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Laser performance of pulse pumped Yb:YAG laser with different products of disc thickness and concentrations from room to cryogenic temperatures

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ABSTRACT

Using different products of disc thickness and Yb ions concentration, we report on the laser performance of Yb:YAG crystals under room and cryogenic temperatures. The optimum crystal parameters have been realized. With a thickness of 0.8 mm, 15 at. % Yb ions doping concentration laser crystal, high optical to optical efficiency of 85.2% and slope efficiency of 89.0% have been achieved and the maximum output energy was 75.6 mJ at ~80 K. Furthermore, the wavelength-switching phenomenon was observed owing to a lower loss cavity with the temperature reduction. Calculation results from the model based on the rate equations were well consistent with the laser output performance. The wavelength-switching effect was also explained by this model.

1. Introduction

Due to the simple energy level structure of Yb ions with only two manifolds relating to the lasing process, Yb-doped materials display the reduction in quantum defect, no up-conversion, concentration-quenching and other deleterious energy transfer mechanisms [1] and become one of the most popular laser media for solid-state lasers in the last twenty years. At room temperature, the energy level structure causes a significant thermal population in the lower laser level of the manifold, which leads to the reabsorption loss at the laser wavelength and presents quasi-three-level characteristics.

Much effort was paid to improve the performance of Yb:YAG laser at room temperature. In 2008, Xue, Y.H. et al. achieved maximum slope efficiency of 78.9% and optical-to-optical conversion efficiency of 55.3% in continuous-wave (CW) Yb:YAG laser pumped by a 969 nm laser diode [2]. Ahmed, M.A. et al. generated an efficiency of 52.5% with an output power of 275 W from a Yb:YAG thin disk laser [3]. In 2014, Nishio, M. et al. reported a high-efficiency continuous-wave laser-diode-pumped Yb:YAG laser at room temperature by a high-intensity pumping with a slope efficiency of 77% and optical-to-optical conversion efficiency of 72% (reference to the absorbed pump power) [4].

In recent years, cryogenic cooling for the gain medium has been demonstrated to significantly improve the output performance of quasi-three-level lasers by several works [5–11]. By the application of the cryogenic cooling, the thermal population on the lower laser level decreases significantly, and the quasi-three-level structure is converted to the four-level structure. Fan, T.Y. et al. demonstrated that the thermal resistivity, the coefficient of thermal expansion, and the thermo-optic coefficient dn/dT all decrease with the decreasing of the temperature in YAG host material and proved cryogenic technique availability [12].

Cryogenic Yb:YAG solid-state lasers have been shown to offer significant potential for reaching higher powers with better beam quality and higher efficiency than corresponding lasers operating at room temperature [12]. In 1999, a slope efficiency of 83% based on the absorbed pump power at 100 K has been demonstrated by Giesen, A. et al.. The Ti: sapphire laser was chosen as a pump source, due to its excellent beam quality and the good spatial mode overlap [5]. Shoji, T. et al. demonstrated a diode-pumped Yb:YAG oscillator with the highest slope efficiency of 90% at the crystal temperature of 70 K and the optical-to-optical efficiency were 74% [13]. In 2005, Ripin, D. J. et al. have improved the average power over 200 W with a 64% optical–optical efficiency [14]. Brown, D.C. et al. in 2010, have reported a Yb:YAG laser operating at 77 K with a slope efficiency of 91.9% and optical to optical efficiency of 84% with a near diffraction-limit Nd: YAG laser operating at 946 nm serving as the pump source [8].

