Noise and transmission performance improvement of broadband distributed Raman amplifier using bidirectional Raman pumping with dual order co-pumps

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Abstract: We demonstrate a low noise bidirectional broadband distributed Raman pumping scheme combining dual order co-propagated pumps without increasing the signal RIN level. The noise performance improvement is compared experimentally and numerically with conventional counter-pumping only and bidirectional pumping with only a 2nd order co-pump for a 70nm bandwidth and 61.5km distributed Raman amplifier. The proposed broadband pumping scheme shows 1.2dB maximum noise figure improvement and extends the long-haul transmission reach up to 6150km with a Q-factor improvement of ~0.7dB compared with counter-pumping only scheme.

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1. Introduction

Distributed Raman amplification (DRA) has become the preferred choice over conventional lumped amplification (i.e. erbium doped fibre amplifier (EDFA)) in long-haul high capacity coherent transmission systems for its seamless, wide and flat bandwidth [1,2] and particularly for its improved optical signal to noise ratio (OSNR) over the entire amplification bandwidth, allowing spectrally efficient high order modulation formats and Nyquist pulse shaping [3,4].

In broadband DRA, multiple pumps are used to broaden the amplification bandwidth and generate a spectrally flat gain profile. Whilst co-pumping allows the effective increase of signal launch power into the fibre, pure counter-pumping is preferred in multi-wavelength pumped distributed Raman amplifiers to reduce pump to signal relative intensity noise (RIN) transfer [5,6] and reduce gain saturation effects. However, in counter-pumped broadband DRA, low wavelength signals suffer more from the thermally generated amplified spontaneous emission (ASE) noise, due to being close to the longer wavelength pumps. This causes the problem of noise figure (NF) tilt or OSNR variation across the amplifier's bandwidth. Due to this NF tilt in counter-pumped systems, overall transmission performance is mainly limited by the ASE-limited low wavelength signals.

One of the potential solutions to this problem is to use a bidirectional pumping scheme with low wavelength 1st order pumps set as co-pumps [7] to improve OSNR in the low wavelengths signal band. However, the noise performance improvement in this case can be outbalanced by the negative impact of RIN transfer from the 1st order co-pumps which are only one Stokes shift away from the signals. Recently, we have experimentally showed that, in a 1st order co-pumped bidirectional DRA, the performance improvement due to OSNR improvement is counteracted by the direct pump to signal RIN transfer which degrades transmission performance when compared to pure counter-pumping [8]. It has also been shown [9] that dual order counter-pumping including a 2nd order pump cascaded with multiple 1st order pumps improves overall OSNR and NF tilt because of the better gain distribution property of higher order pumping. However, this benefit comes at the cost of reduced pump efficiency which reflects in the requirement of high pump power (>1W) of primary 2nd order pump to push the distributed gain further into the span from the output end and amplify the signal before it gets attenuated close to noise level. Hence, the improved noise performance of the amplifier can be hindered by its poor energy efficiency.

In this paper, we propose a bidirectional pumping scheme of a 70nm DRA combining dual order co-pumping with 2nd and 1st order co-pumps to improve optical NF performance without increasing signal RIN. A conventional fibre laser pump is used as 2nd order co-pump, without the need of low pump RIN sources. A semiconductor laser diode is used as 1st order pump seed which has low RIN (~-130dB/Hz), requires very low pump power and is not at the peak of Raman Stokes shift of the 2nd order pump. The choice of pump wavelengths ensures

minimal RIN transfer from the primary 2nd order co-pump to signal, but the improvement of OSNR in the low wavelength signal band still exists, thanks to the broad Raman gain spectrum. Optical NF improvement is then compared numerically and experimentally with that of pure counter-pumping and dual order bi-directional pumping with 2nd order co-pump only. A detailed investigation of signal power variation (SPV) and RIN are also shown for all the pumping schemes discussed here.

Finally, the benefits of improved noise performance are evaluated through long-haul 13 × 120Gb/s DP-QPSK wavelength division multiplexed (WDM) coherent transmission using a re-circulating loop setup. We demonstrate that the proposed dual order bidirectional broadband DRA can extend the transmission reach up to 6150km with a ~0.7dB Q-factor improvement and ~740km reach enhancement compared with counter-pumping only. We also investigate the impact of the 1st order co-pump seed power and RIN level on the transmission performance, and we report that a 1st order seed power of ~21mW with a RIN level below −130dB/Hz is the best choice to achieve maximum transmission reach in our proposed amplifier scheme.

