Analysis of the optimal temperature for the cryogenic monolithic Nd:YAG laser at 946-nm

C. Y. Cho,[1] T. L. Huang,[1] H. P. Cheng,[1] K. F. Huang,[1] and Y. F. Chen[1,2,*]

[1] *Department of Electrophysics, National Chiao Tung University, Hsinchu, Taiwan*
[2] *Department of Electronics Engineering, National Chiao Tung University, Hsinchu, Taiwan*
[*] *yfchen@cc.nctu.edu.tw*

Abstract: The optimal temperature for the cryogenic monolithic Nd:YAG laser at 946-nm is theoretically and experimentally analyzed. It is clear that decreasing temperature can considerably eliminate the thermal population at the lower laser level to enhance the quantum efficiency. However, the narrowing of the absorption bandwidth for the gain medium leads to a reduction of the effective absorption efficiency as the temperature is decreased. Consequently, an optimal temperature for the maximum output power is found to be in the range of approximately 120 K to 140 K. It is experimentally verified that employing a pump source with a narrower emission spectrum linewidth contributes a more efficient output for the cryogenic laser.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3530) Lasers, neodymium; (140.3580) Lasers, solid-state; (140.6810) Thermal effects.

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1. Introduction

The solid-state laser gain medium cooled to the cryogenic temperature has been widely utilized to generate high-power high-beam-quality quasi-three-level lasers [1–10]. The main advantage consists in the elimination of the thermal population at the lower laser level to reduce the reabsorption losses [6]. Moreover, cooling the laser crystal to cryogenic temperature can improve the thermal and thermo-optical properties to maintain the beam quality at high-power operation [10–14]. In past few years, the cryogenic Nd:YAG laser at 946 nm has been experimentally studied by several groups [7–9]. One of experimental results revealed [9] that the efficiency of the output power in a monolithic cavity tended to gradually decrease for the temperature lower than 140 K, which was contrary to the intuitive expectation. From a practical and scientific point of view, the origin of the optimal temperature for the cryogenic monolithic solid-state laser deserves further explorations. It has been confirmed that the bandwidth of absorption spectra for a solid-state laser gain medium will shrink as the temperature decreasing [7–9]. Since the bandwidth of the absorption spectrum at cryogenic temperature can be narrower than the linewidth of a typical fiber-coupled diode, 2 nm, the overall absorption efficiency will reduce significantly. As a result, the analysis of the absorption for the cryogenic laser system should be further revised instead of considering the absorption peak efficiency only.

In the present work, the origin of the optimal temperature for the cryogenic 946-nm laser is theoretically and experimentally investigated. We first thoroughly measure the absorption spectra of the Nd:YAG crystal at temperature from 300 K to 80 K. Experimental results indicate that the absorption bandwidth around 808.6 nm is significantly narrower with decreased temperature. By using the experimental absorption data, we systematically calculate the effective absorption efficiency as a function of pump linewidth at various cooling temperature [15]. Calculated results show that the efficiency reduces as the temperature decreasing. Furthermore, a diode with narrower pump linewidth can be used to achieve a more efficient output at cryogenic temperature. In experiment, we employ two pump diodes with 1-nm and 2-nm pump emission spectrum linewidth to perform the cryogenic Nd:YAG laser. It is confirmed that using the 1-nm-linewidth diode can considerably reduce the influence of the absorption bandwidth narrowing at temperature below 140 K in comparison with the 2-nm-linewidth diode. Our exploration indicates that the optimal temperature for the 946-nm laser is mainly caused by the combining effects of the reabsorption elimination and the effective absorption efficiency reduction. In the end, we further explore the thermal lensing effect at cryogenic temperature. It is verified that the eliminating of thermal lensing can increase the cavity mode size and contribute to a better beam quality. The increasing cavity mode area, on the other hand, may also reduce the output efficiency because of the less pump-to-mode overlapping and leads to the optimal temperature for the 946-nm output.

