Evaluation of Long-haul Coherent Transmission Performance Using Low RIN Forward Raman Pump

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Abstract: Long-haul Raman amplified transmission performance evaluation using different first-order forward pumps including low RIN bismuth-doped fibre laser is presented. 2.8dB Q penalty was observed with forward pump RIN of -140dB/Hz, compared with backward pumping only.
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1. Introduction

Distributed Raman amplification (DRA) can reduce the ASE (amplified spontaneous emission) noise and effectively improve the transmission performance, compared with discrete amplification. This is particularly important when using advanced modulation format with coherent transmission, as the OSNR requirement is higher. In DRA, using forward-propagated pumping can increase amplifier spacing, reduce signal power variation (SPV), and provide superior noise performance over backward-propagated pumping only [1]. However, relative intensity noise (RIN) associated penalty is still the major challenge for using forward pumping in long-haul repeatered transmission [2,3]. Using second order FW-pump, we showed that random distributed feedback fibre laser based Raman amplification with bidirectional second-order pumping improved the maximum reach by 0.7 dB, compared with BW-pumping only, which means the RIN penalty could be successfully mitigated [4,5]. The main problem of using such scheme is that the Raman gain efficiency of second order FW-pump was very low, and the SPV was minimised to ~4 dB over 80 km span. In comparison, using first order FW-pump can improve the Raman gain efficiency (reduce the required pump power), and reduce the SPV to only ~2.5 dB. Therefore, a bismuth-doped fibre laser was developed as a FW-pump with RIN level of only -140 dB/Hz.

Here, for the first time, we present a detailed evaluation of the impact on the transmission performance in a long-haul 100G DP-QPSK WDM coherent transmission system, by using forward-propagated first order pumps with different RIN/power levels based on Raman fibre laser based amplification. We deployed a low RIN bismuth-doped fibre laser as FW-pump, and compared it with commercially available semiconductor laser diodes and Raman fibre laser. We experimentally measured and quantified the Q factor penalty with FW-pump power. Using bismuth-doped fibre laser (-140 dB/Hz RIN), Q factor penalties of 1 dB and 2.8 dB were observed at 3333 km with 89 mW and 166 mW FW-pump power, compared with BW-pumping only. The penalties increased to 1.4 dB using 89 mW semiconductor laser diodes (-135 dB/Hz RIN) and 5.3 dB using Raman fibre laser (-113 dB/Hz RIN). Regardless of the noise reduction using FW-pump, the RIN associated penalty was too high. The findings are useful for the design of a bidirectionally pumped distributed Raman amplification in a repeatered coherent transmission system.

2. Experimental work and results discussions

To evaluate the impact on the transmission performance using different FW-propagated pumps, a recirculating loop experiment was conducted using the set-up shown in Fig. 1.(a). Ten DFB lasers with 100 GHz spacing (from 1542.94 nm to 1550.12 nm) were combined with a 100 kHz linewidth tuneable laser used as a “channel under test” while the corresponding DFB laser was switched off. The combined signals were QPSK modulated at 30G Baud. Normal and inverse 2^{31}-1 PRBS patterns were used for I & Q with a relative delay. A PM EDFA was used to amplify the signal. The resultant 10×120 Gb/s DP-QPSK signals were generated by a polarisation multiplexer with a 300-symbol delay between the two polarisations states before launching into the recirculating loop. The transmission span in the recirculating loop was 83.32 km standard SMF-28 fibre. The total loss was ~17.6 dB, including ~16.5 dB from the fibre and ~1.1 dB from pump signal combiners. To equalise channel powers, a gain flattening filter (GFF) was used after the Raman link. The ~12 dB loss from the GFF, 50/50 coupler, acousto-optic modulator (AOM), and pump signal combiners, 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 by an EDFA. The receiver was a 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 offline with standard algorithms for signal recovery and transmission impairments compensation. Q factors were calculated from bit-wise error counting, and averaged over two million bits.

Schematic diagrams and pump powers for the Raman configurations tested are shown in Fig. 1.(b). For all configurations the Raman gain was set to counterbalance the 16.5 dB attenuation of the fibre. As a baseline, second-order 1366 nm backward pumping configuration with the FBG near the output end of the span was used. The FBGs used were centred at 1448 or 1455 nm with 0.5 nm 3 dB bandwidth and 95% reflectivity. The centre wavelength difference was to match the wavelength of the FW-pump. The first-order random laser at 1448 nm was generated by the resonant mode reaching the lasing threshold in a distributed cavity formed by a distributed feedback (Rayleigh scattering) and an FBG [4,5]. In order to improve the signal-to-noise ratio, three types of FW-pump were used, as forward pumping at 1448 nm could amplify the signal from the input section of the fibre and reduce the signal power variation along the fibre. The first type of FW-pump was the bismuth-doped fibre laser with very low RIN level of only -140 dB/Hz and maximum output power more than 1 W. Details about the bismuth-doped fibre laser can be found in [6]. In comparison, commercially available semiconductor laser diodes with -135dB/Hz RIN level were used as the second forward pump configuration. The output pump was depolarised combining two laser diodes through a polarisation beam combiner, and the maximum optical output power was ~400 mW. Finally a commercially available Raman fibre laser with maximum output power of 5 W and considerably high RIN (-113 dB/Hz) was used as the third forward pump configuration.

