On the Mitigation of RIN Transfer and Transmission Performance Improvement in Bidirectional Distributed Raman Amplifiers

Md Asif Iqbal, Mingming Tan, and Paul Harper

***Abstract*—We develop a novel broadband first order Raman pump for use as a forward pump in transmission experiments. Our results show significant signal relative intensity noise (RIN) reduction, to a level comparable to backward only pumping. The corresponding optical signal to noise ratio can be improved in dual and first order forward pumped 83.32km bidirectional distributed Raman amplifiers by using the proposed broadband pump as a first order pump. A detailed experimental characterization of RIN, signal power evolution and performance of a 10×120Gb/s DP-QPSK coherent WDM transmission system are presented. We report ~10dB RIN reduction and 0.7dB Q factor improvement which allows a 1250km transmission distance increase compared with conventional low RIN and narrowband 1st order pump sources. We also demonstrate that, bidirectional pumping with only broadband 1st order forward pumping at 50mW shows the lowest RIN transfer from pump to signal. This extends the transmission reach up to 8332km with maximum distances increased by 1250km and 1667km compared with conventional backward only and 1st order semiconductor forward pumped bidirectional pumping respectively.**

***Index Terms*—Optical fibre, nonlinear effects, optical fibre communication, optical amplifiers.**

I. INTRODUCTION

DISTRIBUTED Raman amplifier (DRA) has many advantages in modern long-haul coherent dense wavelength division multiplexed (DWDM) transmission systems such as improved optical signal to noise ratio (OSNR) essential for higher order and spectrally efficient modulation formats [1], [2], flexible signal power profile along transmission span enabling efficient nonlinear compensation techniques i.e. optical phase conjugation (OPC) [3], [4] or nonlinear Fourier transform (NFT) [5]. Although DRA with bidirectional higher order Raman pumping [6], [7] is the best choice to maintain a quasi-lossless signal power profile with maximum reduction of amplified spontaneous emission (ASE) noise compared with conventional backward only pumping, RIN transfer [8], [9] from forward pump to the signal is a major drawback in these systems, which may counteract the benefit of improved OSNR. The stochastic intensity fluctuations in the Raman pump also induce relative phase noise through pump-signal cross phase modulation [10] and cross-polarization interactions in polarization division multiplexed coherent transmission systems. RIN transfer mainly depends on the amplitude noise level in the pump(s), pumping configurations and chromatic dispersion of the fibre which determine the walk-off between the pump and signal. There have already been many efforts in reducing the pump to signal RIN transfer such as: introducing high dispersion fibre [11], intensity modulation in dual order Raman pumping [9], forward pumping with incoherent broadband pump [12], [13] and dual order forward pumping with optimized low reflectivity fibre Bragg grating (FBG) at 1st order pump wavelength [14]. Recently we have proposed a RIN mitigation technique in a random distributed feedback (DFB) lasing based bidirectional, dual order DRA without any 1st order forward seed [15]. Although this technique shows improved transmission performance, it requires very high 2nd order forward pump power to transfer the gain efficiently to the signals which are two Stokes shift away from the pump. Using a low RIN, narrowband conventional 1st order forward pump seed (i.e. semiconductor laser diode) improves the overall pump efficiency but transmission performance may still be limited by the RIN transfer from high power 2nd order pump.

RIN transfer from higher order pump to signal not only depends on the pump RIN of the 1st order seed but also on the spectral properties. Recently the use of a large bandwidth pseudo-incoherent pump for RIN transfer reduction has been demonstrated theoretically [12] showing the reduced transfer of amplitude noise due to the non-degenerate four wave mixing (FWM) process among broadband pump and signal frequencies with random phase variations. However, to the best of our knowledge, long-haul WDM coherent transmission performance using a RIN mitigated bidirectional distributed DRA with broadband forward pump is not well documented. An experimental demonstration has been reported for a single channel coherent transmission system, but the performance benefits were not clearly established with conventional backward only pumping and other pump sources [13].

We recently reported significant signal RIN suppression

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using a smooth profile broadband 1st order forward pump, compared with conventional narrowband pump sources in dual order bidirectional DRA [16]. We have also reported some transmission performance benefits compared with conventional pumping schemes in a long-haul coherent WDM transmission setup using both dual order [17] and 1st order [18] forward pumped bidirectional DRAs. Here we extend the results from our previous reports and demonstrate in detail that, our proposed 1st order broadband source can be used both in dual order and 1st order only forward pumped DRA schemes for substantial (>10dB) signal RIN reduction and transmission reach extension compared with widely deployed low RIN, narrowband semiconductor pump and conventional dual order backward only pumping. Firstly, we report the details of the generation process of our proposed inherently depolarised broadband 1st order source, which has much wider 3dB bandwidth (~18nm) than conventional pump sources. Then, we optimize the required forward powers of 2nd order 1365nm and 1st order broadband pumps in dual and first order forward pumping respectively, in order to determine the best balance between improved signal power distribution and minimum signal RIN performance which provides the maximum transmission performances in respective schemes. Finally, at optimum forward pump powers, coherent WDM transmission performances are compared with conventional pumping schemes to demonstrate the benefit of suppressed signal RIN using low noise DRAs. In 10×120Gb/s DP-QPSK coherent WDM transmission system, our proposed dual order forward pumped DRA demonstrates 1250km transmission reach enhancement compared with narrowband 1st order semiconductor pumped dual order forward pumping scheme.

