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Generation of 54 Fs Laser Pulses from a Diode Pumped Kerr-Lens Mode-Locked Yb:LSO Laser *

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A diode pumped Kerr-lens mode-locked femtosecond Yb:LSO laser is experimentally demonstrated for the first time. The 54 fs laser pulses at central wavelength of 1052 nm with a bandwidth of 22.5 nm are obtained at the repetition rate of 113 MHz. To the best of our knowledge, this is the shortest pulse duration ever produced from the Yb-doped orthosilicates lasers family.

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Efficient and compact femtosecond lasers have become essential for a large range of applications in industry, military, and scientific research. Over the past two decades, Yb doped solid state lasers were regarded as increasing potential sources and they have achieved rapid development with the emergence of high-brightness and high-power laser diodes emitting at 940–980 nm. This is not only due to the fact that the absorption peak of Yb doped medium is around 970 nm but also due to the attractive properties of Yb^{3+} ions. First, Yb ions have a simple electronic structure of two manifolds, which leads to nonexistence of some undesirable effects, such as up-conversion, excited-state absorption, concentration quenching, and cross relaxation. Secondly, Yb doped laser media have large fluorescent lifetime as well as broad emission spectrum, which enables us to establish ultrafast lasers with high energy. Lastly, Yb^{3+} ions have small quantum defect and low thermal load. Some kinds of Yb doped laser materials have been successfully demonstrated in femtosecond pulse operation.[1–7] In particular, many Yb-doped solid state lasers are capable of generating sub-100 fs laser pulses by the means of Kerr-lens mode-locking (KLM).[8–17] In contrast from the typical passively mode-locking lasers with semiconductor saturable absorption mirror (SESAM)[18] or other saturable absorbers, such as single-wall carbon nanotube,[19] grapheme,[20] or graphene oxide,[21] there is no additional mode-locking component which results in loss and normal dispersion when mode-locked by the means of KLM. Moreover, the obtainable pulse width is limited only by the gain bandwidth of the active mediums and the dispersion bandwidth of the laser cavity.

The Yb^{3+} doped oxyorthosilicates Lu_2SiO_5 (Yb:LSO) crystal is a potential laser material, as are the other Yb doped oxyorthosilicates, due to its excellent laser properties.[22] First, the ground state energy splitting of Yb^{3+} ion in Yb:LSO crystal is up to 1012 cm^{-1}, which leads to a quasi-four level operation and then to a low pump threshold. Secondly, the Yb:LSO crystal exhibits a fluorescence lifetime as large as 1.68 ms and excellent thermal conductivity of 5.3 $W{\cdot}m^{-1}{\cdot}K^{-1}$ (without doping Yb ions[23]), implying a potential to generate pulses with a high energy. It is worth noticing that Yb:LSO crystal almost keeps its thermal conductivity when the doping concentration increases. Thirdly, broad emission spectra of 73 nm with higher absorption and five emission bands around 1004, 1012, 1032, 1055 and 1083 nm can support the generation of ultrashort pulses shorter than 100 fs. Excellent laser performances on both cw and femtosecond pulse modes have been demonstrated in recent years. The 7.3 W cw power corresponding to a slope efficiency of 62% directly from a diode pumped Yb:LSO laser was obtained in 2005.[23] Then, the first femtosecond mode-locked Yb:LSO laser with 2.6 W average output power and 260 fs pulse duration was reported.[24] In 2011, a KLM Yb:LSO laser was reported by Liu *et al.*;[25] however, only a 2.2 ps pulse was obtained, which is far beyond the possible pulse duration by the means of KLM.

In this Letter, we firstly report on an experimental study of a diode pumped KLM femtosecond Yb:LSO laser. Stable laser pulses as short as 54 fs at 1052 nm were obtained with a pulse repetition rate of 113 MHz. To the best of our knowledge, this is the shortest pulse ever produced from the Yb-doped orthosilicates lasers family.

Based on the consideration of the excellent properties in Yb:LSO crystal mentioned above, we believe

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that a shorter pulse even below 100 fs should be able to be obtained by means of KLM if a longer crystal as well as higher intra-cavity power density are adopted. Thus, we design an optimizing experimental setup as shown in Fig. 1. The laser gain medium is a 5 at.% doped Yb:LSO crystal with a thickness of 3 mm, which is longer than that in Ref. [25]. The thicker crystal is good for increasing the self-phase modulation (SPM) process in the KLM as well as raising the reabsorption in shorter wavelength where there is a larger gain cross section than the longer wavelength. Thus, the net gain profile will turn out to be flatter and smoother than that in Ref. [25]. To remain the laser at a constant temperature for stable and efficient operation, the Yb:LSO crystal was wrapped with indium foil and mounted tightly on a water-cooled copper heat sink block. The copper block was cooled by flowing water, which is maintained at 11℃ during the experiment.

