Quantum-Dot Saturable Absorber and Kerr-Lens Mode-Locked Yb:KGW Laser with >450 kW of Peak Power

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Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

Hybrid action of a quantum-dot saturable absorber and Kerr-lens mode-locking in a diode-pumped Yb:KGW laser was demonstrated. Using a quantum-dot saturable absorber with an 0.7% (0.5%) modulation depth, the mode-locked laser delivered 90 fs (93fs) pulses with 3.2 W (2.9W) average power at the repetition rate of 77 MHz, corresponding to 462 kW (406 kW) of peak power and 41 nJ (38 nJ) of pulse energy. To the best of our knowledge, this represents the highest average and peak powers generated to date from quantum-dot saturable absorber based mode-locked lasers.

OCIS codes: *(140.3480) Lasers, diode pumped; (140.3615) Lasers, ytterbium; (140.7090) Ultrafast lasers; (320.2250) Femtosecond phenomena; (140.4050) Mode-locked lasers; (250.5590) Quantum-well, -wire and -dot devices.*

http://dx.doi.org/10.1364/OL.99.099999

Quantum-dot semiconductor saturable absorber mirrors (QD-SESAM) have attracted a lot of interest for generation of ultra-short laser pulses from solid-state and fiber lasers [1–5] due to their favorable properties when compared with widely used quantum-well counterparts, QW-SESAM [6]. Indeed, because of the strong confinement of free charge carriers to infinitesimal spatial dimension, the density of states are sharply enhanced. In QD-SESAMs this leads to a sub-picosecond recovery time of carriers and low saturation fluence (10-15 μJ/cm^2). Furthermore, the absorption and gain bandwidth are inhomogeneously broadened as a result of Gaussian distribution of dot sizes in absorber structure, which is beneficial for generation of ultra-short laser pulses [1–3]. For example, the femtosecond laser pulse generation using QD-SESAMs has been reported for a Cr:Forsterite laser with the shortest pulse duration of 85 fs and 55 mW of an average output power [1] and also for an Yb:KGW laser with 114 fs pulses and 500 mW of an output power [4].

On the other hand, recent works based on a dual action of the Kerr-lens and quantum-well saturable absorber mode-locking (KLAS) has demonstrated the generation of ultra-short pulses with high average and peak powers [7,8]. In this particular mode-locking regime, a saturable absorber is employed for an initiation and an initial pulse shaping, while the Kerr lensing effect is the primary pulse shortening mechanism enabling the generation of the high peak-power sub-100 fs pulses. It was shown that the benefits of KLAS mode-locking are derived from the balance of both the reliable and self-starting operation of the used QW-SESAM as well as from the fast loss modulation and broadband operation properties of Kerr-lens mode-locking. In fact, in the absence of a semiconductor absorber in a cavity no pure Kerr-lens mode-locking could be initiated and, on the contrary, with a reduced Kerr lensing effect only the Q-switched or multiple pulse mode-locking was supported by the used QW-SESAM. In this context, faster recovery times of the QD-SESAMs can be beneficial to enhance a pulse formation and stabilize the mode-locking regime. Therefore, QD-SESAMs present an attractive alternative for KLAS mode-locking. In this work we explored this possibility and demonstrated the generation of 90 fs pulses with 3.2 W of an average pump power using a QD-SESAM with an 0.7% of modulation depth. At a repetition rate of 77 MHz this corresponded to 462 kW of a peak power and 41 nJ of pulse energy. By means of a QD-SESAM with a lower modulation depth of 0.5%, 93 fs pulses with 2.9 W of an output power can also be generated. To the best of our knowledge, these are the most powerful femtosecond lasers based on the QD-SESAMs demonstrated to date.

