RIN Mitigation and Transmission Performance Enhancement With Forward Broadband Pump

M. Tan, P. Rosa, S. T. Le, V. V. Dvoyrin, Md. A. Iqbal, S. Sugavanam, S. K. Turitsyn, and P. Harper

***Abstract*— We demonstrate that using a broadband, first order, and coherent pump laser enables effective and efficient forward-pumped distributed Raman amplification for long-haul transmission systems, thanks to the simultaneous suppression of ASE noise and RIN-related penalty. We show in both experiments and simulation that this scheme extends the reach of 10 × 120 Gb/s DP-QPSK WDM transmission by a minimum of 50%, compared with low RIN Bi-doped fibre laser and other commercially available pump lasers. Moreover, it requires very low forward pump power, and maintains uniform/symmetric signal power distribution which allows effective nonlinearity compensation.**

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

I. INTRODUCTION

DISTRIBUTED Raman amplification (DRA) can reduce the amplified spontaneous emission (ASE) noise and effectively improve the transmission distance, compared with discrete amplification [1]. This is particularly important, as coherent transmission systems move to higher order modulation formats requiring a higher signal-to-noise ratio (SNR). In DRA, forward-propagated pumping can increase amplifier spacing, reduce signal power variation (SPV), and provide superior noise performance over backward-propagated pumping only [2]. However, the major challenge of forward (FW) pumping is relative intensity noise (RIN) related penalty, particularly for long-haul transmissions [3]–[6]. We previously reported a Raman amplification technique based on random distributed feedback fibre laser with bidirectional second order pumping which suppressed the RIN-related penalty and extended the maximum reach by ∼12% [7]–[9], compared with backward (BW) pumping only. However, the main drawback of that scheme was that the Raman gain efficiency near the span input was very low, requiring up to 1W FW pump power. This was because there was no first order seed when using only second order pumping in the forward direction. On the other hand, using first order FW pump can improve the Raman gain efficiency significantly. Unfortunately, this allows direct interaction between the signal and the pump, which means that the RIN-associated penalty can become more severe [10].

Here, for the first time, we present a detailed evaluation of the transmission performance in a long-haul 100G DP-QPSK WDM coherent transmission system, using forward-propagated first order pump lasers with different bandwidths/RIN/power levels. We demonstrate that, using a FW-propagated coherent fibre laser with much broader bandwidth and relatively low RIN level can extend the maximum transmission distance. This is mainly due to the ASE noise reduction, and more crucially, the signal distortion transferred from the pump RIN is prevented. This configuration is compared to narrower bandwidth pumps, namely a low RIN bismuth-doped (Bi-doped) fibre laser which we developed, conventional semiconductor laser diodes, and a narrowband fibre laser. Using the proposed scheme gives a maximum reach of 7499 km, compared with 4999 km using Bi-doped fibre laser or semiconductor laser diodes and 1500 km using narrowband fibre laser. Unlike other pump lasers, the RIN of the output signal using this broadband laser does not increase dramatically when the pump power increases, and therefore signal power profiles can be adjusted for different nonlinearity compensation techniques [7], [11], [12]. In addition, compared with BW-pumping only, FW broadband pumping reduces the noise figure (NF) tilt across the amplification band and leads to a flatter gain spectrum [13].

II. EXPERIMENTAL SETUP OF THE RAMAN AMPLIFIER USING BROADBAND FORWARD PUMPING

Schematic diagrams for Raman amplifiers configurations are shown in Fig. 1(a) and 1(b). In all configurations, the on-off gain was set to compensate the 16.5 dB loss of the 83.32 km standard single mode fibre (SSMF). As a baseline, second order BW-pumping at 1366 nm with the FBG near the output end of the span was used. First order random fibre laser was generated due to the resonant mode reaching the lasing threshold in a distributed cavity formed by fibre Rayleigh scattering and an FBG [7]–[9]. When forward pumping was used, different FBGs with the same centre wavelength as the forward pump were used. Each FBG had 95% reflectivity and 0.5 nm 3 dB band-width. Four types of the FW pump lasers were compared, a commercially available broadband fibre laser at 1452 nm, a Bi-doped fibre laser at 1448 nm, conventional semiconductor laser diodes at 1455 nm, and a narrowband fibre laser at 1455 nm. Different power levels were used for each pump type to evaluate the impact of FW-pumping. Backward pump powers were adjusted between 1.05 W and 1.25 W to