We also demonstrate that, bidirectional pumping with only 1st order broadband forward pump performs better than that of dual order forward pumped bidirectional DRA for superior RIN mitigation and extends the transmission reach of similar WDM system up to 8332km. We also report maximum transmission reach extensions up to 1250km and 1667km compared with conventional dual order backward only and 1st order semiconductor forward pumped bidirectional pumping schemes, using only 50mW of optimized broadband pump power without requiring higher order pumping schemes.

II. EXPERIMENTAL SETUP

The configuration of dual forward pumped bidirectional DRA are shown in Fig. 1. An 83.32km of standard single mode fibre (SSMF) is used as the amplifier span. The backward dual order pumping consists of a 2nd order 1365nm pump and a high reflectivity (95%) fibre Bragg grating (FBG) with 0.6nm 3dB bandwidth and 1455nm centre wavelength, placed at the end of the span to provide feedback at the 1st order pumping wavelength [15]. We have chosen second order backward only pumping as a reference for minimum RIN DRA scheme here because of its simplicity using one backward pump, and improved noise/transmission performance due to more uniform signal power distribution compared with conventional 1st order semiconductor laser diode pumped counterpart [15]. Dual order forward pumping consisted of a high RIN (-113dB/Hz) 2nd order 1365nm pump combined with the generated broadband 1st order pump at 1455nm, whereas only the broadband 1455nm pump is used in the 1st order forward pumping as described in section IV.

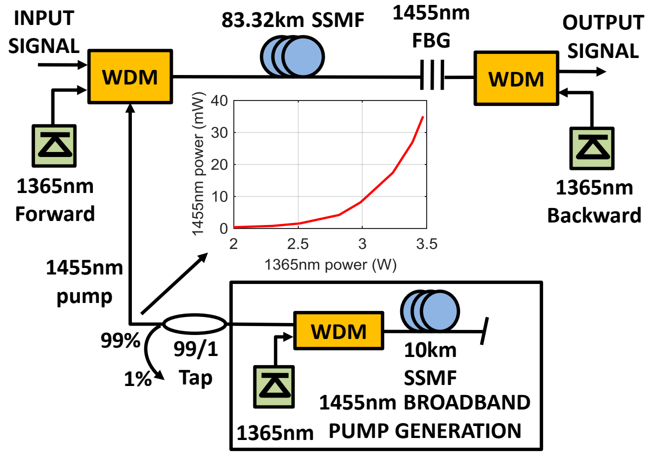

Fig. 1. Bidirectional distributed Raman amplifier span with 83.32km SSMF and proposed dual forward pumping scheme (Insert: relationship between the powers of generated broadband pump and 1365nm backward pump).

In Fig.1, the broadband 1st order forward pump seed is generated by backward pumping a 10km SSMF with a separate 1365nm pump laser at 3~4W power as shown inside the solid box. The choice of 10km SSMF gave the maximum stable output power of the broadband pump before the onset of stochastic pulses due to excessive Rayleigh scattering feedback induced higher order stimulated Brillouin scattering (SBS) Stokes waves [19], using the available (~4W) power of 1365nm pump. However further theoretical optimisation can be done to find the optimum balance between the SSMF length and 1365nm pump power. The Stokes shifted broadband light around 1455nm is first generated by Raman scattering then some portion of broadband light is Rayleigh scattered along the 10km SSMF and amplified by the same 1365nm pump. In a separate 10km SSMF section, maximum 1.5mW broadband 1455nm pump power can be obtained by using ~3.5W 1365nm backward pump power before the onset of stochastic parasitic lasing. Here in Fig. 1, the generated broadband 1455nm pump is coupled into the main 83.32km amplifier span through a 3×1 bidirectional input WDM coupler. The broadband 1455nm pump also gets amplified in the main DRA span by the 1365nm pump(s). Then part of the amplified 1455nm light are reflected back into the seed generation (10km SSMF) span and gets further amplified by the local broadband seed generating 1365nm pump. Finally, 20mW broadband pump power is maintained into the DRA span and monitored using a 99/1 tap, by using optimized 1365nm pump power of ~3.25W. The relationship between different broadband pump powers into the span and generating 1365nm backward pump powers is shown in Fig. 1 insert.

The proposed method is simpler and different from the previously reported techniques [13], [20], which has similar spectral and RIN profiles. Broadband pump source at any specific wavelength band can be generated using the proposed scheme, which requires a piece of passive fibre and high power backward Raman pumping. Whereas, generating wavelength tuned high power and low RIN broadband pump source using super luminescent diode (SLD) or ASE from semiconductor optical amplifier (SOA) is somehow difficult and requires critical design methodologies.

