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1.8 mJ, 3.5 kW single-frequency optical pulses at 1572 nm generated from an all-fiber MOPA system

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High-energy single-frequency optical pulses at 1572 nm were generated from an all-fiber MOPA system for atmospheric CO_2 LIDAR system application. We report the experimental demonstration of 1.8 mJ, a peak power of 3.5 kW at the pulse repetition of 2.5 kHz, as well as 1.3 mJ, a peak power of 2.5 kW at the pulse repetition of 7.5 kHz single-frequency optical pulses at 1572 nm using single-mode large-core polarization-maintaining Er-Yb co-doped silicate glass fiber amplifiers pumped at 976 nm. To the best of our knowledge, this is the highest pulse energy of single frequency at 1572 nm from an all-fiber amplifier system.

OCIS codes: (140.3510) Lasers, fiber; (140.3280) Laser amplifiers; (010.3640) Lidar.

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A robust and alignment-free single-frequency fiber laser system is one of the most useful sources for measuring time distribution of its radiation in various practical sensing applications such as seismic sensing, LIDAR systems, and interferometric laser vibrometry [1–3].

There has been a significant need to develop a high-energy single-frequency optical pulse transmitter at 1572 nm for an atmospheric CO_2 LIDAR system supported by the NASA Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission since 2007 [4]. The ASCENDS mission requires optical pulses at 1572 nm with a spectral linewidth of $\leq$100 MHz, a pulse energy of >3.2 mJ at the repetition rate of 7.5 kHz, a pulse width of 100 ns–1 μs, and beam quality (M2) of <1.5 in a rugged and reliable platform [5]. The single-frequency all-fiber master oscillator power amplifier (MOPA) system has been identified as a promising transmitter option due to many potential advantages for space application [5].

Several authors have reported the generation of high-energy pulses at 1572 nm from an Er-doped fiber amplifier [5,6] or an Er-Yb co-doped fiber amplifier (EYDF) MOPA system [7]. However, most work in the all-fiber MOPA system at 1572 nm has been demonstrated with only several hundreds of microjoule level pulse energy to date. The fundamental challenge is that the available gain at 1572 nm is typically much poorer than the gain at 1535 nm in silica-glass-based fiber amplifiers, which requires a relatively longer length of gain fibers for moderate pulse energy amplification against predominant out-of-band amplified spontaneous emission (ASE) background. Subsequently, a several-meter length of silica-glass-based fiber amplifier system reveals early pulse energy clamping, either induced by stimulated Brillouin scattering (SBS) in the case of a strong seed input or by parasitic lasing of out-of-band ASE in the case of a weak seed input before meeting the final system pulse energy level of millijoules [6].

Simply, to the best of our knowledge, the best approach to attain millijoule-level pulse energy at 1572 nm from the all-fiber MOPA system is to use multi-stage amplification in company with a rigorous out-of-band ASE filtering. The prerequisite is to use gain fibers with a sufficient enough gain per unit length at 1572 nm such that each amplifier in the system can employ a short and a minimum required length of the gain fiber for a moderate-level pulse energy amplification to reduce the detrimental out-of-band ASE. It should be emphasized that the operation level of each amplifier needs to be optimized for the best signal-to-noise ratio (SNR), rather than maximum pulse energy until the end of the pre-amplification process, since improper high-gain operation of a typical fiber amplifier can cause fast ASE growth which results in parasitic lasing, not to mention that within an allowed beam quality, the core size of the gain fibers at each stage of the amplifiers needs to be increased in accordance with the pulse energy growth in order to avoid an SBS-induced pulse energy limit.

In this Letter, we have demonstrated 1.8 mJ, a peak power of 3.5 kW at the repetition rate of 2.5 kHz single-frequency optical pulses at 1572 nm from an all-fiber MOPA system using our proprietary custom silicate glass EYDFAs. To the best of our knowledge, this is the highest pulse energy of single frequency at 1572 nm from an all-fiber amplifier system. We also report that we have achieved 1.3 mJ, a peak power of 2.5 kW at 7.5 kHz operation of the presented system.

