91 nm C+L Hybrid Distributed Raman–Erbium-Doped Fibre Amplifier for High Capacity Subsea Transmission

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Abstract *Hybrid distributed Raman-EDFA amplifiers, with a continuous 91 nm gain bandwidth and 1.4 dB average effective noise figure, are used to enable a record single mode fibre transmission capacity of 120 Tbit/s using 312×35 GBd DP-256QAM over 9×70 km spans.*

Introduction

The consistent growth in global network traffic is driving future optical networks towards spatial and spectral domain parallelism[1] to provide the required capacity. As space division multiplexed (SDM) systems are composed of parallel channels, the single mode capacity will partially dictate the total system capacity. Moreover, the relatively mature single mode transmission systems are still widely deployed, and therefore set the benchmark for what can be achieved in optical fibre communications.

Fundamental limits of an optical communication system are dominated by a combination of noise from the transceiver subsystem, optical amplifier noise, system bandwidth and optical fibre nonlinearity. Recent years have seen several advances in improving the bandwidth of optical amplifiers, and have resulted in recent experimental single-mode fibre (SMF) capacity increases.

Previous record demonstrations have relied on transmission in the C and L bands based on EDFA[2], distributed Raman amplification (DRA)[3] or a combination of the two[4], enabling up to 78 nm bandwidth. Employing EDFAs in each transmission window leads to a spectral gap between the two bands, whereas DRAs provide a continuous transmit bandwidth. A continuous-band 100nm amplifier[5] was developed based on a semiconductor optical amplifier (SOA), enabling an SMF capacity record of 115.9 Tbit/s over 100 km. Although the bandwidth is impressive, SOAs have a relatively high noise figure (NF) compared with DRAs, and so system performance decreases rapidly with distance.

In this work, we designed and tested a continuous 91 nm gain bandwidth hybrid distributed Raman-EDFA (HRE) as a prototype for wideband amplification that has low NF, enabling a record throughput of 120 Tb/s over 630 km of SMF.

Experimental configuration

In the experimental setup, shown in Fig. 1, four carriers spaced at 35.5 GHz were connected to two independent dual-polarization IQ optical modulators, provided by Oclaro, each driven by four 92 GS/s digital-to-analogue converters (DACs) to generate four odd/even channels. A digital root-raised cosine (RRC) filter with 0.01 roll-off was used to spectrally shape the signals and pre-emphasis was applied to overcome the electrical response of the transmitter components. The channels were generated at carrier frequencies which were tuned across the spectrum from 1524.9 to 1615.9 nm, allowing the measurement of 312×35 GBd dual-polarization 256-*ary* quadrature amplitude modulation (DP-256QAM) channels.

The modulated channels were amplified using a pair of 97 nm bandwidth discrete Raman amplifiers with 12.5 dB gain and combined with wideband amplified spontaneous emission (ASE) noise, which emulated co-propagating channels over the entire transmitted bandwidth. The ASE noise, with continuity across the entire 97 nm bandwidth, was generated by a pair of discrete Raman amplifiers to achieve a total output power of 22 dBm within the required 91nm bandwidth, following which, a band stop filter (BSF) was used to create a notch in the ASE within which the modulated channels were positioned. The validity of using ASE noise to emulate aggressor channels was verified in[6], showing that this technique provides a conservative measure of system performance.

A gain equalising amplifier (GEA) with a continuous 98 nm bandwidth was used to amplify

