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Article

Kerr-Lens Mode-Locked Femtosecond Yb:$GdYSiO_5$ Laser Directly Pumped by a Laser Diode

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Abstract: We demonstrate the first Kerr-lens mode-locked operation in a diode-pumped Yb:$GdYSiO_5$ oscillator. Under a diode pump power of 5 W, 141 fs pulses with an average power of 237 mW were obtained at a repetition rate of 118 MHz. The central wavelength was at 1094 nm with a bandwidth of 10.1 nm. Shorter pulses were obtained by adjusting the cavity to operate at a shorter wavelength, resulting in 55 fs pulse duration at the central wavelength of 1054 nm with a bandwidth of 23.5 nm.

Keywords: ultrafast laser; diode-pumped; Kerr-lens mode-locking; all-solid-state laser

1. Introduction

Diode-pumped ytterbium-doped lasers have received continuous attention in past years due to their high conversion efficiency, high average power, and ultrashort pulse duration [1,2]. The ytterbium ion has a very simple electronic energy level structure composed of only two manifolds, $^2F_{5/2}$ and $^2F_{7/2}$. The absorption peaks are located in the 900–980 nm range, which matches well with the emission bands of commercial high-power and high-brightness InGaAs diode lasers. Therefore, it is advantageous to realize high-power, highly efficient, and cost-effective ytterbium-doped solid-state lasers with diode pumping. Owing to the simple electronic energy level structure, Yb^{3+} possesses unique laser properties so that many undesired effects, such as upconversion, excited-state absorption, cross-relaxation, and concentration quenching, may be reduced or eliminated, resulting in low quantum defect and low thermal load. In addition, the large lower-level splitting results in a broad emission bandwidth, which is beneficial to generate ultrashort pulses by various mode-locking techniques. Until now, a number of Yb^{3+}-doped laser materials have been developed to generate femtosecond pulses [3–7]. The shortest pulse duration reported thus far was 32 fs in a Yb:$CaGdAlO_4$ oscillator optically pumped by a fiber laser [8]. Such femtosecond lasers in the 1 μm wavelength range may be a valuable alternative to Ti:sapphire lasers in many applications. With the thin-disk scheme, diode-pumped ytterbium lasers with hundreds of watts of average power [9–11], tens of micro joules of pulse energy [12–14], and sub-100 fs pulse duration [15,16] have been realized.

Among the numerous Yb^{3+}-doped materials, Yb^{3+}-doped oxyorthosilicate exhibits outstanding laser performance in both continuous wave (CW) and mode-locking operation. Yb^{3+} in oxyorthosilicate has a large ground state splitting to form a quasi-four-level band. As a result, the laser threshold is greatly reduced and the laser emission cross-section has a broad band, which is essential for producing ultrashort pulses down to sub-100 fs duration. The Yb^{3+}-doped oxyorthosilicate family has several members, such as Yb:Y_2SiO_5 (Yb:YSO), Yb:Lu_2SiO_5 (Yb:LSO), Yb:Sc_2SiO_5 (Yb:SSO), Yb:Gd_2SiO_5 (Yb:GSO) and their allowed compounds Yb:LYSO and Yb:GYSO. Extensive experiments on CW and mode-locking operations have been carried out with these laser crystals [17–23]. Among them, Yb:GSO has the largest ground state splitting of up to 1067 cm^{-1} for any ytterbium-doped crystals and offers better thermal conductivity than Yb:YSO. However, a strong tendency to cleave along the (100) plane caused by the $P2_1/c$ monoclinic structure of GSO makes it difficult for practical laser applications. A feasible way to overcome the cleavage difficulty is to make an alloyed Yb:$(Gd_{1-x}Y_x)SiO_5$ crystal which incorporates the large ground state splitting of Yb:GSO and good mechanical properties of Yb:YSO. The 50/50 alloyed Yb:GYSO crystal ($x = 0.5$) has a ground state splitting of 995 cm^{-1} and a fluorescence life time of 1.92 ms, indicating it as a promising candidate for the efficient generation of high-power femtosecond lasers.

In this paper, we report the first diode-pumped Kerr-lens mode-locking (KLM) of a Yb:GYSO oscillator. Stable 141 fs pulses were produced at a central wavelength of 1094 nm with 10.1 nm bandwidth. With the pump power of 5 W, an average output power of 237 mW was obtained. The shortest pulse duration of only 55 fs was achieved by adjusting the position of the concave mirror and the angles of the end mirrors where the central wavelength was shifted to 1054 nm with a bandwidth of 23.5 nm. The output power was 27 mW.

