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Development of High-Power Er/Yb Polarization-Maintaining Optical Amplifier for Ground Station Uplink Systems

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ABSTRACT

A high-power Er/Yb polarization-maintaining fiber amplifier is described. The amplifier operates on a single wavelength of 1546 nm and consists of a pre-amplifier with a gain up to 64 dB followed by a double-clad 25/300-µm Large Mode Area (LMA) Er/Yb fiber booster stage, counter-pumped through a (2+1):1 PM combiner by two 140-W 915-nm laser diodes. The design of the amplifier required developing new splicing and re-coating approaches for the LMA PM fibers and characterizing mode-field adaptors for single- mode (SM) and LMA fibers and low-loss high-power PM pump-signal combiners maintaining a high Polarization Extinction Ratio (PER). The amplifier provides a robust diffraction-limited output of more than 50 W from true single-mode PM1550 fiber with an $M^2 < 1.03$ and a long-term (~200 hours) stability better than 5% in constant current mode (i.e., no power control feedback loop). With low-loss, high-quality splices between fibers with different MFDs, the maximum local fiber temperatures were kept below 60^o C. The amplifier design ensured that, even when operating at the 50-W level, the parasitic ASE in the 1-micron region was less than 2 mW. The output PER of >15 dB was limited by the quality of the pump-signal combiner which has a high probability of being improved in the future.

Keywords: Er/Yb amplifier, large mode area fibers, ground station, uplink

1. INTRODUCTION

The next-generation high-bandwidth optical links from earth to space require the development of new high-power WDM sources. Future transmitter sections of optical ground stations (OGT) include C-band transponders capable operating at 100 Gbit/s and above and several (defined by the number of channels) high-power polarization-maintaining (PM) amplifiers as well free-space collimators, multiplexers, demultiplexers and a transmit/receive telescope.

The objective of this work was to develop a 50-W commercially-viable single-wavelength high-power PM Er/Yb amplifier with true single-mode output as well as a high-power collimator for the next-generation of high-throughput communication ground stations.

The commercially viable product should be efficient, monolithic, based on commercially available components and able to operate for a few years with negligible degradation due to photo-darkening. Though Er/Yb amplifiers with powers in the 100 W range have been reported [1-11] they were usually operated at the long edge of the C-band and have not been PM nor fully monolithic until recently [5, 6]. Furthermore, for multi-wavelength ground stations, high-power amplifiers should also be able to cover the wavelength range at the short part of the C-band, i.e., between 1536 and 1552 nm, where the efficiency of the amplifier is lower due to the rapid growth of the 1-micron parasitic ASE that will, at some level, limit the C-band output power and might result in catastrophic damage of the amplifier components caused by giant parasitic pulse formation. Several approaches have been investigated to contain this risk, for example – an additional seed source at a wavelength around 1030-1060 nm [7,8] was used, which not only stabilizes the inversion population in the Yb band but also might, to some extent, act as an additional pump for the main C-band signal. An interesting idea was used in [9] where, instead of an active 1- micron seed, a highly-reflective Fiber Bragg Grating (FBG) in the Yb wavelength range was placed at the pumping end of the amplifier, thus providing generation of power in the Yb-band.

Resonant pumping of high-power Yb-free Er amplifiers has also been investigated [12-14]. This eliminates the 1-micron ASE issue, but requires significantly longer active fibers resulting in associated nonlinear penalties. In addition, resonant pumping is mainly suitable for use at the long-wavelength part of the C- band and in the L-band.

Impressive results have been presented in [1] where double-clad Yb-free Er-doped fiber was pumped directly by 976-nm multimode laser diodes. Unfortunately, this approach also requires a few tens of meters of active fibers and provides reasonable gain only at wavelengths > 1570 nm.

