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RIN induced penalties in G.654.E and G.652.D based distributed Raman amplifiers for coherent transmission systems

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Abstract: Relative intensity noise (RIN) induced penalties were experimentally measured in distributed Raman amplifiers (DRAs) for G.654.E and G.652.D fibres with forward, backward and bidirectional pumping configurations. The measured signal RIN using the G.654.E fibre was ~3.5 dB and ~2 dB lower than the G.652.D fibre with forward (FW) pump configuration for PM-QPSK and PM-8QAM signals, with single span transmission showing a Q-factor improvement of ~3 dB and ~2.5 dB for G.654.E over G.652.D fibres. The performance penalty in a long haul coherent system was evaluated for 28 GBaud PM-QPSK signals using a recirculation loop for backward and bidirectional distributed Raman amplifiers. Our experimental results demonstrate an additional transmission distance of more than 1000 km for G.654.E over its counterpart G.652.D assuming a HD-FEC limit of 8.5 dB.

1. Introduction

The strong demand for optical fibre communication systems with high data rate over longer reach and with advanced modulation format is highly evident [1]. Fibres with large effective area (A_{eff}) provide a smart solution in terms of large spectral efficiency enabling higher channel capacity and longer reach [2]. To address this problem, ITU-T approved G.654.E as a new fibre for terrestrial network [3]. With this development, investigations have already been reported on the practical terrestrial cabling issues, splice loss and applicability of Raman amplification with G.654.E fibre [4]. Additionally, transmission experiments have been performed and the results have shown an extended reach >55% in comparison to standard G.652.D single mode fibre (SMF) for 200Gb/s PM-16QAM signals [5]. Real time transmission up to 600 Gb/s with 122 km spans over a recirculation loop has also been performed [6]. However, an important characteristic of G.654.E fibre is its cable cut-off value, which is < 1530 nm, unlike standard G.652.D whose cable cut-off is <1260 nm [7]. This necessitates further assessment in systems where transmission is carried out below 1530 nm. Transmission below the cable cut-off results in the generation of higher order modes which ultimately can have an adverse effect on system performance primarily due to intermodal coupling and multi path interference (MPI). Experiments with optical supervisory channels (OSC) at 1510 nm using G.654.B-compliant fibres have been performed and reported no significant performance penalty due to MPI induced RIN [8]. Also, analytical modelling for long haul systems over 3000 km to study the impact of MPI-induced RIN in Raman amplifiers operating below cable cut-off has been reported [9,10]. However, experimental validation of the impact of pump RIN in a distributed Raman amplifier (DRA) under different pumping

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configurations for G.654.E fibre and performance comparison with standard G.652.D SMF has not been reported so far.

In this work we experimentally investigated the impact of pump induced signal RIN penalty for a DRA in forward (FW), backward (BW), and bidirectional (BI) schemes with G.654.E-compliant Corning TXF and G.652.D standard SMF fibres. Signal RIN measurements were carried out with standard measurement techniques [11] for FW pumping DRA configurations at 34 and 69 GBaud for PM-QPSK and PM-8QAM signals and results have shown ~ 3.5 dB and ~ 2 dB lower signal RIN in the case of G.654.E when compared to G.652.D fibre. The impact of RIN induced penalty in coherent transmission systems was initially validated with a single channel transmission @ 1550 nm for 98.45 km of G.654.E fibre and 93.18 km of G.652.D fibre at a fixed 18 dB gain using both test fibres under FW pumping configuration. The FW pumping scheme was deliberately chosen in order to maximize the RIN transfer to the signals [12]. Our experimental results show an enhanced performance of G.654.E over G.652.D with Q-factor improvement of ~3 dB and ~2.6 dB for PM-QPSK and PM-8QAM signals at 34 and 69 GBaud baud rate. The performance penalty for long haul coherent systems was validated with a recirculating loop amplified using a BW and BI configured DRA for a 28-GBaud PM-QPSK signal. In the BI configuration 20% of the total power was provided using a FW pump and the remaining 80% was obtained with a BW pump, altogether to compensate the fibre losses. The BI configuration was particularly chosen to induce some finite signal RIN due to the presence of limited FW pump in the transmission system. A separate 100% BW pumped (negligible RIN) full scale transmission was also carried out to analyze the maximum possible transmission reach without any impact on RIN transfer for both fibres, assuming a HD-FEC limit of 8.5 dB. The Q-factor difference between BW and BI pumping for the same fibre type provides a better insight on the RIN induced penalty in a transmission system. Using the BW pumping configuration a maximum transmission reach of ~ 6000 km was obtained for G.654.E, whereas for G.652.D the maximum reach was ~4900 km. The Q penalty i.e. Q-factor difference between BI and BW pumping at fixed distance also shows better performance for G.654.E in comparison to G.652.D, with a maximum Q factor penalty reaching up to ~3 dB for G.654.E and ~4.1 dB for G.652.D fibres.

