Diode-pumped femtosecond solid-state waveguide laser with a 4.9 GHz pulse repetition rate

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We report on the first demonstration of a passively mode-locked, diode-pumped, monolithic Yb:glass channel waveguide laser that incorporates a semiconductor saturable absorber mirror. Stable and self-starting mode-locking is achieved in a Fabry–Perot cavity configuration producing a pulse repetition rate up to 4.9 GHz. The shortest pulse duration of 740 fs is generated with 30 mW of average output power at a center wavelength of 1058 nm. A maximum output power of 81 mW is produced during mode-locking with corresponding pulse duration of 800 fs.

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The development of ultrashort pulse lasers operating at pulse repetition rates in the gigahertz regime is of particular interest for applications in frequency comb metrology [1], optical communications [2], biophotonics [3] and ultrafast optical sampling [4], and a wide range of semiconductor, fiber and solid-state mode-locked lasers have been developed for these purposes. Monolithically integrated edge-emitting or vertical external cavity surface emitting semiconductor lasers are attractive options to produce femtosecond pulses with multi-gigahertz pulse repetition frequencies [5–7]. However, due to the presence of fast gain dynamics during mode-locking, ultrafast semiconductor lasers, in general, are characterized by high timing jitter of hundreds of femtoseconds [8]. Also, the generated average powers are rather limited apart from a few demonstrations where a high-power operation was achieved at low temperatures of a gain chip [7,9]. To develop fiber-based high repetition rate oscillators, a harmonic mode-locking technique [10] is generally used which, however, tends to be less stable than fundamental mode-locking. More recently, Fabry–Pérot high-gain Er-doped ultrafast fiber lasers, that were passively mode-locked by a carbon nanotubes saturable absorber or a saturable Bragg reflector, were demonstrated [11–13] where fundamental repetition rates up to 19 GHz were realized (~1 mW average power in the picosecond regime) [12] and a maximum average output power above 50 mW was produced with ~206 fs pulses at 3 GHz pulse repetition rate [13].

The Fabry–Pérot cavity approach, in combination with solid-state waveguide-based gain media, enables further progress towards the development of more efficient, less expensive, and stable ultrafast and ultrahigh repetition rate laser systems that would offer an integrable status. Diode-pumped solid-state lasers (DPSSL) are excellent candidates for the development of multi-gigahertz repetition rate femtosecond systems because they combine favorable performance characteristics such as low threshold and high efficiency and low intrinsic quantum noise under the operational conditions afforded by cost-effective and compact diode-pumping. Several demonstrations of femtosecond DPSSLs, operating at repetition rates above 1 GHz, have been reported [14–16] where the highest repetition frequency of 4.8 GHz was produced by a Yb:KGdW laser operating around 1040 nm [16]. Further scaling of the pulse repetition rate from a DPSSL can be achieved with waveguide cavity geometry because this offers excellent mode confinement in a gain medium and a correspondingly reduced mode-locking threshold. However, this approach has not been explored fully, as yet. Previously, passively mode-locked Er-doped waveguide lasers, operating around 1.5 μm, have been demonstrated with pulse repetition frequencies in the megahertz range at low average output power levels of about 1 mW or less [17,18].

Here we report for the first time, to our knowledge, passive mode-locking of a Yb:glass channel waveguide laser configured in a diode-pumped monolithic configuration. This laser produced pulses with a duration of 800 fs at around 1052 nm center wavelength with a fundamental pulse repetition frequency of 4.93 GHz and an average output power of 80 mW. The shortest pulse duration of 740 fs was achieved with a 2% output coupling at an average output power of 30 mW.

The channel waveguide sample was fabricated using a phosphate glass substrate (Schott Glass Technologies Inc., IOG-1), doped with 12 wt. % of Yb_2O_3 and containing 24 mol. % of Na_2O [19] to allow a waveguide fabrication by an ion-exchange method. An aluminium (Al) film of 200 nm thickness was deposited on the polished glass substrate by e-beam evaporation following which a standard photolithography technique was applied to define channel openings with widths varying from 1 to 10 μm. These metal patterned samples were then immersed for 10 min in an ion-exchange melt of composition 45 mol. $\%KNO_3$ – 50 mol. $\%NaNO_3$ – 5 mol. $\%AgNO_3$ at 325°C for channel waveguide formation. Following the ion-exchange procedure, the Al mask was chemically removed and the end facets of the glass were polished to give a device length of 20 mm. The refractive index profile of these waveguides at 632.8 nm was determined by using a prism coupling technique (a planar waveguide was fabricated and employed for this purpose). Ion-exchange resulted in a diffused waveguide with an index change of $\Delta n = +6.6 \times 10^{-3}$ on the surface with respect

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to the substrate index of 1.521 and an overall diffusion depth of ~13.8 μm supporting three modes at 632.8 nm.