2. Proposed schemes and amplifier characterization

We have investigated three different types of pumping schemes as shown in Fig. 1. Four 1st order pump wavelengths (1425nm, 1444nm, 1462nm and 1491nm) were used as counter pumps in all the schemes. The choice of pumps gives a flat gain variation ($\sim \pm 0.75$dB) over a 70nm signal bandwidth (1530nm to 1600nm) for a 61.5km amplifier span of standard single mode fibre (SSMF). Commercial low RIN (~-130dB/Hz) semiconductor laser diodes with maximum output power of 300mW were used as 1st order pumps. Two laser diodes at each wavelength were combined through a polarization beam combiner (PBC) to avoid any polarization dependent gain and then combined subsequently with other first order pumps through a cascaded WDM pump combiner to form the counter pumping module. Scheme-1 refers to the counter-pumping only with above mentioned four 1st order pumps as shown in Fig. 1(a). Scheme-2 in Fig. 1(b) shows bidirectional pumping with the same counter pump module and co-pumping by only 2nd order pump at 1365nm. A highly depolarized Raman fibre laser with reasonably high RIN (~-120dB/Hz) and maximum output power of ~5W was used as the 2nd order co-pump.
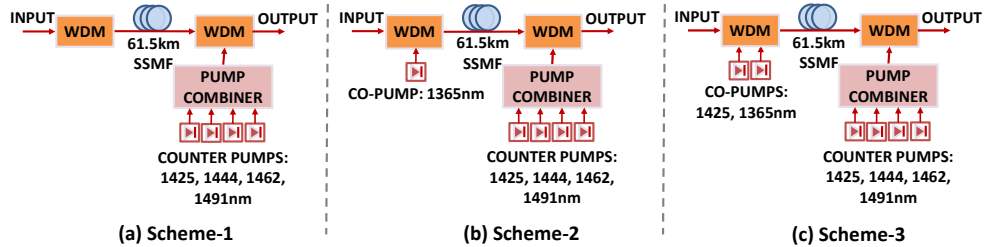

Fig. 1. Schematic of three broadband Raman pumping schemes (a) Scheme-1: counter-pumping only (b) Scheme-2: bidirectional pumping with only 2nd order co-pump and (c) Scheme-3: bidirectional pumping with 1365nm pump and 1425nm pump seed from the input end at 21mW (scheme-3(a)) and 49mW (scheme-3(b)) respectively.

Our proposed bidirectional dual order pumping scheme (scheme-3) consists of 2nd order (1365nm) and 1st order (1425nm) co-pumps as shown in Fig. 1(c). The 1425nm pump acts as a seed which first gets amplified by the 1365nm 2nd order co-pump and then finally amplifies the lower wavelength signals in order to improve the ASE noise performance of the amplifier in that region. A commercially available semiconductor laser diode was depolarized thorough an isolator-PBC-deploarizer (IPBCD) and used as 1st order co-pump seed with only 20~50mW power. Two different pump powers, 21mW and 49mW, have been used for the 1425nm co-pump seed, denoted as scheme-3(a) and scheme-3(b) respectively, whereas a

constant 216mW power was used for the 1365nm co-pump in both bidirectional pumping schemes to allow a fair comparison in terms of RIN transfer from the 2nd order co-pump to the signal. The particular choice of co-pump powers gave the best trade-off between gain flatness and ASE noise generation.

A standard steady state numerical model [10–12] was used to simulate the evolution of WDM signals and pumps in the amplifier. This standard average power model includes all important effects such as: stimulated and spontaneous Raman scattering, pump depletion, ASE and double Rayleigh scattering (DRS) noise, energy transfer due to pump-pump, pump-signal and signal-signal interactions from either directions. The power evolution of any signal or pump frequency (ν) can be described by Eq. (1).