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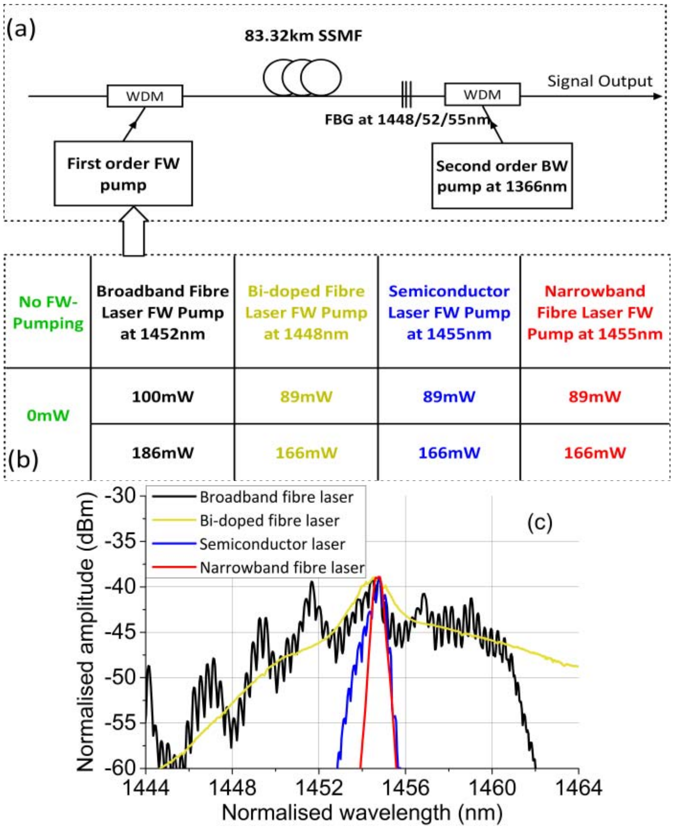

Fig. 1. (a,b) Distributed Raman amplifiers with different FW pump/powers. (c) Measured optical spectra of FW pump lasers.

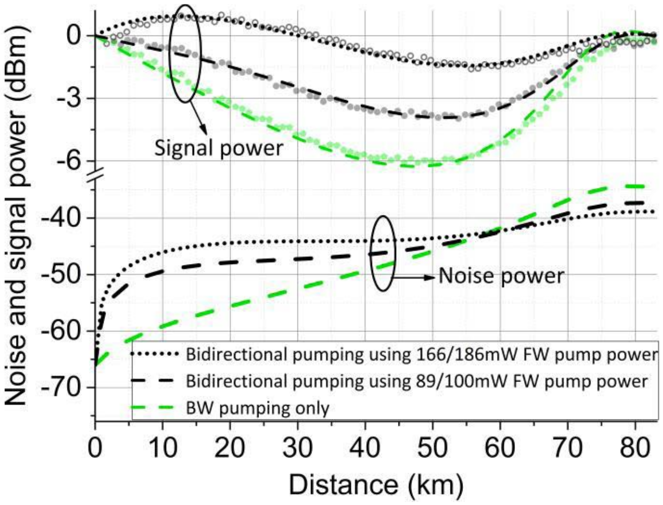

Fig. 2. Measured (scattered points), simulated (lines) signal power profiles and simulated noise power profiles (lines) using BW-pump only, 89/100mW, and 166/186mW FW pump power.

compensate the fibre attenuation, depending on the pumping scheme [7].

The first FW-propagated pump was a 1452 nm commercially available broadband fibre laser with ~8 nm 3 dB bandwidth (shown in Fig. 1(c), the centre wavelengths and the amplitudes are shifted for direct comparisons), a measured RIN level of −135 dB/Hz (at 5 MHz), and 5W maximum output power. The second pump was a 1448 nm Bi-doped fibre laser with 2 nm 3 dB bandwidth, a RIN level of −140 dB/Hz (at 5 MHz), and 1W maximum output power. The Bi-doped fibre laser used a linear cavity configuration with a fibre Sagnac mirror pumped by a 1366 nm fibre laser. Details of the Bi-doped fibre laser which we have developed can be found in [14]. Widely deployed 1455 nm semiconductor laser diodes with 0.8 nm 3 dB bandwidth and −135 dB/Hz RIN (at 5 MHz), were used as the third pump. The pump output was depolarised by combining two diodes through a polarisation beam combiner (PBC). The output power was up to 400mW. A commercially available 1455 nm narrowband fibre laser with 0.5 nm 3 dB bandwidth and high RIN (-113 dB/Hz) was used as the fourth pump. This laser could give up to 5W output power.

