RIN-Penalty Mitigation and Transmission Performance Improvement Using Forward Propagated Broadband First Order Raman Pump

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***Abstract*—We demonstrate that using a broadband pump enables forward-propagated first order distributed Raman amplification by mitigating RIN-associated penalty. This extends the reach of 10 × 120 Gb/s DP-QPSK WDM transmission up to 7499 km, compared with other commercially available pumps. Moreover, using this Raman scheme maintains uniform/symmetric signal power distribution and requires low pump power.**

***Keywords*— coherent communications; Raman amplification;**

I. INTRODUCTION

As coherent transmission systems move to higher order modulation formats a higher signal-to-noise ratio (SNR) is required. Using distributed Raman amplification (DRA) can effectively reduce amplified spontaneous emission (ASE) noise and improve the signal-to-noise ratio, in comparison with discrete amplification. In DRA, using bidirectional pumping can distribute the signal power uniformly along the fibre and provide superior noise performance over backward-propagated (BW) pumping only [1]. However, a major difficulty of using forward Raman pump is relative intensity noise (RIN) and its associated penalty, in particular for long-haul repeated transmission systems [2,3]. We previously showed a Raman amplification based on random distributed feedback (DFB) fibre laser with bidirectional second-order pumping improved the maximum reach by 0.7 dB, compared with BW-pumping only. This indicates the RIN penalty had been significantly mitigated [4]. However, the main drawback of this scheme was due to the use of second order pump in the forward direction with no seed of first order pump, the Raman gain efficiency near the span input was very low. In order to improve the Raman gain efficiency, using first order FW-pump is the simplest way.

Here, we present a detailed evaluation of the long-haul transmission performance in a 100G DP-QPSK WDM coherent transmission system, by using different forward-propagated first order pumps with different RIN/power levels based on Raman fibre laser based amplification. We demonstrate that using a broadband Raman fibre laser with relatively low RIN level can extend the maximum transmission distance without increasing the RIN of the signal, and we compare it with other commercially available pump lasers, i.e. semiconductor laser diodes and narrowband Raman fibre laser. Using the proposed scheme gives a maximum reach of 7499 km, compared with 4999 km using a semiconductor laser diode and 1500 km using a narrowband Raman fibre laser. Furthermore, unlike other pump lasers, the RIN of the output signal using this broadband pump doesn't increase dramatically when the pump power increases. Therefore, different signal power profiles along the fibre can be achieved in order to satisfy the span requirement for different nonlinearity compensation techniques.

II. EXPERIMENTAL SETUP OF RAMAN AMPLIFIED TRANSMISSION SYSTEMS

To quantify the impact on the long-haul transmission performance using different FW-propagated pump lasers, a recirculating loop experiment was conducted using the set-up shown in Fig. 1. Ten DFB lasers spaced at 100 GHz (from 1542.94 nm to 1550.12 nm) were combined with a 100 kHz linewidth tuneable laser ("channel under test"). The combined signals were QPSK modulated at 30G Baud. A PM EDFA was used to amplify the signal. The 10×120 Gb/s DP-QPSK signals were generated through a polarisation multiplexer before the input of the recirculating loop. The transmission fibre in the recirculating loop was 83.32 km standard SMF-28 fibre 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 after the Raman link. The ~12 dB loss from GFF, 50/50 coupler, two acousto-optic modulators (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 by an EDFA. 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 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 for the Raman configurations tested are shown in Fig. 2. For all configurations the on-off gain was set to compensate the 16.5 dB loss of the fibre. As a baseline, second order backward only pumping at 1366 nm with the FBG near the output end of the span was used. The FBG was centred at 1452/1455 nm (0.5 nm 3dB bandwidth and 95% reflectivity). The difference in centre wavelength was to match the wavelength of the FW-pump. The first-order random fibre laser at 1455 nm was generated due to the resonant mode reaching the lasing threshold in a distributed cavity formed by Rayleigh scattering and an FBG [4]. To enhance the signal-to-noise ratio, three types of FW-propagated pumps were used, as forward pumping at 1455 nm could amplify the signal near the input section of the fibre and consequently reduce the signal power variation (SPV). The first type of forward pump was a commercially available broadband (~8 nm 3dB bandwidth) Raman fibre laser with the RIN level of -138 dB/Hz and 5 W maximum output power. In comparison, semiconductor laser diodes with 0.8 nm 3dB bandwidth and -135 dB/Hz RIN level were used as the second forward pump configuration. The pump output was depolarised by combining two laser diodes through a polarisation beam combiner, and the output power was up to ~400 mW. A narrowband (0.5 nm 3dB bandwidth) 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.