Among an Yb-doped laser materials, the Yb:KGW crystals (and sister material Yb:KYW) have been shown to be a suitable gain medium for generation of femtosecond pulses with high average powers [8,9]. A successful mode-locking was also demonstrated with a number of different absorbers, such as QW-SESAM [10], saturable Bragg reflector [11], Kerr-lens [12], carbon nanotubes [13], and graphene monolayers [14]. Recently, pulses as short as 59 fs with 62 mW of an output power were reported [15]. This laser crystal can offer a broad amplification bandwidth (~25 nm), a high emission cross-section (~2.8 × 10−20 cm2), a relatively high thermal conductivity (~3.3 W/m/K), and also a small intrinsic quantum defect [16]. All these distinct properties motivated us to use the Yb:KGW crystal in this work.

The laser used a 5-mm-long Yb:KGW crystal (cut along the Ng-axis) with 1.5 at.% doping level in a Z-fold cavity, as shown in figure 1. The crystal was pumped at 980 nm by a 30 W fiber-coupled laser diode (100 µm core diameter, 0.22 NA) which was focused to a spot size of 300 µm in diameter by two achromatic doublets. The cavity configuration provided a mode size of around 280 µm, which could be precisely tuned by changing the position of the output coupler that was mounted on a translation stage. This allowed for the introduction of the Kerr-lens soft-aperturing effect into the laser cavity by making the laser mode slightly larger than the pump spot size in the crystal. The crystal absorbed 50-60% of the pump power depending on the pump power level. It produced up to 5 W of output power in the continuous wave (CW) regime with a highly reflecting (HR) mirror placed as the end mirror instead of the QD-SESAM. The thermal lens strength of the crystal at pump power of 30 W (18 W absorbed) was estimated to be 10 diopters using a modified ABCD-matrix analysis [17]. An output coupler with transmission of 7.5% was used in the cavity.

For the mode-locked laser operation, two QD-SESAMs (grown by Innolume GmbH) with modulation depths of 0.7% and 0.5% (with 7 and 5 pairs of InGaAs quantum dot layers in the saturable structure, respectively) and a saturation fluence of 25 µJ/cm2 [4] were used. These saturable absorbers exhibited recovery time with a sub-picosecond fast component. The absorbers were used as one of the end mirrors and the beam spot size on them was designed to be initially around 350 µm in diameter. It was changing to a smaller size when the length of the arm at the output coupler side was reduced in order to introduce the Kerr lensing. Two Gires-Tournois interferometer mirrors (GTI) provided a negative dispersion to compensate for the positive dispersion of the crystal and also for the induced chirp from a self-phase modulation (SPM).The laser cavity was initially optimized for the CW laser operation near the middle of the stability region. In this regime the laser could deliver up to 5 W of output power. The HR mirror was then replaced by one of the QD-SESAMs and the GTI mirrors were configured to provide a negative round-trip dispersion of -4400 fs2. Once operating the laser with a QD-SESAM, a Q-switched mode-locked laser regime was readily observed. By reducing the cavity length using a translation stage with an output coupler, a stable mode-locked laser with a spectral bandwidth of around 5 nm could be obtained. At this point, the mode-locked laser was purely supported by the used QD-SESAM and the laser operation was self-starting after a temporary laser beam obstruction. Further reduction of the cavity length resulted in a multi-pulse operation of the laser until a transition to a single pulse mode-locked laser regime could be observed. The latter transition indicated that the Kerr-lens mode-locking regime came into effect since the cavity mode size at this position was slightly larger than the pump beam size in the crystal. Introduction of the Kerr lensing was also accompanied by continuous increase in the spectral width of the generated pulses. The pulsation transitions sequence as a result of reducing the cavity length was similar to the ones previously observed in [7,8]. Similarly, without a QD-SESAM in the cavity no pure Kerr-lens mode-locking could be achieved. Using the QD-SESAM with an 0.7% modulation depth at the pump power of 30 W, the laser could deliver 90 fs pulses (see figure 2) with an average output power of 3.2 W at a repetition rate of 77 MHz. This corresponds to 462 kW of peak power and 41 nJ of pulse energy. With an 0.5% modulation depth QD-SESAM, 93 fs-long pulses with an average output power of 2.9 W at 76.9 MHz repetition rate, corresponding to 406 kW of peak power and 38 nJ of pulse energy, could be generated. The ripple in the spectrum is a known artifact of a spectrometer caused by a multi-mode fiber input, similar to the observation reported in [19].