For the millijoule-level high pulse energy demonstration, we have developed single-mode polarization-maintaining (PM)

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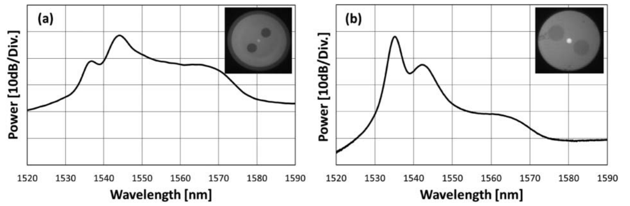

Fig. 1. ASE spectrum of (a) the AdValue Photonics proprietary custom silicate EYDF and (b) a commercial silica EYDF. The inset is the cross-sectional image of the fiber.

double-cladding EYDFs with a high gain per unit length of greater than 2 dB/cm from 1530 to 1560 nm. The gain at 1572 nm is estimated to be larger than 0.5 dB/cm. Among the custom silicate glass EYDFs with different core and cladding sizes, as an example, our standard single-mode silicate EYDF has a core diameter of 8 μm, an inner glass cladding diameter of 145 μm, and an outer glass cladding of 167 μm. The ASE spectrum, as well as the cross-sectional image of the custom silicate EYDF compared with a commercial silica EYDF, is shown in Fig. 1. A prominent feature of the custom silicate EYDF is that the core glass of the fiber is made of silicate glass with co-doping of 1 wt. % of Er and 5 wt. % of Yb such that it is possible to obtain a reasonably broad gain bandwidth of ∼37 nm (1535–1572 nm). Moreover, our silicate glass EYDFs are very flexibly manufacturable so that a various range of desired numerical apertures and geometrical dimensions could be formed by two different kinds of undoped silicate glasses which are designed for inner-cladding glass and outer-cladding glass, and matched with the Er-Yb co-doped core glass.

In the form of a cladding-pumped fiber amplifier system, the optical performance of the custom silicate EYDF has been characterized by measuring the small-signal gain and the SNR with a tunable external cavity diode laser (Phonetics) source at the input power of −6 dBm and compared with the performance of a commercial 10/125 μm double-cladding silica EYDF. A comparison of the wavelength-dependent net gain, i.e., small-signal gain minus total insertion loss and the SNR of the EYDFAs built from a 1 m long custom silicate EYDF and a 2 m long commercial EYDF is shown in Figs. 2(a) and 2(b), respectively.

At a shorter wavelength region below 1545 nm, the commercial silica EYDF showed excellent performance in both net gain and SNR. However, at the longer wavelength region from 1565 to 1575 nm, particularly at 1572 nm, our proprietary custom silicate EYDF performed significantly better than the commercial silica EYDF in both net gain and SNR. Ultimately, we have obtained about 6 dB higher gain, as well as 10 dB higher SNR at 1572 nm than the commercial silica glass EYDF.

To produce high-energy pulses at 1572 nm, we have developed a pulsed seed laser system for a high-energy amplifier system using our standard single-mode silicate EYDF. The seed laser system consists of a single-frequency DFB laser diode with a spectral linewidth of 2 MHz centered at 1572 nm, preamplifiers based on a 1 m long silicate gain fiber, a fiber-pigtailed acousto-optic modulator (AOM) for pulse generation, as well as pulse shaping, and an ASE filter based on a fiber Bragg grating with a 3 dB bandwidth of 0.2 nm in combination with a fiber circulator.

