Nd:YLF laser at cryogenic temperature with orthogonally polarized simultaneous emission at 1047 nm and 1053 nm

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Abstract: A Nd:YLF laser at cryogenic temperature is demonstrated for the first time with orthogonally polarized simultaneous emission at 1047 nm and 1053 nm. By exploring the temperature dependence of the fluorescence and the absorption spectra from the Nd:YLF crystal, the feasibility of simultaneous emission at low temperature is achieved. Due to the local heating from the pump absorption, the optimal temperature with respect to the pump power for balancing output powers of simultaneous emission is thoroughly explored. At the optimal temperature of 138 K, the total output power of the simultaneous emission can reach 3.1 W at an incident pump power of 7.9 W, corresponding to the optical to optical slope efficiency up to 43%.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3540) Lasers, Q-switched; (140.6810) Thermal effects.

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1. Introduction

Lasers with simultaneous multiple-wavelength emissions have been widely used in holography, medical treatment or double-wavelength lidar, etc [1–4]. The Nd:YLF crystal is a uniaxial crystal that can generate lasers with emission wavelengths at 1047 nm and 1053 nm corresponding to π polarization and σ polarization, respectively [5,6]. As a result, the Nd:YLF crystal is a potential gain medium for generating orthogonally-polarized simultaneous emission at 1047 nm and 1053 nm. This realization is of great interest in the application of self-sensing metrology [7, 8]. However, due to the large difference of the stimulated emission cross section between the 1047-nm and 1053-nm emissions at room temperature [9–11], it is a critical issue to balance the gains for achieving the orthogonally-polarized simultaneous emission with equal output powers for two wavelengths. In earlier works [12,13], a wedged a-cut Nd:YLF crystal together with its birefringence property was employed to select the emission at 1047 nm and 1053 nm by separating the resonant path in the cavity. Even though this approach could be used to obtain the simultaneous emission by aligning the optical path just between two resonant paths, the total output power certainly suffered considerable losses arising from the misalignment for balancing the gains.

In 1969, Harmer *et al.* [14] have observed that the ratio between the spontaneous intensities along the σ and π polarizations of the Nd:YLF crystal would increase from the value less than 1.0 to the value greater than 1.0 when the temperature was decreased from 300 K to 77 K. A similar behavior was also observed in the spontaneous fluorescence of the Nd:YAG crystal that the dominated intensity peak changed from 1064 nm to 1061 nm at cryogenic temperature [15]. Recently, the variation of the emission intensities on the temperature has been successfully exploited to demonstrate an efficient operation of the simultaneous two-wavelength emissions in a Nd:YAG laser with the balanced output powers at 1061 nm and 1064 nm by cooling the gain medium to the optimal temperature of 152 K [16]. This demonstration indicates that it is highly feasible to generate an efficient Nd:YLF laser with simultaneous emission at 1047 nm and 1053 nm by using the cryogenic system. So far the cryogenic cooling is mostly adopted to boost the output efficiency of quasi-three-level solid-state lasers [17–22]. Even though the output efficiency cannot be considerably increased by using the cryogenic method for four-level lasers [16], the beam quality can be significantly improved through the enhancement of the thermal-optic property [23].

In this work, we report for the first time a cryogenic Nd:YLF laser with orthogonally-polarized simultaneous emission at 1047 nm and 1053 nm in a collinear resonator. We explore the temperature dependence of the spontaneous fluorescence spectra from the Nd:YLF crystal to confirm the optimal temperature for balancing the emission intensities at 1047 nm and 1053 nm. The absorption coefficient around 806 nm is also reported to verify the output performance with respect to the temperature. Considering the local heating effect from the pump absorption, the optimum temperature for the simultaneous two-wavelength emission is experimentally found to be varied with different pump intensity. At an incident pump power of 7.9 W, the equal output power of 1.55 W for two wavelengths can be simultaneously achieved at a temperature of approximate 138 K. Under the optimal operation, the optical to optical conversion efficiency is 39% and the slope efficiency is up to 43%.