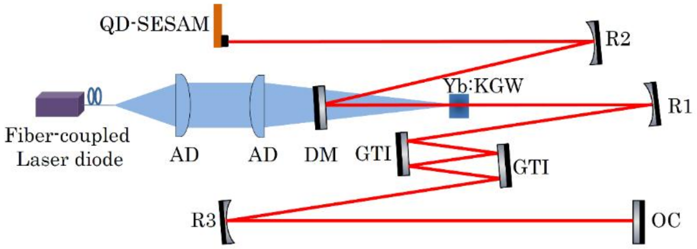

Figure 1. Experimental setup of a mode-locked Yb:KGW laser. AD: achromatic doublets; DM: dichroic mirror; R1-3: concave mirrors; OC: output coupler.

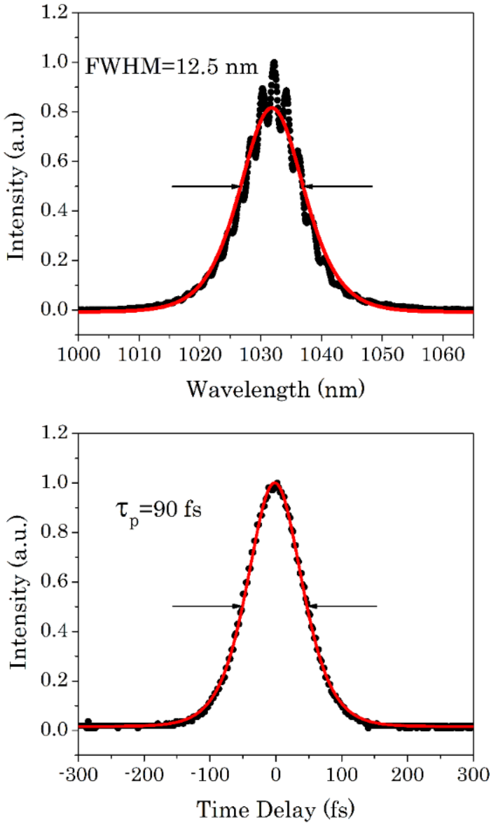

Figure 2. The intensity autocorrelation (a) and the spectrum (b) of the generated pulses with an 0.7% QD-SESAM. The red curves are the $sech^2$ shape fits. The time-bandwidth product was calculated to be 0.317. The ripple in the spectrum is a known artifact of a spectrometer.

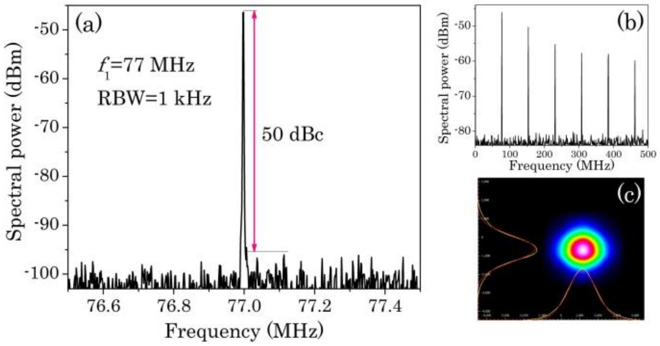

Figure 3. RF spectrum of the pulse train (a) with 0.7% QD-SESAM, wide-span measurements (b), and far-field beam profile of the mode-locked laser (c).