Apart from experimental works, which tried to improve the laser efficiency, theoretical modeling works were also carried out. The model for an end-pumped quasi-three-level laser was developed by Fan, T.Y. and Byer, R.L. in 1987 [15]. For the longitudinally pumped solid-state

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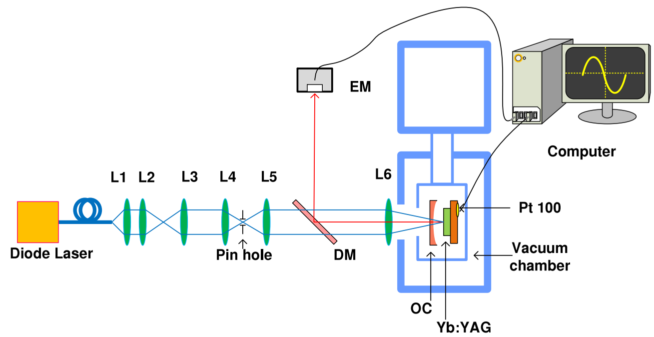

Fig. 1. Schematic layout of diode pumped cryogenic Yb: YAG lasers; EM: energy meter; OC: output coupler; DM: dichroic mirror; L1~L6: a series of lenses.

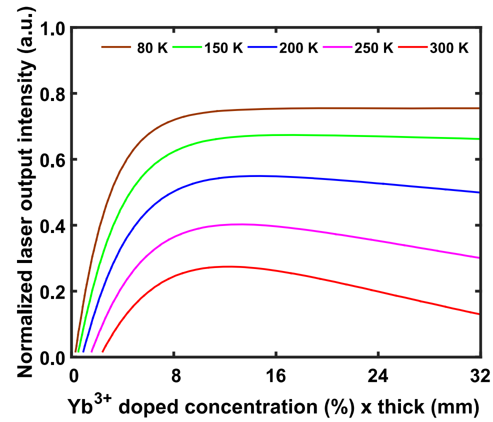

Fig. 2. The normalized laser output intensity as a function of products of disc thickness and Yb ions concentration for different temperatures.

laser considering reabsorption loss was proposed by Risk, W.P. [16]. The model was progressed and has been utilized to investigate and optimize the end-pumped Yb:YAG laser oscillator [17–19]. The model taking temperature dependent mechanical and optical properties and the absorption efficiency of the host into account has been built. The optimum gain medium parameters varying with temperature have been predicted [20,21]. However, the experimental study of the optimum gain medium parameters with the variation of temperature under the operation of pulse pumping was sparse.

To achieve much higher peak pump intensity, the quasi-continuous wave (QCW) mode was a better way in comparison with CW mode [22]. The former could be of benefit to efficient heat management. However, at room temperature, the slope efficiency and optical to optical efficiency of the laser operating at QCW mode was not always higher than that operating at CW mode. This was because the thermal population at the lower laser level must be overcome to realize the population inversion in each pulse of pump light for the QCW operation at room temperature. This thermal issue could be solved by cooling the active medium to cryogenic temperatures, at the same time thermo-optical and spectroscopic properties could be improved.

This paper was devoted to exploring the output performance of laser diode-pumped Yb:YAG laser in pulse-pumped operation mode under the cryogenic to room temperatures. The thermal effects could be neglected under this pump condition. Different products of disc thickness and Yb ions doped concentration for Yb:YAG crystal have been compared at two output couplers. The switching of lasing wavelength was observed with temperature decreasing. Furthermore, the phenomenon of wavelength-switching was carried out. Calculation results from the model based on the rate equations were well consistent with the laser output performance. The wavelength-switching effect could also be explained by this model.