Two pump power levels were used for each pump to achieve different signal/noise power profiles. Signal power profiles along the transmission span measured at 1545.32 nm using a modified optical time-domain reflectometer are shown in Fig. 2, and confirmed with simulations [2]. Here, note that signal power profiles were related to the pump power regardless of forward pump type, so the signal power profiles using different forward pumps were the same. BW-pumping only resulted in the largest SPV of ~6 dB. In a bi-directionally pumped setup, SPV was reduced to 4 dB using 89 mW FW pump power (100 mW for the broadband pump due to its larger 3 dB bandwidth), and ~2.5 dB using 166 mW FW pump power (186 mW for the broadband pump). Simulated noise power profiles are plotted in Fig. 2. First order FW-pumping can amplify the signal near the input section of the fibre, and therefore reduce signal power variation and the ASE noise at the span output [3], [17].

As the RIN of the pump can be transferred to the signal resulting in significant long-haul transmission penalty [3]–[6], the RIN of the signal (at 1545.32 nm) at the span output was experimentally investigated, and the results are shown in Fig. 3(a) and 3(b). The integral RIN over the frequency range between 2 and 40 MHz was shown in the legend. In Fig. 3(a), using 100 mW broadband pump laser, the signal RIN was similar to BW-pumping only over the whole frequency range, indicating low RIN-induced penalty [9]. This is because the noise generated by four wave mixing (FWM) was absent due to the rapid phase variation over a large bandwidth [15]. We experimentally confirmed that the RIN was not transferred to the signal at low frequencies. This was achieved using a 100 mW broadband coherent pump instead of an incoherent source demonstrated in [16]. In comparison, the RIN dramatically increased by 10 dB at low frequency (<10 MHz), when narrow-band Bi-doped fibre laser or semiconductor laser FW pumping with 89 mW pump power was used, despite these pumps had similar or lower RIN to broadband fibre laser [15]. Using high RIN narrowband fibre laser gave the worst signal RIN, which can result in critical penalty on the transmission performance. Further increasing the FW pump power to 166/186 mW worsened the RIN for all the FW-pumping schemes as shown in Fig. 3(b). This means that higher FW pump power might also influence the transmission performance.

III. LONG-HAUL TRANSMISSION RESULTS AND DISCUSSIONS

To evaluate the long-haul transmission performance using different FW-propagated pump lasers, a recirculating loop experiment was conducted using the set-up shown in Fig. 4.

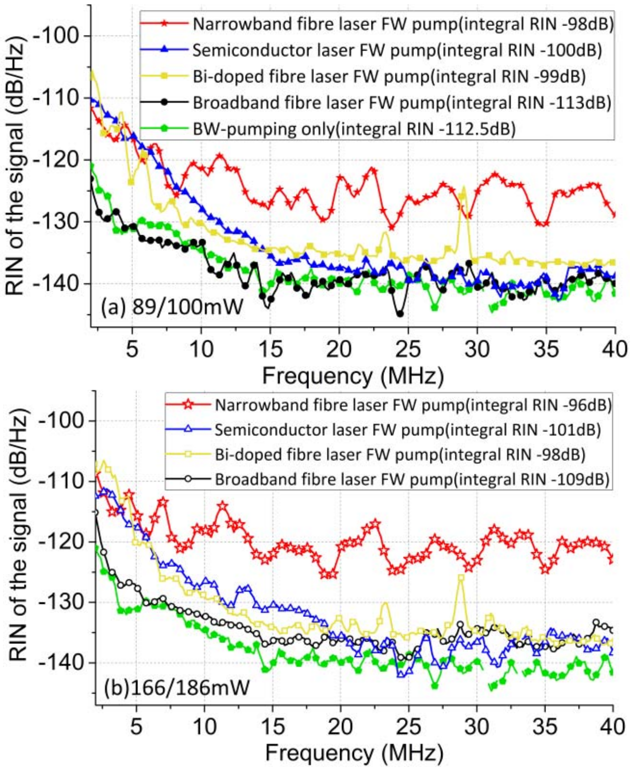

Fig. 3. Measured RIN of the output signal using (a). 89/100mW FW pump power, (b). 166/186mW FW pump power.

