Fundamentally mode-locked, femtosecond waveguide oscillators with multi-gigahertz repetition frequencies up to 15 GHz

Alexander A. Lagatsky,[1] Amol Choudhary,[2,*] Pradeesh Kannan,[2] David P. Shepherd,[2] Wilson Sibbett,[1] and Christian T. A. Brown[1]

[1] *SUPA, School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, KY16 9SS, UK*
[2] *Optoelectronics Research Centre, University of Southampton, Highfield, Southampton SO17 1BJ, UK*
**ac12g10@orc.soton.ac.uk*

Abstract: We demonstrate passively mode-locked Yb^{3+}-doped glass waveguide lasers in a quasi-monolithic configuration with a maximum pulse repetition frequency up to 15.2 GHz. A semiconductor saturable absorber mirror (SESAM) is used to achieve stable mode-locking around 1050 nm with pulse durations as short as 811 fs and an average power up to 27 mW. Different waveguide samples are also employed to deliver pulses with repetition rates of 4.9 GHz, 10.4 GHz and 12 GHz with an average power of 32 mW, 60 mW and 45 mW, respectively. The group velocity dispersion control in the cavity is provided by changing the gap between the SESAM and the waveguide end-face to facilitate a soliton mode-locking regime.

OCIS codes: (140.4050) Mode-locked lasers; (140.7090) Ultrafast lasers; (140.3615) Lasers, ytterbium; (320.7080) Ultrafast devices; (130.2755) Glass waveguides; (230.7380) Waveguides, channeled.

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1. Introduction

There has been a recent focus on the development of ultrafast laser sources with high (> 1 GHz) pulse repetition frequencies (PRF) owing to their various applications in non-linear microscopy [1], optical sampling [2], arbitrary optical waveform generation [3], optical communications [4], frequency metrology [5] and "astro-combs" [6]. These applications drive a desire for a multi-GHz ultrafast source that is compact, power scalable at low noise performance, mass producible and relatively low-cost. To meet these requirements, several sources have been developed in the recent decade. Semiconductor ridge-waveguide lasers [7] and vertical external cavity surface emitting semiconductor lasers (VECSELs) [8] are compatible with current foundry fabrication techniques and can be configured for high PRF operation. However, because of the fast gain dynamics involved during mode-locking, these devices suffer from a high timing jitter up to the picosecond level [9]. Active mode-locking of semiconductor lasers allows a low timing jitter [10], but typically leads to longer pulse durations and requires an external electronic control, making the source more complicated. Harmonic mode-locking is also a well-developed technique to achieve multi-GHz pulse repetition rates in fiber [11], semiconductor [12] or solid-state lasers [13]. Pulse repetition rates exceeding 200 GHz have been reached by applying this technique [13]. However, because of the multiple pulses in the cavity, it is less stable than fundamental mode-locking. Mode-locking at the fundamental PRF in the GHz regime requires cavity lengths shorter than 15 cm, which is technologically challenging. Nevertheless, using carefully engineered cavity configurations repetition rates exceeding 100 GHz have been achieved from a bulk solid-state laser [14].

Fundamentally mode-locked fiber lasers with sub-centimeter gain medium lengths configured in a Fabry-Pérot cavity is another option for the development of high PRF laser sources. Femtosecond pulses with multi-GHz repetition rates have been demonstrated from a range of Er-doped fiber lasers around 1.5 μm with average powers reaching 27 mW, using

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SESAMs or carbon nanotubes as mode-locking devices [15–18]. A femtosecond (~206 fs) Yb-doped fiber laser at 1025 nm has also been demonstrated with a PRF of 3 GHz and an average power up to 53 mW [19]. Using diode-pumped solid-state waveguide lasers in combination with Fabry-Pérot cavity configurations has led to further progress towards the development of low threshold, highly-efficient, multi-GHz ultrafast lasers at a variety of wavelengths. The first demonstration of such laser device was described in [20] where 1.2 mW of average output power was produced at a 400 MHz PRF with pulse durations of 400 fs at around 1.5 μm, based on SESAM mode-locking. This work was followed by demonstration of a 4.9 GHz PRF, 800 fs pulse-duration waveguide laser based on Yb-doped glass at 1.06 μm delivering up to 80 mW [21]. More recently, 1.5 GHz picosecond (1.06 ps), Q-switched mode-locked monolithic Yb:glass waveguide laser was reported with a graphene saturable absorber [22].