2. Experimental setup

Figure 1 schematically depicts the experimental setup for the Nd:YLF laser with cryogenic system. A concave mirror with 350-mm radius of curvature was used as the front mirror with high-transmittance coating (HT, T > 95%) at 806 nm as well as high-reflective coating (HR, R > 99.9%) at 1050 nm. We used a 20-mm 0.8-at.-% a-cut Nd:YLF crystal with a transverse aperture of 3 × 3 mm^2 as the laser gain medium. Both end surfaces of the gain medium were coated to be anti-reflectance (AR, R < 0.1%) at 806 nm and 1050 nm. The laser crystal was mounted in an oxygen-free copper holder with indium foil to improve the heat spreading efficiency. We attached the copper block to the cold finger of the temperature-controlled cryostat (VPF-100, Janis Research Co.) and placed it in a vacuum chamber. A calibrated Pt-Au thermocouple was applied on the material surface with a nano-voltmeter (Lake Shore 331) to measure the temperature. Two plane-parallel optical windows coated with 99.8%-transmittance at a wavelength range from 800 nm to 1700 nm were placed on the vacuum chamber. We utilized a plane output coupler coated with partial reflectance (PR, R = 97%) at 1050 nm. The cavity length of the resonator was approximately 90 mm. We used a 10-W 806-nm fiber-coupled laser diode with a 400-μm fiber core diameter and a numerical aperture of 0.16 as the pump source. The pump light was reimaged into the laser crystal through a 50-mm focusing lens pair with an overall coupling efficiency of approximately 85%.

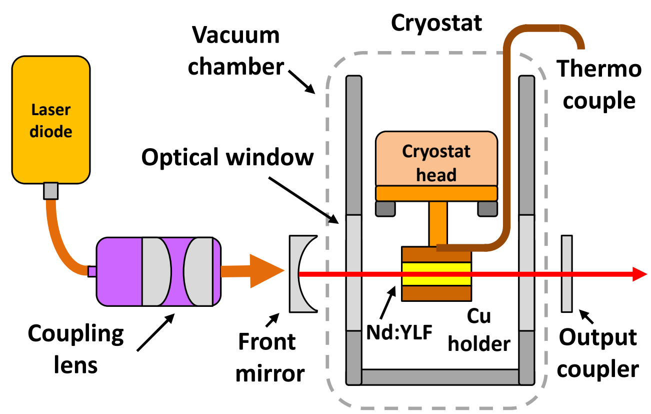

Fig. 1. Experimental setup for the simultaneous orthogonally polarized Nd:YLF laser at cryogenic temperature.

3. Experimental results

At first, we explored the temperature dependence of the fluorescence spectra and the absorption coefficient for the Nd:YLF crystal to anticipate the temperature for balancing output powers of two emission wavelengths since the fluorescence intensity is related to the emission cross-section for the laser oscillation. We utilized an optical spectrum analyzer with 0.1-nm resolution (Advantages, Q8381A) to record the emission spectra. Figure 2 presents the spontaneous fluorescence spectra for π and σ polarizations of the Nd:YLF crystal and the absorption coefficient from 110 K to 290 K. For the observation of the fluorescence spectra, the laser resonator was removed and the pump power was maintained to be approximately 0.5 W. From Fig. 2 (a), we believed that the optimal temperature for balancing output powers at two emission wavelengths was at approximately 170 K. Then, to measure the unpolarized absorption of the Nd:YLF crystal at around 806 nm, we operated the laser diode below threshold and collected the transmittance spectra with and without the gain medium since the laser diode behaved like a broadband light source at such status [23]. As a result, the absorption coefficient of the Nd:YLF crystal can be calculated with the absorption and the crystal length. We further compared the absorption coefficient of the Nd:YLF crystal at different temperature with the normalized emission spectrum of the laser diode operated at 7.9 W. The temperature of the laser diode was approximately 296 K with the peak emission wavelength at 806 nm. From Fig. 2 (b), we find that the absorption coefficient of the Nd:YLF crystal at 806 nm is increased from 2.56 cm^{-1} at 290 K to the maximum value of 2.96 cm^{-1} at around 170 K, then decreased to approximately 2.71 cm^{-1} at 110 K. For the absorption spectral linewidth, it is found to decrease from approximately 3 nm to 2 nm as the temperature was decreased from 290 K to 110 K. Nevertheless, the spectral linewidth near 806 nm for the Nd:YLF crystal at low temperature is still larger than the emission bandwidth of the laser diode, which is approximately 1.5 nm.

