264.7 Tb/s E, S, C + L-Band Transmission over 200 km

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Abstract: We experimentally investigate an extended reach E, S, C + L-band transmission system covering 27 THz with mid-span doped fiber and distributed Raman amplification, measuring 264.7 Tb/s from GMI and 250.8 Tb/s after decoding after 200 km transmission. © 2024 The Author(s)

1. Introduction

New optical transmission bands [1, 2] and fibers utilizing the spatial domain [3, 4] have been widely investigated as solutions to the ever-increasing quest for more optical fiber transmission capacity. Expanding the utilized spectral windows in particular offers a potentially significant benefit in the near-term as a method of extending the life of already deployed optical fibers to provide new transmission bandwidth without the large capital expenditure of new fiber deployment [1, 2]. Combining multi-band systems with high-order modulation and dense wavelength (WL) division multiplexing (DWDM) is a promising approach to fully exploit deployed fiber capacity.

However, moving away from the low-loss window of standard single-mode fibers (SMFs) requires amplification schemes beyond the standard erbium (E)-doped fiber amplifier (DFA) that is a staple of C or C/L-band systems. Previously, S/C/L-band transmission has been explored with various amplifier technologies supplementing EDFAs including semiconductor optical amplifiers, distributed and discrete Raman amplification and Thulium (T-) DFAs. In particular, combining T/E-DFAs with distributed Raman amplification has enabled 256 Tb/s (GMI) transmission covering 19.8 THz over 54 km of SMF [5] and 200.5 Tb/s over 2 x 100 km SMF spans [6]. The addition of U and O-band segments recently led to 119.4 Tb/s transmission on deployed fiber using 25 THz combined bandwidth [7], while E/S/C/L-band transmission with 27.8 THz bandwidth enabled >300 Tb/s transmission over 50 km of SMF [8].

Here, we expand on a recent wideband transmission demonstration [8], exploring multi-span DWDM E/S/C/L-band transmission. We transmit a 27 THz WDM signal comprising 1050 x 25 GHz spaced polarization-division multiplexed (PDM)-64-quadrature-amplitude modulated (QAM) channels from 1416.1 nm to 1622.7 nm over 2 x 100 km SMF spans. In addition to E/T-DFAs, we use a recently developed bismuth (B-) DFA optimised for DWDM transmission in combination with distributed Raman amplification. This combination leads to a 16% increase in decoded data-rate compared to previous 150 km transmission whilst using fewer WDM channels [8]. These results reveal both the need for careful selection of span length and amplifier characteristics to make a successful multi-band amplification strategy as well the potential of BDFA enabled E-band transmission to increase transmission capacity in new and deployed optical fibers.

2. Experimental Description

The experimental set-up is shown in Fig. 1. The transmission set-up comprised a sliding 3 channel test band within a wideband WDM signal constructed from shaped amplified spontaneous emission (ASE) noise. The test-band consisted of a test and 2 neighbouring channels originating from 10 kHz linewidth tunable lasers for S/C/L-band channels and 200 kHz linewidth TLs for E-band signals. S-band signals were amplified in TDFAs with 20 dBm output power and noise figure <7 dB. E-band amplification used germanium-co-doped BDFAs, pumped with 700 mW laser diodes at 1310 nm for a maximum 24 dBm output power and <6dB noise figure across the transmission band at 0 dBm