In this work we report, to the best of our knowledge, the highest PRF of 15.2 GHz from a passively mode-locked solid-state waveguide laser. An average output power as high as 27 mW was achieved at a pulse duration of 811 fs. Group velocity dispersion (GVD) control was realised by adjusting the micron-scale gap between the waveguide and the SESAM surfaces enabling a stable soliton mode-locking regime to be achieved. Using different waveguide samples the PRFs of 4.9 GHz, 10.4 GHz and 12 GHz were also realised with the corresponding average output powers of 32 mW, 60 mW, and 45 mW, respectively.

2. Experiments

The channel waveguides were fabricated in IOG-1 (Schott Glass technologies Inc.) phosphate glass, doped with 12 wt% Yb_2O_3, using a standard ion-exchange technique [21]. The gain characteristics of this glass can be found in [23]. The ion-exchanged glass samples were end-polished to produce a range of samples with lengths of 20 mm, 9.4 mm, 8 mm and 6.5 mm.

A schematic of the experimental set-up is depicted in Fig. 1. The waveguides were pumped by single-mode fibre-coupled laser diodes (3S Photonics) in the 980 nm absorption band. The output was collimated by an aspheric lens having an 8-mm focal length and was coupled into the waveguide through an output coupling mirror (OC) (transmission, T = 2% at the lasing wavelength and T > 99.9% at the pump wavelength) by an aspheric lens with a focal length of 11 mm that formed a pump beam spot radius of 4.4 μm at the waveguide facet. A half-wave plate and an optical isolator protected the pump laser diode from back reflections. A dichroic mirror with high transmission (> 99%) at the pump wavelength and high reflection (> 97%) at the laser wavelength was used to separate incoming pump and outgoing lasing beams. The waveguide cavity was completed by end butting a high-reflectivity mirror to the other end facet of the waveguide for continuous wave (cw) characterization. To select the most suitable waveguides for mode-locking experiments, the cw performance of each channel was measured with a HR/2%OC configuration. After identifying all the promising waveguides, i.e. those delivering the highest output powers, the high-reflectivity mirror was replaced by a SESAM (Batop GmbH, modulation depth = 0.4%, non-saturable losses = 0.3%, relaxation time = 0.5 ps, saturation fluence = 90 μJ/cm^2) for the mode-locking experiments. A 1 × 1 mm^2 SESAM chip was mounted on a copper substrate and placed on a 3-axis flexure stage with high-precision adjusters (20 nm resolution). This enabled accurate control of the gap between the SESAM and the waveguide facet, which was monitored by placing a CCD camera in combination with a long working distance objective lens on the top of the setup. The diagnostic tools included an autocorrelator (Femtochrome Inc., FR-103MN, <10 fs resolution), an ultrafast photodetector (>20 GHz cut-off frequency), a radio frequency spectrum analyzer (Rohde & Schwarz, FSP40) and a power meter.

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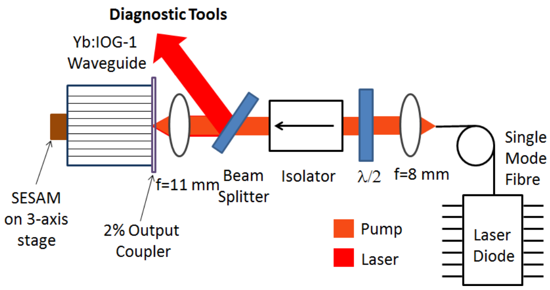

Fig. 1. Schematic of the experimental setup.