A schematic of the mode-locked Yb:glass waveguide laser is depicted in Fig. 1. A single-mode fiber-coupled laser diode operating at 980.6 nm (3S Photonics) and delivering up to 750 mW of average power was used as the pump source. Its beam was first collimated by a 20× aspheric lens ($f = 8$ mm) and coupled into the waveguide through an output coupler (OC) by using a 16× aspheric focusing lens ($f = 11$ mm) that provided an 8.8 μm diameter pump spot size. An optical isolator in combination with a half-wave plate was used to prevent back reflections and a dichroic beam splitter separated the laser emission from the pump radiation. The OC with a transmission of either 2% or 4% at around 1050 nm and low reflectivity ($R < 2\%$) at pump wavelength was directly butt-coupled to the waveguide end-facet with fluorinated liquid. The waveguide cavity was terminated by a high-reflectivity mirror for continuous-wave laser assessments or a semiconductor saturable absorber mirror (SESAM) structure for passively mode-locked operation. The SESAM (Batop GmbH) was characterized by an initial reflection of 99.3% at around 1050 nm, a modulation depth of 0.4%, a saturation fluence of 90 $\mu J/cm^2$ and a relaxation time of 0.5 ps. The waveguide sample was mounted on a copper plate that was cooled actively to 18°C.

Initially, all channel waveguides were characterized during continuous-wave operation to identify those that delivered the highest output powers. A range of high quality channel waveguides with propagation losses less than 0.5 dB/cm were identified and a maximum output power of 156 mW was obtained at 1050 nm (610 mW of incident pump power, defined as the power in front of the waveguide) with the 4% OC. The maximum power obtained with the 2% OC was 108 mW at 1052 nm. The corresponding slope efficiencies were 32% and 27%, and the lasing thresholds were measured to be around 49 mW of the incident pump power. The measured near-field laser mode profile had radii of 5.8×3.8 μm^2 in the horizontal and vertical directions, respectively, and the corresponding M^2 values of the laser output were found to be less than 1.1.

Stable mode-locked operation of the Yb:glass waveguide laser was achieved when the SESAM was end-butted to the gain medium and careful adjustments were made to both SESAM and OC positions relative to the waveguide end facets. To characterize the stability of the mode-locked operation, the radio frequency (RF) spectrum of the pulse train was measured using a fast InGaAs photodiode (11 GHz bandwidth) and an RF spectrum analyzer. The microwave spectrum measured at a span of 1 MHz and resolution bandwidth of 1 kHz shows a clean peak at a fundamental repetition frequency of around 4.926 GHz (Fig. 2). A high signal-to-noise ratio of 60 dB and the absence of side peaks confirm the excellent pulse-to-pulse stability without any evidence of Q-switching instabilities during mode-locking. The wide-span RF spectrum measurements (Fig. 2, inset) in combination with a large scan autocorrelation (~100 ps) indicated single-pulse operation. The input-output characteristics of the Yb:glass channel waveguide laser during ultra-short pulse operation are shown in Fig. 3. With the 4% OC in place stable mode-locking was observed in a range of output powers from 40 to 81 mW, whereas Q-switched mode-locking became evident at lower intracavity powers, noticeably, when the fluence on the SESAM was below 290 $\mu J/cm^2$. Figure 4(a) shows the intensity autocorrelation of the pulses at the maximum output power, implying pulse duration of 800 fs (assuming a sech^2 fit). A time-bandwidth product of 0.46 was deduced from the corresponding spectral width of 2.1 nm at the center wavelength of 1052 nm [Fig. 4(b)]. When the output coupling was changed to 2%, slightly shorter pulse durations of 740 fs were obtained with an average output power of

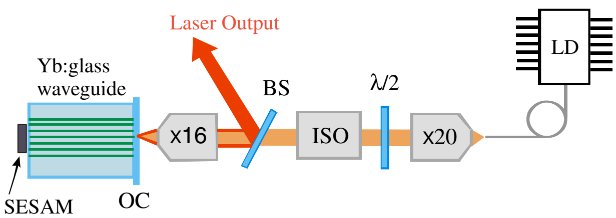

Fig. 1. (Color online) Experimental setup of the mode-locked Yb:glass waveguide laser. LD, laser diode; ISO, optical isolator; BS, dichroic beam splitter; and OC, output coupler.

