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Diode-pumped Kerr-lens mode-locked Yb: GSO laser generating 72 fs pulses

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ABSTRACT

The generation of 72 fs hyperbolic secant pulses centered at 1050 nm with 17.8 nm bandwidth from a diode pumped Kerr-lens mode-locked Yb: GSO laser is demonstrated. With the help of a semiconductor saturable absorber mirror, stable mode-locking with an average output power of 85 mW at a repetition rate of 113 MHz is realized. To the best of our knowledge, this is the first demonstration of Kerr-lens mode-locking in Yb: GSO laser.

1. Introduction

In the past decade, the rapid development of compact, ultrafast lasers with high power were ushering in the new field of scientific researches and industrial applications [1]. It is now widely recognized that solid state lasers based on Yb-doped mediums are suitable in this respect and thus extensively investigated. This is mainly due to the advantages of Yb doped laser materials including large fluorescent lifetime, broad emission spectrum and simple electronic energy structure which results in absence of some undesirable effects such as up-conversion, excited-state absorption, concentration quenching and cross relaxation. Up to now, the generation of femtosecond pulses by using several kinds of Yb doped materials, both crystals and ceramics, has been implemented with remarkable progress [2–7]. Particularly, by means of Kerr-lens mode-locking (KLM) and passive mode-locking with semiconductor saturable absorber mirrors (SESAM), sub-100 fs pulses have also been realized [8–15].

Among the available Yb doped mediums, special attention has been paid to the Yb^{3+} doped oxyorthosilicates (including Yb:GSO, Yb:YSO, Yb:LSO, Yb:SSO, Yb:LYSO, and Yb:GYSO) thanks to their numerous advantages and good qualities compared with those of their competitors [16]. Firstly, the ground state energy splitting of Yb^{3+} ion in Yb doped oxyorthosilicates is large enough to lead to a quasi-four level operation and then a low pump threshold. Moreover, Yb doped oxyorthosilicates exhibit a large fluorescence lifetime and excellent thermal conductivity implying a potential to generate ultrafast pulses with high energy. In addition, the Yb doped oxyorthosilicates have broad emission spectrum as well as absorption peak at the zero phonon line which is significant for diode pumped laser, in which the spectral broadness of high power diode laser is a limiting factor. To date, excellent continuous wave (CW) and femtosecond operation have been realized in different Yb doped oxyorthosilicates [17–26].

Due to the multiple spectral peaks in the fluorescence spectrum of the Yb doped orthosilicates [16], it is difficult to generate sub-100 fs mode-locked pulses. Since the peaks in the emission spectrum have much stronger gain than the valleys, which limit the spectral broadening of the mode-locked pulses. In the case of Yb:GSO, based on the investigations reported in recent years [17,18,27–32], the emission spectrum is as broad as 72 nm with mainly four peaks at 1013 nm, 1031 nm, 1048 nm and 1088 nm. However, the shortest pulse from Yb: GSO laser is only 343 fs up to now [18] which is far beyond the limitation of pulse duration supported by the broad emission spectrum. The gain cross section of the Yb:GSO crystal turns to flatter and smoother as the population inversion parameter decreasing in the range of 1020–1080 nm. So that an effective way to overcome the above issue is

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to operate the Yb:GSO laser at a small population inversion parameter by exploring the KLM technology. Since KLM introduces less loss in the cavity compared to passive mode-locking with SESAM, lower population inversion parameter can be fulfilled.

In this work, we demonstrate a laser-diode pumped KLM Yb: GSO laser, generating pulses as short as 72 fs. The Stable KLM operation is realized with the help of a SESAM, and the average output power is 85 mW. The spectrum of the mode-locked pulses is centered at 1050 nm with a bandwidth of 17.8 nm and the repetition rate is 113 MHz. To the best of our knowledge, this is the first demonstration of KLM in a Yb: GSO laser.

2. Experimental setup

During the experiment, a 5 at% doped Yb: GSO crystal with the size of 3 × 3 × 3 mm^3 was utilized as the laser gain medium. The antireflection-coated Yb:GSO crystal was wrapped with indium foil and mounted tightly on a water-cooled copper heat sink block maintaining a temperature of 11 °C for stable and efficient laser operation. The sketch of the experimental setup is shown in Fig. 1.

The pump source, a fiber-coupled diode laser of emitting wavelength at 976 nm, was employed to end-pump the gain medium. The core diameter of the fiber was 105 μm and the numerical aperture (NA) was 0.22. To couple the pump laser beam from the fiber into the Yb: GSO crystal, an imaging system with a magnification of 0.8 was utilized. A standard X-folded cavity was adopted in this experiment. Both C1 and C2 were dichroic mirrors with radius of curvature (ROC) of 75 mm which were coated with high reflection in the range of 1020–1100 nm and high transmission at 970–980 nm. The small ROC chosen for both C1 and C2 here was helpful to focus the laser into a very small beam waist on the crystal resulting in an enhanced Kerr-lens effect. To compensate for the positive dispersion in the cavity resulted from the crystal and air, a Gires–Tournois Interferometer mirror (GTI) was used to introduce a group delay dispersion of −800 fs^2 per bounce in the 1035–1055 nm range. To effectively enhance the intracavity laser intensity, an output coupler (OC) with 0.4% transmission at 1020–1100 nm was used. High reflective (HR) mirror, which terminated the cavity, was a flat mirror with high reflection in the range of 1020–1100 nm, and was fixed on a translation stage. A curved folding mirror with ROC of 300 mm, C3, was used to focus the laser beam on the HR. C3 also had a high reflection in the range of 1020–1100 nm. The total cavity length was about 1.33 m corresponding to the repetition rate of 113 MHz.

