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High efficient mode-locked Tm:YAP laser emitting at 1938 nm by SESAM

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ABSTRACT

We report a passively mode-locked (ML) Tm:YAP laser pumped by an 790 nm AlGaAs diode. With a semiconductor saturable absorber mirror (SESAM) as mode-locker, stable ML pulses is generated with pulse width of 1.89 ps, repetition rate of 97 MHz, and central wavelength of 1938 nm. The highest ML output power of 710 mW was obtained, to the best of our knowledge, this is the highest output power of SESAM based, Tm ion doped crystalline ML lasers.

1. Introduction

Thulium doped solid state lasers have outputs in the 2 μm region, a wavelength of interest for optical communication, radar systems, remote sensing and medical applications [1–3]. An ultrafast 2 μm laser source is of particular interest in the mid-IR spectral range frequency conversion [4]. Mode-locking is an important technology to generate pulses with pulse duration down to pico- to femtosecond. Up to now, many efforts have been made to realize ultrafast laser sources in fiber and crystalline lasers. Nelson et al. first obtained 500 fs fiber laser pulse by using a spectral filter and the nonlinear polarization rotation approach [5]. Afterwards, higher pulse energy was reported using a Tm-fiber laser with stretched-pulse operation [6]. However, fiber lasers usually have limited output powers, which is typically below 100 mW. For sake of material processing and laser surgery, where high power pulse is needed, it is necessary to take the advantage of crystalline lasers. For Tm and Tm-Ho co-doped crystals, passively ML lasers have been demonstrated by using different saturable absorbers (SAs). As new type of SAs, single walled carbon nanotube (SWCNT) and graphene based SAs were successfully applied in tungstate [7,8], sesquioxide [9], fluoride [10], and disordered garnet single crystals [11]. They are indeed great SA materials with excellent properties, but the low saturation fluence makes them easy to be oversaturated, consequently limits their application in high power laser. Quite recently, topological insulator (TI) has gained significant scientific and technical attention in the field of condensed matters because of the extraordinary charge and spin properties on the edge or surface modes TIs [12]. The combination of the small bandgap bulk (0.2∼0.3 eV) and the gapless surface enables TIs as broad band saturable absorbers [13]. Experimental demonstration of 2 μm pulsed laser have been reported [14,15]. As a kind of developed SA, SESAM has made great contribution to solid-state ML lasers. A lot of industrial high power grade ML lasers are based on SESAMs due to the mature and controllable fabrication. In 2 μm region, it is also the most common type of SAs in passively mode- locked crystalline lasers [16–25]. But we found that no laser mentioned above could deliver an output power exceeding 500 mW. Other than SA methods, quasi-phase-matching is also a promising technique to realize high power passively mode-locking due to its high damage threshold and low residual absorption [26,27]. It should be mentioned that Cheng et al. obtained 1.46 W output power with 4 ps pulse width from a ML Tm:YAP laser [28]. The method they used was intracavity frequency doubling where a periodically poled $LiNbO_3$ (PPLN) was applied. Though outstanding results, it has disadvantages of higher costs and more complex structure. Thus, we dedicated to directly generation of high power ML laser employing SESAMs.

In this letter, a continuous wave mode-locked (CWML) Tm:YAP laser was demonstrated. By selecting a proper output coupler and designing appropriate laser beam radius in the cavity, the maximum output power of 710 mW was obtained, which is, to our best

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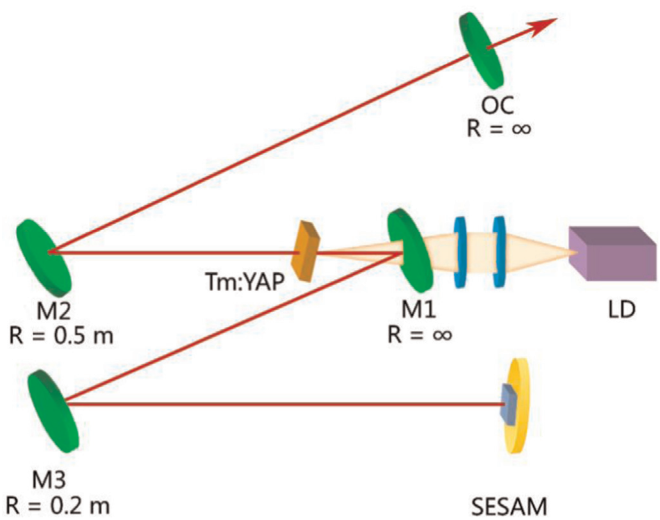

Fig. 1. Schematic of the ML Tm:YAP laser.

Table 1
Parameters of ML lasers.

