High Power EDFAs for Free Space Communication

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Abstract: Progress and performance of high-power EDFAs, in-band pumped by Raman fiber lasers operating at 1480 nm will be reviewed. Applications of these laser systems to free-space communications will be discussed. © 2022 The Author(s)

Free-space optical communication using high-power laser sources is attracting significant interest as optical communications offer 10 to 100 times more bandwidth than RF based systems. High power laser sources suitable for optical communications have matured in recent years, but commercial sources of fibers lasers operating in the 15xx wavelength range with powers in excess of 100 W are still relatively rare. Very-Large Mode Area (VLMA) Er-doped fiber amplifiers [1], in-band pumped by 1480 nm Raman fiber lasers, show significant promise for free-space optical communication applications due to the high powers generated with low nonlinearity. In this presentation, the performance of high-power, VLMA-Er amplifiers will be reviewed.

In recent years, output power from Raman fiber lasers has increased significantly with output powers in excess of 1 kW demonstrated at 1 μm wavelength [2,3]. Longer wavelength Raman lasers pumped by Yb-fiber lasers at 1 μm typically have lower power due to a combination of an increased quantum defect, propagation losses in fibers, and component losses such as background loss in fiber Bragg grating arrays.

Using a cascaded resonator, the wavelength of a Raman fiber laser can be shifted to anywhere within the bandwidth of a silica fiber in a compact fiber laser module [4]. A schematic of a cascaded Raman fiber laser designed to operate at 1480 nm is shown in Fig. 1a. A high power, Yb-doped fiber laser at 1117 nm pumps a cascaded Raman resonator, where a series of nested cavities are created using high-reflection fiber Bragg grating arrays. The cavity wavelengths are separated by the Raman Stokes shift of 13.2 THz in germanosilicate fibers. Fig. 1b shows the output power vs. pump power of a Raman laser emitting 233 W total output power, with 224 W at the desired in-band wavelength of 1480 nm, the highest power demonstrated to-date from a cascaded Raman fiber resonator operating at 1480 nm [5].

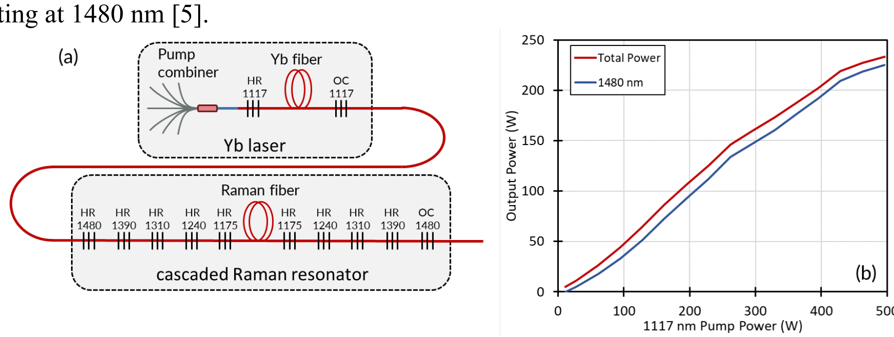

Fig. 1 (a) Schematic of a cascaded Raman resonator pumped by a Yb-doped fiber laser. (b) Output power vs. pump power from a 1480 nm Raman fiber laser demonstrating 224 W at 1480 nm.

Although the out-of-band power in Fig 1b accounts for only 4% of the total power, managing this power becomes important for down-stream components when using the Raman fiber laser as a pump source for other fiber lasers. For example, 1390 nm radiation can, over time, cause irreversible degradation in fused-fiber WDMs [6]. More recently, it was found that even without significant power at 1390 nm, power at other out-of-band wavelengths can cause failure in fused-fiber wavelength-division multiplexers (WDM) [7].

