

# Evaluation of 100G DP-QPSK long-haul transmission performance using second order co-pumped Raman laser based amplification

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**Abstract:** We present, for the first time, a detailed investigation of the impact of second order co-propagating Raman pumping on long-haul 100G WDM DP-QPSK coherent transmission of up to 7082 km using Raman fibre laser based configurations. Signal power and noise distributions along the fibre for each pumping scheme were characterised both numerically and experimentally. Based on these pumping schemes, the Q factor penalties versus co-pump power ratios were experimentally measured and quantified. A significant Q factor penalty of up to 4.15 dB was observed after 1666 km using symmetric bidirectional pumping, compared with counter-pumping only. Our results show that whilst using co-pumping minimises the intra-cavity signal power variation and amplification noise, the Q factor penalty with co-pumping was too great for any advantage to be seen. The relative intensity noise (RIN) characteristics of the induced fibre laser and the output signal, and the intra-cavity RF spectra of the fibre laser are also presented. We attribute the Q factor degradation to RIN induced penalty due to RIN being transferred from the first order fibre laser and second order co-pump to the signal. More importantly, there were two different fibre lasing regimes contributing to the amplification. It was random distributed feedback lasing when using counter-pumping only and conventional Fabry-Perot cavity lasing when using all bidirectional pumping schemes. This also results in significantly different performances due to different laser cavity lengths for these two classes of laser.

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## 1. Introduction

In recent papers we have shown that second order Raman fibre laser (RFL) based amplification can be used to give a symmetric signal power profile, which allows effective all-optical nonlinearity compensation to be achieved using mid-span optical phase conjugation [1, 2]. In that experiment we found that the best transmission performance was achieved using second order counter-pumping only instead of bidirectional pumping. However, using second order bidirectional pumping can reduce the intra-span signal power variation (SPV) to an almost negligible  $\sim \pm 0.8$  dB for an 80 km transmission span, which leads to lower noise figure and higher OSNR which are practically beneficial for advanced modulation formats [3, 4]. This in principle increases the amount of nonlinearity compensation using optical phase conjugation and gives close to the ideal distributed amplification to minimise noise. However, in conventional first or dual order distributed Raman amplification schemes, the penalty using bidirectional pumping due to relative intensity noise (RIN) introduced from co-propagated pump, has been studied in direct detection systems both numerically and experimentally [5-7], but only investigated numerically in coherent transmission systems [8].

Here, we present a detailed evaluation of transmission performance in a long-haul 100G DP-QPSK WDM coherent transmission system, by varying co-propagated second order pump power within the RFL based amplification scheme. Signal power and noise distributions along the fibre for co-pumping power ratios were characterised both experimentally and numerically. The RIN characteristics of the fibre laser and the output signal, and the intra-cavity RF spectra of the fibre laser are also presented.

Based on these pumping schemes, we experimentally measured and quantified the Q factor penalty with co-pump power ratios and transmission performances of up to 7082 km in a long haul transmission system. Using symmetric bidirectional pumping, the maximum transmission distance was reduced to 1666 km with a Q factor penalty of 4.15 dB compared to counter-pumping only. These results are also compared with numerical simulation results which exclude RIN, to further quantify the RIN induced penalty. We find that, although using co-pumping can distribute the gain more uniformly and minimise the amplification noise, the

introduced Q factor penalty is too high regardless of any noise figure reduction. We attribute this Q factor penalty to increased RIN of the output signal which was transferred from increased co-pump power and induced fibre laser. Moreover, we demonstrate that the induced Raman fibre lasing regimes changed from random distributed feedback (DFB) lasing when using counter-pumping only, to conventional Fabry-Perot cavity lasing when using bidirectional pumping [3, 9], which led to a longer RFL cavity length and higher RIN transfer to the output signal [10, 11].