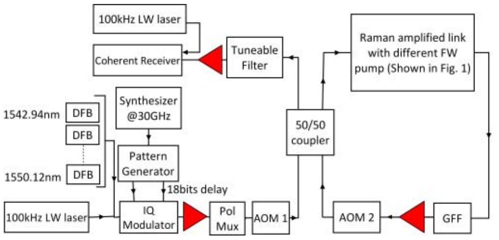

Fig. 4. Schematic diagram of long-haul transmission system using the proposed Raman amplified link illustrated in Fig. 1.

DFB lasers spaced at 100 GHz (from 1542.94 nm to 1550.12 nm) were combined with a 100 kHz linewidth (LW) tuneable laser ("channel under test") to give a 10-channel WDM grid. The combined signals were QPSK modulated at 30 GBaud, using normal and inverse 2^{31}-1 PRBS patterns for I & Q with a relative delay of 18 bits. A polarisation multiplexer with a 300-symbol delay between two polarisations states was used to give 10×120 Gb/s DP-QPSK data. The transmission fibre in the recirculating loop was 83.32 km SSMF with a total loss of ~17.6 dB, including ~16.5 dB from the fibre and ~1.1 dB from pump signal combiners. A gain flattening filter (GFF) was used to flatten the spectrum. The combined loss of ~12 dB from GFF, 50/50 coupler, acousto-optic modulator (AOM) and WDM couplers, was compensated using a single stage EDFA at the end of the loop. The output signal was de-multiplexed by a tuneable filter and amplified. The receiver was a standard polarisation-diverse coherent detection set-up, and the signals were captured with four photo-detectors using an 80 GSa/s, 36 GHz bandwidth oscilloscope. DSP was used for signal recovery and chromatic dispersion compensation. Q were calculated from bit-wise error counting, and averaged over 2 million bits.

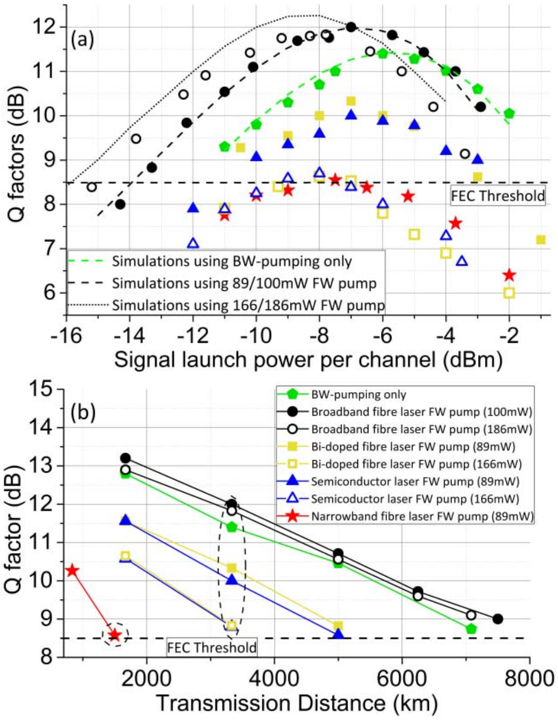

Fig. 5. (a) Measured 1545.32 nm channel (scattered points) and simulated (dashed/dotted lines) Q factors versus signal launch power at 3333km (1500km using narrowband fibre laser). (b) Q factors versus transmission distances.

Fig. 5(a) shows simulated (lines) and experimental (scattered points) Q factors versus signal launch power per channel at 1500km for narrowband fibre laser and at 3333km for all the other schemes. Fig. 5(b) shows Q factors versus transmission distances. In the simulation, 10×120 Gb/s DP-QPSK channels spaced at 100 GHz were transmitted over 3333 km. Due to large number of channels simulated, the random binary sequence length was reduced to 2^{16}-1 compared to a PRBS of length 2^{31}-1 in the experiment. The generated signal was oversampled 4 times providing a total simulation bandwidth of ~4 THz. The propagation of the signal in the fibre link was simulated using the split-step Fourier method, with a step size of ~0.1 km using the simulated signal power profiles (Fig. 2(a)). The noise was modelled as Gaussian noise, which was added to the signal after each step (~0.1 km), following the simulated noise profiles (Fig. 2(b)). For simplicity, the same power and noise profiles were used for all the channels. At the receiver, the channel at 1545.32 nm was filtered using the 8th order super-Gaussian low pass filter with a 3 dB bandwidth of 40 GHz. Both the transmitter and the local oscillator had 100 kHz linewidth.

