12 W *Q*-switched Er:ZBLAN fiber laser at 2.8 μm

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A diode-pumped, actively *Q*-switched 2.8 μm fiber laser oscillator with an average output power of more than 12 W has been realized through the use of a 35 μm core erbium-doped ZBLAN fiber and an acousto-optic modulator; to our knowledge, this is the first 3 μm pulsed fiber laser in the 10 W class. Pulse energy up to 100 μJ and pulse duration down to 90 ns, corresponding to a peak power of 0.9 kW, were achieved at a repetition rate of 120 kHz. © 2011 Optical Society of America

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Pulsed lasers with high average power at wavelengths around 3 μm have potential applications in medicine because the absorption coefficient of biological tissue containing water is very high at such wavelengths [1,2]. Diode-pumped Er-doped fluoride fiber lasers are among the most promising candidates for such purposes [3,4]. In recent years, considerable efforts have been made to increase the cw power capability of 3 μm Er-doped fluoride fiber lasers [5–12], and the maximum power output has now exceeded 20 W [8,11]. Pulsed operation of Er-doped fluoride fiber lasers at pulse durations from nanoseconds to microseconds has also been demonstrated [13–21], as we summarize below. Frerichs *et al.* reported the first demonstration of a *Q*-switched 3 μm fiber laser, obtaining an average power of 500 μW with a peak power of 2.2 W by using an acousto-optic *Q* switch [13]. Passive *Q* switching and mode locking have also been demonstrated with an average power of a few milliwatts by using InAs or gallium saturable absorbers [14,16]. Afterward, an improved output power of nearly 400 mW on average and 700 W at peak was achieved with a mechanically *Q*-switched fiber laser that utilizes a 90 μm core multimode fiber [19,20]. Recently, the average output power has been further increased to 2 W [21]. In addition, a peak power of 2 kW has been demonstrated at a low repetition rate by using a 15 μm core near-single-mode fiber pumped by a flashlamp-pumped Ti:sapphire laser [17]. Although these pulsed 3 μm fiber lasers can provide extremely high peak power, the average power is still low in comparison with that of cw lasers.

In this Letter, we report the highest average output power obtained to date for a pulsed 3 μm fiber laser. *Q*-switched operation with an average output power of greater than 12 W was achieved at repetition rates from 120 to 300 kHz by means of a passively cooled Er-doped ZBLAN fiber and an acousto-optic *Q* switch.

A schematic diagram of the developed *Q*-switched Er-doped ZBLAN fiber laser is shown in Fig. 1. A 2.1 m multimode core double-clad fiber with ZBLAN-based fluoride glass (FiberLabs Inc.) was used as the active medium. The specifications of the fiber core are as follows: diameter, 35 μm; NA, 0.12; and ErF_3 concentration, 6 mol.%. The inner D-shaped cladding of the fiber had diameter of 350 μm and NA of >0.5, and the outer polymer cladding of the fiber had diameter of 450 μm. The pump absorption in the inner cladding was measured to be ~6 dB/m at 0.975 μm. The fiber was conductively cooled by placing it between aluminum plates that were maintained at a constant temperature of 20 °C by water cooling, and the ends of the fiber were held by fiber chuck holders with a U-shaped groove. To cool the ends conductively, the output facet was polished into a slightly convex shape and placed in contact with one side of a sapphire plate of 2 mm in thickness [10]. The other side of the sapphire plate had an antireflection coating. To prevent moisture in the air from inducing optical damage at the output facet of the fiber, the fiber was placed in a nitrogen-purged enclosure [7]. The other end of the fiber was polished at an angle of 8° to avoid parasitic lasing. A Fabry–Perot laser cavity was formed between a high-reflection (HR) mirror and the output facet of the fiber. Two antireflection-coated YAG lenses with focal lengths of 8 mm were used to collimate the beam. A germanium acousto-optic modulator (AOM) was placed in the cavity as a *Q* switch and was driven by a pulsed RF source at 81 MHz. The AOM has a diffraction efficiency of >50%, an optical rise and fall time of 100 ns, and an optical transmission loss of 2% at 2.8 μm. The cavity was adjusted so that lasing occurred when the RF power to the AOM was off. A thin quartz quarter-wave plate (with a transmission loss of 5% at 2.8 μm) was inserted between the fiber and the AOM to compensate for the birefringence of the fiber because the diffraction efficiency of the AOM depends on polarization. A fiber-coupled laser diode was used as a

