoon application). Being able to achieve high data rates over long distances is a desired task for many network operators around the world. Unrepeatered optical fiber links with the distances of 300-500 km represent a particular interest over areas with difficult terrain and uneasy access to electricity, which makes the construction and powering the amplifier huts prohibitively expensive. In this context, a number of research groups have recently studied the maximum achievable distances at 100G [1–4]. In a recently published work [5], 557 km of unrepeatered distance was achieved in a single-channel 100G experiments, and 523 km in 4x100G configuration.

In the present work we report 10-wavelength transmission of 100G DP-QPSK signal over 500km. This extends our previous work where 100G DP-QPSK was transmitted over 500km in a single-channel experiment. To the best of our knowledge, the results shown in this work

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are the first ones to demonstrate 500 km unrepeatered transmission of 1 Tb/s wavelength-division multiplexed (WDM) signal based on 100G coherent technology.

2. Experimental set-up

Figure 1 shows a schematic diagram of 10 WDM-channel 120 Gbit/s transmission experiment over 500.4 km. The output 100G signals from 10 transponders, commercially known as “Volga”, were first combined via the multiplexer (MUX) to create a WDM signal and then passed through a section of a dispersion compensating fiber (DCF) to provide chromatic dispersion pre-compensation. The optimum amount of dispersion pre-compensation was found to be −1300 ps/nm [4]. A 100G WDM signal was subsequently amplified to an overall power of 20.5 dBm, which corresponds to the per-channel launch power into the fiber of 10.5 dBm.

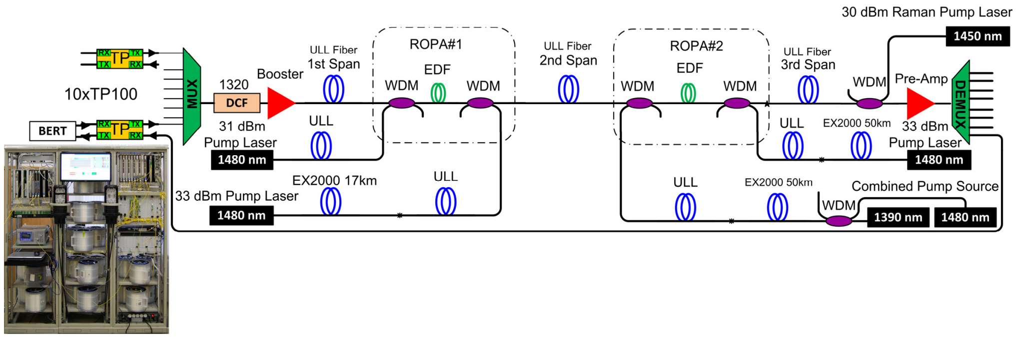

Fig. 1. Schematic diagram of the experimental setup.

The unrepeatered optical fiber transmission line consisted of 3 sections of Corning SMF-28 ULL fiber with lengths of 52.8, 303.3 and 146.7 km to create an overall fiber span of 502.8 km. However, the total fiber length for pump power delivery to remotely pumped optical amplifiers (ROPAs) was 500.5km (signals and pump power were transmitted over two separate fibers). The losses of fiber sections (including splicing losses) were measured to be 8.53, 47.3 and 23.2 dB, respectively (79 dB in total). The average attenuation in the 3 fiber sections was found to be: 0.162, 0.156 and 0.158 dB/km, respectively.

