Characterisation of Linear and Nonlinear Noise of a Dual-Stage Broadband Discrete Raman Amplifier

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Abstract *The linear and nonlinear noise performance of a 70nm, dual-stage, ~20dB-gain discrete Raman amplifier is characterised experimentally using different second-stage fibres. An advantageous IDF-SMF configuration is identified with an improvement in the nonlinear performance by >1dBQ^2 compared with IDF-DCF configurations.*

Introduction

In this paper, we report the experimental characterisation of the linear and nonlinear noise of a high output power and high gain broadband (1530-1600nm) dual-stage discrete Raman amplifier (DRA). We show that using inverse dispersion fibre (IDF) as the 1st stage, and standard single mode fibre (SMF) rather than dispersion compensating fibre (DCF) as the 2nd stage, gives a good balance between low noise figure (NF) and nonlinear noise induced transmission penalties.

In the design of DRAs, small core area fibres with higher Raman gain co-efficient (i.e. DCFs, highly nonlinear fibres (HNLFs), and IDFs) rather than conventional SMFs are usually used to improve the pump conversion efficiency. However, the noise performance of high gain DRAs is strongly impacted by double Rayleigh scattering (DRS) induced multi-path interference (MPI) crosstalk which also limits the maximum net gain up to 15~17dB in single stage DRAs[1].

Dual-stage DRAs can limit the generation of DRS using a mid-stage isolator and also provide higher net gain with low noise[2]. The choice of Raman gain fibre type and length in each stage is important to maintain improved noise and nonlinear performance[3]. Moreover, using gain-fibres with high nonlinear index causes Kerr induced nonlinear penalties due to self-phase modulation (SPM) induced nonlinear phase shift (NPS), cross-phase modulation (XPM) and four-wave mixing (FWM), which can eventually degrade the performance of WDM polarisation-multiplexed (PM) phase modulated coherent transmission systems. So, careful design of high gain broadband DRAs with appropriate choice of Raman gain fibres is required for their optimum use in high capacity coherent WDM systems.

Here, we propose a dual-stage DRA design using 10km of IDF as the 1st stage, which was chosen for this purpose because it gives the optimal trade-off between NF, nonlinear impairments and gain efficiency compared with DCF and SMF[3,4]. We compare performance, in terms of NF and FWM product power, for the same net gain using 10km of SMF, 5km of DCF, and 10km of DCF as the 2nd stage. Finally, in a 5×120Gb/s PM-QPSK WDM coherent transmission system consisting of a single 93.4km span of SMF, we show our proposed IDF-SMF based DRA gives at least 1dB improvement both in optimum launch power and Q^2 factor in the nonlinear regime compared with the DCF 2nd stage based DRA schemes.

Experimental setup

Figure 1(a) shows the experimental setup of our backward pumped dual-stage DRA in which the 1st stage consists of 10km IDF and the 2nd stage includes either 10km SMF or two different lengths (5km or 10km) of DCF. The 1st stage was backward pumped by five 1st order Raman pump laser diodes: 1425, 1444, 1462, 1476 and 1491nm with 351, 236, 99, 16 and 142mW pump power respectively to maintain ~14dB average net gain across 70nm. The 2nd stage was backward pumped with a similar pump set,

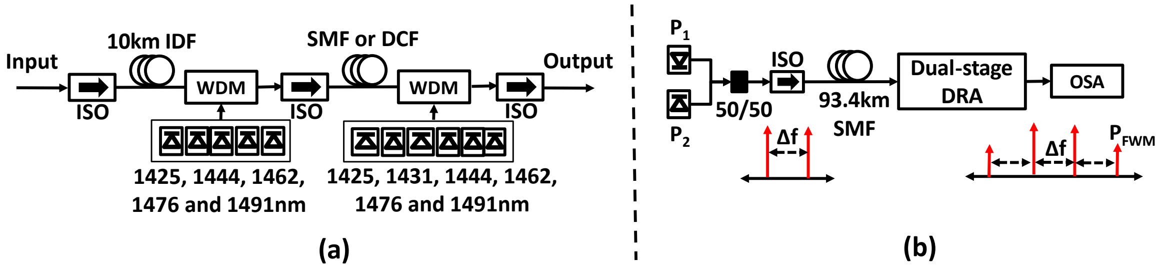

Fig. 1: (a) Schematic of dual-stage DRA schemes and (b) experimental setup of FWM product power measurement

but with an additional 1431nm pump to provide more pump power in the shortest pump wavelength region. The pump powers in the different 2nd stages (Tab. 1) were adjusted to provide a total of ~19.5dB average net gain from the combined 1st and 2nd stages.

