Femtosecond Kerr-lens mode-locked Alexandrite laser

Shirin Ghanbari, Reza Akbari and Arkady Major*

Department of Electrical and Computer Engineering, University of Manitoba, 75A Chancellors Circle, Winnipeg, MB, R3T 5V6, Canada
*a.major@umanitoba.ca

Abstract: The generation of 170 fs pulses at 755 nm from a Kerr-lens mode-locked Alexandrite laser was demonstrated. The laser was pumped at 532 nm and produced 780 mW of average output power with 9.8% of optical-to-optical efficiency. To the best of our knowledge, these are the shortest pulses that have been produced from a mode-locked Alexandrite laser to date.

OCIS codes: (320.7090) Ultrafast lasers; (140.4050) Mode-locked lasers; (140.3600) Lasers, tunable; (140.3580) Lasers, solid-state.

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1. Introduction

Ultrashort pulses of light in the near-infrared wavelength range are essential for many applications such as ultrafast spectroscopy [1], nonlinear microscopy [2], frequency conversion [3], and optical coherence tomography [4]. The generation of ultrashort laser pulses requires laser gain media exhibiting broad emission bandwidths. One of the best examples is a widely tunable vibronic emission from a Ti:sapphire laser crystal permitting direct generation of a few cycle optical pulses [5]. Other well know vibronic laser crystals are Cr-doped colquiriites (Cr:LiSAF, Cr:LiCAF and Cr:LiSGaF) and Alexandrite. Performance of colquiriites, unfortunately, is severely limited by their poor thermal conductivity, exited state absorption and upper-state lifetime quenching at elevated temperatures [6]. On the other hand, Alexandrite (Cr-doped chrysoberyl $BeAl_2O_4$) was the first wavelength-tunable solid-state laser operated at room temperature [7]. Alexandrite has a high thermal conductivity (similar to Ti:sapphire), wide (~100 nm) wavelength tuning range around 750 nm, polarized output, and broad absorption bands in the visible spectral range [7] that can be used for direct pumping with red, green and blue laser diodes. In addition, its $\sigma\tau$ product is larger than that of Ti:sapphire [6], thus offering a possibility of lower threshold. Recently, a red diode end-pumped continuous-wave Alexandrite laser delivered 26 W of average output power with high efficiency [8]. Despite all of these attractive features, mode locking performance of Alexandrite was demonstrated only in the picosecond regime, producing 8 ps pulses as the shortest [9]. In this work we report on >45-fold pulse width reduction by generating 170 fs pulses from a Kerr-lens mode-locked Alexandrite laser. This result can pave the wave for the development of efficient and powerful diode-pumped ultrafast Alexandrite oscillators and amplifiers for industrial, scientific and medical applications.

2. Experimental setup

Kerr-lens mode locking is a powerful and well-known method for generation of ultrashort pulses from solid-state lasers [10] and was adopted as mode locking mechanism in this work. Experimental setup of the Kerr-lens mode-locked (KLM) Alexandrite oscillator is schematically depicted in Fig. 1. The laser used a slightly modified standard delta cavity which consisted of five mirrors and a Brewster-cut crystal. The designed cavity provided a good overlap between the pump and cavity modes and was similar to the one previously used in the continuous-wave (CW) experiments [11]. Mirrors M1-M4 were typical Ti:sapphire laser mirrors and were highly reflecting (HR) in the 650-900 nm range. The radii of curvature of the two concave folding mirrors M3 and M4 were 100 mm. Additional mirror M2 with a radius of curvature of 200 mm was used for fine control of the cavity mode size in the crystal. This arm of the cavity also contained a vertical slit to enable a hard-aperture Kerr-lens mode-locking. The other cavity arm had a pair of SF10 prisms (P1 and P2) for dispersion compensation separated by 37 cm. The output coupler (M5) had a 3% transmission around 750 nm.

A 7 mm-long Alexandrite crystal doped with 0.155% of Cr (NG Synoptics) was used in the experiments. The crystal was held in an aluminum crystal holder which was not actively cooled (see Fig. 1). It 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 by a CW green laser radiation at 532 nm with up to 8 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.

