122.6 Tb/s S+C+L Band Unrepeated Transmission over 223 km link with Optimised Bidirectional Raman Amplification

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Abstract: A 223 km unrepeated transmission link is experimentally demonstrated using 121 nm optical bandwidth. Optimised bidirectional Raman amplification as well as Thulium- and Erbium-doped fibre amplifiers enable a record throughput of 122.62 Tb/s.

1. Introduction

Optical communication systems have been the backbone of global data transmission over the last 30 years [1]. The achievable distance and capacity, enabled by the exceptionally low-attenuation spectral region spanning tens of terahertz, make optical fibre an attractive transmission medium. However, the growth in data demand, driven by cloud computing and data streaming, necessitates expansion beyond the currently deployed C- and L-bands, with the use of the S-band proposed to extend the transmission bandwidth. In configurations where installation of in-line amplifiers is challenging or prohibitive, unrepeated systems are a suitable solution, allowing distances in excess of 200 km to be bridged without repeaters. The capacity and reach of such systems have been extended through the use of novel amplification technologies, such as wideband semiconductor optical amplifiers [2], and the optimisation of distributed Raman amplification (DRA) schemes [3]. These have enabled transmission bandwidth up to 100 nm, including extension of the conventional C- and L-bands to include the long S-band [2]. Figure 1(a) summarises the throughput and distance of recent unrepeated transmission experiments.

In this work, we demonstrate unrepeated 223 km transmission of a 121 nm signal including S-, C- and L-bands, supported by Thulium- and Erbium-doped fiber amplifiers (TDFAs and EDFAs, respectively) along with bidirectional DRA. Forward and backward propagating Raman pumps were optimised using a differential evolution (DE) algorithm and inter-channel stimulated Raman scattering (ISRS) was managed by tilting the signal power spectrum. Overall, we achieve a throughput of 122.62 Tb/s with 490×32 GBaud channels, which corresponds to a record capacity-distance product exceeding 27.3 Pb/s·km, as shown in Fig. 1(a). This result demonstrates the potential of S+C+L band transmission to significantly extend the capacity of unrepeated transmission systems.

2. Experimental Demonstration

Figure 1(b) shows the experimental setup of the S+C+L band unrepeated transmission link consisting of 490×32 GBaud wavelength-division multiplexing (WDM) channels. Three 32.5 GHz-spaced carriers with $<$100 kHz linewidth were generated and amplified by either a TDFA or EDFA. After polarisation alignment, the centre channel and the neighboring channels were connected to two dual polarisation in-phase quadrature (DP-IQ) modulators (35 GHz electrical bandwidth) driven by 92 GSa/s 8-bit digital-to-analogue converters. After amplification, the 3 channels were modulated by digitally pre-distorted [13] 32 GBaud root-raised cosine shaped signals with 1% roll-off. The three transmitted channels were then shifted across the S-, C-, and L-bands. The performance of the centre channel was used to assess the system throughput. Different geometrically-shaped (GS) constellations were used in each optical band according to the channel signal-to-noise ratio (SNR). Co-propagating channels were emulated using wideband spectrally-shaped amplified spontaneous emission (SS-ASE) [14] between 1470 nm to 1620 nm. The SS-ASE was shaped using wavelength selective switches (WSSs) to produce a flat or tilted spectrum. A notch was also carved by the WSSs to position the three transmitted channels. The symbol rate of 32 GBaud was selected because the transceiver SNR was measured to be approximately 27 dB, requiring 31 dB optical signal-to-noise ratio (OSNR), which is just below the maximum notch depth obtainable from the WSSs. Based on the SS-ASE bandwidth and the wavelength of the tunable lasers, the channel-under-test could cover the wavelength range from 1470 nm to 1526 nm in the S-band, from 1531 nm to 1565 nm in the C-band, and from 1572 nm to 1608 nm in the L-band, resulting in 228×, 132×, and 130× channels respectively.

The transmission link consisted of 152 km Corning® SMF-28® ULL fibre and 71 km low water peak G.652.D single mode fibre (SMF) with an average total loss of 39 dB across the S-, C-, L- bands. The forward and backward

