Unrepeatered DP-QPSK transmission over 352.8 km SMF using random DFB fibre laser amplification

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***Abstract*—Unrepeatered 100 Gbit/s per channel WDM DP-QPSK transmission with random DFB fibre laser based Raman amplification using fibre Bragg grating is demonstrated. Transmission of 1.4 Tb/s (14 × 100 Gbit/s) was possible in 352.8 km link and 2.2 Tb/s (22 × 100 Gbit/s) was achieved in 327.6 km without employing ROPA or speciality fibres.**

***Index Terms*—Distributed Raman amplification, coherent detection, unrepeatered transmission, random DFB fibre laser.**

I. 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 [2], [3] resulting in minimisation of the amplified spontaneous emission (ASE) noise [4] and better performance [5].

An amplification scheme that uses fibre Bragg gratings (FBG) to form random distributed feedback (DFB) laser [6] at the beginning and at the end of the transmission span can increase the link margin.

Coherent detection at the receiver offers 3 dB improvement in receiver's sensitivity and allows the compensation of linear impairments to an arbitrarily high degree with digital signal processing (DSP) [7]. The additional spectral efficiency enhancement with polarisation multiplexing makes dual-polarisation QPSK (DP-QPSK) a leading choice of modulation format for optical networks transmitting 100 Gb/s and above [8].

In this paper we investigate the performance of a bidirectionally-pumped second order Raman amplification with random DFB lasing and coherent DP-QPSK signal in an unrepeatered span up to 352.8 km standard single mode fibre without the need for inline dispersion compensation, remote optically pumped amplifier (ROPA), large effective area or ultra-low loss fibre.

II. Experimental set-up

A. Transmitter

The distributed feedback lasers in the transmitter were wave-division multiplexed (WDM) with 100 GHz spacing using PM-AWG multiplexer. The WDM grid was combined with a 100 kHz linewidth tunable laser using a 3 dB polarisation maintaining coupler, which was used as a channel under test. The 100 GHz spaced 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 (with 18 bits relative delay) from the pattern generator. To increase spectral efficiency, the modulated 28.9 Gbaud QPSK signals were polarisation division multiplexed (DP) with a 10 ns delay (equivalent to 289 bits) between two arms to create 115.6 Gb/s per channel DP-QPSK signals, accounting for the 15% overhead of the Soft-Decision Forward Error Correction (SD-FEC). To compensate for the transmitter loss, WDM signals were amplified by an EDFA. The launched power into the span was monitored by the power meter and controlled by a VOA.

B. Transmission Line Set-up

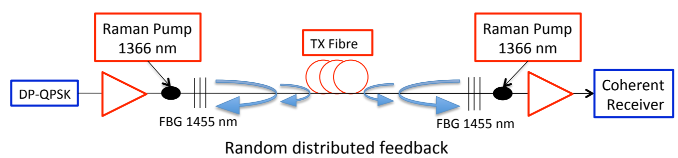

Fig. 1. Unrepeatered transmission line set-up.

The experimental setup of the transmission line is shown in Fig. 1. To form a distributed second-order Raman amplifier with a random DFB fibre laser acting as a first-order pump, highly depolarised Raman fibre laser pumps at 1366 nm combined with the signal by WDM coupler were fed into the transmission span. High reflectivity (95%) FBGs centred at 1455 nm with a 0.5 nm bandwidth were deployed at the beginning and the end of the transmission line to reflect backscattered Rayleigh Stokes-shifted light from the 1366 nm pumps. The wavelength of the FBGs was chosen to be the same in order to provide homogenous gain bandwidth at both ends of the span. Note that although the amplifier configuration is itself similar to that of an ultralong cavity laser, due to the span length, two independent random DFB fibre laser based Raman amplifiers are formed at the beginning and at the end of the transmission fibre [6].

One of the main impairments in bidirectionally-pumped 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 [9], [10]. In a single unrepeatered span the RIN penalties will be relatively low as

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the measured RIN of the lasing at 1455 nm at the beginning and at the end of the transmission span was below -120 dB/Hz for all frequencies starting at 332 kHz (Fig. 2). Simulations in reference [11] show that the RIN transfer in random distributed feedback fiber lasers below 332 kHz will have relatively similar values to those observed at frequencies where our experimental RIN measurement started.

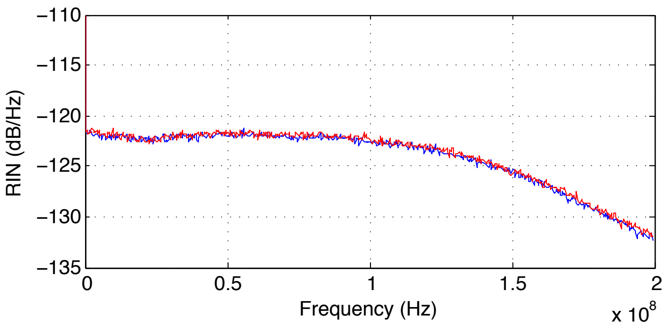

Fig. 2. The RIN measurements of the lasing at 1455 nm in 327.6 km (blue) and 352.8 km (red) link. The starting frequency was 332 kHz.