2. Experimental Layout

The diode-pumped Kerr-lens mode-locked solid-state oscillator was usually considered difficult to realize due to the low brightness of diode lasers. Measures should be taken to initiate effective soft-aperture Kerr-lens mode-locking in the laser crystal. In reference [8] the authors employed a polarized single mode fiber laser as the pump source and realized the shortest pulses of 32 fs in a KLM Yb:$CaGdAlO_4$ oscillator. However, fiber lasers have lower efficiency and higher cost than laser diodes. Therefore, we utilized a fiber-coupled laser diode (Jenoptik, Jena, Germany; JOLD-7.5-BAFC-105) with a small core diameter of 50 μm and a numerical aperture of 0.22 as the pump source. Next, a tight focusing laser cavity was built to enhance the laser intensity in the Yb:GYSO crystal. The overall experimental layout is depicted in Figure 1. The 976 nm output from the fiber-coupled laser diode was reimaged into the crystal by a telescope with a magnification of 1:0.8. The focusing beam waist in the crystal was estimated to be about 20 μm. The laser cavity consisted of a pair of concave mirrors with radii of curvature (ROC) of 75 mm. Both surfaces were coated for high transmission at 976 nm ($R < 2\%$) and high reflection at 1020–1200 nm ($R > 99.9\%$). The laser medium used in the experiment was a 3 mm long, 5 at.% Yb^{3+}-doped GYSO crystal with a 6 × 5 mm^2 cross-section. The main absorption peaks at room temperature were at 900, 918, 950, and 976 nm where the highest one at 976 nm belongs to the zero phonon line of Yb^{3+}. The uncoated crystal was placed at Brewster's angle to minimize the surface reflection. The crystal was wrapped with an indium foil and mounted on a water-cooled copper heat sink kept at 14 °C. Intracavity chirp compensation was realized by a pair of SF6 prisms whose tip-to-tip distance was set as 267 mm. A plane mirror with a transmission of 0.8% in the range of 1020–1200 nm was used as the output coupler (OC). The small coupling rate was employed to increase the intracavity laser intensity for stronger Kerr nonlinearity at the expense of smaller output power. A plane high reflection mirror was placed on a translation stage as the end mirror. The total cavity length was about 1.27 m, corresponding to a repetition rate of 118 MHz. By this cavity design, the laser beam waist in the crystal was calculated to be about 19.1 μm × 17.1 μm. The good overlap between the cavity mode and the pump mode is a prerequisite for effective Kerr-lens mode-locking.

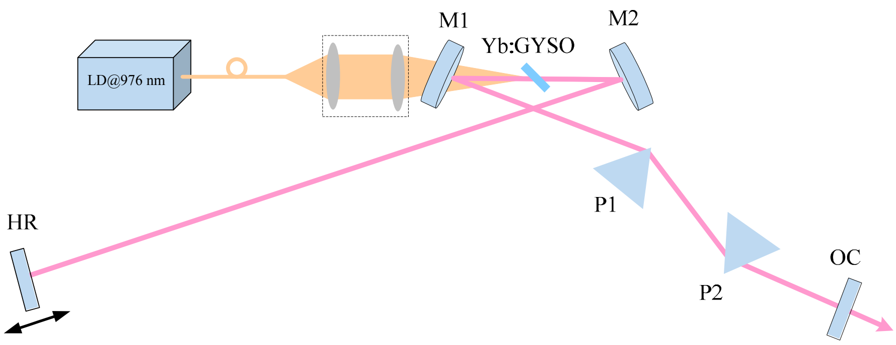


Figure 1. Layout of the Kerr-lens mode-locked Yb:GYSO oscillator. LD: laser diode; M1 and M2: concave mirrors with ROC of 75 mm; P1 and P2: SF6 prisms; HR: high reflection mirror; OC: output coupling mirror of 0.8% transmittance.

3. Experimental Results and Discussions

We firstly characterized the CW properties and wavelength tunability of the Yb:GYSO laser by a simple three-mirror cavity consisting of a plane dichroic mirror, a concave mirror with ROC of 200 mm, and a plane output coupler. Three output couplers with different transmissions (0.8%, 2.5%, and 10%) were used to test the output power. For three OCs the laser wavelengths were all at 1091 nm. The dependence of the CW laser output power on the incident pump power is illustrated in Figure 2. The output power was saturated when the pump power reached 5.6 W. The highest output power of 2.62 W was obtained with a 10% OC. Before saturation, the slope efficiency was about 71%, and it was 58.0% and 47.4% for 2.5% OC and 0.8% OC, respectively. The pump threshold for 0.8% and 2.5% OCs was only 0.61 W. Such low lasing threshold verified the large ground state splitting of the Yb:GYSO crystal (995 cm^{-1}), where thermal population of the upper laser level was rare.

