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10 GHz pulse repetition rate Er:Yb:glass laser modelocked with quantum dot semiconductor saturable absorber mirror

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Semiconductor saturable absorber mirror (SESAM) modelocked high pulse repetition rate (≥10 GHz) diode-pumped solid-state lasers are proven as an enabling technology for high data rate coherent communication systems owing to their low noise and high pulse-to-pulse optical phase-coherence. Compared to quantum well, quantum dot (QD)-based SESAMs offer potential advantages to such laser systems in terms of reduced saturation fluence, broader bandwidth, and wavelength flexibility. Here, we describe the first 10 GHz pulse repetition rate QD-SESAM modelocked laser at 1.55 μm, exhibiting 2 ps pulse width from an Er-doped glass oscillator (ERGO). The 10 GHz ERGO laser is modelocked with InAs/GaAs QD-SESAM with saturation fluence as low as 9 $\mu J/cm^2$.

OCIS codes: (140.7090) Ultrafast lasers; (170.7160) Ultrafast technology; (250.5590) Quantum-well, -wire and -dot devices.

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1. INTRODUCTION

Solid-state lasers, fundamentally modelocked using quantum well (QW) semiconductor saturable absorber mirrors (SESAMs) [1,2], typically exhibit low timing jitter [3,4], high pulse-to-pulse phase coherence, and high individual optical spectral mode signal to noise ratio [5–7]. These features are particularly important, but very difficult to achieve with other laser technologies at high pulse repetition rates (10 GHz or higher) [8]. Those features are critical in applications including ultrahigh speed transmission systems up to 30 Tbits/s [9], optical clocking, multiwavelength sources [10], continuum generation, and frequency metrology [11,12], to name a few. Coherent optical communications is a rapidly growing field due to the continued exponential growth of consumed energy in nonoptical communications servers and networks, as well as the constantly growing need for communication bandwidth.

Quantum dot (QD)-based SESAMs offer many potential advantages for such lasers. In high repetition rate SESAM modelocked lasers [13,14], the pulse energy is very low, requiring relatively tight focusing onto the QW-based SESAM in order to achieve saturation. The tight focusing with highly curved intracavity mirrors limits the design freedom for such compact laser cavities. QD technology [15] has the potential to resolve this issue owing to the lower saturation fluence compared to QWs [16]. The additional degree of freedom introduced by variability of the areal QD density allows for low saturation fluence (Fsat) in conjunction with moderate modulation depth (dR) to be adjustable independent of each other, while for QW-based devices the product Fsat·dR is constant [17]. In addition, the unique characteristic of large inhomogeneous dot size distribution in QD devices offers the promise of broader mode-locked laser bandwidth and more flexibility in the laser central operating wavelength.

We developed an epitaxial process for the realization of high optical quality QDs emitting at 1.55 μm [18]. The QD layer is surrounded by the QW structure in an asymmetric InGaAs/GaAs dot-in-well (DWELL) structure. As shown in the Fig. 1(b) in [19], the room temperature photoluminescence (RT-PL) at 1.55 μm is comparable in power to that of 1.3 μm QD structures. However, the bandwidth of RT-PL at 1.55 μm is almost 10 times broader than at 1.3 μm, resulting in almost 15 times lower peak intensity at 1.55 μm. The QD-SESAM is realized by placing the DWELL structure on the QW-based Bragg mirror designed to operate around 1550 nm [19].

In this paper, we describe in more details the 10 GHz pulse repetition rate Er-doped laser modelocked with QD-SESAM.

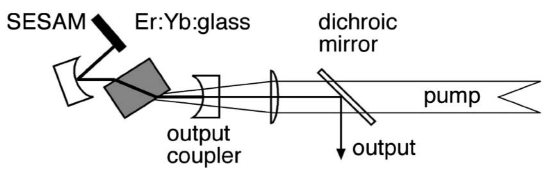

Fig. 1. Layout of the 10 GHz ERGO laser. The gain medium is Er:Yb doped glass, and the QD SESAM is placed at the end of the cavity.

We discuss the output power range in CW and modelocking operation, characterize the laser with the standard ultrafast laser diagnostics, and compare its performance to the same laser modelocked with QW-based SESAM.