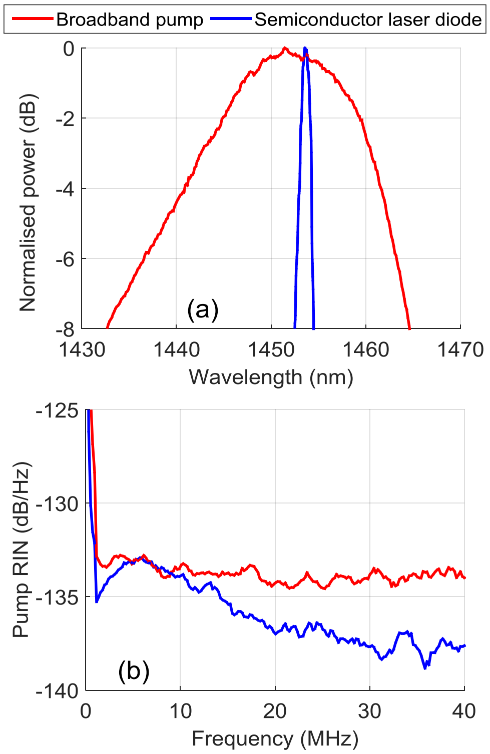

Fig. 2. Comparison of (a) first order pump spectra and (b) pump RIN between proposed broadband pump and conventional semiconductor laser diode pump.

The broadband pump seed is also inherently depolarized due to the randomness of Rayleigh scattered light. The 3dB bandwidth is ~18nm which is much wider than the commercial semiconductor laser diode (3dB bandwidth 0.8nm and RIN level -135dB/Hz). An angle connector is used at the end of 10km SSMF span to minimize any reflection in order to generate a very low RIN (~ -132dB/Hz) broadband pump in an open cavity based configuration [21]. The comparison of RIN and spectral properties between different pumps are shown in Fig. 2 (a) and (b).

A coherent transmission experiment was performed in a recirculating loop setup as shown in Fig. 3. Ten DFB lasers from 194.3THz (1542.94nm) to 193.4THz (1550.12nm) with 100GHz spacing were multiplexed using an arrayed waveguide grating (AWG) to form the WDM grid. The output of the multiplexed signal was then combined with a 100kHz linewidth (LW) external cavity laser (ECL) used as “channels under test (CUT)”. During each measurement, the particular DFB laser was switched off and replaced by the CUT. The continuous wave (CW) signal channels were then QPSK modulated using a Mach-Zehnder I-Q modulator. The applied electrical signal from a pulse pattern generator (PPG) was 30Gb/s, 2^{31}-1 word length, normal and inverse pseudo random binary sequences (PRBS) patterns with a relative delay of 18bits. The output 10×30GBaud QPSK signals were then amplified using a polarization maintaining erbium doped fibre amplifier (EDFA) and polarization multiplexed through a polarization multiplexing (POLMUX) emulator with a relative delay equivalent to 300 symbols (~2ns) between the two polarization states to generate 10×120Gb/s DP-QPSK signals at the input of the loop.

The transmission span in the recirculating loop was formed by the distributed Raman span with 83.32km SSMF with a total loss of 17.6dB including 16.5dB span loss and 1.1dB passive component loss from pump/signal combiners. A dual-stage EDFA was used to compensate the additional 12dB loop losses from gain flattening filter (GFF), 3dB coupler and acousto-optic modulator (AOM). At the receiver, the received signal was first de-multiplexed using a tuneable bandpass filter and then amplified using an EDFA before passing it to a standard polarization diverse coherent receiver with 80GSa/s and 36GHz bandwidth oscilloscope. Digital signal processing (DSP) was applied in offline post-processing for linear impairment mitigation and signal recovery. Q factors were measured from actual bit error counting and averaged over 2 million bits. A HD-FEC limit of 8.5dB Q factor was considered for performance measurement.

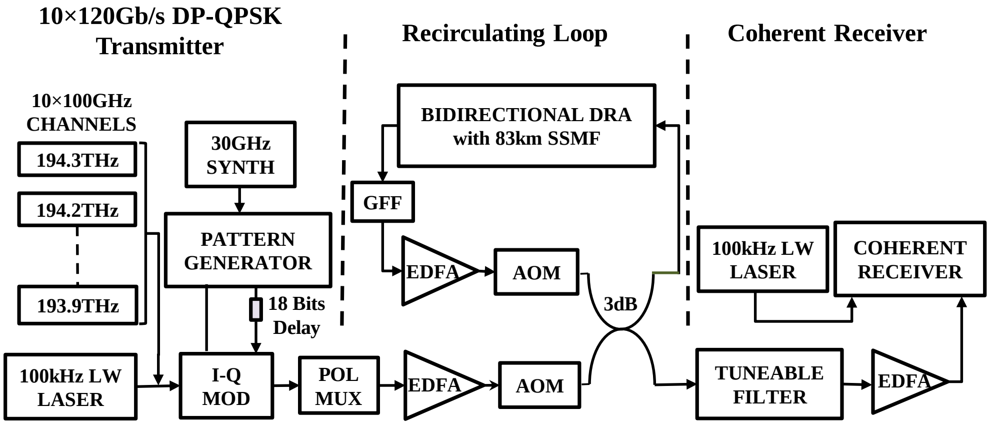

Fig. 3. Schematic diagram of long-haul coherent WDM transmission system in a recirculating loop setup. Abbreviations: SYNTH = synthesizer, POLMUX = polarization multiplexer, LW = linewidth, GFF = gain flattening filter and AOM = acousto-optic modulator.

