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RESEARCH ARTICLE

Diode-pumped 10 W femtosecond Yb:CALGO laser with high beam quality

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Abstract
We demonstrate a diode-pumped femtosecond Yb:$CaGdAlO_4$ (Yb:CALGO) laser with a semiconductor saturable absorber mirror (SESAM) for stable mode-locking operation. A perfect beam profile is measured under 10 W output power with $M_x^2 = 1.017$ and $M_y^2 = 1.016$ in the horizontal and vertical directions, respectively. At the repetition rate of 71.66 MHz, the optical pulse duration is 247 fs and the pulse energy is 140 nJ at the central wavelength of 1041 nm, corresponding to a peak power of 0.56 MW. In addition, we also generate continuous wave (CW) power of more than 15 W with TEM_{00} mode, corresponding to an optical-to-optical efficiency of 44.1%.

Keywords: diode pump; high power femtosecond oscillator; passive mode-locking; Yb:CALGO laser

1. Introduction

High-power ultrafast lasers at a central wavelength of near 1 μm are of great importance in fields such as laser micromachining, terahertz generation, two-photon polymerization, non-linear microscopy, and others[1,2], which greatly drive the development of high-power ultrafast lasers. In recent years, many promising ytterbium-doped (Yb^{3+}-doped) materials have been proved to be suitable for femtosecond oscillators, such as Yb:CaF_2[3], Yb:GYSO[4], Yb:KGW[5], and Yb:$CaGdAlO_4$ (Yb:CALGO)[6]. Among these, Yb:CALGO crystal is the most promising candidate, because the fairly broad emission bandwidth (from 990 to 1080 nm)[7] supports ultrashort pulse generation and high thermal conductivity (11 W m^{-1} K^{-1} for undoped Yb:CALGO crystals) allowing for higher-power laser pumping[8]. For example, Clarkson *et al*. from Italy reported the results of an Yb:CALGO laser that can deliver sub-100 fs pulse duration with 12.5 W average output power, which is the highest average power from an Yb-based solid-state laser[9]. Although stable mode-locking operation in Yb:CALGO laser was realized using a continuous wave (CW) fiber laser centered at 980 nm as the pump source[10], a laser diode (LD) presents a more competitive approach than fiber laser owing to the lower cost and higher power. As we all know, Kerr-lens mode-locking (KLM) is sensitive to the environment and strict to the resonator adjustment, and it cannot be self-started. However, semiconductor saturable absorber mirror (SESAM) mode-locking presents the advantage of being self-starting, and supports higher stability and robustness.

The Yb:CALGO femtosecond oscillator was first reported in 2006, generating 47 fs pulses with 38 mW average output power[11]. Since then, there have been many reports about sub-100 fs Yb:CALGO lasers, although the output power is limited to several watts or even tens of milliwatts[12–16]. Based on Yb:CALGO crystal, the average output power of 3.5 W was generated with a pulse duration of 60 fs[17] and pulses as short as 37 fs with average output power of 0.9 W were demonstrated[18]. Furthermore, the shortest pulse duration down to 32 fs with 0.9 W has

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been recently demonstrated from an Yb:CALGO laser[19]. Recently, a record pulse duration of sub-50 fs with 1.7 MW of peak power was achieved from a KLM Yb:CALGO oscillator[15]. Tian *et al*. demonstrated a high-power KLM Yb:CaYAlO$_4$ (Yb:CALYO) laser generating 59 fs pulses with 6.2 W average power[20]. Furthermore, the Yb:CALGO crystal has great potential for the development of thin-disk lasers. For example, Ricaud *et al*. demonstrated an average output power of 28 W from pulses with a duration of 300 fs and a pulse energy of 1.3 μJ[21]. However, there are few reports on the average power up to the 10 W level based on bulk Yb:CALGO crystal. The power scale limitation results from the low damage threshold and strong thermal lens effect of the gain crystal as well as the low damage threshold and appropriate modulation depth of SESAM. The shortening of pulse width is mainly limited by the long recovery time of SESAM and the suitable amount of compensation dispersion. Therefore, scaling output power while keeping the pulse duration as short as possible is a challenging goal. In addition, the wavelength tuning range of the sub-100 fs Yb:CALGO laser was as broad as 38 nm between 1034 and 1072 nm[22]. It is worth mentioning that a perfect beam profile is measured under 10 W output power with $M_x^2 = 1.017$ and $M_y^2 = 1.016$ in the horizontal and vertical directions, respectively. To the best of our knowledge, the above experimental results represent high beam quality for the Yb:CALGO laser. The beam quality is related to the gain medium, cavity distortion, and thermal blooming. The non-uniform gain distribution of the laser medium deteriorates the beam quality during laser operation, which is especially serious in solid-state lasers. The nonlinear effect is also an important factor leading to beam quality deterioration for high-power lasers. Therefore, it is challenging to achieve high beam quality laser.