2. RIN measurement setup and discussions

A schematic diagram for the RIN experimental setup is shown in Fig. 1(a). A commercial transponder (Oclaro OC-1200) was used to generate PM-QPSK and PM-8QAM signals at 1550 nm. The signal launch power was fixed at 3 dBm which was then coupled to the fibre under test (FUT) using a WDM coupler. A 99/1 tap was used in the fibre input section to monitor the launch power. A Raman fibre laser with maximum 5 W output power and a RIN level of -115 dB/Hz was chosen under FW pump configuration at 1455 nm to induce maximum RIN to the FUT. To ensure fixed RIN level of the pump, the FW pump was driven at 1W output and a variable optical attenuator was used to maintain required power level for different test cases. The setup included either a G.652.D fibre with a span length of 93.18 km and 19.5 dB [4*(SMF – SMF-28e splicing) + Fibre loss] total loss, or a G.654.E fibre with a span length of 98.45 km and total loss of 17.7dB [3*(TXF-TXF splicing) + Fibre loss + 2*(TXF-SMF-28e splicing)]; also, an additional loss of 2 dB was present due to the WDM coupler and optical connectors. The fibre losses were estimated by measuring the optical power at the input and output section of each fibre span with a commercial power meter, with the difference in these values considered as the total fibre loss. The pump powers were adjusted to provide a fixed 18 dB gain whose values were 363 mW for G.652.D and 521 mW for G.654.E. The transmitted signal through the FUT was first decoupled using a WDM splitter and then passed through a variable optical attenuator (VOA) for optimized performance of the photodetector. A low noise photodetector was used as a receiver to measure the RIN noise and the corresponding traces were captured using an electrical spectrum analyzer (ESA).

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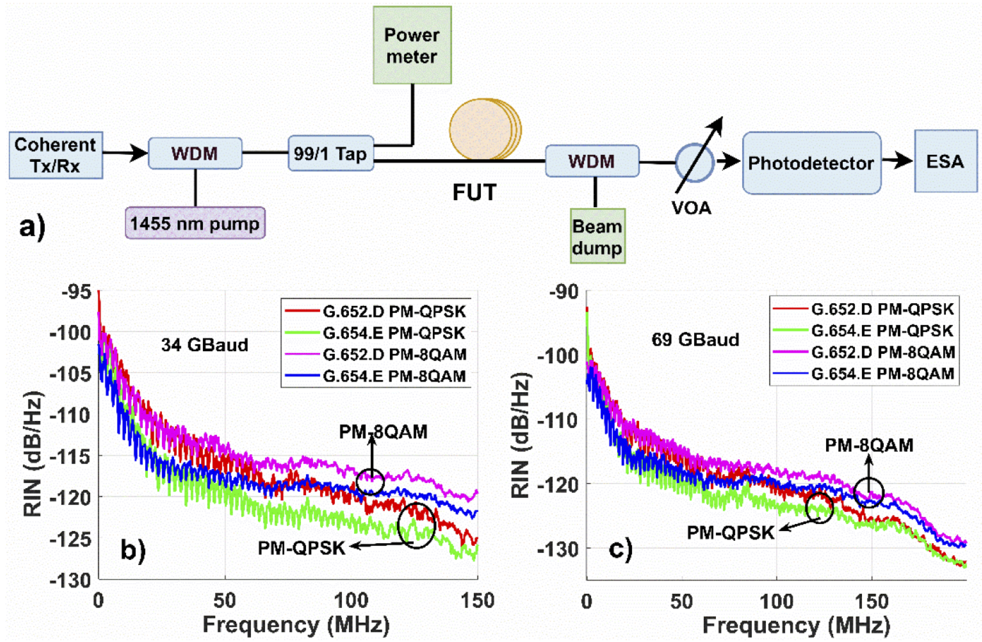