III. RIN Mitigation with Dual Order Forward Pumping

In dual order forward Raman pumping, stochastic amplitude fluctuations from high power and high RIN 2nd order pump is transferred and distributed over the random phases of the broadband 1st order seed. The intensity noise evolution is averaged out over the wide bandwidth of the low RIN pump and subsequent RIN transfer to the signal is mitigated. In this section at first, we experimentally characterize the signal RIN and power variation along the amplifier span at different forward 1365nm pump powers. Transmission performances are then compared to optimize the forward 1365nm pump powers required for the best transmission results.

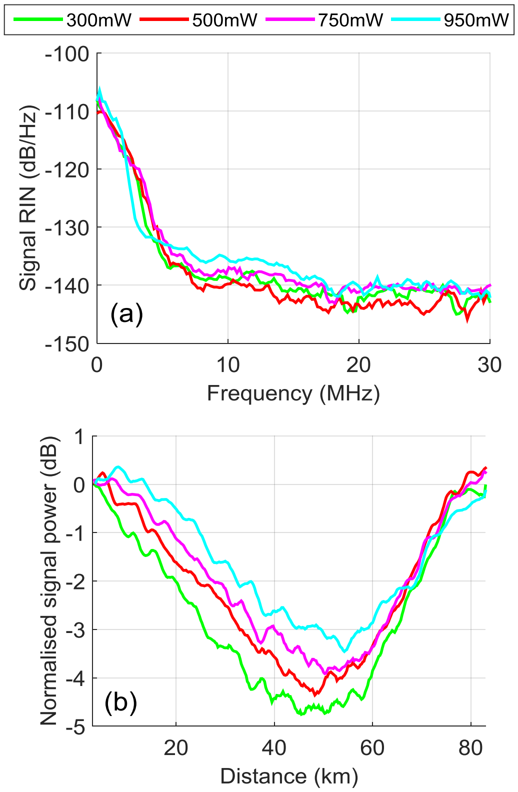

Fig. 4. (a) Signal RIN and (b) signal power variation (SPV) along the span at different forward 1365nm pump powers and fixed 20mW 1455nm power.

In Fig. 4(a) and (b), the signal RIN and power profiles were characterized with different 1365nm and fixed 20mW broadband forward pump powers. Here in the dual order forward pumped bidirectional DRA, the improved signal power distribution and RIN transfer are mainly dominated by the high power 2nd order forward pump. In order to ensure minimum RIN transfer from the forward 1st order pump, we choose only 20mW power of the forward 1st order source which has much lower direct gain contribution to signal, but enough to increase the efficiency of gain transfer from forward 1365nm pump to signal. Further optimization between the forward 2nd and proposed 1st order broadband pump powers can be done in order to find the optimum balance between the signal RIN and noise performance on long-haul transmission systems. SPVs were measured using a modified optical time domain reflectometer (OTDR) technique [22]. The forward 1365nm pump powers and ratios with respect to the total pump powers are given in Table I. Signal RIN levels increased slightly below 20MHz and SPVs improved from 4.8dB to 3dB as forward 1365nm pump power (ratio) was increased from 300mW (19.4%) to 950mW (46%). The signal power profile using dual order pumping with a broadband pump seed can be minimised to ±1.5dB by increasing the second order pump power, but the signal power profile in [15] can be only minimised to ±2dB due to the inefficient forward gain transfer. However, the absence of the first order seed in [15] mitigated the signal RIN more thoroughly.

TABLE I

FORWARD 2ND ORDER PUMP POWER RATIOS USED IN THE CHARACTERIZATION WITH FIXED 20mW 1ST ORDER PUMP POWER

1365nm forward pump power (mW)	1365nm backward pump power (mW)	Total pump power (mW)	1365nm forward pump power ratio (%)
300	1230	1550	19.4
500	1200	1720	29.1
750	1150	1920	39.1
950	1096	2066	46

The transmission results at different 1365nm forward pump powers are also given in Fig. 5(a) and (b). The optimum balance between OSNR and RIN was achieved at 500mW (~29%) of 1365nm forward pump power (ratio) which