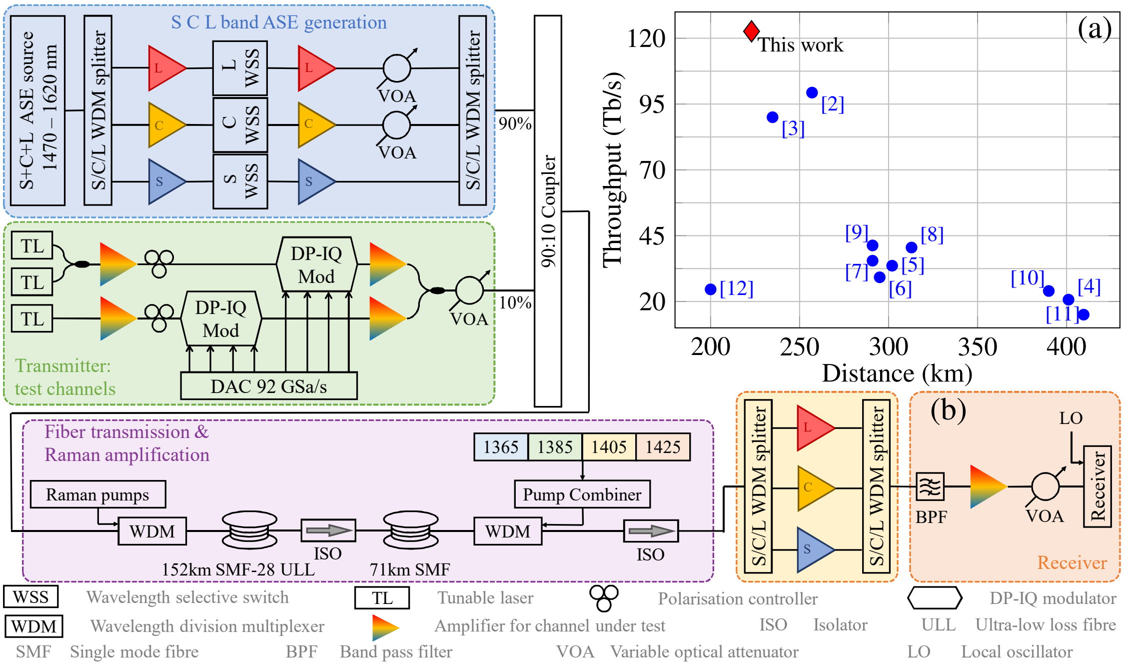

Fig. 1: (a) Throughput and transmission distance of recent unrepeated experiments. (b) Experimental setup for S-, C-, L-band unrepeated transmission over 223km with bidirectional distributed Raman amplification.

Raman pump wavelengths λ and maximum powers P_{max} are listed in Table 1, without considering the WDM insertion loss of about 1dB. The forward Raman pumps improve the signal OSNR and the backward Raman pumps mainly compensate for the power loss in the S-band due to the ISRS power transfer from the S- to L-band. In-line lumped amplifiers were positioned at the end of the fibre link, and the received channel under

Table 1: Raman pumps configuration.

	Forward Pumps								Backward Pumps			
λ (nm)	1410	1417	1423	1430	1437	1445	1451	1458	1365	1385	1405	1425
P_{max} (dBm)	24.27	23.93	21.58	21.09	21.15	21.30	21.03	20.48	27.02	27.02	27.13	27.23
P_{opt} (dBm)	24.27	23.93	21.28	21.09	21.15	18.67	16.90	20.48	27.02	27.02	26.58	23.65

test was filtered out using an optical band pass filter with tunable centre wavelength and a fixed bandwidth of 35 GHz. The channel power was boosted by a pre-amplifier in the corresponding band, and the 70-GHz coherent receiver detected the DP-IQ signal. A 10 bit 256 GSa/s real-time oscilloscope was used to digitise and capture the waveform, and details of the pilot-based DSP can be found in [15]. System performance was quantified in terms of information rates, and the SNR and the post-forward error correction achievable information rate (AIR) after deducting the pilot overhead were estimated for each channel. DVB-S2X low-density parity check codes were used to decode the received signal [16].

Before transmitting data, a coarse OSNR estimation was carried out by carving multiple notches in each band, transmitting the SS-ASE through the fibre link, and measuring the received notch depth (i.e., the received OSNR). The received OSNR was then interpolated to estimate the values for all channels and mapped to SNR and capacity with the Shannon capacity equation. Using the throughput as a metric, optimisation of the launch power tilt and bidirectional pump powers was carried out using the DE algorithm. For each launch power tilt (from 0 dB to 25 dB, with 5 dB step size), the powers of the 8 forward pumps and 4 backward pumps were optimised to find the highest achievable throughput. The best performance was seen with 15 dB launch power tilt, and the optimised pump powers are listed as P_{opt} in Table 1. The total powers of the forward and backward Raman pumps were 1.14 W and 1.69 W, respectively.

3. Result and Discussion

Figure 2a shows the measured tilted spectrum at the fibre input with the inset showing the 3×32GHz channels which were placed within the sliding notch. The launch powers were 19.6 dBm, 12.2 dBm, 8.6 dBm for S-, C- and L-band, respectively, and the signal power was attenuated to match the SS-ASE power spectral density. After 223 km single mode fibre transmission, as shown in Fig. 2b, the orange line shows the spectrum at the fibre output without any amplification, indicating the effect of wavelength-dependent fibre loss and ISRS. The red line shows the received spectrum with bidirectional Raman amplification and lumped amplification. Here, the received signal power is recovered to values similar to the launch powers at most of the wavelengths except the lower half of the S-band, which is due to ISRS and the gain profile of the TDFAs. The maximum Raman on/off gain of more than 30 dB was observed in the S-band with backward Raman pumps only, and more than 40 dB maximum gain with bidirectional Raman pumps, as shown in Fig. 2c. Even though the forward Raman pump wavelengths reach up to 1458 nm, which presents the power transfer peak around mid-C-band, we can observe a gain of about 10 dB throughout the L-band. A small reduction in gain when the forward pumps were added can be seen in the lower wavelengths of the S-band due to stronger ISRS power transfer from S- to L-band. The trade-off between the S- and L-band power spectral density justifies the need to optimise the launch power tilt and the Raman pump powers. Figure 2d shows the received OSNR measured from the notch for different wavelengths per band, and for both the maximum and the optimised pump powers. The average OSNR improved from 16 dB to 16.3 dB, while the approximated capacity increased from 122.8 Tb/s to 124.2 Tb/s. The improvement is mainly in the S-band, allowing a higher throughput by reducing pump power and lowering ISRS, at the cost of slightly poorer performance in L-band. The figure also shows the geometrically-shaped modulation formats transmitted for each channel, which was optimised for the channel SNR [17].