The transmission fibre used in the experiment was standard Sterlite OH-LITE®(E) Single Mode Optical Fibre with approximately 0.19 dB/km loss [12]. The measured loss in 327.6 km (13 $\times$ 25.2 km) and 352.8 km (14 $\times$ 25.2 km) link including splices was 64 dB and 68.6 dB, respectively. The loss from forward and backward WDM was 0.6 dB and 0.8 dB, respectively.

In random DFB fibre laser based amplification the received OSNR is related to the forward pump power, which decreases effective loss at the beginning of the span. On-off gain can be altered by varying the power of the backward pump [13]. To illustrate the variation of received OSNR as a function of a forward pump power for a single channel with a launch power of 6 dBm, backward pump was fixed at 31.37 dBm and forward pump increased from 28.4 dBm to 30.88 dBm (Fig. 3 (blue)). On-off gain variation is shown with forward pump switched off and backward pump increased from 30.3 dBm to 32.1 dBm (Fig. 3 (black)). In both experiments the measurements were done with approximately 0.3 dB step. The span length was 327.6 km.

In the multichannel 327.6 km and 352.8 km transmission experiments the pump powers were optimised to transmit the largest number of channels with BER that could be corrected with SD-FEC. Firstly the backward pump power was set to give enough On-Off gain so that EDFA at the receiver side could recover the WDM signal. Next, the forward pump was increased to give an acceptable OSNR at the coherent receiver and then varied together with total launch power to give the best BER. The optimised pump powers used in the transmission experiments (measured after WDM coupler) are shown in Table. I.

C. Receiver and DSP

The received WDM signal was demultiplexed using a tunable filter with 0.4 nm bandwidth and combined with a

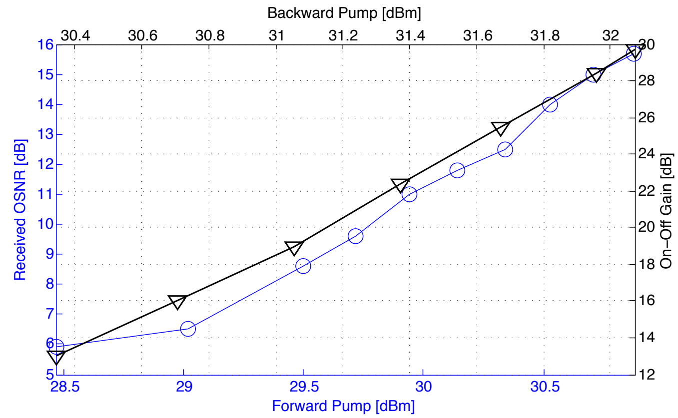

Fig. 3. Received OSNR/0.1nm as a function of forward pump (bottom-left axis, circles) and on-off gain as a function of backward pump (top-right axis, triangles) in 327.6 km link.

TABLE I
UNREPEATERED SPAN PUMP POWERS

Distance [km]	Forward [dBm]	Backward [dBm]
327.6	31.22	32.1
352.8	31.96	32.23

100 kHz linewidth local oscillator (LO) laser in a polarisation-diverse 90 degree optical hybrid. Polarisation multiplexed in-phase (I) and quadrature (Q) signals were recovered using four high-speed photodiodes and captured with a real-time oscilloscope with 80 GSample/s sampling rate and 36 GHz bandwidth. The sampled traces were processed offline using digital signal processing (DSP) with channel correction and equalisation, resampling, static chromatic dispersion compensation [14], clock recovery, constant modulus algorithm (CMA), frequency offset correction and phase recovery [15], [16]. Bit error rates were obtained from bit-wise error counting after averaging over 1 million samples.

III. Transmission Results

The optimum launch power per channel in 327.6 km and 352.8 km link (measured (solid) and simulated (dashed) for the pump powers as in Table I) was found to be 3.07 dBm and -3.76 dBm, respectively. To allow higher signal launch power in the 327.6 km link the forward pump power was lowered. In the 352.8 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 random DFB laser based amplification will also increase the on-off gain noticeably [13]. The launch power sweep for a central channel in each link is shown in the Fig. 4.