The idea of using single-mode Yb-band pumping was realized in [11] where the output of a 1018-nm Yb laser was used as a core pump for a Er/Yb single-mode amplifier. This approach looks very promising if the photodarkening rate can be mitigated. In this work, we have concentrated our efforts on the simplest "standard" approach i.e., pumping double-clad LMA PM fibers with multimode diodes at wavelengths off the 976-nm resonance (< 915 nm in particular), which was proven to be the optimal choice [3,4].
Using pumping at a wavelength well-short of the absorption peak at 976 nm requires somewhat longer fibers but has significant benefits because of the decreased level of 1 micron ASE. Also, since the absorption is ~ 5 times smaller compared to the peak value, it results in a reduced thermal loading rate and thus a reduced fiber temperature. Usage of pump wavelengths shorter than 915 nm also helps to deal with the pump efficiency decrease with the increase of the pump power (LD temperature) since, the decrease in pump LD efficiency is partially offset by the increase in the Yb absorption efficiency due to the increased in pump LD wavelength.

2. AMPLIFIER DESIGN

The high-power amplifier consists of two major parts - the three-stage preliminary PM amplifier with a gain up to 64 dB and maximum output power of 5 W and a power booster based on PM double-clad LMA fiber with 25/300 µm core/cladding dimensions.

The preamplifier as a standalone product could be also used for Pulse Position Modulation (PPM) experiments since it is capable of operating in the range of input signal having an average power between -27 to 10 dBm at C-band wavelengths from 1536 to 1567 nm. Including a mid-stage 100- or 50-GHz narrowband filter results in rejection of unwanted ASE, ensuring low out-of-band ASE noise power. The noise figure of this amplifier for an input signal of -27 dBm was 5 dB. The three stages of the amplifier have maximum gains of 27, 24 and 13 dB, respectively. A schematic diagram of the preamplifier is shown in Figure 1. The first two stages were co-pumped by single-mode 974-nm laser diodes and the third one by a 25-W multimode laser diode at 940 nm. The design of the amplifier ensured that it was protected in the event of loss of input signal since the C-band ASE from first two stages provided sufficient power to suppress catastrophic generation of 1-micron pulses.

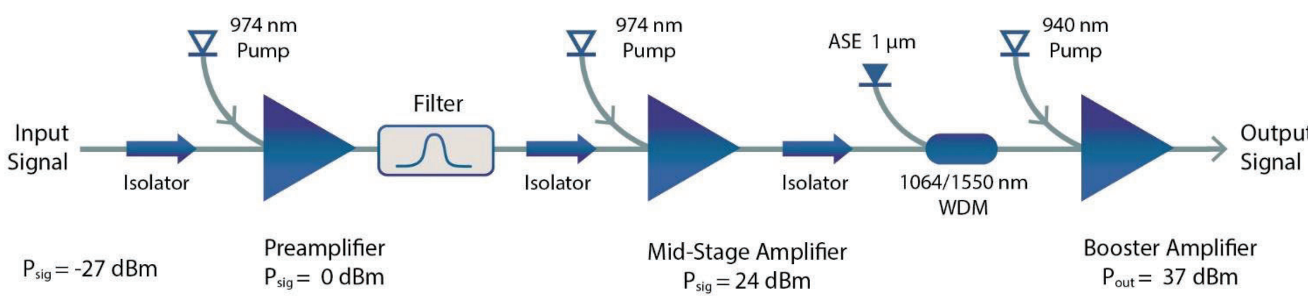

Figure 1. Pre- amplifier optical diagram

The optical diagram of the 50-W power booster is shown in Figure 2. Carefully characterized mode-field adapters (MFA) from PM1550 to LMA fibers have been placed at the input and the output of the amplifier. A 1060/1550 WDM was used to monitor 1-µm ASE to protect the amplifier in case the ASE level were to exceed a preset level. To keep the temperature of the active fiber within a reasonable range, the booster optical train was set on a water-cooled cold plate. The active fiber was wound on a grooved spool with a diameter of 20 cm and was potted using transparent elastomer epoxy having a refraction index very close to the fiber coating and a high elasticity. The temperature of the fiber was monitored using a FLIR camera. It is worth mentioning that splices between the active fiber (PLMA-EYDF-26P/300-HE from Nufern) and the passive matching double-clad fiber (PLMA-GDF-25/300, PM) were also placed inside the grooves on the spool because the splice area usually has higher temperature than the rest of the fiber and requires efficient cooling. The quality of the splice recoating and potting are very important since any air bubbles left between the fiber and the spool surface interrupt local heat removal and lead to a significant increase of the fiber temperature. Specially developed techniques made it possible to reliably avoid air bubble formation and thus keep even the hottest pointes of the fiber at a temperature lower than 60° C at the highest output powers, see Figure 3.

