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Near-infrared, mode-locked waveguide lasers with multi-GHz repetition rates

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ABSTRACT

In this work, we discuss mode-locking results obtained with low-loss, ion-exchanged waveguide lasers. With Yb^{3+}-doped phosphate glass waveguide lasers, a repetition rate of up to 15.2 GHz was achieved at a wavelength of 1047 nm with an average power of 27 mW and pulse duration of 811 fs. The gap between the waveguide and the SESAM introduced negative group velocity dispersion via the Gires Tournois Interferometer (GTI) effect which allowed the soliton mode-locking of the device. A novel quantum dot SESAM was used to mode-lock Er^{3+}, Yb^{3+}-doped phosphate glass waveguide lasers around 1500 nm. Picosecond pulses were achieved at a maximum repetition rate of 6.8 GHz and an average output power of 30 mW. The repetition rate was tuned by more than 1 MHz by varying the pump power.

Keywords: Ytterbium doped gain media, Erbium/Ytterbium doped gain media, waveguide laser, channel waveguides, mode-locked laser, quantum dot devices.

1. INTRODUCTION

High-repetition-rate lasers (i.e. > 1GHz) lasers have gained considerable interest over the last decade owing to various applications in optical frequency metrology [1], calibration of astronomical spectrographs [2], optical sampling [3] and non-linear microscopy [4]. Diode-pumped, solid-state waveguide lasers with integrated saturable absorber elements can be used as high repetition-rate laser sources. These compact devices offer several advantages such as a low lasing threshold, high slope efficiency and a low mode-locking threshold due to the strong saturation of the gain medium and the saturable absorber owing to the small mode sizes. These devices can operate over various spectral regimes and can be mass-produced using standard micro-photonic fabrication techniques.

Using the standard cleanroom processes it is also possible to integrate dispersion compensating elements, Bragg-mirrors structures and possibly saturable absorbers on a single chip. To this end, a sub-picosecond Erbium-doped alumina-silicate glass waveguide laser with a repetition-rate of 400 MHz and wavelength around 1.5 μm was realised by Byun et al. [5]. However, the output power was limited to ~1.2 mW. There have been several previous reports of ultrafast lasers with waveguides as a gain media and the saturable absorber in an external cavity configuration with repetition rates of

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below 1 GHz [6-9], and recently picosecond operation of a femtosecond-written glass waveguide laser at a repetition rate of 1.5 GHz [10] has been demonstrated using graphene as the saturable absorber element.

In this paper we present our high-repetition rate, ion-exchanged waveguide lasers fabricated in phosphate glasses. The Yb^{3+}-doped IOG-1 waveguides were polished to lengths of 20 mm, 9.4 mm, 8 mm and 6.5 mm resulting in repetition rates of 4.9 GHz, 10.2 GHz, 12 GHz and 15 GHz, respectively [11, 12]. Pulse durations of ~ 800 fs with average power of few tens of mWs were achieved around 1050 nm from these devices. Negative group velocity dispersion was introduced into the cavity by controlling the gap between the SESAM and the waveguide via the Gires Tournois Interferometer (GTI) effect. Er,Yb-doped IOG-1 glass waveguides were also fabricated by ion-exchange and two samples of lengths 20 mm and 14.5 mm generated picosecond pulses at a repetition rate of 4.8 GHz and 6.8 GHz [13] at 1500 nm. A novel quantum-dot (QD) SESAM [14] was utilised to initiate self-starting mode-locking. The repetition rate of the waveguide laser was also tuned by controlling the pump power, which could be a promising technique for frequency comb stabilisation.