2. Absorption spectra for the Nd:YAG crystal at cryogenic temperature

To analyze the absorption efficiency for the cryogenic laser, we first measured absorption spectra for the Nd:YAG crystal at temperature from 300 K to 80 K. The experimental setup is shown in Fig. 1(a). We utilized an 808-nm 800-μm-core-size fiber-coupled laser diode operated at below-threshold region as the light source. Hence, the laser diode displayed a broad-band spectrum with emission linewidth of approximately 10 nm, which is illustrated in Fig. 1(b). The spectrum information was recorded by using a grating optical spectrum (Q8381A, Advantest) with 0.1-nm resolution. The emission light was reimaged into the laser crystal through a focus lens pair and had a pump radius of approximately 300 μm on the laser crystal. At first, we recorded the pump emission spectrum as the reference intensity, $I_0(\lambda)$,

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without the laser crystal, where λ was the wavelength. After the gain medium was placed and cooled to different temperature, the transmittance intensity spectrum, $I(T,\lambda)$, can be measured. With $I_0(\lambda)$ and $I(T,\lambda)$, we can obtain the spectra of the absorption ratio at various temperature, $\eta_{abs}(T,\lambda)$, by using.

$$\eta_{abs}(T,\lambda) = 1 - \left[I(T,\lambda)/I_0(\lambda) \right]. \qquad (1)$$

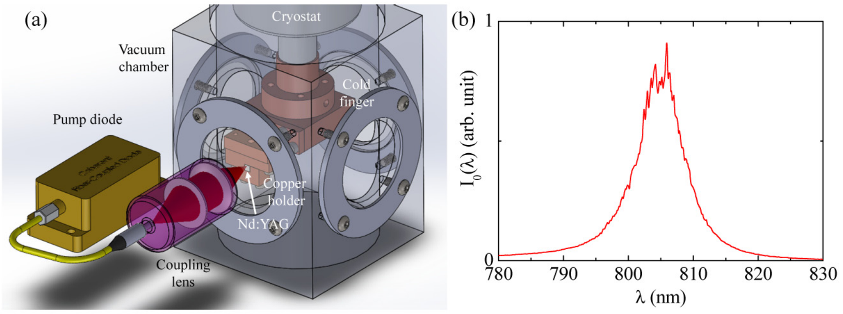

Fig. 1. (a) The experimental setup for the cryogenic laser system and (b) the emission spectrum for the pump diode operated at below-threshold region.

The dimension of the Nd:YAG crystal utilized here was 4 mm in length with a 3 × 3 mm^2 transverse aperture and doped with 1.1-at.-% concentration. Both sides of the gain medium were coated with anti-reflective (AR, $R < 0.01\%$) at 808 nm. The laser crystal was mounted on the copper holder with indium foil to improve the heat dissipation efficiency. We placed the copper holder inside the cryogenic system (VPF-100, Janis Research Co.) to control the cooling temperature. A calibrated Pt-Au thermocouple was attached on the copper holder surface with a nano-voltmeter (Lake Shore 331) to measure the temperature. The copper block was mounted on the cold finger of the temperature-controlled cryostat and placed in a vacuum chamber. Absorption spectra of the Nd:YAG crystal are illustrated in Fig. 2. We can observe the bandwidth narrowing and the peak wavelength shifting as the temperature was decreased. According to Ref. 5, the absorption bandwidth for a common solid-state gain medium will not approach zero even if the temperature was cooled to 4 K. The wavelength shifting rate was found to be approximately 8.64×10^{-4} nm-T^{-1}.

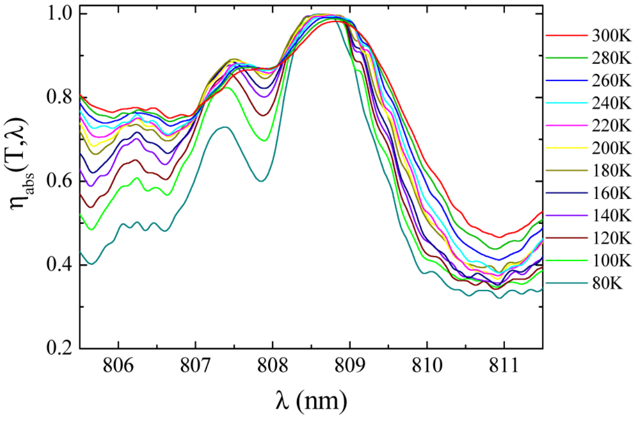

Fig. 2. The measured absorption ratio for the Nd:YAG crystal around 808.6 nm at temperature from 300 K to 80 K.