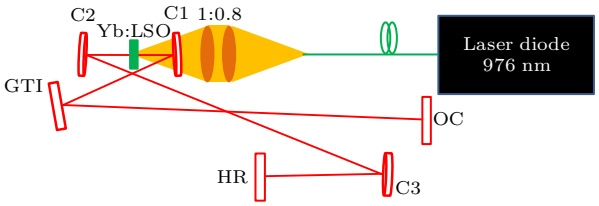


Fig. 1. Experimental setup of the mode-locked Yb:LSO laser.

A fiber-coupled diode laser of emitting wavelength at 976 nm is used to end-pump the laser crystal. The core diameter of the fiber is 105 μm and the numerical aperture (NA) is 0.22. To couple the pump laser from the fiber into the Yb:LSO crystal, an imaging system with a magnification of 0.8 is employed. As is known, the kerr lens effect which plays an important role in KLM strongly depends on the power density in the gain crystal. A tight focusing cavity is adopted in this experiment. Both C1 and C2 are dichroic mirrors with radius of curvature (ROC) of 75 mm, which are coated with high reflection in the range of 1020–1100 nm and high transmission at 970–980 nm. A Gires–Tournois interferometer mirror (GTI) is used here for dispersion compensation. To obtain the broadest spectral of mode-locking, three different GTI mirrors ($-800\,\mathrm{fs}^2$, $-1000\,\mathrm{fs}^2$ and $-1300\,\mathrm{fs}^2$) are attempted in the cavity during the experiment, respectively. To further effectively enhance the intracavity power density, an output coupler (OC) with 0.4% transmission at 1020–1100 nm was employed. C3 is a curved folding mirror with ROC of 300 mm, which is used to focus the laser beam on a flat mirror coated with high reflection in the range of 1020–1100 nm. The flat mirror that terminates the cavity is fixed on a translation stage. The total cavity length is about 1.33 m, corresponding to a repetition rate of 113 MHz. We calculate the intracavity transverse mode based on the ABCD matrix and obtain a beam waist diameter of $14\,\mu\mathrm{m} \times 39\,\mu\mathrm{m}$ ($1/e^2$ level) on the crystal.

As the first step, the resonator is optimized for cw operation. Laser power as large as 301 mW is extracted from the 0.4% OC at the absorbed pump power of 5.3 W. Then, after finely tuning the position of C2 and the pitch angle of the end mirror until two individual longitudinal modes compete against each other, stable KLM operation would be easily obtained if a weak perturbation happens, such as taping the mirrors or pushing the translation stage. At stable mode-locking operation, the output power of the laser is decreased to 25 mW; meanwhile, the wavelength is shifted from 1082 nm to 1052 nm. We attribute the decrease of the output power to the larger re-absorption loss at a shorter wavelength as well as the mismatch in the collimation of the laser cavity. The slight mismatching of the cavity alignment leads the optical axis of the cavity close to a mirror edge, resulting in a hard aperture configuration to discriminate the cw and ML operation through optical losses modulation.

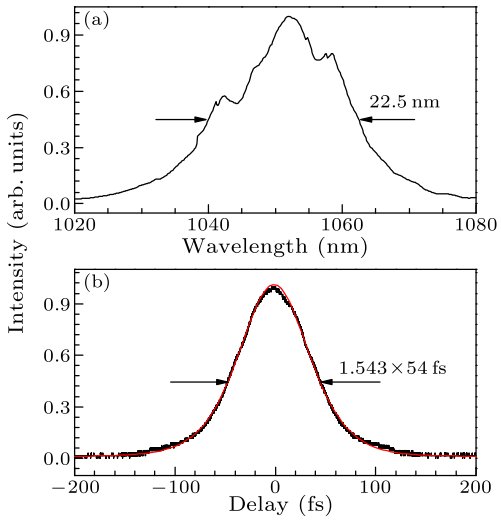


Fig. 2. (a) Optical spectrum of the mode-locked Yb:LSO laser. (b) The corresponding intensity autocorrelation trace of the mode-locking pulses. The experimental data and the sech^2-fitting curve are described by the black and the red curves, respectively.