2. Experiment setup

The experimental set up for cryogenically cooled Yb:YAG as the gain medium was shown in Fig. 1. In laser experiments, three kinds of crystals have been tested, whose doped concentration of Yb ions was 8 at. %, 10 at. %, and 15 at. % with disk thickness of 1 mm, 1 mm and 0.8 mm, respectively. The crystal diameter for all samples was 10 mm. The gain medium was coated with a high reflective coating on the back surface and an antireflection coating on the front surface from 900 to 1070 nm. The plane-concave mirrors with two kinds of transmittances were used as the output couplers (OCs), which had a 500-mm radius of curvature. One had a transmittance of 22.4% at 1030 nm and 13.3% at 1050 nm. The other had a transmittance of 4.8% at 1030 nm and 2.4% at 1050 nm. All the disks were mounted in the copper heat sink using indium solder as an intermediate material to obtain a high thermal conductivity. The temperature of the copper heat sink was controlled by a temperature-controlled cryostat (VNF-100, Janis Research Co.) from 78 K to 300 K. A platinum PT100 probe was held on the back surface of the copper heat sink by a screw to detect temperatures of the heat sink. The double-window structure was used to enclose a vacuum environment to maintain the temperature. The outside window was anti-reflection coated from 900 to 1070 nm on both surfaces and the inside window had no coating. The back surface of the crystal and plane-concave output coupler formed a stable resonator with 3.5 mm cavity length. The laser cavity was put in the inner chamber for the compact structure.

Yb:YAG crystals were pumped by a 200 W fiber-coupled laser diode (DILAS). The fiber had a 400 μm diameter core, 0.22 NA. The temperature of the laser diode could be adjusted to tune to the center wavelength of the laser diode. For the optimized absorption, the center wavelength of the laser diode was set at 938 nm under the condition of our laboratory. To avoid uncontrolled thermal effects, the repetition rate of 1 Hz was selected. Due to the limitation of pump source, the maximum pump pulse duration was 0.5 ms. The laser diode beam was reshaped by a series of plane-convex lenses (L1~L6) and focused on the Yb:YAG crystal. The focal length of the lens L6 was f = 50 mm. The dichroic mirror (DM) was anti-reflection coated at 940 nm, and high-reflection coated at 1030–1050 nm.

3. Theoretical calculation

The laser model of end-pumped Yb:YAG lasers has been developed based on the rate equations [15,16]. Considering the temperature-dependent reabsorption loss of the quasi-three-level system, the theoretical model could be expressed as [19]:

$$2\sigma_e \int_0^1 \frac{\frac{2P_0\eta_a\tau}{h\nu_p\pi w_{P0}^2}y^a - f_{low}N_t l}{1+\frac{4P_c\sigma_e\tau}{h\nu_L\pi w_{L0}^2}y}\,dy = \alpha + T_{oc} \tag{1}$$

where P_0 is incident pump power, P_c is the laser power inside the cavity, h is the Planck constant, ν_P and ν_L are the pump and emission laser frequency, w_{P0} and w_{L0} are the radii of the pump and the laser beams, $a = w_{P0}^2/w_{L0}^2$, σ_e is the stimulated emission cross-section, τ is the lifetime of the upper manifold, η_a is the ratio of the absorbed pump power to the incident pump power, f_{low} is the Boltzmann factors at the terminated laser level, l is the length of gain medium, α is the round-trip loss. By taking temperature dependent stimulated emission cross-section [19], absorption cross-section [23] and the thermal population factor of Yb:YAG crystal into account, the laser model can be used to calculate temperature dependent laser performance. According to Ref. [19], when $P_c = 0$, the pump threshold P_{th} was obtained:

$$P_{th} = \frac{h\nu_p\pi w_{P0}^2(a+1)\left(\alpha+T_{oc}+2\sigma_e f_{low}N_t l\right)}{4\eta_a N_t\sigma_e\tau} \tag{2}$$

Table 1
Values of the parameters used in numerical simulations.

