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Compact passive Q-switching of a diode-pumped Tm,Y:CaF_2 laser near 2 μm

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ABSTRACT

Lasing was realized near a wavelength of 2 μm with a compact linear cavity by using a fiber-coupled 792-nm laser diode as the pump source and a Tm^{3+},Y^{3+} co-doped CaF_2 crystal. By employing broadband graphene oxide (GO) as the saturable absorber (SA), a passive Q-switching Tm,Y:CaF_2 laser was implemented for the first time. When the transmission of the output couple (OC) was 2%, the maximum average output power was measured to be 400 mW with a corresponding repetition rate of 20.22 kHz and a pulse width of 1.316 μs. A maximum continuous-wave (CW) output power of more than one watt was obtained with slope efficiency of 51.5%.

1. Introduction

The popularity of laser diode (LD)-pumped, solid-state-pulsed, 2-μm waveband lasers is increasing, owing to their various applications in the fields of medicine, material processing, academic research, and military purposes, and in their role as pumping sources for other mid-infrared lasers [1–4]. A significant component of any laser system is the lasing material. Rare-earth-ion Tm^{3+}-doped materials have become popular options in implementing 2-μm waveband lasers efficiently in various configurations, such as Tm:KYW, Tm:YAP, Tm:LuAG, and Tm:SSO [5–10]. Tm^{3+}-doped LD-pumped solid-state lasers are one of the most efficient ways to achieve high-frequency, passive Q-switching lasers in the 2 μm band.

In addition, CaF_2 crystals have proven to be a promising host material because of their excellent properties, including ease of growth and transmittance ranges from the far ultraviolet to the mid-infrared [11–13]. In recent years, many studies have been conducted using rare-earth-doped CaF_2 as a lasing material, including Tm:CaF_2 [14], Yb,Na:CaF_2 [15], Nd,Y:CaF_2 [16–18], and Er,Pr:CaF_2 [19]. However, fewer studies have been performed using CaF_2 crystals in the 2-μm band of a pulsed laser. Recently, the spectroscopic characteristics, wavelength-tunable operation, continuous-wave and mode-locking laser performances of Tm,Y:CaF_2 disordered crystal were studied [20,21], indicating that Tm,Y:CaF_2 crystal has significant potential as a lasing material in the 2-μm spectral region. However, at present, no passive Q-switching lasers using a Tm,Y:CaF_2 crystal have been reported in the literature. This is complicated by the need to improve the output power of a continuous-wave Tm,Y:CaF_2 crystal laser to the level of a watt in order to support various applications.

This study utilizes crystalline CaF_2 co-doped with 4 at.% Tm^{3+} and 4 at.% Y^{3+} that was grown by a temperature gradient technique. The absorption and luminescence spectra of the Tm,Y:CaF_2 crystal are shown in Fig. 1(a) and (b), respectively. In Fig. 1(a), the two absorption bands shown, with peaks at 675 nm and 766 nm, correspond respectively to the $^3H_6 \rightarrow {}^3F_3$, $^3F_2$ and $^3H_6 \rightarrow {}^3H_4$ energy transitions of the Tm ions. The absorption efficiency drops significantly away from the absorption peak and the pump wavelength. Fig. 1(b) shows a broad continuous emission spectrum in the range of 1550–2100 nm with a peak at 1846 nm, corresponding to the $^3F_4 \rightarrow {}^3H_6$ energy transition. The fluorescence ceased at 1550 nm due to Tm^{3+} clusters. Thus, this crystal demonstrates appropriate optical properties in its spectral characteristics.

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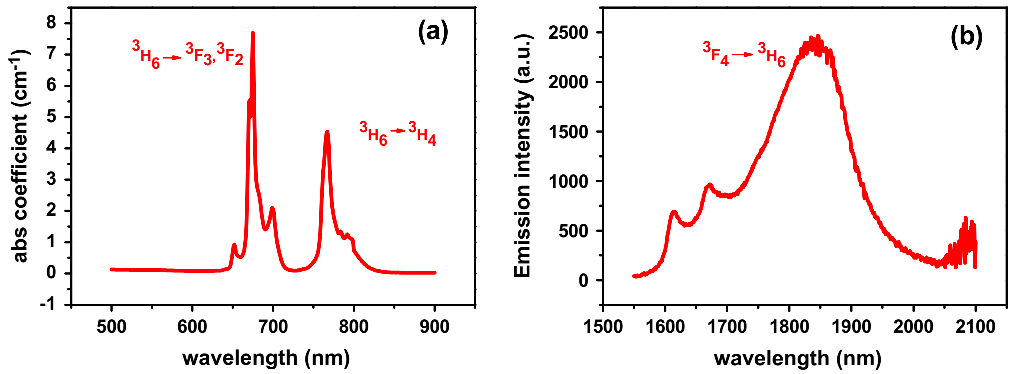

Fig. 1. (a) Absorption spectrum ofTm,Y:CaF_2; (b) Emission spectrum of Tm,Y:CaF_2.

