1200km Coherent O-band Transmission using In-line BDFAs and Standard Single-mode Fibre

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Abstract: We demonstrate a record 1200km reach O-band transmission of a 22.5GBd dual-pol QPSK signal using a recirculating loop with in-line BDFA amplification and 50km spans of standard single-mode fibre.

1. Introduction

Breakthroughs in phosphosilicate Bismuth doped fibre amplifiers (BDFAs) over the past decade [1,2] have spurred on a growing portfolio of studies and demonstrations into this technology, as investigators try not only to exploit the new opportunities for O- and E- band communication that it has unlocked, but also to discover its limitations. Starting from the first, single-span transmission demonstrations [3,4], interest has progressed through to considering advanced direct-detection modulation formats [5], coherent-detection [6] and more recently to capitalising on the wider-than-C-band bandwidth typical of BDFAs [7]. Naturally, it is important to understand the extended O-band reach now on offer, especially with continued saturation of the C-band and the rise of interest in multi-band transmission. As testament to the performance of the BDFA, in [8], O-band BDFAs were used in a recirculating loop experiment to demonstrate the (then) O-band transmission reach record of 600km, using single-side-band quadrature phase shift keying modulation (SSB-QPSK) and direct-detected with a Kramers-Kronig (KK) receiver. In that study, chromatic dispersion (CD) represented a serious limiting factor to reach, with Nyquist shaped on-off-keying achieving a reach of only 360km, prompting the adoption of the KK approach to enable CD compensation (and ultimately the 600km demonstration), albeit with compromised receiver sensitivity.

In this work, to overcome the challenges of CD without sacrificing receiver sensitivity, we adopt a coherent approach, enabling us to transmit a 22.5GBd dual-pol QPSK (90Gb/s) signal over the new record reach of 1211km of standard single-mode fibre (SMF) in a BDFA amplified recirculating loop demonstration with 50km in-loop fibre spans.

2. Experimental Setup

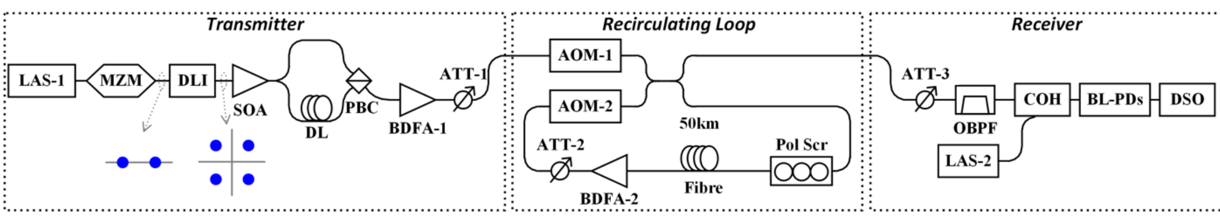

Fig. 1: Experimental setup showing the Transmitter, the Recirculating Loop and the Receiver.

Figure 1 provides a schematic of the setup used to carry out the demonstration, divided into three parts: the Transmitter, the Recirculating Loop and the Receiver. Owing to the poor availability of O-band IQ modulators, we opted to use a simple Mach-Zehnder modulator (MZM) followed by a delay line interferometer (DLI) to carry out quadrature multiplexing, as described in [9]. A 1339-nm CW laser was launched into the MZM, which was driven with a 22.5GBd, $2^{15}-1$ pseudo-random binary sequence that had been filtered with a digital root-raised-cosine filter with a roll-off of 0.25 and resampled to 90GSa/s. The resulting binary phase shift keying (BPSK) signal was launched into the DLI, so that a QPSK signal could be generated through quadrature multiplexing. After this stage, a semiconductor optical amplifier (SOA) was used to boost the signal power before it was split into two tributaries using a 3dB coupler. One of these tributaries was delayed by approximately 18 symbols before they were both recombined using a polarisation beam combiner (PBC), resulting in the fully prepared, 22.5GBd dual-pol QPSK O-band signal. A final stage of transmitter-side amplification was applied using a BDFA, after which the signal's power was regulated using an attenuator (ATT-1) before it was passed onwards to the recirculating loop subsystem. A conventional design was used for the recirculating loop, centred around a 3dB coupler, the inputs of which were connected to two acousto-optic modulators (AOM-1 and AOM-2) to control the data injection into the loop and loop timing. With reference to Fig. 1, the lower output arm of the coupler constituted the input to the loop itself. After entering the loop, the signal first passed through a polarisation scrambler (PolScr), which enabled the system to better emulate the randomly aligned (uncorrelated) polarisation dependent gain (PDG) and polarisation mode dispersion (PMD) that would be expected in a real system. After the scrambler, the signal was launched into a 50.468-km length of *Corning SMF28 Ultra* transmission fibre, which has an insertion loss of 15.2dB at a wavelength of 1339nm. After the transmission fibre, the signal was amplified using the in-loop BDFA (a detailed characterisation of which can be found in [10]). A second attenuator was used to regulate the in-loop power, after which the signal entered the second AOM, the output of which was connected to the second (lower) input of the 3dB coupler. The net loop-loss (at 1339nm) of the components constituting the loop (excluding the BDFA) was 27dB.

