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Actively Q-switched dual-wavelength pumped Er^{3+}:ZBLAN fiber laser at 3.47 μm

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We demonstrate the first actively Q-switched fiber laser operating in the 3.5 μm regime. The dual-wavelength pumped system makes use of an Er^{3+} doped ZBLAN fiber and a germanium acousto-optic modulator. Robust Q-switching saw a pulse energy of 7.8 μJ achieved at a repetition rate of 15 kHz, corresponding to a peak power of 14.5 W. © 2018 Optical Society of America

OCIS codes: (060.2390) Fiber optics, infrared; (060.2410) Fibers, erbium; (060.3510) Lasers, fiber; (140.3480) Lasers, diode-pumped; (140.3540) Lasers, Q-switched.

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Interest in mid-infrared fiber lasers has increased recently due to their versatility for a large number of applications in medicine [1, 2], remote sensing [3–5] and materials processing [6]. Lasers that operate around 3.5 μm are particularly interesting due to their overlap with absorption lines of molecules containing C-H or N-O bonds. This allows for their interaction with molecules such as methane and ethane while having low attenuation by the background atmosphere. One area of continued development is Er^{3+} doped fiber lasers operating around 3.5 μm that use the dual-wavelength pumping (DWP) technique [7] shown in Figure 1. The DWP method uses the long lifetime of the $^4I_{11/2}$ level to establish a large population of ions in this state when pumped with 977 nm. We refer to the pumped state as the virtual ground state (VGS). A 1973 nm pump is then used to excite ions from the VGS to the upper lasing level $^4F_{9/2}$. 3.5 μm lasing to the $^4I_{9/2}$ is followed by a transition back to the $^4I_{11/2}$ virtual ground state via fast multiple phonon decays. Ions are then recycled by the 1973 nm pump through the VGS and upper lasing level.

Since the first demonstration of the DWP scheme [7], a number of advances have been made. This includes increasing the output power, demonstrating wavelength tunability and new understanding of the dynamics of these lasers [8–11]. Maes et al. [12] used an all fiber geometry to demonstrate an output power of 5.6 W at 3.55 μm with a total optical efficiency of 26.4%. Tuning ranges of 450 nm, centred on 3.5 μm, have been demonstrated using a diffraction grating in a Littrow configuration [13]. These lasers were mostly limited to continuous wave (CW) or quasi-CW operation, though self Q-switching and gain switching behaviour has previously been observed [14, 15]. This was due to 3.5 μm gain dynamics caused by the modulation of the 1973 nm pump source. Pulsed Er^{3+}:ZBLAN fiber lasers at 3.5 μm have recently been demonstrated. Qin et al. [16] achieved passively Q-switched and mode locked operation using a black phosphorus saturable absorber mirror. Jobin et al. [17] reported gain switched operation with the use of a Q-switched 1976 nm fiber system as a pump source. These demonstrations of pulsed operation are an important step towards the use of these lasers in many applications.

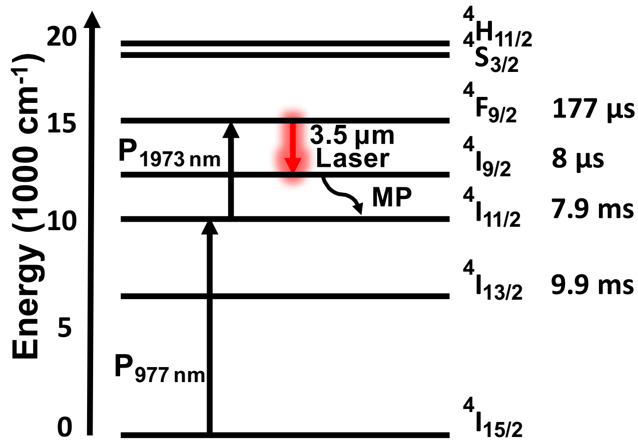

Fig. 1. Simplified energy level diagram of Erbium showing the dual-wavelength pumping method. Energy level lifetimes are shown on the right [8]. The 3.5 μm lasing transition is followed by fast multiple phonon (MP) decays.