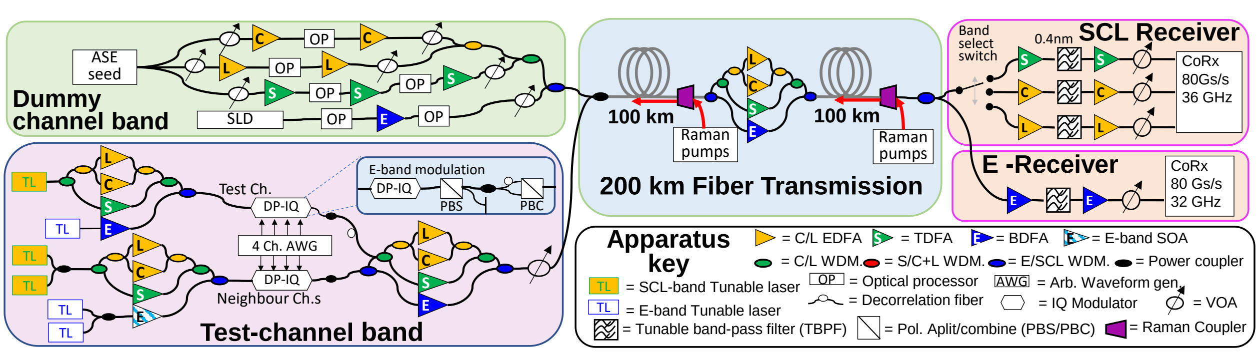

Fig. 1: (a) Experimental set-up for E, S, C + L-band transmission

input power. The non-central test band channels were amplified in an E-band SOA before modulation. The test and neighbour channels were independently modulated in dual-polarization IQ-modulators (DP-IQ) driven by four arbitrary waveform generators (AWGs) operating at 49 GS/s. These produced 24.5 GBd, PDM-64-QAM root-raised cosine shaped signals with a roll-off of 0.01 based on 2^{16}-1 bit pseudo-random binary sequences. The same modulator was used for E-band modulation. However, it was observed that WL dependence of an internal polarization beam splitter (PB-S) severely degraded modulation quality in one polarization. Hence, E-band signals were split in a wideband PBS after modulation with the best polarization signal further split and combined with a fixed delay on one path in a PB combiner (PBC) to reconstruct a PDM signal, shown as an inset in the test-band panel of Fig. 1.

Dummy WL channels were generated from ASE noise [9] shaped using band-specific optical processors (OPs) and DFA amplification. To minimize use of the limited number of BDFAs, the E-band noise seed used a high power super-luminescent laser diode (SLD) with 18 dBm output power centered on 1440 nm. The OPs were used to carve a movable notch in the dummy channel spectrum to accommodate the current test-channel. A custom developed multi-port OP [10] was used for the E-band. The LCOS based device contained 18 individual 1 x 1 ports with minimum loss of 5 dB providing a notch > 40 dB with a double pass configuration. The combined test and dummy channels were transmitted over 2 x 100km spans of OH absorption suppressed SMF with loss of 0.24 dB/km, 0.19 dB/km and 0.21 dB/km at 1440 nm, 1560 nm and 1625 nm, respectively. Between spans, multi-band DFAs compensated for fiber loss with additional Raman amplification achieved using back propagating pumps added in a WDM coupler. The first span used four x 10 nm spaced pumps from 1320 nm to 1350 nm with 250 mW power and the 2nd span used the same combination in addition to a 350 mW pump at 1385 nm. The input transmission spectrum was conditioned by the OPs to have roughly equal power per channel of -4 dBm at the fiber input.

In each band, the receiver path consisted of amplification stages on either side of a 0.4 nm tunable band pass filter (TBPF) centered on the test-channel with a VOA for power adjustment. For S/C/L band signals, a single coherent receiver (CoRx) detected the signal using a 10 kHz linewidth local oscillator (LO). E-band signals used a distinct CoRx with an E-band optimised hybrid, dual-window photodiodes and a 200 kHz linewidth LO laser. The signals were acquired by an 80 GS/s real-time oscilloscope that stored traces for offline processing, similar to [11]. The throughput of each WL channel was estimated from the GMI and independently assessed using LDPC codes from the DVB-S2 standard. Code-rate puncturing was implemented to achieve a bit error rate (BER) below 5×10^{-5} with a 1% overhead outer hard-decision code [11], assumed to remove any remaining bit errors. Signal quality and throughput measurements were performed on three 10 µs traces for each WL channel in turn.