The simulation of the Q value versus launch power sweep (Fig. 4) and BER for each channel in 352.8 km (Fig. 8) was evaluated using numerical simulation in MATLAB. For a fair comparison we keep all the system's parameters unchanged, namely the baud-rate, channel spacing, transmitter and receiver bandwidths. The laser linewidths of both transmitter laser and the LO were set to the typical value of 100 kHz. As a large

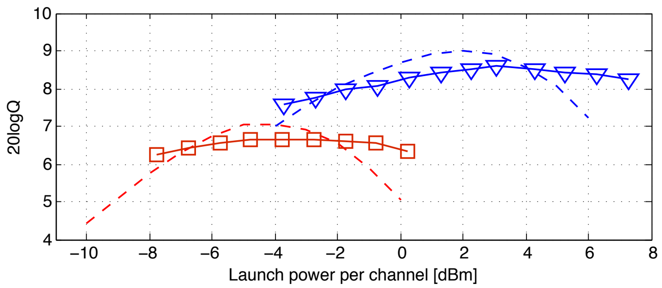

Fig. 4. Simulation (dashed) and the measurements (solid) of the Q value versus launch power per channel in 327.6 km (triangle) and 352.8 km (square) link. The Q factors were obtained from bit error rates.

number of channels were simulated, a random sequence of length 2^{16}-1 was used instead of a PRBS of length 2^{31}-1, which was adopted in the experiment.

When performing full NLSE simulations, additional noise was introduced to account for the EDFAs located at the input and the output of the transmitter section and the resulting OSNR at the transmitter was set to 20 dB/0.1 nm. ASE noise obtained from the simulated noise profile (Fig. 5) was added along the link. The propagation of signal in single span fibre was simulated using the well-known split-step Fourier method, with a step size of $\sim$1 km using the gain profile simulated for each channel as shown in Fig. 5. The Raman noise was modelled as a Gaussian noise, which was added to the signal after each step ($\sim$1 km), following the simulated noise profile. At the receiver, after coherent detection, the channel under test was filtered using a 8^{th} order Butterworth low pass filter. The DSP adopted in simulation was similar to the DSP used in the experiment, which has been described above.

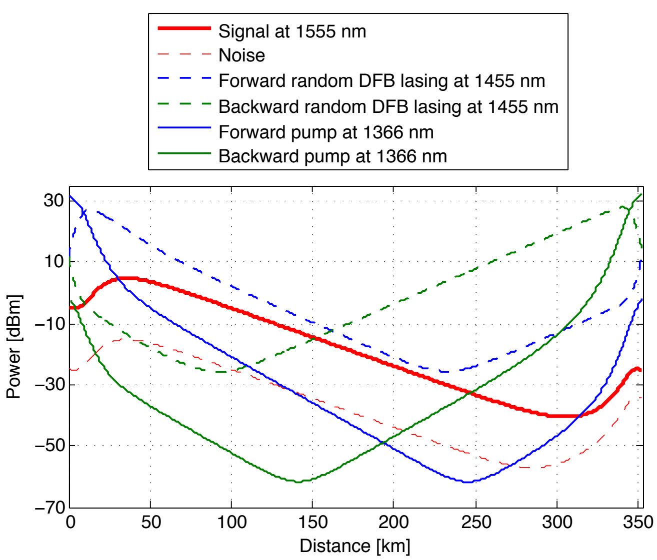

Fig. 5. Simulation of signal (solid red), noise -measured in 0.1 nm bandwidth (dashed red), forward pump (solid blue), backward pump (solid green), forward lasing (dashed blue) and backward lasing (dashed green) power evolution in the 352.8 km link.

The power evolution of the signal, noise, pumps and lasings of each channel were simulated numerically [17] at the optimum launch power per channel (Fig. 4) found experimentally during the pump powers optimisation. The simulation results for a central channel at 1557 nm in 352.8 km link are shown in Fig. 5. The peak-to-peak signal power excursion was only 45.7 dB comparing with the loss of 68.6 dB. The simulation shows that the signal is amplified at the beginning and the end of the fibre by two independently generated random DFB lasers.

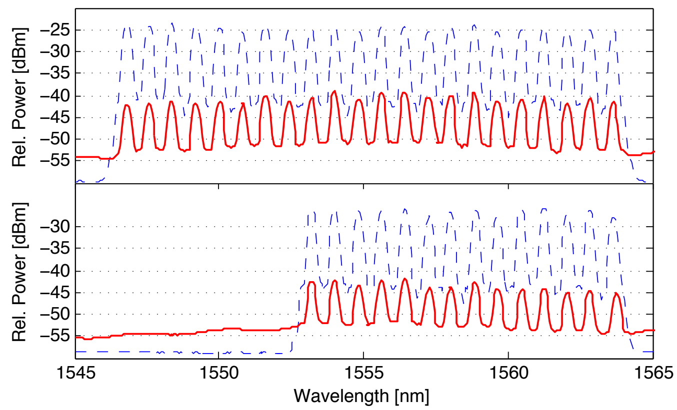

Fig. 6. The transmitted (dashed) and received (solid) WDM spectra in 327.6 km (top) and 352.8 km (bottom) links measured with OSA in 0.1 nm resolution bandwidth.