$$\frac{dP_\nu^\pm}{dz} = \pm \left\{ \begin{array}{l} -\alpha_\nu P_\nu^\pm + \varepsilon_\nu P_\nu^\mp \\[2mm] +P_\nu^\pm \left[\begin{array}{l} \sum_{\mu>\nu} \frac{g_{\mu\nu}}{A_\mu}\left(P_\mu^+ + P_\mu^-\right) \\[3mm] -\sum_{\mu<\nu} \frac{\nu}{\mu}\frac{g_{\nu\mu}}{A_\mu}\left(P_\mu^+ + P_\mu^-\right) - 4h\nu \sum_{\mu<\nu}\frac{g_{\nu\mu}}{A_\mu}\left(1 + \frac{1}{e^{\frac{h(\nu-\mu)}{kT}} - 1}\right)\Delta\mu \end{array} \right] \\[6mm] +2h\nu\Delta\nu\sum_{\mu>\nu}\frac{g_{\mu\nu}}{A_\mu}\left(P_\mu^+ + P_\mu^-\right)\left(1 + \frac{1}{e^{\frac{h(\mu-\nu)}{kT}} - 1}\right) \end{array} \right\} \quad (1)$$

where $P_\nu^\pm$ represents the average power within the frequency interval $\Delta\nu$ either co- (+) or counter- (-) direction at centre frequency ν. The attenuation and DRS coefficients at centre frequency ν are given by α_ν and ε_ν. The Raman gain coefficient at frequency ν with respect to pump at frequency μ, Plank's constant, Boltzmann's constant and absolute temperature are represented by $g_{\mu\nu}, h, \kappa$ and T respectively. The corresponding noise power in both co- and counter- propagated at frequency ν are described by the following Eqs. (2) and (3).

$$\frac{dN_\nu^+}{dz} = -\alpha_\nu N_\nu^+ + \varepsilon_\nu N_\nu^-$$
$$+N_\nu^+ \sum_{\mu>\nu}\frac{g_{\mu\nu}}{A_\mu}\left(P_\mu^+ + P_\mu^-\right) + 2h\nu\Delta\nu\sum_{\mu>\nu}\frac{g_{\mu\nu}}{A_\mu}\left(P_\mu^+ + P_\mu^-\right)\left(1 + \frac{1}{e^{\frac{h(\mu-\nu)}{kT}} - 1}\right) \quad (2)$$

$$\frac{dN_\nu^-}{dz} = \alpha_\nu N_\nu^- - \varepsilon_\nu\left(N_\nu^+ + P_\nu^+\right)$$
$$-N_\nu^- \sum_{\mu>\nu}\frac{g_{\mu\nu}}{A_\mu}\left(P_\mu^+ + P_\mu^-\right) - 2h\nu\Delta\nu\sum_{\mu>\nu}\frac{g_{\mu\nu}}{A_\mu}\left(P_\mu^+ + P_\mu^-\right)\left(1 + \frac{1}{e^{\frac{h(\mu-\nu)}{kT}} - 1}\right) \quad (3)$$

where P_ν^+ and $N_\nu^\pm$ represent the co-propagating average signal power and noise power either co- (+) or counter (-) direction at signal frequency ν respectively.

In the amplifier simulation for gain and noise performance calculation, the above equations were solved numerically considering room temperature, frequency dependent attenuation profile and normalized Raman gain spectra of SSMF considering depolarized

pumps. A noise bandwidth of 125GHz has been used for the NF calculation according to the Eqs. (4) and (5).

$$NF = \frac{P_{ASE}}{E_{ph}B_0 G} + \frac{1}{G} \qquad (4)$$

$$NF(dB) = 10\log 10(NF) \qquad (5)$$

where P_{ASE} and E_{ph} are the ASE noise power and photon energy at frequency v. The on-off gain and reference optical bandwidth are given by G and B_0 respectively.

