Diode-pumped Kerr-lens mode-locked Yb:LYSO laser with 61fs pulse duration

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Abstract: A stable diode pumped Kerr-lens mode-locked (KLM) Yb:LuYSiO$_5$ (Yb:LYSO) laser of generating 61 fs pulses at a central wavelength of 1055.4 nm is experimentally demonstrated. This is, to the best of our knowledge, the first demonstration of femtosecond KLM operation in Yb:LYSO laser, and it is believed that 61 fs is the shortest pulse duration ever produced from an Yb-doped orthosilicate laser. The average output power of the mode-locked laser is 40 mW and the repetition rate is 113 MHz.

OCIS codes: (140.4050) Mode-locked lasers; (140.7090) Ultrafast lasers; (140.3615) Lasers, ytterbium; (140.3480) Lasers, diode-pumped.

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1. Introduction

Diode laser pumped ytterbium lasers with emitting wavelength around 1 μm have attracted increasing interest in the last two decades. Benefiting from the very simple electronic level structure of Yb^{3+} which composed of only two manifolds $^2F_{5/2}$ and $^2F_{7/2}$, most of undesirable effects such as up-conversion, excited-state absorption, cross relaxation or concentration quenching can be well eliminated. Moreover, its relatively large emission bandwidth and quite low quantum defect make Yb^{3+} doped gain media has the potential to generate high power continuous wave (CW) laser up to hundreds watts and ultrashort pulse down to several tens femtosecond. Until now, several of Yb-doped crystals have been successfully used to generate femtosecond laser operation [1–13]. Among them, Yb-doped oxyorthosilicatesYb:Y_2SiO_5 (Yb:YSO) and Yb:Lu_2SiO_5 (Yb:LSO) have been demonstrated with outstanding laser performance on both CW and CW mode-locking operations in the past years. 7.7 W and 7.3 W CW powers corresponding to the slope efficiencies of 67% and 62%, were directly obtained from Yb:YSO and Yb:LSO solid-state bulk lasers respectively in 2005 [14]. 2.6W average output power with 198 and 260 fs pulse durations based on Yb:YSO and Yb:LSO crystals were also reported in 2006 [15]. These excellent laser performances were due to the large ground-state splitting, high thermal conductivities, and broad emission spectrum of Yb:YSO and Yb:LSO crystals [14].

As the alloyed oxyorthosilicate crystal based on Yb:YSO and Yb:LSO, Yb:$LuYSiO_5$(Yb:LYSO) combines the excellent laser performance with the good mechanical properties of both Yb:YSO and Yb:LSO crystals. The energy splitting of Yb^{3+} ion ground state in Yb:LYSO crystal is up to 993 cm^{-1} [16] which leads to a quasi-four level operation and then a low pump threshold, and abroad emission spectra is existing with four strong emission bands around 1005, 1033, 1058 and 1082 nm [16]. This indicates that the mixed crystal has a large full width at half maximum (FWHM) bandwidth and has potential to generate sub-100 fs pulses. Recently, some studies have been investigated based on Yb:LYSO crystals. In the continuous-wave laser operation of Yb:LYSO, a maximal slope efficiency of 96% and output power of 7.8 W were respectively achieved with different pump sources [16]. An efficient diode-pumped self-mode-locking Yb:LYSO laser with 7.8 ps at 1058 nm was also demonstrated in 2010 [17]. In 2011, The first femtosecond operation based on Yb:LYSO laser mode-locked by a semiconductor saturable absorber mirror (SESAM)with 780 fs pulse duration at the center wavelength around 1042 nm was realized [18]. Most recently, a dual-wavelength mode-locking Yb:LYSO laser with 8.0 ps pulses simultaneous running at 1045.5 and 1059.0 nm based on a double-walled carbon nanotube saturable absorber (DWCNT-SA) [19] and a 4.0 ps passively mode-locked Yb:LYSO laser around 1038.3 nm with a reflection type single walled carbon absorber (RSWCNT-SA) [20] were implemented respectively. However, no matter what kind of mode-locking mechanisms are applied, either Kerr-lens mode-locking (KLM) or passive mode-locking with SESAM or CNT, the shortest pulse generated from the Yb:LYSO laser is around 780 fs which is far beyond the limitation of pulse duration supported by the broad emission spectra.

Here, we reported the experimentally demonstration of femtosecond operation in a Kerr-lens mode-locking diode-pumped Yb:LYSO laser and obtained the pulse duration as short as 61 fs at the central wavelength of 1055.4 nm. To the best of our knowledge, this is the first demonstration of femtosecond KLM Yb:LYSO laser and it is believed that 61 fs is the shortest pulse duration ever produced from an Yb-doped orthosilicate laser.