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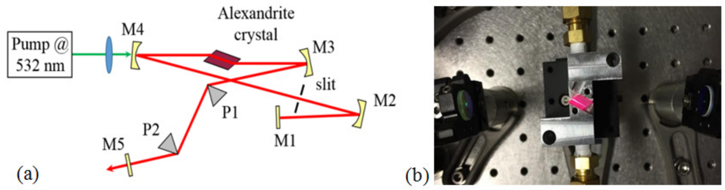

Fig. 1. (a) Schematic layout of the femtosecond KLM Alexandrite laser oscillator and a photograph of the laser crystal between the folding mirrors at low pump power. (b) The path of the pump light in the crystal near its center is clearly visualized by the excited fluorescence.

For the design of Alexandrite KLM cavity in this experiment, the traditional formalism outlined in [12] was used. The Magni plots of the cavity are demonstrated in Fig. 2, where negative values indicate areas of enhanced Kerr lensing. The operating point is indicated by the red dot in the low misalignment sensitivity region, near its inner stability edge.

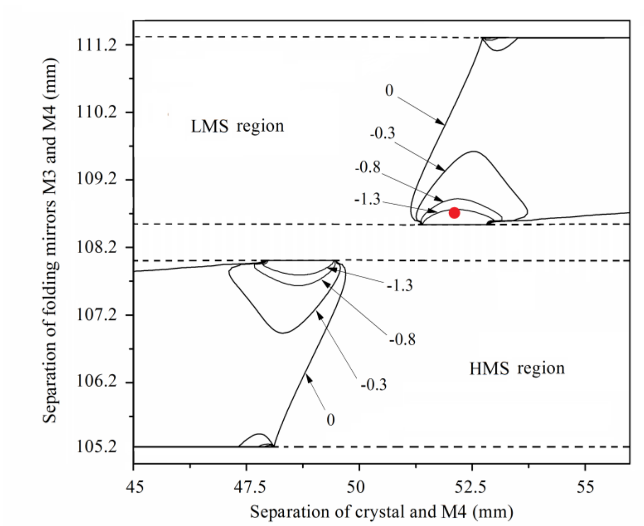

Fig. 2. Contour Magni plots for the used KLM resonator in the tangential plane. Red dot indicates the operating point. Dashed horizontal lines show stability edges. LMS - low misalignment sensitivity region, HMS - high misalignment sensitivity region of the resonator.

3. Results and discussion

In the initial CW experiments the laser could produce more than 1 W of output power at full pump power. By configuring the laser to operate close to one of the stability edges (as shown in Fig. 2) and adjusting the width of the vertical slit, a hard-aperture KLM was achieved. This required careful positioning of the mirror M3 as well as of the crystal. Mode locking was initiated in a usual way, i.e. by small mechanical perturbation such as tapping on a mirror mount.

A maximum average output power of 780 mW was achieved in the mode-locked regime. This corresponds to 9.8% of optical-to-optical efficiency which is comparable to the typical performance of femtosecond Ti:sapphire oscillators [12]. The spectrum was centered at 755 nm and had a FWHM (full width at half maximum) bandwidth of 3.6 nm. The autocorrelation trace of the generated pulses together with the corresponding spectrum are shown in Fig. 3. The time-bandwidth product of the generated pulses was calculated to be 0.32, indicating that they were close to transform limited.

Single pulse mode locking was ensured by using a long scan range (200 ps) autocorrelator and a high speed oscilloscope with photodiode that had combined resolution of ~100 ps.

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Therefore, femtosecond-to-nanosecond time scales were completely covered [13–15]. An additional RF spectrum measurement indicated that the noise level was suppressed by more than 45 dB with respect to the fundamental mode. Wavelength tuning of the generated pulses was not attempted in this experiment.