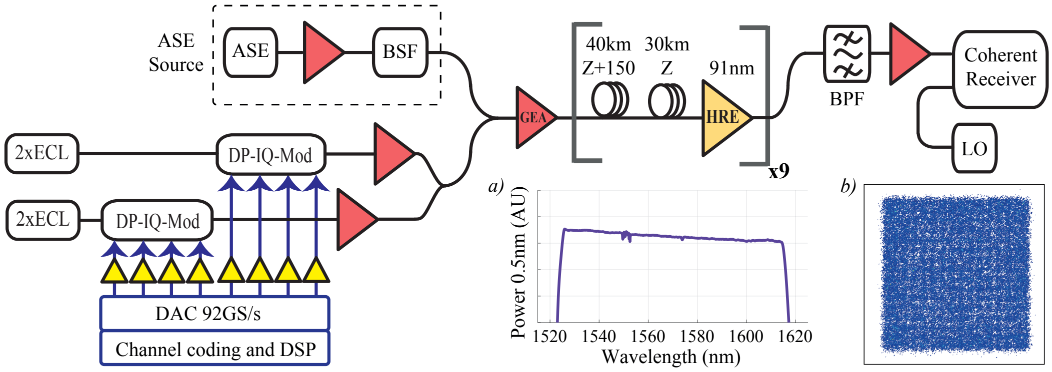

Fig. 1: Experimental setup and a) signal spectrum at the input into the first fibre span (CUI centered at 1551 nm) b) 256QAM constellation in a back-to-back configuration.

and spectrally shape (SS) the combined ASE and modulated channels. The combined SS-ASE and modulated channels occupied a total usable bandwidth of 91.04 nm (11.0758 THz) with a total output power of 22 dBm. The optical spectrum after the GEA is shown as inset (a) in Fig. 1. A power tilt of -2 dB across the bandwidth was applied to equalise the channel performance, taking into account the wavelength-dependent NF of the transmission line amplifiers. The back-to-back 256QAM constellation is illustrated in the inset (b) of Fig. 1.

The transmission link comprised a straight-line of 9 spans, with 70 km of SMF and an HRE in each span. Each fibre span mixed two fibre types: 40 km of Sumitomo Z+150 fibre with an average attenuation of 0.148 dB/km and an effective core area of $149\ \mu m^2$, followed by 30 km of Sumitomo Z fibre with an average attenuation of 0.16 dB/km and an effective core area $81\ \mu m^2$. The Z+150 fibre reduces the nonlinear penalties on the transmit side of the span while the Z fibre provides sufficient Raman gain to achieve 0 dB net gain across the spectrum.

Each HRE provided continuous gain from 1525 nm to 1616 nm and used two counter-propagating pumps at 1427 and 1495 nm, as shown in Fig. 2, with output powers of 300 mW and 310 mW into the transmission fibre, delivering a total power of 19.5 dBm to the EDFA stage. The single EDFA stage boosted the signal to a total output power of 22 dBm, and included a 91 nm gain flattening filter (GFF) to equalise the gain across the entire HRE bandwidth. The distributed amplification approach reduces the NF compared to EDFA only or SOA techniques. As shown in Fig. 3 the effective NF was 1.4 dB on average.

At the receiver, the average signal-to-noise ratio (SNR) across the bandwidth was 18.9 dB. Since the back-to-back SNR was approximately

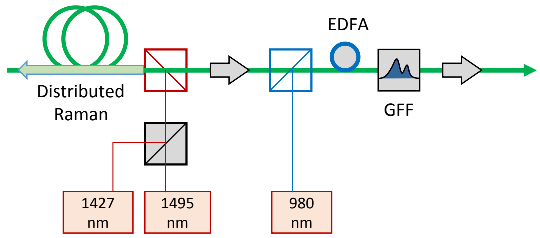

Fig. 2: Repeater block diagram.

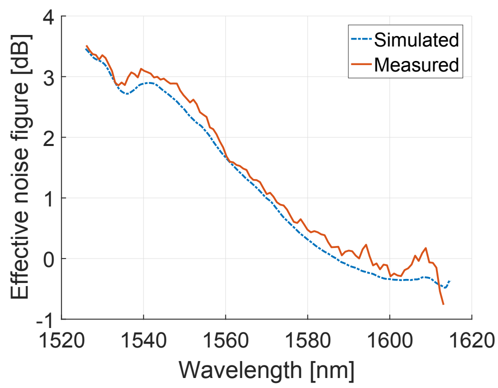

Fig. 3: Effective noise figure of an HRE prototype.

21 dB, this suggests that the SNR degradation is dominated by the transceiver performance and the impact of the HRE ASE is minimal. A band-pass filter (BPF) with a 40 GHz bandwidth was used to filter the channel under test (channel 2 of 4) and exclude the out-of-band noise from the receiver. A phase- and polarization-diverse coherent receiver incorporating 70 GHz bandwidth photodetectors was employed, and the signal was digitised using a real-time oscilloscope with 63 GHz bandwidth, sampling at 160 GSa/s. Digital signal processing was performed as described in[6], which included matched filtering, single step chromatic dispersion compensation, a 21-tap blind adaptive equaliser, frequency offset compensation and decision directed carrier phase estimation. The system performance was quantified in terms of throughput and BER, after decoding with soft-decision forward error correction (SD-FEC).

