

# High-peak-power, high-energy, frequency-doubled fiber lasers at 515 nm, 780 nm, and 935 nm

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## ABSTRACT

By leveraging our patent-awarded glass fiber technology with heavily Yb-, Er-, or Tm/Ho-doped glass fibers over past decade, we have been able to generate high-power laser pulses from an all-fiber laser platform at multiple wavelength bands (1  $\mu\text{m}$ , 1.55  $\mu\text{m}$ , and 2  $\mu\text{m}$ ), all capable of delivering mJ-level pulse energy and 100s of kW peak power. After combining this unique high-power fiber laser technology with nonlinear frequency-doubling technique, we have extended the wavelength access of high energy and high peak power laser pulses from infrared region into visible or deep red region, which provide a robust fiber-based solution to a variety of applications. In this talk, we present our recent development progress on these fiber-based frequency-doubled lasers at 515 nm, 780 nm, and 935 nm, and their potential industrial and scientific applications.

**Keywords:** high power fiber amplifier, master oscillator power amplifier, single frequency laser, frequency doubling, Yb doped fiber laser, Er doped fiber laser, Tm doped fiber laser

## 1. INTRODUCTION

High-peak-power and high-pulse-energy single frequency lasers are highly desirable for many applications like remote sensing, laser spectroscopy, frequency conversion and coherent LIDAR. Fiber lasers have the advantages of compactness, robustness, and maintenance free. However, due to the strong confinement and long geometry, they are significantly limited by nonlinear effects such as self-phase modulation (SPM) and stimulate Brillouin scattering (SBS). To reduce the effective length of the fiber amplifier, higher rare earth doping is preferred; however, in silica fibers, it is limited by concentration quenching and photo darkening. An alternative fiber host is the multi-component silicate glass, which has less-defined glass network and provides much higher rare earth solubility. In addition, different from other fiber hosts like germanate and tellurite glasses, the main glass network of the silicate glass is still  $\text{SiO}_2$ ; this will help to achieve much stronger mechanical strength and better compatibility with conventional passive silica fiber components. In this work, we present AdValue Photonics proprietary high doping and high gain silicate glass fiber amplifiers. By using heavily Yb-, Er-, or Tm/Ho-doped glass fibers, mJ-level pulse energy has been achieved at multiple wavelengths (1  $\mu\text{m}$ , 1.55  $\mu\text{m}$ , and 2  $\mu\text{m}$ ) with up to 100s of kW peak power [1-6]. By consolidating up-to-date nonlinear frequency conversion technology, high peak power fiber based lasers have been extended from infrared to visible or deep red region.

## 2. EXPERIMENTAL SETUP

The schematic diagram of the experimental setup is shown in Figure 1. It consists of two parts. One is the all fiber based master optic power amplifier (MOPA); the other is the free space optics for the second harmonic generation (SHG). The seed laser is a CW or pulsed single frequency fiber laser or fiber coupled distributed feedback (DFB) laser at 1  $\mu\text{m}$ , 1.55  $\mu\text{m}$ , or 2  $\mu\text{m}$ . The peak power of the seed laser is only  $\sim 10$ s of mW. Then it is amplified to a few 100s of mW by a Yb-, Er-, or Tm/Ho-doped fiber pre-amplifier. Then it goes into a fiber coupled acoustic-optic modulator (AOM) for pulse switching and shaping. The AOM is usually triggered by the driver of the seed laser for pulse synchronization. Then the signal laser will enter one or multi-stage booster fiber amplifiers, which are usually made with large mode field diameter (MFD) fibers with a core diameter from 10~20  $\mu\text{m}$ . After booster fiber amplifiers, the peak power is raised to 100s W to kW. Then a band pass filter (BPF) will be used to remove the amplified spontaneous emission (ASE) at other wavelengths. The final stage fiber main amplifier is fabricated with the company's proprietary highly (Yb-, Er-, or Tm/Ho) doped silicate glass fibers with even larger MFD (30~50  $\mu\text{m}$ ) and shorter fiber length (20~60 cm). All the fiber amplifiers are polarization maintaining (PM). The linearly polarized output is collimated and then focused to a nonlinear crystal for SHG. Figure 2 shows the pictures of the main fiber amplifier modules which are commercially available at the company. For the 1  $\mu\text{m}$  fiber amplifier module, the length is  $\sim 20$  cm; for the 1.5 and 2  $\mu\text{m}$  fiber amplifier modules, the length is up to 60 cm.

