Diode-pumped 1.5 μm waveguide laser mode-locked at 6.8 GHz by a quantum dot SESAM

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Abstract. We report a passively mode-locked, diode-pumped waveguide laser operating in the 1.5 μm spectral region using a quantum dot SESAM as the saturable absorber element. A repetition rate of up to 6.8 GHz and an average power as high as 30 mW is obtained during mode-locked operation. Minimum pulse duration of 2.5 ps is produced at a wavelength of 1556 nm. The repetition rate of the source was tuned by more than 1 MHz by changing the pump power, demonstrating a possible route towards integrated pulse repetition rate stabilisation.

1. Introduction

High-repetition-rate (>GHz) mode-locked lasers are beneficial for a wide range of applications including direct optical frequency comb spectroscopy [1], frequency comb calibration of high-resolution astronomical spectrographs [2], arbitrary optical and microwave waveforms synthesis [3], non-linear optical microscopy [4], and real-time ultrafast optical sampling [5]. A harmonic mode-locking technique is normally used to demonstrate multi-GHz operation from a range of solid-state lasers [6-8]; however, such laser sources suffer from pulse to pulse energy fluctuations and high timing jitter arising from the multiple pulses that circulate in the cavity. To achieve high-repetition-rates from fundamentally mode-locked laser sources, short cavity lengths (<15 cm) are required and this can pose a technological challenge. Moreover, due to the reduced intra-cavity pulse energy at multi-GHz repetition rates, specially designed saturable absorbers are required to facilitate low-threshold mode-locked operation. High repetition rates have been achieved from fundamentally mode-locked edge-emitting [9] and vertical external cavity surface emitting semiconductor lasers (VECSELs) [10]. However, due to the fast gain dynamics in semiconductors during mode-locked pulse formation, the timing jitter can be relatively high [11, 12]. Alternatively, diode-pumped solid-state lasers are an attractive option for the realization of compact high repetition rate lasers offering high powers, low quantum noise and short pulse durations. Using carefully designed laser cavities having extremely small footprints, repetition rates in excess of 10 GHz have been obtained at various wavelengths in the near-IR region [13-15].

Diode-pumped solid-state lasers in a waveguide geometry offer several advantages such as low threshold operation and integrated functionality. Saturable absorber elements, when integrated directly with the waveguide, offer the possibility of developing compact mode-locked sources having a reduced mode-locking threshold due to small mode sizes in the gain media and on the saturable absorber. In a cylindrical waveguide geometry, there have been several demonstrations of multi-GHz laser sources where short pieces of highly doped fibres were used as a gain element. Repetition rates of up to 19 GHz have been achieved [16] with an average power < 1 mW, and a power of 50 mW was reached for a repetition rate of 3 GHz [17] near 1 μm using semiconductor saturable absorber mirrors (SESAMs) for passive mode-locking. Mode-locked fibre lasers with a similar architecture have also been operated near 1.5 μm with repetition rates up to 3 GHz and power levels of a few milliwatts [18].

Waveguides with a planar geometry offer additional features such as compatibility with standard micro-fabrication techniques and on-chip integration. Recently, we have demonstrated a fundamentally mode-locked waveguide laser source with a repetition rate of 4.9 GHz near 1 μm [19]. However, to date there have been very limited demonstrations of fundamentally mode-locked waveguide sources near 1.5 μm. Typically, they have not possessed a monolithic configuration, with the saturable absorber element being in an external cavity arrangement. This has increased the cavity length and the resulting pulse repetition rate has been below 1 GHz [20-23]. Recently, an integrated fundamentally mode-locked waveguide laser at 1.5 μm was demonstrated with a repetition rate of 400 MHz [24] and an output power of ~ 1 mW.