For BW-pumping only, the maximum reach was 7082 km, and the best Q factor at 3333 km was 11.4 dB. The experiment and simulations show good agreement. As RIN is not included in the simulations, this indicates that there was no RIN-related penalty in the experiment and that the system performance was limited only by ASE noise and nonlinearity [7]. Using the broadband fibre laser as the FW pump, the optimum Q factor was improved to 12 dB at 100 mW FW pump power. Again, the experimental and simulated Q factors show excellent agreement indicating no significant RIN penalty. The maximum reach was extended to 7499 km. This was because the signal RIN stayed the same as BW-pumping only and the

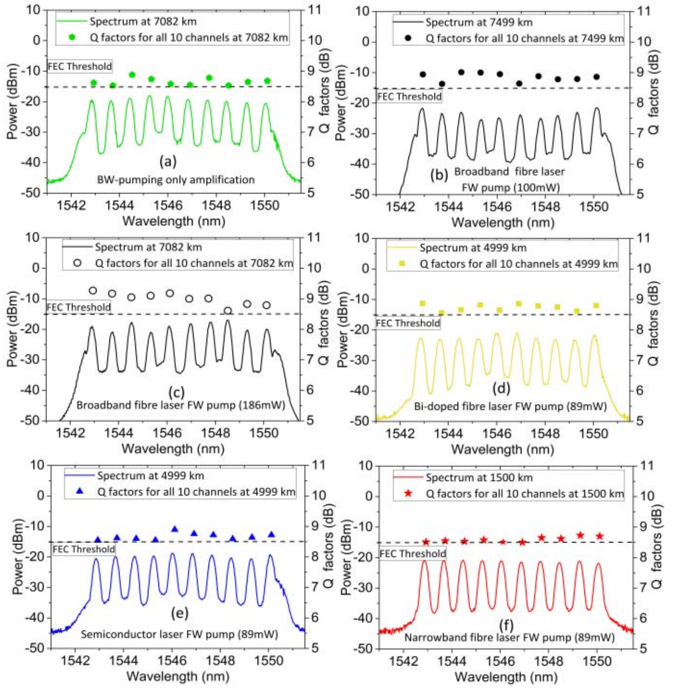

Fig. 6. Q factors and received spectra at its maximum reach. (a) BW-pumping. (b) Broadband fibre laser FW pump (100 mW). (c) Broadband fibre laser FW pump (186 mW). (d) Bi-doped fibre laser FW pump (89 mW). (e) Semiconductor laser FW pump (89 mW). (f) Narrowband fibre laser FW pump (89 mW).

Q factor was improved thanks to a better trade-off between ASE noise and nonlinearity. With 166 mW forward pump power, the best experimental Q was reduced to 11.83 dB and the maximum reach was decreased to 7082 km. The experiment showed a penalty of ∼0.5 dB in comparison with the simulation. We attributed this penalty to the RIN instead of the nonlinearity increase because it was observed for both the linear and nonlinear regimes [18], [19]. Besides, Fig. 3(b) also shows the signal RIN increases slightly with more FW pump power. In the FW-propagated Bi-doped fibre laser setup, the optimum Q factor at 3333 km was only 10.33 dB with 89 mW and 8.63 dB at 166 mW. The maximum reach was reduced to 4999 km, due to the RIN transfer. Similar degradations were found with semiconductor lasers. Using 89 mW narrowband fibre laser as the forward pump, the Q factor was the worst due to its highest RIN and the narrowest 3 dB bandwidth [19], which limited the maximum reach to 1500 km.

As expected from Fig. 2(a), with FW pumping at 89 mW and 166 mW, due to a higher average signal power, the impact of nonlinearity reduced the optimum launch power to −7 dBm and −8 dBm, respectively, compared with −6 dBm using only BW-pumping. Fig. 6 shows Q factors and received spectra at their maximum reach for all schemes. All the channels were above FEC threshold (3.8×10^{-3} in bit error rate).

IV. CONCLUSION

We, for the first time, experimentally demonstrate that, using a first order FW-propagated broadband and low RIN pump laser in distributed Raman amplification suppresses the RIN transfer and reduce ASE noise simultaneously. This results in reach extension of 10 ×120 Gb/s DP-QPSK long-haul transmission by a minimum of 50%, compared to low RIN Bi-doped fibre laser and other commercially available pump lasers with normal bandwidth. Using this broadband pump maintains a minimum of 2.5 dB signal power variation, and requires only ∼100 mW FW pump power, which can enhance the transmission distance, reduce NF tilt, and allow effective nonlinearity compensation. Future work can be focused on the theoretical and analytical study of RIN-related penalty using broadband sources.

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