2. RESULTS

The QD-SESAM is characterized with the precision Fsat measurement system [20]. It exhibits a nonlinear modulation depth of 0.4% and a Fsat of 9 $\mu J/cm^2$. For comparison, the QW-SESAM was characterized with the same precision system and exhibits a nonlinear modulation depth of 0.5%, Fsat of 15 $\mu J/cm^2$, and nonsaturable losses of 0.1%. When operated with the QD-SESAM, the laser shows a lower lasing threshold compared to that when operating with a standard QW-SESAM, suggesting that the QD-SESAM's nonsaturable losses are 0.1% or lower.

The Er-doped glass oscillator (ERGO) laser is depicted in Fig. 1. It is a V-cavity consisting of an 0.5% transmission output coupler, 1 mm thick Er:Yb doped glass plate (QX/Er from Kigre) as the gain medium, a fold high reflection mirror, and a QW SESAM. The output coupler and the fold mirror are strongly curved with radius of curvature <4 mm. The pump diode is a single mode fiber pigtailed diode emitting up to 600 mW at 976 nm manufactured by EM4, model 300076, part number P161-600-976M. Note that we use only up to ~300 mW of pump power. The laser is fundamentally modelocked, meaning that only one pulse is circulating within the cavity. The cavity length is therefore slightly less than 15 mm. Passive fundamental modelocking with a SESAM enables ultralow pulse timing jitter and optical pulse-to-pulse phase coherence, which is essential for high data rate communication systems with coherent modulation formats.

In our experiment, the QW-SESAM in the ERGO laser is replaced with the QD-SESAM described in [19]. Both QD- and QW-SESAM modelocked lasers are built with the same optics. For two sets of results, only the SESAMs are exchanged, and SESAM realignment in the optical axis (*z* axis) and tip-tilt is required. The laser output power and operation range for CW operation and for QD- and QW-SESAM modelocking are displayed in Fig. 2. Since laser is very sensitive to alignment, the new alignment for clean modelocking resulted in lower modelocked power with QD-SESAM. The alignment for modelocking is much more sensitive and challenging than alignment at the laser threshold, as the laser delivers 10 times more power in modelocked operation.

Already at 10 GHz pulse repetition rate, the first optical element that gets damaged is SESAM and not the gain glass, due to tighter focusing onto the SESAM. Therefore, it is critical to increase the focused spot on the SESAM. Lower saturation fluence is then required to avoid *Q*-switching instabilities. Although not extensively characterized, after damaging SESAMs on a couple of spots, the damage threshold of QW and QD SESAMs is estimated to be similar. However, the salient feature of the QD-SESAM is that the measured *Q*-switching threshold is halved when compared to the QW-SESAM. As visible in Fig. 2, the *Q*-switching threshold is at 70 and 130 mW of the pump power for QD- and QW-SESAM, respectively. Therefore, in the future work with QD-SESAM we could increase the focused beam area on the SESAM twice compared to QW-SESAM and achieve stable modelocking while avoiding damage. This opens the route to the development of higher pulse repetition rate modelocked lasers (e.g., 20 GHz and higher) with QD-SESAMs due to less stringent requirements for tight focusing to avoid *Q*-switching.

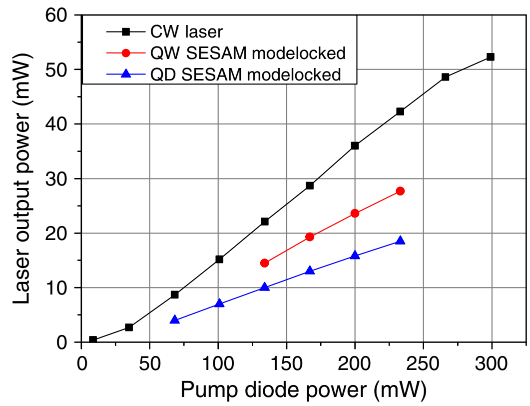

Fig. 2. Laser output power: CW mode using an end mirror instead of SESAM; modelocked mode using QW- and QD-SESAM.