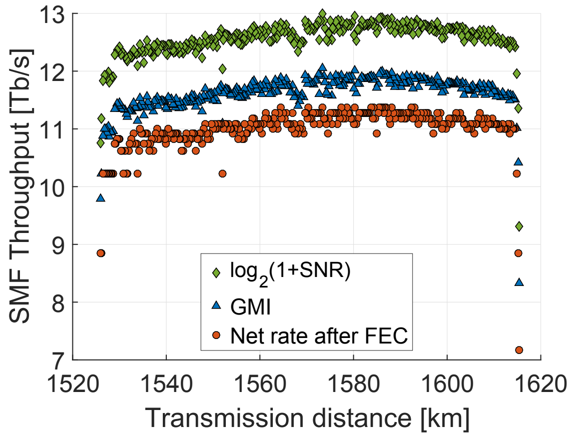

Fig. 4: Throughput per channel over 2 polarizations after 630km.

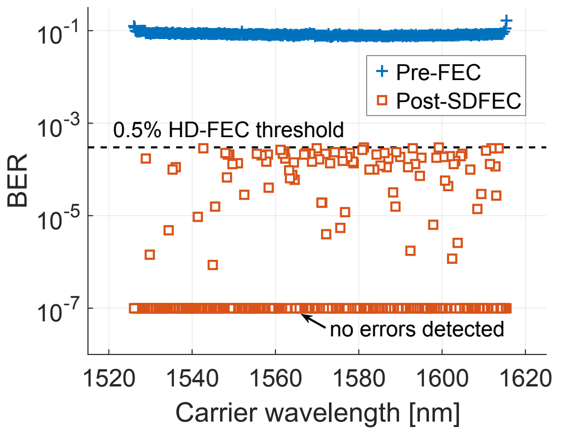

Fig. 5: Pre-FEC and post-SD-FEC BER for all 312 channels.

Results

The information rate of all 312×35 GBd DP-256QAM channels was calculated over the continuous 91 nm bandwidth and is shown in Fig.4. The Shannon limit for the received SNR is given by $\log_2(1+\mathrm{SNR})$ summed over both polarizations. The total received SNR was evaluated as the ratio between the variance of the transmitted symbols $E[|X|^2]$ and the variance of the noise σ^2, where $\sigma^2 = E[|X-Y|^2]$ and Y represents the received symbols. The pre-FEC GMI was calculated using received log-likelihood ratios. A mean penalty of 0.94 bit/symbol between the GMI (11.62 bit/symbol) and the Shannon limit (12.56 bit/symbol) is due to the use of non-optimal finite constellation and bit labeling. For the net rate after inner and outer FEC, the occupied spectrum yields a net bit rate of 10.99 bits/symbol providing a record single mode fibre capacity of 120.0 Tbit/s.

Fig. 5 shows the pre- and post-SD-FEC BER for all 312 channels. The channels were decoded using 12 rate adapted LDPC codes implemented from the DVB-S2x standard. An outer BCH HD-FEC code with a bit error rate (BER) threshold of 3×10^{-4} with 0.5% overhead was assumed. All 312 channels were measured, confirming the total net throughput of 120.0 Tbit/s. The bulk of the codes have a low spread in code rate, 293 out of 312 have between 40-50% FEC overhead. Reducing the number of code rates applied to 7 was found to reduce the total net data throughput to 119 Tbit/s.

Conclusions

This work demonstrated a prototype wide-bandwidth hybrid EDFA-Raman amplifier for transmission over SMF. This technique offers distributed gain, and so inherently maintains a low noise figure and a high SNR over longer transmission distances, compared to previously proposed solutions. In contrast to EDFA-based C+L band transmission systems, the continuous 91 nm gain bandwidth offered by hybrid amplification means that no spectrum is wasted.

We demonstrated record throughput of 120 Tbit/s transmitted over 630 km of SMF, an improvement over the previous capacity record[5], with an extra 4 Tbit/s capacity over more than 6 times longer transmission distance.

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