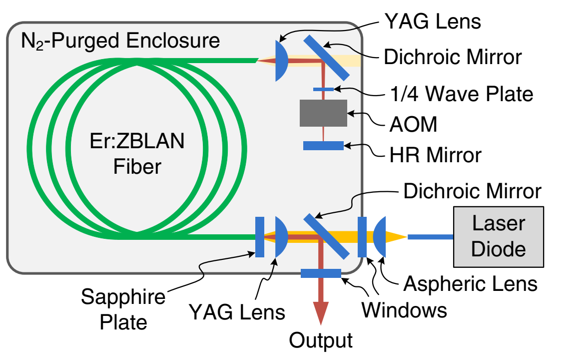

Fig. 1. (Color online) Schematic diagram of actively *Q*-switched Er-doped ZBLAN fiber laser pumped by a fiber-coupled laser diode.

cw pump source and was operated at a wavelength around 0.975 μm. The output fiber of the laser diode had a core diameter of 200 μm and NA of 0.22. A maximum pump power of 75 W was launched into the inner cladding of the fiber through an aspheric collimator lens, an airtight window, a dichroic mirror, the YAG lens, and the sapphire plate. The output beam was directed outside the enclosure by being reflected off the dichroic mirror, and was measured on a thermal power meter, a fast InAs photodetector, and a scanning spectrometer with a focal length of 110 mm.

In cw operation where the AOM was inserted in the cavity but was turned off, the output power increased linearly as the pump power was increased, and the slope efficiency was approximately 17% (with respect to launched pump power). A 12.6 W output power was obtained at the maximum pump power of 75 W. The center wavelength of the output was measured to be about 2.8 μm.

In Q-switched operation, output pulses with a repetition rate corresponding to the switching rate of the AOM were obtained in a range of 120 to 300 kHz at the maximum pump power. At a switching rate less than 120 kHz, prelasing before the AOM was turned off was observed because the gain offset the loss produced by the AOM. At a switching rate greater than 300 kHz, the pulse buildup time exceeded the switching period. Figure 2 shows a typical output pulse train at the lowest repetition rate of 120 kHz, which was measured by using the InAs photodetector with a response bandwidth of >50 MHz. The average output power was 12.4 W, resulting in an average pulse energy of 103 μJ. The fluctuation of the pulse energy was less than $\pm 15\%$. On the other hand, the average output power, which was measured on the power meter with a response time of 1 s, had no significant fluctuations; the fluctuation during operation for 10 min was less than $\pm 0.5\%$. The pulse duration defined as the FWHM was measured to be between 80 and 100 ns, with an average value of 90 ns. The average peak power was calculated to be 0.9 kW from the pulse waveform. A typical laser spectrum is shown in Fig. 3. Although the shape of the spectrum changed over time, the center wavelength did not change significantly from 2.8 μm. The spectral spread also varied over time between 2 and 5 nm (FWHM). Figure 4 shows average power, pulse duration, and pulse energy as a function of the repetition rate in the range from 120 to 300 kHz. The average power was only weakly dependent on the repetition rate, resulting in an inversely proportional relation between the pulse energy and the repetition rate. Accordingly, the pulse energy decreased to 42 μJ at 300 kHz. In contrast, the pulse duration increased with the repetition rate; a pulse duration of 230 ns was measured at 300 kHz.

