150nm SCL-Band Transmission through 70km SMF using Ultra-wideband Dual-stage Discrete Raman Amplifier

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Abstract: We experimentally demonstrate a dual-stage 150nm discrete Raman amplifier with 15dB gain and maximum ~8dB noise figure enabling SCL-band (1475-1625nm) WDM transmission through a 70km SMF using 30GBaud PM-QPSK signals with low transmission penalties. © 2019 The Author(s)

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1. Introduction

In recent years, ultra-wideband (UWB) transmission utilising the unused spectral bands of previously deployed standard single mode fibre (SSMF) has gained considerable attention from the research community and system operators because of its potential to be a short to medium term solution to the inevitable “capacity crunch” [1-3]. One of the challenges for realising future UWB optical transmission networks is the proper design and optimisation of UWB optical amplifiers [1]. So far, SCL-band transmission with high data rate QAM signals has been demonstrated using multi-band rare-earth doped fibre amplifiers [2] and seamless hybrid Raman/semiconductor optical amplifiers (SOAs) [3]. However, the overall transmission performance of such SCL-band systems is limited by the fundamental inter-band stimulated Raman scattering (SRS) induced energy transfer from S to C and L bands [2]. Distributed Raman amplification for S-band and signal power optimisation have been used recently to reduce such SRS-induced penalties for S-band signals within SCL-band transmission systems [2, 3].

In this study, we demonstrate a dual-stage design of SCL-band discrete Raman amplifier (DRA) which provides 15dB average gain with only 3dB ripple and improves ASE noise performance of S-band signals without requiring high power pumps to propagate through the transmission fibre as in the case of distributed Raman amplification or relative intensity noise (RIN) limited co-pumping [4]. We report errorless transmission through 70km SSMF with 152×100GHz-spaced channels in SCL-band using 30GBaud PM-QPSK signals with very low transmission penalty.

2. Experimental setup and characterisation of the SCL band DRA

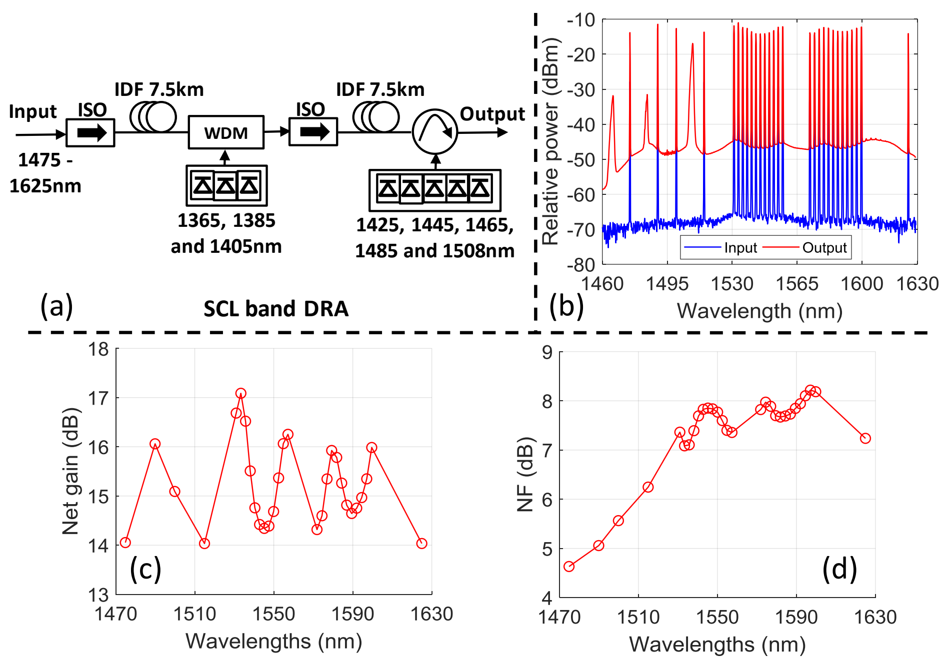

Fig. 1. (a) Schematic diagram of dual-stage DRA; (b) input and output spectra; (c) net gain and (d) noise figure (NF) characteristics.