## 2. Experimental setup

In the RFL based amplification scheme, a matched pair of ~95% reflectivity fibre Bragg gratings (FBGs) with a centre peak at 1455 nm and a 3 dB bandwidth of ~0.5 nm were used with one located at each end of an 83.32 km standard (G. 652) single mode fibre (SMF) span. Highly depolarised second order pumps at 1366 nm with RIN of approximately -120 dB/Hz were used to create an ultra-long Raman fibre laser at the wavelength specified by the FBGs. The second order pumps used here were commercially available fibre laser units which provided very low RIN level for a fibre laser. Although lower RIN levels are possible with semiconductor based devices, fibre lasers were used here as they were the only sources with the required power at 1366nm pump wavelength available on the market. A reduction in RIN might be possible but very difficult, if fibre laser pump design can be improved or multiple semiconductor pumps at required wavelength are combined. The resultant fibre lasing at 1455 nm and pump at 1366 nm provided the amplifications for the WDM signals in the C band [12]. Dual order pumping scheme can be also used to give similar Raman amplification performance but requires more pumps [13].

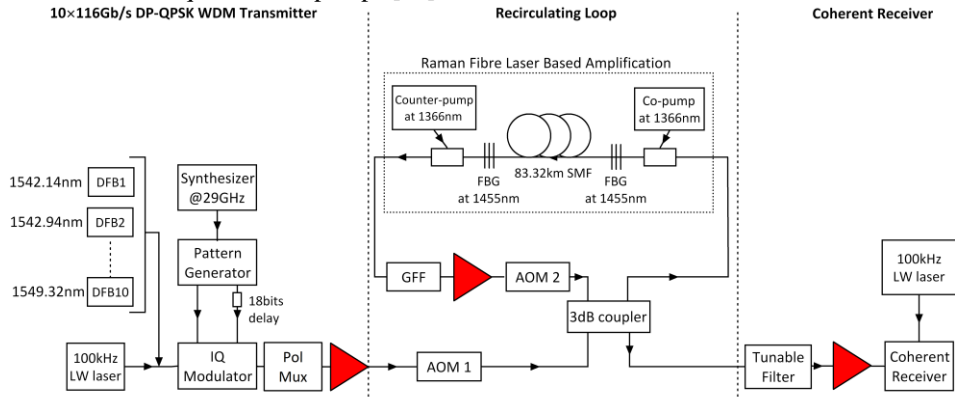


Fig. 1. Experimental setup of DP-QPSK WDM transmitter, recirculating loop using Raman fibre laser based amplification technique, and coherent receiver. AOM: Acousto-optic modulator; GFF: Gain flattening filter

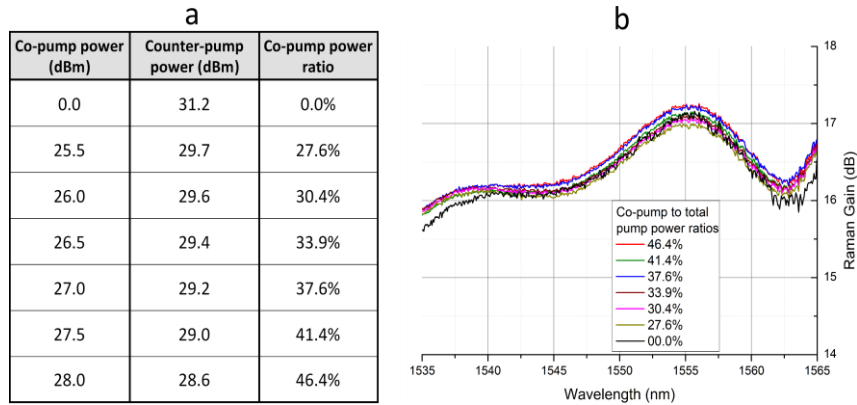


Fig. 2(a). Second order co-propagated, counter-propagated pump power, and co-pump power ratio used in the experiments; (b). Raman gain spectra using different pump power ratios.

