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Quantum-dot saturable absorber and Kerr-lens mode-locked Yb:KGW laser with >450 kW of peak power

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The hybrid action of 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 a 0.7% (0.5%) modulation depth, the mode-locked laser delivered 90 fs (93 fs) pulses with 3.2 W (2.9 W) of 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. © 2016 Optical Society of America

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Quantum-dot semiconductor saturable absorber mirrors (QD-SESAMs) have attracted a lot of interest for the generation of ultrashort laser pulses from solid-state and fiber lasers [1–5] due to their favorable properties, when compared with the widely used quantum-well counterparts, QW-SESAMs [6]. Indeed, because of the strong confinement of free charge carriers to infinitesimal spatial dimension, the density of states is sharply enhanced. In QD-SESAMs this leads to a sub-picosecond recovery time of carriers and low saturation fluence. Furthermore, the absorption and gain bandwidth are inhomogeneously broadened as a result of a Gaussian distribution of dot sizes in the absorber structure, which is beneficial for the generation of ultrashort laser pulses [1–3]. For example, femtosecond laser pulse generation using QD-SESAMs has been reported for a Cr:forsterite laser with the shortest pulse duration of 86 fs and 55 mW of average output power [1] and for an Yb:KYW laser with 114 fs pulses and 500 mW of output power [4].

On the other hand, recent works based on the dual action of the Kerr-lens and quantum-well saturable absorber mode locking (KLAS) has demonstrated the generation of ultrashort pulses with high average and peak powers [7,8]. In this particular mode locking regime, the saturable absorber is employed for initiation and 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 the 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, the faster recovery times of the QD-SESAMs can be beneficial to enhance pulse formation and stabilize the mode locking regime. Therefore, QD-SESAMs present an attractive alternative for KLAS mode locking. In this Letter, we explored this possibility and demonstrated the generation of 90 fs pulses with 3.2 W of average output power using a QD-SESAM with 0.7% of modulation depth. At a repetition rate of 77 MHz, this corresponded to 462 kW of peak power and 41 nJ of pulse energy. By means of a QD-SESAM with lower modulation depth of 0.5%, 93 fs pulses with 2.9 W of output power could 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 the Yb-doped laser materials, the crystals of Yb:KGW (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]. Successful mode locking was also demonstrated with a number of different absorbers, such as QW-SESAM [10], saturable Bragg reflector [11], Kerr-lense [12], carbon nanotubes [13], and graphene monolayers [14]. Recently, pulses as short as 59 fs with 62 mW of output power were reported [15]. This laser crystal offers a broad amplification bandwidth (~25 nm), high emission cross section ($\sim 2.8 \times 10^{-20}$ cm^2), relatively high thermal conductivity (~3.3 W/m/K), and small intrinsic quantum defect [16].

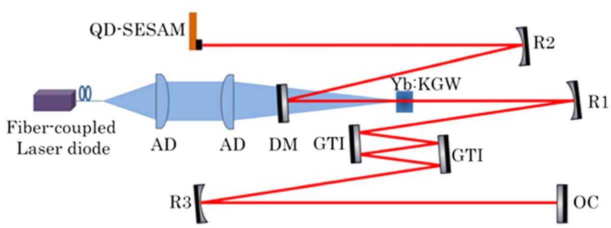

Fig. 1. Experimental setup of a mode-locked Yb:KGW laser. AD, achromatic doublet; DM, dichroic mirror; R1-3, concave mirror; OC, output coupler.

All of these distinct properties motivated us to use the crystal of Yb:KGW in this Letter.

The laser used a 5 mm long Yb:KGW crystal (cut along the Ng-axis) with 1.5% doping level in a Z-fold cavity, as shown in Fig. 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 soft aperturing effect via the Kerr lensing into the laser cavity by making the laser mode size 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, Laseroptik GmbH) mirror placed as the end mirror instead of the QD-SESAM. The thermal lens strength of the crystal at a 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 a 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 seven and five pairs of InGaAs quantum-dot layers in the saturable structure, respectively), and a saturation fluence of 25 $\mu J/cm^2$ [4] were used. These saturable absorbers exhibited recovery time with a sub-picosecond fast component. The absorbers were not water cooled and were used as one of the end mirrors. 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 to introduce the Kerr lensing. Two Gires–Tournois interferometer mirrors (GTI) provided negative dispersion to compensate for the positive dispersion of the crystal and for the induced chirp from 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 fs^2. With a QD-SESAM in the cavity, a *Q*-switched mode-locked laser regime was readily observed. At this point, the fluence on the absorber was ~200 $\mu J/cm^2$. By reducing the cavity length using the 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 mode-locked operation was completely self-starting. For this regime, the fluence on the QD-SESAM was around 240 $\mu J/cm^2$. Further reduction of the cavity length resulted in 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 a continuous increase in the spectral width of the generated pulses. The transition sequence of the pulsed regimes as a result of reducing the cavity length was similar to the ones previously observed in [7,8]. Similarly, without the QD-SESAM in the cavity, no pure Kerr-lens mode locking could be achieved. Using the QD-SESAM with 0.7% modulation depth at the pump power of 30 W, the laser could deliver 90 fs pulses (see Fig. 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. The fluence on the absorber was around 340 $\mu J/cm^2$. With the 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 [18]. A single pulse mode locking regime without instabilities was confirmed by monitoring the femtosecond-to-nanosecond time scales using a wide-range scan (200 ps) autocorrelator and a combination of fast oscilloscope/photodetector with a resolution of ~100 ps [19].

