10 Gbps Transmission from a High Power EDFA for Free Space Communications

Andrew Grimes, Benyuan Zhu, Cang Jin, Jeffrey W. Nicholson
OFS Laboratories, 25 Schoolhouse Road, Somerset, NJ 08873
agrimes@ofsoptics.com

Abstract: We demonstrate a source for free-space optical communications capable of single-channel high data rate transmission (10 Gbps) from a high power EDFA at 1553.33 nm (193 THz). At an output power of 80 W the bit error rate (BER) shows no power penalty compared to a back-to-back measurement. Additionally, we demonstrate narrow linewidth and DWDM performance.

A high-reliability and high-uptime optical link between ground to space would be a paradigm shift for next generation satellite networks [1]. The advantages free space optical (FSO) communication links offer over traditional radio frequency (RF) links include substantially higher data rates, increased transmission security, immunity to RF jamming, a license free spectrum and reduced power consumption. FSO links have become the preferred solution for satellite-to-satellite links, however the ground-to-satellite (G2S) links are still RF, creating a bottleneck in the overall network.

Presently there are many hurdles in achieving the G2S link [2]. The primary hurdle is the atmosphere and its associated turbulence and weather. There are many ways to mitigate this issue, some of which are the use of adaptive optics [3] or a redundancy in the number of stations to form a highly reliable network [4]. This work expands on increasing the transmitted power to improve the overall link resilience.

In a G2S link there is an asymmetry between the power requirements of a transmitter on the ground and a transmitter in space. This asymmetry has been described at the “shower-curtain” effect [5]. This can be understood as the distortion effects imparted on the transmitted beam from the atmosphere happen immediately when transmitted from the ground, while a beam that originates in space is able to travel unperturbed for most of its distance until entering the atmosphere for its final length. Additionally, there is an asymmetry in the receiving optics as optics on the ground may be arbitrarily large, but in space, optics are typically constrained as any increase delivers a SWAP penalty. Consequently, there is a higher power requirement for the ground transmitter compared to the transmitter on a satellite.

Presently, Erbium-Doped Fiber Amplifiers (EDFA) are used to produce high output power at 1550 nm [6]. An EDFA typically uses one of three different pumping architectures, direct diode pumping at 980 nm, a co-doped erbium-ytterbium gain fiber, or a Raman fiber laser emitting at 1480 nm. An EDFA pumped by a Raman laser has some distinct advantages over the other architectures. An EDFA pumped at 1480 nm has a much lower quantum defect in the gain fiber compared to pumping at 980 nm, resulting in a much lower thermal load on the gain fiber. In addition, in-band, core-pumping allows for scaling of the mode-field diameter of the Er-doped gain fiber, reducing nonlinear impairments [7]. These advantages allow for the erbium gain fiber utilized in Raman pumped configuration to be tailored to achieve single-mode high output power levels [8] before the onset of non-linear effects such as stimulated Brillouin scattering (SBS), which would limit the overall output power level, or self-phase modulation (SPM), which would degrade the signal quality. Additionally, using a Raman laser to remotely pump the EDFA allows for the primary heat generating elements to be separated from the final output of the system, resulting in a solution that can be mounted directly to a telescope.

The main drawback of the Raman pumping solution is an increase in complexity and possibly a reduction in overall wall plug efficiency. However, the Raman module used in this work is a commercially available system that can be mounted in a standard 19” rack with overall power consumption <1200 W.

The schematic of the test setup is shown in Fig. 1 (a). During testing two different seed sources were used. The first seed source was a tunable C-band ECL that could provide one or two discrete narrow linewidth outputs. The primary wavelength used was 1553.33 nm, which is 193 THz corresponding with the ITU C#30 frequency. The second test source was the transmit line from a 10 Gb/s transceiver operating at 1553.33 nm. The output from either seed source was set to a constant 0 dBm. The seed was then connected to an EDFA pre-amplifier to increase the signal to 27 dBm. A low pas filter (LPF), with a cutoff above 1560 nm, was spliced to the output of the pre-amp. The LPF output was then spliced to the input of the Very Large Mode Area (VLMA) EDFA. The VLMA-Er gain fiber had a length of 3.2 m, a core diameter of 50 μm, and an absorption of 50 dB/m at 1530 nm. The pump source for the VLMA was a 150 W Raman laser at 1480 nm. This Raman laser has been independently tested to be stable for >1000 hours [9].