To evaluate the influence of increased co-pump power, a recirculating loop experiment was conducted using the setup shown in Fig. 1. The test signals consisted of ten DFB lasers with 100 GHz spacing ranging from 1542.14 nm to 1549.32 nm. A 100 kHz linewidth tuneable laser was used as the “channel under test” while the corresponding DFB laser was switched off during the measurement cycle. The multiplexed signals were QPSK modulated with normal and inverse  $2^{31}-1$  PRBS patterns at 29 Gb/s with a relative delay between I (in-phase) and Q (quadrature). The delay between I & Q was 18 bits. A polarisation multiplexer (PolMux) with a delay of 290 bits between the two polarisation states gave the resultant  $10 \times 116$  Gb/s DP-QPSK signals. An EDFA was used before launch into the recirculating loop. The transmission span in the recirculating loop was 83.32 km SMF-28 with a total loss of  $\sim 17.6$  dB including 16.5 dB from SMF-28 fibre and 1.1 dB from two WDMs. The AOM, 3 dB coupler, gain flattening filter (GFF) within the loop, and WDMs gave a total loss of  $\sim 12$  dB, which was compensated by a single stage EDFA at the end of the loop. The receiver was a standard polarisation diverse coherent detection setup using an 80 GSa/s, 25 GHz bandwidth real time oscilloscope for analogue to digital conversion. Digital signal processing (DSP) was used offline with standard algorithms for signal recovery and linear transmission impairments compensation. Q factors were calculated from bit wise error counting and averaged over two million bits.

The pump powers listed in Fig. 2(a) were used to compensate for the  $\sim 16.5$  dB loss from the transmission fibre span. The Raman gain spectra with the input of amplified spontaneous emission (ASE) noise in Fig. 2(b) show  $\pm 0.6$  dB Raman gain variations across the whole C band with similar spectra for all the pumping configurations.

### 3. Results and discussions

The signal power evolution along the fibre span with different co- and counter-propagated pump powers was measured at the wavelength of 1545.32 nm with a modified optical time-domain reflectometer setup [14]. For each pumping scheme, SPV was calculated as the difference between the maximum and minimum power value along the span. This SPV was used as a metric to compare pumping schemes and is shown as solid lines in Fig. 3(a). Simulations of signal and noise along the fibre are also shown as dotted lines in Figs. 3(a) and 3(b). The lowest peak-to-peak SPV of  $\sim 1.6$  dB was achieved with symmetric bidirectional pumping (co-pump power ratio of 46.4%). With counter-pumping only, the SPV reached  $\sim 5.6$  dB. This shows that the use of second order co-pumping gave a significant reduction in SPV, which also reduces the amplifier noise figure as the noise figure corresponds to the integration of the SPV [15]. Bidirectional pumping and fibre lasing can “push” the gain further from ends of the span from both directions and distribute the gain more uniformly.

If the system performance is limited by the fibre nonlinearity and the ASE noise generated from optical amplifiers, we can expect a noise performance improvement by using more co-pumping. Alternatively, if the RIN induced penalty from co-pumping is ignored, a better performance should be observed while increasing the co-pump power because of the associated reduction in the noise figure. In order to support this argument, we conducted a numerical simulation on the performance of WDM DP-QPSK system while taking into account the power and noise distribution profiles for each pumping scheme. The simulation setup is similar to the experimental one, where  $10 \times 29$  Gbaud DP-QPSK channels with 100 GHz spacing were transmitted over 20 recirculations. As a large number of channels were simulated, a random sequence of length  $2^{16}-1$  was used instead of a PRBS of length  $2^{31}-1$  adopted in the experiment. The generated signal was oversampled 4 times providing a total simulation bandwidth of  $\sim 4$  THz. The propagation of the signal in the fibre link was simulated using the well-known split-step Fourier method, with a step size of  $\sim 1.6$  km using the signal power profiles shown in Fig. 3(a). The Raman noise was modelled as Gaussian noise, which was added to the signal after each step ( $\sim 1.6$  km), following the simulated noise profiles shown in Fig. 3(b). In this simulation, we used the same power and noise profiles for all the channels, for simplicity. The additional noise from an EDFA implemented in the experimental recirculation loop setup was ignored in the simulation, as we would like to focus on the

impact of pumping schemes on the transmission performance only. At the receiver, after coherent detection, the channel under test was filtered using an 8<sup>th</sup> order Butterworth low pass filter. The DSP adopted in the simulation was similar to the one used in the experiment.