Pump wavelength	938 nm
Output wavelength	1030/1050 nm
Laser medium thickness	0.8 mm
Yb^{3+} concentration	20.7×10^{20} cm^{-3}
The transmittance of output couplers	4.8% at 1030 nm, 2.4% at 1050 nm; 22.4% at 1030 nm, 13.3% at 1050 nm
The upper manifold lifetime of Yb: YAG	0.95 ms
Pump absorption cross-section	Ref. [23]
Emission cross-section at 1030 nm	Ref. [19]
Emission cross-section at 1050 nm	4.5×10^{-21} cm^2
The round-trip loss	5.0×10^{-3}

To optimize crystal design, the normalized laser output intensity as a function of products of disc thickness and Yb ions concentration for different temperatures was calculated and shown in Fig. 2. When the laser operating at room temperature, the optimum product of disc thickness and Yb ions concentration was ~12 at. % × mm. As the product augmented, the output laser intensity was decreased, because the value of reabsorption loss at the laser wavelength was larger than that of gain in the zone nearly the end surface of the crystal. With the temperature decreasing, the optical efficiency obviously increased and the optimum value slightly increased. This suggested that the reabsorption loss at the laser wavelength was reduced with the decreasing temperature. When the temperature decreased to ~80 K, the laser output intensity almost kept a constant and did not have an obvious variation. The parameters prepared for numerical simulations were shown in Table 1.

4. Results and discussions

To study the effect of the temperature on the laser performance, we varied the ambient temperature of the crystal from 300 K to 78 K. The pulse pumped output characteristics of three kinds of Yb:YAG crystals with the pump energy of 88.8 mJ were shown in Fig. 3. Fig. 3(a) showed the laser characteristics of Yb:YAG crystals under various temperatures and with output coupler of 22.4% transmittance at 1030 nm. The maximum laser output energy was 75.6 mJ at ~80 K for the crystal of 15 at. % Yb ions doping concentration and 0.8 mm thickness. As the temperature decreased, the output energy increased because of the reduction for the thermal population at the lower laser level and the increase of the stimulated emission cross-section and absorption cross-section. Fig. 3(b) showed Yb:YAG laser output energy as a function of temperatures when the output coupler with the transmittance of 4.8% at 1030 nm was used. The maximum laser output energy was 71.2 mJ at ~78 K for the crystal of 15 at. % Yb ions doping concentration and 0.8 mm thickness.

The optical to optical efficiency versus products of disc thickness and Yb ions concentration for different temperatures with two pump energies was shown in Fig. 4. For the average pump energy of 86.8 mJ, when the product grew, by adopting the crystal of 15 at. % Yb ions doping concentration and 0.8 mm thickness, the better optical efficiency has been achieved. Optical to optical efficiencies were 85.2% and 80.0%, with two output couplers of transmittance.22.4% and 4.8%, respectively. When the transmittance of output coupler at 1030 nm was 4.8%, optical to optical efficiency for the crystal of 10 at. % Yb ions doping concentration and 1 mm thickness, was 23.0% with the average pump energy of 26.3 mJ at room temperature, and slightly higher than other crystals. When the temperature decreased, the crystal of 15 at. % Yb ions doping concentration and 0.8 mm thickness became optimum. This differed from the situation at room temperature. With the 22.4% transmittance of output coupler at 1030 nm, the crystal of 15 at. % Yb ions doping concentration and 0.8 mm thickness, had a better laser performance with the 16.9% optical to optical efficiency (as shown in Fig. 4(a)). For the 22.4% transmittance of output couplers at 1030 nm, the crystal for 15 at. % Yb ions doping concentration and 0.8 mm thickness was optimum still. To either output couplers, the difference of the optical to optical efficiency between optimum crystal and other crystal became obviously at cryogenic temperature (as shown in Fig. 4(b)).

However, as the temperature decreases to ~180 K for the crystals with Yb ions doped concentrations of 10 at. % and 15 at. %, the output energy for the output coupler of the transmittance of 4.8% had a dramatic change as shown in Fig. 3(b), in comparison with the output coupler of the transmittance of 22.4%. To explore this phenomenon, the output laser wavelength was measured, using a Horiba iHR-320 spectrophotometer with the spectral resolution of 0.1 nm. The temperature dependence lasing spectra were shown in Fig. 5. The lasing wavelengths were shifted from 1050.8 nm to 1049.0 nm when the crystal was cooled down from 300 K to 186 K. As the temperature continually decreased to ~180 K, the wavelength-switching effect was found, the laser of 1049.0 nm was dominant, and the laser of 1030.9 nm started appearing. As the temperature further decreased to ~177 K, the laser of 1030.9 nm was dominant, and the laser of 1049.0 nm almost disappeared. The laser wavelength was switched from 1048.9 nm to 1030.9 nm within the temperature range from 187 K to 177 K. Because of a wavelength-switching effect, the dramatic variation of the output energy was caused.