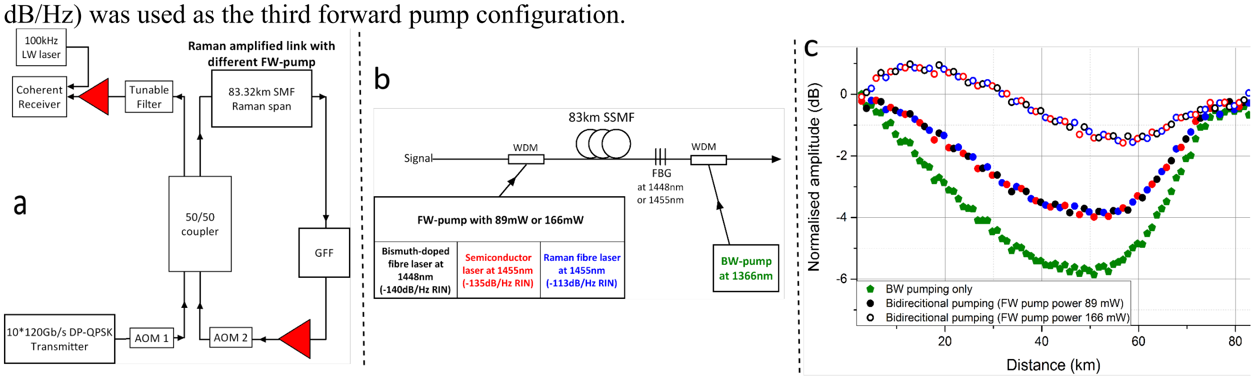

Fig. 1.(a) Experimental schematic diagrams of transmitter, recirculating loop, and coherent receiver. (b). Schematic diagrams of Raman amplified spans using different types of FW-pump. (c). Measured signal power profiles along the fibre using BW-pump only, 89 and 166mW FW-pump power (Here signal power profiles are only related to pump power regardless of FW-pump type).

Signal power profiles along the transmission span measured using a modified optical time-domain reflectometer (OTDR) are shown in Fig. 1.(c). The baseline measurement using BW-pumping only had an SPV of ~6 dB. Using a bidirectionally pumped configuration, signal power variation was reduced to 4 dB using 89 mW FW-pump power, and only ~2.5 dB using 166 mW FW-pump power. This reduction in signal power variation would potentially improve the transmission performance if no RIN-associated penalty from the FW-pump was introduced. Note that the signal power profiles were only related to the FW-pump power regardless of the type of FW-pump, which means all three FW-pumps gave very similar signal power profiles as long as the pump power remained the same.

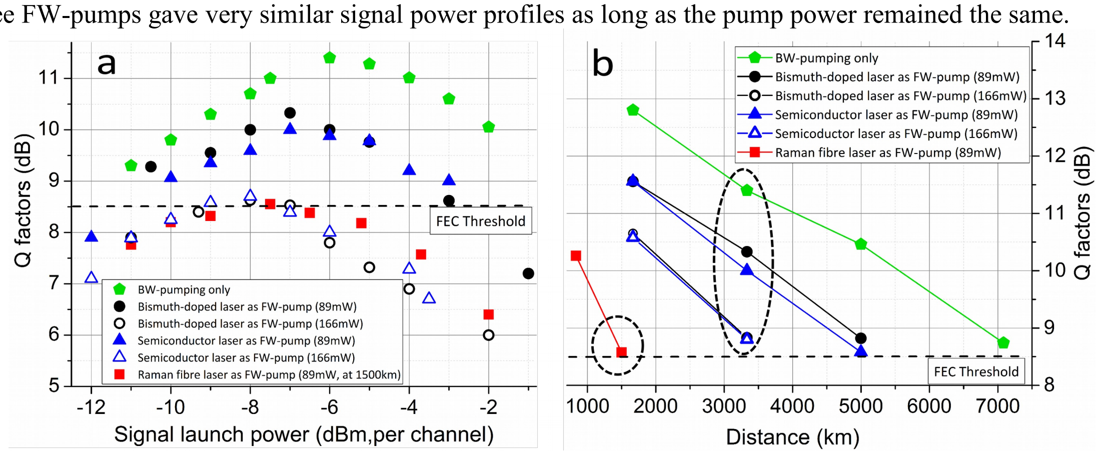

Fig. 2. (a) Q factors versus launch power per channel; (b) Q factors versus transmission distances.