The second harmonic generation (SHG) autocorrelation traces displayed in Figs. 3 and 5 are measured with the commercial Femtochrome FX-103 autocorrelator, and the optical spectra displayed in Figs. 4 and 6 are measured with the optical spectrum analyzer Agilent 86142B. Its resolution of 0.06 nm is approximately two times above the laser longitudinal mode

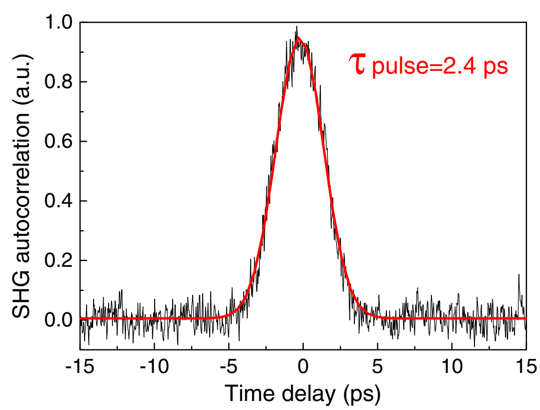

Fig. 3. QD-SESAM modelocked 10 GHz ERGO laser output SHG autocorrelation trace. The SHG autocorrelation is fitted to sech^2 pulse autocorrelation, and the deconvolved pulse duration is FWHM = 2.4 ps.

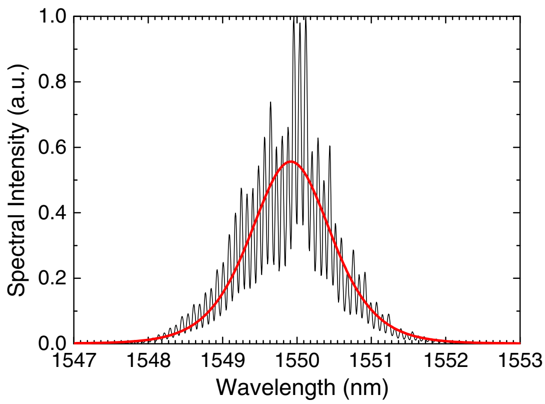

Fig. 4. QD-SESAM modelocked 10 GHz ERGO laser output optical power spectrum. The spectrum is fitted to a sech^2 curve with FWHM = 1.3 nm.

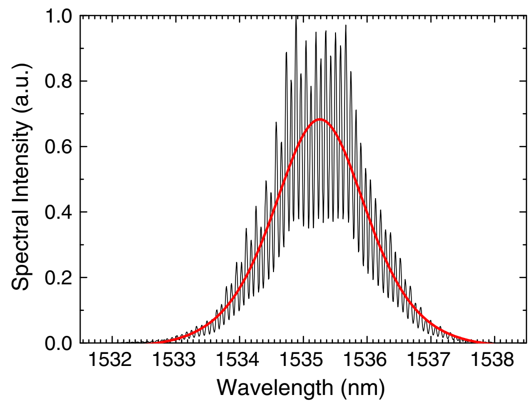

Fig. 6. QW-SESAM modelocked 10 GHz ERGO laser output optical power spectrum. The spectrum is fitted to a sech^2 curve with FWHM = 1.7 nm.

separation of 10 GHz, resulting in not fully resolved fringes from the laser modes. The fringes are visible, but with artifacts; that is, the spectral envelope is not a clean sech^2 shape. Using a heterodyne measurement method, the linewidth of each longitudinal mode in the comb is measured to be less than 1 kHz [7].

The displayed results in Figs. 3, 4, 7, and 8 for the QD-SESAM modelocked laser are obtained for the average output power of 10 mW, using 130 mW of pump power. The modelocked spectral FWHM is 1.3 nm, and the pulse duration is 2.4 ps, assuming sech^2 pulse shape. The time–bandwidth product is calculated to be 0.383, which is approximately 20% above the transform limit. The pulses are longer than the transform limit due to partially uncompensated dispersion from the SESAM.

