25.6 Tbit/s (64x400Gb/s) Real-time Unrepeatered Transmission over 320 km SCUBA Fibres by 400ZR+ Pluggable Modules

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Abstract *We report a record real-time unrepeatered experiment with 64 single-carrier 400Gb/s channels transmission over 320.5km fibre, applying large-area ultra-low loss fibre with average attenuation of 0.146dB/km, high power booster, and backward-propagating 2nd-order Raman without ROPA.*

Introduction

The unrepeatered systems are targeted to transmit the largest capacity over the longest transmission distance without any in-line active elements such as amplifier pumps, thereby reducing the line complexity and system cost. It provides an economical solution for undersea applications such as coastal festoons and island hopping, and for terrestrial routes in the remote hostile areas.

The key techniques for unrepeatered systems include large-area ultra-low loss (ULL) fibre, high-power booster at transmitter, forward- and backward-propagating Raman pumps, remote optically pumped amplifier (ROPA)[1-7]. It has also been shown that dedicated fibres can be used to deliver high pump powers to ROPAs to improve amplification process, thus, to increase the reach [3-4,8]. One of recent investigation trends for unrepeatered systems has been focused on transmitting ultra-high capacity over moderate distances [5-7], while simplifying system complexity, for example, to avoid forward-Raman amplifications. Real-time transmission of 24Tb/s capacity has been achieved over 349km with 120 200Gb/s by using high-power booster and a ROPA with 3rd-order Raman pumping from the receiver end [5], however, the ROPA also adds system complexity. 29.2 Tb/s capacity unrepeatered transmission over 295km with probabilistically shaped 49GBd 64QAM signals using off-line processing is reported without ROPA [6]. Er-Yb double-cladding pumped high power amplifier is used above experiments [5-6]. A record capacity of 80.2 Tb/s with off-line processed probabilistically shaped 49GBd 64QAM signal is reported to transmit over 257.5km using an ultra-wideband semiconductor optical amplifier and backward-propagating Raman pumps without ROPA [7]. Another research trend is to carry single-carrier 400G for unrepeatered transmissions [6-8], for example, 24x400Gb/s PDM-16QAM off-line processed signals are transmitted over 430 km using forward- and backward-propagating Raman, two ROPAs, and dedicated fibres for the ROPA pumps, resulting in 3 fibres for unidirectional transmission [8]. However, high capacity real-time unrepeatered transmission with single carrier 400Gb/s has not been reported.

In this paper, we report real-time unrepeatered transmission of 25.6Tb/s, sixty-four 400Gb/s single carrier DWDM signals with 75GHz channel spacing, over 320.5km fibre using low cost commercially available 400ZR+ pluggable coherent transceiver modules. It takes advantages to use the large-area ultra-low loss fibre with the average loss of 0.146dB/km at 1550nm and is achieved by using a new-designed high-power EDFA booster with output power 30+dBm, and backward-propagating 2nd-order pumped Raman amplification without ROPA. To the best of our knowledge, this is the first time to report single-carrier 400Gb/s *real-time* unrepeatered transmission with capacity large than 25Tb/s and reach over >300km without using ROPA and forward-propagating Raman pumps. This work demonstrates a simple low-cost practical solution for ultra-high capacity (>25Tb/s) unrepeatered transmission system over a moderate distance (>300km).

Experimental Setup

A schematic diagram of experimental set-up is shown in Fig. 1. The transmitters consist of one loading and one measurement path. For the measurement path, three 400Gb/s channels using commercially available 400ZR+ coherent pluggable transceiver modules are set to adjacent channels with 75 GHz spacing and then combined together. The loading path is composed of a broadband ASE source with wavelength ranging from 1529.32nm to 1567.14nm and is notch-filtered by a 50GHz channelized wavelength selective switch (WSS) filter. The 400ZR+ uses open-FEC (O-FEC) which can correct a bit-error-ratio (BER) of ~ 1.89×10^{-2} (Q^2-factor =6.35dB) to BER lower than 10^{-15}. The combined signals are amplified by high power EDFA booster, then sent to the

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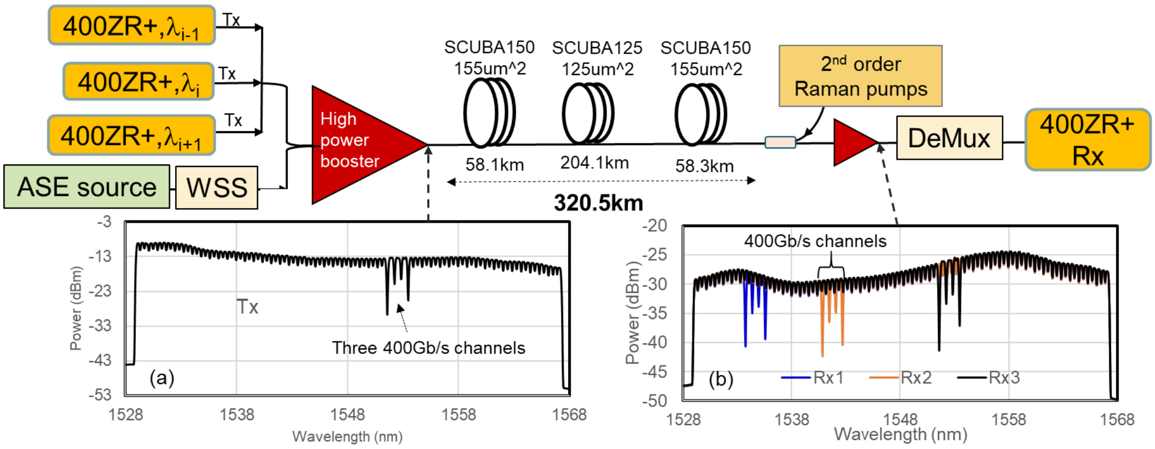