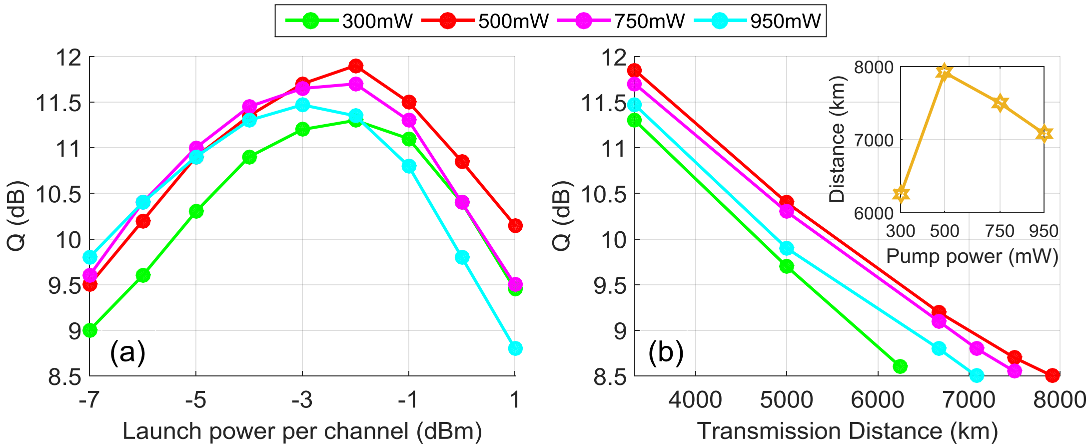

Fig. 5. Comparison of transmission performances measured at 1545.32nm signal: (a) Q factors vs. launch power per channel and (b) Q factors vs. transmission distance at optimum launch power (insert: maximum transmission distances at different 1365nm forward pump powers).

provided maximum Q factor 11.9dB and transmission reach 7915km. Increasing the forward 1365nm power up to 950mW improved the OSNR by reducing the SPV to 3dB (Fig. 4(b)) but transmission reach was degraded down to 7082km due to the increase in signal RIN as shown in Fig. 4(a). On the other hand, forward 1365nm power reduction to 300mW resulted in poorest OSNR and lowest reach up to 6249km. The maximum distances at different forward 1365nm pump powers are also depicted in Fig. 5(b) insert which shows the maximum reach 7915km at 500mW, after that it deteriorates due to increased signal RIN penalty at 750mW and 950mW. Then signal RIN, SPV characterization and transmission performances were compared with conventional 1st order semiconductor forward pumped dual order bidirectional and backward only pumping schemes at optimized 500mW and 20mW forward 1365nm and 1455nm pump powers respectively to show the benefits.

Fig. 6 shows the comparison of signal RIN and SPV at 1545.32nm among two different dual order bidirectional pumping schemes using proposed broadband and conventional low RIN semiconductor laser diode as 1st order seed and dual order backward only pumping. In Fig. 6(a), signal RIN from backward only pumping was the lowest and baseline for minimum signal RIN. The proposed broadband pumped scheme shows similar performance as backward only pumping with slight increase in RIN level at frequencies below 6MHz.

The 1st order broadband seed distributes the transferred RIN from higher order noisy 1365nm pump over the random phases of its wide bandwidth. The overall noise evolution to signal is then averaged out and mitigated significantly. Semiconductor forward pumped scheme shows ~10dB signal RIN level increase below 10MHz despite having the lowest pump RIN (Fig. 2(b)). In Fig. 6(b), both bidirectional pumping schemes show similar SPVs (~4dB) with 2dB improvement than backward only pumping. Our proposed dual order bidirectional DRA scheme shows improved OSNR than backward only pumping and significant signal RIN mitigation compared with conventional semiconductor pump.

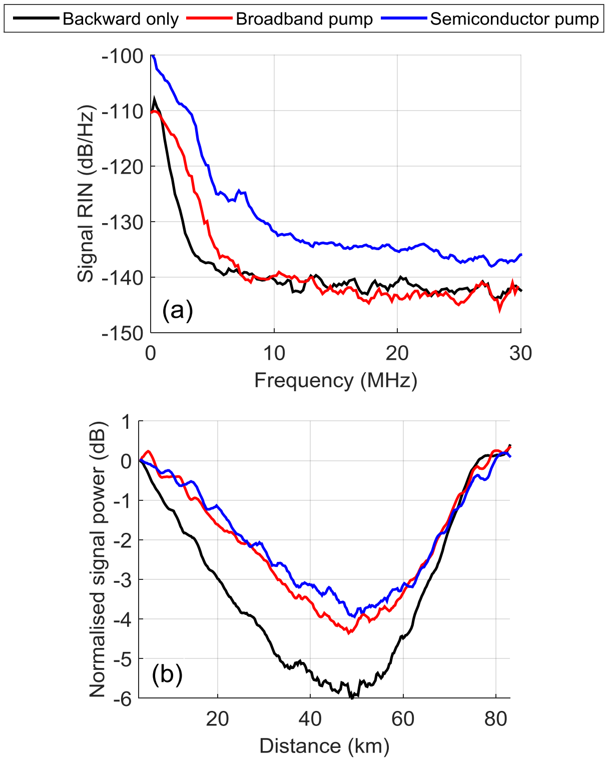

Fig. 6. Comparison of (a) signal RIN and (b) SPVs along the amplifier span for dual order forward pumped bidirectional DRAs with 1st order broadband, semiconductor pump and backward only pumping.