In the experiment, the broadband gain performance of the amplifier was characterized using 100GHz channelized spectral shaping of a supercontinuum source. This source gave an output power of 12dBm over the full 1530-1600nm range of the amplifier with 4dB power variation as shown in the insert of Fig. 2(a). The signal power per channel of the broadband spectral shaped supercontinuum source was −8dBm and no pump depletion was observed at this power level. The signal power evolution along the span was measured for 1530nm signal following a modified standard optical time domain reflectometer (OTDR) technique [13]. The ASE noise performance has been investigated both experimentally and numerically and a comparison of the schemes is presented in terms of optical NF improvement. Here, 1530nm signal is chosen for characterization, which is the lowest wavelength in the amplification bandwidth and suffers most from thermally generated ASE noise.
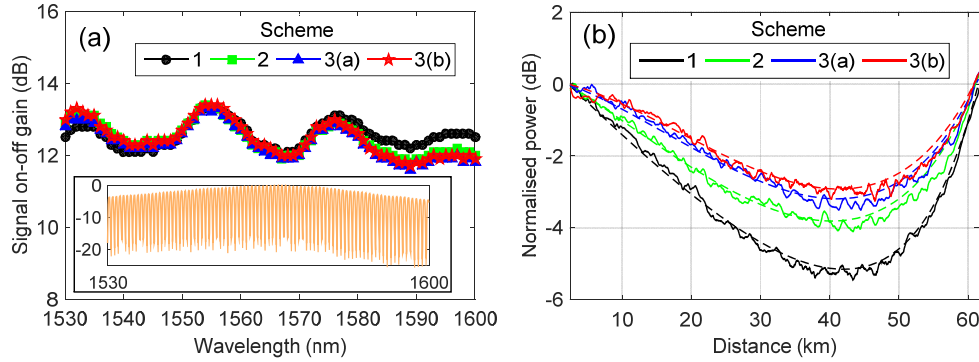

Fig. 2. Characterization of the amplifier at different pumping scheme (a): measured on-off Raman gain (Insert: Normalized 100GHz channelized broadband ASE input) (b): measured (solid) and simulated (dash) power evolution of 1530nm signal.

Table 1. Pump powers used in experimental measurement.

Pumps (nm)	Scheme-1		Scheme-2		Scheme-3(a)		Scheme-3(b)	
	Co-(mW)	Counter-(mW)	Co-(mW)	Counter-(mW)	Co-(mW)	Counter-(mW)	Co-(mW)	Counter-(mW)
1365	-	-	216	-	216	-	216	-
1425	-	254	-	204	21	163	49	131
1444	-	183	-	181	-	181	-	183
1462	-	117	-	121	-	130	-	136
1491	-	164	-	156	-	164	-	172
Total	-	718	216	665	237	638	265	622

Figure 2(a) shows the measured on-off gain with input shown in the insert. In each pumping scheme, counter pump powers were optimized in order to maintain ~12.6dB average on-off gain which compensates both the SSMF span and WDM coupler losses. The overall gain ripple of the amplifier was ± 0.75dB. The simulation results also showed a close match

with experimental measurements but are not shown here in order to maintain clarity. Table 1 shows the pump powers used in each scheme. It can be seen that total counter pump powers requirement decreases as more gain contribution comes from the co-pumps.

The measured and simulated signal power profiles at 1530nm are shown in Fig. 2(b). Simulation results are marked with dashed lines which closely match the measurements (solid lines) and confirms the SPV improvement with dual order co-pumping schemes. Counter-pumping only scheme-1 shows the worst SPV of ~5.2dB. SPV improvements of 1.4dB and 2dB compared with counter-pumping only are shown by scheme-2 and scheme-3(a) respectively. Increasing the 1425nm co-pump seed power from 21mW to 49mW provides additional 0.3dB improvement in scheme-3(b).
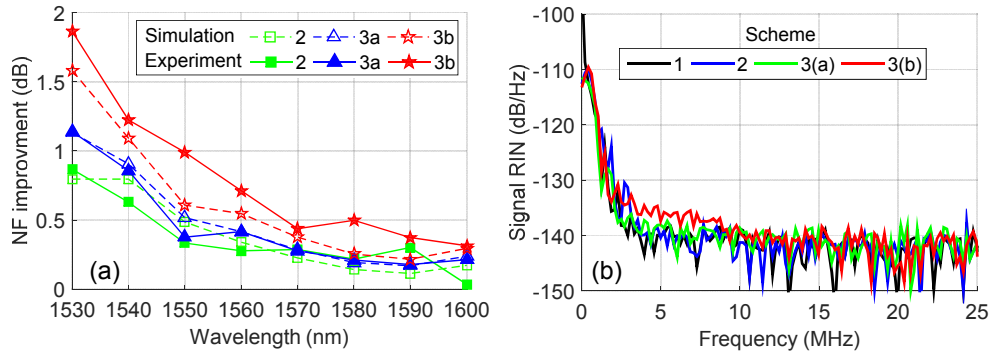

Fig. 3. (a): Measured (solid) and calculated (dash) NF improvement for scheme-2 and 3 with respect to scheme-1 (b) measured signal RIN at 1530nm.