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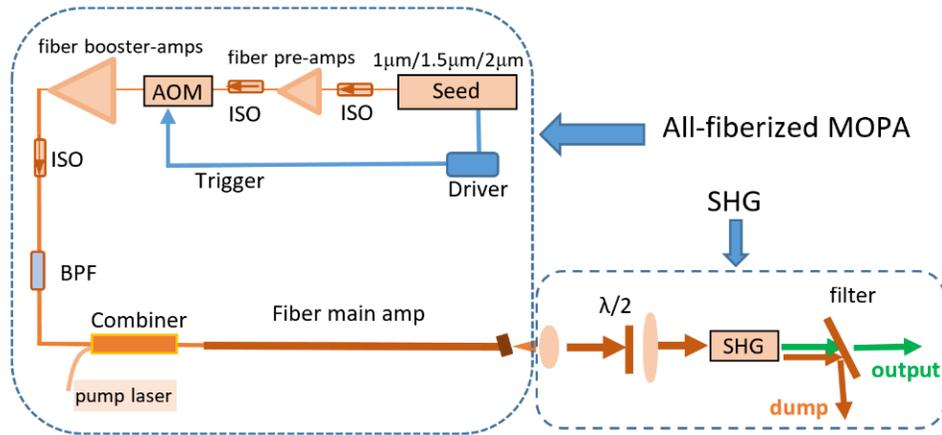


Figure 1. Schematic diagram of the experimental setup. Amps: amplifiers; ISO: fiber isolator; MOPA: master optic power amplifier; BPF: band pass filter;  $\lambda/2$ : half wave plate; SHG: second harmonic generation.

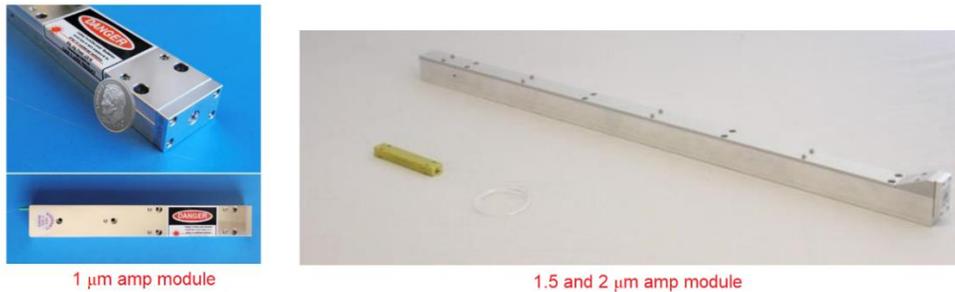


Figure 2. Pictures of the AdValue Photonics large MFD silicate fiber amplifier. Left: 1  $\mu\text{m}$  amplifier module with a length of  $\sim 20$  cm; Right: 1.5 and 2  $\mu\text{m}$  amplifier module with a length of up to 60 cm.

### 3. RESULTS AND DISCUSSIONS

Figure 3 shows output power and pulse energy versus pump power of Yb doped main fiber amplifier. The pulse repetition rate is 10 kHz. At a pump power of 38 W, 15.3 W output power has been achieved. The main fiber amplifier output spectrum measured at a maximum power is shown as an insert in Figure 3. The signal over amplified spontaneous emission (ASE) ratio is better than 40 dB which indicates the ASE level is very low. The output pulse shape measured by a fast photodiode and an oscilloscope is shown in Figure 4 with a pulse duration of 160 ns. With Ophir PE25-C detector, the measured pulse energy is 1.51 mJ which is shown as an insert in Figure 4 (left), corresponding to a peak power of 9.4 kW. The output beam profile is characterized by Ophir Nanoscan which is also shown as an insert in Figure 4 (left). The beam is a single-mode output with excellent beam roundness of better than 95%. The high power 1030 nm output from the main amplifier is collimated and then focused to a LBO crystal for SHG. The LBO crystal is with a Type-I non-critical phase matching (NCPM). It is held by an oven with a temperature setting of  $\sim 187^\circ\text{C}$ . The SHG green (515 nm) laser output at different pump power levels is also shown in Figure 3. At a maximum IR (1030 nm) power of 15.2 W, 5.2 W green output has been achieved. The green laser pulse shape is shown in Figure 4 (right). The pulse width is 93 ns which is much shorter than that of the 1030 nm IR pulse. The green laser pulse energy is 0.52 mJ, corresponding to a peak power is 5.6 kW. The energy measurement is shown as an insert in Figure 4 (right). The green laser beam profile is a clean single mode with a beam ellipticity of  $\sim 87\%$ , which is also shown as an insert in Figure 4 (right). The whole MOPA and SHG parts could be integrated in AdValue Photonics standard laser enclosure which is shown in Figure 5.

