Demonstration of 3,010 km WDM Transmission in 3.83 THz Bandwidth Using SOAs

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Abstract: We transmit 5.53Tb/s over 3,010km using SOAs, ultralow-loss fibers (0.145dB/km) and a new coded modulation format with SE=1.5 b/s/Hz. C-band transmission capacity in a ~602km circulating loop testbed with 3.83THz bandwidth is confirmed with FEC. © 2020 The Author(s)

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1. Introduction

Semiconductor optical amplifiers (SOAs) are known alternatives to EDFA and Raman optical amplification for use in optical communications [1-7, 9]. Advantages include simplicity, small form factor and broadband gain. The performance of SOAs in optical transmission systems is degraded by the nonlinear behaviour of the semiconductor material with respect to the instantaneous signal power. These nonlinear characteristics and the short time constant of their gain dynamics typically limit their application to short transmission distances. Previous WDM transmission distances demonstrated in experiments are limited to 500 km [4]. This work experimentally demonstrates the possible use of SOAs in long haul systems. We show the successful transmission of WDM signals in 3.83 THz bandwidth over 3,010 km distance. The demonstrated capacity of 5.53 Tb/s is achieved using a modulation format with spectral efficiency (SE)=1.5 b/s/Hz and sensitivity of ~4.7 dB OSNR.

2. Testbed Design

The circulating loop testbed is shown in Fig. 1. The transmitter consists of two modulation sections, one dedicated to signals and one used for loading. Eight external cavity lasers (ECLs) at 33.3 GHz spacing are used as signals (4 odd and 4 even). They are modulated at 32.6 Gbaud with raised cosine spectra , β=0.001. Polarization division multiplexing (PDM) is done with a split and delay technique. The even and odd rails are delayed with respect to each other to de-correlate adjacent measurement channels. The second modulation section consisting of 115 lasers tuned to the same channel spacing provides loading over the 3.83 THz transmission bandwidth. We measure BER performance for the 6 center channels of the 8 measurement channels that substitute 8 consecutive loading channels. All 115 channels launched into the testbed carry the same modulation format and symbol rate.

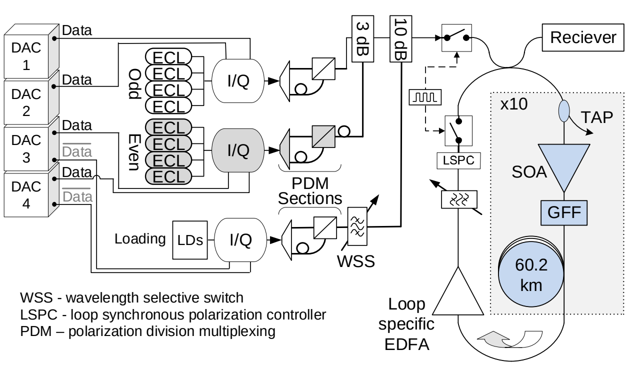

Fig.1: 60.2km ciruclating loop test bed schematic

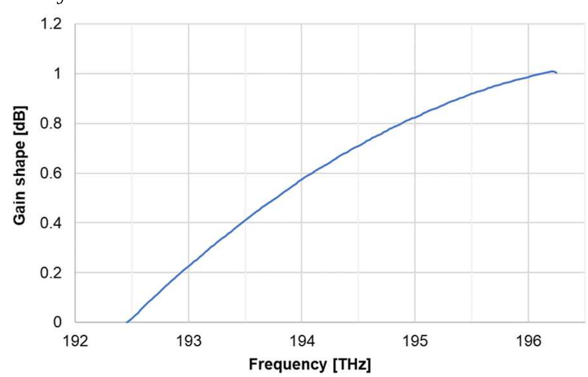

Fig.2: Average gain shape of the SOAs with 60.2km spans

The SOA circulating loop testbed includes ten 60.2 km ultra-low loss fiber spans with 0.145 dB/km loss [8] and ~152μ^2 effective area at 1550 nm wavelength (Fig. 1). Total input power to SOAs is ~1 dBm. Residual gain shape is compensated by wavelength selective switches (WSS). Circulation loop specific losses are compensated by EDFA. Loop synchronous polarization controller (LSPC) is used for more accurate representation of straight-line transmission polarization statistics. The coherent receiver is based on a 90° optical hybrid, 50 GS/s digital sampling scopes and offline processing. The average gain shape of the SOA and the 60.2 km span is shown in Fig. 2. Each SOA is followed by a gain flattening filter (GFF) equalized between 192.566 to 196.40 THz. The transmission bandwidth is chosen as a compromise between the OSNR, gain shape and nonlinear SOA penalties [9]. Nonlinear penalties increase while gain tilt magnitude and average gain decrease as input power increases. Wider bandwidth decreases the impact of nonlinearity but leads to higher equalization losses and lower power per channel. No isolators were used in the testbed except for the EDFA in the loop switch, enabled by use of a nonreflective GFF after each SOA. The average SOA gain and NF in 3.83 THz bandwidth as a function of output power is shown in Fig. 3. All SOAs operate at ~11dB gain which matches the total loss of the fiber span, tap and GFF. At this operating point gain compression is ~3dB while the NF is below 6.5dB