The performance of different bidirectional pumping schemes are compared with respect to NF improvement from counter-pumping only (scheme-1) as shown in Fig. 3(a). NFs were measured every 10nm across the signal bandwidth using a −6dBm tunable CW laser source with the same pump powers shown in Table 1. Simulation results show a good agreement with measurements. As expected, the NF improvement with bidirectional pumping schemes 2 and 3 is the highest at 1530nm and decreases at longer wavelengths because gain contribution from co-pumps are weak in that region. Scheme-3(a) shows 1.2dB maximum measured NF improvement at 1530nm, which is 0.3dB better than that of scheme-2 because of improved SPV and reduced ASE noise as shown in Fig. 2(b). Additional 0.7dB improvement is also shown with scheme-3(b) as the 1425nm co-pump seed power is increased to 49mW.

The measured RIN performance at 1530nm signal is shown in Fig. 3(b). In scheme-2, the power of the 1365nm 2nd order co-pump has been limited to 216mW, which is insufficient to spontaneously generate co-propagating Stokes light that would transfer RIN efficiently to the signal and thus signal RIN remains at the level comparable with counter-pumping only (scheme-1). Scheme-3(a) also does not show any increment in signal RIN level because RIN transfer from higher order 1365nm pump to low power 1425nm co-pump is low, since maximum gain from the 1365nm pump will occur for the 1444 and 1462nm counter components, due to the characteristic Raman frequency shift of about 13THz. There is a slight increase in signal RIN level below 10MHz in scheme-3(b) because of relatively high co-gain contribution from higher power (49mW) of 1425nm co-pump.
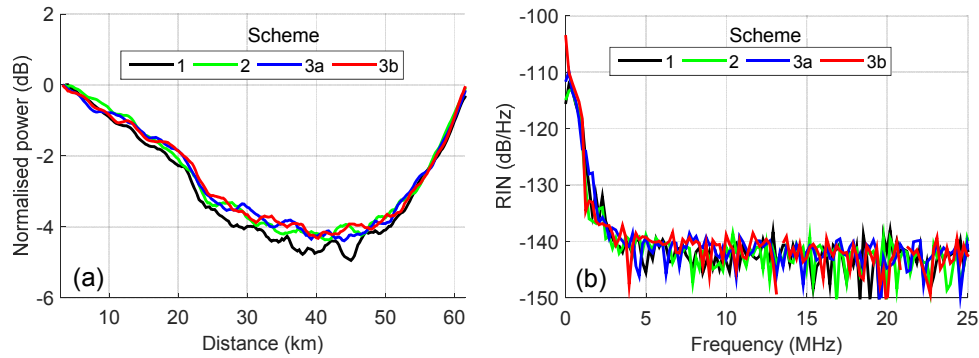
Fig. 4. Measured (a) signal power variations (SPVs) and (b) signal RIN for 1545.32nm signal.

The measured SPVs and signal RIN performances at 1545.32nm are also shown in Figs. 4(a) and 4(b) respectively to verify the OSNR and RIN performances at other wavelength band of the amplifier. A small SPV improvement of 0.5dB and negligible increase in RIN were observed compared with counter-pumping only (scheme-1). Despite having similar power profiles at 1545.32nm, NF improvement from 0.5 to 1dB across different bidirectional pumping schemes could be seen from Fig. 3(a), which mainly come from the overall ASE noise reduction in those schemes.This verifies the benefit of proposed bidirectional pumping scheme in OSNR improvement over the entire amplifier bandwidth without increasing the signal RIN penalty.