3. Results and discussion

Using the 20-mm-long waveguide sample with a 750-mW pump laser diode at 980.6 nm, a cw output power as high as 108 mW was achieved at 1052 nm for waveguides fabricated using mask opening widths between 2 µm and 6 µm. With the SESAM in place, self-starting mode-locking was realized at an average output power of 19 mW [Fig. 2(a)]. All the mode-locking experiments were carried out using waveguides fabricated with mask opening width of 5 µm.

The output from the laser was imaged on a CCD camera [Fig. 2(b)] and the near field laser mode was found to have a Gaussian profile, with $1/e^2$ beam diameters of 11.6 µm and 7.6 µm along the x (in the plane of the waveguide) and *y* (perpendicular to plane of waveguide) directions, respectively. The laser beam quality was measured by focusing the collimated output from the waveguide using a lens with f = 100 mm onto a beam profiler and translating the beam profiler in the focal plane of the lens. The M_x^2 was found to be 1.05 [Fig. 2(c)] and M_y^2 was found to be 1.08 [Fig. 2(d)], indicating a nearly diffraction-limited output.

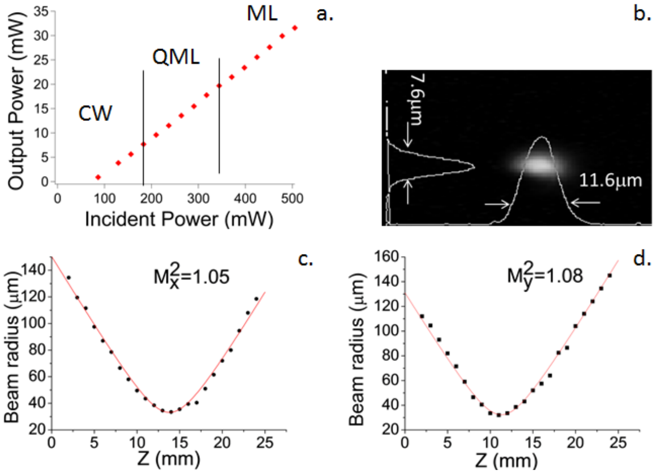

Fig. 2. (a) Output power vs. incident pump power for the 20-mm-long sample. CW denotes continuous wave operation, QML- Q-switched mode-locking and ML- mode-locking; (b) Image of the near-field laser mode on a CCD camera; (c,d) M^2 measurements along *x* and *y* directions with fit (red lines) to the experimental data.

A maximum output power of up to 32 mW was achieved during mode-locking at a PRF of 4.9 GHz [Fig. 3(a)]. The pulses had a sech^2 profile and the pulse duration was measured to be 738 fs [Fig. 3(b)] and the mode-locked laser spectrum was centered at 1058.3 nm with a full-width-half-maximum (FWHM) bandwidth of 2.3 nm [Fig. 3(c)], giving a time-bandwidth product of 0.46 [21]. Stable mode-locking was achieved for about an hour, however, SESAM damage was observed occasionally during the initial alignment procedure due to Q-switching instabilities.

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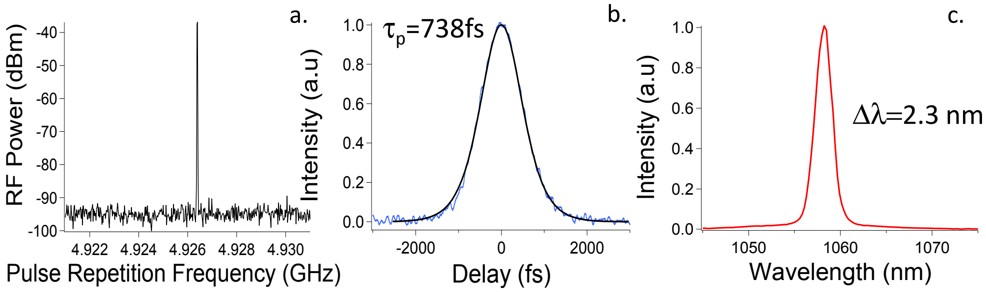

Fig. 3. (a). RF spectra taken with a 10 MHz span and a resolution bandwidth of 10 kHz (b) autocorrelation trace, Blue-experimental data, black-sech^2 fit and (c) optical spectrum measured for the 20-mm-long waveguide laser.