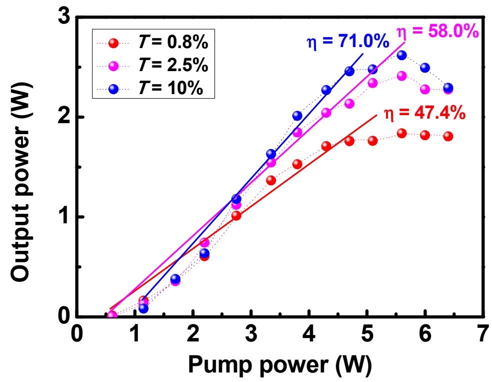


Figure 2. CW output power of the Yb:GYSO laser *versus* the incident pump power for three OCs with different transmissions (0.8%, 2.5%, and 10%).

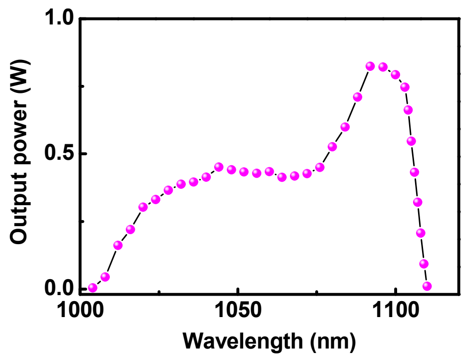


Figure 3. Wavelength tuning curve of the Yb:GYSO laser with a 0.8% transmission output coupler at 3.8 W pump power.

Continuous wavelength tuning of the Yb:GYSO laser was carried out by inserting a highly dispersive SF6 prism into the three-mirror cavity. A 0.8% transmission output coupler was used to explore the wavelength tunability. At a pump power of 3.8 W, the tunable wavelength range is from 1004 to 1110 nm, and as broad as 106 nm, as shown in Figure 3. This was the broadest tuning range from an Yb:GYSO laser, even broader than an Yb:GSO laser [24]. The highest output power appeared at 1092 nm, which indicated that at longer wavelengths, the reabsorption loss was greatly reduced. The very broad and smooth wavelength tuning of the Yb:GYSO crystal were superior for generating ultrashort femtosecond pulses by Kerr-lens mode-locking.

As shown in Figure 1, KLM was realized by adjusting the cavity to the edge of the stability region by translating the M2 mirror toward the crystal and finely adjusting the angles of the HR mirror and OC. At this point, the CW output power was 280 mW under 5 W pump power. Stable mode-locking was initiated by fast moving of the HR mirror. When mode-locked, the oscillator delivered a stable pulse train at a repetition rate of 118 MHz acquired by a fast photodiode and monitored by a digital oscilloscope. The mode-locked output power as a function of the pump power is shown in Figure 4. For comparison, the CW output power when mode-locking was terminated is also displayed. Stable mode-locking could be sustained for a pump power ranging from 3.3 W to 6.0 W. The highest output power of 237 mW was obtained at 5 W pump power.

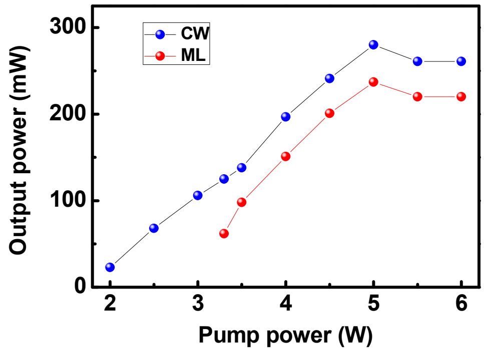
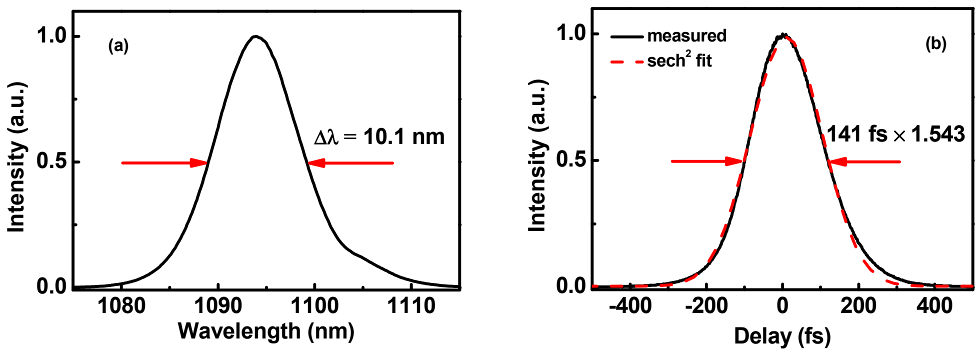


Figure 4. Mode-locked output power (red dots) *versus* the pump power. Blue dots indicate the CW power when mode-locking was terminated.