In this paper, we report on the SESAM mode-locked Yb:CALGO oscillator pumped by the diode laser. The self-starting mode-locked laser pulses as short as 247 fs have been measured with 140 nJ pulse energy at the repetition rate of 71.66 MHz, corresponding to a 10 W average power and 0.56 MW peak power, respectively.

2. Experimental setup

The schematic experimental setup of the SESAM mode-locked Yb:CALGO laser is shown in Figure 1. In our experiment, the fiber coupled LD emitted at 976 nm is used as the pump source, which delivers the maximum power of 50 W. The fiber has a core diameter of 105 μm and a numerical aperture of 0.22. A *c*-cut 4%-doped Yb:CALGO crystal of 4 mm thickness is used as the gain material with broadband anti-reflection coatings at both pump and oscillating laser wavelengths on both sides. Without laser emission, the single-pass absorption of the crystal to the pump laser varies from 50% to 60%, which can be attributed to the wavelength of the pump laser shifting with the increase of the pump power. The thermal lens effect caused by the heat deposition in the crystal will handicap increasing the output power. Hence, the crystal is wrapped with an indium film and placed on the water-cooled heat sinks to dissipate heat at a temperature of 14°C. The mirrors M1–M3 are concave mirrors with radii of curvature of 500, 300, and 500 mm, respectively. The mirror M4 is a plane mirror. The four mirrors mentioned above have high reflection (HR) coating ($R > 99.9\%$) over 1000–1065 nm. The DM represents a dichroic mirror with high transmission (HT) in the range of 820–990 nm and HR in the range of 1030–1200 nm. The transmittance of the flat output coupler (OC) is 10%. The total group delay dispersion (GDD) of two Gires–Tournois interferometer mirrors (GTI1 and GTI2) is -3200 fs^2. A SESAM (BATOP, Germany) is employed to start and maintain mode-locking. Its operational wavelength is 1064 nm with the modulation depth of 2.4%, relaxation time of 1 ps and saturation fluence of $F_{\text{sat}} = 70$ μJ/cm^2. In addition, the SESAM is mounted on a micrometer driven translation stage, which is used to continuously adjust the distance between M1 and the SESAM. The adjustment of distance is an indispensable alignment, which determines the actual power density on SESAM. It is found that the distance between M1 and SESAM varied from 278 to 283 mm, so the mode-locking can be realized. However, when the distance is 281 mm, the Yb:CALGO femtosecond oscillator exhibits the best performance. The advantages of such a ‘Z-type’ cavity structure are easy alignment and control of the intensity on the SESAM. The laser beam radius of 90 μm is designed inside the Yb:CALGO crystal by the *ABCD* matrix calculation. An imaging system with a magnification of two is used to couple the pump laser for optimal mode matching. The SESAM is operated with an incident mode size diameter of 340 μm to tolerate the high intracavity power.

3. Results and discussion

In preliminary experiments, a CW laser was obtained using an HR mirror as the end mirror instead of the SESAM. At the pump power of 34 W, the maximum output power in the CW regime is 15 W, corresponding to the optical-to-optical efficiency of 44.1%. As the HR mirror is replaced by the SESAM, the laser operates on *Q*-switched mode-locking condition because of the large spot size on the SESAM. In addition, this is also related to the 420 μs long fluorescence lifetime of Yb:CALGO crystals, which implies some difficulties in the mode-locking process because the laser gain medium tends to store too much energy and to favor the *Q*-switched regime instead of the mode-locked regime. Therefore, it is more difficult for Yb-doped oscillators to achieve CW mode-locking. As the distance between the M1 and SESAM is adjusted so that the mode size of SESAM becomes smaller, a stable mode-locking is obtained.