Coherent WDM transmission experiments using the setup shown in Fig. 3 have been carried out at the centre WDM channel at 1545.32nm, in order to compare the transmission performances with backward only pumping and other bidirectional pumping schemes. In Fig. 7(a) and (b), backward only pumping shows the optimum Q factor of 11.5dB at 3333km and maximum reach of 7082km respectively. Dual order forward pumping with 1st order semiconductor pump shows 0.7dB Q factor penalty at optimum launch power compared with broadband 1st order pumping due to significant signal RIN penalty. As both the dual order forward pumped DRA schemes have similar signal power profiles (Fig. 6(b)),

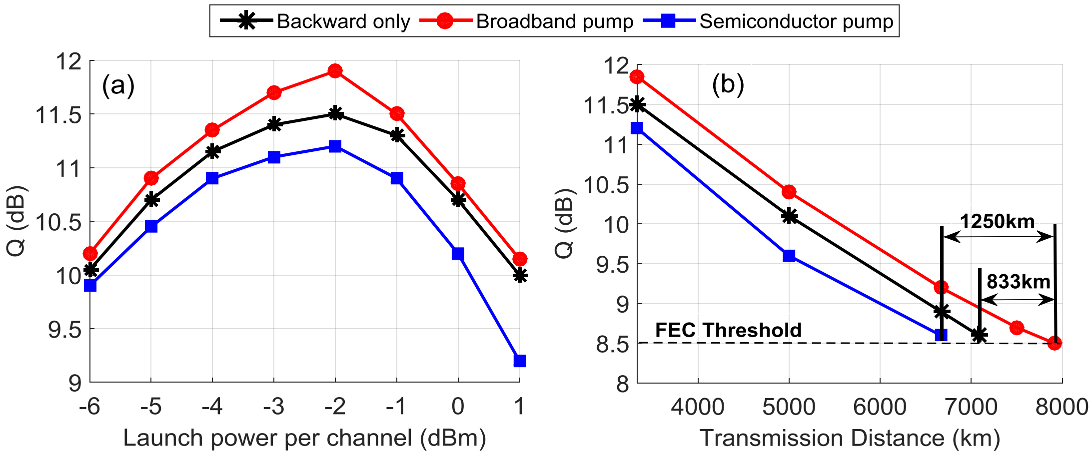

Fig. 7. Transmission performance comparison of dual order forward pumped bidirectional DRAs with different 1st order forward pumps at fixed 500mW and 20mW of 2nd and 1st order pump powers respectively and backward only pumping: (a) Q factors vs. signal launch power per channel at 3333km and (b) Q factors vs. transmission reach at optimum launch power.

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the balance between the ASE noise and nonlinear penalty is almost identical in the transmission experiment. So in the proposed broadband forward pumped bidirectional DRA, any improvement in Q factor performance comes solely from the reduction of signal RIN penalty. The benefits of reduced signal RIN and SPV with broadband 1st order pump provided maximum Q factor of 11.9dB and transmission reach up to 7915km with 1250km and 833km enhanced distances compared with conventional narrowband semiconductor pump and backward only pumping respectively.

These results show that the dual order forward pumped bidirectional DRA with broadband 1st order pump has the potential of simultaneous signal RIN mitigation and OSNR improvement. The optimum trade-off between signal RIN penalty and OSNR improvement was achieved at 500mW 1365nm and 20mW broadband 1st order pump powers with extended transmission reach up to 7915km.

IV. RIN MITIGATION USING FIRST ORDER FORWARD PUMPING

The RIN mitigation technique using forward pumping with only broadband 1st order pump without the need of high power 2nd order 1365nm pump is discussed in this section. The 1st order forward pumped DRA scheme is shown in Fig. 8, in which similar dual order backward pumping and broadband 1st order pump generation technique are used as described in section II. Additionally, high broadband pump powers up to 250mW were obtained by amplifying the generated 1455nm seed from the 10km SSMF through a similar 2nd stage with 10km TrueWave (TW) fibre, using the residual 1365nm pump power from the first stage. The amplified broadband pump powers from the 2nd stage at different 1365nm powers are shown in Fig. 8 insert, which shows that up to 250mW output power can be obtained using ~3.8W of 1365nm pump power, beyond that the output becomes unstable due to random spikes. The amplified broadband pump has slightly narrower spectral profile than Fig. 2(a), but has equal RIN level to Fig. 2(b) for using backward pumping in the 2nd stage.

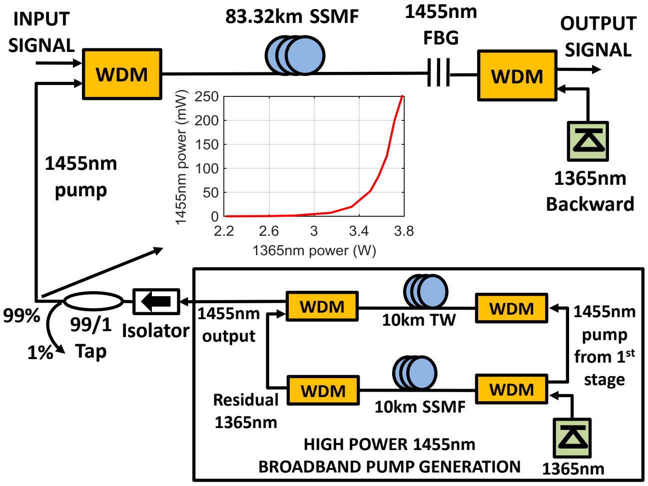

Fig. 8. First order forward pumped bidirectional DRA including the generation scheme of high power broadband 1455nm pump (Insert: broadband pump power vs. generating 1365nm pump powers).