Optical seed pulses with a pulse width of ∼1 μs at 2 kHz were generated by an external modulation of the amplified CW output from the DFB laser at 1572 nm using an AOM in the system. It should be noted that we have initially set the seed pulse width two times longer than the target width of 500 ns considering a pulse width shortening effect due to the non-uniform pulse amplification in a typical high-energy long-pulse fiber amplifier system [8]. In this high-energy fiber amplifier system, it is very important to manage the pulse shape of the amplifier to prevent a steep leading edge growth during the pulse amplification process. For this purpose, we have implemented an AdValue Photonics proprietary programmable pulse shaping unit which can generate a large dynamic range of an arbitrary shape of electrical driving pulses for AOM to mitigate an SBS-induced early pulse energy limit. Ultimately, we have obtained an optimized seed pulses at 1572 nm with a pulse energy of >6 μJ single-frequency laser pulses at the repetition rate of 2.5 kHz with an SNR of >50 dB.

To boost the pulse energy at 1572 nm up to millijoule-level, we have developed a high-energy multi-stage amplifier system using our proprietary single-mode large-core PM double-cladding silicate glass EYDFs. The entire system configuration of the all-fiber MOPA system at 1572 nm based on single-mode large-core PM double-cladding silicate EYDFs is shown in Fig. 3. The entire amplifier system was constructed with three-stage cascaded EYDFAs (EYDFA-1 to 3). First, two amplifiers were configured with a 28 and 33 cm long single-mode large-core silicate EYDFs with a core diameter of 20 μm, and the last stage amplifier was configured with a 55 cm long single-mode large-core silicate EYDF with a core diameter of 45 μm. The single-mode large-core EYDFs are also made of silicate glass with co-doping of 1 wt. % of Er and 5 wt. % of Yb.

From the first two EYDFAs (EYDFA-1 and -2), we could obtain the output pulse energy of >70 μJ and >200 μJ at the pump power of ∼10 W at 976 nm delivered through a PM $(2+1)\times 1$ pump combiner. It should be emphasized that

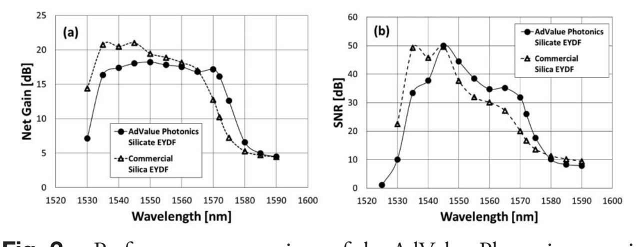

Fig. 2. Performance comparison of the AdValue Photonics proprietary custom silicate glass EYDF and the commercial silica glass EYDF: (a) wavelength-dependent net gain and (b) SNR.

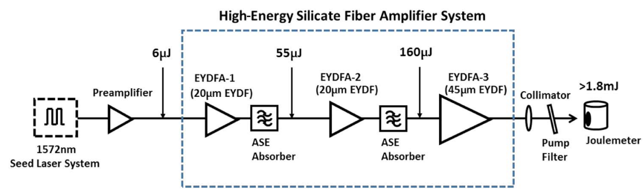

Fig. 3. Schematic of the high-energy all-fiber MOPA system at 1572 nm based on single-mode large-core PM double-cladding silicate EYDFs.

in order to achieve the highest pulse energy from the last stage amplifier, obtaining high-quality input pulses with a high SNR is very crucial. For this reason, we have optimized the operation level of the EYDFAs by slightly lowering the pumping power for a better SNR. At the same time, we have inserted a 70 cm long unpumped same gain fiber with a core diameter of 20 μm after each of the first two EYDFAs' (EYDFA-1 and -2) output as an ASE absorber, on the basis of the intrinsic three-level characteristics of a rare-earth-element-doped fiber amplifier, to absorb undesired ASE background from the silicate glass EYDFs. As can be seen from the optical performance of the silicate EYDF shown in Fig. 2, the signal gain of 1572 nm is >20 dB smaller than that of 1544 nm. Therefore, the absorption of ASE around 1544 nm through the unpumped gain fiber is substantially stronger than the absorption of the signal at 1572 nm. Owing to the unpumped gain fiber-based ASE absorber, we could obtain am SNR of >50 dB at the output pulse energy of 55 μJ from the first stage high-energy amplifier (EYDFA-1) and an SNR of >40 dB at the output pulse energy of 160 μJ from the second stage (EYDFA-2). Continuously, the 160 μJ output pulses at 2.5 kHz were fed into the last stage amplifier (EYDFA-3) based on the 45 μm core diameter fiber.

