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Study of the optical bistability in the laser oscillation of Yb:$GdVO_4$ crystal

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Abstract We have studied the effect of optical bistability exhibited in the laser oscillation of Yb:$GdVO_4$ crystal, revealing the complexities arising from the coexistence and switching of σ and π polarization states characteristic of this crystal. In terms of absorbed pump power, the range for bistable operation can be in excess of 1 W, while the output power generated at the up-threshold can reach as high as 0.71 W. The studies also show significant influence of the Yb concentration, the crystal thickness, the output coupling, and the resonator configuration on the bistable laser operation.

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1 Introduction

Theoretically, optical bistability is an intrinsic feature of a laser containing a saturable absorber in its resonator [1]. It was first demonstrated three decades ago in a CO_2 laser with a SF_6 cell serving as the intracavity saturable absorber [2]. After that it was also found existing in the oscillation of other gas lasers, semiconductor lasers, and fiber lasers [3–5]. For a long time, however, this type of bistable operation has not been achieved with solid-state lasers. Only recently has a diode-pumped Yb:$LuVO_4$ laser been reported exhibiting such bistability in its continuous-wave (cw) oscillation [6]. Shortly later, similar behavior was observed in the cw operation of a Tm, Ho:YLF laser [7].

It has been confirmed in our previous work that such bistability feature of laser operation is shared by all the three ordered vanadates doped with Yb (Yb:YVO_4, Yb:$GdVO_4$, and Yb:$LuVO_4$) and their solid solutions, and is caused by the presence of resonant reabsorption losses inherent to a quasi-three-level system, which take the part of an effective saturable absorber [6, 8, 9]. Among the three ordered vanadates, Yb:$GdVO_4$ seems to be unique in respect of basic characteristics of laser operation; the polarization state of laser oscillation may change with pump power between $\sigma(\mathbf{E}\perp c)$ and $\pi(\mathbf{E}//c)$, and the two orthogonal polarization states can exist simultaneously for some operational range under some circumstances. These features have been studied in our previous work [10], where the emphasis was focused on the polarization state coexistence and switching occurring in the laser operation. As a consequence of such unique polarization-state features, the resulting bistable laser operation of Yb:$GdVO_4$ is likely to be more complex, and more interesting to study in comparison with Yb:YVO_4 and Yb:$LuVO_4$, another two ordered vanadates.

In this paper we report the results from a detailed study of the characteristics of bistable laser operation of Yb:$GdVO_4$ crystal. The effects of Yb doping level, crystal thickness, output coupling, and resonator configuration on the bistable operation have been evaluated experimentally.

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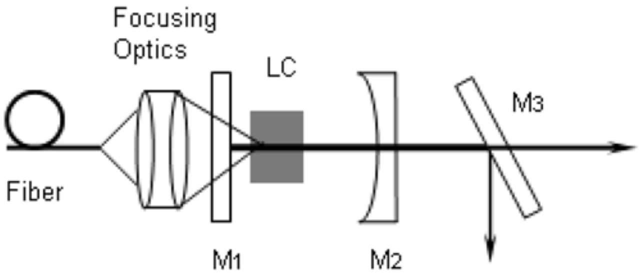

Fig. 1 Schematic diagram of the experimental laser setup. LC: laser crystal

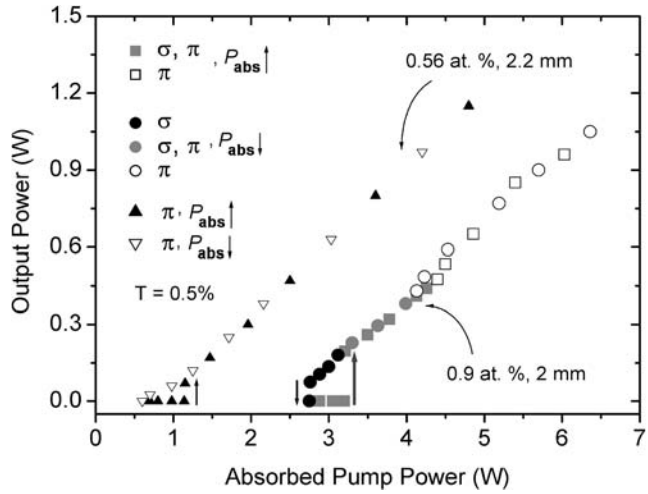

Fig. 2 Output power versus P_{abs} for $T = 0.5\%$ generated with two different crystals: 0.56 at.%, 2.2 mm; 0.9 at.%, 2 mm