Fig. 1: The unrepeatered transmission experimental set-up, (a) transmitter signal optical spectrum recorded after booster, (b) receiver signal optical spectrum recorded before demultiplexer (Demux).

transmission fibre link.

The booster has two stages, in which, the first stage using OFS MP980 EDF is forward-propagating pumped by a 980nm diode, and second stage uses a large-mode-area (LAM) EDF and is backward-propagating core-pumped by a high power 1480nm fibre laser. The LAM EDF has a core diameter of 13.2µm, and peak-absorption of 84dB/m; only 1.0m length LAM EDF is used in second stage to mitigate nonlinear effect. Between 1st and 2nd stages is a gain-flattening-filter (GFF). The EDFA booster has 25dB gain and 30+dBm output power with bandwidth 38.4nm in C-band. The output gain spectrum of the booster is designed in such that the short wavelength channels have relatively higher powers than that of long wavelength. Since stimulated Raman scattering (SRS) transfers energy from the short to the long wavelength as discussed below, this "pre-emphasis" signal power is applied before fibre link to compensate the SRS and the difference in fibre attenuation from the fibre link. The output spectrum after booster is shown in the inset (a) of Fig.1, showing the combination of three consecutive 400Gb/s measurement channels on a 75GHz grid and loading ASE channels.

The 320.5km long transmission link consists of two types of OFS Silica-Core Ultra-Big-Area (SCUBA) fibres [9]: SCUBA150 and SCUBA125; both are G.654D compliant ocean fibre. The SCUBA150 fibre has the effective area (A_{eff}) of 155µm^2 and average attenuation of 0.1450dB/km at 1550nm, while SCUBA125 fibre has A_{eff} of 125µm^2 and attenuation of 0.1469dB/km at 1550nm, resulting the link fibre average loss of 0.1460 dB/km. In addition, the SCUBA fibre has low water-peak loss of 0.57dB/km around 1383nm, which benefit in distributed Raman amplified system. The SCUBA150 fibre spans are located at both ends with 58.1km at the transmitter side, and 58.3km at the receiver side; and 204.1km SCUBA125 is in middle of link. The total link loss is 47.3 dB at 1550 nm including splices. The signals are backward-propagating Raman amplified by 3 semiconductor lasers at wavelength 1429nm, 1447nm, and1465nm as the 1st-order Raman pumps, which are amplified by 2nd-order Raman pump using a high-power fibre laser at 1363nm. Finally, the signals are amplified by an EDFA and then sent to de-multiplexer (DeMux). The selected channel is then sent back to the 400ZR+ receiver. When assessing the system performance, the three 400ZR+ channels are loaded with equal launch powers, and we measure the middle channel among 3 consecutive 75GHz-spaced channels as they are translated across the C-band.

Experimental Results and Discussion

The system performance is jointly optimized with total signal launch power and backward-pumped powers for distributed Raman amplification. The backward-pumped powers of the 1429, 1447 and 1465nm semiconductor lasers are adjusted to be 290, 100 and 150mW respectively aiming to have flattened signal spectrum at receivers, and the powers of 2nd-order pump fibre lasers at 1363nm is varied. To simplify the optimization process, a rough optimum for each power is found first; then one of the powers is scanned while other is fixed. Fig.2 (a) shows the Q^2-factor of the two channels at 1530.53nm and 1554.34nm as a function of total launched power when 2nd-order 1363nm Raman pump powers is set to be around 2.6W. The total optimal signal launch power for short wavelength channel 1530.53nm is slightly less than 29.5dBm, while for the longer wavelength channel, it is about 29.7 dBm. In the experiment, a total launch power of 29.6dBm (11.54dBm per channel) is used. Fig. 2(b) shows the Q^2 performance 2nd-order pump (1363nm) power, while total input power is fixed at ~29.6dBm, and