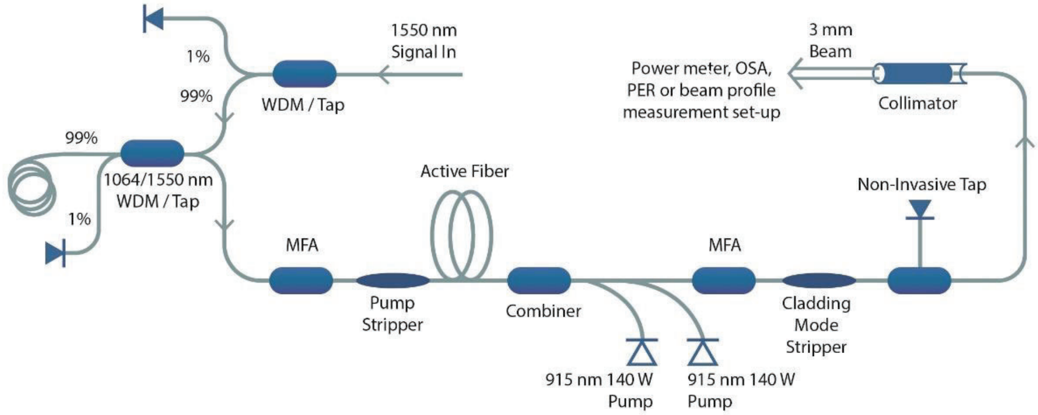

Figure 2. Booster stage optical diagram

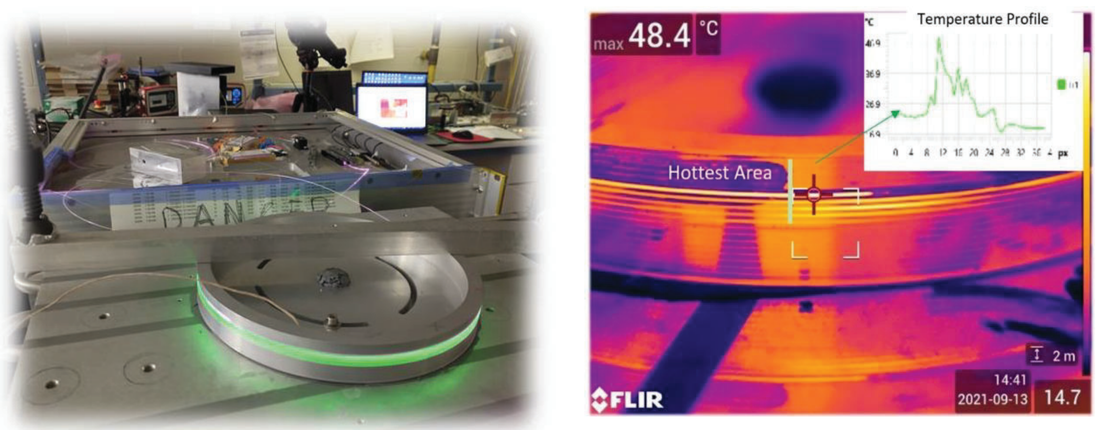

Figure 3. Active fiber on the spool (left) and FLIR camera image (right) at an output power of 40 W.

In Figure 4, the temperature of the hottest point of the fiber is shown as a function of the output power. The output power was measured after the PM1550 fiber spliced to the output of the MFA and cladding mode stripper.