Fig 2a shows a long term burn in of a 150 W, 1480 nm Raman fiber laser with various types of WDMs spliced onto the output. A 1480/1545 nm WDM was found to rapidly degrade after around 75 hours of burn-in. In contrast, a 1480/1600 nm WDM, with a broader wavelength spacing was found to be far less sensitive to the out-of-band power, operating stability for more 200 hours at 150 W input power [7]. Because the 1480/1600 nm WDM helps to remove out-of-band power from the system, another 1480/1545 WDM, spliced onto the output of the 1480/1600 nm WDM was then able to operate at high power with no observable degradation.

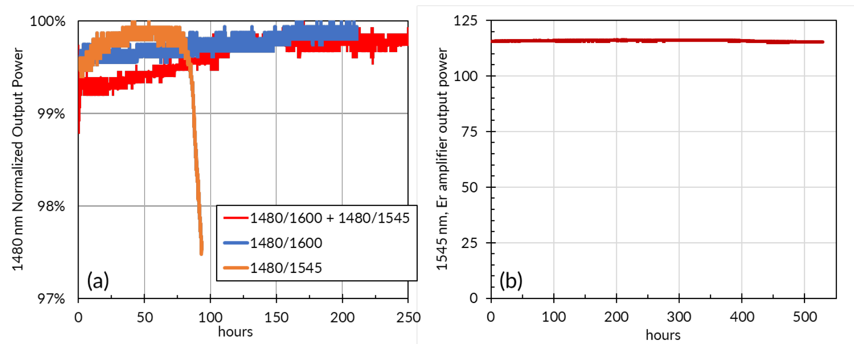

Fig. 2 (a) Output power over time for a 150 W, 1480 nm Raman laser coupled into fused-fiber WDMs (b) Output power over time from a 115 W, 1545 nm Er-doped fiber amplifier pumped by a 150 W, 1480 nm Raman laser

After the burn-in of the individual WDMs, a telecom-grade Er-doped fiber, OFS HP980, was spliced onto the output of the WDMs that had already been burned-in, and a 1 W input signal was amplified to 115 W output power at 1545 nm, and burned-in for an additional 500 hours, with no significant degradation. At this point, the original 1480/1600 nm had been operated at high power for more than 1000 hours. These results demonstrate that a cascade of WDMs designed to remove the out-of-band Raman laser power allows a high power EDFA to operate reliably at more than 100 W output power [7].

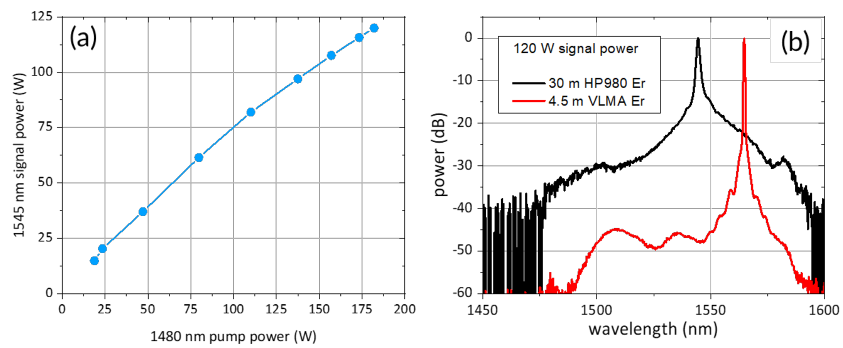

Fig. 3 (a) Schematic of an Er-doped fiber amplifier pumped by a 1480 nm Raman fiber laser. (b) Output power vs. pump power from a 120 Er-fiber amplifier. (c) Spectrum at 120 W output power from an HP980 amplifier, compared to a VLMA-Er amplifier.

The 1545 nm output power vs. 1480 nm pump power from the HP980 amplifier is shown in Fig. 3a. While the amplifier was reliable and worked well, the mode-field diameter (MFD) of telecom-grade Er fiber is very small, on the order of 7 μm, leading to significant nonlinearity. The output spectrum from the HP980 amplifier, shown in Fig. 3b as a black curve, exhibited substantial nonlinear broadening.