The TW fibre has slightly better Raman gain efficiency ($0.6W^{-1}km^{-1}$) than the SSMF ($0.43\ W^{-1}km^{-1}$) and low Rayleigh scattering coefficient as SSMF. The choice of TW fibre length (10km) gives a better balance between the attenuation and amplified output power. Finally, the generated broadband forward pump was given into the amplifier span through an isolator and WDM coupler. The isolator separates the seed generating section from the main amplifier span.

Full characterization of the signal RIN, power variation and transmission experiment were carried out first and then the results obtained have been compared with conventional semiconductor pump based forward pumping and dual order backward only pumping. Forward pump powers from 30mW to 250mW were used for measuring different SPV and RIN performances. Backward 1365nm pump powers were optimized to ensure 0dB signal net gain at the output of the amplifier for different forward pump powers.

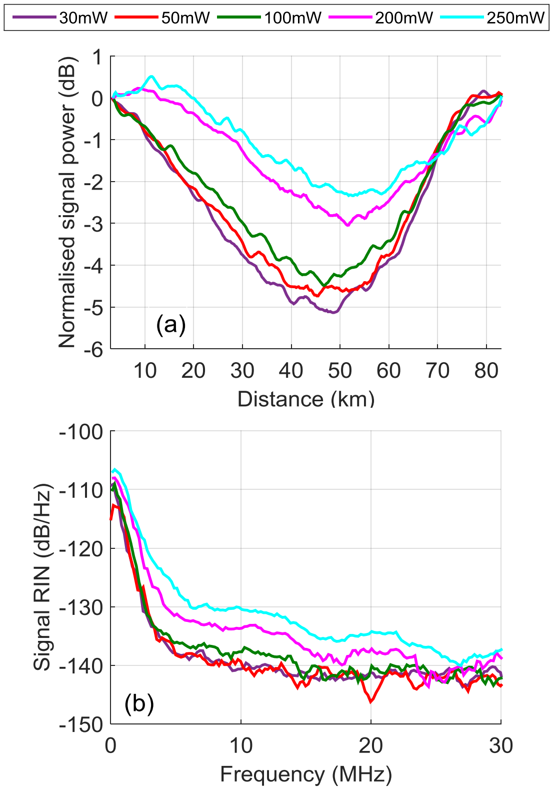

Fig. 9. Characterization of (a) signal power distributions along the amplifier span and (b) signal RIN at 1545.32nm with different powers of 1st order broadband forward pump.

The SPVs and signal RIN with increasing forward 1st order broadband pump powers are shown in Fig. 9(a) and (b) respectively. As expected, increasing the forward pump powers from 30mW to 250mW reduced the SPVs from 5.1dB to 2.5dB, resulting in improved OSNR performances. In Fig. 9(b), no significant signal RIN increase was observed up to 100mW forward pump power. However a sharp increase in signal RIN level was observed beyond 100mW and 10dB increase in signal RIN level was also seen at 250mW.

The impact of improved OSNR with increasing forward pump power and associated RIN penalty have been verified

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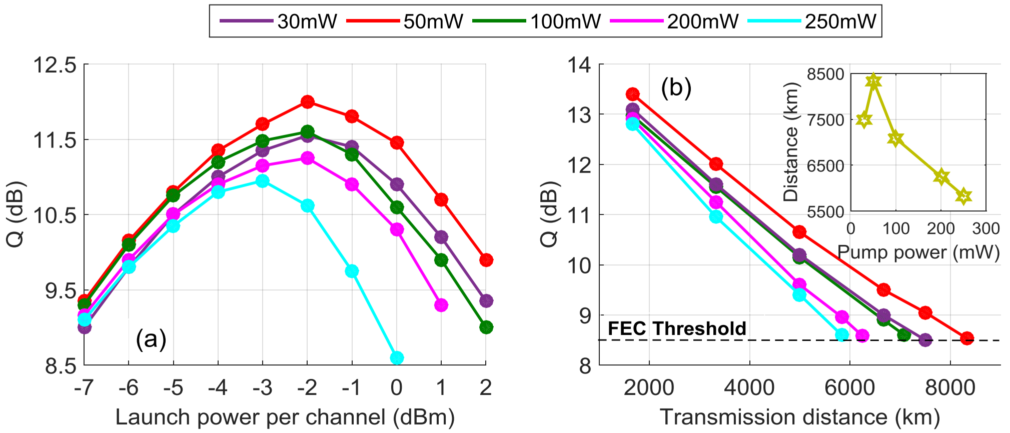

Fig. 10. Transmission performance comparison at 1545.32nm signal: (a) Q factors vs. signal launch power per channel at 3333km and (d) Q factors vs. transmission distance with different powers of 1st order broadband forward pump.

through transmission experiments as shown in Fig. 10(a) and (b). Maximum transmission distances were limited by signal RIN with forward pump powers above 50mW as shown in Fig. 10(b) insert. Although lowest SPV (2.5dB) was achieved at 250mW (Fig. 9(a)), however transmission reach was the minimum, only up to 5832km with Q factor of 11dB due to the high signal RIN penalty. On the other hand, signal RIN was minimum at 30mW but maximum reach was limited to 7500km by the lowest OSNR performance. Broadband forward pumping with 50mW gave the best balance between SPV and signal RIN penalty, resulting in maximum optimum Q factor of 12dB and maximum reach up to 8332km.