3. Results

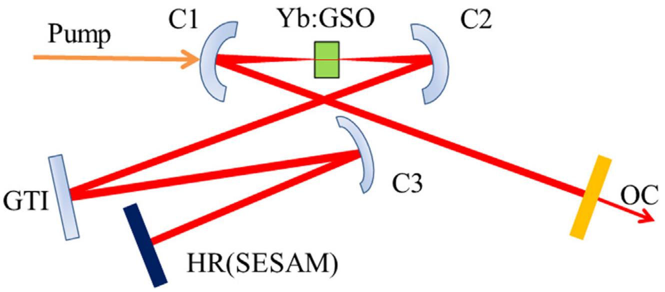

Fig. 1. Experimental setup of the CW and mode-locked Yb:GSO laser.

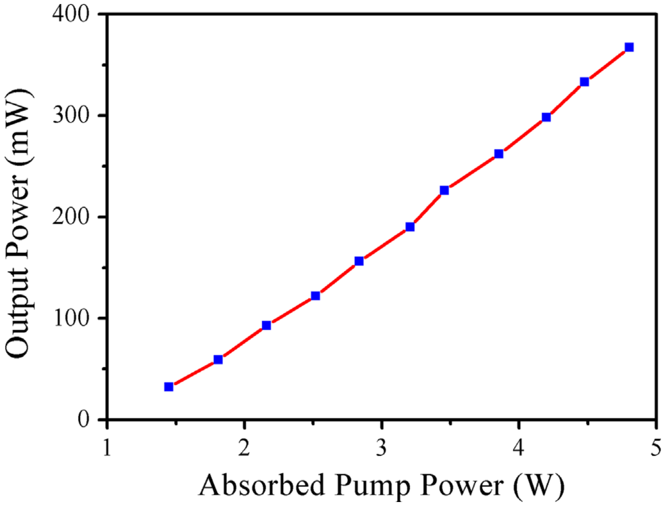

Fig. 2. CW output power depending on the absorbed pump power.

The CW performance of the Yb: GSO laser was firstly characterized. Fig. 2 displayed the output power depending on the pump power. In spite of using an output coupler with only 0.4% transmittance, 367 mW output power was obtained with the absorbed pump power of 4.8 W. Under this output power which was thought high enough to realize mode locking, we finely tuned the position of the mirror C2 to make the oscillator close to the stability edge where the CW power decreased to 60 mW. An evident sign of self-mode-locking was observed by pushing the translation stage. Then KLM could be obtained with the absorbed pump power increased to 6.7 W. However, the mode-locking could only last for a few minutes. In order to make the mode-locking stable and easy for self-starting, the HR was replayed by 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 (also shown in Fig. 1).

Stable mode-locking operation was easily achieved with an average output power of 85 mW. To avoid damages either on the crystal or the SESAM, no more pump power was applied on the crystal. Using a commercial optical spectrum analyzer (YOKOGAWA, AQ6370C), the spectrum of the mode-locked laser was recorded. As evident from Fig. 3(a), the spectrum was centered at 1050 nm with a full width at half maximum (FWHM) of 17.8 nm, which supports a Fourier transform limited sech^2-pulse of 65 fs. The corresponding intensity autocorrelation trace measured by a commercial intensity autocorrelator (FR-103MN, Femtochrome Research, Inc.) is depicted in Fig. 3(b). If a sech^2-shape pulse was assumed, the 111 fs FWHM of the intensity autocorrelation trace indicated the pulse duration of 72 fs. The time-bandwidth-product (TBP) was calculated to be 0.354 which was very close to the transfer limited value of 0.315 for a sech^2-shape pulse.

The radio frequency (RF) spectrum of the KLM Yb: GSO laser was tested via a RF spectrum analyzer (Agilent E4407B) as well as a photo detector (PD) with a 3 dB bandwidth of 1 GHz. As shown in Fig. 4, the RF spectrum of the fundamental beat note had a high signal to noise ratio of 69 dBc centered at 112.9 MHz. Stable mode locking was illustrated by the clean radio frequency spectrum of Fig. 4(a) and (b), where no side peaks of the harmonics of the fundamental frequency were observed.

Based on ABCD matrix calculation, the beam diameter on the crystal was calculated to be 14 μm × 39 μm (1/e^2 level), which implies an elliptical beam profile. The beam quality of the mode-locked laser was measured using a commercial M^2 factor meter (Spiricon M2-200s), as shown in Fig. 5. The M^2 factors were measured to be $M_x{}^2=1.3$, $M_y{}^2=1.4$ in the horizontal and vertical directions, respectively. The near-field beam profile shown as inset in Fig. 5 indicates a nearly fundamental mode operation for the mode-locked laser.