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Bistable performances of diode-end-pumped quasi-three-level Tm,Ho:YLF lasers

Xinlu Zhang [a,*], Liang Yang [a], Li Li [a], Jinhui Cui [a], Youlun Ju [b], Yuezhu Wang [b]

[a] College of Science, Harbin Engineering University, 145 Nan Tong Da Jie, Harbin 150001, China
[b] State Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin 150001, China

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ABSTRACT

The performances of continuous wave, quasi-three-level Tm,Ho:YLF lasers emitting near 2.06 μm with single- and dual-end-pumped configurations are reported. Bistability is observed for single-end pumping but is absent for dual-end pumping. The width of the bistability region and the jump power at the turning point are shown to be functions of both the cavity length and output coupler transmission.

1. Introduction

The development of solid state lasers emitting near 2 μm has remained a topic of particular interest for many years, due to a number of possible applications such as coherent Doppler lidar [1], differential absorption lidar [2], and a possible pump source for an optical parametric oscillator operating in the mid-infrared region [3]. Laser-diode-pumped thulium (Tm) and holmium (Ho) co-doped yttrium–lithium–fluoride (YLF) lasers are the promising candidates to provide coherent radiation around 2 μm for the above-mentioned applications. Tm,Ho:YLF crystals have notable advantages, such as excellent optical damage resistance, low thermal lens effect and a lack of thermal induced birefringence. While many groups have studied the continuous wave and Q-switched end-pumped Tm,Ho:YLF lasers [4–9], little research has focused on the optical bistability (OB) occurring in such sources and how it arises. OB is a phenomenon whereby the system exhibits two different output powers for a given input power [10]. The phenomenon of OB was first reported by Gibbs et al. [11]. Since then it has been extensively investigated because of such potential applications as optical logic, switches, and memory. In addition, OB can be used for non-resonant laser cooling of atoms and molecules in a bistable optical cavity [12]. OB has been observed in many types of lasers such as erbium- or ytterbium-doped fiber laser [13], CO_2 laser [14], semiconductor laser [15], and quantum dot laser etc. [16]. Near room temperature, Tm,Ho:YLF laser is a quasi-three-level system, and reabsorption losses of ground state reabsorption (GSR) can significantly affect the laser threshold and the output characteristics, however, not all (quasi-) three-level lasers exhibit bistability [17].

In this paper we report on the output characteristics of both single-end- and dual-end-pumped Tm,Ho:YLF lasers. In particular, we investigate the influences of cavity length and output coupler transmission on the OB of the single-end-pumped Tm,Ho:YLF laser.

2. Experimental set-ups

Fig. 1 illustrates the experiment set-ups that are used in our experiments. Fig. 1a is a single-end-pumped linear cavity configuration and Fig. 1b is a dual-end-pumped *L* shape cavity configuration. The plano-concave resonators were built. The laser crystal was located inside the laser cavity, very close to the flat rear mirror M_1. The a-cut Tm,Ho:YLF laser crystal has dopant concentrations of 6 at.% Tm^{3+} and 0.4 at.% Ho^{3+} with dimension of 4 mm × 4 mm × 10 mm for the two cavity configurations. The two faces of the crystal were antireflection coated near 2060 and 792 nm. To efficiently remove the generated heat during the experiment, the Tm,Ho:YLF crystal was wrapped with indium and mounted in a copper heat sink. The temperature of the copper heat sink was maintained at 253 K with a thermoelectric cooler. The rear mirror M_1 was a plane dichroic mirror, with high reflection (HR) ($R > 99.8\%$) at 2060 nm and high transmission (HT) ($T > 95\%$) at 792 nm pumping wavelength. M_2 was a 45° dichroic mirror, high reflection at 2060 nm was coated on one side, and high transmissions at 792 nm were coated on both sides. The concave output coupler M_3 had a radius of curvature of 20 cm. The crystal was end-pumped by fiber-coupled laser diodes with the emission wavelength at

* Corresponding author. Tel.: +86 13045122215.
E-mail address: zhangxinlu1@yahoo.com.cn (X. Zhang).