Figure 1(a) shows the proposed DRA consisting of two consecutive 7.5km stages of inverse dispersion fibre (IDF) in which eight backward Raman pumps (1365, 1385, 1405, 1425, 1445, 1465, 1485 and 1508nm) are distributed over the first and second stages to improve the S-band NF and achieve 15dB overall Raman gain by reducing the strong pump-to-pump Raman energy transfer compared with conventional backward pumped single-stage design [5]. Only three pumps are used in the first stage to provide gain to the S-band signals (1475-1530nm), whereas gain in the C+L band is obtained in the second stage using the remaining pumps. The gain and NF of the DRA were characterised using a flat WDM input signal consisting of four S-band CW lasers, 24 channelised ASE signals in the C+L band at 300GHz spacing, and a 1625nm CW laser as shown in Fig. 1(b). The pump powers were 317, 490, 209, 366, 334, 188, 56 and 166mW (with increasing pump wavelength). In the first stage, the S-band signals were amplified above the target 15dB average net gain to balance the Raman energy transfer to longer wavelength signals during propagation through the second stage. The output spectrum in Fig. 1(b) shows that the 1485nm and 1508nm pumps required to provide gain in the L-band overlap the S-band part of the signal band. Consequently, the Rayleigh backscattered (RBS) light from these pumps introduces crosstalk on neighboring WDM signals [6], but its measurable impact was negligible more than +/-2nm away from the pumps.

The net gain profile with only ~3dB variation over the SCL-band is shown in Fig. 1(c) and the corresponding NF with positive tilt through the S-band, followed by a 7-8dB plateau in the C- and L-bands is shown in Fig. 1(d). The overall NF profile is due to the particular dual-stage DRA design adopted here, which enables a low value in the S-band, due to S-band amplification in the first stage, but a presents a higher value in the C- and L-bands due to excess first stage losses and reduced pump-to-pump Raman energy transfer. In fact, the difference in NF between S-band and C- and L-bands in Fig. 1(d) is exaggerated slightly due to the use of only four signals in the former and a regular grid in the latter. In a fully loaded system, we would expect a slight degradation of S-band NF due to increased power spectral density and a slight reduction of L-band NF due to additional SRS-induced energy transfer from loaded S-band. Note that the L-band NF can be further improved with the addition of a low power 1508nm Raman pump in the first stage to provide a modest gain contribution for L-band signals [5].

3. Transmission results and discussion

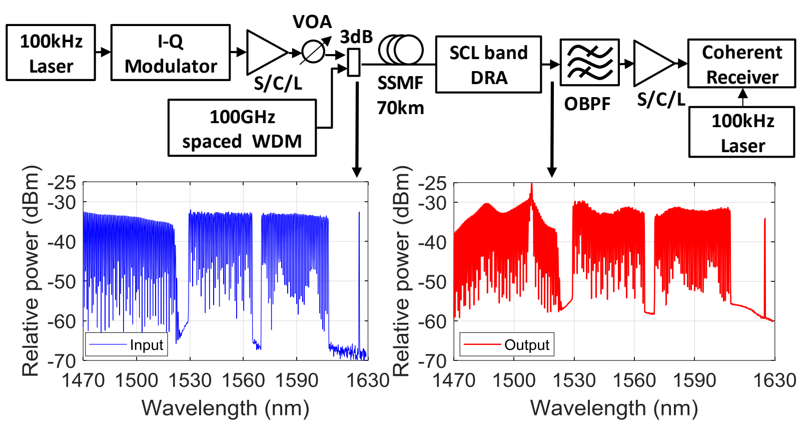

Fig. 2. Coherent transmission experiment setup showing the input spectrum to the span and output spectrum from the DRA.

Figure 2 shows the coherent transmission experiment setup. The transmitter consisted of a tuneable 30GBaud PM-QPSK signal combined with a WDM spectrum using a 3dB coupler. The WDM spectrum consisted of 100GHz-spaced 35GHz ASE channels in S, C and L bands and a CW laser at 1625nm. The S-band spectrum was generated from a supercontinuum source that was filtered using a 50GHz optical interleaver, the output had a 4dB tilt. This was combined with a flat channelised ASE spectra in both C and L bands (obtained using C and L band EDFAs and two WSS channel equalisers). The total input WDM signal power into the span was 16.5dBm (~ -5.3dBm/channel).