Fig. 1. a) Schematic for RIN measurement; Signal RIN for PM-QPSK and PM-8-QAM at b) 34 GBaud c) 69 GBaud.

Signal RIN arises due to fluctuations in the pump power manifesting itself in the form of intensity noise causing a detrimental effect to the signal performance [13]. In a distributed Raman amplifier with FW pumping the induced signal RIN can be represented by Eq. (1) [14].

$$RIN_{sig}^{out} = RIN_{sig}^{in} + RIN_{pump}\ln^2 G\frac{1/L_{eff}^2}{\alpha_p + (2\pi f D\Delta\lambda)^2} \tag{1}$$

From Eq. (1) we can clearly see that signal RIN at the output is a dependent function of the pump RIN and input signal RIN. However, the RIN contribution to any signal also depends on several other fibre and signal parameters such as L_{eff}, the fibre effective length, α_p, the attenuation coefficient at pump wavelength, f, the frequency of the noise components, D, the fibre chromatic dispersion (CD), and $\Delta\lambda$, the pump-signal wavelength separation. The bracketed term in the denominator term of Eq. (1), also known as the pump signal walk-off parameter, plays a significant role in determining the amount of pump RIN transfer to any signal. The larger the value of this walk-off parameter, the lower will be the transfer of pump RIN to any given signal. Hence, with higher order pumping techniques, RIN transfer can be minimized, a technique that has been well explored [15,16]. Also, the use of high positive dispersion fibre leads to larger pump signal walk-off and results in lower RIN transfer. The value of dispersion for G.652.D is 16 ps/nm/km, whereas for G.654.E it is about 21 ps/nm/km [5]. Hence, theoretically the signal RIN should be lower in case of G.654.E based Raman amplification in comparison to its counterpart G.652.D.

Figure 1(b) and 1(c) shows the different values of signal RIN in the frequency range of 0-150 MHz for PM-QPSK and PM-8QAM signals at 34 and 69 GBaud baud rate. The RIN for G.654.E was observed to be approximately 3.5 dB and 2 dB lower at > 50 MHz frequencies for both PM-QPSK and PM-8QAM signals at 34 and 69 GBaud baud rate. This enhanced performance of G.654.E over G.652.D fibres is in good accordance with the theoretical prediction of signal RIN dependency on fibre chromatic dispersion. Hence, one can say that despite the presence of higher order modes in the G.654.E fibre due to pump operation at 1455 nm, which is well below

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its cable cut-off, the impact of pump to signal RIN transfer is limited by its pump signal walk-off parameter. Thereby, fibre chromatic dispersion is the primary factor in determining the amount of pump RIN transfer to any given signal.

3. Single span transmission with forward pumping DRA

To investigate the performance penalty of both the fibres, single span transmission with a FW pumped DRA was performed. The FW pumping configuration was specifically chosen to investigate the worst case scenario with maximum RIN injection. The experimental setup for single span transmission can be seen from Fig. 2(a). As above, a commercial transponder (OC-1200) was used to generate PM-QPSK and PM-8QAM 1550 nm signals at 34 and 69 GBaud baud rate. The modulated signals were then amplified with a transmitter (Tx) EDFA with a fixed output power. A VOA was used to perform the launch power sweep and the input power to the FUT was monitored by a 99/1 tap. A 1455nm pump coupled with a WDM coupler was used as a FW pumped DRA to provide a fixed 18 dB gain, similar to that of the RIN measurement setup. The transmitted signal was then decoupled using a second WDM coupler to separate the pump from the modulated signal. The receiver (Rx) section comprised a VOA and Rx-EDFA to provide a fixed output power to the transponder for optimized performance. The detected signal