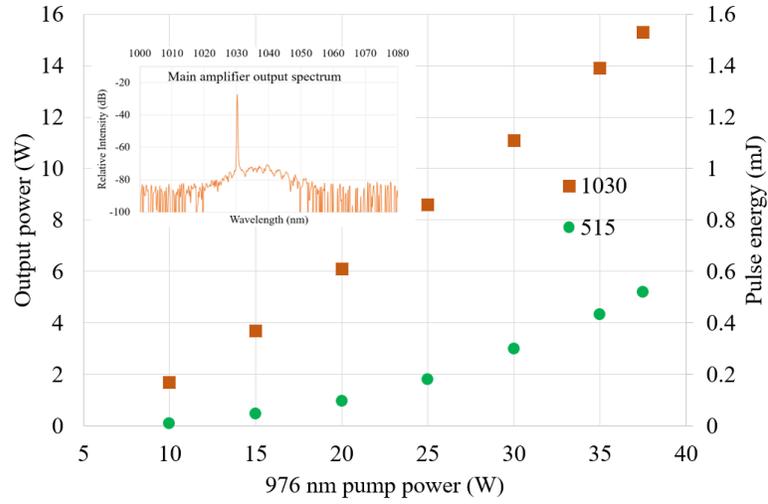


Figure 3. The 1030 nm and 515 nm output power and pulse energy versus 976 nm pump power. The insert is the 1030 nm main fiber amplifier output spectrum measured at the maximum output power.

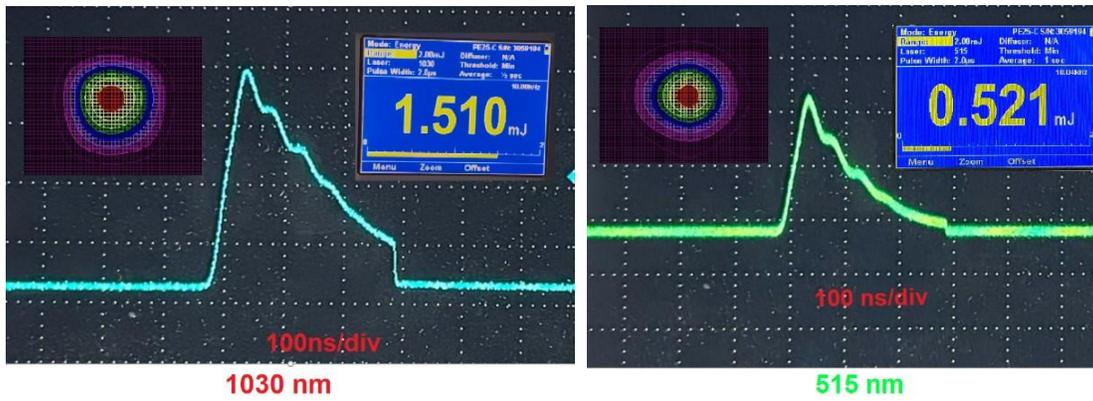


Figure 4. The 1030 nm (left) and 515 nm (right) output pulse shape measured at the maximum output power. The inserts are beam profiles and pulse energy measurements, respectively.



Figure 5. Picture of the AdValue Photonics standard laser enclosure. The size is also shown.

Figure 6 shows the performances of the 1.5  $\mu\text{m}$  Er doped main fiber amplifier and its SHG. For the purpose of higher peak power, shorter pulse duration (6.0 ns) has been selected by 1535 nm seed laser with a pulse repetition rate of 100.8 kHz. Er only doped fiber has much lower absorption at 976 nm than Yb doped fiber. In addition, at this experiment, the gain fiber length is limited to  $\sim 30$  cm for the compact footprint size. Therefore, its slope efficiency is much lower than that of 1030 nm Yb doped fiber amplifier. At a pump power of 154 W, the 1535 nm output power is 12.7 W. The calculated pulse energy is 126  $\mu\text{J}$  with a peak power of 21.0 kW. With a NCPM LBO crystal at  $\sim 110^\circ\text{C}$ , 6.0 W 768 nm output power is obtained. 768 nm pulse is getting even shorter (4.4 ns vs 6.0 ns) than the 1535nm pulse, as shown in Figure 7 (left). The calculated pulse energy is 59.5  $\mu\text{J}$  and peak power is 13.5 kW. The 768 nm laser beam profile measured by Ophir Nanoscan is shown in Figure 7 (right). It is a single mode with a slight beam ellipticity of  $\sim 85\%$ .

