Nyquist-WDM PDM-QPSK Transmission over SMF-28 Fibre Using URFL Amplification

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ABSTRACT

Nyquist-WDM PDM-QPSK transmission over standard SMF-28 fibre with novel distributed URFL amplification is reported for the first time. Transmission over 6157 km in a recirculating loop, and 320 km in an unrepeatered link without a ROPA were demonstrated.

Keywords: Nyquist PDM-QPSK, ultra-long Raman fibre laser (URFL), unrepeatered transmission

1. INTRODUCTION

In long-haul and unrepeatered links, distributed Raman amplification offers good noise performance and can be used to optimise the signal power evolution within the transmission span. In particular, higher-order pumping can reduce variations of the effective gain-loss coefficient along the span.

A novel amplification scheme that uses fibre Bragg grating (FBG) to form an ultra-long Raman fibre laser (URFL) [1] along the transmission fibre allows to achieve 2nd order 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 [2]. This can be used to realise a quasi-lossless span, approximating the optimal case for transmission performance [3]. Nyquist wavelength-division multiplexing (N-WDM) maximises spectral efficiency (SE) through the use of optimal pulse shaping, allowing WDM channel spacing at, or close to, the baud rate [4].

In this paper, we investigate, for the first time, the combined use of advanced N-WDM signaling and URFL based amplification. The transmission performance of 9 x 10 Gb/s N-WDM polarization division multiplexed (PDM)-QPSK channels with a SE of 3.73 b/s/Hz over 6157 km of standard SMF-28 fibre is experimentally assessed in a recirculating loop and record 320 km in an unrepeatered span without inline dispersion compensation, remote optically pumped amplifier (ROPA), large effective or ultra-low loss fibre.

2. EXPERIMENTAL SET-UP

2.1 Nyquist WDM Transmitter

The experimental set-up of the 10 Gbaud N-WDM PDM-QPSK transmitter is shown in Fig. 1(a). An ECL with a linewidth of 10 kHz is used at the input to an optical comb generator (OCG). The OCG uses two cascaded intensity modulators (one driven at 21.4 GHz) and a phase modulator to generate 9 channels with a spacing of 10.7 GHz. The nine lines from the comb generator are separated using cascaded interleavers to allow odd and even channels to be modulated separately. The electrical driving signals for IQ-modulators were generated offline in MATLAB, quantized to 6 bits for Micram VEGA DACII DACs and uploaded to Xilinx Virtex 5 FPGA-RAMs. Nyquist pulse shaping (root raised cosine (RRC) filters with a roll-off factor of 0.01), and a pre-emphasis filter to compensate the frequency response of the DACs were applied to four 2^{15} de Bruijin sequences de-correlated by 0.25 of the pattern length in the digital signal processing (DSP). Additionally, anti-imaging filters and RF-amplifiers were used before the modulators.

After odd and even channels were separately modulated by the IQ-modulators, the two sets of channels were amplified and combined with a 3 dB optical coupler to form the 9-channel 10 GBaud N-QPSK signal with

10.7 GHz channel spacing. PDM was emulated to double the spectral efficiency. At this stage, one of the arms is delayed by 18 ns using additional fibre and the other one with a variable optical delay line.