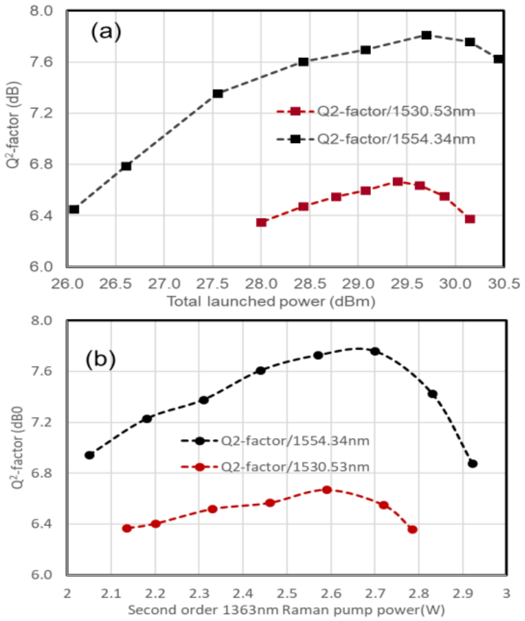

Fig.2: Q^2-factor of channel 1530.53 and 1554.34nm vs total signal launch power when 1363nm pump power was fixed; (b) Q^2-factor vs 2^{nd} -order pump power when the total signal launched power fixed at ~29.6dBm.

the optimum power of 2^{nd}-order pump is around 2.6~2.7W. The Q^2-factor performance of short wavelength is much worse than that of longer wavelength channels.

Inset (b) of Fig.1 plots three optical spectra at receiver when the 400Gb/s measurement channels are translated different locations across C-band, showing uniform loading of the 400ZR+ signal channels. The received power variation between channels is less 5dB. Although the channels are pre-emphasised at the fibre line input as aforementioned, the short wavelength channels still have lower power as well as lower OSNR than that of long wavelength. One of the

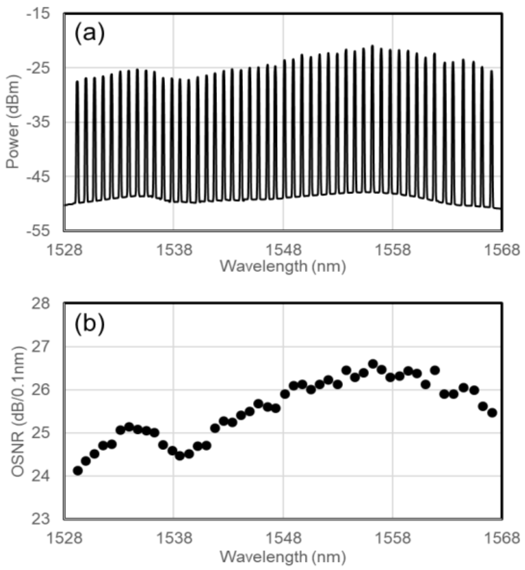

Fig.3: (a) received 48 dummy channel spectra used to measure received OSNR, (b) measured received OSNR.

reasons is that the 1429nm Raman pump see much less Raman gain from the 2^{nd}-order 1363nm Raman pump, as the wavelength of 2^{nd}-order pump is not optimized in the design.

To accurately measure the OSNR, we inject 48 around 100GHz spaced dummy channels, which has the same total input power as the total signal power into the booster, to measure the OSNR of the 48 dummy channels [5-6], and the received 48 dummy channel spectra is shown in Fig.3 (a). The measured average OSNR value is 25.56 dB/0.1nm (see Fig.3 (b)), and we therefore expect the average OSNR of the 64 400Gb/s channels to be 24.3 dB/0.1nm. The OSNR variation is less than 2.5dB, and OSNR at short wavelength channels is lower than at long ones.

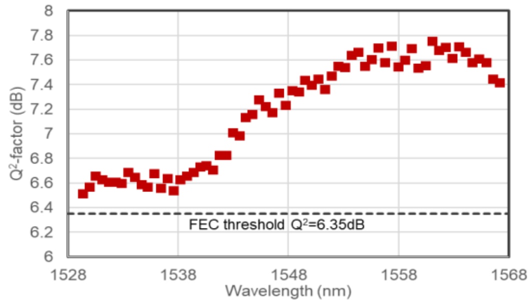

Fig.4: Measured Q^2-factor of 64 400ZR+ channels after 320.5km unrepeatered transmission.

The Q^2-factors (deduced from the measured BER) are plotted in Fig. 4 for all 64 channels. The mean and worst Q^2 factor values are 7.2 dB and 6.52 dB, respectively. The Q^2 variation is 1.24dB, and the Q^2 at short wavelength channel range (1529.32~1542.34nm) is worse than at long ones, which is due to poor OSNR and is also constrained by non-linear Kerr effect. Nevertheless, all Q^2-factors are well above the FEC limit and no FEC error is recorded during this measurement. To the best of our knowledge, this is the highest capacity of single carrier 400Gb/s real-time unrepeatered transmission demonstration. The reach is limited by the channels at the short wavelength, and their BER can be improved by optimizing the wavelength of the 2^{nd}-order Raman pump, or using two 2^{nd}-order Raman pump lasers. On the other hand, the channels at long wavelength range are only limited by their OSNR.

Conclusions

Real-time unrepeatered transmission of 25.6Tb/s over 320.5km fibre has been demonstrated using commercially available 400ZR+ pluggable modules, this is achieved by using large-area ultra-low loss fibre with average attenuation of 0.146dB/km at 1550nm and a new-designed high power booster, and backward-propagating 2^{nd}-order Raman without ROPA.

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