40.5 Tb/s, 312.9 km, Unrepeatered Transmission Using Erbium-Doped Tellurite Fiber Amplifiers

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Abstract *We demonstrate the use of wideband erbium-doped tellurite-fiber amplifiers, combined with bidirectional Raman amplification, to achieve the record unrepeatered transmission of a 60 nm, 40.5 Tb/s, WDM signal over 312.9 km without the use of a ROPA. ©2023 The Author(s)*

Introduction

Unrepeatered links are used in undersea or terrestrial connections where electrically powered inline amplification is either too costly or impossible to deploy[1]. These links can reach hundreds of kilometers[2]–[4] with throughput of tens of terabit per second[5],[6], thanks to ultra low-loss fibers and advanced amplification techniques. The latter include wideband semiconductor optical amplifiers[6]–[9] and bidirectional distributed Raman amplification (DRA)[4]–[6],[10]. Alternatively, tellurite-glass fiber amplifiers have been proposed to achieve seamless C+L band amplification[11]. In particular, erbium-doped tellurite-fiber amplifiers (EDTFAs) have been demonstrated with $>$70 nm bandwidths across C and L bands[12],[13]. These amplifiers can potentially enable fully wideband unrepeatered transmission systems without separate C and L band components or the loss of associated couplers. Furthermore, the wavelength range of the system can be more easily optimized to better suit the unrepeatered link loss. Despite these advantages, the use of EDTFAs for unrepeatered links is yet to be addressed.

Here, we investigate the use EDTFAs along with bidirectional DRA to enable unrepeatered transmission of a 60 nm signal through a 312.9 km link without remote optically pumped amplifiers (ROPAs). Apart from the DRA, we use exclusively EDTFAs in the system including signal generation, transmitter booster and receiver preamplification. This allows aligning the transmission bandwidth to the lowest link loss wavelength region, around 1576 nm. We achieve a net throughput above 40.5 Tb/s using 290 polarization multiplexed 16-ary quadrature amplitude modulation (PM-16QAM) signals at 24.5 Gbaud. This is the highest reported capacity and capacity-distance product for unrepeatered links longer than 300 km without the use of ROPAs, as shown Fig. 1. It demonstrates the potential of EDTFAs for wideband unrepeatered transmission links.

Experimental Demonstration

Fig. 2-a) shows the typical amplified spontaneous emission (ASE) power spectrum of the EDTFAs used in this work, which envelops the C band and a large part of the L band. Fig. 2-b) shows the

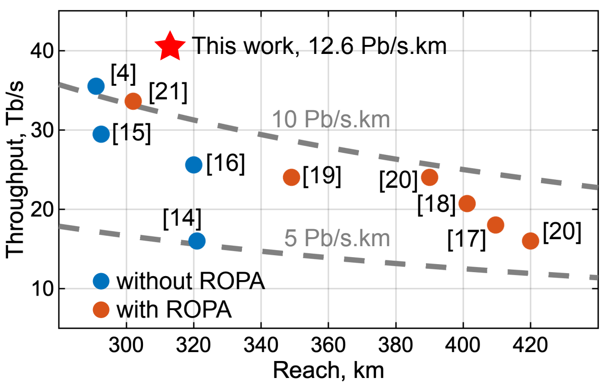

Fig. 1: Throughput and reach of recent unrepeatered transmission experiments.[4],[14]–[21]

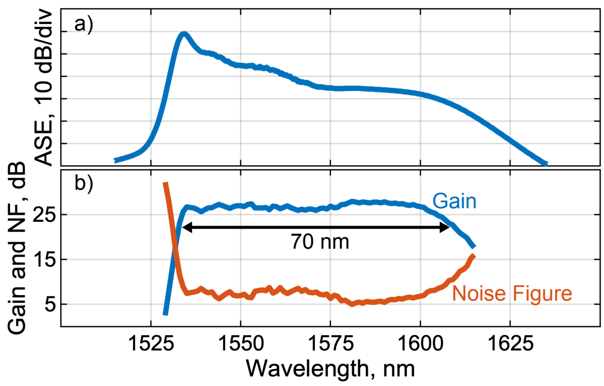

Fig. 2: Characterization of the EDTFAs. a) ASE power spectrum; (b) gain and noise figure spectra.

