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1.21 W passively mode-locked Tm:LuAG laser

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Abstract: A watt-level output passively mode-locked Tm:LuAG bulk laser with an InGaAs semiconductor saturable absorber mirror (SESAM) is demonstrated for the first time. A maximum average output power of 1.21 W at 2022.9 nm has been achieved with a pulse duration of 38 ps and a repetition rate of 129.2 MHz. The results indicate the potential of Tm:LuAG crystals as candidate for realizing high power ultrafast lasers at 2 μm.

OCIS codes: (140.3070) Infrared and far-infrared lasers; (140.3580) Lasers, solid-state; (140.4050) Mode-locked lasers; (320.7090) Ultrafast lasers.

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1. Introduction

Ultrafast all-solid-state lasers operating in 2 micrometer spectral regions have well-known wide applications in the fields of industry, defense, medical treatment, and scientific research [1–4]. Mode-locking Tm^{3+} doped bulk lasers provide ideal approaches to achieve such kind of lasers, especially with the aids of passive mode-locking method based on saturable absorption, which has gained its popularity in generating ultrafast 2 μm lasers due to the advantages of simplicity, compactness, reliability and the ability to generate ultrashort pulses [5]. However, most of the reported mode-locked Tm-doped bulk lasers working either in picosecond or femtosecond regime were limited to less than 1 W of average output, although a mode-locked Tm:YAP laser with PPLN nonlinear mirror yielded a maximum average output power of 1.67 W [6]. The damage threshold of saturable absorbers is considered as one of the power limiting factors. To date, various saturable absorbers have been successfully utilized in realizing passively mode-locked Tm-doped bulk lasers, such as semiconductor saturable absorber mirrors (SESAMs) [1, 7–11], single-walled carbon nanotubes (SWCNTs) [12, 13] and graphene [14–16]. Since the SWCNT and graphene could be easily damaged under high pump level [13, 14], the obtained 2 μm mode-locking laser powers by using SWCNT saturable absorbers ranged from 35 mW [12] to 240 mW [13], while the achieved output powers from graphene based mode-locked 2 μm lasers were mainly constrained around 100 mW [14–16]. SESAMs are usually employed for realizing high power ultrafast laser system in the near-infrared spectral region due to the considerable damage threshold. For the commercial SESAMs for 2 μm lasers (Batop GmbH, Germany), the damage threshold reaches about 4 mJ/cm^2, which enables SESAMs to be utilized in high power ultrafast lasers. Very recently, an output power as high as 830 mW has been successfully generated from a mode-locked Tm:CYA laser based on a commercial SESAM [17], verifying the possibility of SESAM for realizing watt-level output mode-locked Tm-doped lasers.

On the other hand, the high quantum defect in Tm-doped lasers would aggravate the thermal load inside the laser crystal and further limit the power scaling of Tm-doped bulk lasers [18]. So the Tm-doped bulk crystals with large thermal conductivity could alleviate the thermal loading in order to achieve high power mode-locked laser output. The garnet crystal YAG has been proven to be excellent laser host for Tm ions due to its stable structure, remarkable thermal conductivity, and optical properties [19, 20]. Generally, for Tm-doped crystals, a high doping concentration is required to ensure an efficient cross-relaxation process between the adjacent Tm ions, which could greatly improve the lasing efficiency. However, due to the notable mass difference between Tm and Y ions, the thermal conductivity of Tm:YAG crystal exhibits a significant degradation under a high Tm doping level [21]. Such phenomenon can be greatly alleviated in a Tm:LuAG crystal since the masses of the Tm and Lu ions differ by only 3%, which results in homogenous thermal properties [12, 21]. For example, the thermal conductivity of 4% Tm:LuAG is about the same as 4% Tm:YAG even though the pure LuAG has a thermal conductivity only 60% that of YAG [22]. In addition, LuAG is harder than YAG, which is believed to have a higher damage threshold [23]. Up to now, a maximum average output power of 4.91 W has been achieved from a continuous wave (CW) Tm:LuAG laser [24]. Very recently, we have also realized a CW Tm:LuAG laser with a comparable maximum average output power of 4.42 W, and a slope efficiency as high as 49.5% was obtained [25]. Moreover, wavelength tunable and Q-switched Tm:LuAG lasers have been realized with Watts-level output power [26, 27]. The above results also show that Tm:LuAG lasers emit long wavelengths within the spectral range ~2018-2029 nm where the atmospheric transmission window is located [25]. Therefore, stable mode-locking is expected to be easily obtained from a Tm:LuAG laser at room temperature due to the weak water vapor absorption, which makes Tm:LuAG crystal very attractive for realizing high power mode-locked lasers at 2 μm. However, to the best of our knowledge, no mode-locked Tm:LuAG laser has been reported.