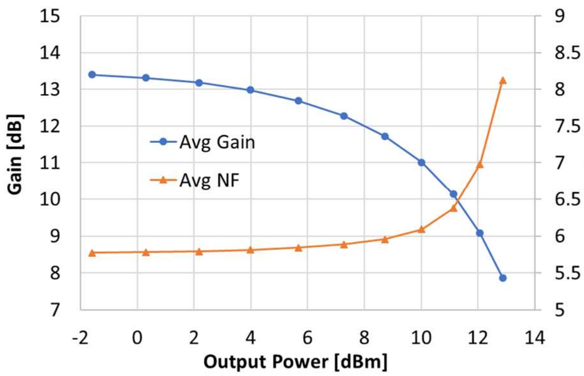

Fig. 3: Average gain and NF in 3.83THz bandwidth

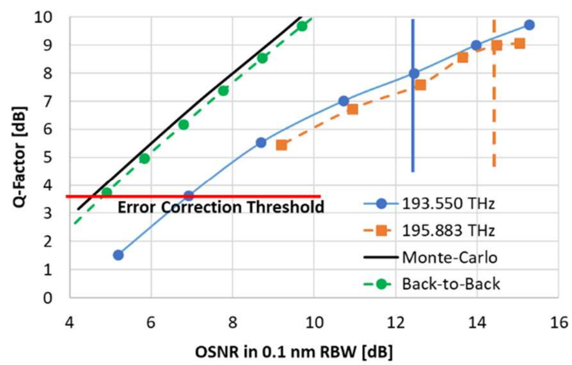

Fig. 4: Modulation format performance. Vertical lines indicate nominal OSNR for each channel

3. Modulation Format

The 8D QPSK based modulation format designed for this experiment is suitable for operation at low SNRs and provides margin against elevated transmission performance fluctuations. A genetic algorithm was used to maximize the Euclidian distance of the 16 8D symbols. The mapping was optimized with a genetic algorithm to minimize the Hamming distance between symbols with smallest Euclidian distance resulting in a reversible nonlinear inner code with a rate of 1/2. The outer FEC code is a quasi-cyclic low-density parity check (LDPC) of length 40,048, girth 8 and column weight 4 with a code rate of 0.75. Combining, the inner and outer code results in an overall code rate of 0.38 and SE of 1.5 b/s/Hz. The FEC encoding is split between the two polarizations to provide joint polarization encoding. The bits are first FEC encoded before being interleaved and encoded by the inner 1/2 code to form the final 8D symbols. Net SE after the addition of 1.67% of pilot symbols and 33.3 GHz spacing is 1.44 b/s/Hz. Iterative decoding using 5 inner LDPC iterations and 10 outer iterations between the maximum a posteriori (MAP) decoder and LDPC decoders is performed. Fig. 4 shows the transmission and noise loaded back-to-back performance of the modulation format and the theoretical curve. The OSNR implementation penalty at the FEC threshold is 0.25 dB. The error correction threshold at BER=10-15 of 3.6 dBQ is obtained from Monte Carlo simulations over an AWGN channel.

4. Results

Fig. 5 shows the results of the Q-factor and OSNR measurements after 3,010 km transmission. The performance of all channels is above the error correction threshold. We obtain Q-factors for each channel using 12 sets of measurements, each containing 4.2 million samples. All data sets are processed independently and decoded with no errors using off-line DSP and FEC algorithms and support 5.53 Tb/s capacity. OSNR in 0.1 nm resolution bandwidth measured after 3,010 km transmission is also shown in Fig. 5. Power pre-emphasis for two channels plotted against back-to-back measurements are shown in Fig. 4. Measurements are performed by changing the power of eight consecutive channels at the transmitter and reporting the performance of a center channel of the group. Nonlinear behaviour of the pre-emphasis curves is mainly related to SOA nonlinearities considering the relatively small launch power into the fiber. They also indicate that transmission performance is not limited by ASE performance of SOAs. The transmission distance is limited to 3,010 km and is impacted by performance fluctuations related to significant polarization dependent gain (PDG) of the SOAs used in this experiment. The SOA PDG is wavelength dependent with lower PDG measured for shorter wavelengths. We measure the performance of six channels in this region and show the minimum decoded Q for each channel as a function of distance in Fig 6. Smaller variations in this wavelength region allow a longer transmission distance of 4,800 km. Further illustration of PDG related impairments is shown in Fig. 7, where we plot the difference between the Q-factors of the two polarizations. The nominal difference ranges from ~1 dBQ in the short wavelength region to more than 8 dBQ at longer wavelengths. This effect contributes to the high average performance margin required for error free decoding at the transmission distance of 3,010 km (Fig. 5).