The output linewidth (FWHM) was produced by the Gaussian curve fit and shown in Fig. 6. It was observed that the laser linewidth at 1030 nm decreased from 0.92 nm at the room temperature to 0.35 nm at ~78 K, when the transmittance of the output coupler at 1030 nm was 22.4%. The linewidth at 1050 nm for 4.8% transmittance of the output coupler was wider than that at 1030 nm for 22.4% transmittance of the output coupler under the condition of the identical temperature. This indicated that the gain width at ~1030 nm was slightly wider than the gain width at ~1050 nm at room temperature and with temperature decreasing, because the gain width at ~1050 nm did not have an obvious reduction in comparison with that at ~1030 nm.

Fig. 7 showed numerical and experimental results of output energy as a function of pump energy with different temperature for the 15 at. % Yb:YAG crystal with 0.8 mm thick and 22.4% output coupler transmittance at 1030 nm. The numerical simulations of the laser output energy were in good agreement with experimental data for different pump energy. However, when the pump energy decreased, the discrepancy between the calculated and the experimental results at the room temperature were because with the temperature of the crystal increasing from cryogenic to room temperatures, the thermal population of the lower laser level increases. This means that the reabsorption loss at the laser wavelength enhances under the condition of low pump power density. Thus, for the pump beam profiles of Gaussian shape, the gain of high-order resonator transverse mode could be less than the total intra-cavity loss, only low-order resonator transverse modes could oscillate. On the other hand, for the pulse pump, the model did not take build-up time of laser pulse into account. The build-up time should increase to overcome the thermal population on the lower laser level and reach the laser threshold at room temperature. For the case of high pump intensity and cryogenic temperature, the population inversion simply needs the shorter build-up time.

The temperature dependent threshold of pump power intensity under the condition of different intra-cavity losses for ~1050 nm and ~1030 nm oscillations was shown in Fig. 8. The wavelength-switching lasers for Yb:YAG materials have been reported on previous articles with tuning intra-cavity losses at the emitted wavelength [24]. Other articles also have explained this effect with reabsorption loss at ~1050 nm lower than that at ~1030 nm [19,25]. Nevertheless, as displaying in our results, both explanations were insufficient. The laser threshold strongly depended on intra-cavity losses and the temperature of the gain medium. In comparison with ~1030 nm, lasering at ~1050 nm had a relatively lower stimulated emission cross-section; therefore, the threshold of lasering at ~1050 nm was more sensitive to