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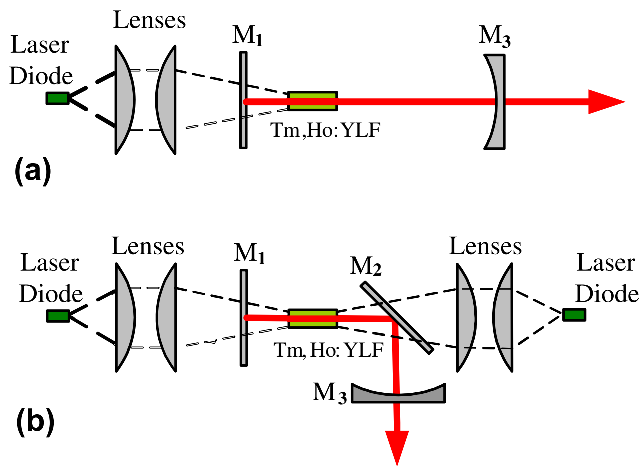

Fig. 1. Experimental set-ups for the diode-pumped Tm,Ho:YLF lasers, (a) the single-end-pumped configuration, and (b) the dual-end-pumped configuration. The plane mirror M_1 and M_2 have $T > 95\%$ at 792 nm and $R > 99.8\%$ at 2.06 μm, the output coupler M_3 is partially transmitting at 2.06 μm.

792 nm. The diameter and numerical aperture of the fiber core were 400 and 0.22 μm, respectively. Two lenses of 50 mm focal length focused the pump beam to a spot radius of about 250 μm at the position of the crystal.

3. Results and discussion

We consider first the single-end-pumped configuration. Fig. 2 shows the output power as a function of the incident pump power with the 3% output coupler. When the pump power is increased from zero, no laser oscillation at 2.06 μm laser is observed until a critical point of pump power, referred to as on-threshold, is reached at $P_{in} = P_{on} = 4.3$ W, at which the output power jumps from zero to a level of 82.5 mW. Above this point the output power increases nearly linearly with pump power. When the pump power is decreased starting from a level in excess of P_{on}, the output power decreases with nearly the same slope, with the laser still oscillating for pump powers below P_{on}. Further reduction of the pump power eventually leads to cessation of the 2 μm laser oscillation at the off-threshold $P_{off} = 2.7$ W, somewhat lower than the on-threshold. In

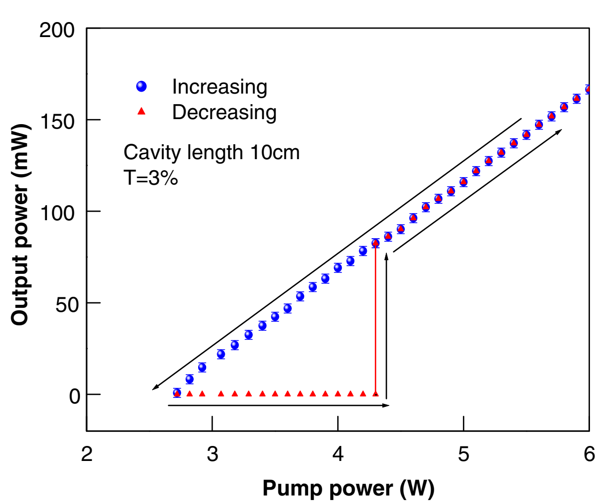

Fig. 2. The output power as a function of the pump power for the single-end-pumped configuration with the output coupler transmission $T = 3\%$ (showing a hysteresis loop).

other words, the power output curve as a function of pump power follows a hysteresis loop. In the pump power range defined by $P_{off} < P_{in} < P_{on}$, the operation of the Tm,Ho:YLF laser is bistable, and the output power at a given pump level depends on the way that this pump level is reached. At the same time, it is noted that when the pump power is below on-threshold, the green fluorescence of 540 nm ($^5F_4 + {^5S_2} \rightarrow {^5I_8}$) becomes stronger as pump power is increased. Once laser oscillation begins, however, the green fluorescence becomes very weak [18].