Quantum dot (QD) SESAMs [25] are recently developed saturable absorbers, which offer a lower saturation fluence, faster recovery time and lower non-saturable losses when compared to their quantum well counterparts. The concentration of the QDs can also be controlled to facilitate the required modulation depth for stable mode-locking at high repetition rates. So far, GaAs-based QD SESAMs have been successfully used for passive mode-locking of lasers in the ~ 1-1.3 μm wavelength region [25]. However, it is difficult to shift the wavelength of operation of GaAs-based devices to about 1.5 μm due to significant challenges in materials engineering. Recently, QD-SESAMs have been used for the first time to demonstrate modelocking around 1.5 μm in a bulk Er,Yb:glass laser [26]. A repetition rate of up to 10 GHz was reached with an average output power of 8 mW.

In this letter, we report, for the first time to our knowledge, an ion-exchanged channel waveguide Er,Yb-doped phosphate-glass monolithic laser passively mode-locked by a QD-SESAM. We demonstrate a pulse repetition rate of up to 6.8 GHz near 1.55 μm with the corresponding pulse duration of 2.5 ps and an average power as high as 30 mW. Control of the pulse repetition rate by changing the pump power is also demonstrated allowing its tuning by more than 1 MHz during mode-locked operation.

2. Fabrication details

Channel waveguides were fabricated in a commercially available phosphate glass from Schott Glass Technologies Inc. (IOG-1), doped with 1.16 wt. % of erbium (Er) and 4.77 wt. % of ytterbium (Yb) using a standard ion-exchange technique as described in [19].

The 1550 nm QD-SESAM was grown by a solid-source III-V molecular beam epitaxy reactor (VG 90). The InGaAs/GaAs QDs were positioned in an asymmetric InGaAs quantum well pair (dot in well – DWELL structure) with 1 nm lower $In_{0.18}Ga_{0.82}As$ layer and 6 nm upper $In_{0.31}Ga_{0.69}As$ layer grown on the top of a DBR mirror, and capped by a GaAs layer. The DBR consists of 31 pairs of 115 nm GaAs and 134 nm $Al_{0.98}Ga_{0.02}As$ layers. The growth temperatures for the DWELL structure and for the GaAs and AlGaAs layers were 530°C and 565°C, respectively. The SESAM was designed to have a resonant-type structure. The detailed description for the fabrication and characterization of the QD-SESAM can be found in [26].

3. Experiments

3.1 Experimental Setup

The experimental setup was similar to that described in [19]. The waveguide laser cavity was formed by a 2% output coupler (OC) and a high reflectivity mirror (for continuous wave laser experiments) or a QD-SESAM (for the modelocking experiments). The pump was coupled into the cavity through the OC, which had > 99% transmission at 974 nm. A dichroic mirror was installed between the isolator and the pump coupling lens to separate the pump and laser wavelengths. The QD SESAM was kept on a kinematic mount to control the tip and tilt to align it with the waveguide and also to control the gap between the SESAM and uncoated surface of the waveguide. Such a micron-size gap plays an important role in mode-locking through the formation of a Gires-Tournois interferometer (GTI) structure that in certain conditions serves to generate an exploitable amount of negative group velocity dispersion (GVD) [19].

3.2 Continuous wave characterisation

Laser cavities were formed with the 20-mm-long and 14.5-mm-long waveguides by end-butting a 2% OC and a high reflectivity mirror. All the waveguides in both glass samples were tested to determine those waveguides from which the highest output power is delivered. The maximum output powers of 28 mW and 64 mW were obtained with the 20 mm and 14.5 mm long samples, respectively, at 620 mW of incident pump power. The optimum laser performance was obtained for waveguides corresponding to Al mask opening widths between 5 μm and 7 μm, and lasing wavelengths of 1564 nm and 1558 nm were measured for the longer and shorter sample, respectively. The propagation losses were estimated to be < 0.5 dB/cm for both the waveguides from the measured slope efficiencies. The lower output power from the longer sample is attributed to higher total cavity losses due to the increased propagation length and re-absorption losses. The near-field pump mode radii were measured to be 8.1 μm and 5.3 μm in the horizontal and vertical directions, respectively, which is in a good agreement with the simulated values of 7.5 μm and 4.9 μm.

