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High-capacity multi-span transmission performance characterization of broadband discrete Raman amplifier

LUKASZ KRZCZANOWICZ,* MD ASIF IQBAL, IAN PHILLIPS, PAUL HARPER, AND WLADEK FORYSIAK

Aston Institute of Photonic Technologies, Aston University, Birmingham, B4 7ET, UK
*l.krzczanowicz@aston.ac.uk

Abstract: The performance of a multi-span transmission link compensated with a >75nm broadband discrete Raman amplifier is experimentally evaluated using multiple DP-x-QAM modulation formats over a multi-channel C + L band WDM grid with up to 182 × 50 GHz spaced channels.

1. Introduction

Most currently deployed WDM systems operate in the C-band using erbium doped fibre amplifiers (EDFAs), with bandwidth limited to ~40 nm. The constantly growing demand for increased system capacity has resulted in resurgent interest in using other transmission bands [1], driving a need for broadband amplification techniques. C + L band EDFA-based transmission systems for ultra-long-haul submarine transmission have been proposed, developed and operated [2], as well as S + C+L amplifier-based systems for shorter distances [3], but these solutions create a "bandwidth gap" between the bands. Among seamless gain bandwidth solutions, a hybrid Raman/EDFA C + L system has been investigated recently [4]. Also, ultra-wide Semiconductor Optical Amplifiers (SOAs) can be used due to their flexibility in amplification bandwidth [5] but these are known to introduce nonlinear distortions due to signal pattern effects [6]. Among other potential solutions are Raman amplifiers, which also have fully configurable gain spectra [7–9], and are of two general types. The discrete Raman amplifier (DRA) investigated here, uses a highly nonlinear fibre to localize pumping and gain to each amplifier node, while the distributed Raman amplifier potentially offers the best performance of all these, but requires high power pumping of the transmission fibre. Recently, all-Raman S + C+L band solutions were proposed: a 150 nm dual stage discrete design [10], and a 150 nm hybrid distributed S-band/discrete C + L band architecture [11].

In this paper, we experimentally evaluate the performance of high capacity transmission links compensated with broadband (>75 nm) discrete Raman amplifiers. We use a state-of-the-art, commercial transceiver to generate 69.4Gbaud DP-16QAM, DP-32QAM and DP-64QAM signals at a central C-band channel [12] and compare the DRA compensated link performance with an EDFA compensated system in a single span, 75 km long transmission, and in a triple span 215 km scenario. A WDM C + L band spectrum, shaped into 88 × 100 GHz spaced channels is loaded into the links and the penalty on the test channel is measured [13]. In the triple-span scenario we load the spectrum with 182 × 50 GHz spaced WDM channels over C- and L-band, and measure the transmission performance of a 34.7Gbaud DP-64QAM signal over selected channels in the C-band, reporting BER values below the FEC threshold level. Finally, we use the same 182 channel grid to transmit 30Gbaud DP-QPSK signal over C- and L-band. We measure the Q^2 performance of L-band transmission to be comparable to C-band, showing that DRAs are

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a viable solution for high capacity, short reach, seamless broadband transmission systems, such as those required for Data Centre Interconnects (DCIs) [14].

