Unrepeatered PDM-QPSK transmission over 350 km standard fibre using URFL based amplification

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Abstract: Unrepeatered 115.6 Gbit/s per channel WDM PDM-QPSK transmission with novel URFL based amplification is demonstrated. Transmission of 1.4 Tb/s was possible in 350 km link and 2.2 Tb/s was achieved in 325 km without employing ROPA or speciality fibres.

OCIS codes: 060.2320, 060.1660

1. Introduction

In unrepeatered wave-division-multiplexed (WDM) links, distributed Raman amplification offers good noise performance and can be used to optimise the signal power evolution within the transmission span [1]. In particular, higher-order pumping can reduce variations of the effective gain-loss coefficient along the fibre by improving the distribution of gain within the span. A novel amplification scheme that uses fibre Bragg grating (FBG) to form an ultra-long Raman fibre laser (URFL) [3] along the transmission fibre allows to achieve 2nd cascade pumping of the signal with a single pump wavelength only. Contrary to conventional 2nd order Raman amplification, in URFL the gain profile can be modified by selecting appropriate FBGs. This can be used to realise a quasi-lossless span, approximating the optimal case for transmission performance [6].

Coherent detection offers better receivers sensitivity comparing to direct detection. It allows for multilevel modulation formats being used with comparable required OSNR per bit as in noncoherent counterparts [4]. Polarisation-division multiplexed QPSK (PDM-QPSK) transmission is a leading modulation format for 100 Gb/s optical networks [5].

In this paper we investigate the performance of the URFL based amplification with the coherent PDM-QPSK signal in an unrepeatered span up to 350 km without inline dispersion compensation, remote optically pumped amplifier (ROPA), large effective or ultra-low loss fibre.

2. Experimental set-up

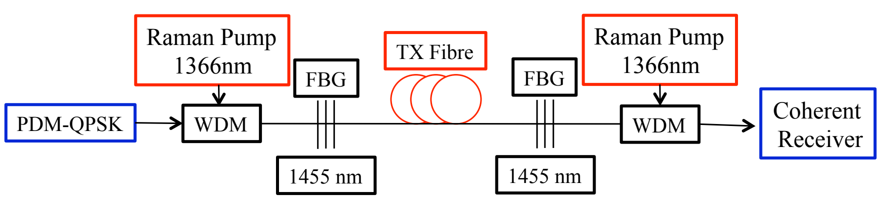

Fig. 1. Unrepeatered transmission line set-up

2.1. WDM PDM-QPSK Transmitter

Distributed feedback (DFB) lasers were wave-division multiplexed (WDM) with 100 GHz spacing using PM-AWG multiplexer. A 100 kHz linewidth tunable laser was used as the channel under test. This was combined with the DFB channels using a 3 dB polarisation maintaining coupler. The 100 GHz WDM signal was modulated by an IQ modulator driven by 28.9 Gbit/s, 2^{31}-1 word length with normal and inverted PRBS patterns from the pattern generator. The delay between two arms was set to 18 bits to give an integer number. To increase spectrum efficiency, the modulated 28.9 Gbaud QPSK signal was polarisation division multiplexed (PDM) with a 10 ns delay (equivalent to 289 bits) between two arms and resulted in 115.6 Gb/s per channel DP-QPSK signals. To compensate for the transmitter loss, WDM signals were amplified by an EDFA. The launch power into the span was monitored by the power meter and controlled by VOA.

2.2. *Transmission Line Set-up*

The transmission line setup is shown in Fig. 1. To form a distributed second cascade URFL based amplifier, highly depolarised Raman fibre laser pumps at 1366 nm combined with the signal by WDM coupler were fed into a cavity created by a matched pair of high reflectivity (95%) FBGs centred at 1455 nm with a 0.5 nm bandwidth and 0.3 dB loss which were deployed at the beginning and the end of the transmission line. The reflected Stokes-shifted light from the 1366 nm pumps created an ultra long fibre laser at the wavelength of the FBGs which in turn amplified the light in C-band region.