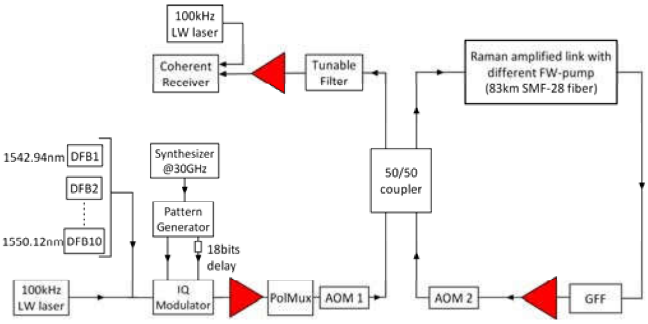

Figure 1. Experimental setup of long-haul transmission system

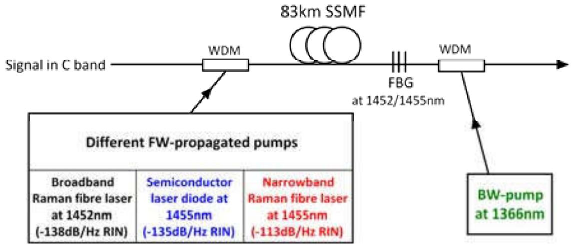

Figure 2. Schematic diagrams of Raman amplification schemes using different types of forward pumps

Signal power profiles along the transmission span measured using a modified optical time-domain reflectometer (OTDR) are shown in Fig. 3. Using BW-pumping only resulted in an SPV of ~6 dB. In a bi-directionally pumped setup, signal power variation was reduced to 4 dB using 89 mW FW-pump power (100 mW for the broadband FW-pump because of larger 3dB bandwidth), and only ~2.5 dB using 166 mW FW-pump power (186 mW for the broadband pump). Assuming no RIN-associated penalty from the forward pump is introduced, this reduction in signal power variation should lead to the improvement of the transmission performance. Here, note that signal power profiles are mainly related to pump power regardless of forward pump type, so the signal power profiles using different forward pumps are the same.

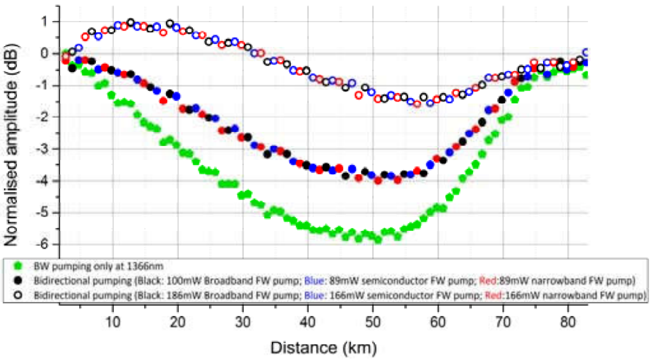

Figure 3. Measured signal power profiles along the fibre using BW-pump only, 89-100, and 166-186mW FW pump power (signal power profiles are mainly related to pump power regardless of forward pump type)

The RIN of the signal could lead to significant penalty on the long-haul transmission performance [3]. RIN of the signal at the span output were experimentally investigated for all the pumping schemes and are shown in Fig. 4. The detailed setup for RIN measurement can be found in [3]. In Fig. 4, using 100 mW broadband Raman fibre laser, the RIN of the output signal was similar to BW-pumping only over the whole frequency range, which indicates RIN-induced penalty didn't exist on the transmission [4]. Increasing the pump power to 186 mW, the RIN was increased slightly by 2 dB at low frequency range below 20 MHz. In comparison, the RIN dramatically increased by 10 dB at low frequency range using semiconductor laser with 89 mW pump power, regardless of similar pump RIN to the broadband pump. Using high RIN narrowband pump made the RIN worse, up to 20 dB increase in the signal RIN, which may result in critical penalty on the transmission performance.

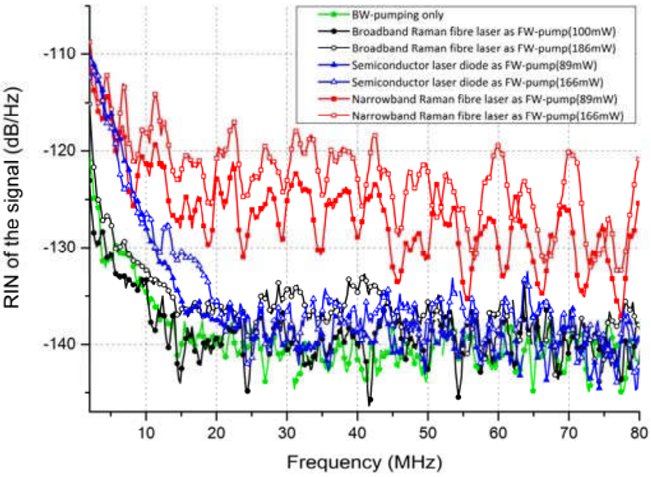

Figure 4. RIN of the output signal using different forward pumps

III. TRANSMISSION RESULTS AND DISCUSSIONS

Fig. 5 shows Q factors versus signal launch power per channel at 3333 km for different Raman configurations except that narrowband Raman fibre laser was used as the FW-pump: that configuration could not achieve 3333 km, so results are shown at 1500 km which was the maximum distance that could be achieved. Fig. 6 shows Q factors versus transmission distances. The circled points in Fig. 6 are the Q factors at optimum launch powers shown in Fig. 5.