2. Experimental setup

In order to evaluate the potential gain bandwidth of the Yb:LYSO crystal for mode-locking operation, we calculated the gain cross section σ_{gain} depending on several values of the population inversion parameter β as described in Fig. 1. β is the ratio of the number of excited ions to the total number of Yb^{3+} ions and is linked to the gain cross section by formula: $\sigma_{gain} = \beta\sigma_{em} - (1-\beta)\sigma_{abs}$, where σ_{em} and σ_{abs} are the emission and absorption cross sections, respectively. It can be seen that the gain profile turns to flatter and smoother as β decreasing in the range of 1020 ~1080 nm.

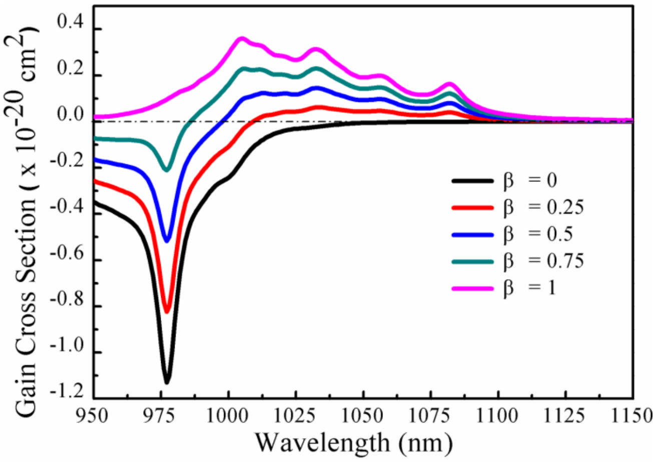

Fig. 1. Gain cross section spectra of Yb^{3+} ions for different values of population inversion parameter β.

A 3mm long, 5 at.% doped Yb:LYSO crystal with antireflection-coating was used as the laser gain medium. To remain the laser at a constant temperature for stable and efficient operation, the Yb:LYSO 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 was maintained at 10°C during the experiment. The laser crystal was end-pumped by a fiber-coupled diode laser emitting at 976 nm with a maximum output power of 25 W. The core diameter of the fiber is 105 μm and the numerical aperture (NA) is 0.22. We used an imaging system with a magnification of 0.8 to couple the pump laser from the fiber into the Yb:LYSO crystal. Figure 2 shows the sketch of the experimental setup. A standard X-folded cavity was employed in the experiment. Both M1 and M2 were dichroic mirrors with radius of curvature (ROC) of 75 mm coated with high reflection in the range of 1020-1100 nm and high

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transmission at 970-980 nm. The small ROC chosen for both M1 and M2 here was helpful to focus a much smaller beam waist on the crystal resulting in an enhanced Kerr-lens effect. A Gires-Tournois Interferometer mirror (GTI) with group velocity dispersion of −800 fs^2 per bounce in the 1035-1055 nm range was used for dispersion compensation. A plane mirror with 0.4% transmission at 1020-1100 nm was selected to be the output coupler (OC) for improving the intra-cavity power density. To initiate the mode-locking, a curved folding mirror M3 with ROC of 300 mm was used to focus the laser beam on a SESAM (BATOP GmbH), which was designed for 0.4% modulation depth at 1064 nm, 90 µJ⁄cm^2 saturation fluence, and a relaxation time of less than 500 fs. The total cavity length was about 1.33m corresponding to the repetition rate of 113 MHz. The calculation of the intra-cavity transverse mode based on the ABCD matrix showed that the beam waist diameters on the crystal and on the SESAM were 14µµm x 39µµm and 54µµm x 54µµm (1/e^2 level), respectively.

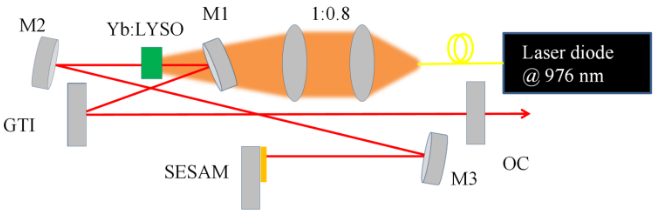

Fig. 2. Experimental setup of the mode-locking Yb:LYSO laser.

