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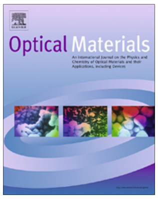

Direct diode-pumped 58 fs Yb:$Sr_3Y_2(BO_3)_4$ laser

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ABSTRACT

The ultrafast laser performance of Yb:$Sr_3Y_2(BO_3)_4$ (SYB) crystal has been demonstrated for the first time to the best of our knowledge. The Yb:SYB laser was driven to work in SESAM-assisted Kerr-lens mode-locking (KLM) operation, and 58 fs pulses were generated at the central wavelength of 1054.6 nm. A maximum average output power reached 400 mW with a slope efficiency of 13.5%. The experimental results indicated Yb:SYB crystal as a promising candidate for achieving ultrashort lasers.

1. Introduction

Ultrafast laser sources are useful for a variety of scientific research and applied studies. To date, semiconductor saturable absorber mirrors (SESAMs) have assisted to achieve successful mode locking in a broad range of solid-state-lasers with various cavity designs [1]. Besides, Kerr-lens mode-locking (KLM) is also a feasible technique for generating ultrashort pulses [2]. In a pure KLM laser, the available pulse width is only limited by the gain bandwidth of the gain medium and intracavity dispersion bandwidth. Therefore, KLM shows potential of producing shorter pulses than those with SESAMs for the broadband gain medium with considerable nonlinear refractive index (n_2). However, KLM technique still suffers from obvious drawbacks. First, the KLM lasers are not easy to self-start, which is usually achieved with external perturbations to the laser cavity. Second, the cavity mirror alignments require submillimeter-scale precision. One method to relieve these difficulties is to introduce a “real” saturable absorber (SA), e.g., SESAM [3–5] or carbon nanotube (CNT) [6], in helping achieve stable mode-locking operation. The cavity alignment and the starting of the pulsed operation are significantly simplified by the SA while maintaining the ability of generating short pulses. Hence, the so-called SA-assisted KLM laser systems are worthy of our attention and it is meaningful to explore novel laser gain medium for achieving such lasers.

Yb^{3+} ion has been recognized as one of the most promising dopants for efficient diode-pumped ultrafast lasers, considering the favorable properties of Yb^{3+}-doped materials, such as no parasitic up-conversion effects and broad emission bands. In addition to achieving mode-locked lasers based on SESAM [7], Yb^{3+}-doped crystals show promising potentials of realizing KLM lasers [4,5,8–12]. In recent years, thanks to the excellent saturable absorption properties, many two-dimensional materials have also emerged as promising SAs in Yb-bulk lasers, such as e.g. graphene, MoS_2 and WS_2 [13–17]. The shortest graphene mode-locked pulse in the Yb-doped crystal laser was about 30 fs, generated from a Yb:CALYO laser [13]. Using the saturable absorption of WS_2, pulses of 736 fs was obtained from a Yb:YAG laser [17].

Among the available Yb^{3+}-doped crystals, Yb^{3+}-doped borates have attracted much attention until now, because they usually have good physical and chemical properties, broad emission spectrum and considerable nonlinear refractive index [18,19]. As a member of the $M_3R_2(BO_3)_4$ (M = Ca, Sr, Ba; R = La—Lu, Y) family, $Sr_3Y_2(BO_3)_4$ (SYB) crystallizes in orthorhombic system with *Pnma* (No. 62) space group. Y^{3+} and Sr^{2+} ions can randomly occupy three independent sites statistically to form the metal-oxygen distorted polyhedrons with coordinated oxygens in SYB crystal. Recently, by partially replacing Y^{3+} ions and Sr^{2+} ions with Yb^{3+} ions, 3 at.% Yb^{3+}-doped SYB crystal has been successfully grown by our group [18]. The study on its polarized spectroscopic properties shows that the stimulated emission cross section ($1.2 \times 10^{-20}\ cm^2$) at emission peak is lower than that of Yb:YAG ($2.2 \times 10^{-20}\ cm^2$) and Yb:KGW ($2.8 \times 10^{-20}\ cm^2$) [20], but large compared to Yb:

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CALGO (0.75×10^{-20} cm^2) [21], Yb:LSO (0.14×10^{-20} cm^2) [22] and many other Yb^{3+}-doped borate crystals, such as Yb:YCOB (0.55×10^{-20} cm^2) [23] and Yb:BOYS (0.2×10^{-20} cm^2) [24]. The large emission cross-section is preferred for suppressing the Q-switching instability in the mode-locking lasers. In addition, Yb:SYB has a fluorescence lifetime of 1.13 ms, which is relatively shorter than those of Yb:LSO (1.68 ms) [22], Yb:YCOB (2.65 ms) [18] and Yb:CaF$_2$ (2.4 ms) [25]. Long lifetime will counteract soliton stabilization and result in difficulty to stabilize a continuous-wave mode-locked laser [25]. Moreover, due to the random distribution of Yb^{3+} ions at three independent lattice sites, high degree of disorder has been induced inside the Yb:SYB crystal structure, which can cause significant inhomogeneous gain bandwidth broadening, thus benefit the generation of ultrashort pulses. The ~70 nm emission bandwidth [18], which is broader than many other widely-used Yb^{3+}-doped crystals, eg. Yb:YAG (10 nm), Yb:KYW (24 nm) and Yb:KGW (25 nm), etc. [20], supports Yb:SYB crystal to generate less than 50 fs ultrashort pulses. However, the ultrafast laser performance of Yb:SYB crystal has not been experimentally studied so far.

In this paper, we experimentally demonstrate a diode-pumped mode-locked Yb:SYB femtosecond laser, which was driven to work in SESAM-assisted KLM operation. 58 fs pulses at the central wavelength of 1054.6 nm were obtained with a maximum average output power of 400 mW, corresponding to a slope efficiency of 13.5%. To the best of our knowledge, this is the first demonstration of ultrafast mode-locking operation with Yb:SYB crystal.