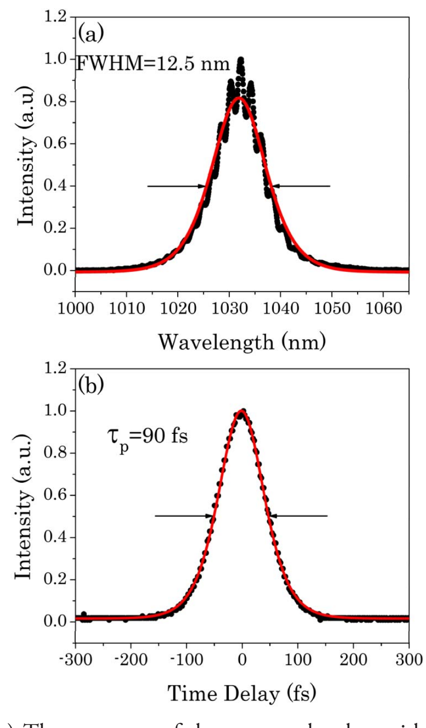

Fig. 2. (a) The spectrum of the generated pulses with 0.7% QD-SESAM and (b) intensity autocorrelation. The red curves are the $sech^2$ shape fits. The time-bandwidth product was calculated to be 0.317. The ripple in the spectrum is a known artifact of the spectrometer.

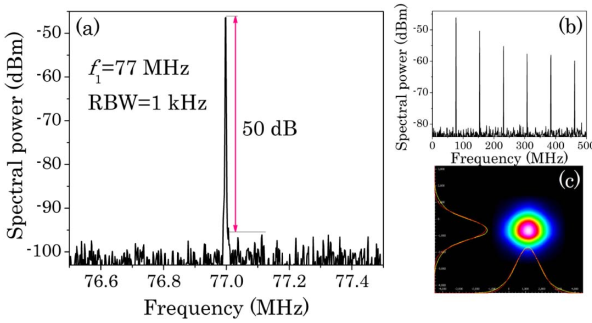

Fig. 3. (a) RF spectrum of the pulse train with 0.7% QD-SESAM, (b) wide-span measurements. (c) Far-field beam profile of the mode-locked laser.

The radio frequency (RF) spectrum of the 90 fs mode-locked laser is shown in Fig. 3. The spectral power of the fundamental mode was 50 dB above the noise level. In a wide-range RF scan measurement [Fig. 3(b)], no additional peaks between the higher order modes were observed indicating clean mode locking. The drop of intensity of high-order harmonics in the RF spectrum was caused by the biasing conditions of the used photodetector and did not affect the observation of mode locking instabilities. The far-field beam profile of the mode-locked laser which was near diffraction limited with $M^2 < 1.2$ is also shown in Fig. 3(c). Such powerful lasers with 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 the work in this Letter 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 the generation of femtosecond pulses using Yb:KYW, Cr:forsterite, and Ti:sapphire laser crystals [4,1,24]. A summary of all reported results is compiled in Fig. 4. For example, the mode-locked Yb:KYW laser delivered 114 fs pulses with 500 mW of average output power (41 kW of peak power) and 200 fs pulses with a higher average power of 1.15 W (53.7 kW of peak power) [4]. Therefore, our results represent a ~2.8 times increase in output power and an ~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] and based on QW-SESAM, the longer pulses generated in this Letter could be a result of 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 a 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 94 fs pulses with 12.5 W of average output power was recently reported in [26].

In summary, a powerful diode-pumped Yb:KGW mode-locked laser based on the 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 self-starting and initial pulse forming with further pulse shortening achieved through the introduction of the 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 the 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 the 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 the 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.

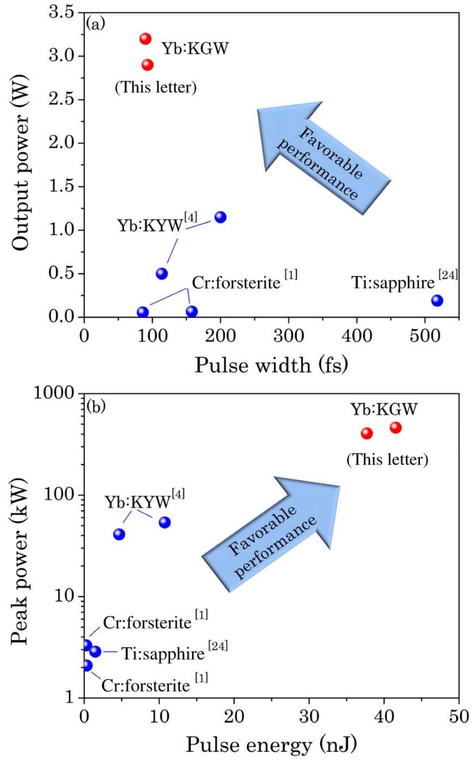

Fig. 4. Current and previous mode-locked laser results with QD-SESAMs [1,4,24].

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