Monolithic narrow linewidth pulsed fiber laser transmitters in the C- and L-band for coherent LIDAR applications

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Introduction

LIDAR and active remote sensing spectroscopy can benefit greatly from laser transmitters based on high power narrow linewidth pulsed lasers that are monolithic, all-fiber-based construction, and readily scalable in power using a fiber MOPA configuration. For these applications, a high precision measurement highly depends on the linewidth or coherence length of the fiber laser pulses. Therefore, the fiber laser pulses should have large enough pulse duration (100 ns-500 ns) to take full advantage of the narrow linewidth in a transform-limited pulse. In longer ns pulses that are single spatial mode and very narrow linewidth, laser power scaling in fiber amplifiers has been difficult due to optical nonlinearities, primarily from stimulated Brillouin scattering (SBS). There are three main approaches to increase the SBS threshold. One is to reduce the overlap integral between the optical and acoustic fields as accomplished by proper index and glass profile design. The second is using a temperature gradient or strain gradient to alter the SBS spectrum along the fiber (which essentially shortens the interaction length). The third is to make fibers with large mode areas (LMA) to reduce the optical intensity in the core.

In this paper, we have designed and fabricated large core SM PM highly Er/Yb co-doped phosphate glass fibers (LC-EYPhF) with core sizes of 25 μm and 30 μm in order to develop high stimulated Brillouin scattering (SBS)-threshold, single-mode (SM), polarization maintaining (PM), high power fiber amplifiers, especially suitable for long pulses with transform-limited linewidth. Phosphate glass fibers enable higher dopant densities (than silica fibers), and make possible much shorter fiber lengths without sacrificing optical gain. This allows decreased interaction length and increased SBS threshold. Based on this large core, short length fiber, we have implemented a monolithic pulsed fiber laser MOPA at 1530 nm, and achieved a peak power of 2.02 kW for 105 ns pulses with transform-limited linewidth.

Laser spectroscopy of O_2 A band in the range of 760-770 nm can be adapted to determine atmospheric pressure and temperature by analyzing the shape and strength of the A band absorption lines. The operating wavelength 1530 nm of the fiber laser can be frequency-doubled to satisfy this remote sensing application; namely, laser spectroscopy of diatomic oxygen A band in the range of 760 nm-770 nm. We have achieved high-energy pulses at

1530 nm which have been successfully frequency doubled by using a periodically poled lithium niobate (PPLN) crystal, resulting in a high peak power of 271 W for SHG pulses at 765 nm. Moreover, in the L band, more than 80 µJ per pulse at 1572 nm with 1-2 µs pulse width and transform-limited linewidth have been achieved by using a similarly constituted monolithic fiber laser MOPA system, oriented towards CO_2 coherent remote sensing.

Experimental Results

We have developed two kinds of single-frequency fiber laser seed sources. The first is an all fiber Q-switching laser using fiber stress birefringence induced by a piezoelectric. In this method, a piezo compresses the fiber creating stress birefringence, and this birefringence acts as a waveplate, changing the polarization state of the light in the fiber. This Q-switch mechanism is similar to using an electro-optic modulator, where the polarization is modulated to switch the laser between high and low feedback states. However, this method is more compact and much more economical. The pulse width can be tuned from ~10 ns to sub-microsecond by tuning the repetition rate and the pump level. The repetition rate can be tuned from 10's Hz to > 600 kHz. The pulse shape over the full range of repetition rates is Gaussian-like.

The second type is a nanosecond single-frequency fiber laser seed that consists of a directly modulated fiber laser. The CW single-frequency fiber lasers are NP Photonics' CW single-frequency fiber lasers. Two fiber-coupled EOMs with high bandwidth (up to > 10 GHz) and a superior extinction ratio (ER) of 40 dB were used. An arbitrary waveform generator (AWG) generates the electrical pulses with smooth front edge in order to suppress front edge steepening, which, if not done properly, can result in dynamic saturation in a cascaded fiber amplifier system that is oriented towards high power/energy pulse scaling. The repetition rate is set by the trigger and can be up to 38 MHz. Two EOM electrical drivers produce the final RF voltages by amplifying the electrical pulses to the half-wave (V_π) voltage level of the EOMs. The two pulsed seeds operate at a single frequency, and the linewidth of the fiber laser pulses are very close to transform limited.