All shorter waveguide samples, namely, 9.4 mm, 8 mm and 6.5 mm, were pumped by a laser diode operating at the maximum of the Yb:glass absorption band at 973.4 nm in order to increase the absorption of the pump. In each case, the pump power was set to a value at which stable mode-locking was achieved. For the 9.4-mm-long sample, the characterization was carried out at an average output power of 60 mW. The gap between the waveguide and the SESAM surfaces was measured to be ~41 μm. Mode-locked operation was not as stable as that achieved for the 20-mm-long sample, possibly due to the mode competition between 1030 nm and 1045 nm wavelengths observed during the laser operation. The PRF was measured to be 10.4 GHz as seen from the clean peak on the RF spectrum in Fig. 4(a). At stable mode-locking conditions, the autocorrelation trace [Fig. 4(b)] had a sech^2 pulse profile with a pulse duration of 757 fs. The laser spectrum was centered at 1041.4 nm with a FWHM bandwidth of 2.7 nm [Fig. 4(c)], which gives a time-bandwidth product of 0.56.

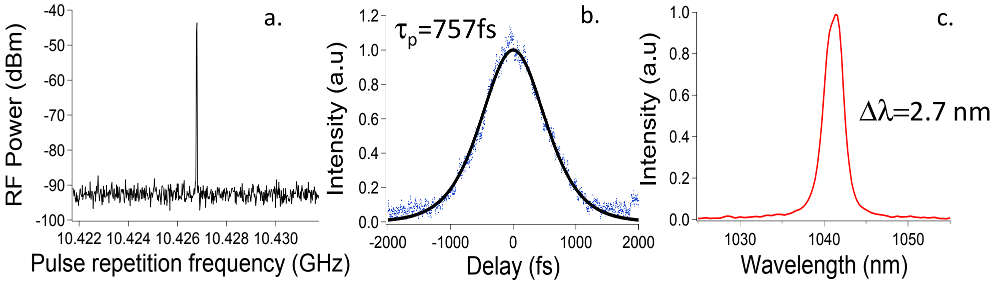

Fig. 4. RF spectra taken with a 10 MHz span and a resolution bandwidth of 10 kHz (b) autocorrelation trace, Blue-experimental data, black-sech^2 fit and (c) optical spectrum measured for the 9.4-mm-long waveguide laser.

Similar experiments were performed with the 8-mm and 6.5-mm-long samples, and characterization was carried out at an output power of 45 mW and 27 mW, respectively. PRFs and sech^2-profile pulse durations of 12 GHz [Fig. 5(a)], 824 fs [Fig. 5(b)] and 15.2 GHz [Fig. 6(a)], 811 fs [Fig. 6(b)] were observed for the 8-mm and the 6.5-mm-long sample, respectively. The optical spectrum was centered at 1045.7 nm with a corresponding FWHM bandwidth of 1.9 nm for the 8-mm-long sample [Fig. 5(c)], and the 6.5-mm-long waveguide sample operated at a wavelength of 1047.4 nm with a FWHM bandwidth of 2.1 nm [Fig. 6(c)]. These mode-locking results were achieved at a measured gap of ~26 μm between SESAM and the waveguide.

The low-threshold mode-locking and sub-picosecond pulse generation from our waveguide lasers can be attributed to a soliton formation mechanism, i.e. when the pulse phase shift due to self-phase modulation (SPM) in the gain medium is compensated by negative group velocity dispersion (GVD). Indeed, stable mode-locking was observed at intra-cavity pulse energies in the range of 0.1-0.3 nJ, which are in good agreement with the calculated critical pulse energy of 0.095 nJ required to overcome Q-switching instabilities in the case of a soliton mode-locking regime [see Eq. (27) of [24]].