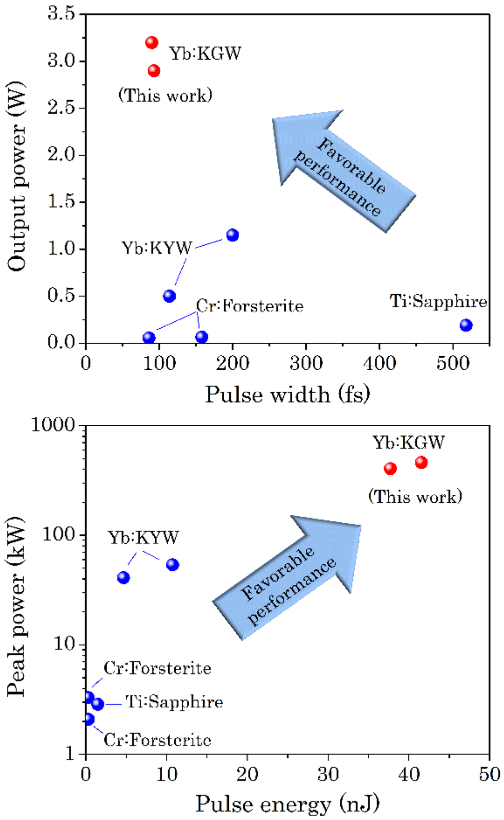

Figure 4. Current and previous mode-locked laser results with QD-SESAMs [1,4,22].

The radio frequency (RF) spectral power of the 90 fs mode-locked laser is shown in figure 3. The spectral power of the fundamental mode was 50 dB above the noise level. In a wide-range RF scan measurement, no additional peaks between the higher order modes were observed indicating clean mode-locking. The far-field beam profile of the mode-locked laser which was near diffraction-limited is also shown in the figure 3(c). Such powerful lasers with a good beam quality form an excellent platform for application in nonlinear optical experiments such as frequency conversion [20,21], nonlinear microscopy [22] and ultrafast spectroscopy [23].

The results of this work in terms of the peak power and the energy of the generated pulses compare favorably with all previous works where QD-SESAMs were used for a generation of femtosecond pulses using Yb:KYW, Cr:Forsterite and Ti:Sapphire laser crystals [1,4,24]. A summary of all reported results is compiled in figure 4. For example, the mode-locked Yb:KYW laser delivered 114 fs pulses with 500 mW of an average output power (41 kW of peak power) and also 200 fs pulses with a higher average power of 1.15 W (53.7 kW of peak power) [4]. Therefore, our results represent ~2.8 times increase in output power and ~8.6 times increase in peak power with respect to previous results. In the sub-100 fs regime these numbers rise to 58 and 140 times, respectively.

When compared with the 67 fs mode-locked Yb:KGW laser reported in [7] , the longer pulses generated in our current work could be a result of a dispersion overcompensation due to the uncertainty in dispersive properties of the used QD-SESAMs. We believe that further optimization of the mode-locking performance can lead to the generation of even shorter femtosecond pulses. A good candidate for high power regime with ultrashort pulses is also an Yb:CALGO crystal [25] which is characterized by a broader gain bandwidth and higher thermal conductivity than Yb:KGW. For example, the generation of 9 fs pulses with 12.5W of average output power was recently reported in [26].

In summary, a powerful diode-pumped Yb:KGW mode-locked laser based on dual-action of a quantum-dot saturable absorber and the Kerr lensing effect was demonstrated. The quantum-dot saturable absorber with a fast recovery time and a broad gain bandwidth was used for the self-starting and initial pulse forming with further pulse shortening achieved through the introduction of Kerr lensing effect. The resultant mode-locked laser delivered 90 fs pulses with an average output power of 3.2 W by using a QD-SESAM with a modulation depth of 0.7%. This corresponded to 462 kW of peak power and 41 nJ of pulse energy. With the same laser system and a QD-SESAM with a modulation depth of 0.5%, 93 fs pulses with 2.9 W of average power and 406 kW of peak power (38 nJ of pulse energy) could be generated. Our results showed remarkably higher average output and pulse peak powers when compared to previous works with QD-SESAMs. Further optimization of the laser system and more careful dispersion compensation should result in the generation of even more powerful and shorter pulses.

Acknowledgment. This work was supported by the Natural Sciences and Engineering Research Council of Canada, University of Manitoba, and Western Economic Diversification Canada.

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