One of the main impairments in bi-directionally distributed Raman amplifiers is relative intensity noise (RIN) transfer from the forward pump. This can add 0.1 dBQ penalty for a pump RIN of -110 dB/Hz [2]. In a single unrepeatered span the RIN penalties in URFL configuration will be relatively low as the measured RIN of the bi-directionally oscillating lasing at 1455 nm was below -120 dB/Hz for all frequencies (Fig. 2 b).

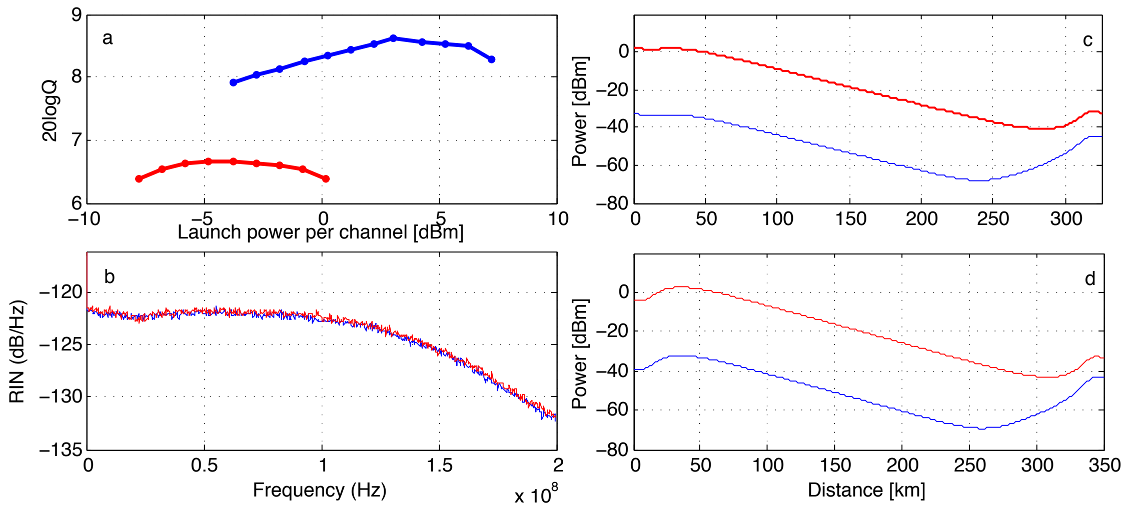

Fig. 2. a) The optimum launch power per channel versus Q value in 325 km (blue) and 350 km (red) link. b) The RIN of the lasing at 1455 nm in 325 km (blue) and 350 km (red) link. c) Signal and noise power distribution in the 325 km and d) 350 km links.

The transmission fibre used in the experiment was standard Sterlite OH-LITE®(E) Single Mode Optical Fibre with 0.19 dB/km loss. The measured loss in 325 km and 350 km span was 65 dB and 69 dB respectively.

The received OSNR is related to the forward pump power which decreases the effective gain in the beginning of the span. The on-off gain can be altered by varying the power of the backward pump. The optimised forward and backward pump powers used for the multichannel transmission experiments (measured after WDM coupler) were 31.22 dBm and 32.1 dBm in 325 km link and 31.96 dBm and 32.23 dBm in 350 km link respectively.

2.3. *Receiver and DSP*

The received WDM signal was demultiplexed using a tunable filter with 0.4 nm bandwidth and combined with a 100 kHz linewidth local oscillator (LO) laser in a polarisation-diverse 90 degree optical hybrid. Detected polarisation multiplexed I and Q signals were captured with a real-time oscilloscope with 80 GS/s and 36 GHz bandwidth. The sampled traces were processed offline using digital signal processing (DSP). Bit error rates were obtained from bit-wise error counting after averaging over 1 million samples.

3. Transmission Results

The optimum launch power per channel for 325 km and 350 km link (measured at the central and the edge channels of the grid (Fig. 3)) was found to be 2.78 dBm and -4.7 dBm respectively. This is strictly dependent on the forward pump power which was set to a minimum for the 325 km link allowing higher input power. In the 350 km span, the received OSNR was the main consideration in the pump power optimisation process: high forward pumping limited the maximum launch power. Lower input power in URFL amplification will also increase the on-off gain noticeably [9].