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3. Analysis of the optimal temperature for the cryogenic 946-nm laser

The output enhancement for the 946-nm Nd:YAG laser at cryogenic temperature is mainly caused by the elimination of thermal population at lower laser level. We can theoretically analyze the thermal population, $N_a(T)$, by expressing it as a partition function [16, 17]:

$$N_a(T) = N_0 \exp\left(-E_a / kT\right) \Big/ \sum_i \exp\left(-E_i / kT\right), \tag{2}$$

where N_0 is the total dopant concentration, E_a is the level energy of the lower laser level, k is the Boltzmann factor, and E_i are energies of other lower manifolds for the lower laser level. For the 946-nm transition of the Nd:YAG crystal, the lower manifolds correspond to level energies of E_i = 308 (cm^{-1}), 199 (cm^{-1}), 130 (cm^{-1}), and 0 (cm^{-1}), respectively [16]. The lower-laser-level energy of the 946-nm transition is E_a = 857 (cm^{-1}) [16]. With Eq. (2), we can find that the population decreases to approximately zero when the cooling temperature is lower than 140 K, which is shown in Fig. 3(a). The result indicates that the reabsorption for the 946-nm laser can be nearly eliminated and the laser will behave like a four-level system. Hence, the output power should be enhanced to a maximum value at cryogenic temperature.

On the other hand, the effective absorption efficiency of the Nd:YAG crystal can be calculated by considering the overlapping of the Nd:YAG absorption spectrum and the pump diode emission spectrum. We utilize a Gaussian profile to represent the pump spectrum for the laser diode:

$$S_{pump}(\lambda, \Delta\lambda) = \sqrt{\frac{2}{\pi(\Delta\lambda)^2}} \exp\left[\frac{-2(\lambda-\lambda_0)^2}{(\Delta\lambda)^2}\right], \tag{3}$$

where λ_0 is the central pumped wavelength and $\Delta\lambda$ is the linewidth of the pump spectrum. Here, we assume the pump linewidth to be approximately the FWHM (full-width-half-maximum) of a Gaussian profile. Using the temperature-dependent absorption spectra, $\eta_{abs}(T,\lambda)$, and $S_{pump}(\lambda,\Delta\lambda)$, we can obtain the effective absorption efficiency at various temperature:

$$\eta_{eff}(T, \Delta\lambda) = \int \eta_{abs}(T, \lambda) S_{pump}(\lambda, \Delta\lambda) d\lambda. \tag{4}$$

Figure 3(b) and 3(c) demonstrate the effective absorption efficiency with respected to the pump linewidth and cooling temperature, respectively. It can be seen that the effective absorption decrease as pump linewidth increased for all cooling temperature, which indicates that using a narrower linewidth pump source should be more efficient for the cryogenic laser system. From Fig. 3(c), it shows that the absorption reduction is more significant when the temperature was lower than approximately 140 K. By taking into the consideration of the reabsorption loss elimination and the effective absorption efficiency reduction, the 946-nm laser output at cryogenic temperature may have an optimal temperature at below 140 K. Noted that if a gain medium with different absorption spectrum was employed, the effective absorption efficiency will be different, which might lead to a different optimal temperature.