3.3 Mode-locking results

For the mode-locking experiments the HR mirror was replaced by the QD-SESAM and its position was carefully adjusted relative to the waveguide end-facet to achieve stable mode-locked operation. Q-switched modelocking was observed for a pump power of 415 mW with a corresponding output power of 5.6 mW with the 20-mm long waveguide sample. The Q-switched pulse train was recorded using a photo-detector and an oscilloscope. The response of the detection system was not fast enough to resolve the individual pulses in the Q-switched envelope, but Q-switched mode-locking operation was confirmed from the radio-frequency (RF) spectrum measurements. The Q-switching repetition rate was 370 kHz and the pulse duration was 106 ns. When the pump power was increased up to 513 mW, CW modelocking was observed at an output power of 6.7 mW and the corresponding gap between the SESAM and the waveguide was ~13 μm. The round-trip group velocity dispersion was estimated to be about – 2000 fs^2. The RF spectrum recorded at span of 10 MHz and the resolution bandwidth of 10 kHz is shown in figure 1 (a) indicating a clean peak at 4.85 GHz. A maximum output power of 9 mW was achieved during mode-locking. The autocorrelation trace and the corresponding optical spectrum are shown in the figures 1 (b) and 1 (c) respectively, indicating nearly transform-limited $sech^2$ pulses of duration 2.5 ps at a centre wavelength of 1556 nm.

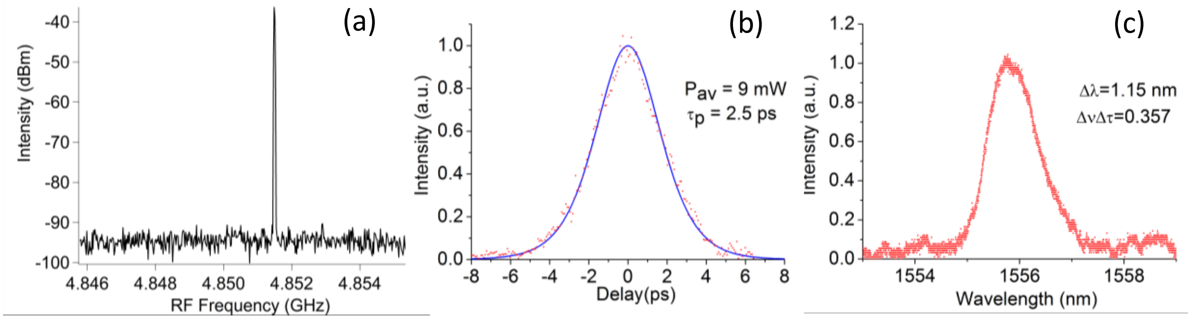

Figure 1. (a). Radio frequency spectrum, (b). Autocorrelation trace, red-experimental data, blue line- sech^2 fit and (c) optical spectrum for the 4.8 GHz waveguide laser.

With the 14.5-mm-long waveguide sample, self-starting mode-locking was found to occur at a pump power of 558 mW, at which the corresponding output power of 25 mW was measured. The gap between the waveguide and the SESAM samples was similar to that used with the longer sample. The maximum output power obtained during mode-locked operation was 30 mW. The RF spectrum is shown in figure 2 (a), and a clean peak at 6.8 GHz can be observed. Figure 2 (b) and (c) shows the autocorrelation trace and the output spectra, respectively. The pulse duration was measured to be 5.4 ps and the spectral width was measured to be 0.76 nm at a central wavelength of 1544.4 nm.