The fiber end of the last stage amplifier (EYDFA-3) was angle-cleaved with an angle of ∼10 degree to avoid the unnecessary signal feedback. The output was collimated by a plano-convex lens with a focal length of ∼4 cm. Then the output pulse energy at 1572 nm was recorded using a commercial joulemeter (Gentec, Mach5) after a pump filter in free space, and the pulse trace was recorded using an InGaAs photodetector (ThorLabs, PDA10D) and an oscilloscope (Tektronix, TDS 754A).

The output pulse energy from the last stage amplifier (EYDFA-3) pumped at 976 nm is shown in Fig. 4(a). At the pulse repetition rate of 2.5 kHz, we have obtained, to the best of our knowledge, the highest pulse energy of 1.803 mJ at the pump power of 151 W delivered through a PM $(2 + 1) \times 1$ pump combiner by two of 976 nm wavelength-locked 85 W pump diodes. The output pulse trace from the last stage EYDFA at the pulse energy level of 1.8 mJ at 2.5 kHz is shown in Fig. 4(b). The output pulse width was measured to be ∼510 ns FWHM. The corresponding peak power of the pulse energy of 1.8 mJ was estimated to be >3.5 kW from the measured pulse width. When the pump power increased to the output pulse energy of >1.7 mJ, an energy saturation behavior was observed. Furthermore, the output pulses become unstable at the pulse energy of 1.8 mJ. It should be noted that the system output is not limited by SBS at this energy level, since the theoretical SBS threshold

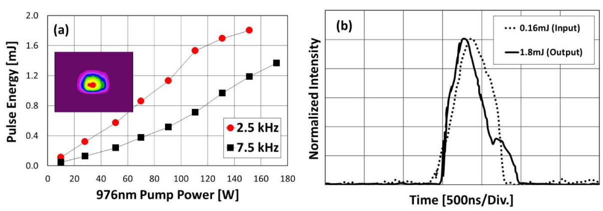

Fig. 4. Measured output pulse energy at (a) 2.5 and 7.5 kHz versus pump power and (b) the pulse traces at 2.5 kHz at the pulse energy of 1.8 mJ. The inset is a typical beam profile of the last stage power amplifier.

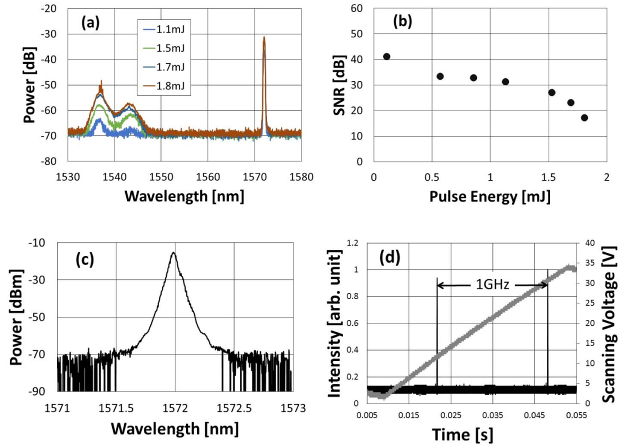

Fig. 5. Measured output optical spectra from (a) the last stage amplifier at 2.5 kHz and (b) the SNR versus the output pulse energy. (c) Zoomed-in view of the optical output spectrum at 1572 nm from the last stage amplifier (resolution bandwidth: 0.05 nm) and (d) the Fabry–Perot interferometer scan of the output optical spectrum at 1572 nm from the last stage amplifier for confirming single-frequency operation.