Here, for the first time, we demonstrate a watt-level output passively continuous wave mode-locked (CWML) Tm:LuAG laser by using an InGaAs SESAM. A maximum average CWML output power of 1.21 W with a pulse duration of 38 ps and a repetition rate of 129.2 MHz was obtained at the wavelength of 2022.9 nm. The results strengthen that Tm:LuAG crystals are a promising gain medium suitable for realizing high power ultrafast lasers at 2 μm.

2. Experimental setup

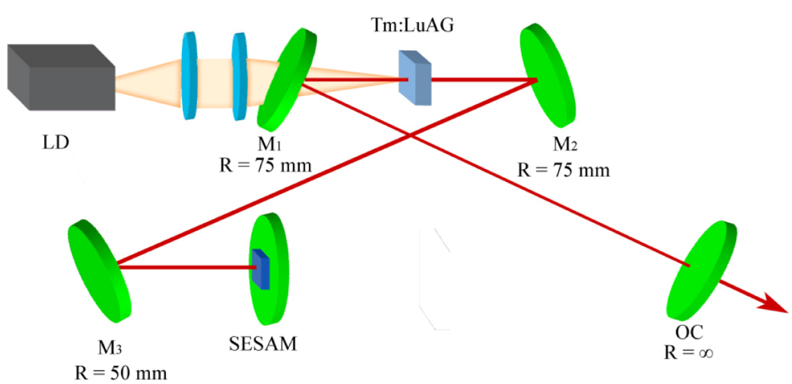

Fig. 1. Experimental setup of the passive CWML Tm:LuAG laser

The experimental configuration of the passively CWML Tm:LuAG laser is shown in Fig. 1. A fiber-coupled laser diode with a maximum output power of 30 W was used as the pump source. Its emission wavelength was 789 nm at 15 °C. The pump light was focused into a 4 × 4 × 8 mm^3, 6 at. % doped Tm:LuAG laser crystal through a 1:1 imaging module, which delivered a pump spot radii of 50 μm. The laser crystal was wrapped in indium foil and mounted in a copper block cooled to 13 °C with water. In order to suppress the etalon effect and improve the stability of the mode-locking operation, the laser crystal was tilted with a small incidence angle with respect to the cavity axis. The X-type laser cavity was constructed by five mirrors with a total physical length of 116 cm. M_1, M_2, and M_3 were concave mirrors (R = −75 mm for M_1 and M_2, R = −50 mm for M_3) with high reflectivity (HR) coated (reflectivity> 99.9%) from 1820 to 2100 nm and antireflection (AR) coated from 750 to 850 nm (reflectivity < 2%). The output couplers (OCs) employed in the experiment were flat mirrors with different transmissions of 2%, 3% and 5% at the spectral region from 1820 to 2150 nm. According to the ABCD matrix theory, the beam waist radii inside the Tm:LuAG crystal were calculated to be 50 × 52 μm in sagittal and tangential planes, respectively, which matched well with the pump light spot. An InGaAs SESAM with the following parameters provided by the commercial source (Batop GmbH, Germany): a non-saturable loss of 0.68%, a saturation fluence of 70 μJ/cm^2, a modulation depth of 1.2% and a relaxation time of 1 ps was used for starting and stabilizing the mode-locking laser. The cavity beam waist on the SESAM can be varied over a wide range (~50-90 μm in radii) by adjusting the distance between SESAM and mirror M_3.

3. Experimental results and discussions

At first, the continuous-wave (CW) operation of Tm:LuAG laser was achieved by replacing the SESAM with a plane mirror with HR coated (reflectivity> 99.9%) from 1820 to 2100 nm. A laser power meter (MAX 500AD, Coherent, USA) was employed for the power measurement. The Tm:LuAG crystal absorbed about 85% of the incident pump power under no lasing condition. The CW lasing properties were investigated by using OCs with three different transmissions. Among these cases, a maximum average output power of 3 W was obtained by using OC of T = 5%, corresponding to a slope efficiency of 31.5% [see in Fig. 2(a)]. The maximum average output powers of 2.45 W and 2.7 W were also achieved by using OC of T = 2% and T = 3%, respectively, corresponding to slope efficiencies of 24.5% and 28.2%. In each case, the emission wavelength was always located at 2022 nm at low pump levels but shifted to 2023 nm when the pump power was increased.