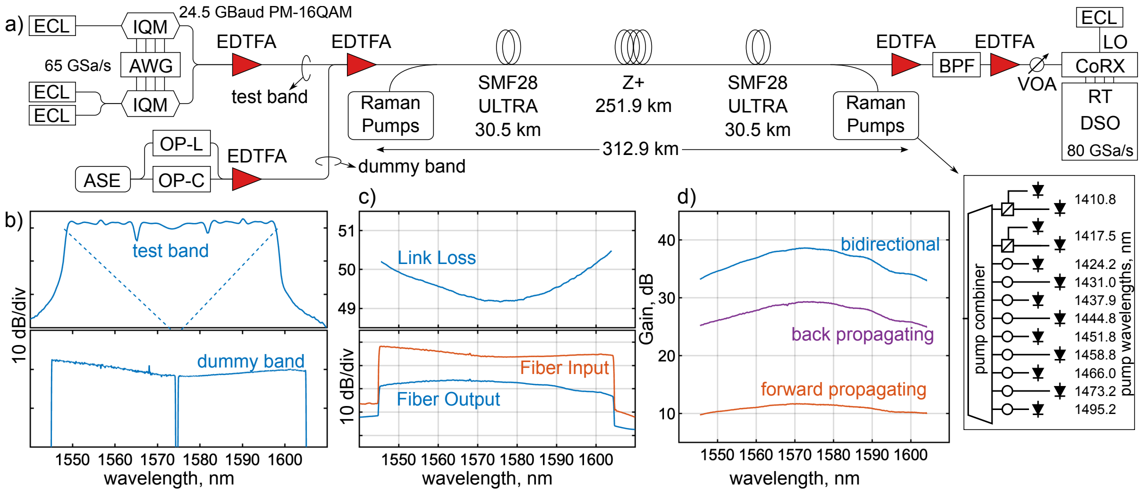

Fig. 3: Simplified diagram of the unrepeatered transmission setup (a). Power spectra of the test and dummy bands (b), the link loss and the signal power at the fiber input and output (c). Spectra of the forward, backward and bidirectional Raman gain (d).

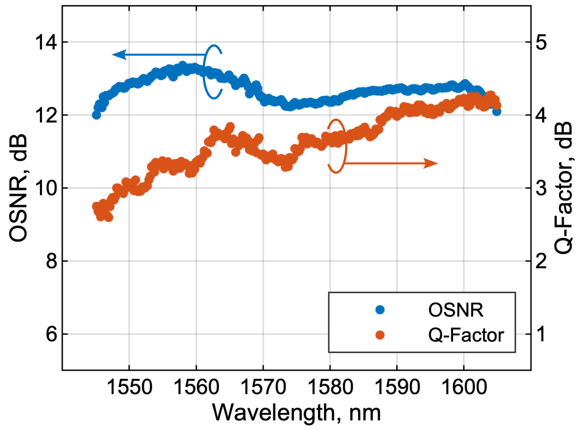

Fig. 4: OSNR measured at the fiber output and Q-Factor estimated by direct error counting.

small signal gain of this EDTFA, with a 3dB bandwidth extending from 1534 nm to 1604 nm for a total of 70 nm. Within this region, the noise figure ranges from 5 dB to 8.8 dB, as shown in Fig. 2-b).

Fig. 3-a) shows the experimental setup for unrepeatered transmission. A 3-channel sliding test band was produced by modulating the lightwaves from three 10 kHz linewidth external cavity lasers (ECLs) with 2 dual-polarization IQ modulators (IQMs) driven by a 65 GSa/s arbitrary waveform generator (AWG). One of the lightwaves was independently modulated to produce the test channel. The 2 remaining lightwaves were jointly modulated to form nearest neighbor dummy channels. The generated signals were 24.5 GBaud PM-16QAM with a root-raised cosine shape and a roll-off of 0.01. The test band was coupled with a dummy band produced by spectrally shaping ASE noise with C and L band optical processors (OPs) between 1545 nm and 1605 nm. The OPs also carved a notch to accommodate the test band, as shown in Fig. 3-b). Both dummy and test bands were amplified using EDTFAs before being coupled. A booster EDFTA launched the 60 nm signal with a power of 18 dBm.

The transmission line consisted of 312.9 km of fiber, of which the first and last 30.5 km segments were Corning SMF28 ULTRA, with an effective area of 87 μm^2. The remaining fiber was a 251.5 km Sumitomo Z+ fiber with an effective area of 150 μm^2. Fig. 3-c) compares the loss spectrum of the link, including the impact of stimulated Raman scattering, with that of the transmission band at the fiber input and output. The loss spectrum had a minimum of 49.1 dB at 1576 nm, roughly matching the center of the transmission band, intentionally placed at 1575 nm.

For distributed amplification, we used bidirectional Raman pumps with 13 pumps for each propagation direction with wavelengths between 1410.8 nm and 1495.2 nm, as shown in Fig. 3-a) and powers between 50 mW and 200 mW. The launch power spectrum was shaped using the OPs to roughly equalize the optical signal-to-noise ratio (OSNR) at the fiber output after Raman amplification, as shown in Fig. 3-c). The forward and backward propagating Raman amplification gain spectra are shown in Fig. 3-d) with maximums of 11.7 dB at 1570.5 nm and 29.3 dB at 1574.8 nm, respectively. The maximum total on/off raman gain was 38.6 dB at 1572.6 nm.

Fig 4 shows the OSNR at the fiber output. This was measured by switching off the test band and measuring the power difference between the ASE within the test band notch and the ASE adjacent to the notch. The OSNR varied between 12 dB and 13.3 dB across the spectrum.