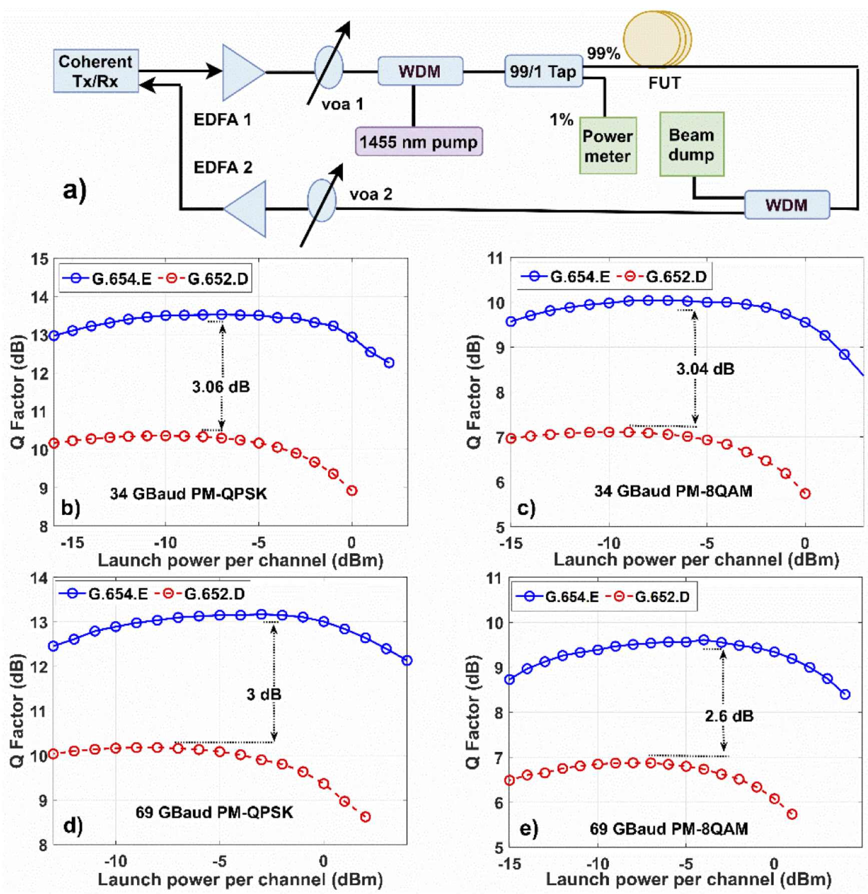

Fig. 2. a) Schematic of single-channel transmission; Q Factor versus launch power per channel for b) 34 GBaud PM-QPSK; c) 34 GBaud PM-8QAM; d) 69 GBaud PM-QPSK and e) 69 GBaud PM-8QAM

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was processed with the built in transponder DSP to calculate the resultant bit error rate (BER) and converted to its corresponding Q factor.

Figure 2(b)-(e) show the performance penalty of both test fibres with FW pumped DRA. A significant improvement of Q-factor in G.654.E over G.652.D can be observed from the above figures. A Q-factor difference of ~3 dB and ~2.6 dB was observed for PM-QPSK and PM-8QAM signals at both 34 and 69 GBaud. We attribute the superior performance of G.654.E over G.652.D primarily due to its positive CD induced lower RIN penalty. Also, the Q penalty between two different baud rates for a given modulation format was observed to < 0.5 dB for both transmission fibres. Furthermore, an additional positive shift in the optimum launch power can be seen in G.654.E due to its larger effective area (A_{eff}) in comparison to its counterpart G.652.D [5].