The autocorrelation trace is very noisy because the pulse energy is very low (only about 0.5 pJ entering the autocorrelator) and the pulses are long (2 ps), considering the sensitivity of this autocorrelator model. The peak in the autocorrelation is just a noise peak and not the coherence spike resulting from poor quality of modelocking, as the peak was different depending on the time of capturing results. In addition, the coherence spike should be in the middle of the autocorrelation trace. There are fringes visible in the optical spectrum, which are longitudinal modes of the laser. The 10 GHz pulse repetition

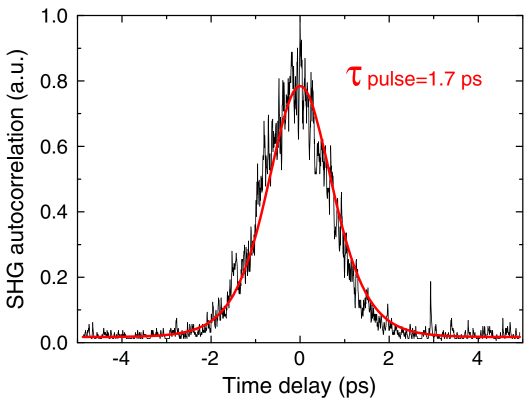

Fig. 5. QW-SESAM modelocked 10 GHz ERGO laser output SHG autocorrelation trace. The SHG autocorrelation is fitted to sech^2 pulse autocorrelation, and the deconvolved pulse duration is FWHM = 1.7 ps.

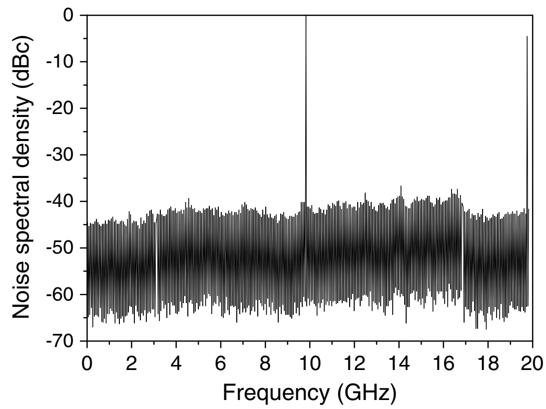

Fig. 7. RF spectrum of the output pulses from QD-SESAM modelocked 10 GHz ERGO laser. Total span is 20 GHz with resolution bandwidth of 1 kHz. The laser is not locked to a reference signal.

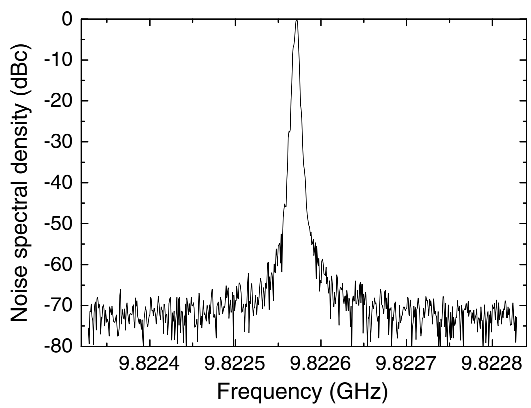

Fig. 8. RF spectrum of the output pulses from QD-SESAM modelocked ERGO laser. Total span is 500 kHz with resolution bandwidth of 1 kHz. The laser is not locked to a reference signal.

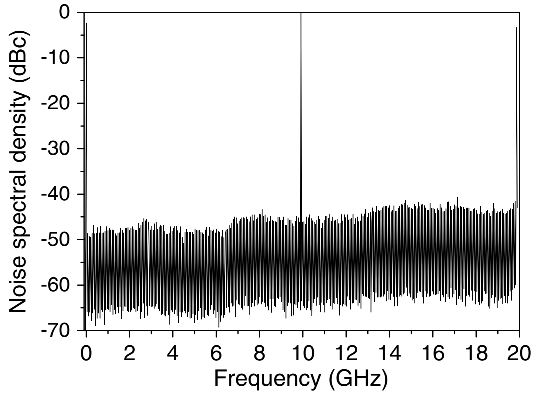

Fig. 9. RF spectrum of the output pulses from QW-SESAM modelocked 10 GHz ERGO laser. Total span is 20 GHz with resolution bandwidth of 1 kHz. The laser is not locked to a reference signal.

rate corresponds to 100 ps pulse separation and ~0.1 nm fringe separation. We observed the pulse train also on the fast sampling oscilloscope, and there was no visible multipulsing. This is also demonstrated in radio frequency (RF) spectra with 20 GHz span, where there are no side peaks apart from 10 GHz carrier frequency, 80 dB below the carrier peak, down to the instrument noise limit (see Figs. 7 and 9).