The transmitted and received spectra of the WDM grid in 327.6 km and 352.8 km unrepeated transmission measured with OSA in 0.1 nm resolution bandwidth is shown in Fig. 6. There was no gain flattening filter or channel pre-emphasis in the transmission setup. The variation in the gain flatness measured at the receiver end (taking into account the initially transmitted WDM spectra, which were not fully optimised in terms of gain flatness) was less than 1 dB in both, the 327.6 km (17 nm bandwidth) and 352.8 km (11 nm bandwidth) transmission experiments. This 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 at different wavelengths [18].

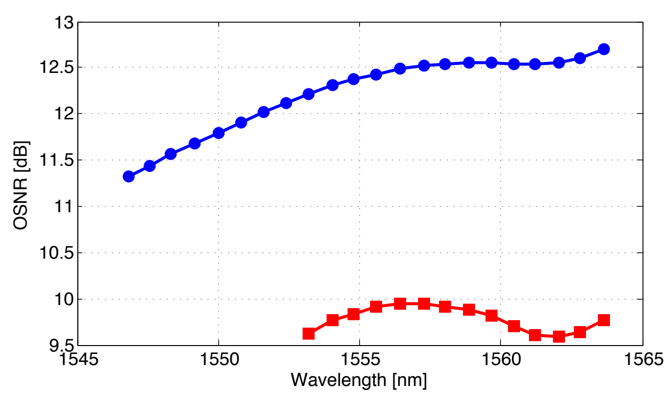

Fig. 7. The simulated results of received OSNR in 327.6 km (blue circles) and 352.8 km (red squares) links measured in 0.1 nm resolution bandwidth.

The power distribution of each WDM channel was simulated numerically using the optimised pump (Table I) and launch powers (Fig. 4). The simulated results of received OSNR, obtained for an unpolarised, CW seed signal, and without a polarisation filter (i.e. integrating the total noise in both polarisations) are plotted in Fig. 7. The actual OSNR in the receiver for each polarisation-multiplexed channel will be nearly 3 dB higher.

The experimental BER measurement results for all channels are shown in Fig. 8. The 100 Gbit/s transmission was achieved for all 22 channels in 327.6 km and 14 channels in 352.8 km link using soft decision FEC with 15% overhead (1.9 × 10^{-2}). In order to confirm the maximum unrepeatered distance that could be achieved with proposed amplification method in standard single mode fibre, we simulated the transmission for each WDM channel in 352.8 km link (Fig. 8, dashed red). The simulations agree with our experimental results.

We can notice a large BER overhead in the 327.6 km link that would certainly allow for the transmission of additional channels, however, due to limited resources the maximum number of channels we could transmit was 22. Alternatively, 7% hard decision FEC (3.8 × 10^{-3}) could be applied, which would result in a higher bit rate per channel.

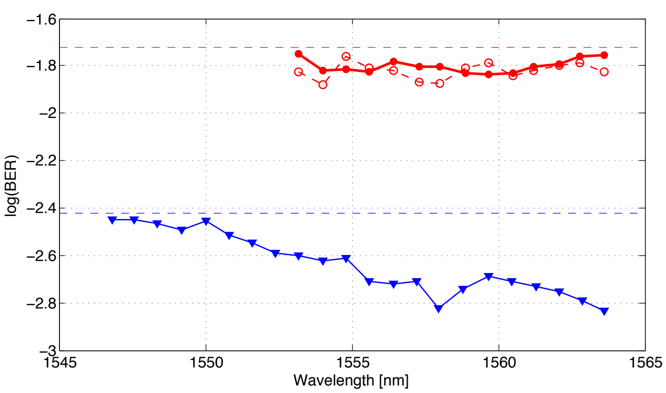

Fig. 8. Experimental BER results in 327.6 km (triangle) and experimental (solid) and simulated (dashed) in 352.8 km (circle) link. Horizontal dashed lines indicates hard- (3.8 × 10^{-3}) and soft- (1.9 × 10^{-2}) decision FEC limit.

IV. Conclusion

Transmission of 2.2 Tb/s in an unrepeatered 327.6 km and 1.4 Tb/s in 352.8 km has been 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. In [19] authors showed 342.7 km of an unrepeatered SMF transmission but with lower capacity. The record high capacity of 15 Tb/s unrepeatered transmission was presented in [20] and 4 Tb/s in [21], however, in both papers the total link attenuation was lower than in our case.

Random DFB fibre laser based Raman amplification with a single pump wavelength is compatible with both direct detection [13], [22] and advanced coherent modulation formats [23], which means that our proposed setup could be readily used to upgrade existing installed standard single mode fibre links.

Acknowledgment

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