To form remotely optically pumped amplifiers (ROPAs) we used Erbium Doped Fiber Amplifiers (EDFAs), pumped over two separate optical fibers at 1480nm. The maximum power into the section used for ROPA pumping was limited by the spurious lasing threshold due to the presence of Raman effect and non-resonant distributed feedback from Rayleigh scattering. The maximum pump power launched into SMF-28 ULL fiber (effective area is 83 μm^2) was determined to be 31 dBm. Three of out of four sections used for ROPA pumping also contained Corning Vascade EX2000 fibers (effective area of 112 μm^2) with the length of at least 20km. The use of Vascade EX2000 enabled an increase of the maximum launch power to 32.5 - 33 dBm

One of the main characteristics of single-span transmission system is optimal signal power launched into line, when the maximum OSNR margin is achieved. This optimal power primarily depends of fiber type and slightly (within the range of 1 dB) depends on length of the link. For SMF-28 ULL fiber and transponder “Volga” used this quantity was found to be 14 dBm. Due to presence of transmitter-side ROPA in the described experimental setup it’s necessary to take into account the nonlinearity from the second span, so the link becomes double-span equivalent.

Since ROPA1 was operating in a strong saturation mode, the signal output power was almost proportional to the power of the pump wavelength [Fig. 2(a)]. The distance from the transmitter and ROPA1 was optimized by ensuring that the ROPA1 output power has reached the threshold at which nonlinear effects become pronounced.

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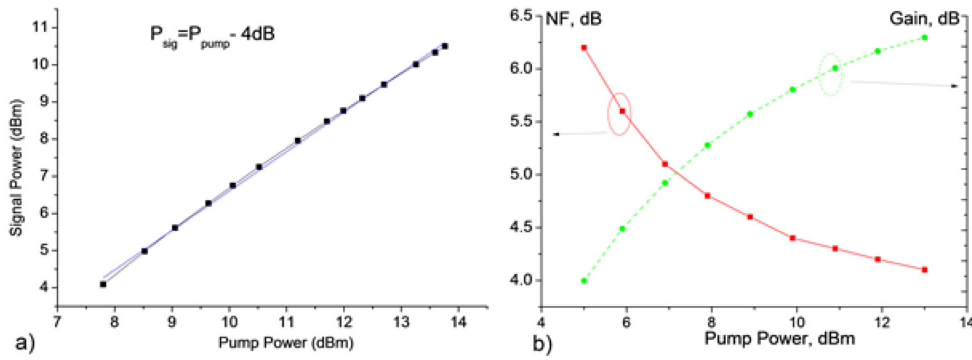

Fig. 2. a) ROPA1: Measured output power as a function of pump power in the saturation mode, input power is −2.5 dBm; b) ROPA2: Correlation between noise figure (solid red curve) and gain (dashed green curve) for an amplifier operating in a small signal gain. All measurements are performed for 193.5 THz channel.

The transmission and the two pump section lengths used in this experiment were measured to be 52.8, 50.5 and 50.4 km, respectively. Each of the two paths for pump delivery to ROPA1 consisted of SMF-28 ULL fiber, with 17km of Vascade EX2000 additionally used in one of the pump delivery paths. To estimate the fiber attenuation at the pump wavelengths we used the following methodology: the average fiber attenuation at 1550nm was first measured using an Optical Time-Domain Reflectometer (OTDR) and found to be 0.159 dB/km in both pump delivery paths (including splice losses). We then added an average increase in attenuation of 0.035 dB/km to account for the difference between the pump attenuation at 1480nm and the measured attenuation at 1550nm. The average attenuation at the 1480nm pump wavelength was, therefore, estimated to be 0.194 dB/km (9.8 dB total loss per fiber section). For ROPA1 pumping we used two lasers with output powers of 31 dBm and 33 dBm, respectively, and both operating at 1480nm. The total power in the beginning of pump delivery section was 35.1 dBm, and the pump power that reach ROPA1 was 25.3 dBm. The output power after ROPA1 was measured to be 21.3 dBm, or 11.3 dBm/channel. In conjunction with 10.5 dBm of optical power incident into the first span, it corresponds to total nonlinear phase shift for optical power 13.9 dBm/channel launched into single span configuration.