4. Long haul transmission with backward and bidirectional pumping DRA

The single span transmission experiment with a FW pumped DRA described above shows improved performance of the system with G.654.E fibre over G.652.D. However, attributing the performance benefits shown in Fig. 2(b)-(e) solely to reduced RIN is too simplistic since G.654.E fibre also has lower non-linear coefficient and lower fibre loss, features which also lead to Q factor improvement [5]. Nevertheless, the major contribution to performance penalty is due to RIN as it highly dominates in FW pumped DRAs and overshadows the other non-linear effects.

To segregate the RIN penalty in coherent transmission we performed a single channel, recirculating loop transmission experiment at 1550 nm with the fibres. Our two test cases included BW and BI pumping schemes, which were specifically chosen as for BW pumping the RIN penalty is negligible and the performance degradation is primarily due to nonlinear effects and fibre attenuation. However, an additional impact of RIN apart from fibre nonlinearities and attenuation should be present in the BI pumped case due to the limited usage of FW pumping. Hence, the Q factor difference between BW and BI pumping for same fibre type should give a more accurate analysis of the RIN impact on these test fibres.

Figure 3 shows the experimental setup with a recirculation loop for BW and BI pumped DRAs with G.654.E and G.652.D as test fibres. A 28 GBaud PM-QPSK signal at 1550 nm was launched using a coherent transmitter. The generated signal was then passed through a Tx-EDFA and a VOA for launch power sweep and the input power to the FUT was monitored using a 95/5 tap. The recirculating loop comprised a pair of acousto-optic modulators (AOMs) and a 3 dB coupler for signal insertion and recovery. As above, the FUT included either 93.18 km of G.652.D fibre or 98.45 km of G.654.E fibre with a span loss of 19.5 dB and 17.7 dB, respectively. The DRA stage comprised of 1455 nm laser sources configured either for BW or BI pumping. The required pump powers for the BW configuration were 436 mW and 624 mW for G.652.D and G.654.E fibres, respectively. For the BI pumping, 20% of the total BW pump power (i.e. 20% of 436 mW and 624 mW) was used as a FW pump whose values were 86 mW and 125 mW for G.652.D and G.654.E respectively, and the additionally required pump powers were provided by a BW pump to compensate the fibre and WDM losses. The fractional FW pumping percentage was chosen at 20% to enable the clearly measureable impact of RIN transfer to the modulated signal over distances of several thousand km. The amplifier section was followed by a narrow band pass filter (BPF) to filter out any additional noise. The loop section included an additional EDFA (loop EDFA) with a noise figure (NF) of 6 dB, which was used to compensate an extra 13 dB of loop losses (AOMs + BPF+ 3dB coupler loss). The receiver chain comprised a 95/5 tap whose 5% power was used to monitor the output OSNR and 95% was transmitted to the Rx-EDFA. The transmitted signals were then mixed with a 100 kHz local oscillator and the corresponding traces were captured using an 80 GSa/s, 36 GHz real time scope. The coherent detection was followed by a standard offline DSP for data recovery on the captured traces. The recovered symbols together with the transmitted symbols were then used to derive the corresponding Q factor.

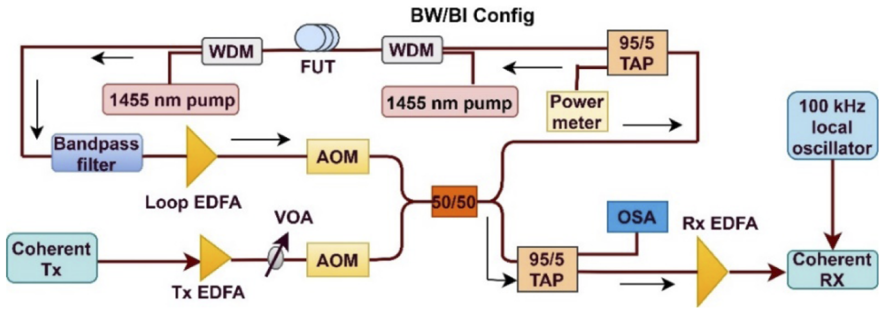

Fig. 3. Recirculation loop schematic for single-channel transmission in coherent systems.