Signal power distributions and RIN levels were then compared with conventional 1st order semiconductor pumped bidirectional DRA at the optimized 50mW forward pump power and backward only pumping schemes as shown in Fig. 11(a) and (b) respectively. Both bidirectional DRAs showed similar SPVs with ~1.3dB improvement over the worst performed backward only pumping. In Fig 11(b), broadband forward pumped bidirectional DRA showed no signal RIN increase compared with the minimum RIN baseline backward only pumping. Although semiconductor pump has the lowest RIN profile (Fig. 2(b)), however a clear increase of signal RIN level was observed in semiconductor pumped scheme as shown in Fig. 11(b). This was mainly because of the coherence of narrow linewidth pump that could not average out the RIN evolution through non-degenerate FWM process.

Transmission performances were also compared with conventional bidirectional pumping using 50mW 1st order semiconductor pump and backward only pumping schemes as shown in Fig. 11(c) and (d). Proposed broadband pumping extended the transmission reach up to 8332km with maximum

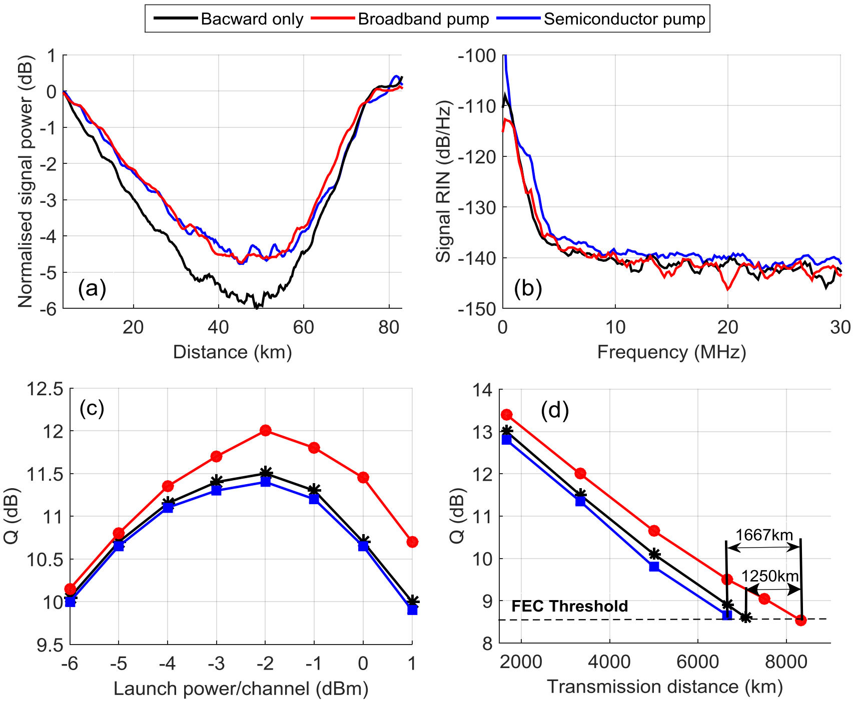

Fig. 11. Characterization (without marker) of (a) SPVs (b) signal RIN; and transmission performance comparisons (with marker) (c) Q factors vs. launch power per channel at 3333km and (d) Q factors vs. transmission distance at optimum launch power.

Q factor of 12dB measured at 3333km. The benefit from improved OSNR by reducing the SPV resulted in minimum of 0.5dB improved Q factor at optimum launch power than backward only pumping. Transmission distances were also enhanced by 1250km and 1667km compared with backward only and bidirectional pumping with forward 1st order semiconductor pump respectively as shown in Fig. 11(d). So, first order forward pumping with reasonably low RIN broadband pump has simpler design without requiring the high power 1365nm 2nd order pump as in the dual order and showed the best transmission performances.

V. CONCLUSIONS

We have experimentally demonstrated that, a low RIN and broadband 1st order pump can simultaneously mitigate the signal RIN and improve OSNR in both dual and 1st order forward pumped bidirectional DRAs. In the proposed dual order forward pumped bidirectional pumping scheme, including a broadband 1st order seed extends the transmission reach of 10×120Gb/s DP-QPSK coherent WDM system up to maximum 7915km with 0.7dB Q factor improvement and 1250km transmission reach enhancement compared with conventional low RIN, narrowband semiconductor pump. Additionally, reach extension of 833km was achieved compared with backward only pumping at optimized 1st order broadband forward pump powers of 20mW and 500mW of 2nd order 1365nm pump.

Finally a simple broadband 1st order forward pumped bidirectional DRA scheme has been demonstrated which reduces the pump power requirement. Using only 50mW of broadband pump, this technique gives the best transmission performance and effectively extends the 1Tb/s DP-QPSK WDM transmission reach to maximum 8332km with 1667km and 1250km reach extensions compared with 1st order semiconductor forward pumped bidirectional and backward only pumping respectively.

Our results show that the correct choice of forward pump with low RIN (i.e. < -135dB/Hz) and most importantly very broad 3dB bandwidth (i.e. 18nm) can significantly mitigate the RIN transfer from pump to signal and allow the extended reach of long-haul coherent transmission system utilizing the benefits of ASE noise reduction.

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