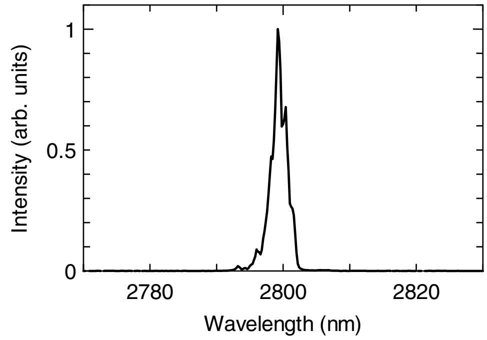

Fig. 3. Typical laser spectrum at a repetition rate of 120 kHz.

We used a multimode fiber core considerably larger than typical single-mode fluoride fibers in order to obtain high pulse energy by avoiding high gain, which leads to amplified spontaneous emission loss and parasitic lasing, and also to prevent optical damage to the fiber due to high peak power. As a result, the maximum pulse energy of ~100 μJ was obtained, but the lower limit of the repetition rate was attributable to the low diffraction efficiency of the AOM. Higher pulse energies can possibly be achieved by lowering the repetition rate because the peak laser intensity on the fiber was estimated to be ~100 MW/cm^2, which is 1 order of magnitude lower than that obtained by Dickinson *et al.* from a 200 ns pulsed ZBLAN fiber laser [17]. In fact, we did not find any damage to the fiber in the course of the present experiments. We also attempted to use a first-order diffracted beam from the AOM as the intracavity beam in order to achieve higher modulation depth, but we have not obtained satisfactory results because the output power decreased drastically due to the low diffraction efficiency of the AOM.

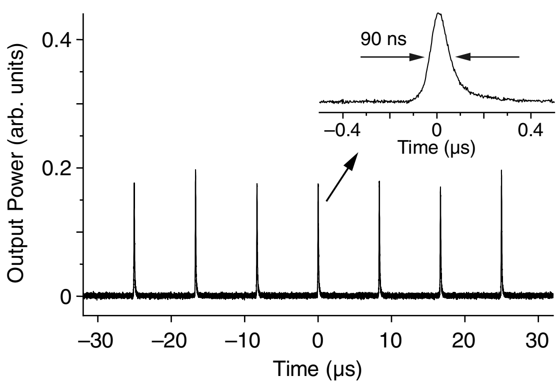

Fig. 2. Typical output pulse train from the Q-switched fiber oscillator at a repetition rate of 120 kHz. Inset: a pulse waveform.

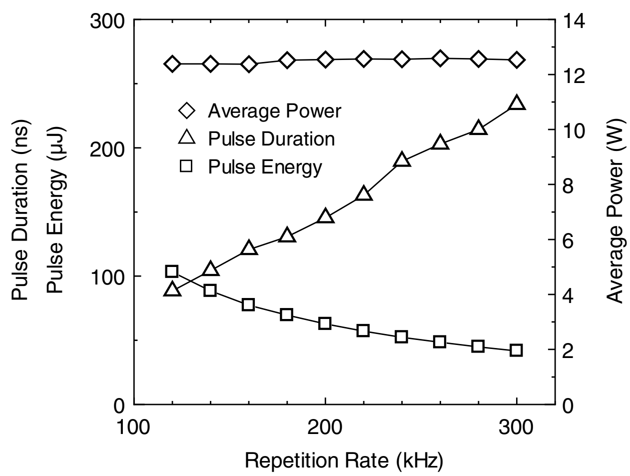

Fig. 4. Average power, pulse duration, and pulse energy as a function of repetition rate.

In summary, we have demonstrated actively *Q*-switched operation of a 2.8 μm Er-doped ZBLAN fiber laser with an average output power of more than 12 W at repetition rates from 120 to 300 kHz. A maximum pulse energy of ~100 μJ was obtained, although higher energy operation at a lower repetition rate was unsuccessful due to the low modulation depth of the AOM. Increases in the pulse energy and the peak power are expected to be possible by improving the *Q*-switching device.

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