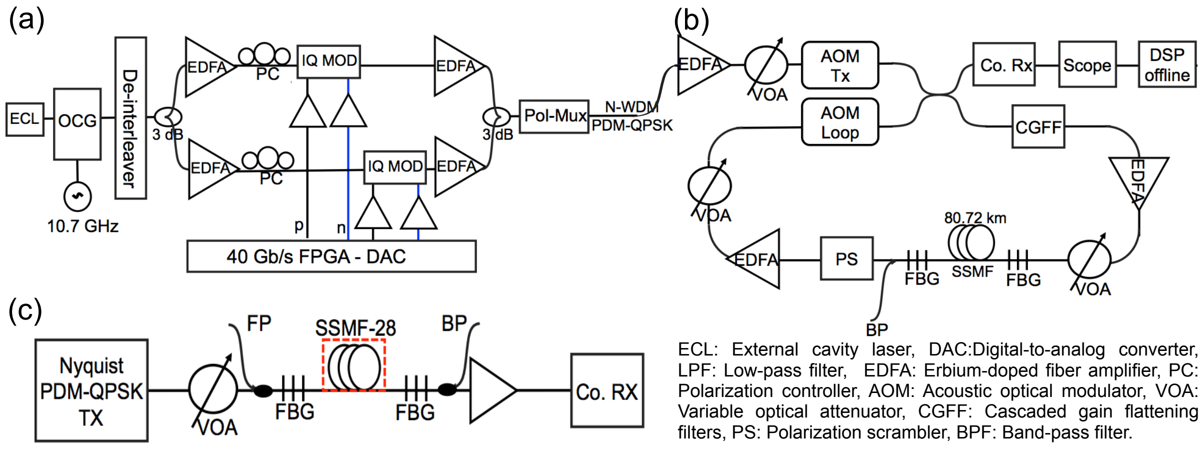

Figure 1. (a) Transmitter, (b) Recirculating loop, and (c) Unrepeatered span

2.2 Transmission Line Set-up

A recirculating loop with a single 82.1 km span of SMF-28 fibre was used to investigate the transmission performance over long-haul distances, as shown in Fig. 1(b). To reject out of band ASE, 5 cascaded asymmetric MZM filters were included in the loop. Furthermore, SMF-28 fibre span lengths of 240 km, 280 km and 320 km were tested in single-span unrepeatered transmission. For both long-haul and single-span unrepeatered transmission, an URFL based amplification technique was used [1]. FBGs with a reflectivity of 95% and a bandwidth of 0.5 nm centred at 1457 nm were included at each end of the transmission span to reflect the Stokes shifted light generated by the primary 1366 nm pump. The insertion loss of 1366/1550 nm coupler and FBGs for both forward and backward directions measured at 1550 nm wavelength were 0.6 dB and 0.8 dB, respectively.

In the recirculating loop experiment, optimal performance was achieved with backward pumping only whereas bi-directional pumping was used for the unrepeatered experiment. The backward pump power was optimized at 30.4 dBm for 75 recirculations (6157 km) maintained at this level for all measurements. The powers used in co- and counter-pumps in the unrepeatered experiment were 28.5 dBm and 30.9 dBm for 240 km, 28.7 dBm and 32.3 dBm for 280 km and 31.5 dBm and 32.1 dBm for 320 km.

2.3 Receiver and DSP

In both experiments, coherent detection was utilized by employing a phase and polarization-diverse digital coherent receiver. An ECL with a linewidth of 100 kHz was used as the local oscillator. The signal was captured by using a real-time digital sampling oscilloscope (Tektronix DPO 72004) with a sampling rate of 50 GSa/s and a 16 GHz hardware bandwidth. In offline processing, DSP was applied on the acquired waveforms as follows: The signal was de-skewed, normalized and resampled to 2 samples per symbol. This was followed by digital chromatic dispersion (CD) compensation [5]. A matched filter was applied to reduce the computational complexity at the adaptive equalizer stage. An 11-tap butterfly structure FIR filter using constant modulus algorithm was used to compensate for polarization mode dispersion. For phase recovery, carrier phase estimation was performed using a 4^{th} power Viterbi and Viterbi estimator [6]. Finally, the signal was decoded by using hard decision on samples.

3. TRANSMISSION RESULTS

3.1 Long Haul Transmission

The signal power distribution along the 82.1 km span was measured with a modified optical time-domain reflectometer as plotted in Fig. 2. There was a power variation of only 4 dB over the entire length of the fibre span. The transmission performance, as a function of distance, was shown in Fig. 2 at a launch power of -10 dBm per channel (measured at the input to the FBG). The error bars indicate the range of BER values measured over 10 consecutive measurements. A transmission distance of 6157 km was achieved with BER below at the FEC limit of 3.8×10^{-3} (assuming 7% overhead). Note that the loop configuration restricted the launch power to -10 dBm, and we expect enhanced performance at the optimum fibre launch power level of -8.5 dBm.