2. EXPERIMENTAL DETAILS

2.1 Waveguide fabrication

A 200-nm-thick layer of aluminium (Al) was deposited by e-beam evaporation on the polished Yb^{3+}-doped and Er^{3+},Yb^{3+}-doped phosphate glass samples (IOG-1 from Schott Glass technologies Inc), following which a 1.3-μm-thick photoresist layer (S1813) was spin-coated on them. Using photolithography, channel openings of widths 1 μm to 10 μm in steps of 0.2 μm were opened and the resist-masked samples were chemically etched to transfer the photoresist mask onto the metal layer. After solvent removal of the photoresist, the samples were immersed in a molten salt mixture comprising of 45 mol% KNO_3 − 50 mol% $NaNO_3$ − 5 mol% $AgNO_3$ in an ion-exchange furnace. The glass samples were kept at a temperature of 325°C for 10 minutes for the Yb^{3+}-doped glass and for 30 minutes for the Er^{3+}, Yb^{3+}-doped glass. The Na^+ ions in the glass were exchanged with the K^+ and the Ag^+ ions in the ion-exchange melt, leading to a local increase in the refractive index. Next, the metal mask was chemically removed and the Yb^{3+}-doped glass samples were polished to lengths of 20 mm, 9.4 mm, 8 mm and 6.5 mm and the Er^{3+}, Yb^{3+}-doped glass samples were polished to lengths of 20 mm and 14.5 mm.

2.2 Quantum dot SESAM fabrication

The QD-SESAM [14] used for mode-locking the Er^{3+}, Yb^{3+}-doped glass around 1.5 μm was grown in a solid-source molecular beam epitaxy machine. 31 pairs of GaAs (115 nm) and $Al_{0.98}Ga_{0.02}As$ (134 nm) were grown on a GaAs substrate to form the distributed Bragg reflector (DBR) structure. On top of the DBR mirror, a dot in well (DWELL) structure was grown. The DWELL structure comprised of a 1-nm-thick layer of $In_{0.18}Ga_{0.82}As$ followed by the InGaAs/GaAs quantum dot layer and finally a 6-nm-thick layer of $In_{0.31}Ga_{0.69}As$. On top of the DWELL structure, a GaAs capping layer was grown. The In-layers were grown at a temperature of 530°C and the GaAs layers were grown at 565°C.

2.3 Experimental setup

The waveguides were pumped by a single-mode, fibre-coupled laser diode delivering a power of up to 850 mW at a wavelength of 974 nm (3S photonics). The output from the pump was collimated by an aspheric lens with a focal length of 8 mm and was coupled into the waveguide through an output coupling mirror (R=98% at the lasing wavelength and R<0.1% at the pump wavelength) by either an aspheric lens with focal length of 11 mm for pumping the Yb^{3+}-doped glass waveguides or an aspheric lens with focal length of 15.4 mm for pumping the Er^{3+}, Yb^{3+}-doped glass waveguides. After the f=8 mm collimating lens, a combination of a half-wave plate and an optical isolator was installed in the pump path to protect the laser diode from feedback from the waveguide. The waveguide cavity was completed by end-butting a high reflectivity (HR) mirror for continuous wave (CW) characterisation or a SESAM for mode-locking experiments. A commercially available SESAM from Batop GmbH was used for mode-locking the Yb^{3+}-doped glass waveguides and the QD-SESAM was used for mode-locking the Er^{3+}, Yb^{3+}-doped glass waveguides. A dichroic mirror installed before the launching lens was used to separate the pump and the laser beams. The laser beam reflected from the dichroic mirror was then passed through a combination of a half-wave plate and an isolator and then coupled into a single-mode fibre.

The output of this fibre was split by a 3-dB coupler and was fed into a spectrometer and a radio frequency (RF) spectrum analyser. A flip mirror was placed before the coupling stage, which was used to steer the beam to an autocorrelator to measure the pulse duration. The output power was measured before the isolator using a thermal power meter.