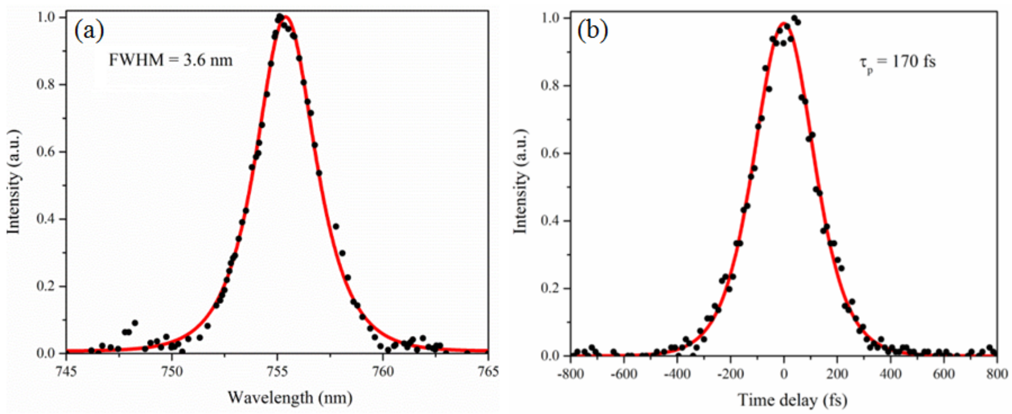

Fig. 3. Measured (a) spectrum and (b) autocorrelation trace of the pulses with fits assuming a *sech*^{2} profile.

Due to the proximity of the generated wavelengths (~755 nm) to the visible range and intensity of the laser radiation, it was clearly visible on a white background. A photograph of the laser beam and its transverse intensity profiles in the CW and mode-locked regimes are shown in Fig. 4. The laser operated in the fundamental transverse mode with an estimated beam quality factor of M^2<1.2.

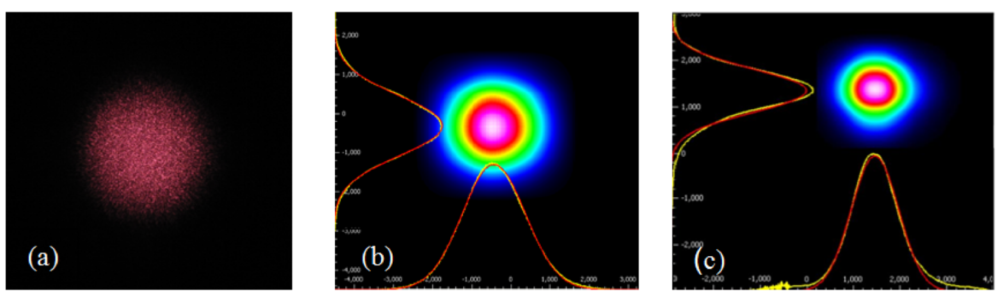

Fig. 4. Laser beam on paper surface (a) and its intensity profiles in the CW (b) and mode-locked (c) regimes. Beam size change in (b) and (c) is due to the different locations of the CCD camera in the CW and KLM experiments.

Considering the repetition rate of 80 MHz, the generated laser pulses had energy of ~9.8 nJ and >57 kW of peak power. We believe that these are the first femtosecond pulses that were generated from a passively mode-locked Alexandrite laser. A photograph of the developed laser is shown in Fig. 5.

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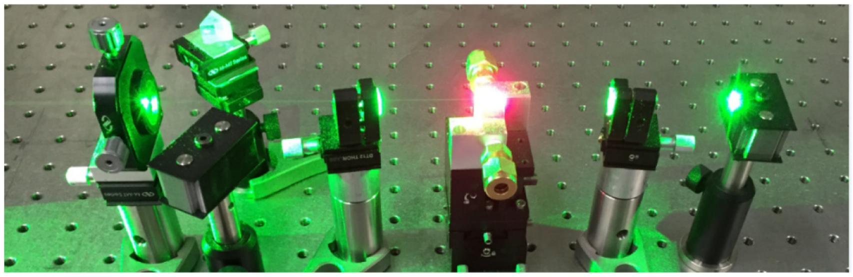

Fig. 5. Photograph of the pumped Alexandrite crystal in the laser cavity.

4. Conclusions

A femtosecond Kerr-lens mode-locked Alexandrite laser was demonstrated. Pulses as short as 170 fs were generated with 780 mW of average output power. Owing to the broad tuning range (~85 nm) of Alexandrite [11] and recent data on its dispersive properties [16] even shorter pulses (down to 10 fs) should be possible with careful dispersion management. We believe that extension to the visible diode pumping can open the way for the development of efficient ultrafast Alexandrite oscillators and amplifiers. With currently available red diode pump powers (>60W) [8], femtosecond operation with an output power in the range of 10 W should be possible. Power scaling can be also explored using thin-disk technology due to the reasonably low quantum defect.

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