2. Single span transmission performance characterization

The experimental transmission setup is shown in Fig. 1. The transmitter comprised of C- and L-band EDFAs, whose amplified spontaneous emission (ASE) spectra were shaped with wavelength selective switches (WSS) into 100GHz-spaced, 70 GHz wide channels in the ranges 196.0-191.5THz (1529.55-1565.49 nm) and 190.8–186.7THz (1571.24–1605.74 nm), resulting in totals of 46 and 42 channels in the C- and in L-band, respectively. These ASE channels were combined with the channel under test, which was generated by a state-of-the-art, commercial transceiver capable of transmitting multiple advanced modulation formats (from DP-QPSK to DP-64QAM) at up to 69.4Gbaud (50Gbaud for the signal and the remaining for 27% FEC and other overheads). An attenuator at the span input was used to adjust the launch power to the span, which was monitored by a 5% tap. The span itself consisted of 75 km of SMF with 14.6 dB loss (measured at 1550 nm), followed by a broadband DRA comprising backward pumped (1425, 1445, 1465, 1485 and 1508 nm), 7.5 km long inverse dispersion fibre (IDF), providing sufficient gain to compensate for the SMF losses [9]. At the input of the receiver, a narrow band-pass filter (BPF) separated the channel under test from neighboring ASE channels. The filter was followed by an EDFA, operated in constant power mode to ensure the receiver was working at its optimum receive power level of P_{RX}=-5dBm throughout the experiment, and specifically during channel power sweeps. A 5% tap to the optical spectrum analyzer (OSA) was used to aid BPF alignment.

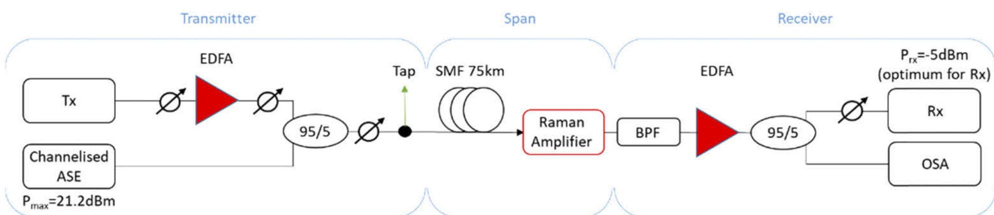

Fig. 1. Experimental setup.

2.1. Single channel transmission test

Single channel transmission at 193.7THz (1547.71 nm) was tested first to benchmark performance of a central C-band spectral channel, expected to experience the highest interference level from neighboring ASE channels in subsequent WDM tests (see 2.2). The per channel power sweep was performed for three modulation formats (DP-16QAM, DP-32QAM and DP-64QAM) and compared with a similar system replacing the DRA with an EDFA, to provide a benchmark against which to evaluate the performance penalty introduced by the DRA. As seen in Fig. 2, the optimum launch power for the DRA case was 3dBm for all three modulation formats, resulting in BER_{DRA}=4.63e-4 for DP-16QAM (BER_{EDFA}=3.11e-4), BER_{DRA}=8.32e-3 for DP-32QAM (BER_{EDFA}=7.18e-3) and BER_{DRA}=3.46e-2 for DP-64QAM (BER_{EDFA}=3.37e-2), with the FEC threshold for error-free transmission being 3.6e-2. In all three cases, the performance in the linear regime (below optimum launch power) was slightly better for the EDFA case due to the amplifier noise figure (NF) difference (NF_{DRA}=6.1 dB, NF_{EDFA}=5.5 dB, measured at 193.7THz). The performance in the nonlinear regime (above optimum launch power) is seen to roll over slightly faster in the DRA case, indicating increased nonlinear penalties, arising from signal propagation in the DRA fibre [8]. The gap between the optimum performance point of the two amplifying schemes becomes narrower with increasing order of modulation format, as a result of saturation in the highest achievable SNR within the transceiver [15].