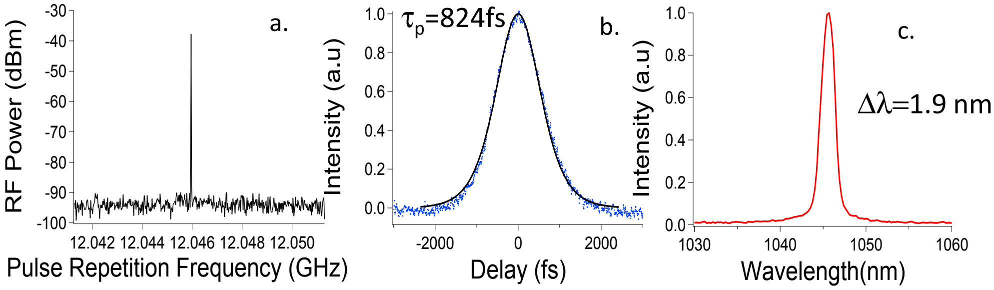

Fig. 5. RF spectra taken with a 10 MHz span and a resolution bandwidth of 10 kHz (b) autocorrelation trace, Blue-experimental data, black-sech^2 fit and (c) optical spectrum measured f or the 8-mm-long waveguide laser.

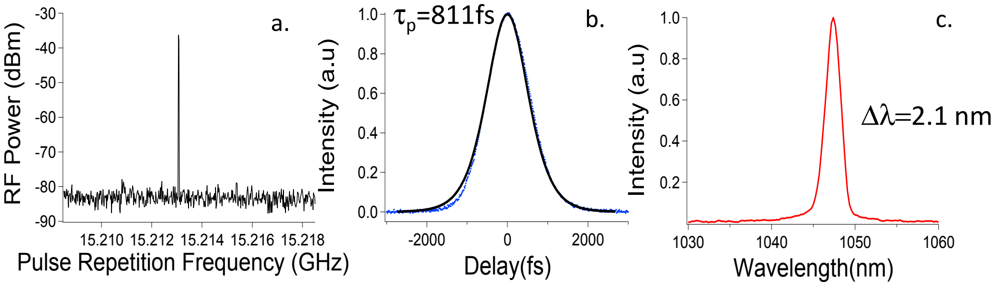

Fig. 6. RF spectra taken with a 10 MHz span and a resolution bandwidth of 10 kHz (b) autocorrelation trace, Blue-experimental data, black-sech^2 fit and (c) optical spectrum measured for the 6.5-mm-long waveguide laser.

The required negative GVD in our experiments originates from the micron-scale gaps between the SESAM/OC and uncoated surfaces of the waveguide structure. This leads to the formation of equivalent Gires-Tournois interferometer (GTI) structures [25] that provide a sufficient amount of negative GVD suitable to support a soliton mode-locking regime, as was previously shown in the case of a bulk laser system [26]. The net GVD was estimated to be around –6200 fs^2 for the 20-mm-long-waveguide cavity (920 fs^2 is the GVD due to the Yb^{3+}-glass waveguide and –7120 fs^2 is contribution from the GTI) and - 680 fs^2 for the 6.5-mm-long waveguide (300 fs^2 is the GVD due to the Yb^{3+}-glass waveguide and the contribution of the GTI is –980 fs^2). It should be noted, however, that the value of the GVD depends very sensitively on the GTI gap (~80 fs^2/nm) and, although, we have provided a precise control of the gaps, it was not possible to fully balance the second order dispersion and the self-phase modulation which explains the generation of slightly chirped pulses.

4. Conclusions

In conclusion, diode-pumped solid-state waveguide lasers were demonstrated with fundamental PRFs in the range of 4.9-15.2 GHz. The shortest pulse duration of 738 fs was observed at a PRF of 4.9 GHz, and the maximum average output power of 60 mW was generated at a 10.4 GHz PRF. Precise adjustment of the SESAM position relative to the waveguide end-face was used to introduce negative GVD and facilitated a self-starting soliton-mode-locking regime. Further optimization of the pump scheme towards a fully integrated design and adjustment of the SESAM parameters, which could include integrated dispersion control, would lead to the development of robust, portable and stable ultrafast laser systems suitable for a range of applications where GHz PRFs are in demand.

Acknowledgments

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