Optical bistability in the operation of a continuous-wave diode-pumped Yb:$LuVO_4$ laser

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Abstract: We report on sizable optical bistability in the operation of a continuous-wave diode-pumped Yb:$LuVO_4$ laser, as a result of the resonant reabsorption losses in the laser crystal which increase with the temperature. Significant intensity fluctuations have been observed in a small operational region near the critical point.

OCIS codes: (140.5680) Rare earth and transition metal solid-state lasers; (140.3580) Lasers, solid-state; (140.3480) Lasers, diode-pumped.

References and links

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1. Introduction

Since its first discovery in late 1970's, optical bistability has been found existing in many different optical systems. Generally, these optical systems fall into two categories: passive cavities containing either a saturable absorbing or a nonlinear dispersive medium, and laser systems with intracavity saturable absorbers [1, 2]. Recently, a different kind of so-called intrinsic optical bistability was discovered in some active optical materials such as Yb:$Cs_3Lu_2Br_9$ and Yb:$YCa_4O(BO_3)_3$, in which the intensity of cooperative luminescence exhibits bistable behavior [3,4].

The first clear demonstration of optical bistability in lasers was reported nearly three decades ago using a CO_2 laser with a SF_6 cell serving as the saturable absorber [5]. Since then it has been observed in many types of lasers, such as the semiconductor laser with a split

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resonator [6], the two-section InAs quantum dot laser [7], the Er-doped fiber ring laser [8], and the twin-microdisk laser developed very recently [9]. So far, however, such optical bistability has not been observed in solid-state lasers.

One common feature of the different lasers mentioned above is the presence of an effective intracavity saturable absorber which is responsible for the occurrence of the optical bistability. In this respect, the trivalent Yb ion is of particular interest, it has a $[Xe]4f^{13}$ electronic configuration, giving rise to two spin-orbit split terms $^2F_{7/2}$ and $^2F_{5/2}$. In the crystal field of the host, each term will further split, forming a ground state manifold ($^2F_{7/2}$) and an excited state manifold ($^2F_{5/2}$). Therefore, an Yb-laser operating at room temperature will always suffer inevitable resonant losses arising from the thermal population of the terminal level which depend on the ground state splitting for the given host. However, such resonant losses, in principle, can simultaneously act as an inherent effective saturable absorber, and result, under certain circumstances, in optical bistability. Here, we report our observation of optical bistability in the operation of a continuous-wave (cw) Yb:$LuVO_4$ laser end-pumped by a high-power laser diode.

2. Experimental results and discussion

For the present experiment, a 2-mm-thick ***a***-cut Yb:$LuVO_4$ crystal with an aperture of 4×4 mm^2 was used. It was coated for high transmission at both the expected laser (~1040 nm) and the pump (985 nm) wavelength. The Yb concentration was 1.56 at. % which results in a small signal absorption of ~70% for the π- and ~36% for the σ-polarization at pumping wavelengths near 980 nm. The crystal was placed inside a compact plano-concave cavity, very close to the flat mirror through which the focused pump beam with NA = 0.2 was coupled into the cavity. The pump spot radius in the position of the crystal was ~100 µm. The pump light was unpolarized. The temperature of the copper holder in which the crystal was fixed was maintained at 15°C by use of a water-cooling system. Several 25-mm radius-of-curvature concave mirrors with transmission ranging from T = 0.5% to 2% were used as output couplers. The physical cavity length was 22 mm.

Efficient cw operation was achieved at room temperature with this Yb:$LuVO_4$ laser. An output power of 3.02 W (T = 0.5%) at an emission wavelength of 1049 nm was obtained for an absorbed pump power of P_{abs} = 10.23 W, which gives an optical-to-optical efficiency of 29.5%; the slope efficiency was determined to be 38%. The output beam was polarized parallel to the ***c***-axis (π polarization) in the entire operational range which is consistent with our previous work [10]. The emission wavelength shifted progressively from 1039 to 1049 nm with increasing pump power as a consequence of the increasing reabsorption losses which depend on the thermal population of the terminal laser level. Figure 1 shows the input-output characteristics of the laser for T = 0.5%. When the absorbed pump power was increased starting from zero, the laser would not start oscillating until a critical point, referred to as up-threshold, was reached at $P_{abs} = P_{th,up}$ = 4.2 W, at which the output power jumped from zero to a substantial level of 0.73 W. Above this point the output power scaled almost linearly with pumping power. If the pump power was reduced starting from a level in excess of $P_{th,up}$, the output power would decrease with nearly the same slope, with the laser still oscillating for pump powers below $P_{th,up}$. Further reduction of the pump power would eventually lead to cessation of the laser oscillation at the down-threshold $P_{th,down}$ = 2.9 W, where the output power dropped from 0.12 W to zero. Therefore, a sizable hysteresis loop in the dependence of the output power on the pump power was present. In the pump power range defined by $P_{th,down}<P_{abs}<P_{th,up}$, the operation of the Yb:$LuVO_4$ laser was bistable; the output power at a given pump level depended on the way this pump level was reached.