of the last stage amplifier (EYDFA-3) with a core diameter of 45 μm is estimated to be >5 mJ [9]. Evidently, we have measured the onset of parasitic lasing at 1535 nm at the pulse energy of around 1.8 mJ. The spectral evolution of the output pulses from the last stage amplifier (EYDFA-3) at the pulse energy of >1 mJ was measured with an optical spectrum analyzer (Yakogawa, AQ6370), and the corresponding SNR measurements versus output pulse energy are shown in Figs. 5(a) and 5(b), respectively. At 1535 nm, the ASE growth rate became faster after a pulse energy level of 1.5 mJ as can be seen from the SNR measurement. From the output energy of 1.7–1.8 mJ, the SNR was suddenly dropped by 6 dB due to the parasitic lasing at 1535 nm. Spectral purity of the output signal at 1572 nm was investigated at the finest resolution bandwidth of 0.05 nm. The zoomed-in view of the output signal spectrum at 1572 nm from the last stage amplifier is shown in Fig. 5(c). There was no apparent sign of spectral distortion from the measured output signal at 1572 nm. We have verified the single-frequency operation of our all-fiber MOPA system using a scanning Fabry–Perot interferometer (Micron Optics, FFP-SI) with a free spectral range of 1 GHz and a resolution of <10 MHz and shown in Fig. 5(d).

Based on the measured spectra in Fig. 5(a), we believe that the last stage amplifier (EYDFA-3) in our current system is yet to be optimized, so that the system output energy could be further improved through another stage of an optimized large signal amplification process from ∼500 μJ to >3 mJ utilizing a short length of Advalue Photonics proprietary super large-core single-mode PM silicate glass EYDF with a core diameter of ∼60 μm. In this case, we will need to lower the pump power for EYDFA-3 to obtain the pulse energy of ∼500 μJ at the gain level of ∼6 dB free from parasitic lasing. Consequently, some of the underpumped sections of the gain fiber in the EYDFA-3 could contribute to obtaining a better SNR from the amplifier acting as an ASE absorber, since the length of the gain fiber in the EYDFA-3 is long enough to produce the pulse energy of >1.8 mJ.

Similarly, we have also operated the entire high-energy MOPA system at the pulse repetition rate of 7.5 kHz. It should be noted that the AOM gating pulse window in the seed laser system was re-optimized for the system operation at 7.5 kHz to achieve a sufficient enough pulse energy which can saturate the first stage high-energy EYDFA. The measured output pulse energy at the pulse repetition rate of 7.5 kHz is shown in Fig. 4(a). To the best of our knowledge, we have obtained the highest pulse energy of 1.36 mJ, a peak power of ~2.5 kW with a pulse width of 505 ns at the pulse repetition rate of 7.5 kHz. At 7.5 kHz operation, the measured pulse energy curve did not show a clear indication of energy saturation behavior. No parasitic lasing issue was found from the system at the 7.5 kHz operation, and the maximum output pulse energy was only limited by available pump power from the two 80 W diodes at 976 nm.

In conclusion, we have successfully demonstrated single-frequency optical pulses at 1572 nm with a maximum pulse energy of 1.8 mJ, a peak power of 3.5 kW at 2.5 kHz, as well as 1.3 mJ, a peak power of 2.5 kW at the pulse repetition rate of 7.5 kHz using our proprietary single-mode large-core PM Er-Yb co-doped silicate glass fiber MOPA system pumped at 976 nm. To the best of our knowledge, the presented pulse energy is the highest pulse energy of single frequency at 1572 nm from an all-fiber MOPA system, which is very promising for the NASA ASCENDS mission. In our system, we used a 1572 nm performance-improved short length of Er-Yb co-doped silicate glass fiber in a multi-stage all-fiber MOPA system in combination of pulse shaping to mitigate early pulse energy clamping induced by undesired SBS. In addition, we have creatively utilized an optimum length of unpumped gain fibers as an efficient ASE absorber to suppress the out-of-band ASE peaks at 1535 and 1544 nm. Based on our 1.8 mJ demonstration, we believe that we could further improve the system output utilizing a short length of AdValue Photonics proprietary super large-core single-mode PM silicate glass EYDF with a core diameter of ~60 μm.

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