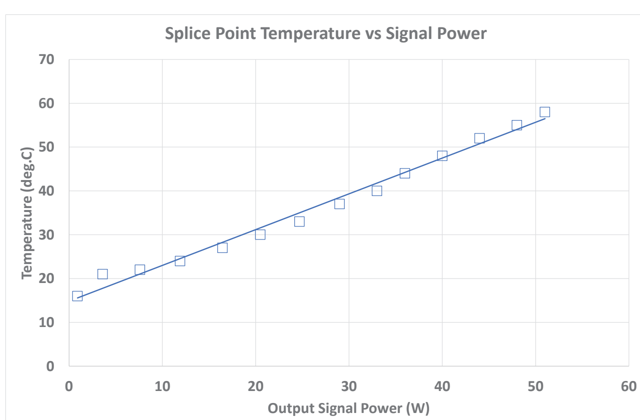

Figure 4. Temperature of the hottest point on the active fiber vs single-mode output power.

Avoiding rapid growth of the 1-micron ASE is a key to reliable operation of high-power Er/Yb amplifiers using double-clad fiber. We have compared co- and counter-pumping configurations using fibers from different suppliers and it was concluded that the counter-pumping scheme and PLMA-EYDF-25P/300-HE fiber was by far the best solution, see Figure 5.

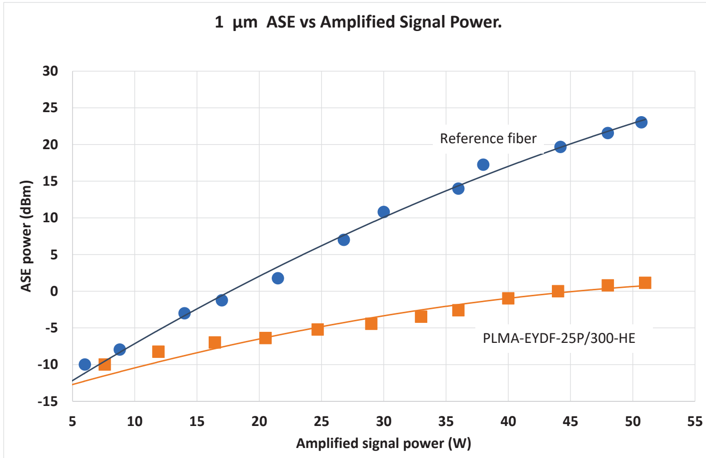

Figure 5. 1-µm ASE power comparison of the amplifiers made of PLMA-EYDF-25P/300-HE and a typical reference active fiber, both fibers having optimal length for a 1546 nm signal.

3. RESULTS

The measurement results shown in this section were obtained after the cladding mode stripper at the output of the true single mode standard PM1550 fiber from Corning which was subsequently spliced to the output collimator (see Figure 2.) The output spectrum at an output power of 50 W is shown in Figure 6. The suppression of the long-wavelength C-band ASE was > 43 dB for a 1-nm resolution of the Optical Spectrum Analyzer.