Fig. 3 shows the graphic illustrations of population inversion region at on-threshold pump power for the single- and dual-end-pumped configurations. For the single-end-pumped configuration as shown in Fig. 3a, when the pump power is increased from zero to the on-threshold pump power, the fore part of Tm,Ho:YLF crystal has a population inversion in the region (gain region) near to the pump beam entrance facet due to relatively high pump power. The rear part of Tm,Ho:YLF crystal, however, does not reach population inversion in the region (absorption region) furthest from the pump beam entrance facet due to the relatively low pump power. When the pump power is increased from zero, and there is no laser action, the number of photons in laser cavity is near zero, and the GSR of ground state $^5I_8$ in the absorption region to 2 μm photon is very strong due to the quasi-three-level characteristic of the Tm,Ho:YLF crystal. So the cavity has a relative high loss δ_1 and the laser has a relative high threshold pump power. In addition, in the absence of lasing (below the on-threshold), as the pump power is increased, excited state absorption (ESA) and energy transfer upconversion (ETU) processes play an important role [9]. Because the ESA and ETU processes decrease the population of the upper level $^5I_7$, the threshold pump power increases still further. When the pump power P_{in} is increased to the on-threshold pump power P_{on}, the gain of the laser is slightly more than the loss δ_1, and the laser begins to oscillate. Because the upper energy lifetime in gain region is reduced greatly due to the ETU and ESA effects [19], the saturation intensity of the absorbing region is lower than that of the gain region, and the GSR in the absorption region is easer to be saturated than the gain in gain region. Therefore with the increase of intracavity laser signal, the loss of the laser abruptly decreases from a relatively high value δ_1 to a relative low value δ_2. Furthermore, once the laser begins to oscillate, the ESA and ETU processes will be reduced by the 2 μm stimulated emission due to the sudden drop of inversion population density in the upper level caused by the drop of intracavity loss. So we can note that there is a big jump in output power when the pump power is equal to P_{on}. Above on-threshold, gain saturation increases with increasing output power causing the gain to fall to δ_2, at which moment the output power becomes stable. As long as the system is undergoing laser oscillation, GSR is reduced due to saturation in absorption region, and the laser keeps a low loss δ_2. At the same time the 2 μm stimulated emission reduces the ESA and ETU processes. So when the pump power is decreased from a relative high value (more than P_{on}), the output power decreases linearly with the same slope and the laser still keeps oscillating until the pump power is decreased to a smaller threshold pump power P_{off}.

To investigate the influence of the cavity length on the optical bistability, we changed the cavity length of the Tm,Ho:YLF laser

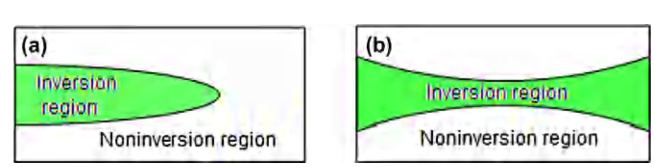

Fig. 3. Population inversion region at on-threshold pump power, (a) the single-end-pumped configuration, and (b) the dual-end-pumped configuration.