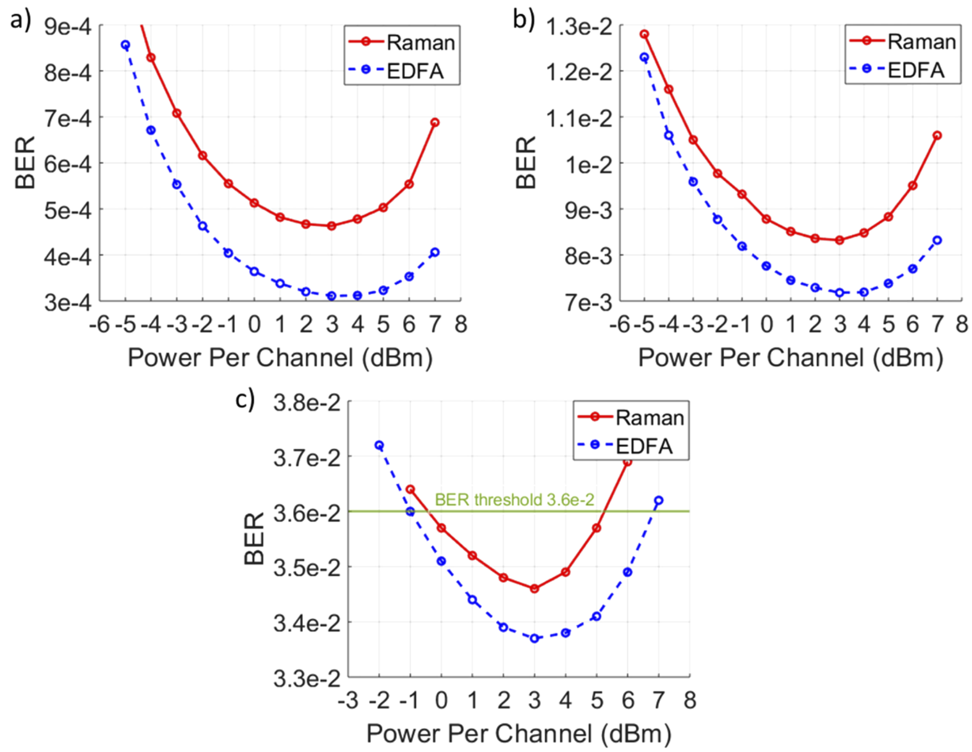

Fig. 2. BER vs power per channel measured @193.7THz after 75km transmission with DRA or EDFA compensation, with different modulation formats: a) DP-16QAM, b) DP-32QAM, c) DP-64QAM.

2.2. WDM transmission test

Since the 69.4Gbaud, DP-64QAM performance was close to the FEC threshold (Fig. 2(c)), we chose 69.4Gbaud DP-32QAM for further investigation of WDM transmission to enable a greater range of BER measurements. Figure 3(a) shows the multi-channel spectrum for this experiment ranging from 1529.55 nm to 1605.74 nm, with the gap between 1565.49 nm and 1571.24 nm resulting from the channel generation method (limited by the EDFAs ASE bandwidth). This part of the spectrum could still be amplified by the seamless DRA, which provided >75 nm gain bandwidth. The maximum output power of the WDM spectrum was limited by the output power of the C- and L- band EDFAs used for channel generation; 21.2dBm distributed evenly over the 88 channels resulted in a maximum power per channel of 1.75dBm for the WDM power sweep, in which the channel under test was controlled to the same power level as its neighbors for all measurements. Figure 3(b) shows a comparison of BER values for the 193.7THz test channel with no neighbors (the same as in Fig. 2(b)) and with loaded C + L bands, after 75 km of SMF transmission with broadband DRA amplification. The best performance for the loaded system was attained for the maximum tested power per channel available (1.75dBm) with a $BER_{DRA,WDM}$=1.01e-2, while the single channel performance showed $BER_{DRA,1CH}$=8.4e-3 at the same launch power point. The difference between these measurements is attributed to the increased nonlinear interference generated by adding neighboring WDM channels. The performance of other channels within the system is estimated to be of similar order (in lower C-band) or even better (in L-band) because of the tilted NF characteristic of broadband DRAs [9], benefitting the transmission channels at higher wavelengths.

