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InP/InGaP quantum-dot SESAM mode-locked Alexandrite laser

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ABSTRACT

A semiconductor saturable absorber mirror (SESAM) passively mode-locked Alexandrite laser was demonstrated. Using an InP/InGaP quantum-dot saturable absorber mirror, pulse duration of 420 fs at 774 nm was obtained. The laser was pumped at 532 nm and generated 325 mW of average output power in mode-locked regime with a pump power of 7.12 W. To the best of our knowledge, this is the first report of a passively mode-locked Alexandrite laser using SESAM in general and quantum-dot SESAM in particular.

Keywords: Infrared and far-infrared lasers; pulsed lasers; tunable lasers; mode-locked lasers; ultrafast lasers

1. INTRODUCTION

Ultrafast laser sources in the near-infrared spectral region are highly desirable for a wide range of applications, including ultrafast spectroscopy [1, 2], nonlinear microscopy [3, 4], optical coherence tomography [5], and nonlinear frequency conversion [6, 7]. Ultrashort pulses are typically produced by laser gain media which have broad emission bandwidths. Currently, Ti:sapphire is the most commonly used broadband vibronic laser crystal that can directly generated a few cycle optical pulses [8, 9]. On the other hand, Alexandrite (Cr-doped chrysoberyl BeAl2O4) is another example of vibronic laser crystal [10] that has a wide (~100 nm) wavelength tuning range around 750 nm and high thermal conductivity (similar to Ti:sapphire) [11, 12]. Its other advantages are highly polarized output radiation and broad absorption bands that can be used for direct pumping with visible laser diodes [13, 14]. Unlike Ti:sapphire, Alexandrite can be directly pumped with red laser diodes because its absorption band covers most of the visible spectral range [10,13]. In addition, its larger $\sigma\tau$ product [15] presents a prospect of lower laser threshold. Furthermore, a diode-pumped Alexandrite laser was shown to produce >26 W of output power in the continuous wave regime [13] which significantly exceeds output from widely used Ti:sapphire lasers. Despite these advantages, femtosecond laser mode locking was demonstrated only recently and resulted in the generation of 170 fs long pulses from a Kerr-lens mode-locked (KLM) Alexandrite laser [16]. At the same time, passive mode locking with a semiconductor saturable absorber mirror (SESAM) is an effective method that is widely used with Nd-doped and Yb-doped gain media to produce ultrashort pulses [17-24] because it does not require critical cavity alignment that is needed in case of KLM lasers [25, 26]. Therefore, the extension of SESAM mode locking to Alexandrite is a promising alternative. In this respect, quantum-dot SESAMs (QD-SESAMs), which can provide broadband absorption and emission spectra attributed to the inhomogeneous broadening associated with the size dispersion of QDs, are particularly attractive for generation of ultrashort pulses. In this work we report on the first passively mode-locked Alexandrite laser using an InP/InGaP QD-SESAM that produced femtosecond pulses as short as 420 fs at 774 nm with an output power of 325 mW and pulse repetition frequency of 80 MHz. The results of our work open the way for the development of efficient diode–pumped ultrashort pulse Alexandrite lasers that can rival the currently used Ti:sapphire lasers in many industrial, scientific and medical applications.

2. EXPERIMENTAL SET-UP

The experimental setup of the QD-SESAM mode-locked Alexandrite laser is schematically shown in figure 1. The designed 5-mirror cavity was similar to the one previously used in the KLM experiments [16]. The Brewster-cut

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Alexandrite crystal was 7 mm in length and doped with 0.155% of Cr. The crystal was mounted on a translation stage which helped to optimize its position with respect to the pump and cavity mode foci. The crystal was pumped at 532 nm by a frequency-doubled Nd:YVO4 laser with a maximum power of 7.3 W (Finesse, Laser Quantum). The pump was focused into a ~45 µm spot size diameter inside the crystal by a 150 mm focal length lens. About 85% of the pump power was absorbed in the crystal. Mirrors M1-M3 were highly reflecting (HR) in the 650-900 nm range. The Alexandrite crystal was placed between the two folding mirrors (M1 and M2) with 100 mm radii of curvature. The cavity contained the InP/InGaP QD-SESAM which was used as one of the plane end mirrors. Previously, the QD-SESAM used in this work was tested with Ti:sapphire lasers to produce picosecond pulses at 800 nm and had a non-saturable loss of ~1% [22]. In general, the QD-SESAMs were shown to offer low saturation fluence [22], controllable modulation depth [27] and broadband operating wavelength range [22, 28-32]. An appropriate mode spot size on the QD-SESAM was obtained by using the focusing mirror M3 with the radius of curvature of 200 mm. The delta cavity geometry (see figure 1) resulted in a spot size diameter of about 53 µm within the Alexandrite crystal and approximately 171 µm on the QD-SESAM. The effect of thermal lensing [33,34] was also considered in the cavity design. Two SF10 prisms (P1 and P2) separated by 345 mm were used to compensate for the positive intracavity dispersion. The output coupler (M4) had 3% transmission around 750 nm.