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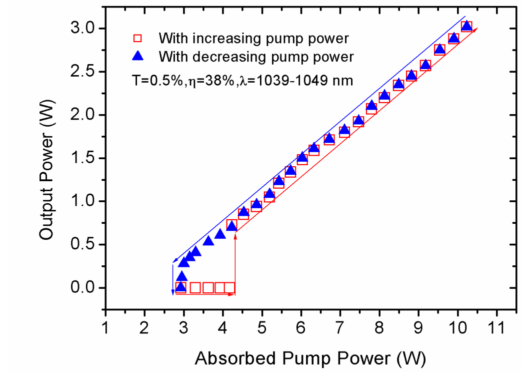

Fig. 1. Dependence of the output power of the Yb:$LuVO_4$ laser on the absorbed pump power, showing a sizable hysteresis loop.

For the pump conditions used in the present experiment, a part of the 2-mm thick Yb-doped crystal near its unpumped end would be characterized by much weaker level of inversion and hence increased reabsorption. The inhomogeneous inversion is a consequence of the highly divergent nature of the pump beam and the relatively high crystal absorption. Thus this part of the crystal could play the role of a saturable absorber leading to the bistable operation of the Yb:$LuVO_4$ laser. To verify this explanation, we replaced the 2-mm thick crystal by a 0.15-mm one which was uncoated but had the same doping-level, maintaining all the other laser conditions unchanged. In this case, no bistability in the laser operation was observed; the threshold was reached at P_{abs} = 0.9 W with a negligible output, and there was no difference when the pump power was increasing or decreasing. Obviously, as a result of the inversion created along the whole length of the thin crystal, the resonant losses due to reabsorption were greatly reduced in this case. This is confirmed by the substantially shorter oscillation wavelength (1019 nm) measured with the 0.15-mm thick Yb:$LuVO_4$ crystal. Thus, the observed bistability is related to the presence of (saturable) reabsorption losses in the active medium.

The absorbed pump power required for reaching threshold in the present Yb:$LuVO_4$ laser was quite high, which is expected to cause a significant thermal load inside the crystal. The resulting temperature rise in the crystal might play an important role for the observed optical bistability because the primary effect of changing temperature is the redistribution of the population in the two manifolds leading to increased reabsorption at higher temperature. To investigate the influence of the thermal load, we reduced the average pump power by employing a chopper with 1/12 duty cycle, rotating at 50 Hz. In this case, the laser reached threshold at much lower pump levels but the bistability remained: The absorbed pump powers measured at the up- and down-thresholds, in terms of instantaneous power, were $P_{th,up}$ = 2.21 W and $P_{th,down}$ = 1.65 W. The corresponding instantaneous output power at the up- and down-threshold was 0.19 and 0 W, respectively. The comparison with the case of true cw operation reveals that the bistability is affected to a great extent by the thermal load which confirms that it is related to the resonant reabsorption losses. It should be noted, however, that although the average absorbed pump power at the up-threshold was only 0.18 W (pump duration ~1.7 ms) and the thermal effect inside the crystal was greatly reduced, it was still possible to observe the hysteresis loop.

The hysteresis loop itself can be qualitatively explained by continuous heating of the crystal followed by stronger reabsorption, which increases the threshold and makes it necessary to further increase the pump level which in turn produces even more heat. In the absence of lasing (below the up-threshold), when increasing the pump power, nonradiative relaxation processes play an important role. In contrast, when starting from the lasing condition and decreasing the pump power, the stimulated emission increases the part of the radiative relaxation suppressing the nonradiative part which leads to less heat production and reduced down-threshold. The real situation is much more complicated because in the threshold regions both the wavelength and the polarization might change during the transition between the two states. The above explanation based on the role of the thermal effects is consistent with the observed narrowing of the hysteresis region to 0.7 and 0.3 W in terms of P_{abs} when the output coupler transmission was increased to T = 1% and 2%, respectively. Nevertheless, the fact that the hysteresis loop was observed also with the chopper means that the physical effect behind the bistability is strongly affected by the temperature but heating is not solely responsible for it.