3. Transmission results and discussion

In the last section, we have shown the noise performance characterization of different pumping schemes over the 70nm amplification bandwidth with maximum improvement achieved at the lowest signal wavelength. In our experimental transmission performance evaluation L-band equipment was not available to test the full bandwidth. However as the aim of this work was to reduce the overall NF tilt by improving the OSNR of low signal wavelengths, some evaluation can be done using only the C band and measuring the improvement in the low wavelength channels compared with counter-only pumping. So here transmission results were measured at 1530.33nm signal in a WDM coherent transmission setup. Performances of all other WDM channels were also measured at maximum transmission reach.
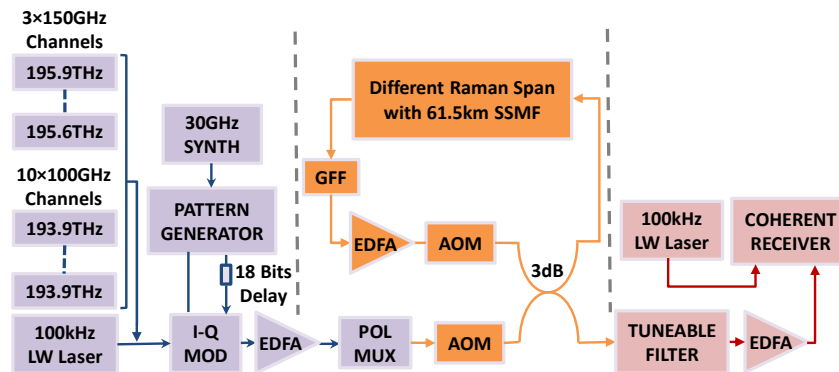

Fig. 5. Re-circulating loop setup for coherent WDM transmission with broadband distributed Raman amplified span (Abbreviations: SYNTH = synthesizer, MOD = modulator, LW = linewidth, POLMUX = polarization multiplexer).

A re-circulating loop setup was used as shown in Fig. 5. A 13 channel WDM grid was considered, consisting of three 150GHz spaced channels (195.6~195.9THz) in the lowest amplification band and other ten 100GHz spaced channels from 193.4~194.3THz. A 100kHz linewidth tunable laser as "channel under test" was combined with the grid. The WDM signals were QPSK modulated at 30GBaud using 2^{31}-1 PRBS data pattern with 18bits relative delay between I and Q. The modulated signals were then amplified by a PM-EDFA and polarisation multiplexed with a 300 symbols equivalent delay line in between two polarisation states. The 13 × 120Gb/s DP-QPSK signals were launched into the re-circulating loop through an acousto-optic modulator (AOM). The distributed Raman amplifier span consists of a 61.5km SSMF with 12dB loss and 1.1dB loss from pump signal combiner pair from both ends. The gain fluctuation in amplified output signals after the Raman link was equalized using a gain flattening filter (GFF). The 12dB additional loop specific loss from GFF, 3dB coupler and AOM was compensated using a dual stage EDFA at the end of the loop. At the receiver, output signal is first de-multiplexed using a narrowband filter and then amplified by an EDFA. A polarisation diverse coherent receiver with 80GSa/s, 36GHz bandwidth oscilloscope was used to capture the signal. Offline digital signal processing (DSP) was applied to process the data and calculate Q-factors from measured bit-error rates averaged over 2 million bits.
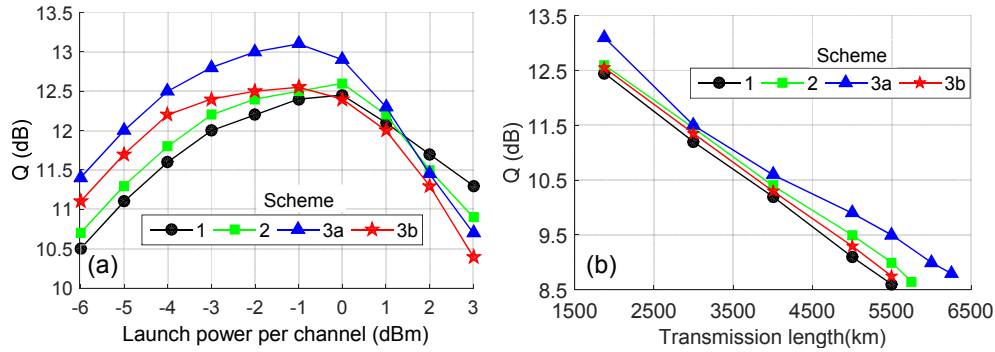

Fig. 6. Transmission performance of different pumping schemes measured at 195.9THz signal: (a) Q-factors versus launch power per channel at 1875km transmission distance (b) Q-factors versus transmission lengths at optimum launch power.