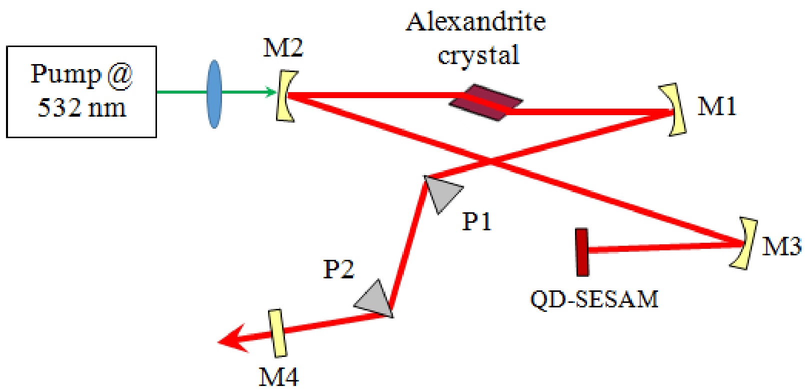

Figure 1. Schematic of the QD-SESAM mode-locked Alexandrite laser.

3. RESULTS AND DISCUSSION

The mode-locked laser operation was initiated and sustained by the InP/InGaP QD-SESAM used as one of the end mirrors. The reflectivity of the QD-SESAM sample is shown in figure 2(a). The used QD-SESAM was originally designed for Ti:sapphire [22], so it shifted the Alexandrite emission wavelength from the typical 755 nm [12] to longer wavelengths. Reliable mode locking with an average output power of 325 mW at the incident pump power of 7.12W was achieved. Pulses as short as 420 fs in duration were produced with 1.7 nm wide (FWHM, full width at half maximum) spectrum centered at 774 nm that indicated a time-bandwidth product of 0.359. It is worth noting that a standard (quantum well) SESAM from Batop which was optimized for 800 nm operation could not initiate mode locking with the same setup. This probably can be explained by the reflectivity band of this sample shown in figure 2(b) which was centered at 800 nm and therefore introduced high loss at the peak wavelength of Alexandrite.

The fluence on the QD saturable absorber was about 590 $\mu J/cm^2$ and no damage was observed. The autocorrelation trace of the pulses and the corresponding spectrum are displayed in figure 3(a) and figure 3(b), respectively. Furthermore, stable single-pulse mode locking and the absence of Q-switching instabilities were confirmed using a long scan range (200 ps) autocorrelator and a fast oscilloscope/photodetector with photodiode that had a combined resolution of ~100 ps [35,36]. Considering the repetition rate of ~80 MHz, 420 fs laser pulses had energy of ~4.1 nJ and peak power of >9.5 kW. The transverse intensity profile of the beam in the mode-locked regimes is shown in figure 4. The laser operated in the fundamental transverse mode. The laser threshold was at about 2.5 W and the mode locking threshold was approximately at 4.55 W of incident pump power. Multi-pulse oscillation was observed at higher than 7.12 W of pump power. The generated pulses in this work are longer than the previously obtained ones from the KLM Alexandrite laser

[16] probably due to the imperfect compensation of the dispersion and generally faster response of the Kerr-lensing effect employed in KLM [37].