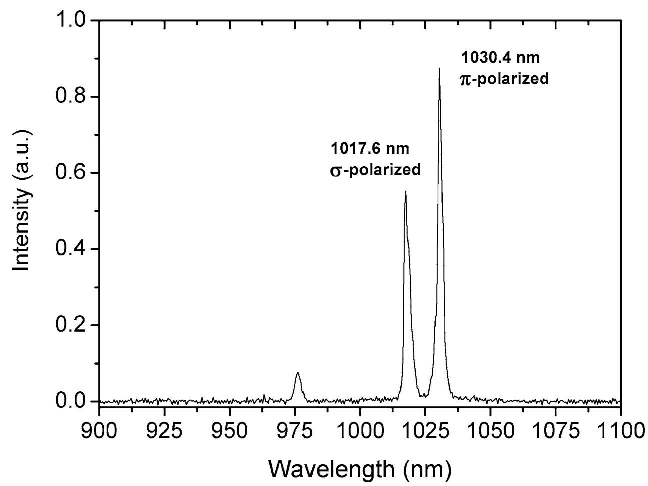

Fig. 3 Laser emission spectrum recorded at $P_{abs} = 3.5$ W for the 0.9 at.%, 2-mm crystal

2 Experimental setup

As shown schematically in Fig. 1, the resonator we utilized to generate laser oscillation with Yb:$GdVO_4$ was formed by a plane reflector (M_1) and a concave coupler (M_2). The inner surface of M_1 was coated for high reflectance at 1015−1230 nm (>99.8%) and high transmittance at 880−990 nm (>97%), while the outer surface was coated for antireflection (AR) at ∼980 nm. Several concave output couplers were used, with radius of curvature (R_2) equal to 25 or 50 mm, and their output couplings (transmissions) were in the range of $T = 0.5$–5%. Two different doping levels were studied with Yb concentration in the crystal determined to be 0.56 and 0.9 at.%, respectively. The crystal samples used were *a* cut, uncoated, with an aperture of 3.3 mm ×3.3 mm. Their thickness was 2.2 or 3.2 mm for the 0.56 at.% doped crystal, and 2.0 mm for the 0.9 at.% doped one. The pump source employed was a fiber-coupled diode (fiber core diameter of 200 μm and NA of 0.22) producing unpolarized radiation at 974−981 nm depending on the output power level. The pump radiation was focused first by focusing optics and then delivered through M_1 onto the laser crystal. The generated laser radiation was divided into two beams by a calibrated splitter (M_3), making it possible to measure the output power and to monitor/record the laser emission spectrum simultaneously.

3 Results and discussion

We first studied the effects of Yb concentration and crystal thickness on the resulting bistable laser operation by employing the resonator formed with the plane reflector and a coupler of 50-mm radius of curvature. The resonator was adjusted carefully to make it work in a near-hemispherical configuration, in order to achieve efficient laser operation.

Figure 2 shows the relations between the output power (P_{out}) and the absorbed pump power (P_{abs}) for the 0.9 at.%, 2-mm crystal and the 0.56 at.%, 2.2-mm crystal, respectively, measured through increasing the pump power from $P_{abs} = 0$ and then decreasing the pump power from the highest level. The output coupling was $T = 0.5\%$. Clearly, with other conditions being identical, the difference in Yb concentration resulted in significantly different characteristics of the bistable laser operation. With increasing P_{abs}, the laser oscillation reached its up-threshold at $P_{abs} = P_{th,up} = 3.21$ W, in the case of the 0.9 at.%, 2-mm crystal, where the output power jumped from $P_{out} = 0$ W to $P_{out} = 0.2$ W. The laser radiation was found consisting of both σ- and π-polarized components, with a coexistence region extending up to $P_{abs} = 4.26$ W. Above this pump level the σ-polarized oscillation ceased, leaving only the π-polarized one. Figure 3 illustrates an emission spectrum recorded at $P_{abs} = 3.5$ W, showing the σ-polarized oscillation at 1017.6 nm and the π-polarized one at 1030.4 nm.