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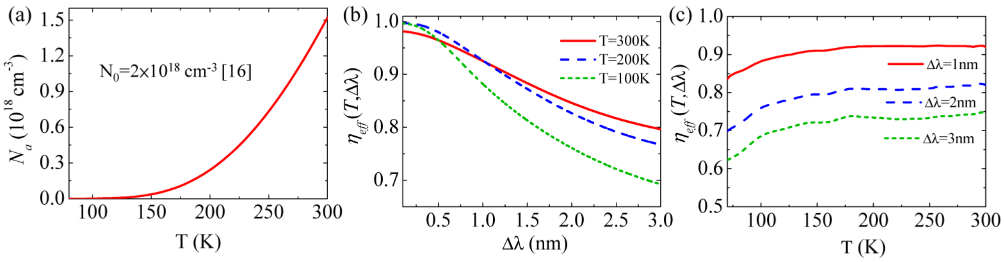

Fig. 3. (a) Theoretical analysis of thermal population at lower laser level of the 946-nm transition for the Nd:YAG crystal and the calculated effective absorption efficiency with respected to (b) the pump linewidth and (c) the cooling temperature.

4. Experimental results

To confirm the theoretical analysis, we employed two pump diodes with pump linewidths of 1 nm and 2 nm to demonstrate cryogenic 946-nm lasers. Core diameters of two pump diodes were both 800 μm. Emission spectra of two pump diodes are plotted in Fig. 4. We further illustrate the absorption spectra at 300 K and 80 K in Fig. 4 for a better comparison. It can be seen that the emission spectrum for the 2-nm-linewidth pump diode was slightly larger than the absorption bandwidth around 808 nm at 80 K. Since the absorption peak of the Nd:YAG crystal will shift when the temperature was decreased, we utilized a home-made diode driver to control the pump wavelength by changing the diode temperature. A 4-mm-long Nd:YAG crystal coated with monolithic cavity on both sides was replaced into the cryogenic system to generate the 946-nm laser. The first surface of the Nd:YAG crystal was coated with high-reflection (HR, R > 99.9%) at 946 nm and high-transmittance (HT, T > 95%) at 808 nm, 1064 nm and 1320 nm. The second surface of the gain medium was high-transmittance coated at 1064 nm and 1320 nm as well as partially reflective (R = 97%) coated at 946 nm.

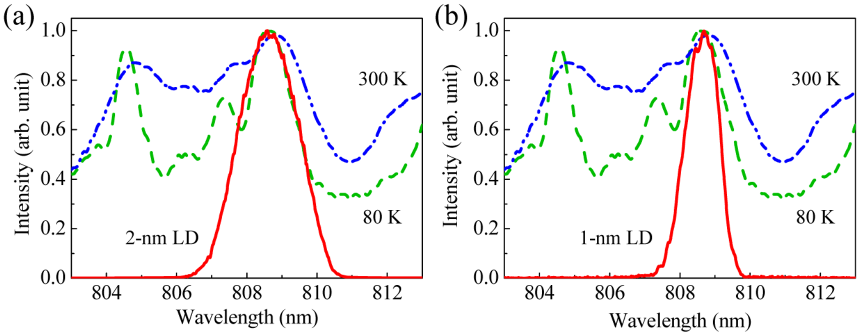

Fig. 4. The emission spectra of pump diodes with pump linewidth of (a) 1 nm and (b) 2 nm (solid line) and the absorption spectra for the Nd:YAG crystal at 300 K and 80 K (dash line).

For the laser output, the comparison between utilizing two pump diodes are demonstrated in Fig. 5. When the temperature was decreased from room temperature, the incident threshold pump powers, P_{th}, for both monolithic lasers were decreased from approximately 3.5 W. By careful adjusting the pump wavelength, minimum threshold value of approximately 1.1 W were obtained at approximately 130 K and 170 K for using 1-nm and 2-nm pump diodes respectively. As the temperature was further decreasing to 90 K, we observed that the threshold power raise to barely 1.2 W with the 1-nm pump diode. On the other hand, up to 2.7-W threshold power was obtained by using the 2-nm pump diode at such temperature. In addition to the threshold power, similar tendency were observed for the output power when utilizing different pump diodes. The output power, P_{out}, observed in Fig. 5(b) was obtained with incident pump power of approximately 17 W. In Fig. 5(b), we found that a maximum