Figure 6(a) shows the experimentally measured Q-factors versus different launch powers per channel at 1875km transmission distance for 195.9THz (1530.33nm) signal in different Raman pumping schemes as described in Fig. 1. The maximum Q-factor for counter-pumping only (scheme-1) was 12.4dB at optimum launch power per channel of 0dBm when signal RIN penalty is considered to be negligible. A small Q-factor improvement of ~0.2dB was observed in scheme-2. In our proposed dual order co-pumping scheme-3(a), Q-factor improvement was ~0.7dB and optimum launch power was minimised to −1dBm compared with scheme-1 due to additional nonlinearity from higher average signal power along the span. The improvement comes from the improved NF and no signal RIN penalty. But increasing 1425nm co-pump power to 49mW in scheme-3(b), the maximum Q-factor was reduced to 12.5dB due to additional RIN penalty from co-pumps although NF improvement was the highest (~1.8dB) compared with counter-pumping only as shown in Fig. 3(a). At the optimum launch powers per channel (−1 and 0dBm) for different pumping schemes, total launched signal powers into the span were calculated as 10.2 and 11.2dBm. Insignificant pump depletion could be expected at this higher power per channel levels and above, but it remains the same for all the bidirectional pumping schemes discussed here and will not affect the general conclusion of overall noise performance improvement without increasing the signal RIN penalty [14,15].

The Q-factors versus transmission distance at optimum launch power for different pumping schemes is presented in Fig. 6(b). Scheme-3(a) showed a maximum Q-factor of

13.1dB at optimum launch power and maximum transmission distance achieved was 6150km with 738km reach extension than that of counter-pumping (5412km). Scheme-2 also showed ~250km transmission reach enhancement compared with scheme-1 due to 0.2dB improved Q-factor, whereas scheme-3(b) achieved similar distance (5412km) like counter-pumping only due to additional signal RIN penalty.
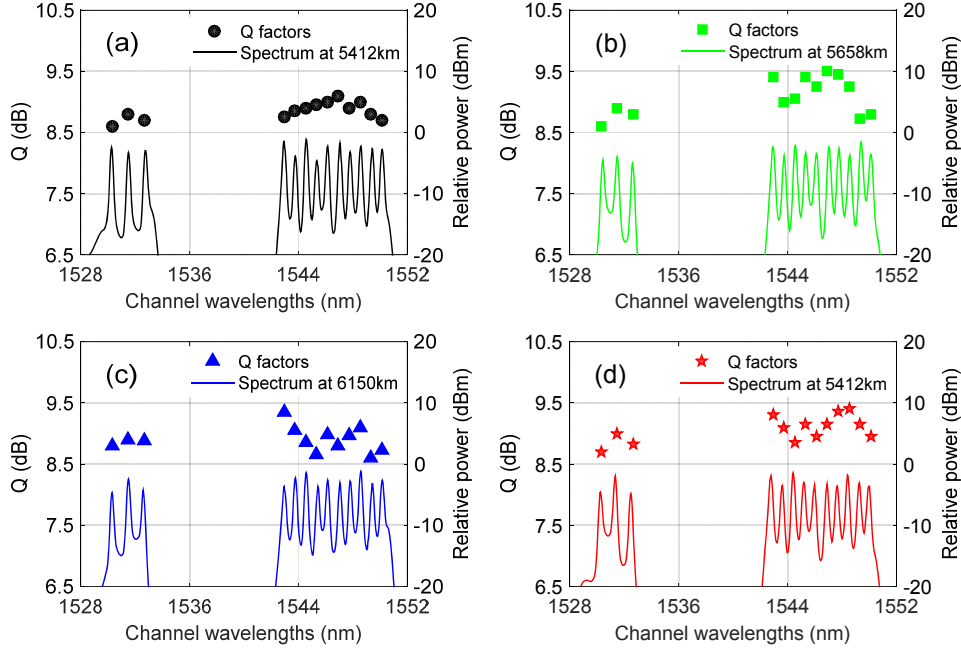

Fig. 7. Q factor of each signal channel and received spectra at respective maximum distance: (a) counter-pumping only (scheme-1); (b) scheme-2; (c) scheme-3(a) and (d) scheme-3(b) considering forward error correction (FEC) threshold of Q = 8.5dB.

The received spectrum and Q-factor of each WDM signal at maximum reach have also been measured and shown in Fig. 7, demonstrating Q-factor above FEC threshold of 8.5dB in each case. So, the benefit of improved noise performance with dual order co-pumping in broadband DRA resulted in extended transmission reach given that 1st order pump seed's power remains reasonably low (~21mW) and has very low pump RIN (~-130dB/Hz) even with noisy 2nd order co-pump with RIN level about −120dB/Hz.