A number of different methods have been used to achieve pulsed operation in Er^{3+} and Ho^{3+} doped fiber lasers around 3 μm [18]. Acousto-optic modulators (AOMs) [19–23] have successfully been used as active Q-switches, with Tokita et al. [24] achieving an average output power of 12 W with 90 ns, 100 μJ pulses at 2.8 μm. This corresponds to a peak power of 0.9 kW. In this paper we present what is to the best of our knowledge, the first actively Q-switched Er^{3+}:ZBLAN fiber laser operating at 3.47 μm.

The experimental set-up used for active Q-switching experiments is shown in Figure 2. The pump lasers are a commercially available 977 nm fibre-coupled laser diode (LIMO HLU30F200-977) and an in-house built Tm^{3+} doped silica fibre laser operating at 1973 nm. The pump light is launched into the fiber through a dichroic mirror by an aspheric lens. The fiber is butted against the dichroic mirror which is highly reflective (HR) at the lasing wavelength of 3.5 μm and highly transmissive (HT) at the pump wavelengths. The 2.8 m long, double-clad, Er^{3+} doped ZBLAN fibre was manufactured by Le Verre Fluoré. It has a 16 μm diameter core and a 240/260 μm double truncated circular inner cladding. The NA of the core was measured to be 0.08 at 3.5 μm by launching a single mode, 3.5 μm laser beam into the fiber core and observing the divergence of the emerging beam from the distal fiber tip.

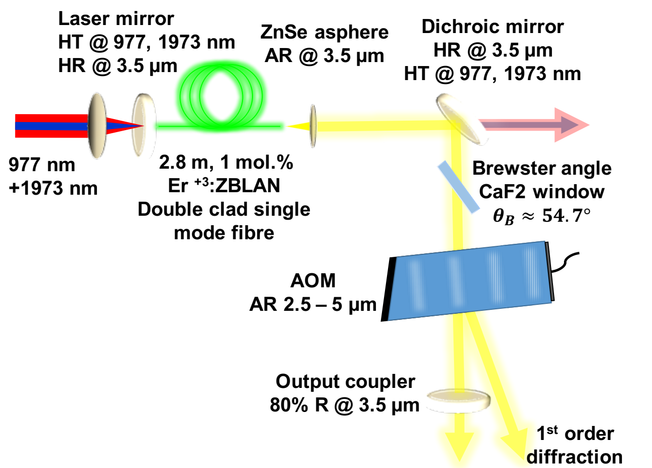

Fig. 2. Schematic of the DWP system including an AOM as an active Q-switch. HT, HR and AR correspond to highly transmissive, highly reflective and anti reflective.

The laser light emitted by the output end of the fiber is collimated by an anti reflective (AR) coated ZnSe aspheric lens before being incident on another mirror that is HR at 3.5 μm and HT at the pump wavelengths. This greatly reduces the pump light that is incident on the germanium AOM (Isomet 1210) which is AR coated from 2.5 to 5 μm. The laser resonator is completed with an 80% reflectivity output coupler mirror. A CaF_2 window is included in the laser cavity at Brewster's angle to force linearly polarised operation, parallel to the mounting base of the AOM, maximising its diffraction efficiency. The AOM is driven by a pulsed 81 MHz RF source and is aligned such that lasing occurs on the zero order diffraction. The function generator (Aim-TTi TG5011A) used to produce the pulsed RF source outputs a rectangular wave with variable duty cycle. The duty cycle is the percentage of time the laser cavity has high loss. The output of the laser system was passed through a 3 μm long pass filter and monitored by an InAs photodetector (Teledyne Judson J12TE2-66D-R250U), thermal power meter and monochromator. The temporal resolution of the measuring setup is limited by the InAs photodetector (bandwidth DC to 16 MHz).

The launched 977 nm pump power was fixed at 4.3 W while the 1973 nm pump was maintained at 3.6 W, the highest power level that allowed for stable output of the Q-switched system. The AOM repetition rate was varied from 5 to 100 kHz, giving stable Q-switched operation. Pulsing became unstable outside of this range of frequencies with pulse clipping seen at higher frequencies and the emergence of multiple pulsing at lower frequencies. The AOM duty cycle was adjusted at each value of the repetition rate to achieve stable Q-switching. The values of the duty cycle are shown in Table 1.