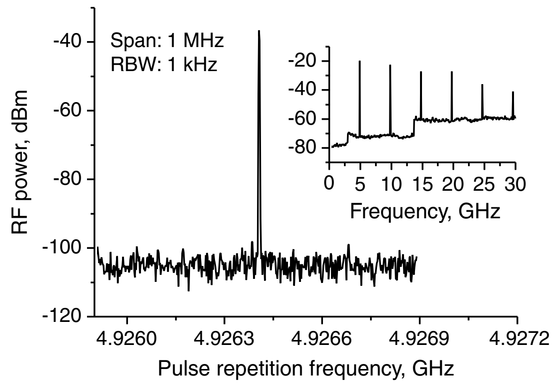

Fig. 2. RF spectrum at fundamental repetition frequency of the pulse train from the mode-locked Yb:glass waveguide laser. The inset shows the RF spectrum on a 30 GHz span at a resolution bandwidth of 1 MHz.

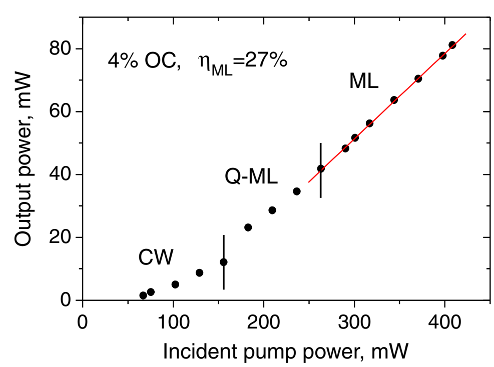

Fig. 3. (Color online) Average output power of the Yb:glass channel waveguide laser with the SESAM in place as a function of the incident pump power. CW, continuous-wave operation; Q-ML, Q-switched mode-locking; and ML, pure mode-locking regimes.

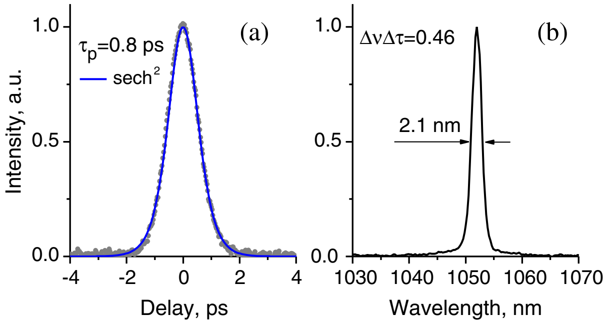

Fig. 4. (Color online) (a) Intensity autocorrelation trace of the pulses from the mode-locked Yb:glass waveguide laser with the 4% OC and (b) corresponding optical spectrum.

30 mW and a 2.3 nm width optical spectrum centered at 1058 nm (a time-bandwidth product of 0.46).

We believe that the stable mode-locking and sub-picosecond pulse generation from our waveguide laser is most probably due 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, the critical pulse energy which is required to overcome Q-switching instabilities was estimated to be about 0.2 nJ in our experimental case. This value is much less than the critical pulse energy of 3.6 nJ that would be required for a non-soliton mode-locking regime. It is in a good agreement with previous results where >10 times reduction in the critical pulse energy was demonstrated due to soliton effects in a solid-state mode-locked laser [14]. In the mode-locked waveguide laser described here, the negative GVD originated from the micrometer-size gaps between the OC or the SESAM and uncoated surfaces of the waveguide structure. This leads to the formation of equivalent Gires–Tournois interferometer (GTI) structures that in certain conditions serve to generate an exploitable amount of negative GVD [20]. Based on the soliton area theorem, we have estimated the net GVD to be around -4000 fs^2. It should be noted, however, that GVD value depends very sensitively on width of the GTI gap. Although, we have not provided a precise control of the gaps, their widths were adjusted by applying some mechanical pressure to the SESAM or to the OC to find stable mode-locking conditions.

In conclusion, passive mode-locking of a diode-pumped Yb:glass channel waveguide laser with a SESAM device is demonstrated for the first time to the authors' knowledge. A pulse repetition frequency up to 4.9 GHz was realized with the shortest pulse duration of 740 fs from a monolithic Fabry–Perot waveguide cavity arrangement. An average output power of up to 81 mW (an optical-to-optical efficiency of 20%) was produced at 1052 nm with the corresponding pulse duration of 800 fs. We believe that pulse repetition rate scaling is feasible with shorter waveguide samples and that the pulse durations could be further reduced by using optimized SESAM designs and cavity parameters, such as net GVD and the output coupling level to increase both the gain bandwidth and the SPM parameter. Also, an average output power above 100 mW level can be achieved with a multiple diode lasers pumping scheme [13].

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