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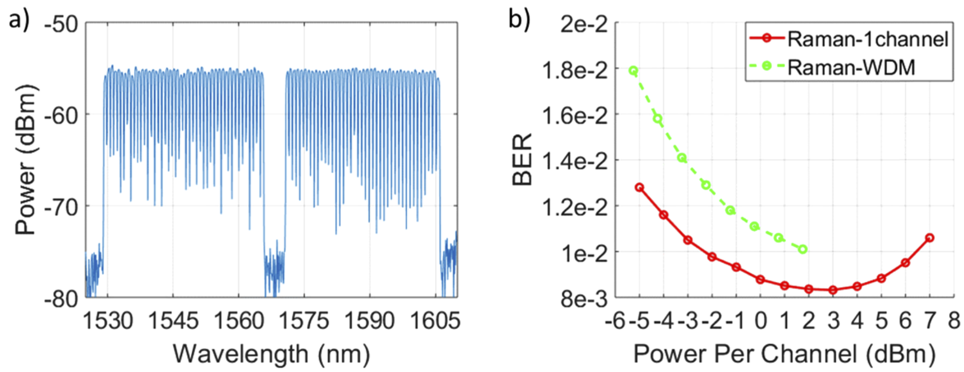

Fig. 3. WDM transmission: a) 46 + 42 channels C + L band spectrum, b) BER vs power per channel @193.7THz after 75 km transmission with DRA compensation for single channel and WDM transmission with DP-32QAM modulation format.

3. Multi span transmission performance

The multi span experimental transmission used a modified experimental setup versus section 2 (Fig. 1). On the transmitter side, the C + L band ASE spectrum was reshaped into 50GHz-spaced, 35 GHz wide channels in the ranges 1529.55-1565.9 nm (191.45-196.0THz) and 1570.42–1607.9 nm (186.45-190.9THz), resulting in totals of 92 and 90 channels in the C- and in L-band, respectively. These settings allowed us to perform the transmission with two different modulation formats and still successfully recover the signals:

- DP-64QAM in the C-band, with the data rate scaled down to 34.7Gbaud, described in detail in section 3.1.
- 30Gbaud DP-QPSK over C + L band, described further in section 3.2.

The three SMF spans used were 75km + 70km + 70 km, each followed by a broadband DRA comprising backward pumped IDF, providing sufficient gain to compensate for the SMF losses [9]. The details of each span are shown in Table 1.

Table 1. Span configuration

Span number	SMF length (km)	SMF loss @1550nm (dB)	Raman IDF length (km)	Raman pumps used (nm)
1	75	14.6	7.5	1425, 1445, 1465, 1485, 1508
2	70	14.2	7.5	1425, 1444, 1462, 1476, 1491
3	70	14.4	10	1425, 1431, 1444, 1462, 1476, 1491

3.1. DP-64QAM transmission test

Figure 4 shows the transmission spectra of the input signal (Fig. 4(a)) and after 3 spans of transmission (Fig. 4(b)), with the gap between 1565.9 nm and 1570.42 nm resulting from the channel generation method, as described above. Due to the energy transfer from shorter to longer wavelengths, the gains in the L-band were higher than in the C-band. This effect accumulates with the number of spans leading to a noticeable power mismatch between the output channels and can be avoided by using gain flattening filters (GFFs) between the spans.

The transmission performance after 215 km was measured for selected channels in the C-band (the transceiver was operational only in this region). The maximum output power of the combined

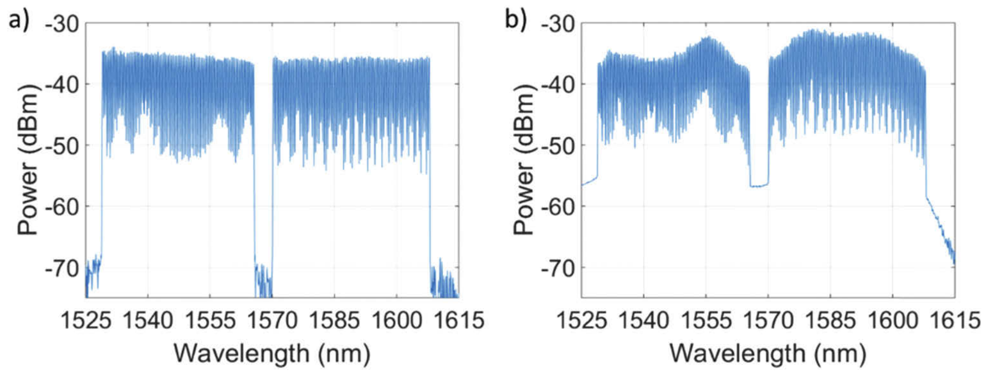

Fig. 4. Transmission spectra: a) 92 + 90 channels at input, b) after 3 spans of transmission.