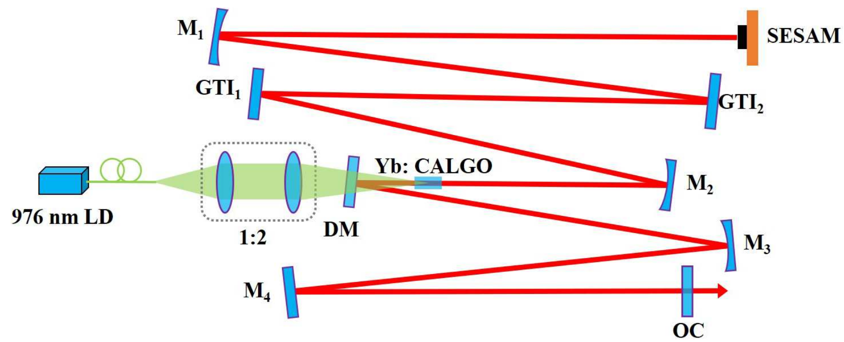

Figure 1. Schematic diagram of the experimental setup. DM, dichroic mirror; GTI1, GTI2, Gires–Tournois interferometer mirrors; LD, fiber-coupled laser diode; M1–M3, concave mirrors; M4, plane mirror; OC, output coupler; SESAM, semiconductor saturable absorber mirror.

However, Meng *et al.*[23] have reported the Yb:CALGO laser delivering 93 fs pulses with maximum average output power of 4.5 W. Then, we obtained promising results with the generation of 156 fs pulses at 7 W. To further scale the output power and shorten pulse duration, the HR mirrors with low dispersion and higher-quality SESAM were employed. The spot sizes on SESAM were increased to 340 μm to reduce its fluence by adjusting the distance between the SESAM and the M1. Furthermore, the adjustment of distance between M2 and the gain material is an indispensable alignment. Compared with the 2600 fs^2 of negative GDD in the previous experiment[23], the negative GDD in this experiment is increased to 3200 fs^2. The mode-locked laser performance of the Yb:CALGO laser is shown in Figure 2. At a pump power of 34 W, the maximum average output power in the SESAM mode-locked regime is 10 W, corresponding to the optical-to-optical efficiency of 29.4%. The mode-locking threshold is 15 W for a pump laser. Some theoretical explanations for achieving such high power are as follows. Indeed, the SESAM with appropriate parameters is a key element to achieve such high-power laser. For a SESAM mode-locked Yb-doped thin-disk oscillator, the requirements for SESAM are as follows[24]: the large saturation fluences on the SESAM are needed, and the damage threshold of SESAM is required to be as high as possible owing to large intracavity fluences. The *Q*-switching can be suppressed with lower modulation depths. In addition, two-photon absorption (TPA) is the main factor limiting the laser power scaling. Therefore, SESAM with appropriate parameters should be chosen to reduce the TPA effect. Furthermore, the high thermal conductivity of the Yb:CALGO crystal allows it to be pumped by high-power laser. Moreover, the optimized heat sink design of the crystal results in better cooling effect and reduces the thermal lens. Finally, the average output power can be scaled by increasing the transmittance of the output mirror to 10%. In addition, output power stability of the mode-locked laser is measured, as shown in Figure 3. The root-mean-square (RMS) stability of average output power over 3 h is better than 0.65%, which indicates excellent laser performance. The central wavelength and full width at half maximum (FWHM) spectral bandwidth of the mode-locked pulses are 1041 nm and 5 nm, respectively, as measured by an optical spectrum analyzer (OSA, Yokogawa AQ6370C) and shown in Figure 4. Assuming a $sech^2$-pulse shape, the 247 fs pulse from the Yb:CALGO oscillator is measured by the intensity autocorrelator (pulseCheck, APE), as shown in Figure 5. The measured pulse duration of 247 fs is close to the Fourier transform limited pulse duration of 227 fs.