3. Results

Figure 2 shows optical spectra along the 200 km transmission link. The characteristics of the first Raman amplified span are shown in Fig. 2 (a). The launched E/S/C/L-band input signal (black), becomes tilted at the fiber output (blue) by the combination of stimulated Raman scattering (SRS) and the fiber loss profile (dashed grey, right-axis). The

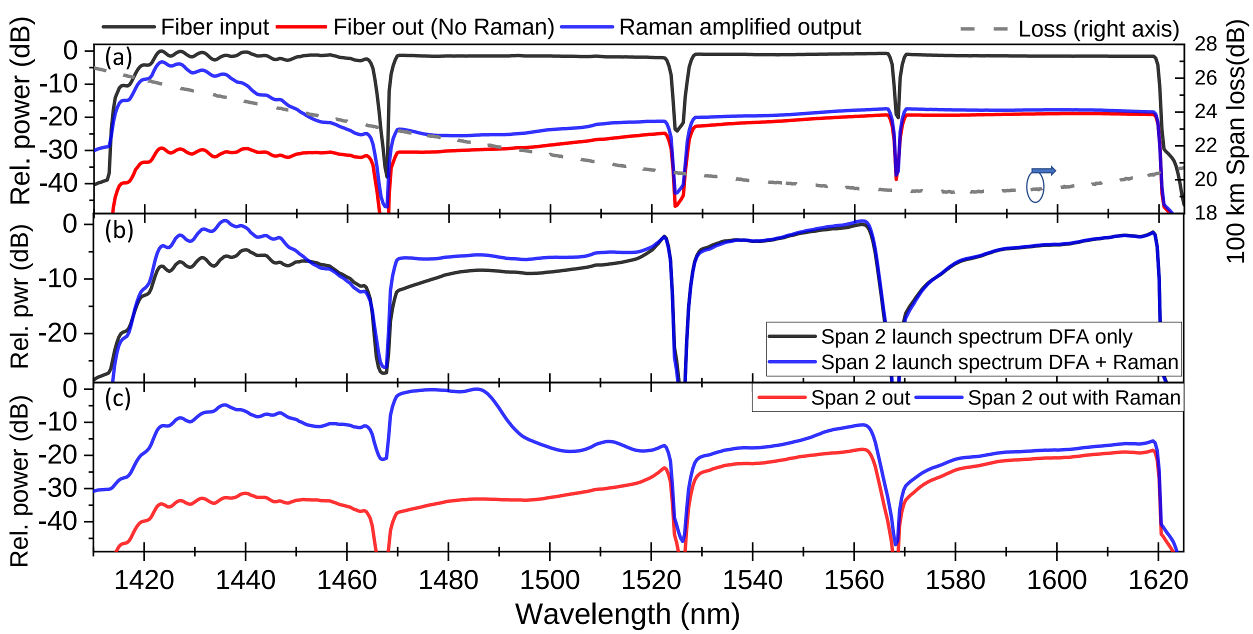

Fig. 2: Wideband signal spectra (a) left-axis E/S/C/L-band signal at input (black) + output (red) of first fiber span with Raman amplification profile (blue). Right-axis span loss of 100 km fiber span, (b) Launch spectra after mid-stage DFA amplification with and without Raman pumps acting on first span, and (c) output of span 2 with and without Raman amplification in both spans.