This paper reports the first implementation of a diode-pumped, passive Q-switching Tm,Y:CaF_2 laser with a graphene oxide saturable absorber (GOSA). Several aspects of passive Q-switching lasers are discussed in detail, including output characteristics such as the variation of laser pulse width and the variation of the repetition rate with the absorbed pump power. In addition, using a simple flat-concave cavity, output power of over 1 watt continuous-wave was achieved.

2. Experimental setup

Graphene [22,23] is a new class of 2-D single atom thick materials which possess a unique smooth-sided conical band structure and has zero band gap. Relatively graphene oxide (GO) is a much more attractive material to be used for commercial photonic product as it could be mass producing by using chemical methods, which has been widely applied in pulse lasers in the 1–2 μm band in recent years [24–27]. The GO sheet used in this experiment was fabricated using ultrasonic agitation following a chemical oxidation of the graphite. The nonlinear optical absorption of the GO is shown in Fig. 2, and was obtained using a picosecond pulse fiber laser at ~2000 nm as a source. The resulting GOSA had a modulation depth (ΔT) of 23.1% and unsaturable loss of 12.4%. Both values were large, which was attributed to the fact that the thickness and concentration of our SA can be chosen flexibly.

The schematic of the Tm,Y:CaF_2 CW laser is shown in Fig. 3. In our experiment, a commercial 792-nm fiber-coupled CW laser diode was used as the pumping source, delivering a maximum power of 30 W with a fiber core diameter of 105 μm and a numerical aperture (NA) of 0.22. The pump beam was expanded into the gain medium by a coupling system of 1:2. The Tm,Y:CaF_2 crystal with 4 at.% Tm^{3+} and 4 at.% Y^{3+} was used as the laser gain medium, and had dimensions 3 mm × 3 mm × 7 mm. The crystal was wrapped in a piece of indium foil and mounted in a copper block cooled by water at a temperature of 13 °C. A compact cavity, consisting of a plane mirror and a group of output couplers (OCs) of radius 100 mm, provided transmission of 2% and 5% between 1900 and 2000 nm. The laser pulse trains were recorded by a 1-GHz digital oscilloscope (model MDO4104C made by Tektronix in the USA) and a fast photodiode detector (model ET-5000 made by Electro-Optics Technology in the USA) with a rising time of 250 ps. A laser power meter (model 30A-SH-V1 made by OPHIR in Israel) was used to measure the output power.

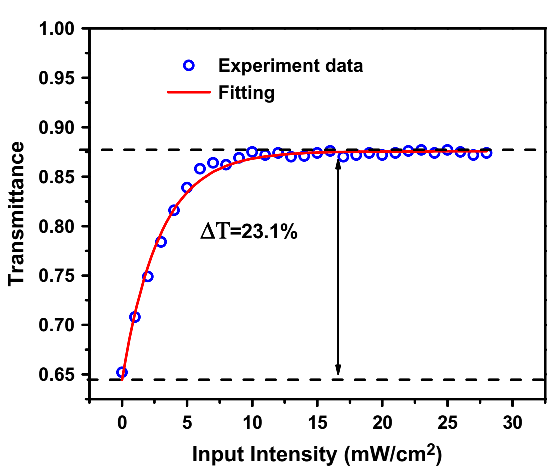

Fig. 2. Nonlinear transmittance of the graphene oxide saturable absorber.

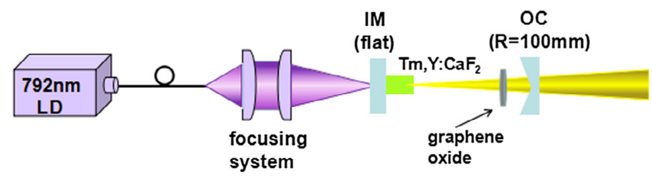

Fig. 3. Schematic of the Tm,Y:CaF_2 laser setup.

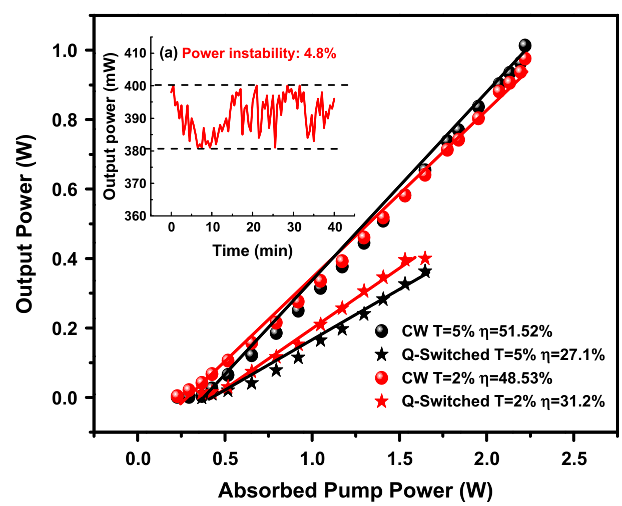

Fig. 4. Output power versus the absorbed pump powers for CW and Q-switching operation. The inset (a) describes the output fluctuation versus time.

3. Results and discussion

Initially, operation of the diode-pumped Tm,Y:CaF_2 CW laser was performed. As shown in Fig. 4, when the absorbed pump