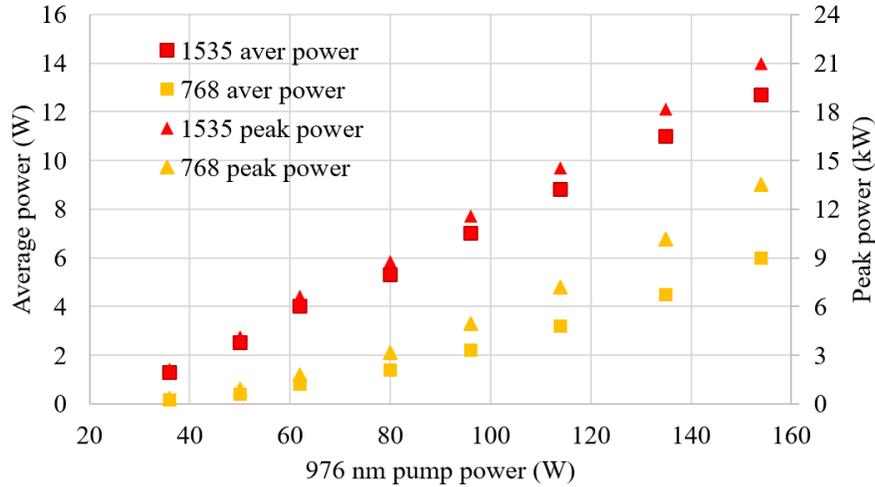


Figure 6. Er doped main fiber amplifier output and its SHG. 1535 nm and 768nm power and peak power vs 976nm pump power.

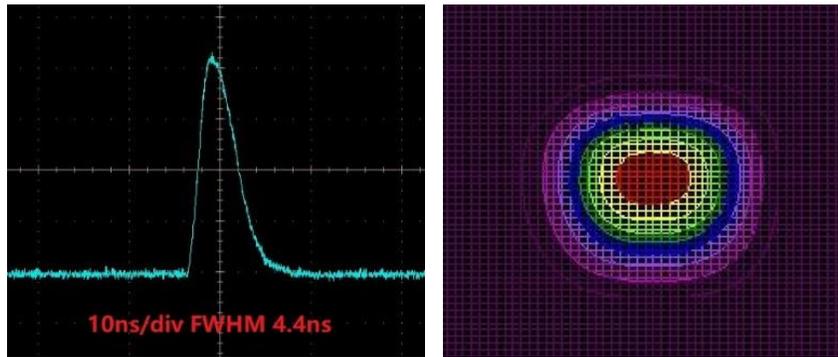


Figure 7. Left: 768 nm laser pulse shape; Right: 768 nm laser beam profile. Both are measured at 4.2 W output.

For the 1871 nm Tm doped fiber amplifier, the pulse repetition rate is 1 kHz. The gain fiber length of the main amplifier is kept short ( $\sim 20$  cm) to avoid re-absorption of the 1871 nm signal laser. Figure 8 shows the main fiber amplifier output pulse energy versus 793 nm pump power. The output pulse energy increases faster at lower pump power and shows significant saturation at high pump power. The 1871 nm pulse energy is 0.90 mJ at 22.8 W pump power; further increasing the pump power to 44.2 W, the maximum pulse energy is 1.1 mJ. The output laser spectrum at 1.1 mJ is shown as an insert in Figure 8. Since 1871 nm is significantly of the gain peak ( $\sim 1900$  nm) of the Tm doped fiber, the signal over ASE ratio is less than 9 dB, for which the majority average power is ASE rather than the 1871 nm signal laser. The pulse shape and

pulse train at 1.1 mJ are shown in Figure 9. The pulse duration is ~170 ns, corresponding to a peak power of ~6.5 kW. The beam profile and pulse energy measurement at 1.1 mJ are shown as inserts in Figure 9 (left).