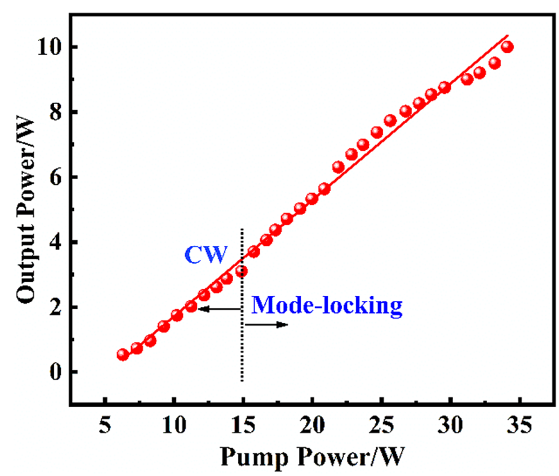

Figure 2. With a 10% transmittance of OC, average output power versus pump power for the Yb:CALGO laser at 1041 nm.

The typical pulse train of mode-locking in the time scale of 2 ns, 10 ns, and 2 μs is collected by a fast photodiode and recorded by an oscilloscope (DS4024, RIGOL), as shown in Figure 6, and no evidence of *Q*-switching is observed. The radiofrequency (RF) of the mode-locked pulses is measured by an RF spectrum analyzer (E4402B, Agilent). As shown in Figure 7, the fundamental beat note at ∼71.66 MHz with a signal-to-noise ratio above 64 dB was characterized at a resolution bandwidth (RBW) of 1 kHz. Figure 7 (inset) shows the RF scan measurement in the 1 GHz range, no additional peaks and *Q*-switched sign were observed with an RBW of

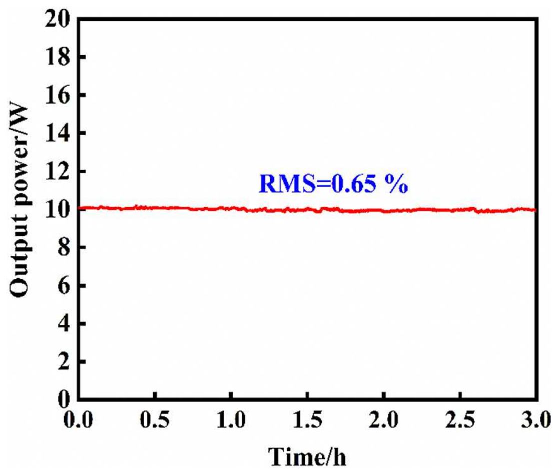

Figure 3. The output power stability of the Yb:CALGO oscillator in 3 h.

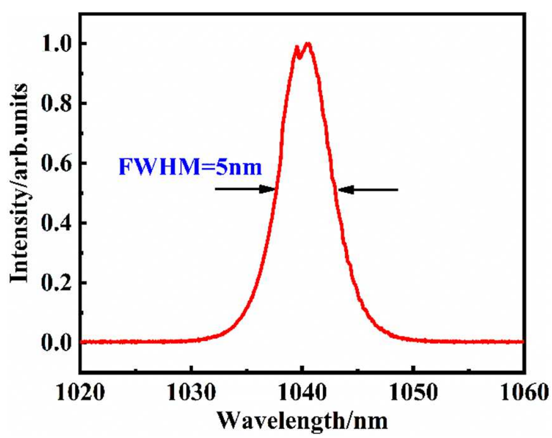

Figure 4. The output laser spectrum of Yb:CALGO femtosecond oscillator.

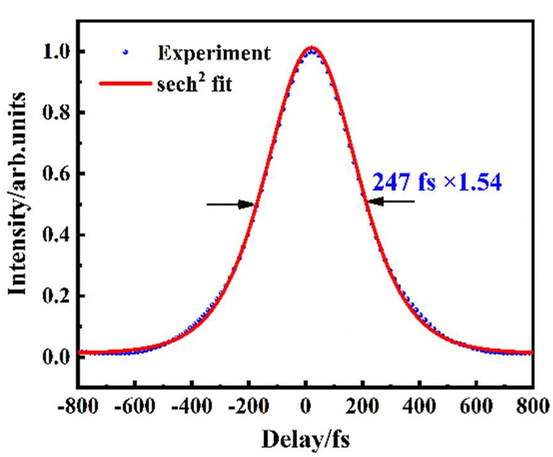

Figure 5. Autocorrelation trace of center wavelength of 1041 nm.

