intensity and the poor signal-pump overlapping ratio due to different refractive indices, especially from a long crystal. In order to achieve higher pulse energy at 3 µm regime, an OPCPA system was tested. The OPCPA system was based on a 20 mm long MgO-doped PPLN crystal with a grating period of 29.98 µm. The pump power was continuously tuned by a combination of a half waveplate and a polarizer. Up to 19.6 W pump power at repetition rate of 100 kHz was delivered into the PPLN crystal. Both pump beam from high energy fiber laser and idler beam from OPG were stretched by a grating stretcher to ~20 ps and then focused into the PPLN crystal with beam diameters of 330 µm. The pump beam delay was carefully adjusted to make it overlapped with 3 µm beam thus the output power was optimized. The amplified signal power and idler power as a function of pump power are shown in Fig. 4. Up to 3.77 W idler power (37.3 µJ pulse energy) and 6.3W signal power were obtained with 19.6 W pump power. The spectra for idler and signal beams at maximum output power level from OPCPA are shown in Fig. 5. The amplified signal beam had a central wavelength of 1655 nm and a FWHM spectrum bandwidth of 38 nm [Fig. 5(a)]. The idler beam had a central wavelength of 2766 nm and a FWHM spectrum bandwidth of 91 nm [Fig. 5(b)]. The output pulse train of signal was measured with a 10 GHz InGaAs photodetector [Fig. 6(a)]. The 100 kHz pulse train of idler output was measured by a fast InAs detector [Fig. 5(b)].

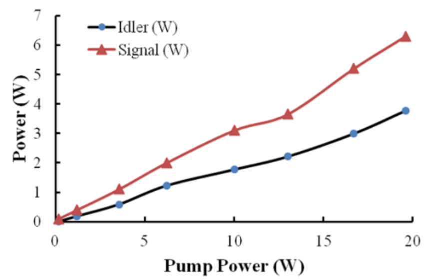

Fig. 4. OPA output power as function of pump power.

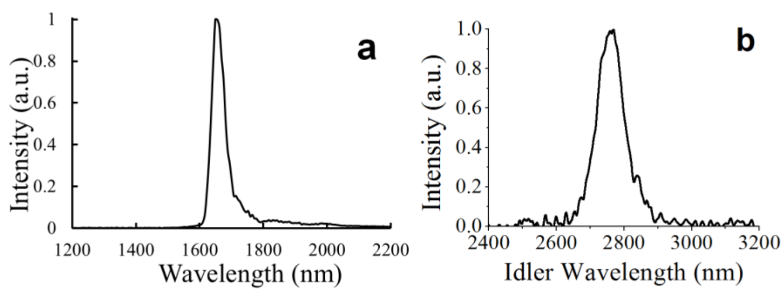

Fig. 5. OPA output spectra for (a) Signal wavelength; (b) Idler wavelength.

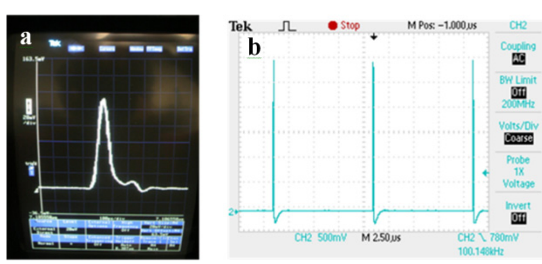

Fig. 6. OPA output pulse train for (a) Signal wavelength; (b) Idler wavelength.

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5. Er:ZBLAN fiber amplifier

Finally, the 3 µm pulse train from OPCPA was injected into the last stage of high energy Er:ZBLAN fiber amplifier to further boost the pulse energy. The setup of high energy amplifier is shown in Fig. 7(a). The active medium is a 5 m-long Er-doped double clad ZBLAN fiber with a core diameter of 33 µm and a pump cladding diameter of 330 µm (OgMentum). The Er-ion concentration is 6 mol%. Both ends of the fiber were polished with an angle of around 10 degrees to avoid parasitic lasing. The 3 µm pulse train from OPA was focused by an antireflection (AR) coated CaF_2 lens onto one end of the gain fiber. In order to achieve higher pulse energy, a germanium acousto-optic modulator (AOM) was used as a pulse picker to lower the pulse repetition rate. A diffraction efficiency of up to 90% at 2.8 µm was measured, including the transmission losses from AOM input and output surfaces. The optical rising and falling time of the AOM was 100 ns/mm beam size and the amplifier was adjusted to be operated when the RF power to the AOM was on. The reverse pumping scheme was used in this experiment. Up to 11W pump beam from a fiber coupled laser diode with central wavelength of 975 nm was delivered into the gain fiber. The pump beam was collimated first and then focused onto the end of the Er:ZBLAN fiber with a beam diameter of 280 µm. The pump beam was reflected by a dichroic mirror which had a high reflectivity at pump wavelength and high transmittance at signal wavelength near 3 µm regime. The amplified 3 µm wavelength passed through the dichroic mirror and then was collimated by another AR coated lens to output.

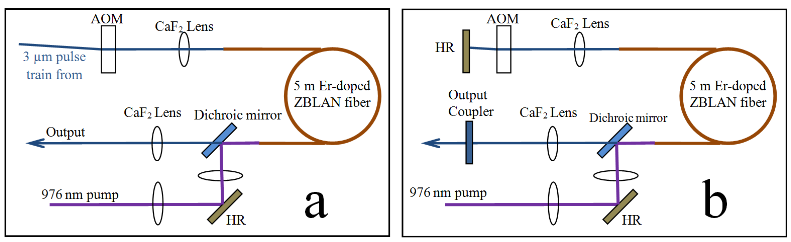

Fig. 7. Er:ZBLAN fiber experimental setup for (a) high energy amplifier and (b) Q-switched 3 µm fiber lasers.