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output power of 8.9 W was obtained at 150 K using the 2-nm pump diode. By utilizing the 1-nm pump diode, the optimal temperature decreased to 130 K and the output power increased to approximately 10.3 W with the optical-to-optical conversion efficiency of 60.5%. When the temperature was decreased to 90 K, the output power of 10.0 W was obtain with 1-nm pump diode which was higher than that observed with 2-nm pump diode, 7.3 W. It was verified that the narrower linewidth for the pump diode was essential to obtain better laser output at cryogenic temperature. By considering the results from experiment and theoretical analysis, we believed that the range of the optimal temperature for the cryogenic 946-nm laser might be in the range from 120 K to 140 K. It is worth to mention that there are some laser diodes employing volume Bragg grating (VBG) which can emit a super-narrow linewidth less than 0.5 nm. From the theoretical analysis in Fig. 3(b), it revealed the fact that the optimal temperature can be lower and a better efficiency might be obtained when such laser diode was applied.

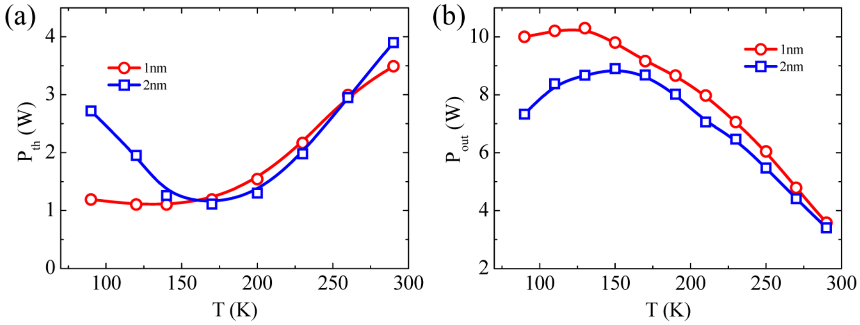

Fig. 5. Temperature dependence of (a) incident threshold pump powers and (b) output powers for 946-nm monolithic lasers using pump diodes with emission linewidths of 1 nm and 2 nm.

5. Discussion for the optimal temperature of the 946-nm laser

The theoretical and experimental result indicated that the optimal temperature for the output performance of 946-nm Nd:YAG laser was mainly caused by the combining effect of the reabsorption elimination and the decreasing of effective absorption efficiency at lower temperature. However, there were still some minor issues that can be further discussed for such unique phenomenon of the cryogenic 946-nm laser. For example, the increasing emission cross section at cryogenic temperature [8] will enhance the gain of the 946-nm output. However, the absorption reduction was more significant than the enlarging of emission cross section at cryogenic temperature. As a result, the influence of emission cross section will be limited. The energy transfer upconversion (ETU) for different doping concentration might affect the performance at cryogenic temperature as well. One of the interesting topics was that the thermal lensing effect of the gain medium will be less effective at cryogenic temperature due to the improvement of thermal conductivity. Since the monolithic cavity was a plane-parallel resonator which was stabilized by the thermal lens effect, the output performance at cryogenic temperature may be influenced. We investigated the thermal lensing effect by measuring the output beam size of the 946-nm laser at different temperature. The cavity mode size on the laser crystal, which was the beam waist of the output beam, can be calculated with the output beam radius at two different distances, z_1 and z_2, by using [18]:

$$\omega_0 = \frac{\lambda}{\pi}\sqrt{\frac{z_2^2 - z_1^2}{\omega^2(z_2) - \omega^2(z_1)}}. \tag{5}$$

With the beam waist, the thermal focal length can be further obtained by assuming an internal focusing lens was on the pump side of the gain medium [18]:

