Real-time 59.2 Tb/s Unrepeated Transmission over 201.6 km Using Ultra-wideband SOA as High Power Booster

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Abstract *We perform a 201.6 km-long unrepeated transmission using an UWB seamless SOA with a maximum output power of 24.4 dBm jointly with backward distributed Raman pumping achieving 59.2 Tb/s total throughput using real-time transponders. ©2022 The Author(s)*

Introduction

Ultra-Wideband (UWB) systems arouse recent interest thanks to their ability of approximately linearly expanding the total fiber throughput by increasing the bandwidth of Wavelength Division Multiplexing (WDM) optical transmission systems. Extending the bandwidth beyond C band becomes one of the most promising approaches to increase the total throughput[1], with a first clear next step to move to C+L transmission systems[2]. C+L systems implementation comes with several challenges[3] as Stimulated Raman Scattering (SRS), fiber Wavelength Dependent Loss (WDL), amplifier gain ripples, etc.

As potential cost-effective solutions, using a seamless amplifier in a repeaterless transmission system can significantly reduce cost and complexity while requiring wideband gain and high output power[4]–[15]. Semiconductor Optical Amplifiers (SOA) have been demonstrated to exhibit more than 100 nm (12.5 THz) continuous operation bandwidth under custom design and achieve 115 Tb/s transmission system over 100 km, which shows the feasibility of C+L band amplification using SOA technology[4].

In the context of repeaterless systems using seamless amplifiers, high throughput has been demonstrated in C+L band with offline transponders[4]–[6], while there are only records of throughput in C band with real-time transponders[9]–[15]. A net throughput of 80.2 Tb/s over a single span of 257.5 km has been demonstrated over 100 nm by using a seamless UWB SOA booster and backward Raman Amplification using offline transponders[5]. By using unique high power booster and third-order backward Raman amplification without Remote Optically Pumped Amplifier (ROPA), a real-time throughput of 30.5 Tb/s over 276.4 km long fiber has been reported using only C-band operation[9]. Over up to 420 km unrepeated transmission link, a real-time demonstration of 16 Tbit/s WDM system has been achieved by collaboration of extended C-band Erbium-Doped Fiber Amplifier (EDFA) and Distributed Raman Amplifier (DRA) with ROPA[10].

In this paper, we demonstrate a 59.2 Tb/s transmission by using real-time transponder with seamless amplification within 102 nm total optical bandwidth over an unrepeated transmission span of 201.6 km-long Pure Silica Core Fiber (PSCF). Seamless amplification is achieved here by using a single UWB SOA amplifier jointly with backward first-order Raman pumping without ROPA. Achieving a maximum output power of 24.4 dBm using our seamless UWB SOA is a critical point in order to set all channel powers near their optimal values and succeed to perform error-free transmission with the commercial real-time transponders. This demonstration is positioned among previous similar works as shown in Fig. 1, achieving one of the highest throughput using real-time transponders with a C+L-band seamless amplification in repeaterless transmission system[9]–[15].

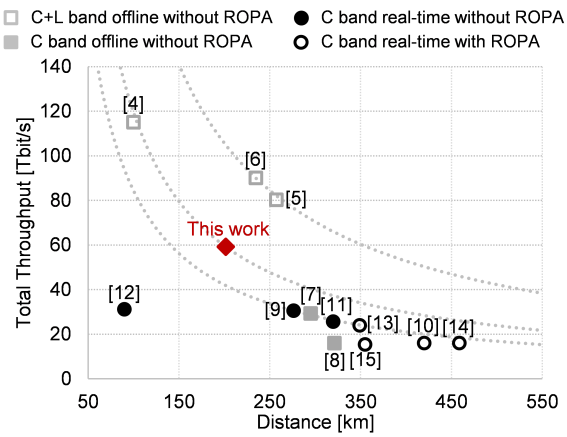

Fig. 1: Record of throughput versus distance for repeaterless transmission system with seamless amplification.

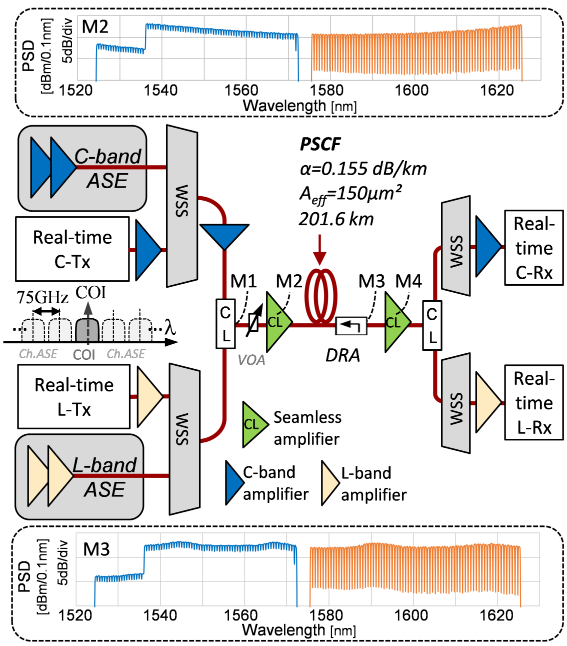

Fig. 2: Transmission system setup.