In comparison, Very-Large Mode Area (VLMA) Er-doped fiber amplifiers have a 50 μm core diameter and MFD of 37 μm, and are also suitable for high-power, amplifiers at 15xx [1]. For fundamental mode operation, the VLMA-Er fibers are core-pumped by 1480 nm Raman fiber lasers. The VLMA fibers are highly doped, requiring only a few meters of length. The combination of large MFD and short fiber length provides very low-nonlinearity at high powers with a diffraction limited output beam. The red curve in Fig. 3b shows the spectrum from a CW 1560 nm laser amplified to 120 W output power. In contrast to the HP980 nm result, the VLMA-Er fiber amplifier exhibits negligible spectral broadening. The low background level between 1500 nm and 1550 nm is due to a long wavelength tail in the high power, 1480 nm Raman laser output.

In addition to CW amplification, VLMA-Er fiber amplifiers are suitable for amplifying pulses with pulse widths from femtoseconds to microseconds. To demonstrate the utility of VLMA-Er fibers for high-power, free-space optical communications, a seed laser at 1560 nm with 10 GHz pulse repetition rate, 3 ps pulse width, and 2 W average power was amplified to 120 W average power in the 4.5m long VLMA-Er amplifier. Fig 4a shows the output spectrum at 120 W, compared to the input spectrum, displaying only a small amount of nonlinear broadening at maximum power. The autocorrelation measured at maximum power had a FWHM of 5.8 ps, shown in Fig. 4b. The 120 W pulse train with 3 ps pulse width and 10 GHz rep-rate corresponded to 4 kW peak power demonstrating the capability of the VLMA amplifier to provide low-nonlinearity pulse amplification at high average powers and high peak powers [8].

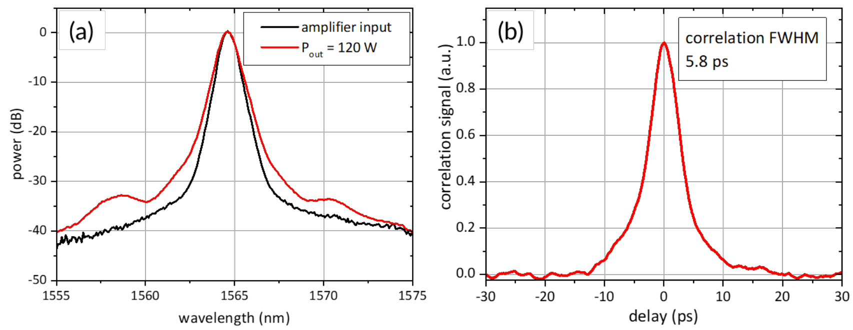

Fig. 4 (a) Input and output spectrum VLMA-Er amplifier at 120 W output power. (b) Autocorrelation of the pulse at 120 W output power.

The ability to amplify to high peak power with negligible spectral broadenings is one of the major benefits of VLMA-Er amplifiers for free-space optical communications. Self-phase modulation spectrally broadens high power amplified signals. This spectral broadening can have a significant impact on the received signal to noise if the SPM broadens the signal linewidth beyond narrow-band filters used in the optical receiver. The spectral broadening in amplified signals was evaluated as part of the NASA Laser Communication Relay Demonstration (LCRD) program for transmitting data from a ground terminal to a space terminal in geosynchronous orbit. Typical commercial Er-doped fiber amplifiers caused an unacceptable loss in received signal due to SPM induced broadening. In contrast, the ratio of out-of-band power to in-band power for the VLMA amplifier was nearly constant over the 10 W range of operating power, meeting the LCRD requirements with significant margin [9]. As a result of the demonstrated performance of the VLMA-Er amplifier, it is now also under consideration in the design of a new generation of low-cost ground terminals for ground to space communications [10].

In conclusion, Er-fiber amplifiers pumped by high power Raman lasers can readily generate average powers in excess of 100 W. With recent advances in Raman lasers, these amplifiers can run reliability at output powers more than 100 W. The VLMA-Er fiber technology, with the high doping levels and large mode-field provide ultra-low nonlinearity amplification and minimal SPM-induced broadening, making them suitable for free-space optical communications.

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