3. MODE-LOCKED YB:PHOSPHATE GLASS WAVEGUIDE LASER

With the 20-mm-long Yb:phosphate glass waveguide sample, mode-locked operation was observed at an average output power of 19 mW. On increasing the pump power, an output power of up to 32 mW was achieved at a repetition rate of 4.9 GHz as seen from Figure 1(a). The pulses were measured to be 740 fs and had a good fit to a sech^2 profile as shown in Figure 1 (b). The mode-locked laser spectrum was found to be centred at 1058.3 nm and had a full-width-half-maximum (FWHM) of 2.3 nm (Figure 1(c)), resulting in a time-bandwidth product of 0.46.

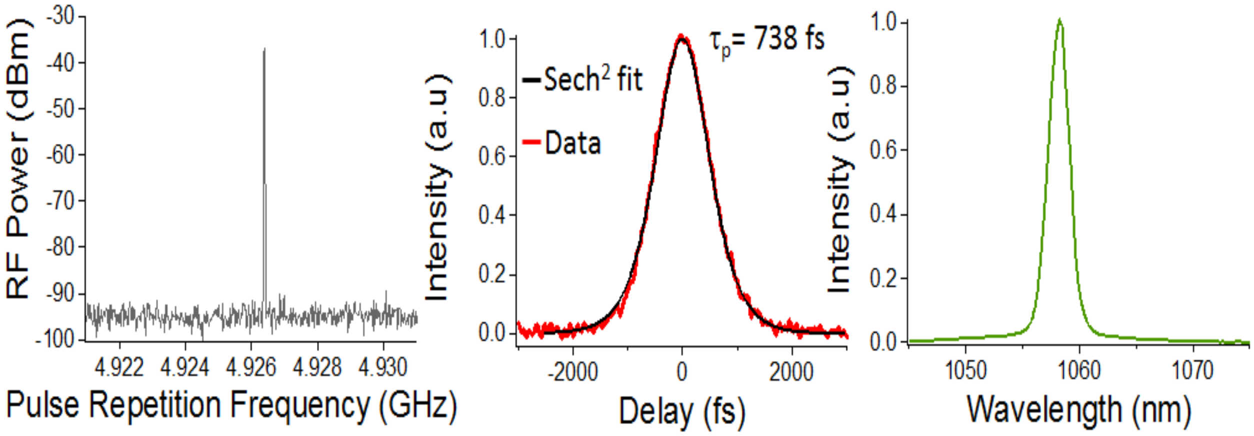

Figure 1. (a). RF spectrum, (b) autocorrelation trace, and (c) optical spectrum measured for the 20-mm-long Yb^{3+}-doped phosphate glass waveguide laser.

Similarly, mode-locking experiments were carried out with the 9.4-mm-long, 8-mm-long and 6.5-mm-long waveguide sample and the results obtained have been summarized in Table 1. A maximum repetition rate of 15.2 GHz was obtained with the 6.5-mm-long waveguide sample.

Table 1: Summary of results obtained with different Yb^{3+}-doped glass waveguide lasers.

Sample length (mm)	**Repetition-rate (GHz)**	**Pulse Duration (fs)**	**Center wavelength (nm)**	**Time-bandwidth product**	**Output power (mW)**
20	4.9	738	1058.3	0.46	32
9.4	10.4	757	1041.4	0.56	60
8	12	824	1045.7	0.43	45
6.5	15.2	811	1047.4	0.49	27

The experimentally measured critical pulse energy for the 20-mm-long waveguide laser was 0.2 nJ, which is an order of magnitude lower than the theoretically estimated value for the non-soliton mode-locking case (see equation 16 of [15]). The low-threshold mode-locking from our waveguide lasers can be attributed to a soliton formation mechanism. The critical pulse energy was calculated to be 0.095 nJ for the soliton mode-locking case (see equation 27 of [15]) which is in good agreement with our experimentally observed values. The necessary group velocity dispersion (GVD) is introduced into the cavity by controlling the gap between the SESAM and the waveguide, which essentially behaves as a Gires-Tournois interferometer (GTI) structure. The net dispersion in the cavity was estimated to be around -6200 fs^2 [16] for the 20-mm-long-waveguide cavity, where 920 fs^2 is the contribution from the Yb^{3+}-glass waveguide and -7120 fs^2 is the contribution from the GTI.