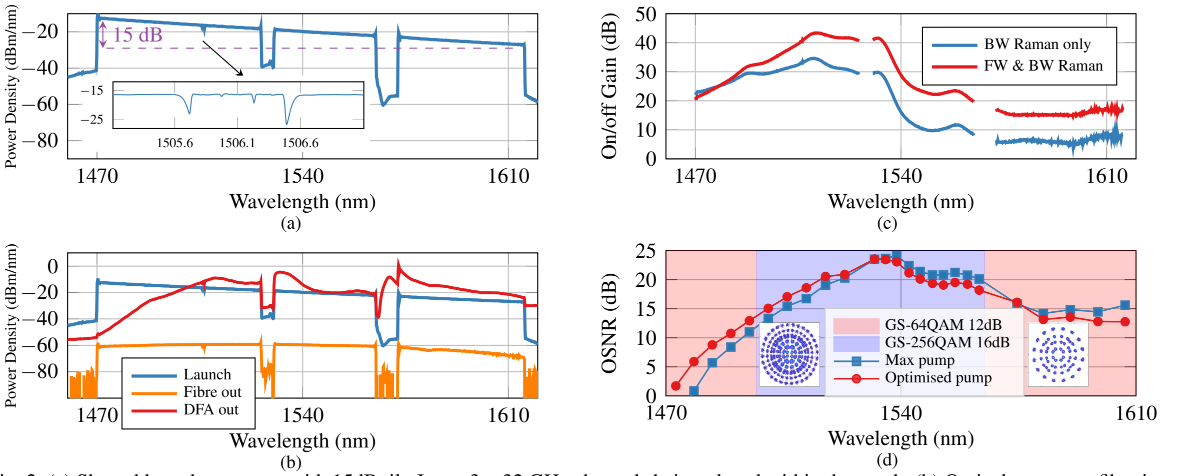

Fig. 2: (a) Shaped launch spectrum with 15dB tilt. Inset: 3×32 GHz channels being placed within the notch. (b) Optical spectra at fibre input, fibre output and doped fibre amplifier (DFA) output. (c) Raman amplification on/off gain. FW: forward, BW: backward. (d) Received OSNR in the optimisation process and the choice of different constellation shaping methods.

Figure 3 shows the received measurement, with both SNR and AIR values, after the transmission over 223 km. At the lowest S-band wavelengths, the OSNR is too low to transmit any data and the total optical bandwidth used is 121 nm. 49.31 Tb/s, 45.66 Tb/s, and 27.65 Tb/s were achieved for S-, C-, and L-band, respectively, totalling 122.62 Tb/s. The gap to the estimated capacity of 124.2 Tb/s is mainly attributed to the pilot overhead.

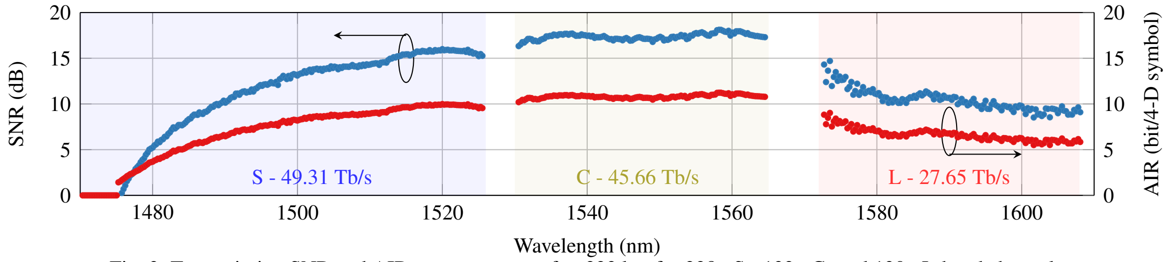

Fig. 3: Transmission SNR and AIR measurements after 223 km for 228×S-, 132×C- and 130×L-band channels.

4. Conclusion

We have experimentally demonstrated an ultra-wideband (121 nm) unrepeated transmission link of 223 km with a total throughput of 122.62 Tb/s, using bidirectional Raman amplification and doped fibre amplifiers. The launch power profile and Raman pump powers were optimised to overcome the inter-channel stimulated Raman scattering. To the best of our knowledge, this work achieved the highest capacity distance product, 27.34 Pb/s · km, for an unrepeated single mode fibre link.

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