Tab. 1. Pump powers used in the 2nd stage

Pumps (nm)	SMF 10km (mW)	DCF 5km (mW)	DCF 10km (mW)
1425	278	107	89
1431	188	87	71
1444	221	100	95
1462	135	50	17
1476	115	12	4
1491	260	120	72
Total	1197	476	348

The net gain and NF over the 70nm amplifier bandwidth were characterised using 24x300GHz spaced channels of spectral shaped amplified spontaneous emission (ASE) from C and L band EDFAs. Nonlinear performance of the different DRA schemes was characterised using a FWM efficiency measurement as shown in Fig. 1(b)[5], where the 19.5dB loss of the 93.4km SMF transmission span was compensated using the DRA. Two tuneable CW lasers (P_1 and P_2) at 3dBm power and a high resolution (150MHz) optical spectrum analyser (OSA) were used. The FWM efficiency was measured at the output of the DRA around 191.9THz, varying the frequency separation (Δf) between the lasers from 1GHz to 50GHz.

Finally, the performance of the three dual-stage DRA schemes was characterised through a single span coherent WDM transmission experiment, using a standard 120Gb/s PM-QPSK transmitter consisting of five 100GHz spaced WDM signals (193.8~194.2THz)[6]. At the transmitter, the WDM signals were amplified to 23dBm using a booster EDFA and the input signal power into the 93.4km SMF span was varied from -5.7 to 12.3 dBm/ch using an input attenuator to maintain fixed input OSNR. The pump depletion in the 1st stage was insignificant, so the same pump powers as used for NF characterisation were used in the 1st stage. However, to ensure no drop-in signal power at the highest signal power levels due to pump depletion, the 2nd stage multi-pump module was replaced by a high power 1455nm fibre laser pump, and pump powers were adjusted at different signal powers to maintain a constant net gain of ~19.5dB. A standard polarisation diverse coherent receiver with 80GSa/s and 36GHz bandwidth was used at the receiver. The received signal was post-processed using offline digital signal processing (DSP) and Q^2 factors were calculated from the error vector magnitude (EVM) of the received constellations.

Results and discussion

Firstly, the net gain and NF performance of the different DRA schemes were measured using the 24 spectrally shaped ASE channels over 70nm at -20dBm/ch power. The average net gain and overall gain flatness were kept similar at ~19.5dB and ~2.2dB respectively for all the DRA schemes as shown in Fig. 2(a). The NF of all three schemes was found to be quite similar, as shown in Fig. 2(b), which is expected, given it is mainly dominated by the unchanged 1st stage. The maximum NF of the IDF 10km 1st stage was 6.5dB and <1dB NF degradation was observed in the dual-stage DRAs. The NF tilt was due to the backward pumping configuration and could be further improved by using bidirectional pumping[6,7]. We also measured the net gain and output power keeping the pump power fixed in both stages and results are shown in Fig. 2(c). The saturated output power is >22dBm in the IDF-SMF case, whereas the IDF-DCF cases showed saturation output powers reduced by at least 1.5dB, mainly due to more efficient power transfer from shorter to longer wavelength pumps and signals.

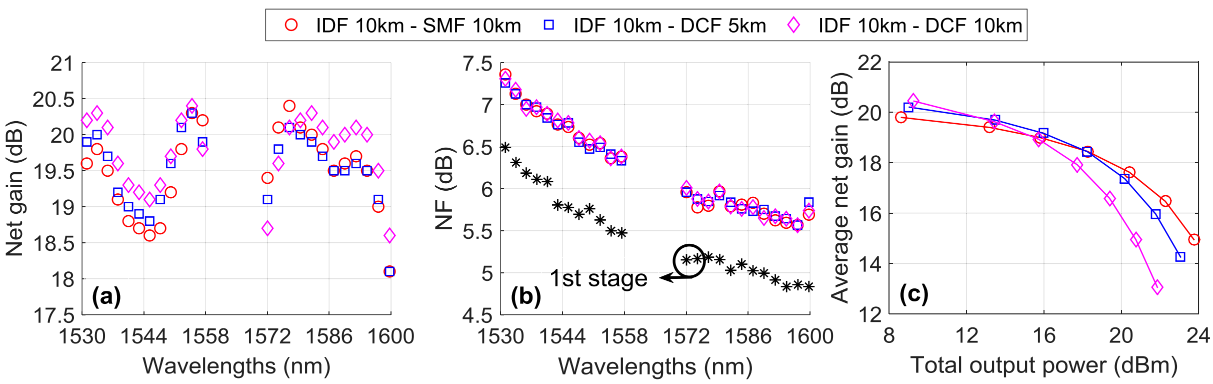

Fig. 2: Performance comparison among different DRA schemes: (a) net gain vs. wavelength; (b) NF vs. wavelength; and (c) average net gain over 70nm bandwidth vs. total output power