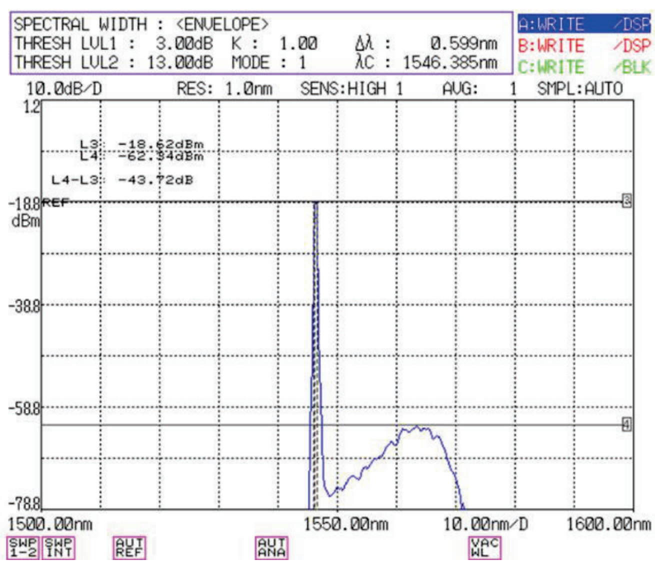

Figure 6. Output signal spectrum at an output power of 50 W

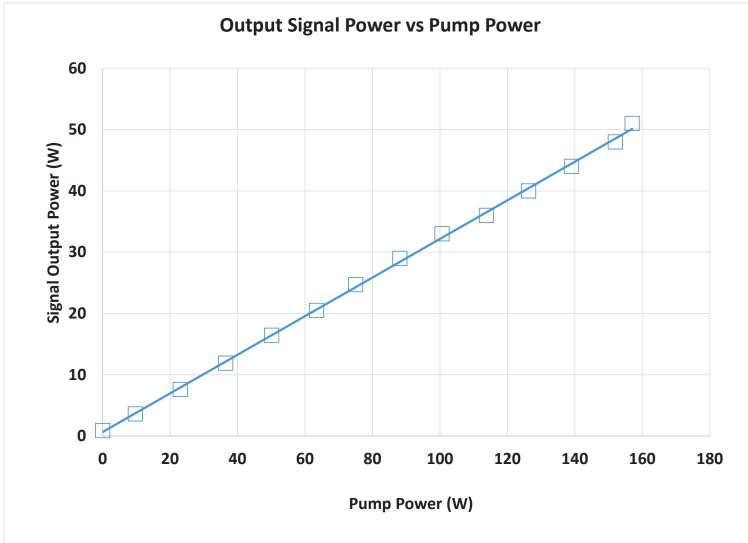

Figure 7. Output power vs booster pump current

The signal output power vs pump power is shown in Figure 7 for a booster input signal power of 2 W and optimal length of the LMA fiber of 3.3 m. The fiber used in the test has not shown any significant power degradation due to photodarkening during more than 180 hours, see Figure 8.

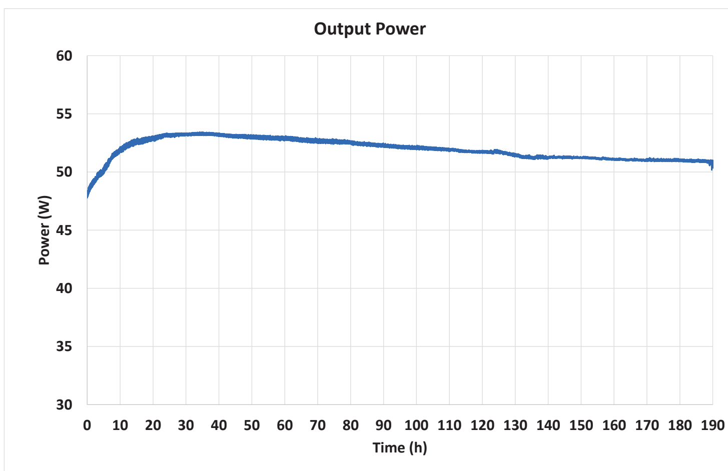

Figure 8. Long term stability test

Measurements of the M^2 and PER have been made after the specially designed high-power collimator. The set-up for the M^2 measurements is shown in Figure 9a. After the collimator output, the beam was attenuated using three optical wedges, each reflecting light at a small angle. Then, the beam was focused by a 302-mm focal-length lens and the beam profile was measured along Z axis using a Thorlabs beam profiler. The M^2 value was then calculated using the standard equation for a Gaussian beam. It was found that both Mx and My values are smaller than 1.03 i.e., the beam was truly diffraction limited.

The PER was measured using a version of the M^2 set-up shown in Figure 9a. In place of the lens, a Glan-Taylor polarizer was inserted and the beam profiler was replaced by a power meter. The minimum transmitted power value was recorded vs time and normalized on a maximum transmitted power value.

The results obtained are shown in Figure 10. As one can see, the PER was randomly fluctuating between 30 and 15 dB. We have tested all components in the optical train, including the active fiber (using a 1625-nm probe beam), and have found that it was the pump/signal combiner that was causing the PER fluctuations. We believe that there is a high probability that the PER of the pump/signal combiner can be improved and the amplifier PER target value of 20 dB achieved.