Fig. 2.(a) shows Q factors versus launch power sweeps at 3333 km for all Raman configurations except that the Raman fibre laser was used as the FW-pump: that configuration could not achieve 3333 km, so results are shown at 1550 km which was the maximum distance that could be achieved. Fig. 2.(b) shows Q factors versus transmission distances. The circled points in Fig. 2.(b) are the Q factors at optimum launch powers shown in Fig. 2.(a). Using the

BW-pumping only, the best Q factor was 11.4 dB at -6 dBm optimum launch power per channel. Consequently, BW-pumping only scheme gave the longest transmission distance of 7082 km. As the bismuth-doped fibre laser was used as the FW-pump, the optimum Q factor decreased to 10.3 dB with 89 mW FW-pump power, and the maximum reach degraded to 4999 km. This was due to significant RIN-associated penalty from the pump, because the Q factor should be improved due to the amplifier noise figure reduction and uniform signal power distribution [2,3]. As expected from Fig. 1.(c), the impact of nonlinearities degraded the optimum launch power to -7 dBm, because using FW-pump resulted in higher average signal power. With 166 mW FW-pump power, more severe Q factor penalty was observed, and Q factor was degraded to only 8.63 dB. Consequently, the maximum reach was only 3333 km. The optimum launch power was -8 dBm due to only 2.5 dB signal power variation. Here, noted that using higher FW-pump power degraded the system performance even with very low launch power per channel (i.e. -10 dBm), as the impact of fibre nonlinearity was negligible. Slightly worse performances can be found using semiconductor laser diodes, as its RIN level was slightly higher than bismuth-doped fibre laser. When using Raman fibre laser as the FW-pump, the transmission performance was much worse because of its relatively high RIN (-113 dB/Hz) and associated penalty, limiting the maximum reach to only 1500 km. Fig. 3 shows Q factors and received spectra at maximum transmission distances for BW-pumping only, bidirectional pumping with bismuth-doped laser, semiconductor laser, and Raman fibre laser. All the channels were above FEC threshold (3.8×10^{-3} in bit error rate).

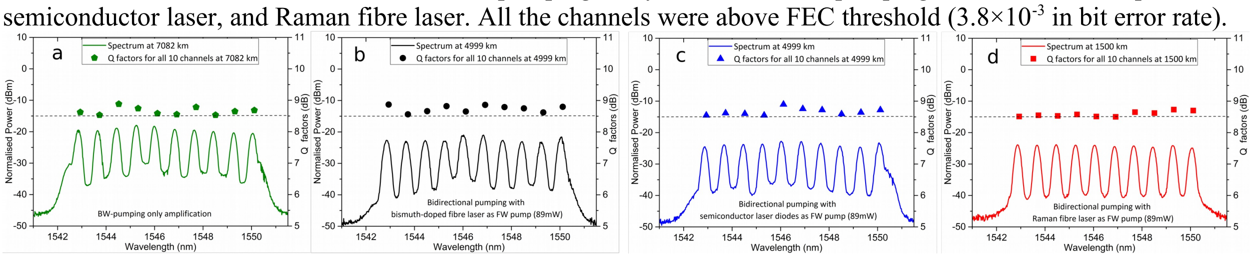

Fig. 3. Q factors and received spectra measured at its maximum reach; (a). BW-pumping only amplification at 7082km; (b). Bidirectionally pumping with bismuth-doped laser FW-pump at 4999km; (c). Bidirectionally pumping with semiconductor laser FW-pump at 4999km; (d). Bidirectionally pumping with Raman fibre laser FW-pump at 1500km.

The requirements of FW-propagated Raman pump lasers are commonly recognised as: 1) wavelength stability; 2) low Stimulated Brillion scattering (SBS); 3) low relative intensity noise [6]. As the wavelength selective FBGs were used in all cases, the lasing wavelengths were very stable. SBS was easily avoided as the laser linewidths were very broad (up to 3 nm) which significantly increased SBS threshold. The RIN of our bismuth-doped fibre laser was suppressed to only -140 dB/Hz. Even with this RIN level, the Q factor penalty at 40 recirculations could be >1 dB using only 89 mW FW-pump power, and 2.8 dB using 166 mW FW-pump power, in comparison with BW-pumping only scenario. When using high RIN Raman fibre laser, the Q factor penalty could be increased severely to 5.3 dB. Such penalty would be even higher and accumulated with more recirculations. So far, the only way to avoid such penalty without significantly changing output gain spectrum is to use second order pump with very low reflectivity FBG near the input end, which can mitigate the signal RIN and improve the transmission performance [4].

3. Conclusion

We present a detailed experimental investigation of long-haul transmission performance using first order pump lasers with different RIN/power levels, including a low RIN bismuth-doped fibre laser. Our results show even with FW-propagated -140 dB/Hz bismuth-doped fibre laser, the Q factor penalty was 2.8 dB using 166 mW pump power, compared with BW-pumping only. Understanding and quantification of RIN impact with FW-pumping is important for designing bidirectionally pumped distributed Raman amplification in long-haul coherent transmission systems.

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