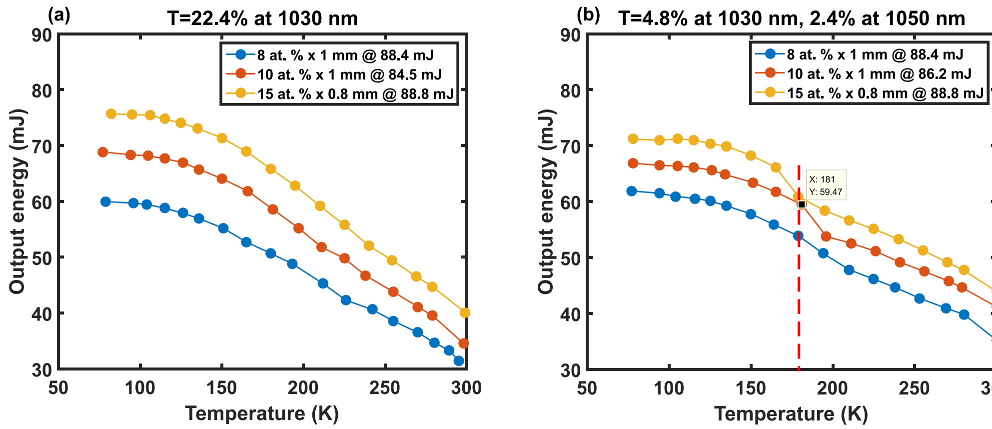

Fig. 3. Output energy of Yb: YAG lasers as a function of the temperature of Yb: YAG crystals with different Yb^{3+} doped concentrations under 22.4% output coupling at 1030 nm (a) and 4.8% output coupling at 1030 nm (b).

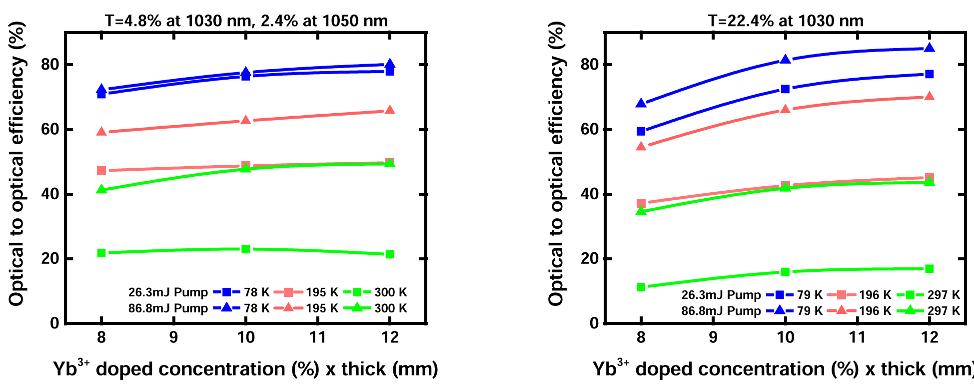

Fig. 4. Optical-to-optical efficiency of Yb: YAG lasers as a function of products of disc thickness and Yb ions doped concentration with different temperatures under different output couplings.

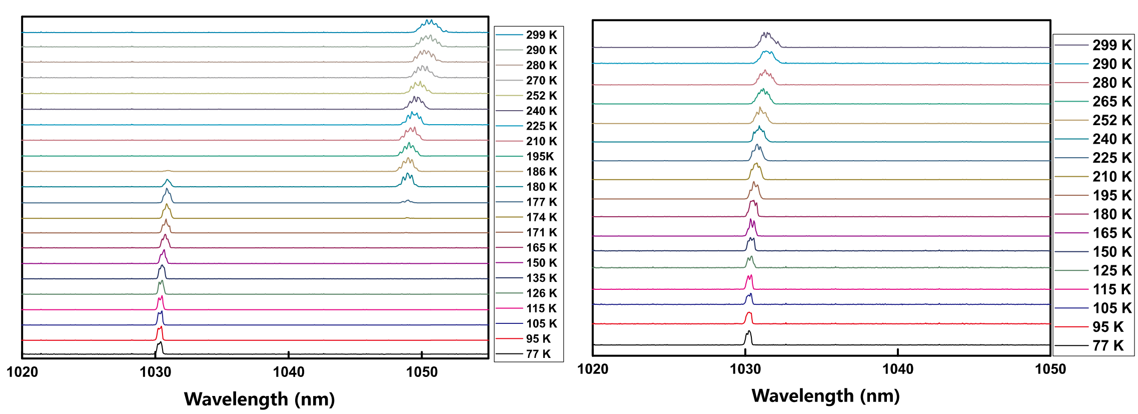

Fig. 5. Laser spectra of Yb: YAG lasers with the crystal of 15 at. % Yb ions concentration for T = 4.8% (left) and T = 22.4% (right).