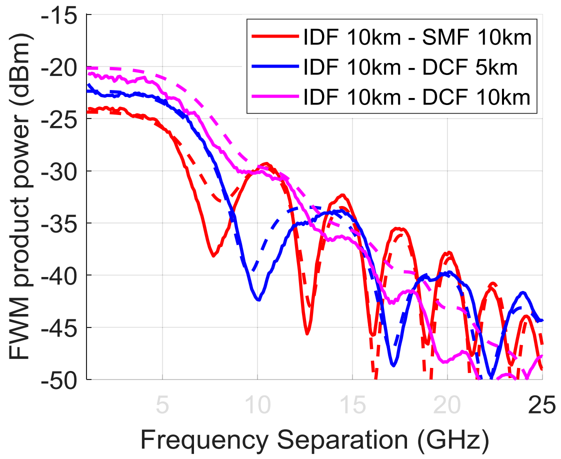

Fig. 3: Experimental (solid) and theoretical (dash) FWM product power as a function of the frequency separation between two CW lasers (3dBm each)

The nonlinear noise performance of the three DRA schemes were characterised both experimentally and theoretically[5] in terms of FWM product power using the setup shown in Fig. 1(b). As expected, the results (Fig. 3) show that the DCF 2nd stage based DRAs gave higher FWM product power than that of SMF due to smaller core area and the resulting higher nonlinearity of the DCF. The IDF-SMF scheme showed 2.3dB and 3.3dB FWM product power reduction at the maximum values obtained at 1GHz frequency separation when compared with the IDF-DCF schemes with 5km and 10km of DCF, respectively. Similarly, the integrated FWM power over 1 to 15GHz gave -18.8dBm which is 1.8dB and 3.3dB lower than that of the IDF-DCF 5km and 10km schemes, respectively.

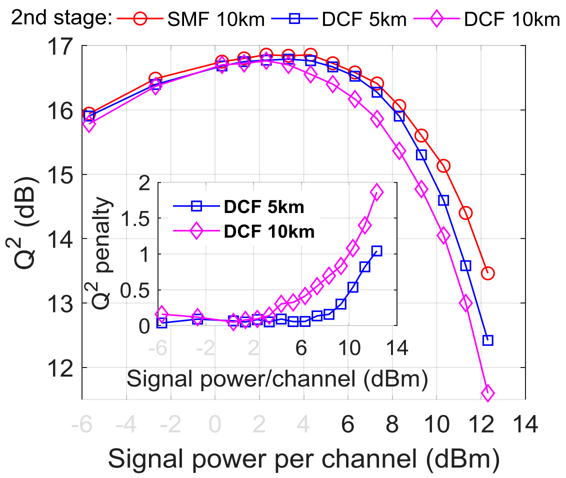

Fig. 4: Q^2 vs. signal power per channel for different dual-stage DRA schemes (Insert: Q^2 penalty with respect to the best performed IDF 10km – SMF 10km based DRA)

Finally, the dual-stage DRA scheme was characterised using a single span coherent transmission experiment with 5×120Gb/s PM-QPSK signals. Fig. 4 shows the Q^2 factor vs. signal launch power per channel for the centre WDM signal (194THz). Only five channels were chosen in order to maintain a sufficiently high launch signal power into the transmission span to observe and compare the nonlinear performance over a single span.

The IDF-SMF based DRA showed the maximum Q^2 factor of 16.9dB with 0.1~0.2dB improvement compared with the DCF 2nd stage based DRA schemes. In the amplifier noise limited linear regime, all the schemes showed similar performance which can be expected from the NF features shown in Fig. 2(b). However, significant Q^2 factor degradation was observed in the nonlinear regime at high signal powers due to the Kerr nonlinearities for the DCF 2nd stage based schemes, as also supported by the FWM product power growth shown in Fig. 3. The Q^2 factor penalties of the IDF-DCF DRAs compared with IDF-SMF based DRA are shown in the inset of Fig. 4, with maximum Q^2 factor degradation due to nonlinear penalties up to 1.9dB and 1.1dB for the IDF-DCF DRAs with 10km and 5km of DCF, respectively. In repeated systems, we expect these Kerr-induced nonlinearities will accumulate and DCF based DRAs will show much stronger Q^2 factor degradation than the SMF based DRA.

Conclusions

We have characterised a novel design of dual-stage DRA in terms of linear and nonlinear noise performance. We have confirmed that while the linear noise (NF) is mainly dominated by the 1st stage, the nonlinear noise induced penalties can be reduced significantly by using a larger core area fibre in the high power 2nd stage. Our IDF-SMF based DRA shows 2dB optimum launch power improvement and up to 1.9dB Q^2 factor improvement in the nonlinear regime compared with an IDF-DCF 10km 2nd stage based DRA.

Acknowledgements

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