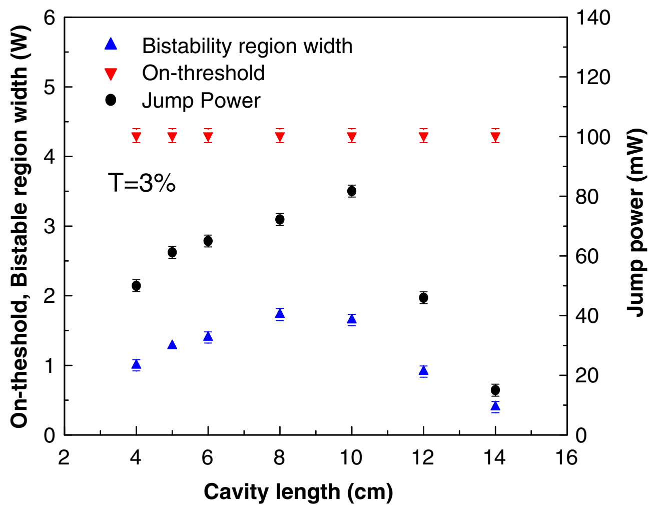

Fig. 4. Width of bistable region and jump power as a function of cavity length with the output coupler transmission $T = 3\%$.

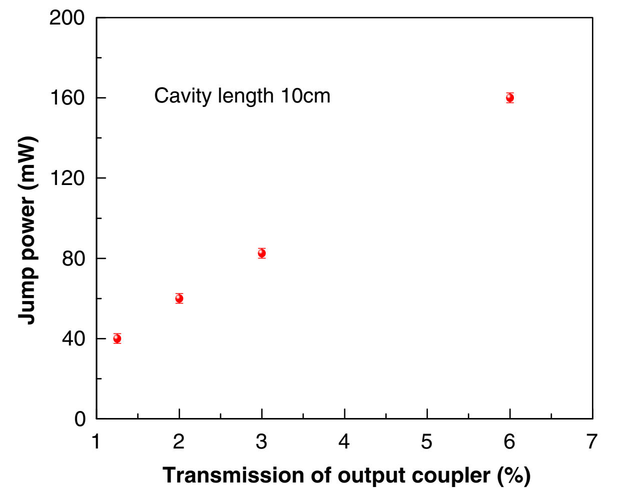

Fig. 6. Jump power as a function of the output coupler transmission for the cavity length of 10 cm.

when the other parameters of the laser were fixed. The on-threshold pump power, width of bistability region, and jump value of the output power (jump power) at the on-threshold pump power of the Tm,Ho:YLF laser as a function of cavity length are shown in Fig. 4. We can note from Fig. 4 that the width of bistability region and the jump value of the output power increase with the cavity length from 4 cm, and respectively arrive at maximum values 1.75 W and 82 mW when the cavity length is increased to 8 and 10 cm, respectively, which are followed by a decrease with a further increase of the cavity length. But the on-threshold does not change with the cavity length.

We also tested the influence of the transmittance of the output coupler on the optical bistability. The threshold pump power and the width of bistability region as a function of the output coupler transmittance at 2 μm are shown in Fig. 5. Here one sees that the on-threshold pump power and the off-threshold pump power increase almost linearly with the transmittance of the output coupler, and the width of bistability region almost remains constant independent of the output coupler transmittance.

The jump power at the on-threshold as a function of the output coupler transmittance was also measured as shown in Fig. 6, and is seen to be a linear function of it.

To analyze further the reason of bistability output, the dual-end-pumped configuration was adopted. The powers of both pump laser diodes were changed synchronously, the output power as a function of total pump power (sum of that from both pump diodes) for a transmittance $T = 3\%$ was obtained as shown in Fig. 7. Here, it can be noted that the output power changes linearly with the pump power, and the phenomenon of optical bistability is absent for the dual-end-pumped configuration. Furthermore, it can also be noted that the dual-end-pumped Tm,Ho:YLF laser has a lower threshold pump power (2 W) compared to that of the single-end-pumped laser (2.7 W for the P_{off} and 4.3 W for the P_{on}) due to the reduction of GSR.