2. Nonlinear refractive index of laser crystal sample and femtosecond laser setup

To evaluate the Kerr effect of a-cut Yb:SYB crystal employed in this work, we employed Z-scan technique to measure the nonlinear refractive index (n_2) at 800 nm, which trace was shown in Fig. 1. According to the method described in Ref. [26], we estimated the value of n_2 to be 6.4×10^{-16} cm^2/W. The value of the nonlinear refractive index was larger than that of 3.1×10^{-16} cm^2/W for Ti:sapphire laser crystal [27], which indicated the potential of Yb:SYB crystal for realizing efficient KLM lasers.

Unlike pure KLM lasers, which cavity is usually designed at the edge of the stability region in order to maximize self-amplitude modulation (SAM), the laser cavity here was designed to work close to center of the stability region, since enough large SAM could be introduced by the assisted SESAM to initiate the mode-locking operation.

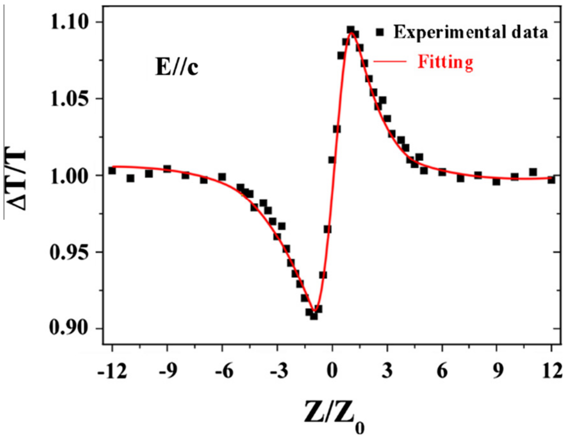

Fig. 1. Z-can trace for a-cut Yb:SYB sample at a peak power intensity at focus of 250 GW/cm^2.

The schematic diagram of the laser set up is shown in Fig. 2. A 3 at.% doped a-cut 5.5-mm long Yb:SYB crystal with anti-reflection coated at 900–1100 nm on both sides was directly pumped by a fiber-coupled diode laser emitting at 977 nm with a 200 μm fiber-core diameter and a numerical aperture of 0.22. The crystal was cooled at 13 °C by water and placed at a small incident angle with respect to the cavity axis to suppress the etalon effect. Using a 1.8:1 optical collimation system, the focused pump beam was reimaged into the crystal with a radius of 55 μm. The oscillation laser mode radius inside the Yb:SYB crystal was calculated to be 80 μm × 75 μm, which was designed to be larger than the pump spot, thus a soft-aperture would be effectively introduced when the enhanced Kerr lensing effect happened inside the crystal. Due to the power intensity dependent Kerr lensing effect, the pulse wings with lower power intensity would suffer from the soft aperture induced loss seriously, while the peak of pulse could be efficient gained, thus the pulse would be efficiently shorted. In addition, the relatively long crystal employed here could provide extra loss to the pulse wings, which functioned like an additional soft-aperture [12]. Moreover, such kind of soft-aperture could be influenced by changing the position of crystal with respect to the focal point of pump beam, which also provided a feasible way to control the intracavity ultrashort pulse formation. The employed SESAM had a saturation fluence of 120 μJ/cm^2, a modulation depth of 0.6% and could introduce nearly zero group delay dispersion (GDD) in the spectral range of 1020–1080 nm. The laser beam was focused by a 250-mm radius-of-curvature mirror onto SESAM with a radius of about 225 μm. The transmittance of the output coupler was 1.5%. The GDD introduced by the Yb:SYB crystal was about 1000 fs^2 for a single pass. To reduce the intracavity losses and keep our oscillator compact, we compensated the intracavity dispersions with two plane Gires-Tournois interferometer (GTI) negative-dispersion mirrors. An amount GDD of −3600 fs^2 per round trip was introduced, which compensated the GDD inside the cavity and balanced the self-phase modulation (SPM) introduced by the gain medium.

3. Results and discussion

By changing the positions of mirror M2 and Yb:SYB crystal carefully as well as adjusting the output mirror M5, a stable continuous-wave mode-locking (CWML) operation was achieved. The CWML regime can be sustained while the absorbed pump power was increased from 4.9 to 6.2 W. Fig. 3 shows the dependence of the average output power and pulse duration on the absorbed pump powers. As the absorbed pump power increased, the pulse duration became a little shorter and the average output

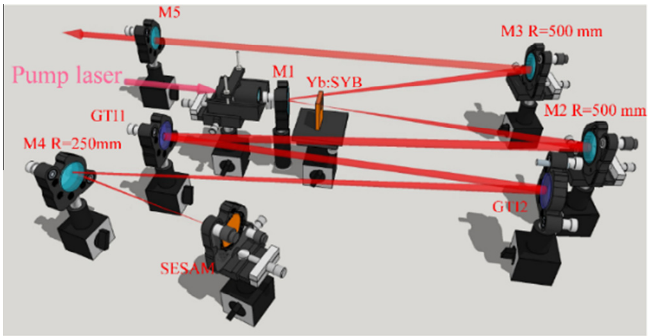

Fig. 2. Experimental setup of the mode-locked Yb:SYB laser. M1, input mirror: dichroic mirror coated for high transmission at the pump wavelength and high reflection (HR) in 1020–1080 nm spectral region; M2, M3 and M4, HR fold mirrors; M5, output coupler; GTI 1, and GTI 2, HR Gires-Tournois interferometer mirrors introducing GDDs of −550 fs^2 and −1250 fs^2 per bounce, respectively.