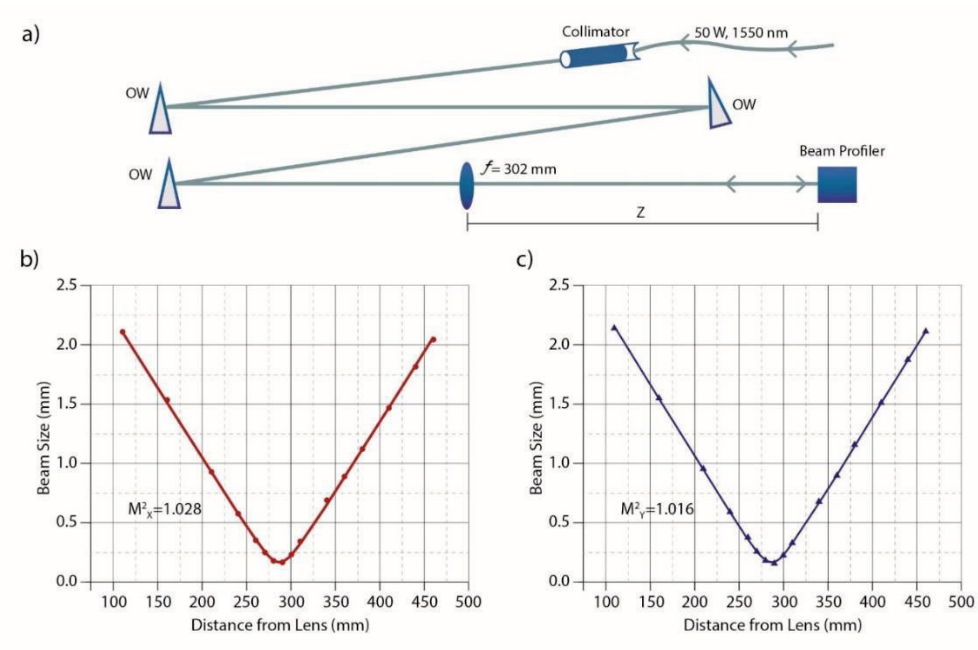

Figure 9. a) M^2 measurements set-up, b) and c) M^2_x and M^2_y

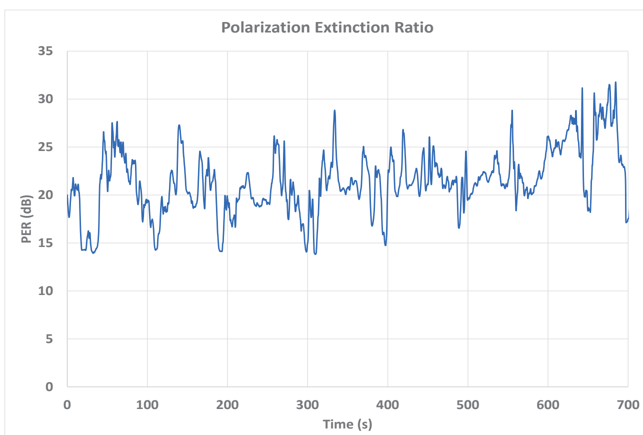

Figure 10. Polarization extinction ratio versus time.

4. CONCLUSION

A high-power Er/Yb polarization-maintaining fiber amplifier based on commercial components has been developed. The amplifier consists of a preamplifier with a gain up to 64 dB and a double-clad 25/300 µm Large Mode Area (LMA) Er/Yb fiber booster stage, counter-pumped through a (2+1):1 PM combiner by two 140-W 915-nm laser diodes. The amplifier, operating at a single wavelength of 1546 nm, provides a robust diffraction-limited output of more than 50 W from true single-mode PM1550 fiber with an $M^2 < 1.03$ and a long-term (~200 hours) stability better than 5%. With careful optimization of splicing and recoating techniques, the temperature of the hottest point along the active fiber was < 60 °C at the maximum output power. The output PER of >15 dB was limited by the quality of the pump/signal combiner which has a high probability of being improved in the future.

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