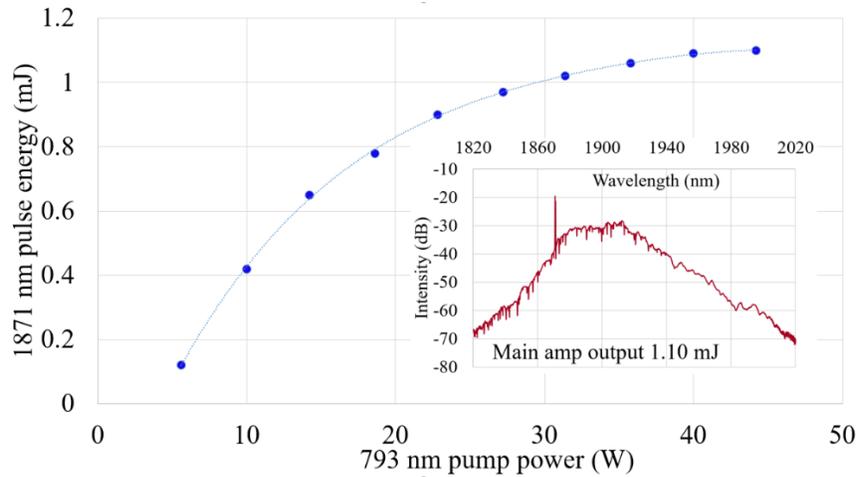


Figure 8. Main amplifier 1871 nm pulse energy VS 793 nm pump power. Insert: output spectrum.

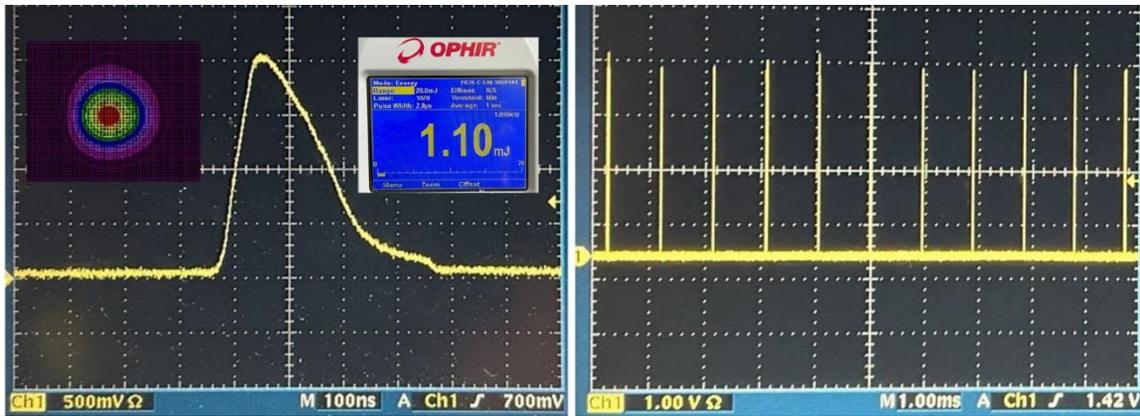


Figure 9. Pulse shape and pulse train at 1.1 mJ pulse energy output. Inserts (in the left figure): beam profile and pulse energy measurement.

The 1871 nm output beam from the main fiber amplifier is collimated and focused to a nonlinear crystal for SHG. The nonlinear crystal is a Periodically Poled Lithium Niobate (PPLN). Since the temperature control oven for the PPLN is not available at the time of the test, the PPLN is kept at ~32 °C by a water chiller temperature control. To avoid damage, the output pulse energy is limited to ~100 μJ. As we know, the 1871 nm DFB seed wavelength can be tuned by TEC control of the driver board. To investigate the SHG bandwidth of the PPLN, the DFB temperature has been tuned from 15 °C to 35 °C, which is shown in Figure 10. From 15 °C to 35 °C, the SHG wavelength is tuned from 934.3 nm to 936.0 nm, corresponding to a fundamental seed wavelength tuning from 1868.6nm to 1872.0 nm. Figure 11 shows SHG efficiency versus DFB temperature tuning. For 100 μJ fundamental laser input pulse energy, the best efficiency is obtained at 22°C (934.9 nm) with a pulse energy of 22 μJ, corresponding to a conversion efficiency of 22%. At 15 °C (934.3 nm) and 32 °C (935.7 nm), the efficiency dropped to ~15%. Therefore, we estimate the 60% efficiency bandwidth for the current PPLN is ~2.8 nm@1871 nm. Much higher efficiency and even better bandwidth will be expected if an oven is used to control the temperature of the PPLN more precisely. The experiment with higher 1871 nm pulse energy input for SHG is still in progress. The second harmonic generation beam profile detected by an IR viewer

card is also shown in Figure 11. It is a single mode laser with an excellent beam roundness. Table 1 is a summary of the all three laser experiments, except for the 935 nm SHG generation. The high power SHG generation with PPLN is still in progress and will be reported separately.