To study the amplification capability of Er-doped ZBLAN fiber pulse amplifier, especially at low repetition rates, the Q-switched operation of 3 µm fiber laser was tested. As shown in Fig. 7(b), the amplifier was modified to a Q-switched laser cavity by adding two cavity mirrors. One end of the cavity was a gold mirror reflector. The other end was an output coupler mirror with a transmittance of 40%. When the AOM was running at 1 kHz repetition rate, the laser output nanosecond pulse with energy of up to 201µJ at pump power of 5W. The output pulse energy as a function of pump power is shown in Fig. 8(a). A typical output pulse train captured by a fast InAs photodetector with the highest pulse energy of 201 µJ is shown in Fig. 8(b). The measured FWHM pulse duration was 33.5 ns. We believed that the pulse duration was mainly limited by the AOM rising time. Figure 8(c) shows a typical output spectrum. The central wavelength was 2784.5 nm and bandwidth was around 0.4 nm. The amplified spontaneous emission (ASE) background was also measured. When Q-switch was off all the time, the measured ASE power level was less than 10 mW, which was smaller than 5% of the averaged output power at 1 kHz Q-switched operation. In the experiment of Q-switched operation, the pump power was limited to 5W to protect the Er:ZBLAN fiber from possible thermal damage.

In the Er:ZBLAN fiber amplifier experiment, the AOM was used as a pulse picker to reduce the pulse repetition rate to 10 kHz. The measured average power of 3 µm seeding pulses was 280 mJ right before the fiber end, corresponding to a pulse energy of 28 µJ. Up to 10.6 W 976 nm pump power was delivered into the gain fiber. The amplifier boosted the pulse energy to 84 µJ and boosted the average power to 840 mW. The output pulse energy as

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a function of pump power is shown in Fig. 9(a). The output spectrum with maximum pulse energy obtained in this experiment is shown in Fig. 9(b). After amplification, the spectrum bandwidth was narrowed to 55 nm which was mainly due to the gain narrowing effect from Er:ZBLAN fiber. Er:ZBLAN fiber has a gain peak near 2.8 μm. Background noise was also estimated in this experiment. When there was no seeded pulses, ASE background of up to 35 mW was observed at the maximum pump power of 10.6W. Considering the ASE power can be further suppressed when the amplifier is seeded, the ASE was remained at a low level comparing with the amplified output power of 840 mW with the same pump power. The seed pulse duration was around 20 ps. As ZBLAN fiber has a GVD of 62 fs^2/mm near 3 μm regime [15], after passing through a 5m-long ZBLAN fiber the pulse duration can be stretched for an extra 4 ps in the worst case. Thus, the amplified pulse duration was estimated to be less than 24 ps. To the best of our knowledge, the pulse energy of 84 μJ measured in this experiment is the highest pulse energy obtained from a picosecond chirped ultrafast Er:ZBLAN fiber laser/amplifier.

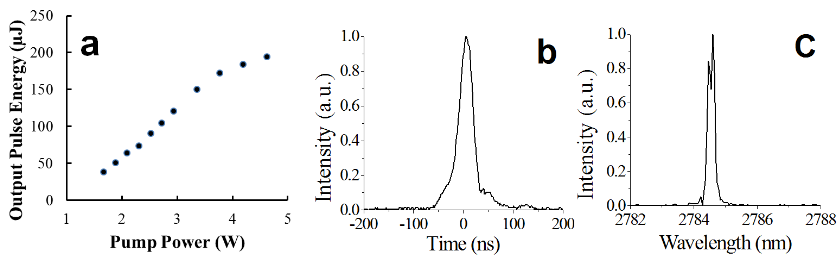

Fig. 8. Experiment result from Q-switched 3 μm Er:ZBLAN fiber laser. (a) Pulse energy as a function of pump power at 1 kHz; (b) Output pulse train with a pulse energy of 201 μJ; (c) A sample laser output spectrum.

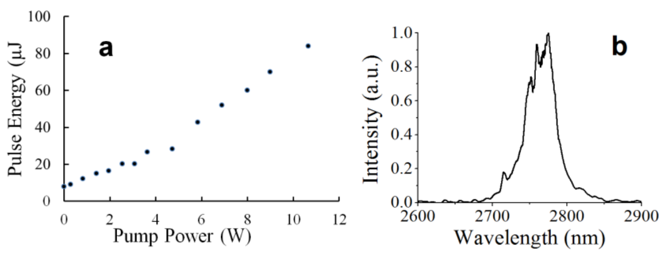

Fig. 9. Experiment results from 10 kHz Er:ZBLAN fiber amplifier. (a) Output pulse energy as a function of pump power; (b) A sample output spectrum.

5. Conclusions

In conclusion, we demonstrated the highest pulse energy (84 μJ) ultrafast 3 μm Er:ZBLAN fiber laser/amplifier system. The 103 fs seed laser pulse train was generated and amplified through MgO-doped PPLN OPG and OPA systems with pulse energy of 12.4 μJ and at a repetition rate of 100 kHz. To the best of our knowledge, this is the highest pulse energy obtained from a fiber laser pumped OPA system in the MIR spectrum range (around 3μm). An Er:ZBLAN fiber amplifier was used to further boost the pulse energy to 84 μJ with a broadband spectrum (55 nm). The output pulse duration was about 24 ps. A pulse energy of up to 201 μJ obtained in the experiment of Q-switch operation indicates the potential for further scaling of the energy at 3 μm. Further scaling of the pulse energy and reduction of the pulse width is ongoing in PolarOnyx.

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