For a ROPA pumped from the receiver end, in the majority of practical configurations the output power is below the saturation power. This means that such ROPA is operating in the weak signal amplification regime, where gain and noise figure are independent of the input power and depend only on pump power. For the ROPA used in this experiment (which contained 8 meters of active fiber), such correlation is shown in Fig. 2(b). In this case, the OSNR at the output of ROPA2 is directly proportional to the input signal power, and the attenuation in the middle transmission fiber section significantly affects the overall bit error ratio (BER). For that reason, for the middle transmission fiber section we used fiber spools with the lowest available attenuation. The splice losses in this fiber section were measured to be below 0.02 dB.

For the given position of ROPA1, the optimum position of ROPA2 was determined from the dependence of OSNR on the distance between ROPA2 and the receiver (when only one WDM channel was transmitted) using Friis formula as shown in Fig. 3. In those calculations, the impact of Amplified Spontaneous Emission (ASE) noise from ROPA1 was neglected, and we assumed that the main contributions to OSNR were coming from ROPA2. The attenuation on pump wavelength was estimated to be 0.190 dB/km, and the attenuation on signal wavelength – 0.156 and 0.158 dB/km, for the middle and last fiber sections, respectively (the total pump power at 1480nm was 35 dBm). The OSNR on Fig. 3 was calculated using the experimentally obtained values for EDFA noise Fig. (6 dB), Raman gain (30 dB) and Raman noise figure (−1.8 dBm).

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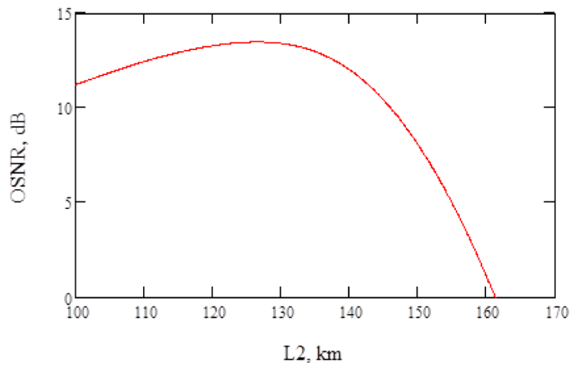

Fig. 3. OSNR dependence from the distance between ROPA2 and the receiver end.

For ROPA 2 pumping we used two hybrid fiber paths with the length of 147.6 and 147.2 km. Each section consists of SMF-28 ULL and 50 km of Vascade EX2000 fiber to increase maximum level of launch pump power. The pump source for one of the fiber paths contained a high-power 2 W laser, operated at 1480 nm. For the second fiber path, we used two pump sources: the first was a 2 W laser operated at 1390 nm to provide 2nd-order pumping; the second source contained a semiconductor laser with output power of 20 dBm, operated at 1480nm. The fiber loss (at pump wavelength 1480 nm) for the two pump delivery paths were measured to be 28 and 29 dBm, respectively. To compensate for the losses in the last transmission fiber section we also used a distributed Raman amplifier with a counter-propagating pumping at 1450nm (Fig. 1). The Raman pump power was 29.4 dBm, and Raman on-off gain in the SMF28 ULL fiber was measured to be 30 dB.

The spectral dependence of gain and noise figure for ROPA2 measured at the same conditions as in the main experiment are presented on Fig. 4. As one can see, we observe significant rising of noise figure up to shorter wavelengths. It explains the choice of set of long-wavelength channels for 1 Tb/s transmission.

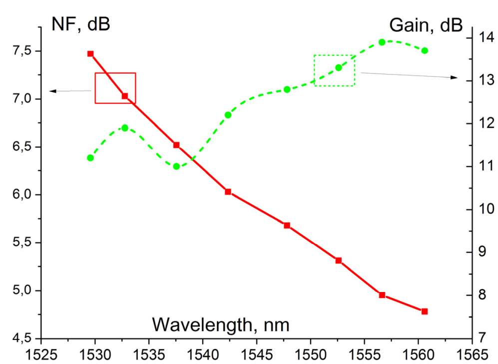

Fig. 4. Spectral dependence of gain and noise figure for ROPA2.