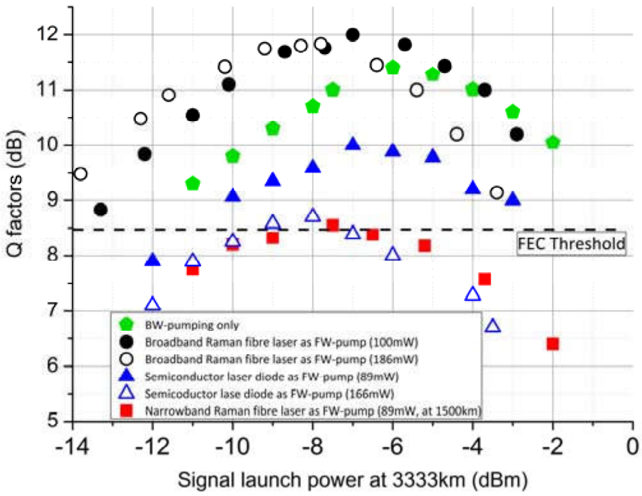

Figure 5. Q factors versus signal launch power per channel

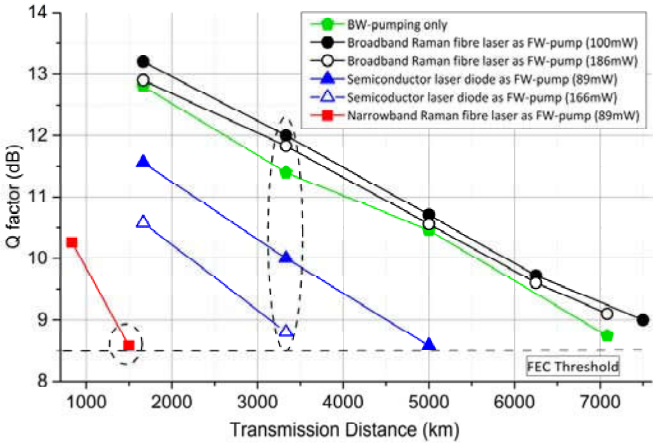

Figure 6. Q factors versus transmission distances

Using the BW-pumping only, the best Q factor was 11.4 dB at -6 dBm optimum signal launch power. Consequently, BW-pumping only scheme gave a transmission distance of 7082 km. Using broadband Raman fibre laser as the FW-pump, the optimum Q factor was improved to 12 dB with 100 mW FW-pump power, and the maximum reach was extended to 7499 km. This was because the signal RIN stayed the same and therefore the Q factor was improved due to the amplifier noise figure reduction and uniform signal power distribution [3,4]. As expected from Fig. 3, the impact of nonlinearity reduced the optimum launch power to -7 dBm, as FW-pumping resulted in a higher average signal power. With 166 mW forward pump power, a Q factor of 11.83 dB was achieved at the optimum launch power of -8 dBm. The maximum reach was slightly decreased to 7082 km. This was due to the slight increase in the signal RIN. In the FW-propagated semiconductor laser diode setup, the optimum Q factor at 3333 km was only 10 dB with 89 mW and 8.7 dB at 166 mW. The maximum reach was 4999 km, much worse in comparison with BW-pumping only and FW-propagated broadband Raman pump. When using narrowband Raman fibre laser as the forward pump, the transmission performance was much worse because of its relatively high RIN (-113 dB/Hz) and narrow 3dB bandwidth, limiting the maximum reach to only 1500 km. Here, we noted that using higher FW-pump power degraded the performance even with very low launch power per channel (i.e. -10 dBm), as the impact of fibre nonlinearity was negligible. Q factors and received spectra at maximum transmission distances for all the Raman configurations are available at the conference. All the channels were above FEC threshold (3.8×10^{-3} in bit error rate).

Therefore, to improve the transmission performance using first order FW-propagated pump in DRA for long-haul transmission, the required pump should essentially have the low RIN level (i.e. <-135 dB/Hz). Low stimulated Brillion scattering (SBS) is also required, but this is easily achieved due to the low pump power being used [6]. More importantly, a broadband 3dB bandwidth (i.e. 8 nm) is crucial to reduce the RIN transfer.

IV. CONCLUSION

We have demonstrated that using a broadband low RIN FW-propagated pump in distributed Raman amplification can effectively extend the reach of 10 ×120 Gb/s DP-QPSK long-haul transmission without increasing the RIN of the signal, in comparison with other commercially available Raman pump lasers. This scheme offers the best transmission performance, maintains only 2.5 dB signal power variation, and requires low pump power. In addition, using such a scheme can provide a symmetric link which maximises the benefit of nonlinearity compensation using mid-link OPC, or a low signal power variation for a nonlinear Fourier transform based transceiver.

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