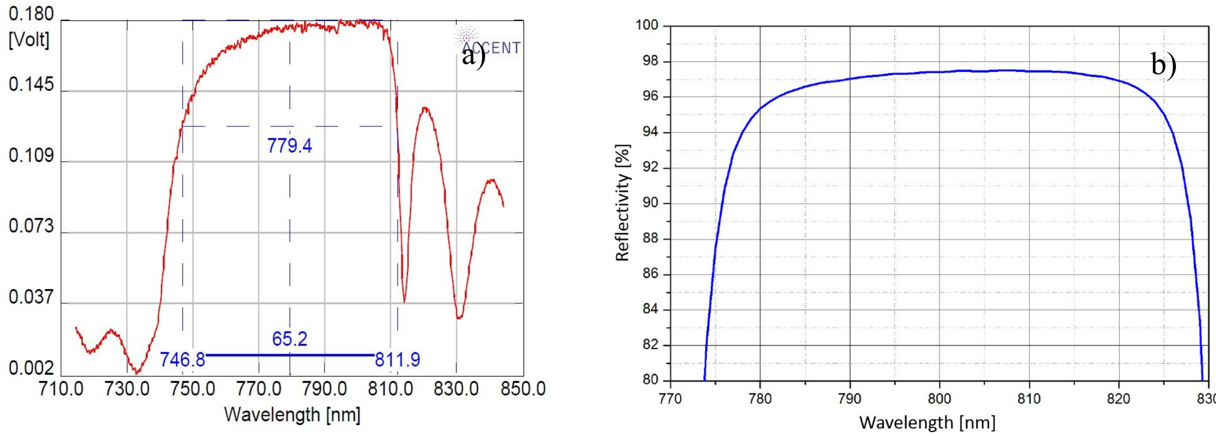

Figure 2. Reflectivity bands of the used (a) QD-SESAM and the (b) Batop SESAM samples.

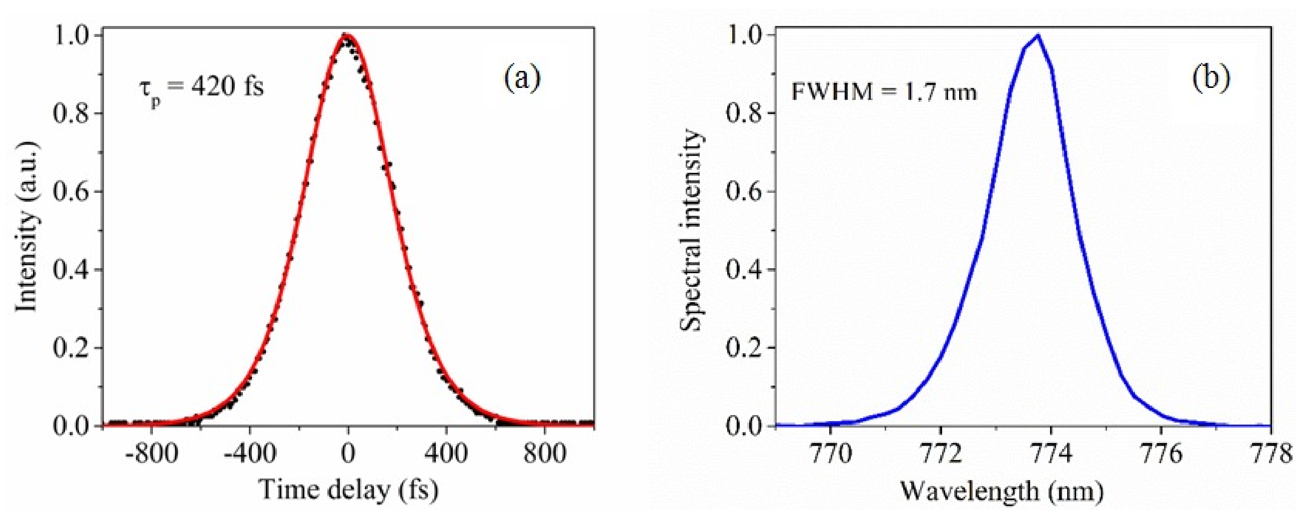

Figure 3. Measured (a) autocorrelation trace of 420 fs pulses with fit assuming a *sech2* intensity profile and (b) their optical spectrum.

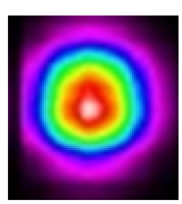

Figure 4. Transverse beam intensity profile of the mode-locked laser.

4. CONCLUSIONS

In conclusion, a passively mode-locked Alexandrite laser using an InP/InGaP QD-SESAM was demonstrated. Pulses with duration as short as 420 fs with an average output power of 325 mW were generated. The laser was pumped with up to 7.12 W at 532 nm and operated around 774 nm. To the best of our knowledge, this is the first report of a passively mode-locked Alexandrite laser using a SESAM in general and a quantum-dot SESAM in particular. Due to the broad tuning range (~85 nm) of Alexandrite [12], a careful dispersion management [38] should lead to the generation of even shorter pulses. In addition, more efficient mode locking should be possible by designing QD-SESAMs specifically for Alexandrite laser crystal that has a gain peak around 755 nm wavelength [10, 11]. Also, low quantum defect of visible diode pumping [13, 14] should lead to efficient and powerful ultrafast Alexandrite oscillators that will be very attractive for various applications including nonlinear frequency conversion [39-42], multiphoton microscopy [43,44], and ultrafast spectroscopy [45].

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