5. Results and discussions for long haul transmission with BW and BI pumping

From Fig. 4 we can clearly see an improved performance of G.654.E over G.652.D fibre for both BW and BI pumped DRAs with 10 span and 20 span transmission. The peak to peak (PK-PK) Q factor difference for each fibre type demonstrates the performance penalty in the presence of finite RIN, i.e. for BI pumping, and negligible RIN for BW pumping only. From Fig. 4(a) and 4(b) we can see the detrimental effect of RIN accumulating in BI pumping with its effect being more significant for G.652.D than G.654.E fibre. The PK-PK Q factor difference for 10 span transmission was ~3 dB for G.652.D fibre whereas, for G.654.E it was only ~1.6 dB. Similarly for 20 span transmission the difference was ~ 4.1 dB and ~ 2.4 dB for G.652.D and G.654.E fibres, respectively. These results from Fig. 4 clearly demonstrate that the RIN penalty for G.652.D is larger than in G.654.E, and the detrimental effect of RIN accumulates, significantly degrading the signal performance with an increase in transmission distance.

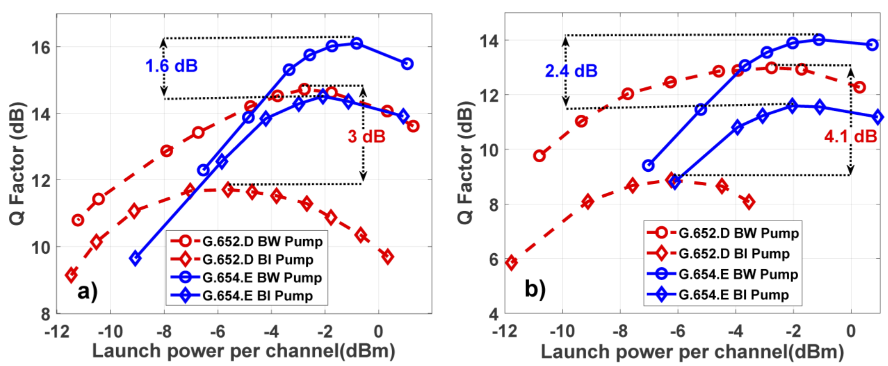

Fig. 4. Q factor vs launch power per channel with BW and BI pumping DRA for 28 GBaud PM-QPSK a) 10 span b) 20 span transmission distance.

Figure 5(a) shows the maximum achievable transmission distance assuming a HD-FEC limit of 8.5 dB. Our experimental results show G.654.E outperforming G.652.D for all test cases. The transmission reach for G.654.E was > 1000 km in comparison to G.652.D with its maximum reach extending out to ~ 6000 km for the BW pumped DRA, while for G.652.D this value is ~4900 km. Similarly, such superior performance can also be observed in the BI pumped case where G.654.E transmission distance extended up to ~3000 km in contrast to G.652.D whose maximum reach was limited to ~1800 km. The Q penalty (PK-PK difference in Q factor between BW and BI pumped Raman) in Fig. 5(b) shows a lower value for G.654.E with a maximum penalty of ~3 dB for ~3000 km transmission distance whereas for G.652.D this penalty rises to

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~4.1 dB for merely ~1800 km transmission distance. The experimental results of Fig. 5(a) and 5(b) clearly demonstrate that the RIN penalty in G.654.E is lower than G.652.D, and therefore G.654.E can perform as a better gain medium in DRA systems for terrestrial networks [10]. Figures 6(a) and 6(b) show the output optical spectra for G.652.D and G.654.E fibres after 20 span transmission with BW pumped DRA.