Increasing the pump power up to above 200 mW increases the modelocked output power up to 19 mW, but in this operation range we run the risk of damaging the SESAM due to tight focusing. For 130 mW of pump diode power, the pulse duration and the output power are in the same range for the QW- and QD-SESAM modelocked 10 GHz ERGO lasers, namely 1.7 ps, 14.5 mW and 2.4 ps, 10 mW for QW- and QD-SESAMs, respectively.

For comparison, Figs. 5, 6, 9, and 10 show the modelocking results with QW-SESAM. The pulse duration is 1.7 ps, assuming sech^2 pulse shape. The optical spectrum FWHM is 1.7 nm, yielding a time–bandwidth product of 0.372, which is approximately 20% above the transform limit. The QW- and QD-SESAM dispersion is estimated to be 300–500 fs^2.

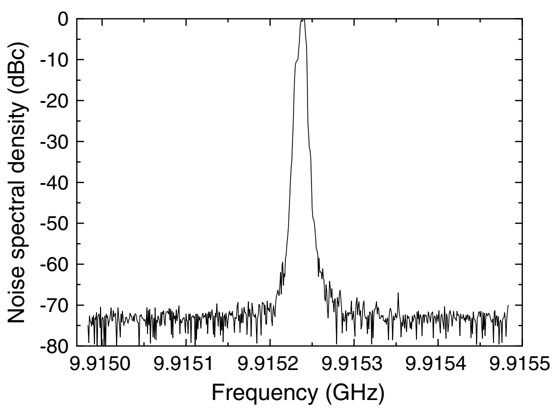

Fig. 10. RF spectrum of the output pulses from QW-SESAM modelocked ERGO laser. Total span is 500 kHz with resolution bandwidth of 1 kHz. The laser is not locked to a reference signal.

In addition to the autocorrelation and the optical spectrum, it is important to measure RF spectra for every modelocked laser in order to verify that it is really modelocked, that it generates low noise, and that the output beam is single spatial mode TEM_{00}. The laser output RF spectra are measured with the 25 GHz Picometrix fast photodiode and the microwave spectrum analyzer Agilent 8565EC. The results for QD-SESAM modelocking are depicted in Figs. 7 and 8, whereas those for QW-SESAM are shown in Figs. 9 and 10. The RF spectra in Figs. 7 and 9 demonstrate low noise fundamental modelocking at 10 GHz in the single spatial mode TEM_{00}. There are no other peaks in the RF spectra except at 10 GHz. Figures 8 and 10 show the laser carrier peak RF spectra with a span of 500 kHz. This spectrum demonstrates low timing jitter of the laser. However, it is important to note that the laser is not locked to a reference signal. Therefore, the peak drifts slowly in time due to environmental thermal fluctuations, and it is very difficult to measure the RF peak linewidth with, for instance, 50 kHz span.

The optics in the laser are glued on stainless steel holders, which results in typical QW-SESAM modelocked laser long term stability of years without user intervention. The QD-SESAM modelocked laser was stable for weeks during the experiments, and we expect long term stability of years, similar to the QW-SESAM modelocked laser.

3. CONCLUSIONS

In high pulse repetition rate lasers, QD technology offers lower saturation fluence for SESAMs and therefore more design freedom for the laser cavity, when compared to QW-based SESAMs. We have achieved 10 GHz pulse repetition rate QD-SESAM modelocked laser operating at 1550 nm, generating 2.4 ps pulses with 10 mW of average power. The twice lower *Q*-switching threshold with QD-SESAM compared to QW-SESAM suggests the potential to increase the beam waist diameter on the QD-SESAM in an improved and possibly simpler laser design for the 10 GHz laser. This will enable simpler building and longer lifetime of higher repetition rate (e.g., 25 or 50 GHz) fundamentally modelocked lasers, which are highly desired in optical communications and other applications. When scaling up from 50 to 100 GHz repetition rate, the cavity becomes extremely short (<1.5 mm) and gain thickness (1 mm for 10 GHz cavity) becomes the limiting factor, as described in [14]. The gain glass must be produced thinner and higher doped in order to fit and achieve sufficient gain.

Our future work will focus on further optimization of the QD-SESAM fabrication to include multiple In(Ga)As QD layers in order to increase the modulation depth. This should enable generation of shorter pulses and higher pumping to extract higher laser output power without double-pulsing.

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