the variation of the intra-cavity loss. For a room temperature operation, the threshold of lasering at ~1030 nm was 1.5 times that at ~1050 nm because of the strong reabsorption loss at ~1030 nm. The threshold decreased as the temperature was decreased. When the temperature decreased, the stimulated emission cross-section at ~1030 nm increased as reported by Ref. [26]. However, the stimulated emission cross-section at ~1050 nm was approximately a constant. When the temperature was higher than 187 K, the pump power threshold at ~1030 nm was lower than that at ~1050 nm. When temperature was sequentially increasing, the lasers preferred to oscillate at ~1050 nm.

Fig. 9 showed slope efficiency of Yb:YAG lasers as a function of heat sink temperature for the crystal of 15 at. % Yb-doped concentration and 0.8 mm thickness. In our experiments, the slope efficiency was increasing with cryogenic temperature decreasing. When the crystal temperature decreased to 100 K or lower, the slope efficiency was almost constant. The maximum slope efficiencies of 89% and 80.8% were achieved in the two corresponding output couplers, *i.e.* 22.4% and 4.8% transmittance, in pulse pumped mode. Slope efficiency and optical to optical efficiency were calculated by considering of the non-absorbed pump energy.

Nevertheless, although the maximum optical efficiency has been obtained, the optimum result could not be realized under the present condition. The larger products of disc thickness and Yb ions concentration will be examined in future. On the other hand, the absorption

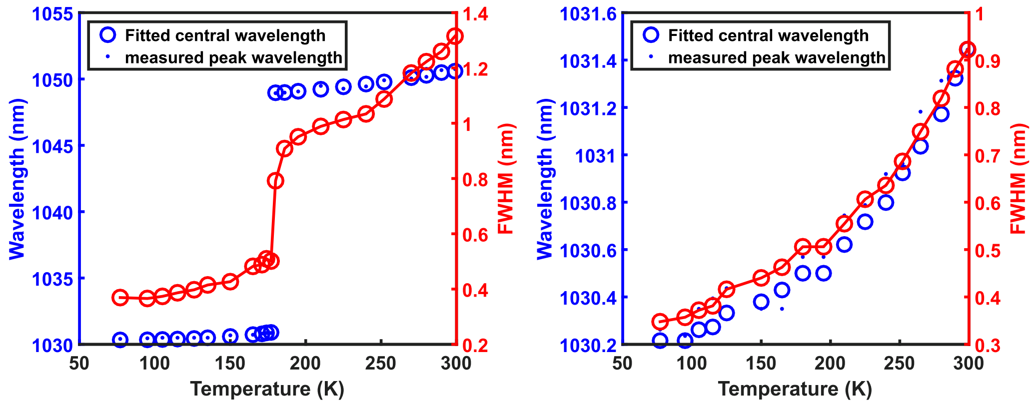

Fig. 6. Measured peak wavelength, fitted central wavelength and FWHM linewidth values for Yb: YAG laser as a function of temperature with output coupler of T = 4.8% (left) and T = 22.4% (right).

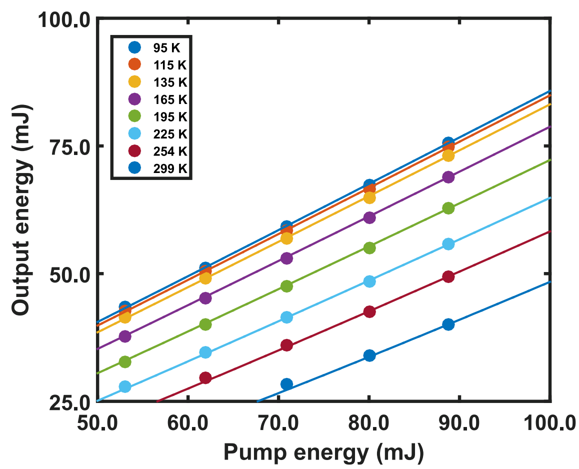

Fig. 7. Output energy as a function of pump energy with different temperatures. The solid lines show the calculation results, the solid dots show the experimental data.