The presence of coexistence of σ and π polarization states in the laser oscillation arises from the closeness in gain cross sections ($\sigma_g(\lambda)$) for the two orthogonal polarizations at different wavelengths. The gain cross section, defined by $\sigma_g(\lambda) = \beta\sigma_{em}(\lambda) - (1-\beta)\sigma_{abs}(\lambda)$, with $\sigma_{abs}(\lambda)$ and $\sigma_{em}(\lambda)$ being respectively the absorption and emission cross sections, and β the inversion ratio (the fraction of Yb ions excited to the upper manifold), is the parameter that determines the polarization and emission wavelength in the operation of a quasi-three-level laser (like Yb:GdVO$_4$) consisting of no polarization- and wavelength-selective elements. The spectral structures of $\sigma_{abs}(\lambda)$ and $\sigma_{em}(\lambda)$ of Yb:GdVO$_4$ lead to very close σ_g for σ and π polarizations at some specific different wavelengths (see e.g. Fig. 5 in Ref. [10] for $\beta = 0.12$), enabling laser oscillations to occur simultaneously in the two orthogonal polarizations at different emission wavelengths.

The polarization-state switching upon changing the pump power is connected with emission-wavelength shifting. With increasing pump power the thermal population in the lower laser level will be strengthened as a result of increased thermal load generated in the crystal; this will cause more internal losses, forcing the laser oscillation to shift to longer wavelengths, where, according to the calculation of $\sigma_g(\lambda)$ [10], the π-polarized σ_g dominates the σ-polarized one. Therefore, π-polarized oscillation is expected once the pump power is increased to a sufficiently high level. This is just the situation observed with increasing P_{abs} with the Yb:GdVO$_4$ laser.

In the process of pump power decreasing, the purely π-polarized oscillation could be maintained down to an even lower pump level than $P_{abs} = 4.26$ W, due to the bistable nature of the operation. Only with the pump power further reduced to $P_{abs} = 3.99$ W could the σ-polarized oscillation build up, forming a second coexistence range which extended down to $P_{abs} = 3.12$ W (below the up-threshold). Decreasing the pump power further led to purely σ-polarized oscillation, which could be sustained until the down-threshold was reached at $P_{abs} = P_{th,down} = 2.76$ W, at which the output power dropped abruptly to zero from $P_{out} = 0.075$ W.

The above observations are indicative of the complex nature of the bistable operation of Yb:GdVO$_4$, originating from the strong gain competition between the σ and π polarization states which is characteristic of the laser oscillation of this crystal [10]. It is also noted that the laser starts oscillating in σ and π polarizations simultaneously at the up-threshold, differing also from the case of $Yb_{0.0054}$:$Y_{0.3481}Gd_{0.6465}VO_4$, a mixed vanadate exhibiting very strong bistability in its laser oscillation [9].

Also depicted in Fig. 2 are the results for the 0.56 at.%, 2.2-mm crystal, obtained under the same resonator and pump conditions. In contrast to the complex operational features of the 0.9 at.%, 2-mm crystal, the situation turns out to be much simpler for the lower-doped crystal, as no polarization-state switching is involved in the laser operation. The up- and down-thresholds occurred at $P_{abs} = 1.15$ W and $P_{abs} = 0.6$ W, respectively, giving a bistable operation range of $\Delta P_{abs} = 0.55$ W. One notes that the output power could fall continuously to zero at the down-threshold, indicating a weak bistability effect. The weakening in the bistability effect results from the reduced resonant losses existing in the lowly doped crystal, which is also responsible for the considerable reduction of the laser thresholds, as can be seen from Fig. 2.

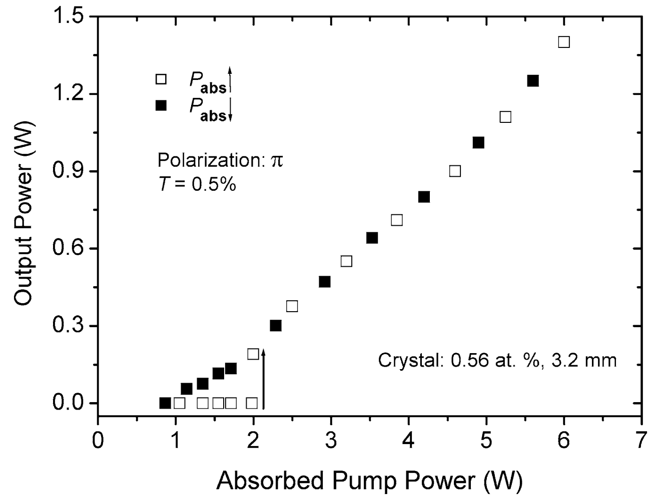

Fig. 4 Output power versus P_{abs} generated with the 0.56 at.%, 3.2-mm crystal

The weaker resonant losses due to the lower Yb concentration can be compensated by increasing the crystal thickness. Consequently, the effect of bistability can be strengthened to some extent simply by using a longer crystal. Figure 4 illustrates the relation of output power versus P_{abs} for the 0.56 at.%, 3.2-mm crystal, measured with other conditions kept unchanged. In comparison with the case of the shorter crystal (Fig. 2), the optical bistability is enhanced substantially, with the bistability range expanded from $\Delta P_{abs} = 0.55$ W (for the 2.2-mm crystal) to $\Delta P_{abs} = 1.1$ W (for the 3.2-mm crystal).