For the dual-end-pumped Tm,Ho:YLF laser crystal, population inversion region at on-threshold pump power is shown in Fig. 3b. When the pump power is increased to the threshold, the crystal is pumped along the whole of its length, all of which has a population inversion. In other words, there is no longer any region of the crystal that purely absorbs the 2 μm laser when the pump power is increased to threshold pump power. Thus, for the dual-end-pumped configuration the nonlinear saturation phenomenon of GSR no longer exists. Above threshold, the gain remains constant, and output power grows linearly with increasing pump power and there is no bistability. We concluded from this that

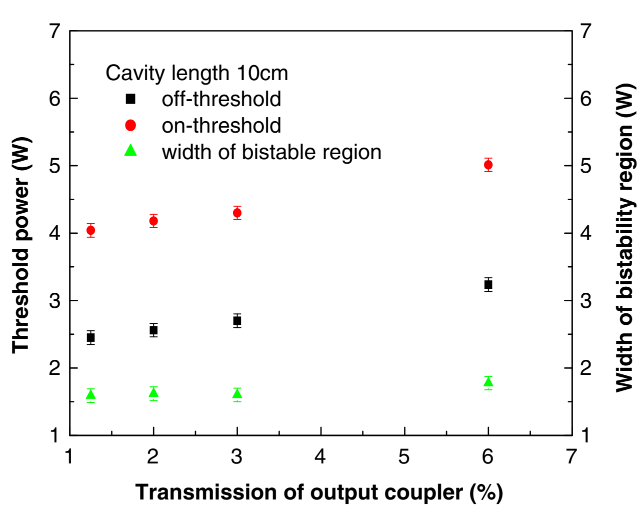

Fig. 5. Threshold pump power and width of bistable region as a function of the output coupler transmission for the cavity length of 10 cm.

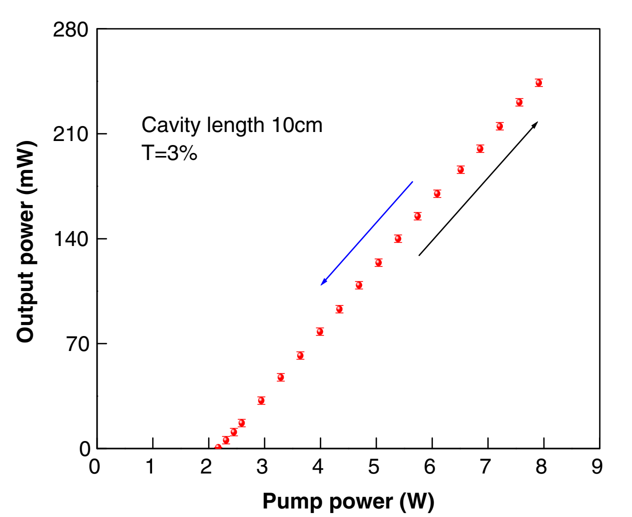

Fig. 7. Output power as a function of pump power for the dual-end-pumped configuration (no showing a hysteresis loop).

the occurrence of OB in single-end-pumped Tm,Ho:YLF lasers is mainly due to the nonlinear saturation of Ho^{3+} $^5I_8$ GSR to 2 μm photons and the ETU and ESA effects play an important role.

4. Conclusion

The bistable output of a 792 nm laser diode single-end-pumped continuous wave Tm,Ho:YLF laser at 2.06 μm has been reported. When the temperature of the Tm,Ho:YLF crystal is 253 K, the width of the bistable region is 1.6 W, and the jump power at the turning point is 82.5 mW for the transmission of 3%. The influences of the output coupler transmittance and the cavity length on the optical bistability are obtained experimentally. With the dual-end-pumped configuration, the optical bistability phenomenon is absent. We conclude that the optical bistability of Tm,Ho:YLF laser mainly results from the cooperation of the nonlinear saturation of GSR to 2 μm laser in the non-inversion region, ETU and ESA effects. The bistable Tm,Ho:YLF laser may be used in all-optical switching and modulation at a wavelength of 2 μm.

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