Direct measurements of pre-FEC BER performance of transmission system depending on spectral channel number are presented in [4].

3. Experimental results and discussion

To study the 10x100G performance we measured the bit error ratio (BER) of each channel during the WDM transmission, which were located on the 100 GHz ITU-T frequency grid. The launch power into each WDM channel was optimized to minimize the pre-FEC BER difference across all ten transmitted channels. The real-time BER measurements over the course of 8 hours showed excellent stability and are shown in Fig. 5. The transponders

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“Volga” used in this experiment employed soft-decision FEC, with the pre-FEC threshold of $1.91 \cdot 10^{-2}$ [6].

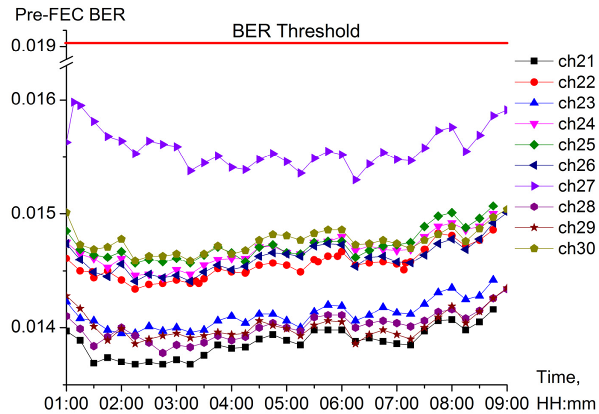

Fig. 5. Long term pre-FEC BER measurements.

Additionally, the absence of post-FEC errors on the client side was monitored using a BER-analyzer. The spectrum at the end of the transmission line was measured using a monitor output of the pre-amplifier and is shown on Fig. 6. For the 10 WDM received channels the OSNR (normalized to the bandwidth of 0.1 nm) varied from 13.44 and 14.15 dB.

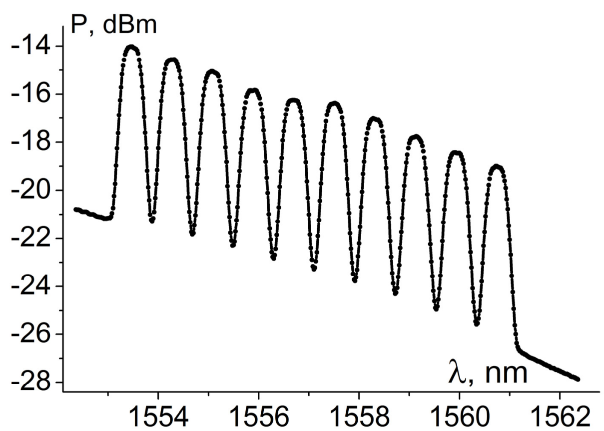

Fig. 6. The spectrum of 10 received WDM channels measured after the pre-amplifier at the receiver side at the resolution bandwidth of 0.5 nm.

The power of 10 WDM channels at the output of ROPA1 was equalized by tuning output powers of each WDM channel at the transmitter. To achieve this equalization the signal power of shorter wavelengths was slightly enlarged because they effectively pump long wavelength channels in strongly saturated ROPA1. However, due to the joint gain slope of ROPA2 and distributed backward Raman amplifier with pump wavelength 1450 nm, the spectral power profile of 10 WDM channels was tilted with an estimated slope of 0.7 dB/nm (Fig. 5). The simulated power evolution as a function of distance is shown on Fig. 7(a), where the presence of ROPA1, ROPA2 and backward-pumped Raman amplifier are clearly visible (52.8 km - ROPA1 location, 358.8 km – ROPA2 location, 358.8-505.5 km – backward pumped Raman). Figure 6(b) shows the evolution of OSNR (0.1 nm noise bandwidth) as a function of distance. The OSNR at the input of the fiber is 50 dB, and did not change significantly during the first transmission section (0 – 52.8 km), since both the signal and ASE noise are attenuated by an equal amount. The signal at the input of ROPA1 contained a

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significant amount of ASE noise, so the change in OSNR after passing through ROPA1 was significantly smaller than the noise figure of this amplifier (approximately 6 dB).