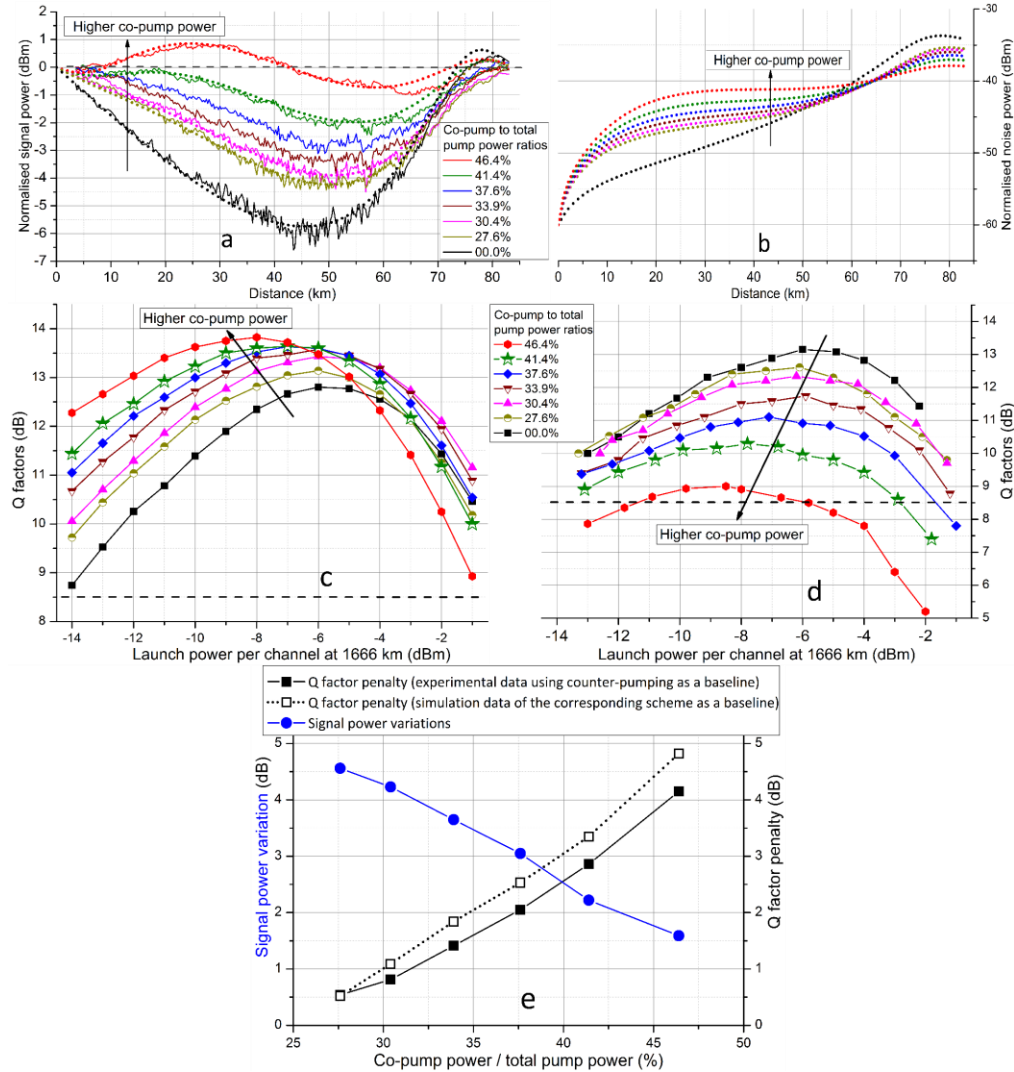


Fig. 3(a). Simulations (dot line) and experimental data (solid line) of signal power profiles with different co-pump power. (b). Simulated noise distributions with different co-pump powers. (c). Simulated Q factors versus launch power per channel at 1666 km using 1545.32 nm channel assuming that the system performance is limited by ASE noise and fibre nonlinearity only. (d). Measured Q factors versus launch power per channel at 1666 km using 1545.32 nm channel. (e). Co-pump power ratios versus signal power variations (SPVs) and Q factor penalties.