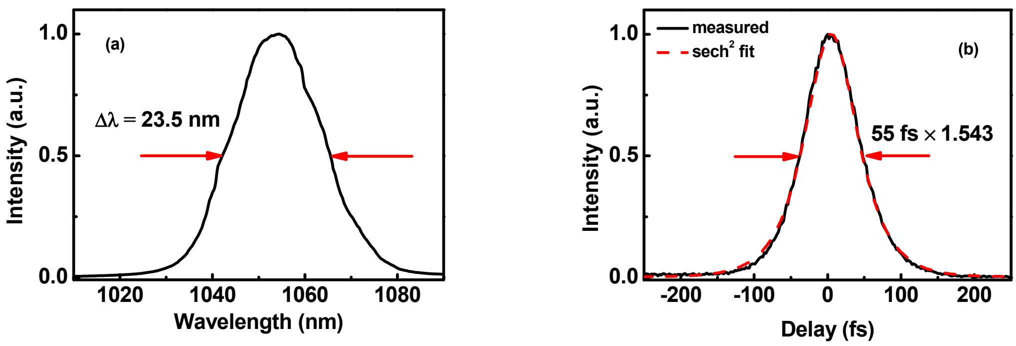


(**a**) (**b**)

Figure 5. (**a**) Spectrum of the femtosecond pulses centered at 1094 nm; (**b**) Autocorrelation trace of the femtosecond pulses (black curve) and the sech^2-fitting curve (red dashed line).

The spectrum of the femtosecond pulses was characterized with an optical spectral analyzer (Yokogawa, Tokyo, Japan; AQ6370). It was centered at 1094 nm with a 10.1 nm wavelength bandwidth. As shown in Figure 5a, the mode-locking spectrum reached above 1110 nm. The new wavelength component above 1110 nm was mainly due to self phase modulation in the crystal. The pulse duration was characterized by an intensity autocorrelator (APE PulseCheck USB, Berlin, Germany), as shown in Figure 5b (black curve). If a sech^2-shape pulse was assumed, the pulse duration was 141 fs. In a 50 ps scanning range, only one pulse was observed, indicating that the mode-locking was in single-pulse operation. The time-bandwidth product of the pulses was 0.357, close to the Fourier transform limit of $sech^2$ pulses.

As described before, the laser tends to lase at longer wavelengths with low pump thresholds due to small thermal population caused by the large splitting of the ground manifold. However, according to the room-temperature unpolarized emission spectrum of the Yb:GYSO crystal, broader emission bandwidth appears within the 1039 nm and 1056 nm bands. Therefore, one may expect to get much shorter pulses when mode-locking in this spectral range. We carefully aligned the laser cavity to another mode-locking regime by adjusting the position of the concave mirror M2 and optimizing the angles of HR and OC where the central wavelength shifted to the shorter wavelength. The shortest pulse duration of 55 fs was obtained. The corresponding spectrum is shown in Figure 6a. The central wavelength was at 1054 nm with 23.5 nm bandwidth. The time-bandwidth product was 0.349. Due to the higher pump threshold and larger reabsorption coefficient at shorter wavelengths as well as the surface reflection loss by the prisms, the output power was lower than that at 1094 nm. The average power was only 27 mW for a pump power of 5 W. The output power may be increased by replacing the prism pair with customized Gires-Tournois interferometer (GTI) mirrors and by optimizing the transmission of the output coupler. Since the Yb:GYSO crystal has a broad emission spectrum, sub-50 fs pulses should be feasible with the KLM method.



(**a**) (**b**)

Figure 6. (**a**) Spectrum of the femtosecond pulses centered at 1054 nm; (**b**) Autocorrelation trace showing the pulse duration was 55 fs assuming a $sech^2$ pulse shape. Black curve, measured data; red dashed line, $sech^2$ fitted curve.

4. Conclusions

In conclusion, we studied the diode-pumped Kerr-lens mode-locked Yb:GYSO oscillator for the first time. Based on the good spectral properties of the alloyed Yb:GYSO crystal, stable KLM operation was achieved with 141 fs pulse duration and 237 mW average power at 5 W diode pump power. The laser emission was centered at 1094 nm with a 10.1 nm bandwidth. Shorter pulses of 55 fs duration were obtained by adjusting the cavity to operate at 1054 nm. The mode-locking bandwidth was as broad as 23.5 nm with an output power of 27 mW. Higher output powers and shorter pulse durations down to sub-50 fs with the Yb:GYSO crystal may be obtained by reducing the cavity loss and optimizing chirp compensation.

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Author Contributions

Zhiyi Wei, Jiangfeng Zhu, Junli Wang and Zhaohua Wang conceived and designed the experiments. Ziye Gao and Wenlong Tian performed the experiments. Jiangfeng Zhu, Zhiyi Wei, Ziye Gao, Wenlong Tian and Liangbi Su analyzed the experimental data. Lihe Zheng, Liangbi Su and Jun Xu provided the crystal. Jiangfeng Zhu wrote the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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