WDM spectrum was 21.2dBm, distributed over the 182 channels, resulting in a maximum power per channel of -1.4dBm, which was the upper limit for the WDM power sweep, in which the channel under test was controlled to the same power level as its neighbors. Figure 5(a) shows the power sweep of a 34.7Gbaud DP-64QAM central C-band channel at 1547.71 nm, which was expected to experience a high interference level from neighboring ASE WDM channels, and two channels at each end of the C-band (1529.94 nm and 1565.09 nm).

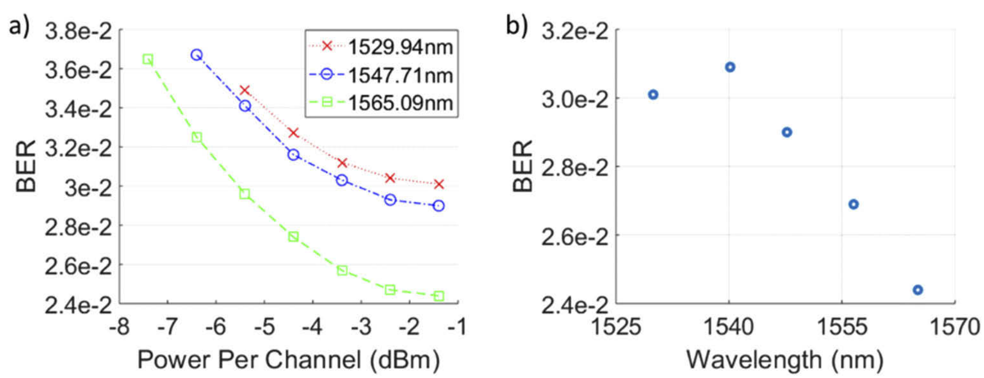

Fig. 5. DP-64QAM BER performance after 215km: a) power sweep for selected channels at 1529.94nm, 1547.71nm and 1565.09nm, b) best achieved BER for channels from Fig. 5(a) with two additional points: 1540.16nm and 1556.55nm.

The performance of each channel improved (lower BER) with increasing launch power, while the BER improvements gradually reduced for each measured step (1 dB sweep), until the power per channel reached -1.4dBm. The shape of the plot suggests that this point is close to the achievable optimum and the performance is expected to deteriorate as the power increases further, due to increasing nonlinear transmission penalties [8].

Figure 5(b) shows the transmission performance of selected channels after 215km of transmission measured at the maximum achievable power (-1.4dBm per channel), resulting in the highest measured $BER_{@1540.16nm}$=3.09e-2 and slowly improving with wavelength, reaching the lowest measured $BER_{@1565.09nm}$=2.44e-2 at the end of the C-band. This trend can be ascribed to the tilted NF characteristic of broadband DRAs [9], benefitting the transmission channels at longer wavelengths, suggesting even better performance is likely in the L-band. The final tested point was measured to be $BER_{@1529.94nm}$=3.01e-2 and we ascribe its slightly better performance than $BER_{@1540.16nm}$ to its position on the edge of the spectrum, which results in less nonlinear interference generated by neighboring WDM channels. The FEC threshold for error-free transmission was 3.6e-2, leaving room for possible transmission with higher baud rate signals or over a larger number of spans (and longer total transmission distance), which was not possible to investigate at present with an in-line configuration due to current equipment limitations.