The output of the VLMA amplifier was coupled into free space, where it passed through a 0.1% beam splitter. The primary output was sent to a power meter and the picked off beam was coupled into a single-mode fiber where it was either connected to diagnostic equipment or to the receive line for the Bit Error Rate (BER) measurements to be made.

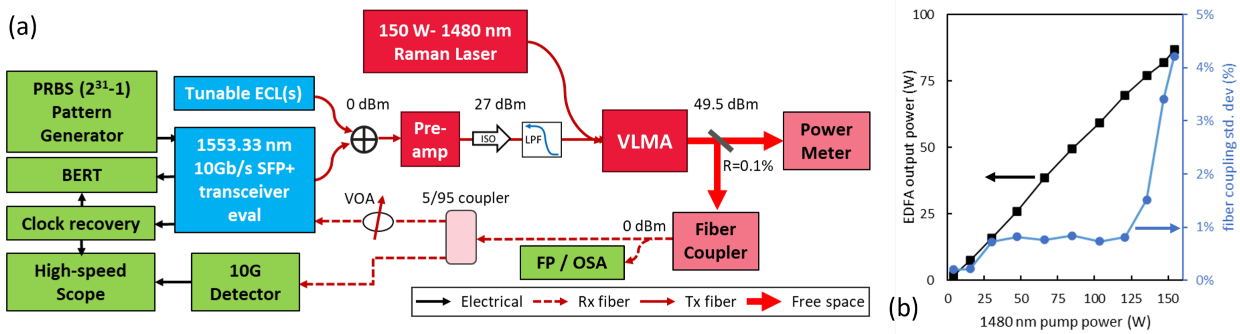

Fig. 1 (a) Schematic of Amplifier and Test Setup (b) EDFA output vs pump power, standard deviation when coupling output to a single mode fiber is shown on second axis.

The maximum output power achieved from the VLMA was 87 W at a 1480 nm pump power of 154 W, as shown in Fig. 1 (b). A power penalty measurement [10] was made to determine if the VLMA imparted any loss penalty on the BER. The power penalty measurement characterizes the BER vs a change in received power. The input power to the measurement is kept at a constant level and the power is adjusted with a variable optical attenuator (VOA). To characterize the minimum loss condition a back-to-back (B2B) measurement is made, shown in Fig 2(a), where the transceiver is directly looped back to the receive line. Typically, the power penalty measurement will be made in the most lossy state then the loss element will be dialed back until there is no penalty when compared to the B2B measurement. At an output level of 80 W, the VLMA showed no power penalty, meaning that the VLMA does not impart any distortion to the transferred signal of 10 Gbps. Above 80 W, the stability of power level in the fiber began to dramatically decrease, preventing an accurate BER measurement. We believe this instability could be related to transverse mode instability but have not studied it in detail at the time of writing.