The receiver consists of a third attenuator to regulate power and to prevent oversaturation of the detectors. The optimum received power was found to be -5dBm and so power was limited to this value. After this attenuator, an optical bandpass filter (OBPF) with a 1.2nm 20dB bandwidth was used to reject out-of-band ASE, before the signal was passed into a dual-polarisation 90° coherent optical hybrid (COH). The outputs of this hybrid were connected to 22GHz bandwidth balanced photodiodes (BL-PDs) equipped with transimpedance amplifiers to improve sensitivity. The electrical outputs of these photodetectors were finally measured using a 40Gsa/s, 16GHz bandwidth digital storage oscilloscope (DSO) for demodulation using offline digital signal processing (DSP). The DSP itself consisted of a coarse fixed CD compensation followed by a conventional constant modulus algorithm (CMA) for residual CD and PMD compensation, Kalman filter based phase tracking and a 71-tap adaptive equaliser.

3. Results

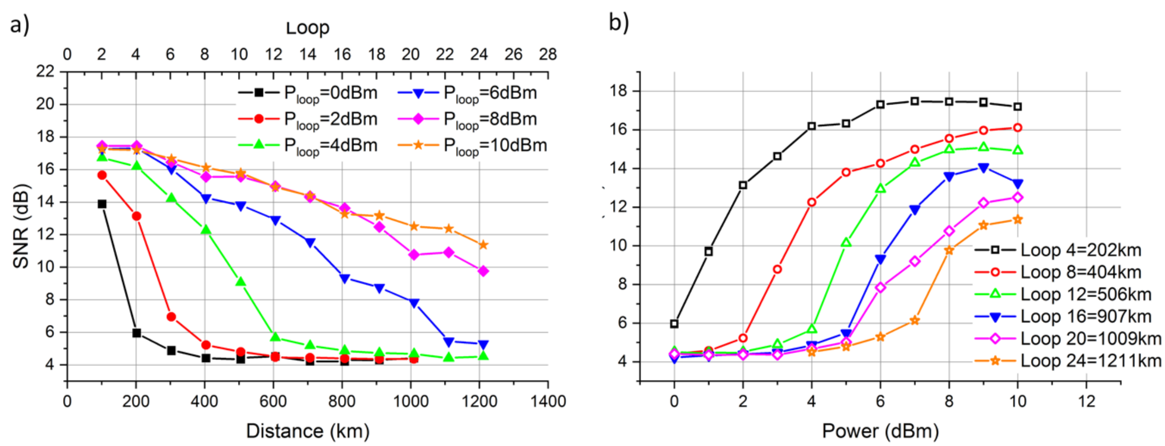

Fig. 2: a) Plot of SNR vs distance for different loop power conditions; b) Plot of SNR vs loop power at different distances.

Firstly, the impact of the launch power upon the quality of the received signal was studied. We set the power after ATT-1 and ATT-2 such that the optical power within the loop remains constant at all times, that is to say, the average power of the data entering the loop **during** the loading stage (loop 0) was equal to the total power (not just the in-band power) re-entering the loop during each subsequent round trip (30 round trips were allowed between each loading stage), with the natural implication being that net total loop gain was 0dB. Within the loop, the power was controlled immediately after the BDFA using ATT-2 to prevent excess optical power from propagating through subsequent optical elements and we define this power after ATT-2 to be P_{loop}. Given the symmetry of the system after both amplifiers, it happens that the power just after ATT-1 is approximately equal to that after ATT-2.