The simulation result is presented in Fig. 3(c) where the Q factor is plotted versus launch power for each pumping scheme using the 1545.32nm channel. We would like to stress that no RIN induced impact was considered in this case. As expected, the Q factor was improved with increasing co-pump power, because the amplifier noise figure was reduced due to more uniform gain distribution. The Q factor was improved from 12.8 dB using counter-pumping only to 13.9 dB using symmetric bidirectional pumping. However, in the experimental results as shown in Fig. 3(d), the measured Q factor was decreased from 13.1 dB to 9 dB as the co-pumping power was increased. This result clearly indicates that using higher co-pumping power introduced an overall Q factor penalty, despite the reduction in amplifier noise figure due to flatter signal power variations. On the other hand, there was also a reduction in the

optimum launch power in both cases as co-pump power is increased. This is due to the more uniform power level – for the same launch power there is more nonlinear penalty as co-pump power is increased hence optimum launch power is decreased. It also indicates that the nonlinear threshold changed as the integral of SPV traces due to the increase of effective nonlinear length. Here, it should be noted that using higher co-pump power degraded the system performance even with relatively low launch power per channel (i.e. -13dBm), when the impact of fibre nonlinearity was negligible, which means that the increase of effective nonlinear length was not responsible for the performance degradation, as the co-pump power was increased. The associated Q penalties and the SPV versus co-pump power ratios are shown in Fig. 3(e). As co-pump power was increased, the SPV became smaller. However, the Q factor penalty (solid black line) assuming the optimum Q factor with counter-pumping only at 1666 km as a baseline became very significant after 1666 km, from 0.54 dB with 27.6% co-pump power ratio, to 4.15 dB with 46.4% co-pump power ratio. Alternatively, the Q penalty (dotted black line) assuming the simulated optimum Q factor for each corresponding pumping scheme is shown in Fig. 3(e). It shows that the Q penalty was even larger, as the simulations excluded the RIN induced impact and only considered the noise reduction due to higher co-pumping power.