Table 1. Repetition Rate and Duty Cycle Values

Repetition rate (kHz)	Duty cycle (%)
5	98
10	95
15	90
20	85
30	85
40	75
50	75
60	70
70	55
80	35
90	5
100	3

The results are displayed in Figure 3 and show a maximum pulse energy of 7.8 μJ occurring at a repetition rate of 15 kHz, corresponding to a peak power of 14.5 W. The shortest pulses

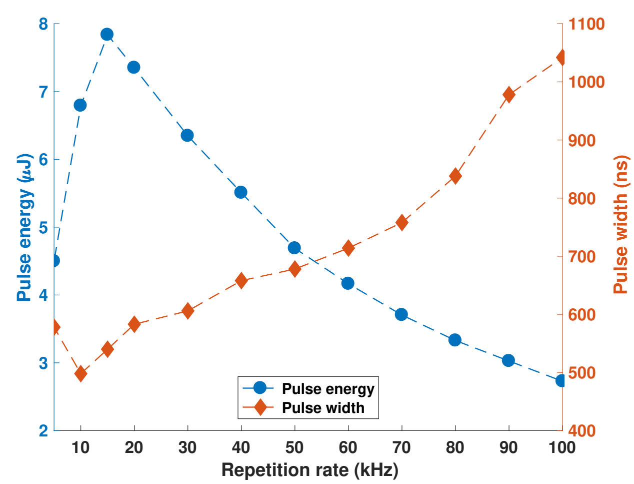

Fig. 3. Pulse energy and width as a function of AOM repetition rate.

with a full width at half maximum (FWHM) of 498 ns occurred at a repetition rate of 10 kHz (Figure 4). The reduced pulse energies at lower repetition rates has previously been discussed by Henderson-Sapir et al. [25] based on a numerical model of the system. The greater time average population in the upper

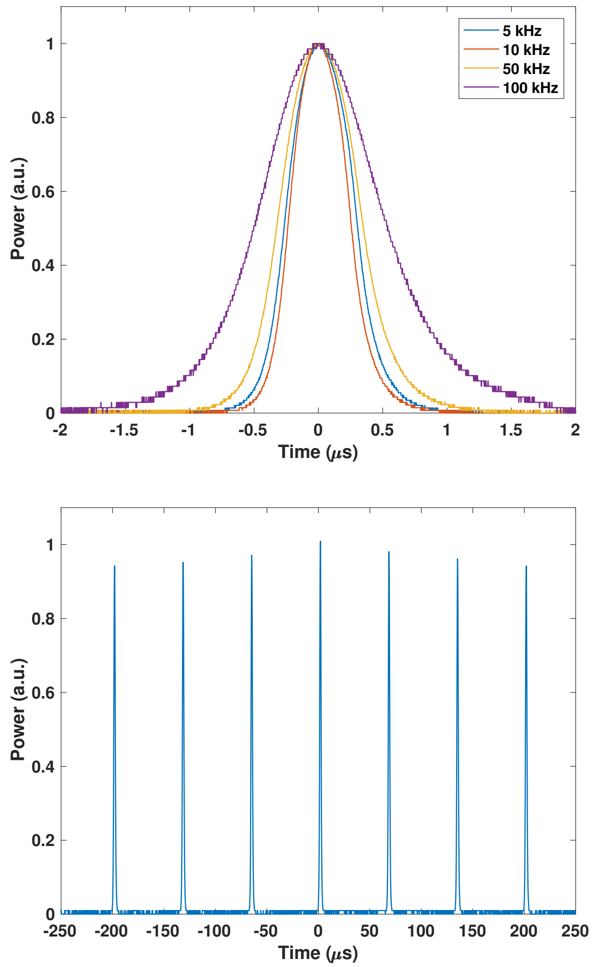

Fig. 4. Top: averaged pulses at a number of different repetition rates. Each pulse is the average of 16 individual pulses. The shortest pulses with a FWHM of 498 ns occurred at a repetition rate of 10 kHz. Bottom: averaged pulse train at a repetition rate of 15 kHz. The peak power is estimated to fluctuate by 5%.