In order to determine the optimum operating condition of the system, we studied the impact of P_{loop} on received signal-to-noise-ratio (SNR). Fig. 2-a provides plots of received SNR as it varied with propagation distance (loop count) for a range of P_{loop} values from 0dBm to 10dBm. It is clear that increasing P_{loop} increases reach, with little evidence of nonlinearity, save perhaps for the similarity between the measurements for 8dBm and 10dBm. Fig. 2-b provides the same SNR data, but this time plotted against the loop power, for a selection of propagation distances. Again, it can be seen that the longest reach considered, 1211km, favours the highest launch power available of 10dBm (and so this was considered the optimum value of P_{loop}, to be used in all subsequent measurements). Unfortunately, higher launch powers could not be tested, owing to the gain of the in-loop BDFA, however, a comparison between the results for loop powers of 9dBm and 10dBm does imply the system is approaching its nonlinear performance limit.

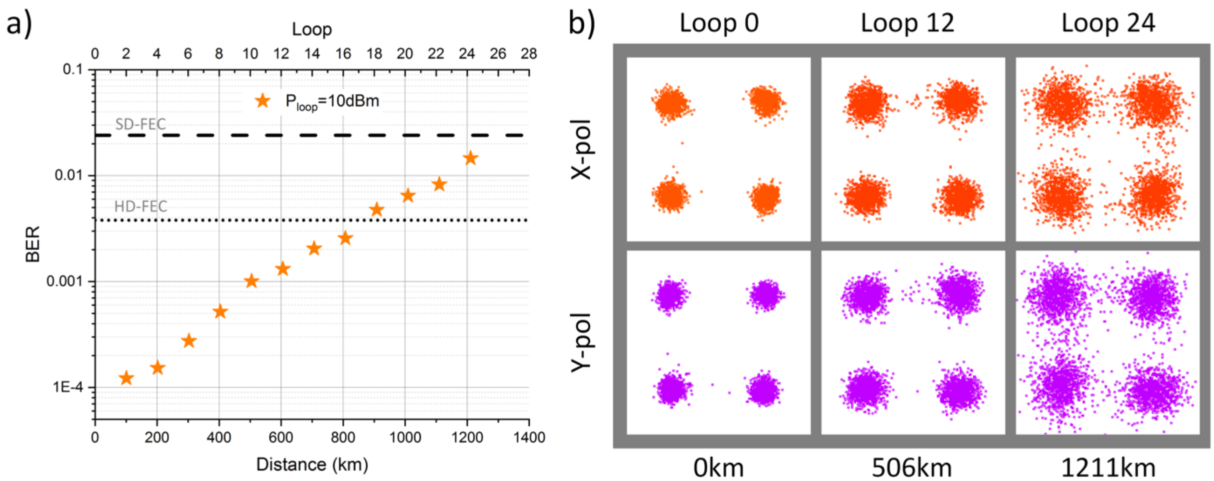

Fig. 3: For P_loop=10dBm: a) BER vs distance, b) Constellation plots for selected propagation distances.

Next, BER measurements were carried along the propagation distance of 1211km, the results of which are provided in Fig. 3-a, along with the hard-decision forward error correction (HD-FEC) limit of 3.8×10^{-3} and the soft-decision forward error correction (SD-FEC) limit of 2.4×10^{-2}. Defining the system reach as the transmission distance supporting BERs below these thresholds, it can be seen that a reach of at least 807km is achievable with HD-FEC whilst a reach of at least 1211km is expected with SD-FEC, both of which represent new record demonstrations for O-band transmission reach.

The constellation diagrams provided in Fig. 3-b for a selection of propagation distances corroborate this conclusion. A largely white-noise-like deterioration in signal quality is visible with increasing propagation distance, with no visible evidence of nonlinear degradation. A similar performance between X and Y polarisation can be seen in all cases, showing that the BDFA is capable of supporting polarisation multiplexed signals over such distances.

3. Conclusions

We demonstrate a new record O-band transmission reach record of 1211km (assuming the use of SD-FEC) by adopting intradyne coherent detection in a recirculating loop using in-line O-band BDFA amplification and transmission over 50km spans of standard SMF. The results show the potential of the BDFA to be used in moderate-haul scenarios. Moving forward, the adoption of a gain flattening filter will allow us to extend this work into a WDM scenario.

3. Acknowledgements

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