3.2. DP-QPSK transmission test

Since the commercial transceiver was capable of C-band transmission only, a 30Gbaud DP-QPSK signal was used to indicate the transmission performance in the L-band. This signal was generated using an IQ modulator and a polarization multiplexer (PolMux), combined with the channelized ASE and captured on the receiver side using an 80GSa/s, 36GHz real-time oscilloscope, then processed offline using in-house Digital Signal Processing (DSP), where the Q^2 was derived from the constellation diagram distribution [8,9], as the BER values were too low for direct measurement in this scenario. Figure 6 shows the transmission performance after 3 spans of SMF (215km) measured for 5 channels in the C- band (1529.94nm, 1540.16nm, 1547.71nm, 1556.55nm, 1565.09nm) and 5 channels in the L- band (1571.24nm, 1581.6nm, 1589.99nm, 1598.47nm, 1605.31nm); the back-to-back Q^2 was measured to be 21.6dB. The measured performance was very uniform, in a range 18.3-18.55dB, with a slight upward trend with wavelength, which is in agreement with the BER performance from Fig. 5(b) and suggests that the DP-64QAM performance in this region should not be worse than in the C-band. The decrease of Q^2 at wavelengths higher than 1590nm is attributed to the bandwidth of the band pass filter used at the receiver side, whose operating range is specified as 1490-1590nm.

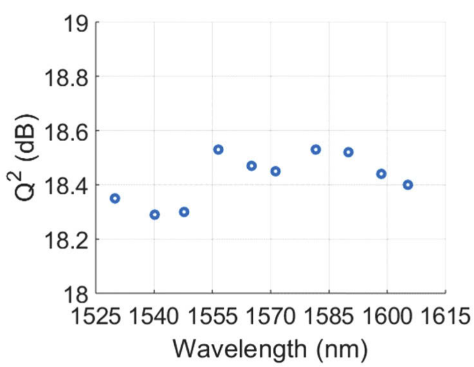

Fig. 6. Q^2 (dB) DP-QPSK transmission performance after 215km measured over C- and L-band.

4. Summary

We have experimentally demonstrated the performance of high capacity transmission links compensated with broadband (>75 nm) DRAs. First, we compared the transmission of 69.4Gbaud DP-16QAM, DP-32QAM and DP-64QAM C-band signals (193.7THz/1547.71 nm) over a single span of SMF (75 km) compensated with two different amplifiers: a DRA and an EDFA. We have shown that with the increase of modulation format order (and therefore higher OSNR requirements) the optimum performance of both amplification schemes becomes increasingly comparable for short reach transmission (BER_{DRA}=3.46e-2 and BER_{EDFA}=3.37e-2 for 69.4Gbaud DP-64QAM signals). Second, we measured the penalty induced on the measured channel resulting from loading the system with 88 × 100 GHz spaced channels distributed over C- and L-bands. A 69.4Gbaud DP-32QAM channel at 193.7THz was used and a BER increase from $BER_{DRA,1CHANNEL}$=8.4e-3

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to $BER_{DRA,WDM}$=1.01e-2 was observed. By identifying a link scenario resulting in performance above BER threshold at 3.6e-2, we performed a multi span 215 km long transmission over 3 spans of SMF, each compensated with a DRA. The C- and L- band spectrum was reconfigured into 182 × 50 GHz channels and the transmitted signal was set to 34.7Gbaud DP-64QAM. We measured selected C-band channels to be all above threshold level with the highest BER in low C-band region $BER_{@1540.16nm}$=3.09e-2, decreasing towards longer wavelengths, and therefore leaving sufficient margin for possible transmission with higher baud rate of signals over a larger number of spans. To test the performance of the DRA in the L-band, we transmitted 30Gbaud DP-QPSK signal over both C- and L- bands, recording a Q^2>18.3 dB. The measured transmission performance shows that the DRA is a viable solution for high capacity, short reach, seamless broadband transmission systems, making it potentially suitable for future increased capacity inter-data-centre and metro applications.

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Disclosures

The authors declare no conflicts of interest. Md Asif Iqbal is now with British Telecom Laboratories, Polaris House, BT Adastral Park, Martlesham Heath, Ipswich IP5 3RE, UK.

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