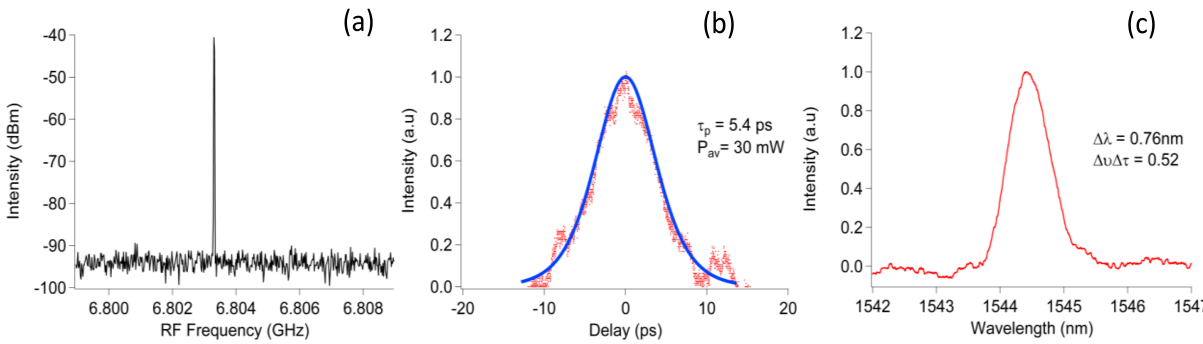

Figure 2. (a). Radio frequency spectrum, (b). Autocorrelation trace, red-experimental data, blue line- sech^2 fit and (c) optical spectrum for the 6.8 GHz waveguide laser.

After mode locking was achieved with a repetition rate of 6.8033 GHz, the central frequency was tuned by increasing the pump power from 586 mW to 684 mW. A frequency shift of up to 1090 kHz was observed for an increment of 100 mW, as is evident from figure 3.

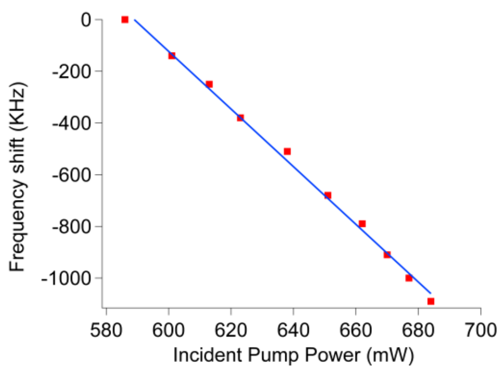

Figure 3. The shift in the repetition rate of the 6.8 GHz laser as a function of pump power.

This effect has previously been used to stabilise a waveguide laser cavity with a repetition rate of 750 MHz in conjunction with a piezo-controlled SESAM [23] to achieve a timing jitter of 14 fs and was attributed to atomic dispersion [27] which should reduce the refractive index for the lasing wavelength at higher powers. It should also be noted that, the thermo-optic coefficient (dn/dT) for the glass is negative. However, in our experiments, the negative shift in the pulse repetition frequency during the power increase indicates an increment in the optical length of the waveguide sample which we attribute to thermal expansion being the dominating effect.

4. Conclusions

In conclusion, we have demonstrated the first, to the best of our knowledge, waveguide laser mode-locked by a quantum dot SESAM and the highest repetition rate from a fundamentally mode-locked Er^{3+}-doped waveguide laser of 6.8 GHz. An output power as high as 30 mW was obtained during mode-locked operation. Near-transform-limited pulses with a pulse width of 2.5 ps are generated at a repetition rate of 4.8 GHz. Fine control of the repetition rate is demonstrated by varying the pump power and may offer a future route to integrated stabilisation. Such diode-pumped, compact waveguide sources can pave the way for numerous applications. Future work will include an investigation of the power scaling of these sources through master-oscillator-power-amplifier configurations.

Acknowledgments
A. C and A. A. L contributed equally to this work. This work was supported by the EPSRC under project EP/H035745/1, EP/H038035/1 and EP/J008052/1 and by EU FP7 project FastDot. We would also like to acknowledge Prof. J.Wilkinson for providing the Schott glass. We would also like to thank N. Sessions and Dr. S. Ganapathy for useful discussions.

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