We also investigated the impact of different pump RIN of the 1st order seed on transmission performance. For this purpose we used the same semiconductor pump laser diode but drove it with low current which is enough to get 21mW output power. At low drive current, the pump RIN level was very high about ~-120dB/Hz which subsequently transferred to signal and increased 1530.33nm signal RIN level up to ~4dB as shown in Figs. 8(a) and 8(b) respectively. The additional signal RIN reduced the maximum Q factor (13.1dB) of scheme-3(a) to 12.7dB. Due to the additional Q factor penalty the transmission reach was reduced down to maximum of 5658km which was still better than that of scheme-1 (5412km), mainly due to the proper choice of co-pump wavelengths and power which allows minimal RIN transfer to the signal. So low power 1st order pump seed with low RIN (< −130dB/Hz) has to be used in the proposed dual order co-pumping scheme in order to get the best transmission performance. As a future work, we also suggest the use of a low RIN and broadband 1st order co-pump seed instead of the narrowband semiconductor laser diode for further OSNR improvement by allowing more gain from higher order co-pump without increasing the RIN transfer [16,17].
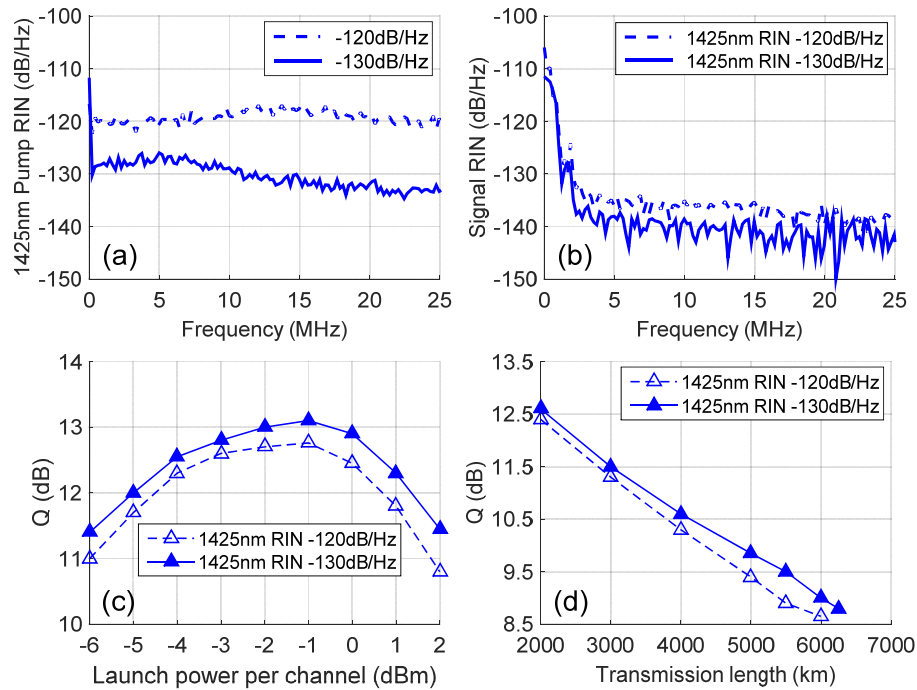
Fig. 8. Performance comparison of scheme-3(a): (a) using two RIN levels of the 1st order 1425nm co-pump by varying the drive currents and (b) signal RIN; (c) Q-factors versus signal launch power per channel and (d) Q-factors versus transmission distance at optimum launch power measured at 1530.33nm signal.

4. Conclusions

We have demonstrated the overall noise performance improvement and noise figure tilt reduction of a broadband distributed Raman amplifier using bidirectional amplification with dual order co-pumping seeded by a first order pump without deteriorating the signal RIN performance. We have also investigated the impact of 1st order co-pump seed power and RIN level on the trade-off between noise figure improvement and net transmission performance. We have reported that despite the use of fibre laser with relatively high RIN level for second-order co-pumping, using ~21mW of 1st order co-pump seed with RIN level below −130dB/Hz shows no increase in signal RIN and improves transmission performance. Although the bi-directional pumping configuration requires additional pump lasers there is a significant advantage in transmission performance with the transmission reach of 13 × 120Gb/s DP-QPSK long-haul transmission extended by a minimum of 14% up to 6150km compared with conventional counter-pumping.