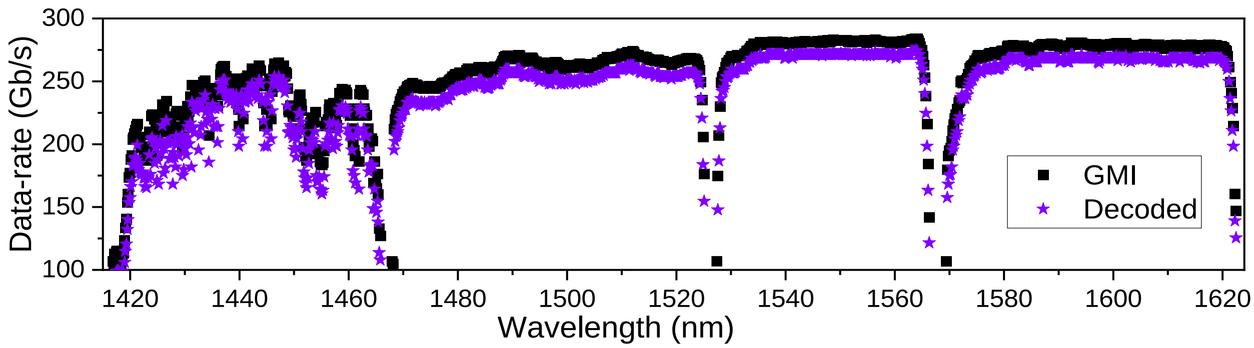

Fig. 3: GMI estimated and LDPC decoded data-rate after 200 km transmission

addition of the 1320-1350 nm Raman pumps provides some gain across the E-band with some gain at low S-band wavelengths and increased SRS slightly boosting C/L-band signals. Some ripples are evident in the E-band input spectrum and arise from the SLD used to generate dummy channel spectrum which is imperfectly compensated in the E-band OP. Fig 2(b) shows the output spectra of the mid-span amplification stage. The impact of higher input power when utilizing the first span Raman pumps leads to higher output power in the B/T-EDFAs, with little impact on the C/L-band EDFAs. Whilst the C-band profile largely resembles the SRS tilted spectrum at the output of span 1, an additional strong gain tilt is added by the L-band EDFA giving >15 dB power variation across the band. We note that although previously [8], an additional 1385 nm Raman pump provided large Raman ON-OFF gain across S-band channels, in this span, the higher input power to the B/TDFAs also lead to gain tilt that reduced available E-band spectrum. The 1385 nm pump was used in the second span providing large gain across E and low S-band channels, as shown in Fig. 2(c), which again shows that increased SRS slightly boosts the power of C and L-band signals when the Raman pumps are utilized.

The signal quality measurements are summarized in Fig. 3 which shows the GMI-estimated and decoded data-rates as a function of wavelength. The majority of C and L-band channels have a GMI data-rate between 260 Gb/s and 285 Gb/s decreasing at the edge of amplifier gain windows and a small reduction in the L-band region suffering from gain tilt after mid-stage amplification. In S-band, the data-rate ranges from 270 Gb/s to around 240 Gb/s at lower wavelengths with some peaks coinciding with gain of Raman pumps evident in Fig.2. In E-band, the per-channel data-rates appear to be conditioned primarily by the Raman amplified spectral shape shown in Fig. 2, with a number of dips in data-rate that is believed to arise from a combination of water absorption in E-band components (OP and TBPF) and ripple originating from the SLD that results in variation of channel OSNR after setting test-band power in relation to it. The combined data-rate of all 1050 WDM channels after 200 km transmission was 264.7 Tb/s when estimated from the GMI and 250.8 Tb/s after LDPC decoding. The per band estimated data-rates were 62.5, 79.8, 54.3 and 66.2 Tb/s from 287, 310, 199 and 254, E, S, C and L-band channels, respectively.

4. Summary

We have experimentally investigated multi-span DWDM transmission of a wideband E, S, C + L-band signal spanning 27 THz. Transmitting 1050 x 25-GHz spaced PDM-64QAM channels over a 200 km link, with mid-stage amplification from bismuth, thulium and erbium DFAs, we record a GMI estimated data-rate of 264.7 Tb/s or 250.8 Tb/s after LDPC decoding. The results show the importance of balancing the varying span loss and Raman gain across spectral bands to the amplifier characteristics in order to maximize data-throughput and the potential of E-band transmission to increase the information carrying capability of new and deployed optical fibers.

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5. References

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