The power evolution of the signal and noise of the central channels in 325 km and 350 km links was simulated numerically [3] at the optimum launch power per channel and is shown in Fig. 3. The peak-to-peak signal power excursion was only 43.5 dB in 325 km and 45.7 dB in 350 km span comparing with the losses of 65 db and 69 dB respectively.

The transmitted and received spectra of WDM grid in 325 km and 350 km unrepeatered transmission is shown in Fig. 3. There was no gain flattening filter or channel pre-emphasis in the transmission setup. The penalty in the gain flatness variation of the spectra at the receiver end was less than 1 db, which is very low taking into account that only single wavelength 'raw' pumps were used. This could be further optimised with appropriate pump powers and/or additional FBGs. The received OSNR was measured for each channel. To keep the channel count fixed, an additional signal was added at the lower wavelength of the grid while the measured channel was switched off in order to measure the noise floor. The experimental BER measurement results for all channels are shown in Fig. 3. Error free transmission for all 22 $\times$ 115.6 Gbit/s was achieved in 325 km with 7% hard decision FEC 3.8 $\times$ 10^{-3}. Due to low received OSNR in 350 km link it was not possible to receive all 14 $\times$ 115.6 Gbit/s channels error free therefore soft decision FEC with 1.9 $\times$ 10^{-2} limit was used.

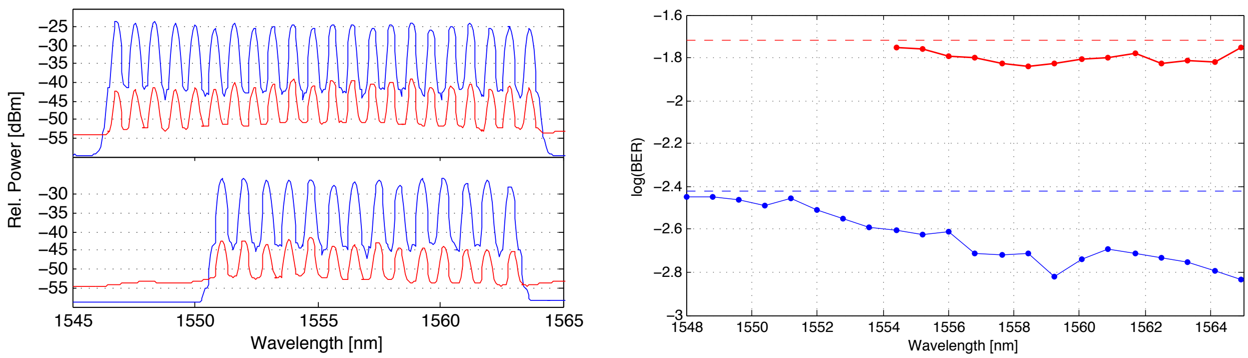

Fig. 3. Left: The transmitted (blue) and received (red) WDM spectra in 325 km (top) and 350 km (bottom) links. Right: Experimental BER measurement results in 325 km (blue) and 350 km (red) link. Dashed lines indicates hard- (3.8E-3) and soft- (1.9E-2) decision FEC limit

4. Conclusion

The transmission of 2.2 Tb/s in an unrepeatered 325 km and 1.4 Tb/s in 350 km have been simulated and experimentally demonstrated. To the best of our knowledge, this is the highest capacity achieved in an unrepeatered link at this distance without employing ROPA, inline dispersion modules or specialty fibres. URFL based amplification was also demonstrated in ASK and DPSK transmissions with direct detection using standard SMF-28 fibre in [8, 9].

The results confirm that URFL based amplification with only a single pump wavelength is compatible with both, direct detection and advanced coherent modulation formats. Such a configuration could be used to upgrade existing installed links.

5. Acknowledgement

This work was funded by UK EPSRC Programme Grant UNLOC EP/J017582/1.

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