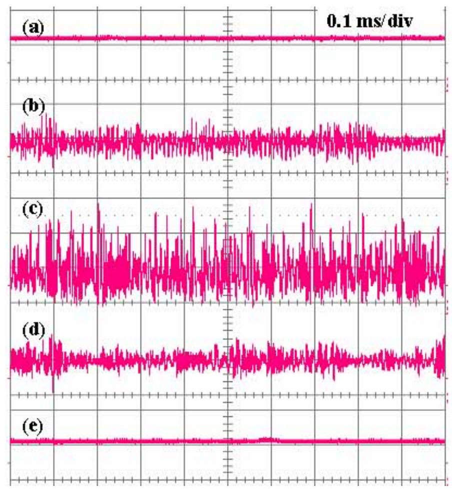

Fig. 2. Oscilloscope traces of the laser output showing the intensity fluctuations near the up-threshold. The traces from (a) to (e) were recorded when the pump power was decreased through the up-threshold point. The horizontal time scale is 0.1 ms/div.

Bistable operation was clearly predicted within the theoretical model used by Lugiato et al. [11] for a laser having an absorbing medium inside its resonator. Another interesting effect accompanying the bistability are the significant intensity fluctuations expected to occur in the transition region near the critical point (up-threshold) [11]. Indeed, such fluctuations were observed in the present Yb:$LuVO_4$ laser on sub-millisecond time scale when passing this region starting from the lasing state. Figure 2 shows a series of oscilloscope traces of the laser output recorded while the pump power was decreased through the up-threshold point (from (a) to (e)). Near the critical point, the region in which the fluctuations were observed covered a pump power range corresponding to ΔP_{abs} = 0.6 W, the most significant fluctuations occurring close to the up-threshold point.

Table 1. Absorbed pump power at threshold for different Yb-doped crystals (for vanadates, $P_{th} \equiv P_{th, up}$)*

host	$LuVO_4$	$GdVO_4$	YVO_4	$Lu_{0.162}Gd_{0.823}VO_4$	$Lu_{0.465}Gd_{0.52}VO_4$
P_{th} (W)	2.6	2.2	2.1	2.5	2.9
host	$KLu(WO_4)_2$	$NaGd(WO_4)_2$	$YAl_3(BO_3)_4$	$GdCa_4O(BO_3)_3$	$Ca_3(NbGa)_{2-x}Ga_3O_{12}$
P_{th} (W)	0.51	0.58	0.62	0.51	0.48

*Experimental conditions: a plano-concave resonator formed by a plane high reflector and a T = 0.5%, 50-mm radius-of-curvature concave output coupler (cavity length ~50 mm). All crystals were of high optical quality, uncoated, 2–3 mm thick, with cross section of 3.3 mm × 3.3 mm; their small-signal absorption at the pump wavelength was 40–85%. Efficient laser operation was achieved with all of these crystals with slope efficiencies ranging from 50% to 80%.

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We have observed bistable laser operation under similar experimental conditions also in other Yb-doped vanadates including Yb:YVO_4, Yb:$GdVO_4$, and Yb:$Lu_xGd_{1-x}VO_4$. We studied several other different Yb-doped crystals, such as $KLu(WO_4)_2$, $NaGd(WO_4)_2$, $YAl_3(BO_3)_4$, $GdCa_4O(BO_3)_3$, $Ca_3(NbGa)_{2-x}Ga_3O_{12}$, etc., searching for bistable laser operation, but with none of them was it possible to observe a hysteresis loop in the input-output characteristics. Thus optical bistability seems to be a common feature only of the Yb-doped vanadate lasers. What distinguish the Yb-doped vanadates studied by us from other Yb-doped crystals are the higher pump levels required to reach the laser threshold under identical resonator conditions (Table 1). As can be seen from the table, the laser thresholds of the Yb-doped vanadates were roughly 3–5 times higher than those of the other crystals. The (resonant) losses which are responsible for the increased thresholds of the Yb-doped vanadates lasers might be strongly dependent on the crystal temperature and the same holds for the magnitude of the observed bistability effect. Given the strong effect of temperature one can expect that the bistable behavior will depend on the thermal conductivity. It is known that tungstates have lower thermal conductivity than vanadates but no reliable data exist in the literature on the influence of Yb-doping on the thermal conductivity of the different vanadates and tungstates and this influence can be strong and dependent on the passive ion (Y, Gd, or Lu) that is substituted in the host. While the spectroscopic features of Yb seem similar in the different hosts, at present one cannot rule out the possibility that some additional heating (also below the laser threshold) is caused by existing or induced absorbing defect centers, which even do not affect the measured fluorescence lifetime and the estimated quantum efficiency, because all Yb-doped vanadates are still in the initial stage of their development.

3. Conclusion

In summary, we have observed, for the first time to our knowledge, sizable optical bistability in the operation of a diode-pumped Yb:$LuVO_4$ laser, which is attributed to resonant absorption losses in the active medium affected by the thermal load. Significant output fluctuations occur in the transition region near the up-threshold, which is in agreement with theoretical predictions. Such optical bistability seems common to all Yb-doped vanadate lasers.

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