After transmission, the signal was amplified by an EDTFA and filtered with a tunable band pass filter (BPF) to select the channel under analy-

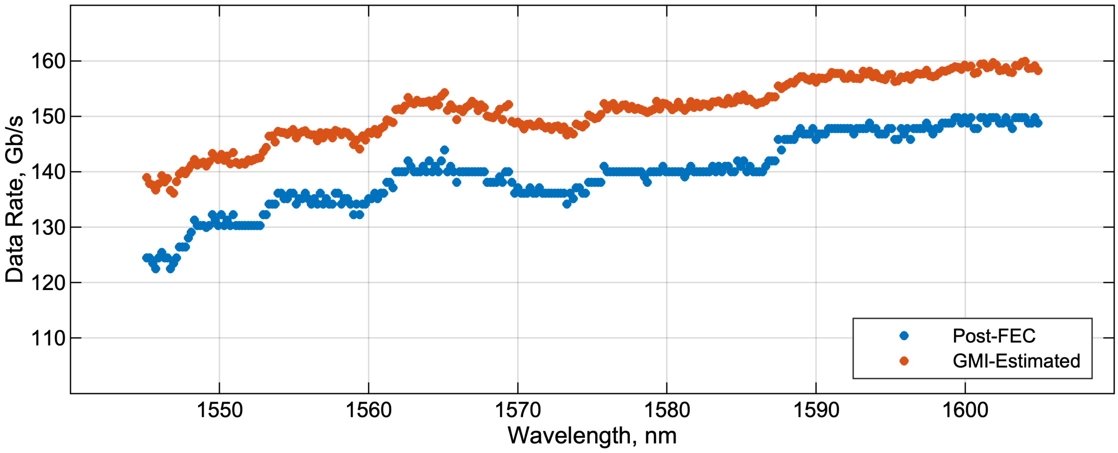

Fig. 5: Throughput estimates for each of the 290 channels after FEC decoding and using the GMI.

sis. This channel was further amplified by an EDTFA followed by a variable optical attenuator (VOA), used for power control. A coherent receiver (CoRX) was used to detect the signal, after mixing with a 60 kHz linewidth local oscillator (LO). 10 µs traces of the signal were acquired by an 80 GSa/s real-time digital sampling oscilloscope (RT-DSO) and stored for offline processing.

The digital signal processor consisted mainly of a time-domain 17-tap 2×2 multiple-input multiple output subsystem operating at 2 samples per symbol. The MIMO equalizers were initially derived using a least-mean squares data-aided algorithm, switching to decision-directed operation after convergence. Carrier recovery was performed within the equalizer loop. After recovery, we estimated the Q-factor through direct error counting, as shown in Fig. 4. It can be noted that the Q-factors did not follow the OSNR and ranged from 2.6 dB to 4.2 dB. A quick investigation revealed that this was a result of degradation introduced by the last receiver EDTFA, which had a significantly lower performance at short wavelengths for narrow band signals.

We estimated the post-FEC throughput by emulating the decoding of the processed signals using the DVB-S2 codes[22], as previously described[5]. We used code puncturing to increase the rate granularity of the original soft-decision codes to 0.01 and assumed an additional hard decision outer code[23] to correct any remaining errors. The latter had a 1% overhead and an FEC threshold of 4.5×10^{-5} minus a 10% margin. For comparison purposes, we also compute the upper bound of the reachable throughput using the generalized mutual information (GMI).

Fig. 5 shows the estimated post-FEC throughput for all 290 channels. The throughput per channel ranged between 122.5 Gb/s and 149.7 Gb/s, reaching an average spectral efficiency of 5.58 b/s/Hz. It is shown that the throughput follows roughly the same wavelength dependency as the Q-factor shown in Fig. 4. The total throughput of the system was 40.5 Tb/s. However, this value could be increased using better codes up to a theoretical bound of 43.7 Tb/s, estimated using the GMI.

Our results show the potential of the use of Tellurite fibers for amplification in wideband unrepeatered transmission systems. However, it should be noted that the amplifiers used in this experiment have been manufactured in the early 2000's and are well past their expected lifetimes. For this reason, we assume that substantial improvements on noise and gain properties may be achieved with new devices. An example of such limitations was the launch power, which was restricted to 18 dBm, forcing the system to operate within the linear regime. This also limited the transmission band to 60 nm centered on the link-loss minima, providing the best tradeoff between launch power per channel and channel count.

Conclusions

We demonstrated a 312.9 km unrepeatered transmission system supported exclusively by erbium-doped tellurite-fiber amplifiers (EDFTAs) and distributed Raman amplification. The link carried a 40.5 Tb/s WDM signal spanning a 60 nm bandwidth from 1545 nm to 1605 nm, seamlessly crossing the C and L band boundary. This was the first demonstration of long distance unrepeatered links using EDTFAs and constitutes a record capacity and capacity-distance product for unrepeatered links longer than 300 km without the use of ROPAs.

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