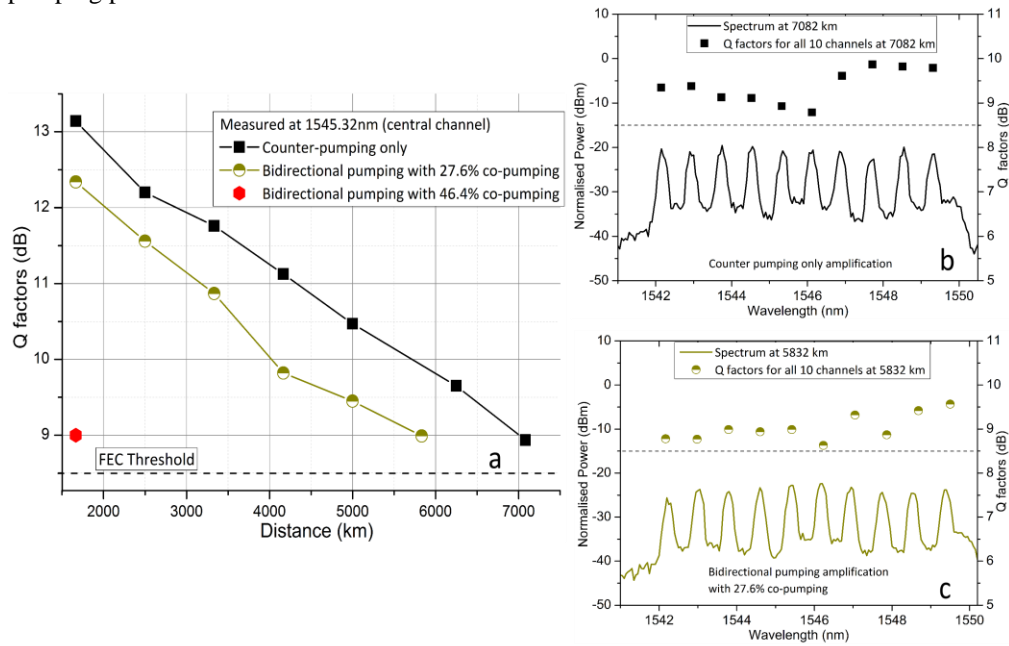


Fig. 4(a). Q factors of the central channel at 1545.32 nm versus transmission distances using different pump powers. (b). Q factors for all ten channels and received spectra measured at 7082 km with counter-pump only. (c). Q factors for all ten channels and received spectra measured at 5832 km with 27.6% co-pump power ratio.

Figure 4 (a) shows Q factors versus transmission distances of the 1545.32 nm channel using 0%, 27.6%, and 46.4% co-pump power ratios. Figures. 4 (b) and 4(c) show the spectra and Q factors for all ten channels at maximum transmission distances. The results show that the maximum transmission distance of 7082 km in terms of 8.5 dB Q factor threshold (equivalent to  $3.8 \times 10^{-3}$  in bit error rate) was achieved with a counter-pumping only configuration. This was reduced to 5832 km with co-pump power ratio of 27.6%. As for 46.4% co-pump power ratio, the reach was decreased significantly to only 1666 km.

In order to understand the performance degradation, we performed the experimental characterisations of Raman fibre laser and the output signal for different pump powers. The schematic design of the experiment is shown in Fig. 5. First, we measured the RIN of the output signal after one span at 1545.32 nm from a continuous-wave low RIN ( $\sim -140$  dB/Hz) tuneable laser source, which was used in the transmission experiments. The setup for RIN



measurement between 1 MHz and 200 MHz was based on an ultra-low-noise photo-receiver and an electrical spectrum analyser.

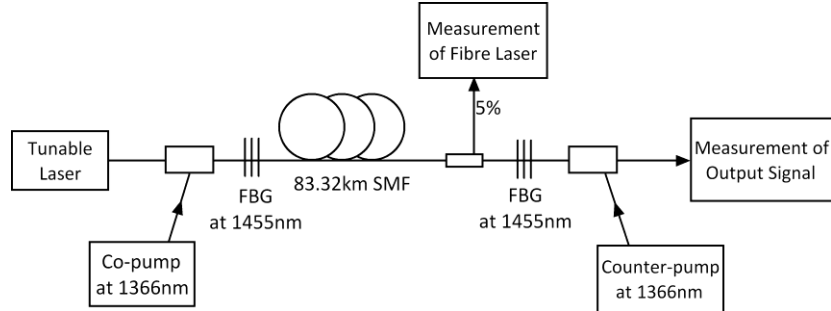


Fig. 5. Experimental setup of the measurement of Raman fibre laser at 1455 nm and output signal

The reason why we focused on the low frequency range is because high frequency components of RIN from the pump are averaged along the fibre and there is little effect in co-pumping scheme because of the “walk off” between propagating velocities of signal and pump [16]. The results in Fig. 6(a) show that there was an increase of up to ~18 dB in output signal RIN as the co-pump power ratio was increased from 0% to 46.4%. The RIN of the induced fibre laser at 1455 nm was very similar for all co-pumping configurations and reached the maximum value of -120 dB/Hz at around 100 MHz. In the counter-pumping only scenario, the RIN was lower, particularly in the low frequency range below 40 MHz where we can notice up to 4 dB reduction. Figure. 6(b) shows the measured intra-cavity RF spectra of the fibre laser at 1455 nm for various co-pump powers, respectively. Note that the traces in Fig. 6(b) were deliberately offset to aid comparison – the relative power is unimportant. There is a clear difference in the intra-cavity RF spectra for the bidirectional and the counter-pumping only schemes. The RF spectra shown in Fig. 6(b) indicate that there were two regimes of fibre lasing. For all bidirectional pumping schemes there was a laser mode spacing of ~1.2 kHz corresponding to an 83 km Fabry-Perot cavity i.e. the transmission span was effectively an ultra-long Raman fibre laser. This mode spacing was independent of co-pump power, because it is only the length of the cavity (i.e. the transmission fibre span) which determines the mode spacing [17]. With counter-pumping only no mode structure was observed, therefore we concluded that a random distributed feedback laser with a half-opened cavity was created [9].