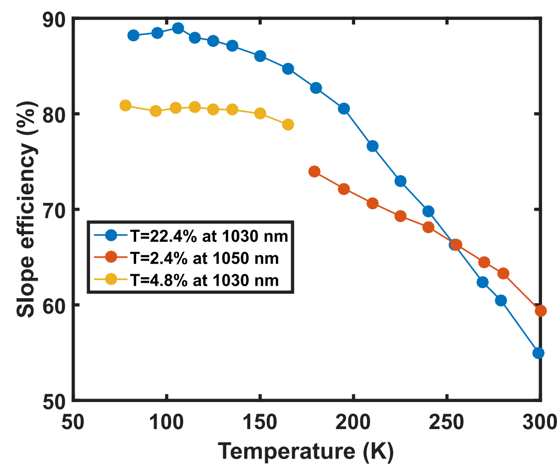

Fig. 9. Slope efficiency of Yb: YAG lasers as a function of temperature.

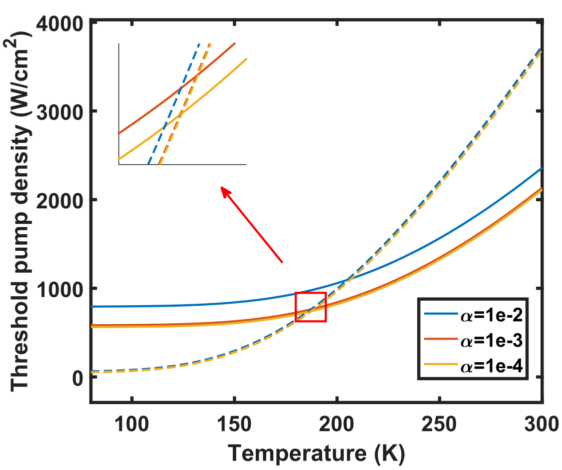

Fig. 8. The temperature dependent threshold of the pump power intensity under the condition of different intra-cavity losses for 1050 nm (solid line) and 1030 nm (dash line) oscillations.

efficiency of the Yb:YAG crystal with 15 at. % Yb ions doping concentration and thickness of 0.8 mm was 99.2% at 77 K. The absorption efficiency of the crystal was close to 100%. Further increase of the product might not be lead to an outstanding improvement at the laser performance.

5. Conclusion

In conclusion, cryogenically cooled Yb:YAG laser has been shown to deliver high optical to optical and slope efficiency at pulse pumped mode. A comparative study on pulse pumped mode operation of Yb:YAG laser from cryogenic to room temperatures by pumping at 938 nm was presented. When compared among three kinds of Yb:YAG crystals for different products of disc thickness and Yb ions concentration, the crystal with 15 at. % Yb ions doping concentration and thickness of 0.8 mm, seemed to be the best for the laser performance. The optical to optical efficiency and slope efficiency were 85.2% and 89.0% at the maximum incident pump energy under the condition of 22.4% transmittance of the output coupler with this crystal at ~78 K. We obtained the highest slope efficiency in case of the 22.4% transmittance of the output coupler, owing to the higher gain of Yb:YAG and lower loss. We presented that wavelength-switching effect resulted from the variation of the stimulated emission cross-section around 1030 nm and 1050 nm and the difference of the reabsorption loss for the lower laser level at the laser wavelength. The wavelength-switching effect and output performance have been explained by the laser model, and the theoretical results were well consistent with experimental data. Our results revealed a possibility of high-efficiency oscillation pumped by the high-brightness emitter laser diode even if operating in QCW mode. Higher transmittance of the output coupler should be used to improve the output power and slope efficiency in this experiment as we expect.

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