Apart from the Yb concentration and thickness of the crystal that determine the amount of the resonant losses, the resonator configuration is also capable of affecting the bistable laser operation. To study the influence of the resonator we modified the resonator configuration by changing the radius of curvature of the coupler from $R_2 = 50$ mm to $R_2 = 25$ mm, and adjusting the cavity length to keep it in a near-hemispherical condition. The output coupling was 1%. Figure 5 shows the output power versus P_{abs} for the 0.9 at.%, 2-mm crystal, measured with increasing as well as decreasing the pump power, displaying different characteristics of bistable operation from the case of the previous resonator. The most pronounced difference is the output power generated at the up- and down-thresholds, which was measured to be 0.71 and 0.18 W, respectively, much higher than the corresponding values obtained from the first resonator. In the

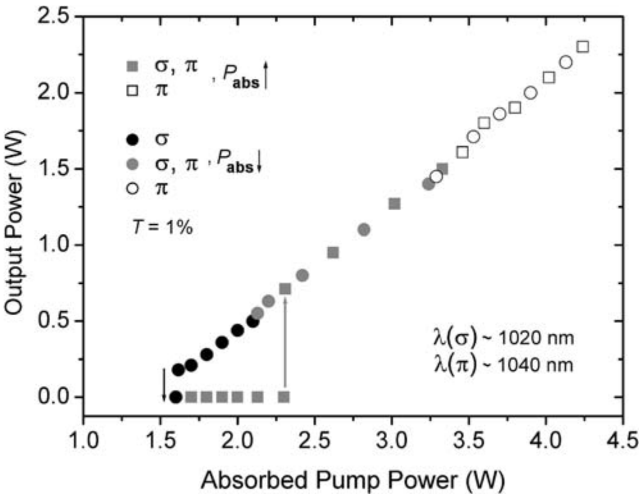

Fig. 5 Output power versus P_{abs} generated with the 0.9 at.%, 2-mm crystal by employing the resonator of $R_2 = 25$ mm

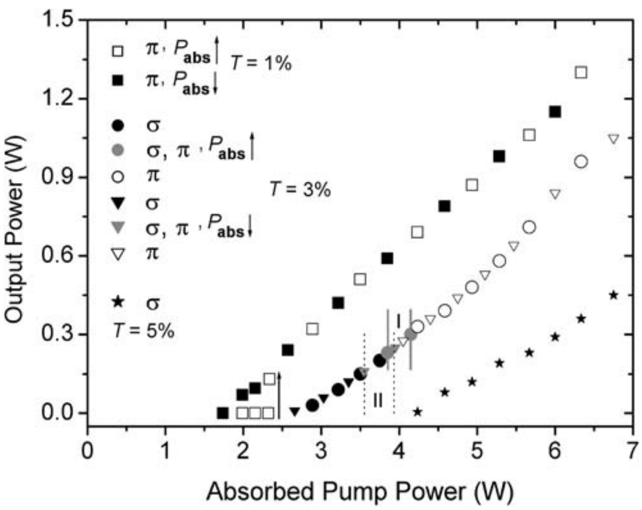

Fig. 6 Output power versus P_{abs} for $T = 1\%, 3\%$, and 5% obtained with the 0.56 at.%, 2.2-mm crystal by employing the resonator of $R_2 = 25$ mm, $L = 23$ mm

process of decreasing the pump power, the σ, π coexistence region extended down to $P_{abs} = 2.13$ W, crossing the bistability range limit at $P_{abs} = P_{th,up} = 2.31$ W. It is also noted from Fig. 5 that the bistability region shifted as a whole toward the low pump power side by $\sim$1 W, in comparison with the situation of the first resonator (Fig. 2).