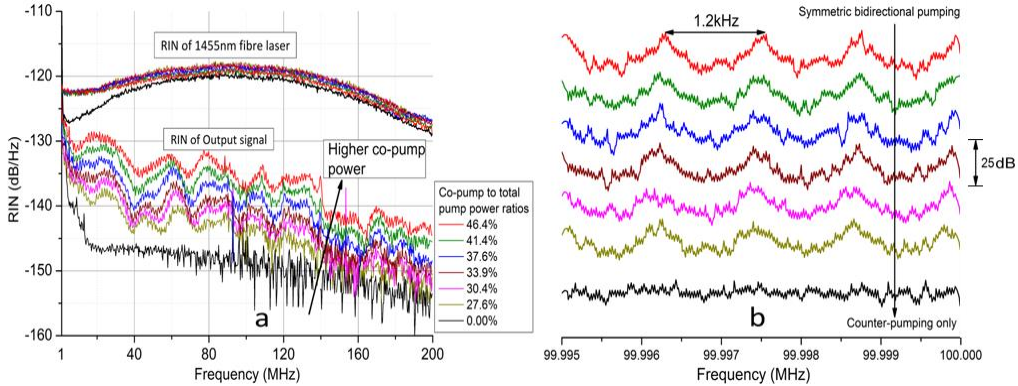


Fig. 6(a) Measured RIN of the Raman fibre laser and the output signal after 83 km span. (b) Measured mode spacing of the Raman fibre laser.

The transmission degradation can be explained as follows. Among the schemes including the use of co-pump, the RIN was transferred to the signal from both the first order Fabry-Perot ultra-long Raman fibre laser and the primary second order co-pump, which causes various penalties [8, 18]. These RIN induced penalties increased with increasing co-pump power. For

the counter-pumping only scheme, indeed, the RIN of the induced Raman fibre laser was lower in the low frequency range. It was actually a modeless random DFB laser with much shorter cavity length (30-40 km) than Fabry-Perot cavity laser (83 km) [3, 11]. The RIN of the fibre laser would get transferred to the output signal more severely for Fabry-Perot fibre laser based amplification with the longer cavity [10]. The random DFB laser based amplification technique can be further optimised using a slightly modified configuration which significantly reduces the RIN-induced penalty [13].

#### **4. Conclusion**

In this paper, based on long-haul 100G DP-QPSK WDM transmission using RFL based amplification scheme, we performed an experimental evaluation of the impact on the transmission performance with different co-propagated second order pump power, from counter-pumping only to symmetric bidirectional pumping. Using the experimental and simulations results, the relationship between signal power variation and Q factor were analysed considering the situation with and without the RIN induced penalty from co-pump. While using second order co-pump indeed minimised variation in signal power and hence the amplifier noise figure, the introduced Q factor penalty associated with RIN was too high for any overall performance improvement. The Q factor penalty could be as high as 4.15 dB after 1666 km using symmetric bidirectional pumping (46.4% co-pump power ratio), compared with counter-pumping only. We attribute the Q factor penalty to increased RIN of the output signal which was transferred from first order Raman fibre laser and increased second order co-pump power. However it may be possible to improve the signal RIN performance with the use of lower RIN pumps than the -120dB/Hz RIN fibre lasers used here. Two types of lasing regimes were observed, a random DFB lasing for counter-pumping only and conventional Fabry-Perot cavity lasing for bidirectional pumping schemes. For bidirectional pumping schemes, the transmission performances were degraded, because more RIN from the fibre laser and the co-pump was transferred to the signal due to higher input co-pump power. But for the counter-pumping only scheme, the RIN of induced fibre laser was reduced only in the low frequency range. The RIN of signal was significantly lower all over the measurement frequency range, because the RIN transfer to the output signal was lower in a shorter random fibre laser cavity than in a long Fabry-Perot laser cavity.

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