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$$f_{th} = \left(\frac{\pi\omega_0^2}{\lambda}\right)^2 \frac{n}{l_{med}} + \frac{l_{med}}{n}, \tag{6}$$

where n was the refractive index of the Nd:YAG crystal and l_{med} was the length of the gain medium. The experimental result were shown in Fig. 6(a) and 6(b) with $n = 1.82$ and $l_{med} = 4$ mm. To eliminate the effect of high order transverse mode output, we measured the beam parameters at the pump power slightly above the room-temperature threshold, 5 W. We also plotted the theoretical analysis of temperature dependence of the thermal conductivity, $K_c(T)$, for the Nd:YAG crystal in Fig. 6(c). The thermal conductivity can be obtained by using [10]:

$$K_c(T) = \frac{a}{\left[\ln(bT)\right]^c} - \frac{d}{T}, \tag{7}$$

where $a = 1.9 \times 10^6$ (Wcm^{-1}K^{-1}), $b = 5.33$ (K^{-1}), $c = 7.14$, $d = 331$ (Wcm^{-1}). It was found that the cavity mode size and the thermal focal length both increased significantly when temperature was lower than 140 K. The increasing tendency was verified to be caused by the thermal conductivity at low temperature. The increasing cavity mode size will reduce the efficiency because of the decreasing of pump-to-mode overlapping [19]. As a result, it also indicated that the optimal temperature might be at approximately from 120 K to 140 K. It was worth to mention that the experimental result of beam waist increasing also suggested the improvement of the output beam quality at cryogenic temperature. However, although we tried to eliminate the effect of high order transverse mode output in the experiment, the beam radius was still found to be smaller than the pump radius, especially at temperature higher than 140 K. A relatively small cavity mode size will cause the multi-mode output and decreased the beam quality [20]. The result implied that the calculation of thermal lensing might need to be further revised by considering the output beam quality factor changing. Hence, the detail discussion of beam quality improvement needed to be confirmed with more specific experimental results. The comparison between different cavity configurations may also be an interesting issue to be further investigated.

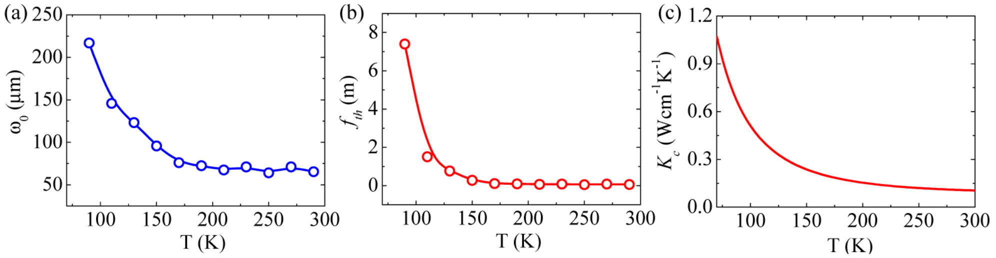

Fig. 6. Temperature dependence for (a) and (b) the experimental results of mode radius and the thermal lensing on the Nd:YAG crystal as well as (c) the theoretical analysis for the thermal conductivity of the Nd:YAG crystal.

6. Conclusion

We investigate the origin of the optimal temperature for the monolithic 946-nm Nd:YAG laser at cryogenic temperature theoretically and experimentally. The mechanism for the improvement of cryogenic 946-nm laser is theoretically confirmed to be the reduction of reabsorption loss. On the other hand, the narrowing of absorption bandwidth around 808 nm for the Nd:YAG crystal at lower temperature will decrease the effective absorption efficiency. With the measured absorption ratio at temperature from 300 K to 80 K, we analyze the effective absorption efficiency with respected to the pump linewidth. It is found that using a pump diode with narrower linewidth contributes to a more efficient output at cryogenic temperature. Experimentally, we employ two pump diodes with pump linewidth of 1 nm and

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2 nm for comparison. It is confirmed that at temperature below 140 K, the influence of narrowing absorption bandwidth is significantly reduced when using the 1-nm-linewidth pump diode. As a result, the theoretical and experimental results both indicate that the main mechanism for the optimal temperature is caused by the combining effects of reabsorption loss elimination and the absorption efficiency reduction. We further discuss plenty minor issues that may also influence the optimal temperature. One of the discoveries is that the thermal lensing elimination at cryogenic temperature may reduce the output efficiency since the pump-to-mode overlapping is decreasing. The increasing of beam size also implied the fact that the output beam quality is improved at cryogenic temperature. However, the detail discussions need to be verified by exploring more specific experiments.

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