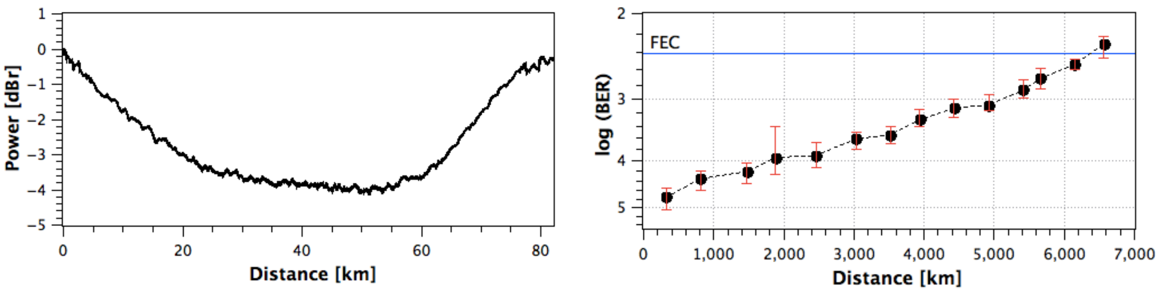

Figure 2. Measured gain profile in 82.1~km (left) and BER results (right) in long-haul transmission.

3.2 Unrepeatered Transmission

Numerical simulations of the signal power evolution for the 320 km unrepeatered link delivering a peak-to-peak signal power excursion of 40 dB (compared to a span loss of 64 dB) and an OSNR of ~9 dB for a launch power of -10 dBm/channel were presented in Fig. 3. The maximum span length in the unrepeatered transmission experiment with average BER (based on 10 consecutive measurements) below the FEC limit was 320 km as shown in Fig. 3.

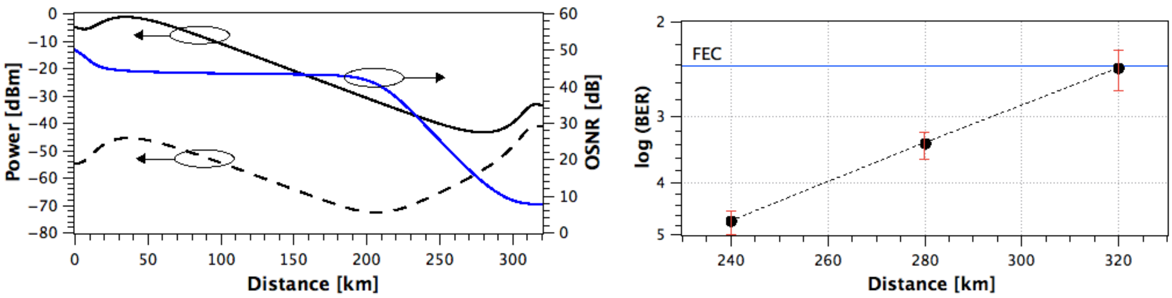

Figure 3. Simulation results for 320~km link (left) and BER results (right) in unrepeatered transmission.

4. CONCLUSIONS

The transmission of 9 channel 10.7 Gbaud N-WDM PDM-QPSK, with a SE of 3.73 b/s/Hz over 6157 km standard SMF-28 fibre using a recirculating loop and a record 320 km unrepeatered single-span have been experimentally demonstrated. To our best knowledge, this is the first time that the high spectral efficiency of N-WDM has been combined with distributed 2nd order URFL based amplification. The record distance ASK and DPSK transmissions with direct detection in unrepeatered links using URFL amplification technique with SMF-28 fibre only were obtained in [7]. The results confirm that URFL based amplification with a single pump wavelength only is compatible with both, direct detection and advanced coherent modulation formats and can be used to upgrade already existing links.

ACKNOWLEDGMENTS

The support under the UK EPSRC Programme Grant UNLOC (Unlocking the capacity of optical communications) EP/J017582/1, and EPSRC grant COSINE EP/I012702/1 is gratefully acknowledged.

EPSRC CDT in Photonic Systems, Oclaro and Huawei are thanked for studentship support for P. Rosa, M.S. Erkılınç and S. Kilmurray.

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