The PM-QPSK channel was first amplified by a particular booster amplifier i.e. a thulium doped fibre amplifier (TDFA) in the S-band and an EDFA in either C- or L-band, and then introduced between two 100GHz-spaced channels. The transmission loss (14.3dB) from the 70km SSMF span was compensated by the proposed dual-stage DRA. The input and output spectra are shown in Fig. 2(insert), in which the peak in the output spectrum is due to the RBS light of the 1508nm pump which had much higher power than adjacent S-band amplified signals. In the absence of a suitable WSS, it was not possible to introduce guard bands around the overlapping S-band pumps, so the crosstalk from the RBS components of the overlapping pumps was maximum. At the receiver end, the PM-QPSK signal was filtered out using a tuneable optical bandpass filter (OBPF) and amplified by the corresponding pre-amplifier before passing on to the coherent receiver where the signal was received with an 80GSa/s, 36GHz bandwidth oscilloscope and processed by offline digital signal processing.

The transmission performance of the PM-QPSK modulated signal was measured every ~5nm from 1475nm to 1608nm. Although the SCL-band DRA provided gain up to 1625nm, measurements beyond 1608nm were not possible due to the limited gain bandwidth of the L-band EDFAs. First, we measured the back-to-back (B-2-B) Q^2 factors of our transceiver setup at different wavelengths in S-, C- and L-band as shown in Fig. 3(a) by black circles. The average Q^2 factor for the central region 1530-1590nm signals was ~20.2dB. For wavelengths below 1520nm, the decrease in B-2-B Q^2 factors was mainly due to increasing NF of the TDFAs and decreasing available power to the local oscillator. The sharp drop in the B-2-B Q^2 factor from S to C band was due to the change in amplifier type from TDFA to EDFA. In the L-band at 1590nm, the step change in B-2-B Q^2 factors resulting in significantly worse upper L-band signals was mainly due to a required change of tuneable filter for the spectral region above 1590nm.

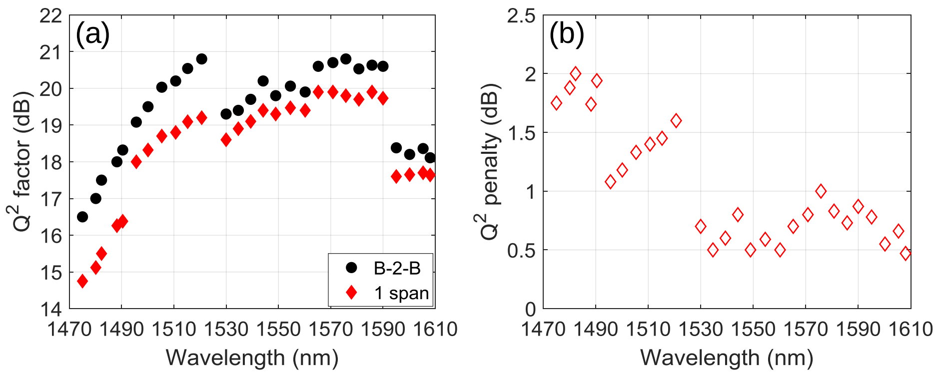

Fig. 3. (a) Comparison of Q^2 factors at different wavelengths between B-2-B and single span measurements and (b) Q^2 penalties vs wavelengths.

The Q^2 factors (red diamonds) after single 70km SSMF transmission were well above the HD-FEC limit of 8.5dB for PM-QPSK and followed the same trend as the B-2-B performances shown in Fig. 3(a). The Q^2 penalties with respect to the B-2-B are shown in Fig. 3(b) indicating <1dB transmission penalty in C- and L- bands, and a notable increasing trend in the lower S-band. We measured no additional penalties on the signals, ±2nm apart from the overlapping pumps in S-band. The higher transmission penalties up to 2dB in the S-band are despite the lower S-band NF shown in Fig. 1(c), and are mainly attributed to the low OSNR of the transmitted PM-QPSK signals in this region, which could be improved with a better S-band transceiver, and to additional nonlinear penalties. Arising from the previously mentioned excess gain required in the first stage of the DRA to compensate for subsequent SRS induced energy transfer [5], we expect these additional nonlinear penalties can be reduced via optimisation of the Raman gain fibre lengths of the dual-stage DRA. In particular, a trade-off between NF improvement and nonlinear penalty should be possible along the lines previously described [5].

4. Conclusion

We have experimentally demonstrated SCL-band WDM transmission through 70km SSMF using a dual-stage DRA with 150nm bandwidth (1475-1625nm). The dual-stage design of the DRA provides ~15dB average net gain with 3dB gain variation and significantly reduces the S-band NF without requiring any distributed gain or co-pumping. We report, an error-free 70km SSMF transmission of 30GBaud PM-QPSK WDM signals with Q^2 penalties of only 0.5-1dB in C+L band and up to 2dB in S band with respect to B-2-B performances.

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