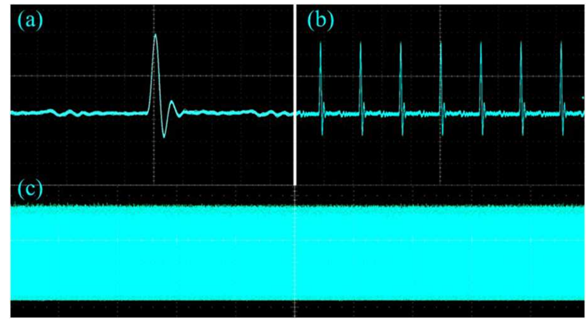

Figure 6. The typical pulse train of mode-locking in different timescales: (a) 2 ns, (b) 10 ns, and (c) 2 μs.

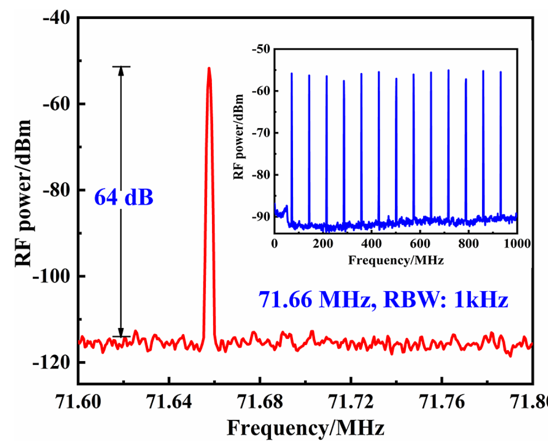

Figure 7. Typical RF spectrum of the Yb:CALGO laser with the RBW of 1 kHz. Inset: RF spectrum at 1 GHz wide-span with the RBW of 300 kHz.

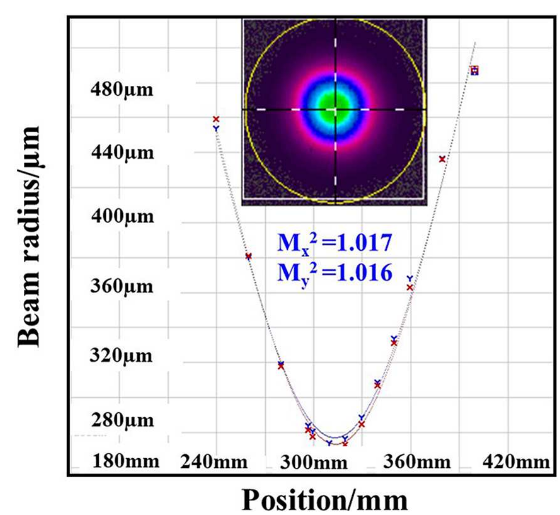

Figure 8. The beam spatial profile of the Yb:CALGO laser at the output power of 10 W.

300 kHz, which fully confirmed the good performance of the Yb:CALGO oscillator with thorough CW mode-locked pulses.

The beam quality is a crucial parameter to evaluate the laser performance. In this work, the Yb:CALGO mode-locked oscillator with output power of 10 W exhibits a high beam quality factor, and M^2 is measured to be 1.017 and 1.016 in the horizontal and vertical directions by a commercial M^2 factor meter (Spiricon M^2-200s), as shown in Figure 8.

4. Conclusions

In conclusion, we have presented a passively mode-locked Yb:CALGO oscillator that delivers 247 fs pulse duration and 140 nJ pulse energy at the repetition rate of 71.66 MHz, corresponding to an average power 10 W and a peak power 0.56 MW. Reliable and self-starting soliton mode-locking is achieved using a SESAM. The actual time-bandwidth product of 0.342 was close to the Fourier transform limitation for a $sech^2$ pulse shape (0.315). In particular, the beam quality factor M^2 is better than 1.02. Moreover, we also obtain more than 15 W of CW power with high optical-to-optical efficiency of 44.1%.

In our experiments, power scaling in the Yb:CALGO laser is limited by a range of parameters such as the damage threshold of SESAM as well as available crystal sizes and doping concentration. Higher power and shorter pulses were expected to be obtained by increasing the spot size on the SESAM, replacing the output mirror with different transmittance, and accurately compensating for the dispersion in the resonator. We foresee that the combination of the excellent optical properties of Yb:CALGO and the use of a high-power LD pumping scheme will make mode-locked Yb:CALGO lasers very attractive in various applications, such as seeding solid-state amplifiers, the pumping of optical parametric oscillators, multi-photon imaging, and terahertz applications.

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