The optimized spectral is obtained by using the GTI with a group velocity dispersion of $-800\,\mathrm{fs}^2$ per bounce as shown in Fig. 2(a). The optical spectrum of the mode-locked laser pulses is measured by an optical spectrum analyzer (YOKOGAWA, AQ6370C). The full-width at half-maximum (FWHM) bandwidth of the spectrum is 22.5 nm with a central wavelength at 1052 nm, which supports a transform limited sech^2-pulse of 51.6 fs. Figure 2(b) depicts the corresponding intensity autocorrelation trace measured by a commercial intensity autocorrelator (FR-103MN, Femtochrome Research, Inc.). The FWHM bandwidth of the autocorrelation trace is about 83 fs, corresponding to the pulse duration of 54 fs if a sech^2-shape pulse is assumed. The time-bandwidth product is 0.322, which is close to the value of 0.315 for the transform limited sech^2-shape pulse.

To characterize the status of the mode-locking operation, the rf spectrum is also measured, as described in Fig. 3. The signal is recorded for both a frequency window of 0.2 MHz with 1 kHz resolution bandwidth (RBW) and a 1 GHz with 100 kHz RBW (inset), re-

spectively, via a photo detector (PD) with a 3 dB bandwidth of 1 GHz and a rf spectrum analyzer (Agilent E4407B). The signal-to-noise ratio of the fundamental beat note at 113 MHz is 78.3 dBc. Stable mode locking operation is illustrated by the clean rf spectrum shown in Figs. 3, where no side peaks of the harmonics of the fundamental frequency are observed. Once started by a slight perturbation, the mode-locking operation could stably last for several hours.

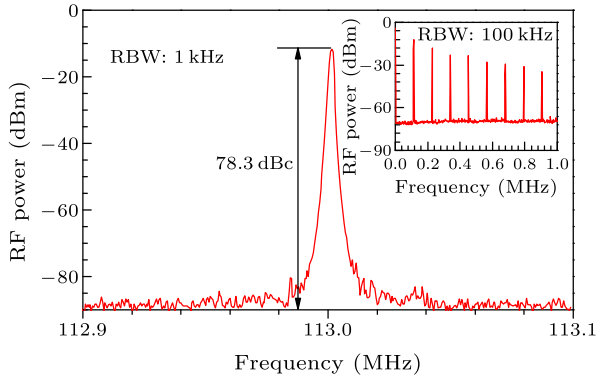


Fig. 3. The rf spectrum of the mode-locked Yb:LSO laser with the RBW of 1 kHz. Inset: the rf spectrum of 1 GHz wide-span range with the RBW of 100 kHz

Table 1. Femtosecond mode-locking performances of different Yb doped orthosilicate lasers.

Crystal	Output power (mW)	Pulse duration (fs)	
Yb:GSO	396	343	Ref. [28]
Yb:YSO	410	122	Ref. [24]
Yb:LSO	2600	260	Ref. [24]
Yb:SSO	38	71	Ref. [26]
Yb:GYSO	300	210	Ref. [27]
Yb:LYSO	40	61	Ref. [17]
Yb:LSO	25	54	This work

Up to now, several kinds of Yb doped orthosilicates crystals have been demonstrated with femtosecond laser operation.[17,24,26–28] The femtosecond mode-locking performances of the Yb^{3+}-doped orthosilicates lasers are summarized as listed in Table 1. To the best of our knowledge, the 54 fs pulse realized here is the shortest one so far obtained from Yb-doped orthosilicates lasers.

In conclusion, we have presented what is to our knowledge the first diode-pumped KLM femtosecond laser based on an Yb:LSO crystal. Furthermore, we demonstrate the shortest laser pulses ever produced from an ytterbium-doped orthosilicates laser. Using a 5 at.%, 3 mm long Yb:LSO crystal, stable KLM operation with pulse duration as short as 54 fs has been obtained at a repetition rate of 113 MHz. The average output power is 25 mW and the central wavelength is at 1052 nm with 22.5 nm bandwidth. In the consideration that it is mature to obtain Yb:LSO crystal with as large as 18 mm × 18 mm size from Zheng *et al.* by the Czochralski method, as well as the excellent thermal conductivity of 5.3 $W \cdot m^{-1} \cdot K^{-1}$,[23] which is close to the value of Yb:YAG and more than that of Yb:KGW, a higher average power, to several tens of Watts, and pulse energy, up to mJ level, offer potential to realize further chirped pulse amplification, which is our next step. This is very attractive for applications in optical frequency combs and strong field physics.

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