The characteristics of bistable laser operation of Yb:GdVO$_4$ were also studied with the 0.56 at.%, 2.2-mm crystal in the second resonator ($R_2 = 25$ mm). To highlight the effect of bistability the resonator was further modified by shortening the cavity length (L) to 23 mm. Shown in Fig. 6 are the relations between the output power and P_{abs}, obtained by employing different output couplers of $T = 1\%, 3\%$, and 5%. In the case of $T = 1\%$, the laser reached its up-threshold with increasing pump power at $P_{abs} = 2.34$ W, with a finite output power measured to be 0.13 W. It was found that the laser started oscillating initially at 1016 nm in σ polarization, and then shifted to 1030 nm with the polarization state switching from σ to π. Above the up-threshold the laser oscillation remained in π polarization, with the emission wavelength varying slightly from 1030 to 1031 nm. Upon decreasing the pump power, the π-polarized oscillation could be maintained down to $P_{abs} = 1.74$ W, where the laser oscillation switched to σ polarization and then disappeared. The resulting bistability range extends over $\Delta P_{abs} = 0.6$ W.

Compared to the case of $T = 1\%$, the operation with the coupler of $T = 3\%$ proves to be more complex. Upon increasing the pump power from $P_{abs} = 0$ W, the laser oscillation reached up-threshold at $P_{abs} = 2.9$ W, building up in σ polarization with an output power of 0.03 W. The purely σ-polarized oscillation grew with pump power up to $P_{abs} = 3.85$ W, where the π-polarized oscillation set in, forming a coexistence region (marked by I in Fig. 6) extending up to $P_{abs} = 4.15$ W. Above this region the oscillation was in pure π polarization. In the process of pump power decrease, starting from a high level, the purely π-polarized oscillation could be kept down to a lower pump level entering the coexistence region I, i.e. the coexistence region in the case of decreasing P_{abs} was shifted as a whole to lower pump level, as indicated by region II in Fig. 6. This is also a direct consequence of the bistable nature of the laser operation. As the pump power was reduced further, the laser oscillation arrived eventually at the down-threshold at $P_{abs} = P_{th,down} = 2.66$ W, where the output power dropped from 0.01 W to zero. One sees that the effect of bistability here has already become very weak.

It is easy to see from Fig. 6 that the resulting effect of bistability is greatly diminished with the output coupling increased from $T = 1\%$ to $T = 3\%$. As shown in Fig. 6, the optical bistability was actually vanishing when the laser was operated with the coupler of $T = 5\%$, where the relations of the output power versus P_{abs} measured through increasing and decreasing the pump power are indistinguishable.

For comparison, Table 1 summarizes the primary parameters characterizing the degree of the optical bistability existing in the laser operation of the Yb:GdVO$_4$ crystal generated under different experimental conditions.

4 Conclusions

In summary, we have studied the optical bistability exhibited in the laser oscillation of Yb:GdVO$_4$ crystal. A bistable operation range in excess of 1 W in terms of absorbed pump power is demonstrated, while the output power generated

Table 1 Parameters characterizing the degree of the optical bistability in the laser operation of Yb:$GdVO_4$ crystal. Here R_2 is the radius of curvature of the output coupler and L is the length of the resonator

Resonator	Crystal	T (%)	$P_{th,up}$ (W)	$P_{th,down}$ (W)	ΔP_{abs} (W)	$P_{out,up}$ (W)	$P_{out,down}$ (W)
$R_2 = 50$ mm,	0.9 at.%, 2 mm	0.5	3.21	2.76	0.45	0.2	0.075
hemispherical	0.56 at.%, 2.2 mm	0.5	1.15	0.6	0.55	0.07	0
	0.56 at.%, 3.2 mm	0.5	2.0	0.9	1.1	0.19	0
$R_2 = 25$ mm,	0.9 at.%, 2 mm	1	2.31	1.61	0.7	0.71	0.18
hemispherical		1	2.34	1.74	0.6	0.13	0
$R_2 = 25$ mm,	0.56 at.%, 2.2 mm	3	2.9	2.66	0.24	0.03	0.01
$L = 23$ mm		5	4.23	4.23	0	0	0

at the up-threshold can amount to as much as 0.71 W. In comparison with the bistable laser operation generated with either Yb:YVO_4 or Yb:$LuVO_4$, additional complexities are present in the case of Yb:$GdVO_4$, resulting from the possible coexistence and switching of σ and π polarization states. The study also reveals the significant influence of the Yb concentration, the crystal thickness, the output coupling, and the resonator configuration on the resulting effect of optical bistability in the laser operation.

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