Experimental Setup

The transmission system experimental setup is shown in Fig. 2. On the transmitter side, wide Amplified Spontaneous Emission (ASE) noise sources are shaped by C- and L-band Wavelength Selective Switch (WSS) to emulate 80 and 78 ASE-shaped WDM channels in C and L band respectively, following a spacing grid of 75 GHz. The Channel Of Interest (COI) is generated either using a C- or L-band real-time transponder supporting either 200 Gb/s PDM-QPSK or 400 Gb/s PDM-16QAM modulation which is multiplexed with their respective ASE-shaped WDM channels. C and L band are multiplexed by a commercial C+L (de)multiplexer with an average loss of 1 dB and amplified by a unique UWB SOA booster with maximum total output power of 24.4 dBm at the entrance of the transmission line. The saturation output power defined as the optical output power leading to a 3 dB reduction from small-signal gain at steady state is 25 dBm for the UWB SOA booster. The total output power and output power profile of the SOA booster can be adjusted by the Variable Optical Attenuator (VOA) and WSSs.

The transmission line is a unique repeaterless span of 201.6 km long Pure Silica Core Fiber (PSCF) with 0.155 dB/km attenuation coefficient and $150\,\mu m^2$ effective area. At the end of this fiber, a DRA is used including 6 multiplexed first-order backward pumps from 1415 nm to 1515 nm by a step of 20 nm with pumps current of 1860 mA, 1100 mA, 1200 mA, 700 mA, 200 mA, 800 mA respectively and a second seamless SOA amplifier is used to compensate span loss. The average values of Raman on-off gain is approximately 8.4 dB and the extreme gain difference is less than 1.4 dB.

On the receiver side, after both C and L band being demultiplexed, COI is selected using either C- or L-band WSS, amplified and launched in real-time coherent Receiver (Rx) for Bit-Error Rate (BER) measurements, which can be converted to Signal-to-Noise Ratio (SNR). The COI are swept across all of the 158 channels with channel throughput chosen to be either 200 Gb/s or 400 Gb/s to get error-free transmission. An Optical Spectrum Analyzer (OSA) and power meter are used at each measurement point referred as M1 to M4 for power and Optical Signal-to-Noise Ratio (OSNR) measurements.

Results

As shown in Fig. 3(a), for a maximum total power of 24.4 dBm at the entrance of the transmission line, the span loss varies with wavelength due to the SRS effect and Wavelength Dependent Loss of PSCF fiber. The fiber loss is characterized by entering a low-power tunable laser source to avoid the SRS effect. Fiber splicing and connectors add 3 dB additional losses over the entire transmission line. The SRS power transfer tilt is approximately 2.8 dB and 2 dB in C and L band respectively. The SRS channel power transfer is obtained here by subtracting the fiber loss from the total span loss. The SRS effect causes the worst transmission performance of the channels located in the short wavelength region of the C band which is below the FEC limit of the real-time transponder with 400 Gb/s PDM-16QAM modulation. After determining the shortest wavelength of the channel that can operate with PDM-16QAM modulation, the power of the channels working with PDM-QPSK modulation is reduced by using WSSs to minimize the SRS effect on other channels as shown in the inset spectra of Fig. 2. The C- and L-band channel bandwidths are slightly different here due to the difference in the WSSs with different filter transfer functions.

Fig. 3(b) shows the measured OSNR in the C and L band for different total output powers of the SOA booster respectively. For a maximum total output power of 24.4 dBm, the average OSNR in 0.1 nm is 16.4 dB for PDM-QPSK modulation while it reaches up to 24.4 dB for PDM-16QAM modulation. When the total output