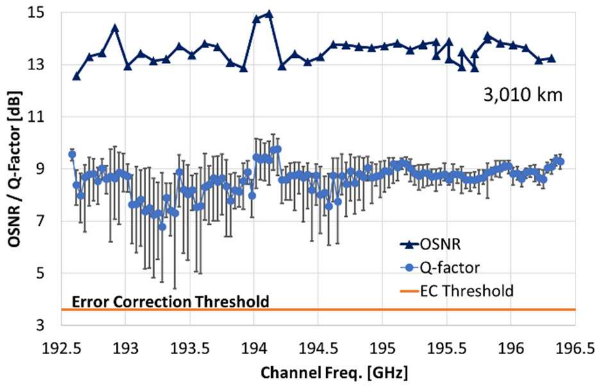

Fig 5: Performance and OSNR after 3,010 km distance

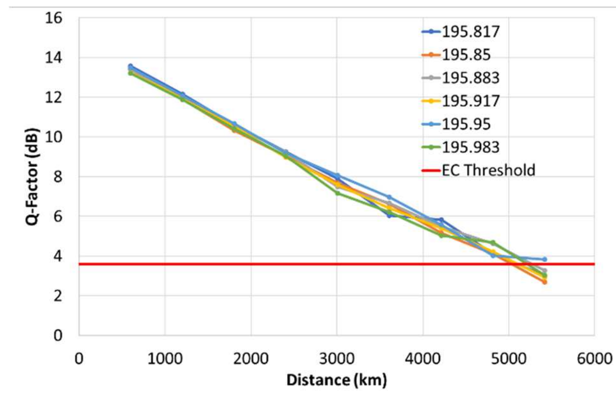

Fig 6: Performance vs. distance for six short wavelength channels

Figure 8 shows these variations as a histogram of decoded Q-values for all measurements of all 115 channels for three different distances. Mean Q decreases with distance as the size of the Q fluctuations increases, ultimately limiting the transmission distance to 3,010km.

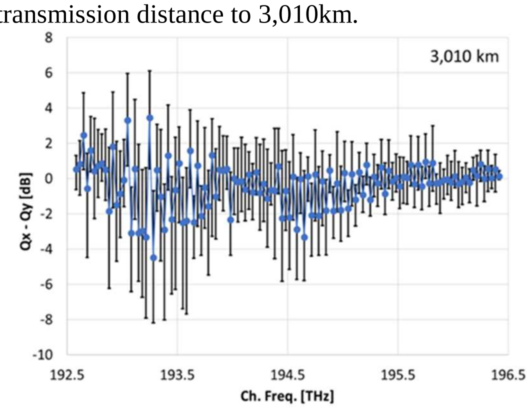

Fig 7: Average and maximum Q-factor difference

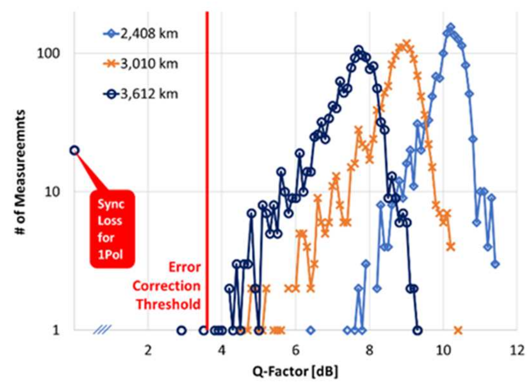

Fig. 8: Q-factor histograms

5. Conclusion

We demonstrate the first long haul WDM transmission using SOAs. We achieve 5.53 Tb/s capacity after 3,010 km using an 8D modulation format with SE=1.5 b/s/Hz designed for operation at high receiver sensitivity. All data collected for channels in the entire bandwidth is FEC decoded with no errors. Transmission performance is significantly affected by PDG of the SOA amplifiers. We also show a maximum 4,800 km transmission distance for a band of short wavelength channels. This opens a possibility of long-haul application for SOAs with improved polarization diversity characteristics.

6. Acknowledgements

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