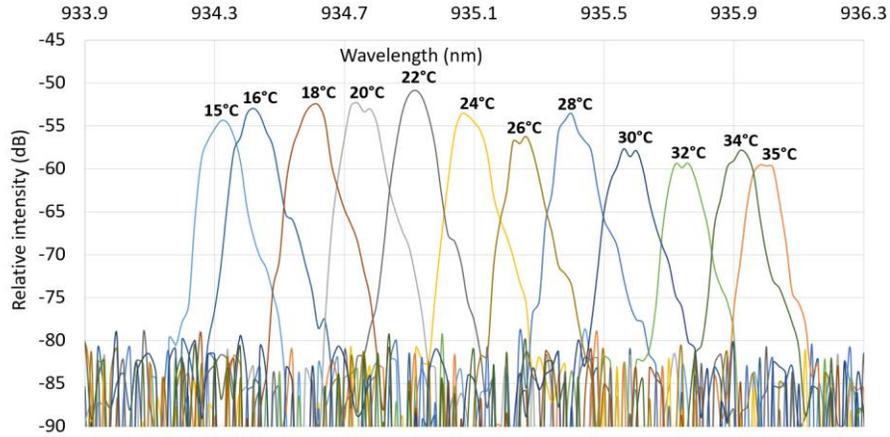


Figure 10. PPLN SHG wavelength versus DFB seed temperature.

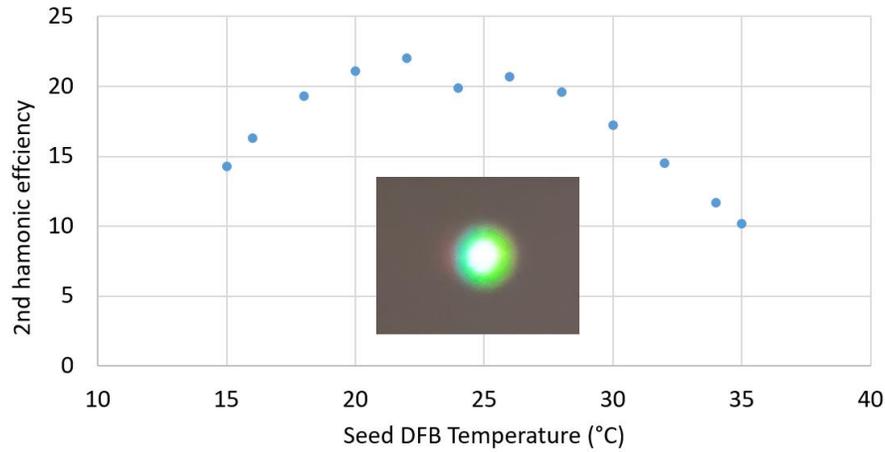


Figure 11. PPLN SHG efficiency versus DFB seed wavelength tuning by TEC. Insert: beam profile of the SHG (935 nm) detected by a IR viewer card.

Table 1. Summary of the test.

$\lambda$ (nm)	Average power (W)	Pulse repetition rate (kHz)	Pulse energy	Pulse duration (ns)	Peak power (kW)
1030	15.3	10	1.51 mJ	160	9.4
515	5.2	10	0.52 mJ	93	5.6
1535	12.7	100.8	126 $\mu$ J	6.0	21.0
768	6.0	100.8	59.5 $\mu$ J	4.4	13.5
1870	>>1.1 w/ASE	1.0	1.10 mJ	170	6.5

## 4. CONCLUSIONS

In summary, with the company's proprietary highly Yb-, Er-, or Tm/Ho-doped large MFD silicate glass fiber amplifiers, we have demonstrated all fiber based high energy single frequency laser at 1030 nm, 1535 nm and 1871 nm, respectively. Up to mJ pulse energy has been achieved with tens of kW peak power. SHGs at 515 nm, 768 nm and 935 nm have been achieved by using a LBO or PPLN crystal with multi-Watt average power and multi-kW peak power. In addition, wavelength tuning has been accomplished by the TEC control of the DFB seed laser. Since Yb-, Er- and Tm/Ho- doped fibers all have broad gain spectra and wide wavelength tuning range, the current laser systems could be definitely extended to other wavelengths and meet more applications.

## ACKNOWLEDGEMENTS

The authors acknowledge the funding support from National Aeronautics and Space Administration (NASA) with the contracts: 80NSSC24CA14, 80NSSC21C0459 and 80NSSC23PB295.

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