3. Results and discussion

At first, the laser cavity was optimized under CW operation at the pump power of 9 W. Then by fine-tuning the pitch angle of the SESAM, the stable mode-locking operation was reached. The shortest pulse duration was obtained by further tuning the pitch angle and the output power of the laser was reduced from 260 mW (CW operation) to 40 mW (CW mode-locking operation), meanwhile, the wavelength was shifted from 1090 nm to 1055 nm. We attributed the decrease of the output power to the mismatch in collimation of the laser cavity as well as the larger re-absorption loss at shorter wavelength. However, we regard the mismatch in collimation as the main factor which causes the decline ofβ, further results in possibility to mode-locking with broad band. We did not increase the pump power over 10 W to protect the crystal and the SESAM from damage and the mode-locking operation was totally self-starting and stable. It is worth noting that the mode-locking operation was not sensitive to the pump power that once mode-locking was self-started, stable mode-locking would exist until the pump power decreased to nearly CW threshold. Using a commercial intensity autocorrelator (FR-103MN, Femtochrome Research, Inc.), we measured the intensity autocorrelation trace as shown in Fig. 3(a). The FWHM bandwidth of the autocorrelation trace was about 94 fs, corresponding to a pulse duration of 61 fs if a sech^2-pulse shape was assumed. Figure 3(b) describes the corresponding optical spectrum of the mode-locked pulse measured by an optical spectrum analyzer (Ocean Optics, HR4000CG-UV-NIR). The FWHM of the spectrum was 22 nm with a central wavelength at 1055.4 nm, which corresponding to a 53.2 fs transform limited sech^2-shape pulse. The time bandwidth product of the laser is 0.361 that is close to the value of 0.315 for the transform limited sech^2-pulse. It is possible to obtain much shorter pulse by more finely controlling the intracavity dispersion as well as compensating outside the cavity in future steps.

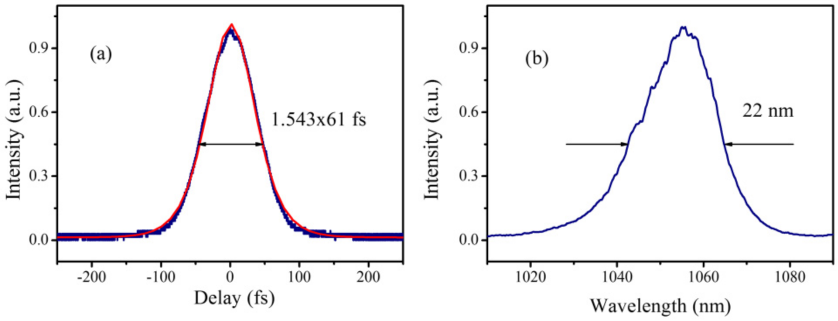

Fig. 3. (a) Intensity autocorrelation trace of the mode-locking pulses. The experimental data and the sech^2-fitting curve are described by the blue curve and the red curve, respectively. (b) The corresponding laser spectrum.

Radio frequency (RF) spectrum of the laser was also measured with a RF spectrum analyzer (Agilent E4407B). As revealed in Fig. 4(a), the fundamental beat note was 112.97 MHz with a high extinction down to 78 dBc. Figure 4(b) is the wide-span measurement which exhibits the high harmonics of the fundamental beat note. It is easy to see that the laser was in a stable mode-locking operation from the RF spectrum. Once the mode-locking was started, stable mode-locking operation could last for several hours.

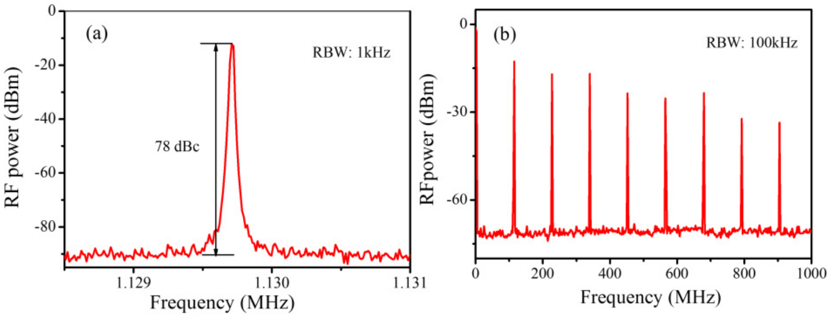

Fig. 4. Radio frequency spectrum of the mode-locked Yb:LYSO laser. (a) RF spectrum of fundamental beat note with the RBW of 1 kHz. (b) RF spectrum of 1 GHz wide-span range with the RBW of 100 kHz.

In our experiment, we slightly mismatched the cavity alignment, resulting in the cavity close to the edge of a stable cavity, which is beneficial for kerr-lens mode-locking. And according to reference [17], Yb:LYSO crystal has the character to realized self-mode-locking operation. So we have reasons to surmise the short pulse of 61 fs was generated by kerr-lens mode-locking instead of SESAM mode-locking. To investigate the role of Kerr-lens effect, we use a flat mirror with high reflection in 1μm range instead of the SESAM. The flat mirror was fixed on a translation stage to initiate the KLM. Just finely tuning the flat mirror without change anything else, KLM operation was obtained by pushing the translation stage lightly. 68 fs pulse duration shown in Fig. 5 was obtained by further optimization; however, the mode-locking was not stable and lasted only several minutes. Comparing the similar results with and without SESAM, we claimed that the SESAM in our experiment plays a role to start and stabilize the Kerr-lens mode-locking operation.