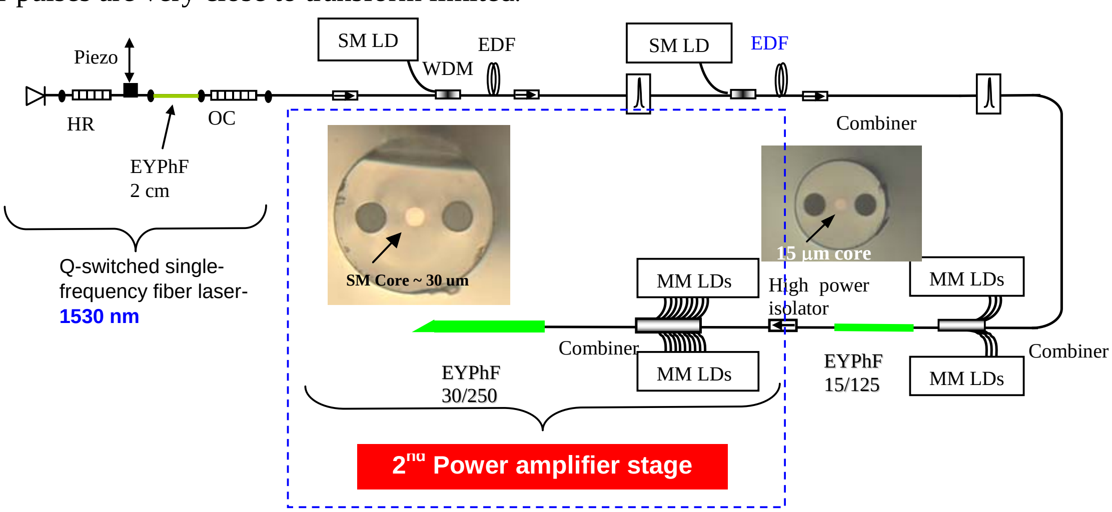

Fig. 1 Schematic of the monolithic Q-switched pulsed fiber laser based on the new large core highly Er/Yb co-doped phosphate fiber 30/250.

Fig. 1 shows the schematic of the monolithic pulsed fiber laser in MOPA, which has been designed and implemented for high power/energy with long pulse duration (> 100ns) and narrow linewidth. The pulse seed is a Q-switched fiber laser seed at 1530 nm. Previously, we have achieved > 300 W peak power for 153 ns pulses by using 15 μm core phosphate fiber. Here, we have successfully fabricated another new large core SM PM highly Er/Yb co-doped phosphate glass fiber 30/250 with core NA 0.0395, whose cross-section is shown in Fig. 1. Importantly, this fiber has real SM performance due to the low core NA=0.0395, achieved by precisely controlling the glass refractive indices and made into a gain fiber by a rod-in-tube preform method. The high Er/Yb co- doping concentration in phosphate glass fibers results in the highest gain per unit length ~ 5 dB/cm in the C-band. According to theoretical estimation, the optimized length of this fiber is about 15 cm. By using this 30/250 μm fiber, a 2nd power amplifier stage has been implemented.

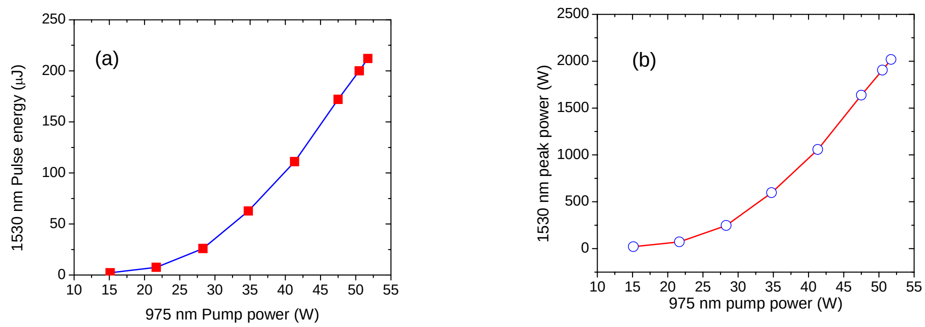

Fig. 2 (a) Output pulse energy of the 2nd power fiber amplifier at different pump power; (b) Output peak power of the 2nd power fiber amplifier at different pump power.