4. MODE-LOCKED ER,YB:PHOSPHATE GLASS WAVEGUIDE LASER

With the 20-mm-long Er,Yb:phosphate glass waveguide sample, Q-switched modelocking was observed at an incident pump power of 415 mW which resulted in an output power of 5.6 mW. The repetition rate was measured to be 370 kHz and the Q-switched pulse envelope duration was measured to be 106 ns. On increasing the pump power to 513 mW, self-starting CW mode-locking was observed with a corresponding output power of 6.7 mW. The total dispersion in the cavity was estimated to be about – 2000 fs^2, with the contribution of the Er,Yb:phosphate glass and the GTI being -840 fs^2 and the -1160 fs^2, respectively. The RF spectrum was centred around 4.8 GHz as shown in figure 2 (a). On increasing the pump power further, a maximum output power of 9 mW was measured The pulses were measured to be 2.5 ps and had a good fit to a sech^2 profile as shown in Figure 2 (b). The mode-locked laser spectrum was found to be centred at 1556 nm and had a full-width-half-maximum (FWHM) of 1.2 nm (Figure 2(c)), resulting in a time-bandwidth product of 0.36.

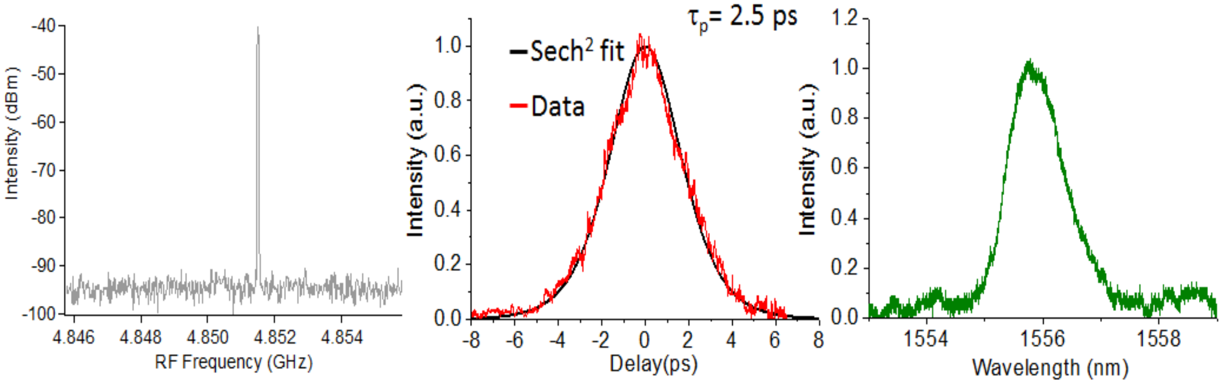

Figure 2. (a). RF spectrum, (b) autocorrelation trace, and (c) optical spectrum measured for the 20-mm-long Er^{3+},Yb^{3+}-doped phosphate glass waveguide laser.

A similar experiment was carried out with the 14.5-mm-long sample and a repetition rate of 6.8 GHz and a maximum output power of 30 mW was achieved. The results for both the waveguide samples has been summarised in Table 2.

Table 2: Summary of results obtained with different Er^{3+},Yb^{3+}-doped glass waveguide lasers.

Sample length (mm)	**Repetition-rate (GHz)**	**Pulse Duration (ps)**	**Center wavelength (nm)**	**Time-bandwidth product**	**Output power (mW)**
20	4.8	2.5	1556	0.36	9
14.5	6.8	5.4	1544.4	0.52	30

After mode-locking was achieved at a repetition rate of 6.8033 GHz, pump power was increased further to study its effect on the repetition-rate. It was found that the repetition-rate decreased by more than 1 MHz on increasing the pump power by 100 mW as seen from figure 3. This is attributed to the thermal expansion of the waveguide due to the increasing pump power.