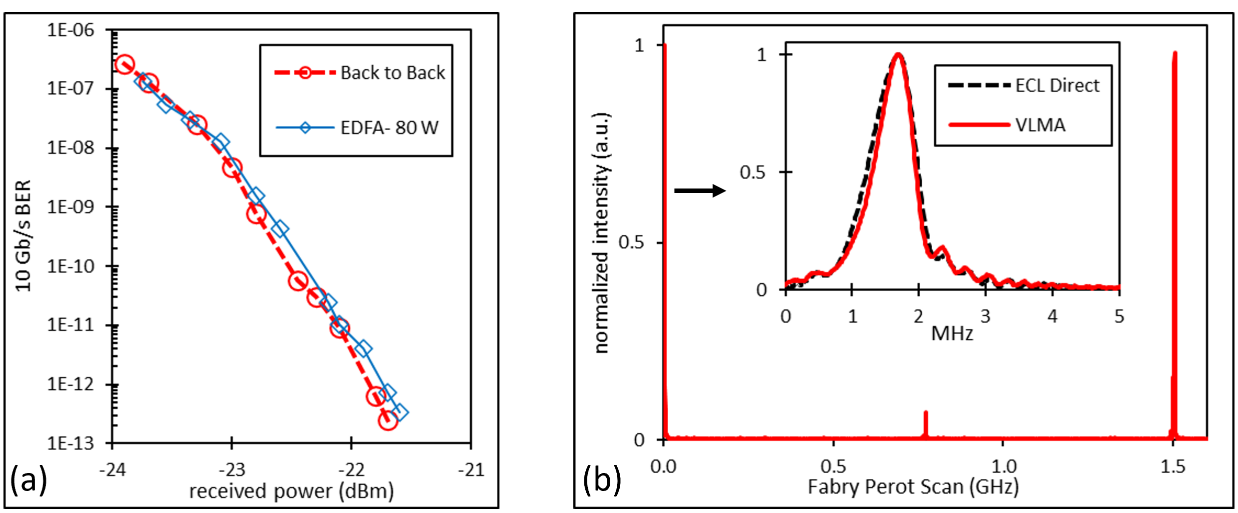

Fig. 2 (a) Power penalty measurement (b) Linewidth measurement at maximum power, inset shows zoomed in and compared to the direct ECL measurement.

The narrow linewidth performance of the VLMA amplifier was also investigated. This is necessary as the linewidth from a coherent transmitter is greatly reduced when the transmitter is idle with no data being sent. To characterize this performance a 1.5 GHz Fabry Perot (FP) cavity (Thorlabs Model: SA30-144) with a finesse of ~1500 was used. The direct output from the ECL was used to align and characterize the FP cavity, resulting in a measurement resolution of ~1 MHz. The pick off beam of the VLMA output was then coupled into the FP via a single mode fiber. The reference ECL and 85 W VLMA output show no measurable difference in their respective linewidths Fig. 3(b). This result also validates that there is no additional broadening from SPM or cross phase modulation (XPM). Additionally, SBS was not observed in any measurement when using this narrow linewidth source, as monitored using a reverse port of a tap spliced before the VLMA input. SBS was not expected as the SBS threshold for a typical VLMA fiber when pulsed with a narrow linewidth source is >100 kW. Using commercially available PM VLMA-Er fiber the narrow linewidth CW output would make the VLMA a very high-power laser source for AMO physics or quantum metrology.