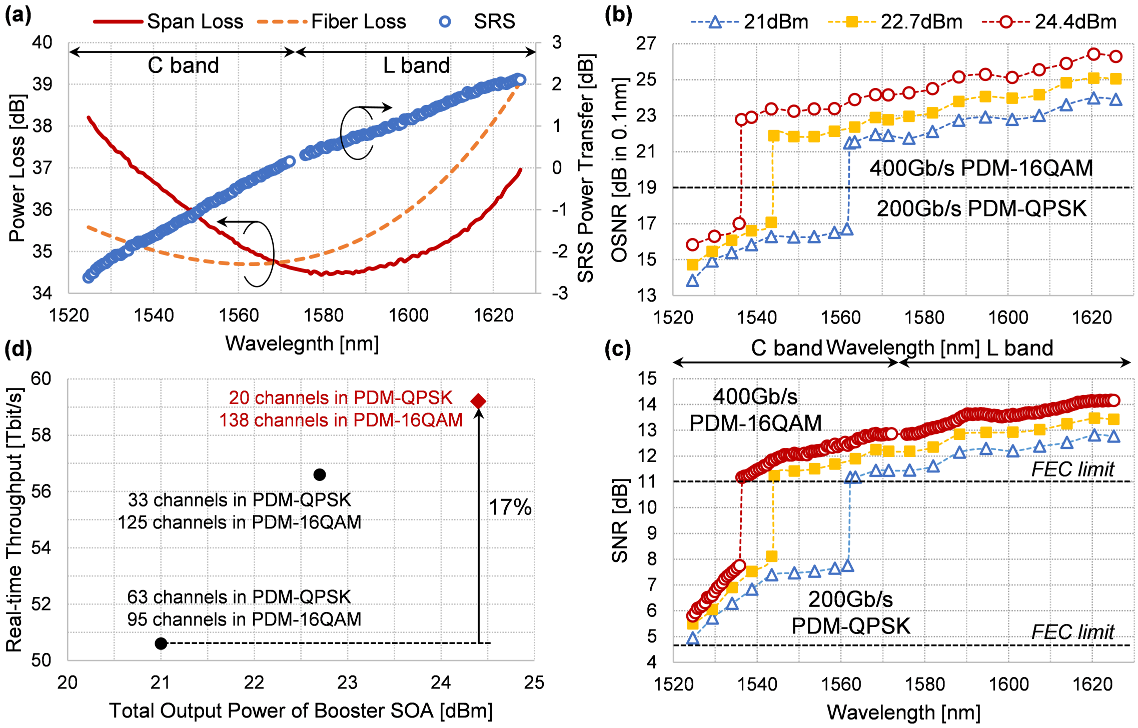

Fig. 3: C- and L-band transmission performance in terms of (a) Span loss and SRS power transfer, (b) Measured OSNR, (c) Measured SNR and (d) Real-time total throughput for the three configurations

power decreases, the OSNR will decrease, which causes the SNR of channels that operate properly with PDM-16QAM modulation to be below the FEC limit as shown in Fig. 3(c), thus more channels are required to be changed to PDM-QPSK modulation.

In the case of applying 24.4 dBm total output power of the first seamless UWB SOA booster, a maximum real-time throughput of 59.2 Tb/s is achieved and SNR are measured for all of the 158 channels as shown in Fig. 3(c). Due to the SRS effect, the transmission performance of channels at shorter wavelength are the worst ones. Comparing with the OSNR values, SNR values at shorter wavelengths in C band also indicate potential SOA nonlinear impairments. SNR values are equal to 5.8 dB to 7.8 dB for 200 Gb/s PDM-QPSK and 11.2 dB to 14.2 dB for 400 Gb/s PDM-16QAM modulation and 20 channels operate in PDM-QPSK modulation and 138 channels operate in PDM-16QAM modulation.

In order to estimate the throughput gain from the highest value of the SOA booster output power of 24.4 dBm, we also measure 2 other cases with lower output power, one at 22.7 dBm and the other at 21 dBm. In the case of 22.7 dBm output power, 33 channels should operate in PDM-QPSK modulation while in the case of 21 dBm, up to 63 channels are forced to operate using PDM-QPSK modulation. Therefore, for all of the 158 channels, when the total output power of the SOA booster increases from 21 dBm[5], 22.7 dBm to 24.4 dBm, the real-time throughput increases from 50.6 Tbit/s, 56.6 Tbit/s to 59.2 Tbit/s respectively, which is an improvement of up to $17\,\%$ as shown in Fig. 3(d).

Conclusions

We have demonstrated an unrepeated transmission system over a 201.6 km PSCF span combining a high output power seamless 102 nm wide SOA booster and a first-order backward-pumping DRA without ROPA. Thanks to a maximum total output power of 24.4 dBm, a real-time 59.2 Tb/s total throughput is achieved over 20 channels with 200 Gb/s PDM-QPSK modulation and 138 channels with 400 Gb/s PDM-16QAM modulation, which is one of the highest throughput using real-time transponders with a seamless amplification in repeaterless transmission system.

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