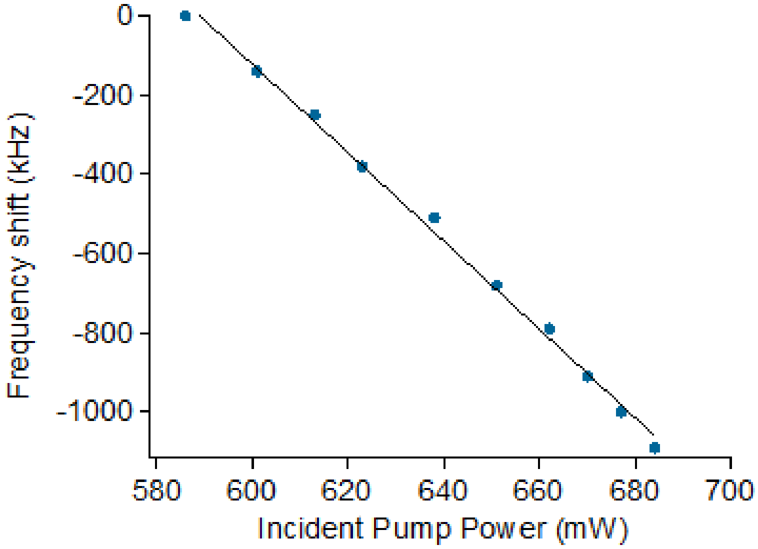

Figure 3. The change in the repetition-rate of the 14.5-mm-long waveguide laser on increasing the pump power.

5. CONCLUSIONS

In conclusion, diode-pumped, solid-state waveguide lasers were demonstrated around two different spectral regimes. Using Yb^{3+}-doped phosphate glasses, sub-picosecond operation was demonstrated around 1 µm with a repetition-rate of up to 15 GHz. Dispersion control in the laser cavity was facilitated by controlling the separation between the waveguide and the SESAM promoting self-starting, soliton mode-locked operation. Using Er^{3+}, Yb^{3+}-doped phosphate glasses, we have also demonstrated the first waveguide laser mode-locked by a quantum dot SESAM. Around 1.5 µm, a repetition rate of up to 6.8 GHz was achieved. The central repetition-rate was accurately controlled by varying the incident pump power which can offer a route for on-chip frequency comb stabilisation. Future work would also include, mode-locking of ion-exchanged Tm-doped waveguides [17] to demonstrate a high repetition-rate source around 2 µm.

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REFERENCES

[1] Jones, D. J., Diddams, S. A., Ranka, J. K., Stentz, A., Windeler, R. S., Hall, J. L., and S. T. Cundiff, “Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis,” Science 288 (5466), 635–639 (2000).

[2] Chih-Hao, Li, Benedick, A. J., Fendel, P., Glenday, A. G., Kartner, F. X., Phillips, D. F., Sasselov, D., Szentgyorgyi, A., and Walsworth, R. L., “A laser frequency comb that enables radial velocity measurements with a precision of 1 cm s-1,” Nature 452 (7187), 610-612 (2008).

[3] Bartels, A., Cerna, R., Kistner, C., Thoma, A., Hudert, F., Janke, C., and Dekorsy, T., "Ultrafast time-domain spectroscopy based on high-speed asynchronous optical sampling," Rev. Sci. Instrum. 78 (3), 035107 (2007).

[4] Chu, S.-W., Liu, T.-M., Sun, C.-K., Lin, C.-Y., and Tsai, H.-J., "Real-time second-harmonic-generation microscopy based on a 2-GHz repetition rate Ti:sapphire laser," Opt. Express 11 (8), 933-938 (2003).

[5] Byun, H., Hanjani, A., Frolov, S., Ippen, E. P., Pudo, D., Shmulovich, J., and Kartner, F. X., "Integrated low-jitter 400-MHz femtosecond waveguide laser," IEEE Photon. Tech. Lett. 21 (12), 763-765 (2009).