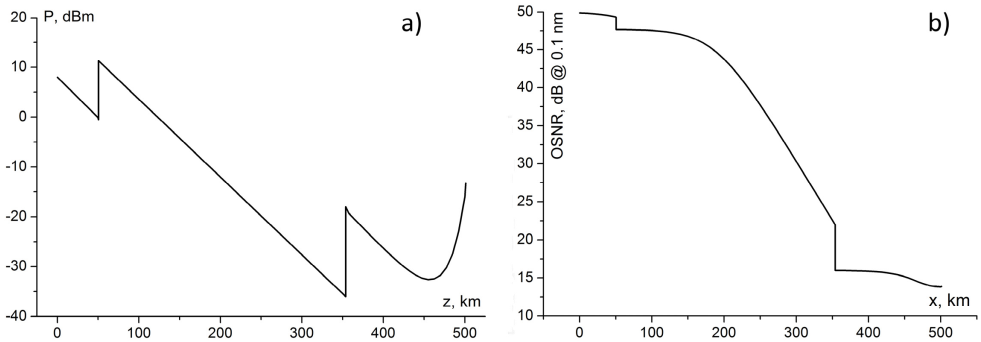

Fig. 7. Evolution of (a) Power vs. distance; (b) OSNR vs. distance. Both at 1556.6 nm.

The signal at the output of ROPA1 still contained a significant amount of ASE noise. Up to 150km both signal ASE noise powers were attenuated equally, therefore, the OSNR did not incur a significantly reduction. From approximately 150-200 km the ASE noise power became smaller than the quantum noise threshold, causing a significant decrease in OSNR. After 200 km ASE noise power became equal to quantum noise power, therefore, OSNR started to decrease proportionally to the decrease in signal power (the slope of the OSNR curve was determined by fiber attenuation). The most critical parameter needed to achieve the maximum level of OSNR is the noise figure of ROPA2 (equal to ~5 dB). The use of backward pumped Raman amplifier in the 3rd transmission section allowed to decrease the noise level – the received OSNR was 13.8 dB, which was sufficient for post-FEC error free operation. Finally, the optical powers for each channel were slightly predistorted to equalize pre-FEC BER values.

It must be noted that the number of transmitted WDM channels was limited by the available power of the optical amplifier. We observed that in such a WDM link the total power at the output of ROPA1 almost does not depend on the number of channels (N_{CH}). However, the power per channel was reduced by approximately N_{CH} compared to the signal power in a single-channel transmission. It was, therefore, essential to increase the pump power, which could be done by only reducing the distance from the transmitter to ROPA1. The increase in the maximum achievable length ΔL of a WDM link (compared to a single-channel link) was calculated using the following formula:

$$\Delta L = \frac{10 \cdot \log\left(N_{CH}\right)}{\alpha} \tag{1}$$

where α is the fiber attenuation at the pump wavelength. In most practical cases, a forward-pumped ROPA does not provide a significant gain when the number of WDM channels N_{CH} is greater than 10.

4. Conclusion

In this work we achieved 10x120 Gb/s DP-QPSK unrepeatered transmission over 500 km using commercially available T8 "Volga" transponders and ultra-low loss Corning SMF-28 ULL fiber. To the best of our knowledge, this is the longest 100G WDM unrepeatered transmission reported to date. Such record result was achieved through the optimization of the powers and locations of the two ROPAs, optimal dispersion pre-compensation, ultra-low-loss Corning SMF-28 ULL fiber, and low required OSNR of T8 "Volga" transponders. To the best of our knowledge, this is the longest unrepeatered 100G-based transmission distance with an overall capacity of 1 Tb/s.

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