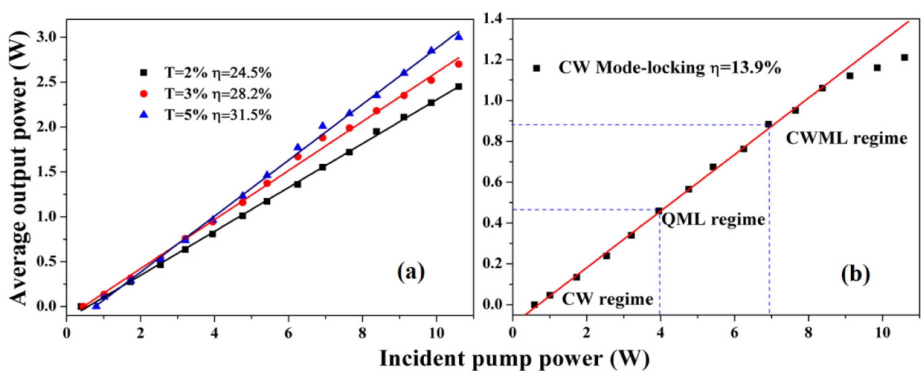

Fig. 2. The power performance of the (a) CW and (b) CWML Tm:LuAG laser

In order to achieve mode-locking, an OC of T = 2% was employed since it could give a low intracavity loss and thus lower the mode-locking laser threshold. We also tried other OCs with transmission larger than 2%, but due to the larger intracavity loss, only metastable Q-switched mode-locking (QML) was observed. With the SESAM employed in the resonator cavity and aligning the mirrors and positions of SESAM carefully, the laser began to oscillate

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when the incident pump power reached 0.59 W, which was a little higher than that of 0.39 W in CW regime due to the insertion loss of the SESAM. As the incident pump power increased to 6.92 W, the laser operation switched from metastable QML regime to stable CWML regime, and the corresponding output power was 0.88 W. The CWML could be sustained for long time while the incident pump power did not exceed 10.6 W. A maximum CWML average output power of 1.21 W was achieved at the maximum incident pump power of 10.6 W, corresponding to a slope efficiency of 13.9%. The available power scale was benefited from the thermally induced increase of beam radii on the SESAM from ~90 μm to ~120 μm with the pump power increased from lasing threshold to the maximum power of 10.6 W correspondingly. Under the maximum output power, the M^2 factor of the mode-locked laser beam was measured to be 1.15 in tangential plane and 1.11 in sagittal plane, respectively, by using a 10.0/90.0 knife-edge method, indicating a nearly diffraction limited output beam. With the pump power further increased, the CWML operation became unstable since the strong thermal load inside the laser crystal introduced by the high intensity power pumping.

The CWML operation was self-starting and was maintained stable over hours without external disturbance. Besides, in the case of external interruption, it could be restarted easily without realigning the laser cavity. To evaluate the stability of the mode-locked operation, a fast InGaAs photo-detector (EOT, ET-5000, USA) was used for detecting the signal and a spectrum analyzer with a bandwidth of 4 GHz and a resolution bandwidth (RBW) of 100 Hz (N9913A, Agilent Inc.) was employed for measuring the radio frequency (RF) spectrum. Figure 3 shows the first beat note of the RF spectrum of the stable continuous wave mode-locking with a repetition rate of 129.2 MHz under an incident pump power of 10.6 W. As shown in Fig. 3, the clean peak at the repetition rate of 129.2 MHz without side peaks, which exactly agrees with the roundtrip time of the cavity, reveals stable continuous wave mode-locked operation of the laser as well as the absence of the Q-switching instabilities. Besides, the high signal-to-noise ratio up to 60 dB indicates a pure mode locking with very few continuous wave components. Moreover, the RF spectrum in a wide span of 1.4 GHz as shown in the inset of the Fig. 3 indicates single pulse operation of the CWML Tm:LuAG laser. However, an obvious decrease of harmonic intensity around 500 MHz was already observed, which was attributed to two aspects. One is possibly from the input power induced saturation effect in the photodetector, which would cause the bandwidth reduction of the photodetector. The other one may come from the loss of the employed RG-58 type coaxial cable for connecting the photodetector and RF analyzer, because the larger loss for higher frequencies in such type cables would reduce the bandwidth considerably.

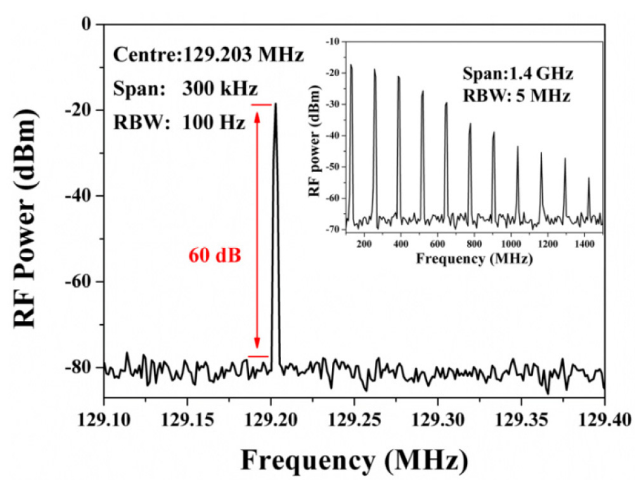

Fig. 3. RF spectrum of CWML Tm:LuAG laser.