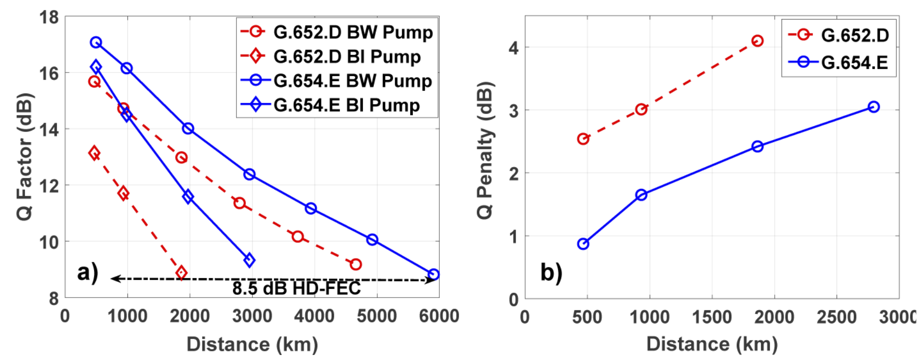

Fig. 5. BI and BW pumping for G.652.D and G.654.E a) Q Factor vs Distance b) Q penalty in BI pumping (with respect to BW pumping) vs distance.

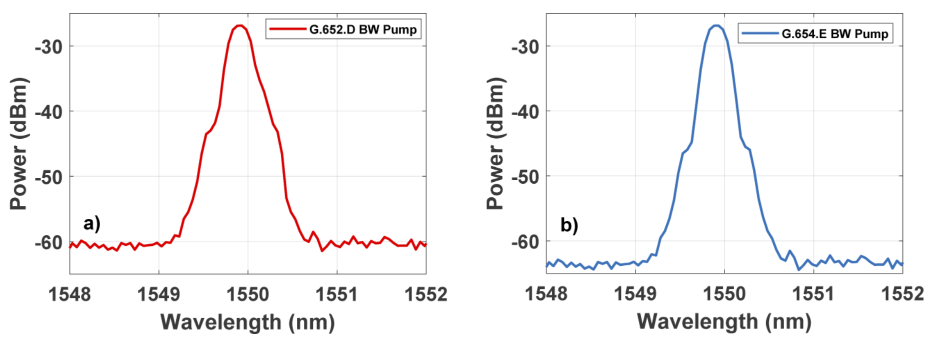

Fig. 6. Output optical spectrum of 1550 nm signal with BW pumped DRA after 20 span transmission for a) G.652.D and b) G.654.E fibre.

6. Conclusion

We experimentally evaluated the performance penalty due to RIN in G.652.D and G.654.E fibre links for FW, BW and BI pumped DRAs. The RIN at a fixed 18 dB signal gain was found to be approximately 3.5 dB and 2 dB lower for G.654.E than its counterpart G.652.D for 34 and 69 GBaud PM-QPSK and PM-8QAM signals. The lower value of signal RIN in G.654.E is primarily due to the parametric dependence of pump to signal RIN transfer on fibre chromatic dispersion. The performance penalty due to RIN was initially investigated using a FW pumped DRA with a 1550 nm modulated signal. Our transmission results with a FW pump DRA showed an enhanced single span transmission performance for G.654.E with a Q factor improvement of ~3 dB and ~2.6 dB for PM-QPSK and PM-8QAM signals at 34 and 69 GBaud baud rate. Further investigation on the RIN penalty was carried out with BW and BI pumped DRAs using a recirculating loop. For all the test cases, G.654.E exhibited superior performance in terms of maximum transmissible distance and Q penalty. The PK-PK Q factor differences with 28 GBaud PM-QPSK modulated signals for 10 and 20 spans were observed to be ~ 1.6dB and ~2.4 dB

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for G.654.E. In contrast these differences were ~3dB and ~4.1 dB for G.652.D. The maximum transmission distance assuming a HD-FEC limit of 8.5 dB with G.654.E was ~6000 km and ~3000 km whereas, for G.652.D the transmission distance was ~4900 km and ~1800 km with BW and BI pumping, respectively.

Our experimental results with all test cases clearly show that RIN induced penalty in G.654.E fibre is lower than its counterpart standard G.652.D SMF despite its cable cut-off value > 1530 nm, implying the presence of higher order modes below its cable cut-off has a negligible effect on its performance penalty. This certainly makes G.654.E a suitable candidate for DRA assisted networks for conventional C band transmission.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are available in Aston Research Explorer [17].

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