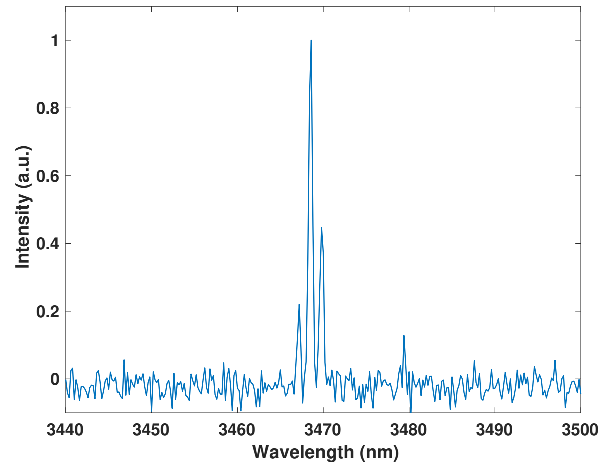

Fig. 5. Typical laser spectrum with multiple lines running around 3.47 μm.

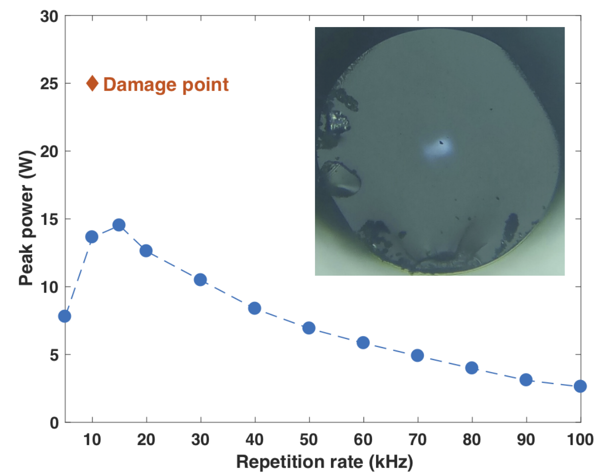

Fig. 6. Peak power of the Q-switched system as a function of repetition rate. Increased pump powers saw the peak power rise to 25 W before damage occured. Inset: the damaged fiber tip.

lasing level $^4F_{9/2}$ allows more ions to spontaneously decay from this level and leave the lasing cycle. This results in a reduced population inversion at the time of Q-switching and lower pulse energies. A typical wavelength spectrum is shown in Figure 5. Multiple laser lines can be seen running around 3.47 μm with their relative intensities varying over time. The lasing lines persist over the course of 2 hours, but tend to shift to other wavelengths in the wide gain spectrum of erbium under changing pumping conditions. Increasing the incident powers of the 977 and 1973 nm pumps above 5 and 4 W respectively saw a decrease in pulse width to 340 ns at a repetition rate of 10 kHz, giving a peak power of 25 W. However, this resulted in damage to the input end of the fiber (Figure 6). Shorter pulses and higher peak powers could possibly be achieved with increased pump powers, if measures are taken to prevent fiber tip damage. This could include the addition of fiber end caps and the use of a fiber Bragg grating in place of the input dichroic mirror.

Numerical modelling of a Q-switched, DWP, Er^{3+}:ZBLAN fiber laser has previously been completed by Henderson-Sapir et al. [25]. The model predicts a minimum pulse width of 88 ns with an energy of 44 μJ. This occurred at a repetition rate of 20 kHz with incident pump powers of 4 W and 5.5 W for the 977 nm and 1973 nm sources respectively. The Q-switch modelled in this work was, however, ideal with no insertion loss and the output coupler mirror butted against the output end of the fiber. This means there were no losses due to intra-cavity lenses or mirrors. It is worth noting that this modelling did not include the $^4F_{9/2} \rightarrow {}^4F_{7/2}$ excited state absorption (ESA) at the second pump wavelength recently described by Maes et al. [10]. This ESA may have a significant effect when Q-switching due to the large population of ions produced in the $^4F_{9/2}$ state while the losses of the laser cavity are high. These additional features will be addressed in future work.

The results from this work show qualitatively similar behaviour to that seen in numerical modelling [25] with maximum pulse energies occurring around 15 kHz. The peak powers achieved in practice are lower however, due to limitations of incident pump powers and the losses introduced by the added components. Nevertheless, this demonstration of Q-switched operation is promising as a first step towards high peak power operation at 3.5 μm from a fiber laser, which is necessary for LiDAR applications.

In conclusion, we have demonstrated the first actively Q-switched fiber laser operating at 3.47 μm, with a robust maximum peak power of 14.5 W achieved at a repetition rate of 15 kHz. Combining pulsed operation with wavelength tunability and linewidth narrowing of mid-infrared fiber lasers, could see the beginning of the use of these lasers in remote sensing experiments.

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