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The autocorrelation trace and spectrum of the mode-locked pulses are shown in Fig. 4. The pulse duration was measured by a commercial autocorrelator (APE GmbH, Pulse Check 150). By assuming a $sech^2$ shaped pulse, the mode-locking pulse duration of 38 ps was achieved, corresponding to an intensity FWHM of 59 ps. Limited to the time window of the employed autocorrelator which could give a maximum pulse duration of 35 ps, the full autocorrelation trace could not be recorded. Obviously, the pulse duration obtained here was larger than those of other mode-locked solid-state 2 μm lasers with comparable watt-level output power, such as 4.7 ps from the 1.67 W output PPLN nonlinear mirror mode-locked Tm:YAP laser with pulses [6] and 1.89 ps from the 0.71 W output SESAM mode-locked Tm:YAP laser [28]. However, the slope efficiency of 13.9% achieved here was superior to that of 8.2% as shown in Ref [6], and also comparable with that of 14.6% obtained in Ref [28], where the output power of 0.71 W was much lower than that in this work.

The output laser spectrum was also recorded with an optical spectrum analyzer (APE GmbH, APE WaveScan) with a resolution of 0.4 nm. The emission wavelength of the mode-locking laser was located at 2022.9 nm with a spectral FWHM of 0.42 nm, as shown inset of Fig. 4. Due to the low resolution of the employed spectrometers, we omit to give a time bandwidth product here. Considering the spectrum FWHM of 0.42 nm, the minimum pulse duration even with proper dispersion compensation would be more than 10 ps by assuming a $sech^2$ pulse shape. However, according to our previous results with the same SESAM [7], the relatively long pulses could be hardly shortened by intracavity dispersion compensation, limited by the narrow gain spectrum [29].

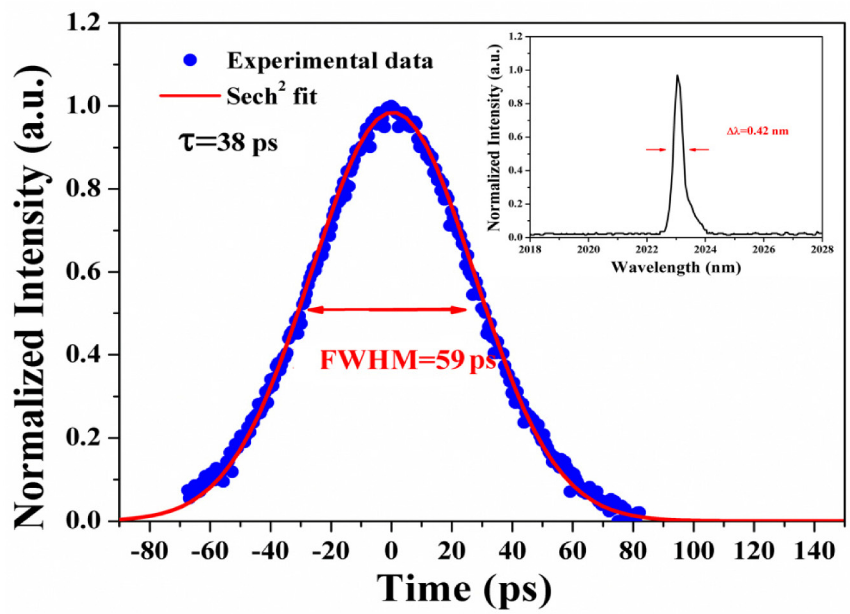

Fig. 4. Autocorrelation trace of the mode-locked Tm:LuAG laser. Inset: the corresponding spectrum centered at 2022.9 nm.

4. Conclusion

In conclusion, a passively CWML Tm:LuAG bulk laser with watt-level output power was presented for the first time. Stable passive mode-locking operation with a maximum average output power of 1.21 W was achieved, and 38 ps pulses with high signal-to-noise ratio up to 60 dB were generated. To the best of our knowledge, this is the highest average output power ever achieved from SESAM mode-locked Tm doped bulk lasers. The results verify the potential of Tm:LuAG crystals for realizing high power ultrafast rod and thin disk lasers at 2 μm.

Acknowledgments

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