Experiment	OC [%]	Mode size on SESAM [μm]	Maximum ML power [mW]
I	2	50	173
II	2	80	285
III	5	80	522

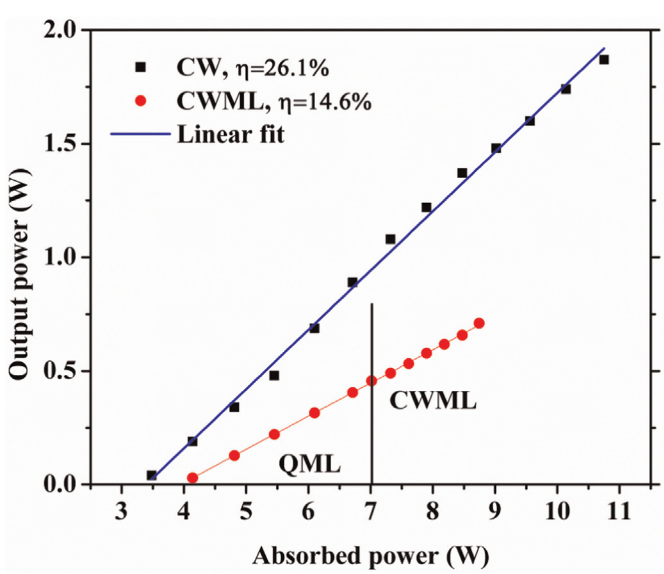

Fig. 2. CW and CWML output power versus absorbed pump power.

knowledge, the highest value in SESAM based, Tm ion doped crystalline ML lasers. Stable ML pulses with pulse width of 1.89 ps were obtained at the repetition rate of 97 MHz.

2. Experiment setup

Fig. 1 shows the schematic of the laser experiment. A 7 mm long a-cut Tm:YAP crystal with Tm^{3+} concentration of 3 at% was used as the gain medium, with dimensions of 3×3 mm^2. To ensure excellent heat dissipation, the crystal was wrapped with indium foil and held in a copper block which was cooled at 18 °C. The pump source was a fiber-coupled AlGaAs laser diode emitting at 790 nm, and the coupling fiber has a core diameter of 400 μm and an NA of 0.22. The pump beam was focused into the crystal by a 1:1 coupling lens system so that we could get enough mode volume to realize high power laser operation. A five-mirror W-shape resonator was adopted for ML operation. M1 was a flat mirror and it was antireflection (AR) coated at 790 nm and high reflection (HR) coated in a broad band around 2.0 μm. M2 and M3 were folded mirror whose radii were 500 mm and 200 mm, and they had the coating system with M1. A flat output coupler (OC) was chosen as the end mirror, and two different optical transmittances (T=2%, 5%) were used in the experiment research. A commercial SESAM from BATOP Gmbh was selected as the mode-locking element. Its saturation fluence and modulation depth were 70 μJ/cm^2 and 1%, and it was placed to an adjustable stage which enabled us to control its position and angle precisely.

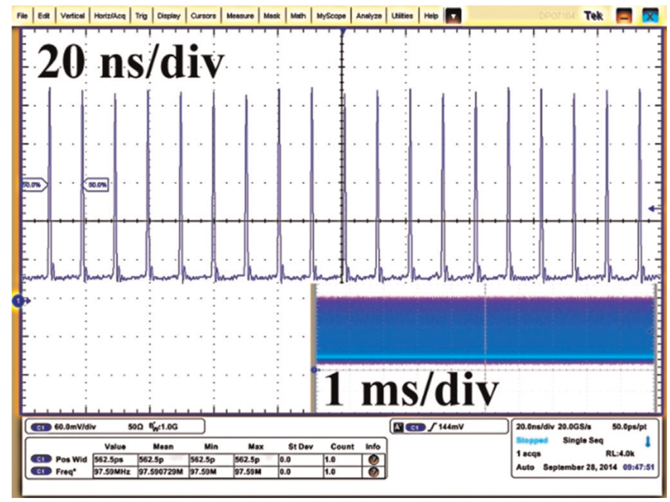

Fig. 3. Oscilloscope traces of pulse train in different time scale: 20 ns/div, inset 1 ms/div.

3. Results and discussion

Before the maximum CWML output power was obtained, several laser cavities were tried to search the proper laser beam radius on the SESAM and proper transmittance of the OC. The laser beam radii in the crystal and on the SESAM can be adjusted by altering the distances between M1-M2 and M1-M3. CWML pulse could be successfully acquired by carefully tuning the pump power and cavity mirrors (including the SESAM), and the main parameters of the laser cavities and laser results are listed in Table 1. The OC T=5% is preferred because it can couple more energy and limit the intracavity power. Increasing the beam radius on SESAM properly also helps it from suffering overmuch fluence.

At last, the laser beam radii in the crystal and on the SESAM were designed to be 210 μm and 105 μm, respectively. This alignment can ensure an optimum mode-to-pump ratio for fiber-coupled diode end-pumped lasers including the thermal effect into the analysis.

The laser output power in continuous wave (CW) and CWML regime versus the absorbed pump power is shown in Fig. 2.

The CW operation of Tm:YAP laser in the well-designed W-type cavity was first investigated by using a HR flat mirror replacing the SESAM. The maximum output power of 1.87 W was obtained under the absorbed power of 10.75 W, giving a slope efficiency of 26.1%. Then ML operation was carefully studied utilizing the SESAM. Stable CWML pulse could be realized in the absorbed power range from 7.0 W to 8.7 W, and the maximum output power of CWML laser was 710 mW, corresponding to the slope efficiency of