Fig. 2 (a) shows the output pulse energy at different pump powers for the 2nd amplifier stage when the input pulse duration is 112 ns at 1530 nm with repetition rate of 8 kHz. The highest pulse energy is 0.212 mJ, and it is free of SBS effects. The amplified pulse width of 105 ns is slightly narrower than the seed pulse width of 112 ns, and they are both Gaussian-like. Fig. 2 (b) shows the output peak power from the 2nd amplifier stage at different pump powers. It is worth noting that the highest peak power can reach 2.02 kW for 105 ns pulses with repetition rate of 8 kHz.

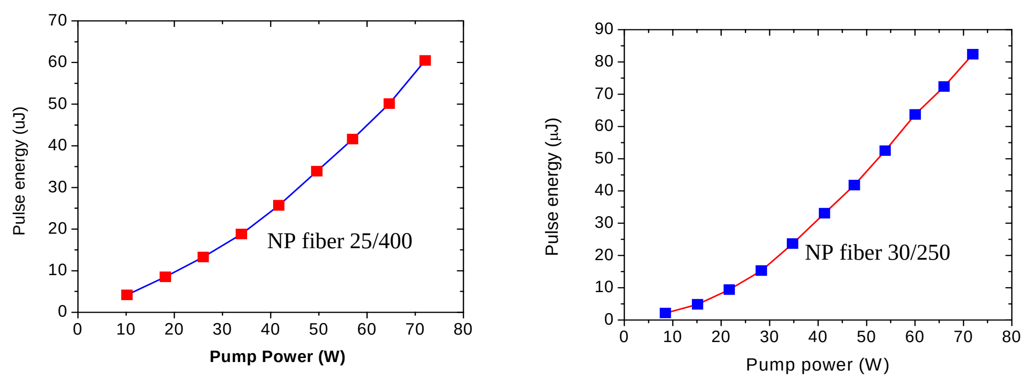

Fig. 3 Pulse energy results at 1572 nm for two NP fibers in the 2nd power amplifier stage at different pump power levels

For high-energy fiber laser pulses at 1572 nm, the directly modulated fiber laser pulse seed was used. Two pre-amplifier stages were used to scale the pulse seed. In these two pre-amplifier stages, commercially available active fibers with regular core sizes (~ 9 μm) were used. After pre-amplifier stages, the measured pulse energy can be up to μJ level (1.5-2 μJ) when the rep. rate is 10 kHz and pulse width 1-2.5 μs. We used highly Er/Yb co-doped phosphate fiber 15/125 in the 1st power amplifier stage. When the amplified signal directly emanates from this NP fiber (angle cleaved end), the maximum SBS-free pulse energy can be up to ~ 22 μJ when the rep. rate is 10 kHz. The pulse width for the amplified pulses decreased slightly (1-5%) (~ 2.6 μs). When the amplified signal emanates from a delivery fiber (15 um core) passing through an isolator and an ASE filter, the SBS-threshold is about 7.5 μJ. For the 1st power amplifier stage, we set the pulse energy in the range of 5-6 μJ as the seed of the 2nd power amplifier stage. We built the 2nd amplifier stage by using two large core highly Er/Yb co-doped phosphate fibers 25/400 and 30/250, respectively. The amplified signal emanates from the end facet of angle cleaved fibers. Fig. 3 shows the pulse energy results for two NP fibers in the 2nd power amplifier stage when using different pump power levels. One can see that for 25/400 fiber, the maximum SBS-free pulse energy is ~ 60.5 μJ. For 30/250 fiber, the maximum SBS-free pulse energy is ~ 82.4 μJ.

Conclusions

In summary, we have successfully fabricated large core SM PM highly Er/Yb co-doped phosphate glass fibers 25/400 and 30/250. By using these new specialty fibers in the 2nd power amplifier stage, we have achieved the highest peak power of 2.02 kW for 105 ns pulses at 1530 nm with transform-limited linewidth; the corresponding pulse energy is about 0.212 mJ, which is the highest value for monolithic fiber laser pulses with longer ns pulse width and transform-limited linewidth. The system features specialized high SBS threshold fiber amplifiers based on highly co-doped phosphate glass fibers, and represents an important new development for coherent LIDAR and remote sensing applications. Moreover, the high energy fiber laser pulses at 1572 nm with transform-limited linewidth using a similarly configured monolithic fiber laser MOPA system can be directly applied to CO_2 coherent remote sensing.