[6] Valle, G.D, Osellame, R., Galzerano, G., Chiodo, N., Cerullo, G., Laporta, P., Svelto, O., Morgner, U., Rozhin, A. G., Scardaci, V., and Ferrari, A. C., "Passive mode locking by carbon nanotubes in a femtosecond laser written waveguide laser," Appl. Phys. Lett. 89 (23), 231115 (2006).

[7] Beecher, S. J., Thomson, R. R., Psaila, N. D., Sun, Z., Hasan, T., Rozhin. A. G., Ferrari, A. C., and Kar, A. K., "320 fs pulse generation from an ultrafast laser inscribed waveguide laser mode-locked by a nanotube saturable absorber," Appl. Phys. Lett. 97 (11), 111114 (2010).

[8] Schlager, J. B., Callicoatt, B. E., Mirin, R. P., and Sanford, N. A., "Passively mode-locked waveguide laser with low residual jitter," IEEE Photon. Technol. Lett. 14 (9), 1351-1353 (2002).

[9] Schlager, J. B., Callicoatt, B. E., Mirin, R. P., Sanford, N. A., Jones, D. J., and Ye, J., "Passively mode-locked glass waveguide laser with 14-fs timing jitter," Opt. Lett. 28 (23), 2411-2413 (2003).

[10] Mary, R., Brown, G., Beecher, S. J., Torrisi, F., Milana, S., Popa, D., Hasan, T., Sun, Z., Lidorikis, E., Ohara, S., Ferrari, A. C., and Kar, A.K., "1.5 GHz picosecond pulse generation from a monolithic waveguide laser with a graphene-film saturable output coupler," Opt. Express 21 (7), 7943-7950 (2013).

[11] Choudhary, A., Lagatsky, A. A., Kannan, P., Sibbett, W., Brown, C. T. A., and Shepherd, D. P., "Diode-pumped femtosecond solid-state waveguide laser with a 4.9 GHz pulse repetition rate," Opt. Lett. 37 (21), 4416-4418 (2012).

[12] Lagatsky, A. A., Choudhary, A., Kannan, P., Shepherd, D. P., Sibbett, W., and Brown, C. T. A., "Fundamentally mode-locked, femtosecond waveguide oscillators with multi-gigahertz repetition frequencies up to 15 GHz," Opt. Express. 21 (17), 19608-19614 (2013).

[13] Choudhary, A., Lagatsky, A. A., Zhang, Z. Y., Zhou, K. J., Wang, Q., Hogg, R. A., Pradeesh, K., Rafailov, ,E. U., Sibbett, W., Brown, C. T. A., and Shepherd, D. P., "A diode-pumped 1.5 μm waveguide laser mode-locked at 6.8 GHz by a quantum dot SESAM," Laser Phys. Lett 10 (10), 105803 (2013).

[14] Zhang, Z. Y., Oehler, A. E. H., Resan, B., Kurmulis, S., Zhou, K. J., Wang, Q., Mangold, M., Suedmeyer, T., Keller, U., Weingarten, K. J., and Hogg, R. A., "1.55 μm InAs/GaAs Quantum Dots and High Repetition Rate Quantum Dot SESAM Mode-locked Laser," Sci. Rep. 2, 477 (2012).

[15] Honninger, C., Paschotta, R., Morier-Genoud, F., Moser, M., and Keller, U., "Q-switching stability limits of continuous-wave passive mode locking," J. Opt. Soc. Am. B 16 (1), 46-56 (1999).

[16] Kärtner, F.X. and Keller, U., "Stabilization of soliton like pulses with a slow saturable absorber," Opt. Lett. 20 (1), 16-18 (1995).

[17] Choudhary, A., Kannan, P., Mackenzie, J. I., Feng, X., and Shepherd, D.P., "Ion-exchanged Tm$^{3+:}$glass channel waveguide laser," Opt. Lett 38 (7), 1146-1148 (2013).