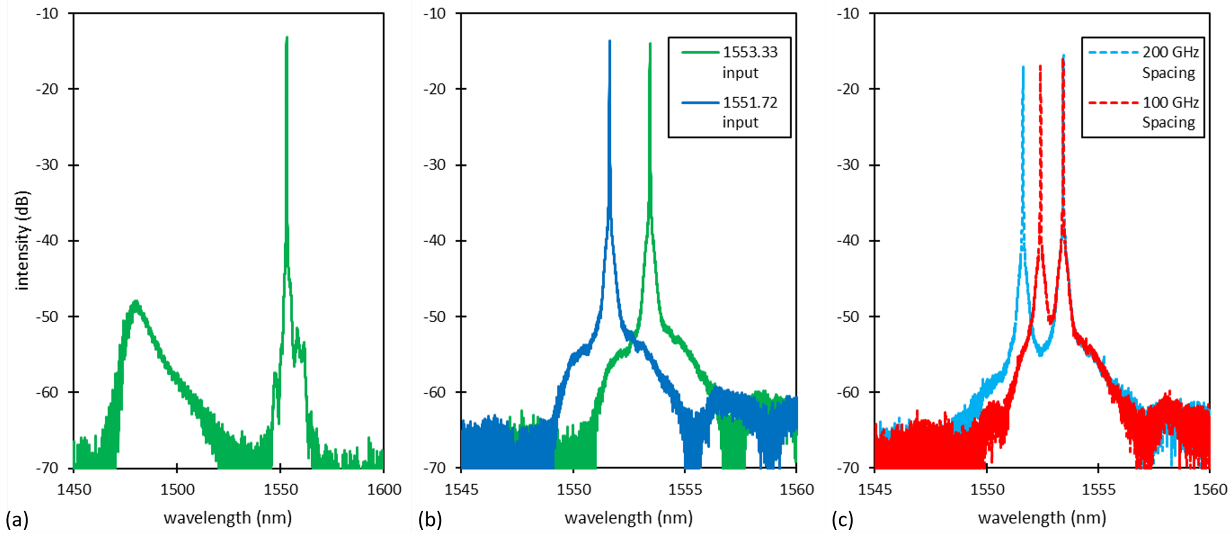

Fig 3 (a) Wide Spectrum of the 1553.33 nm output (b) Individual Spectra of 1553.33 and 1551.72 output (c) 100 and 200 GHz WDM Signals

To test the suitability of VLMA as a DWDM source two input signals were combined and used as the seed source. Each seed source was set to 0 dBm, resulting in a total power after the 3 dB splitter of 0 dBm. The output power of the VLMA was then increased to the level that produced of 85 W with a single input wavelength, as seen in Fig. 3(a). The output power from the VLMA showed no difference when operated with either a single or dual tone seed, apart from an expected 3 dB reduction in the peak intensity for each channel when a dual tone seed was used, as shown in Fig. 3(b) and (c). The spacing of the seed wavelengths was set to 200 and 100 GHz, additionally the wavelength separation was continuously decreased until the difference in wavelength was not able to be measured with the monitoring OSA. When operated with any of these wavelength separations the dual channel output showed no additional frequency components that may be generated from a four-wave mixing process induced by either SPM or XPM. Given the short length and large MFD of the VLMA fiber, this was an expected result.

In conclusion we have demonstrated that the VLMA exhibits no non-linear effects and imparts no power penalty to high data rate transmission of output power levels up to 80 W. The VLMA fiber used may still be further optimized for high-average power CW performance to increase the overall system efficiency.

References

[1] M. Y. Abdelsadek et al., "Future Space Networks: Toward the Next Giant Leap for Humankind," IEEE Transactions on Communications, (2023), doi: 10.1109/TCOMM.2022.3228611.

[2] R. Barrios et al., “Link Budget Assessment for GEO Feeder Links based on Optical Technology,” International Journal of Satellite Communications and Networking, (2020), doi:10.1002/sat.1371.

[3] LC Roberts et al., “Performance of the adaptive optics system for Laser Communications Relay Demonstration's Ground Station 1,” Appl Opt., (2023), doi: 10.1364/AO.486752

[4] NK Lyras et al., “Cloud Free Line of Sight Prediction Modeling for Optical Satellite Communication Networks,” IEEE Communications Letters 21, (2017), doi: 10.1109/LCOMM.2017.2681073

[5] Aviv, David G., “Laser Space Communications,” (Artech House Publishing, Norword, MA, 2006), pg. 88.

[6] Y. Horst et al., “Tbit/s line-rate satellite feeder links enabled by coherent modulation and full-adaptive optics,” Light Sci Appl., (2023), doi: 10.1038/s41377-023-01201-7.

[7] J. C. Jasapara et al., “Diffraction-limited fundamental mode operation of core-pumped very-large-mode-area Er fiber amplifiers,” IEEE J. Sel. Top. Quantum Electron. 15(1), 3–11 (2009), doi:10.1109/JSTQE.2008.2010262

[8] J. W. Nicholson et al., "High average power, 10 GHz pulses from a very-large-mode-area, Er-doped fiber amplifier," J. Opt. Soc. Am. B 34, A1–A6 (2017). doi: 10.1364/JOSAB.34.0000A1

[9] A. Grimes et al., "Long term, stable, 115W output from an erbium fiber amplifier pumped by a Raman fiber laser," Proc. SPIE 12400, Fiber Lasers XX: Technology and Systems, (2023), doi: 10.1117/12.2650430

[10] B. Zhu, “Entirely passive coexisting 10G-PON and GPON compatible reach extender using Raman amplification,” Opt Express, (2012), doi: 10.1364/OE.20.002290.