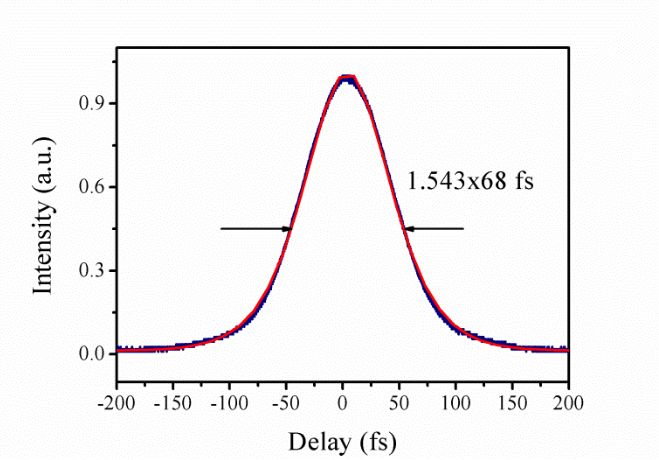

Fig. 5. Intensity autocorrelation trace of the mode-locking pulses without SESAM.

Generally speaking, smooth and broad laser gain spectrum is desired for generating mode locked pulses as short as possible. Due to the multiple spectral peaks on the fluorescence spectrum of Yb doped orthosilicates, it is difficult to generate sub-100 fs mode locked pulses, because the peaks on the emission spectrum have much stronger gain than the valleys, which limit the spectral width of the mode-locked pulses. An effective approach to obtain sub-100 fs pulses from Yb doped orthosilicate lasers is slightly mismatching the alignment so that the laser will operate with a smaller population inversion parameter β and the cavity will be close to the edge of a stable cavity which is beneficial for kerr-lens mode-locking operation. In this way, broader spectrum and shorter pulses will be achieved at the cost of much smaller output power due to the increasing of cavity loss. However, high power nearly Watt scale may be obtained by using a bigger output coupler. The femtosecond mode-locking performances of the Yb^{3+}-doped orthosilicate lasers was summarized as shown in Fig. 6. It is worth to notice that the results in Fig. 6 obtained from Yb doped orthosilicate lasers except those from Yb:LYSO laser and Yb:SSO laser were realized without the misalignment of the cavity. It is possible to generate sub-100 fs pulses for other Yb doped orthosilicate crystals with cavity in slightly misalignment. However, the 61fs pulse is the shortest one so far obtained from the Yb-doped orthosilicate lasers.

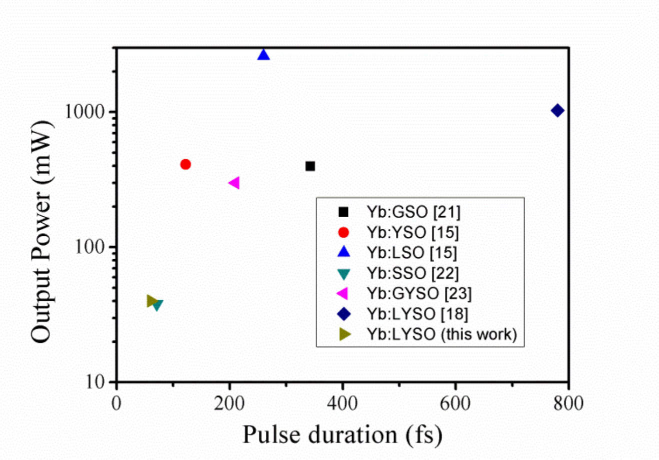

Fig. 6. The femtosecond mode-locking performances of the Yb^{3+}-doped orthosilicate lasers.

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4. Conclusion

To conclude, stable Kerr-lens mode-locking of Yb:LYSO laser with pulse duration as short as 61 fs had been obtained at a repetition rate of 113 MHz. The average output power was 40 mW and the central wavelength was at 1055.4 nm with 22 nm bandwidth. Considering that the fiber core diameter of the pump laser is 105 μm which is not matching the laser spot size on the crystal well and the pump power was no more than 10 W, we believe that even higher output power should be possible if using a bigger output coupler and a pump laser with higher power and higher brightness such as a fiber laser. Shorter pulse duration may be achieved by further controlling the intra-cavity dispersion as well as compensating outside the cavity. It is believed that Yb:LYSO crystal is an excellent laser material for ultrafast pulse generation and has potential to be applied in solid state optical frequency comb.

Acknowledgments

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