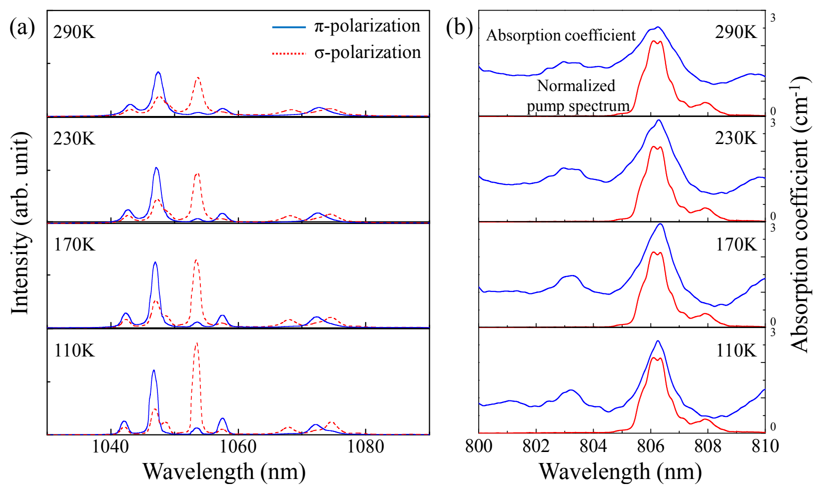

Fig. 2. The temperature dependence of the fluorescence spectra on two polarizations from the Nd:YLF crystal and the comparison between the absorption coefficient as well as the normalized pump spectrum at 290 K, 210 K, 170 K and 110 K.

Figure 3 shows the total output power with respected to the incident pump power of the Nd:YLF laser at different temperature. We found out that the total output power at the room temperature of 290 K was slightly lower than output powers at other temperatures. At 290 K, the output power was 2.7 W at an incident pump power of 7.9 W with the optical to optical slope efficiency of 39%. When the temperature was decreased, the output power reached approximately 3.1 W at the same pump power of 7.9 W and the slope efficiency was up to 43%. We believed that the power scaling of the Nd:YLF laser at low temperature may come from the improvement of the absorption coefficient as well as the enhancement of the thermal-optic property for the laser crystal. To explore the dynamic of the orthogonally polarized Nd:YLF laser, we utilized a polarization beam splitter to separate the output power of two polarizations and recorded the output performance. Figure 4 plots output powers at 1047 nm and 1053 nm with respect to the cooling temperature at numerous incident pump powers. With the incident pump power of 7.9 W and the optimal temperature of approximately 138 K, we obtained a Nd:YLF laser with 1.55-W output powers at both 1047 nm and 1053 nm. The stimulated emission spectrum with various temperatures at the pump power of 7.9 W is demonstrated in Fig. 5 (a). We found out that central peaks of the Nd:YLF laser at 1047 nm and 1053 nm would shift toward longer wavelengths with shifting rates of approximately 4.5×10^{-3} nm K^{-1} and 2.7×10^{-4} nm K^{-1} respectively when the temperature was decreased. Figure 5 (b) depicts the temporal dynamic of the orthogonally polarized Nd:YLF laser at 1047 nm and 1053 nm, which implied that the laser output at two polarizations are simultaneously continuous wave without anti-phase dynamic. The laser beam qualities for each polarization were found to be maintained at approximately 1.3.

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Transverse distributions for two polarizations of the Nd:YLF laser operated at the optimal temperature with incident pump power of 7.9 W were presented in the inset of Fig. 6.

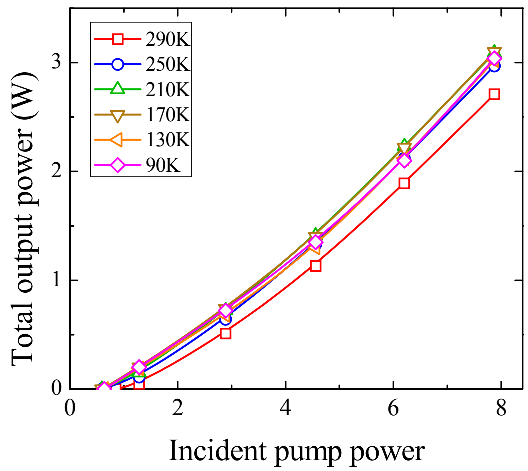

Fig. 3. Total output powers of the cryogenic Nd:YLF laser with respect to the incident pump power at different temperature.

Because of the local heating from the pump absorption, we can further observe from Fig. 4 that the optimal temperature for balancing output powers at two wavelengths depends on the pump power. As a result, the optimal temperature for different pump intensities was further reported to confirm the contribution from the local heating, which is shown in Fig. 6. It is worth to mention that with the linear fitting curve in Fig. 6, the optimal temperature of the orthogonally polarized Nd:YLF laser was found to approach to 153 K when the pump intensity decreased to zero, which was lower than the temperature of 170 K that we anticipated from the fluorescence spectra in Fig. 2. We believed that the temperature difference comes from the different thermal effect between π polarization and σ polarization in the Nd:YLF crystal [11]. However, the detail discussion needs further investigation since the accurate calculation related to numerous complicated thermal properties of the gain medium when the crystal was cooling to the cryogenic temperature. The inset in Fig. 6 shows transverse distributions for the Nd:YLF laser at 1047 nm and 1053 nm with the optimal temperature of 138 K and the pump power of 7.9 W.

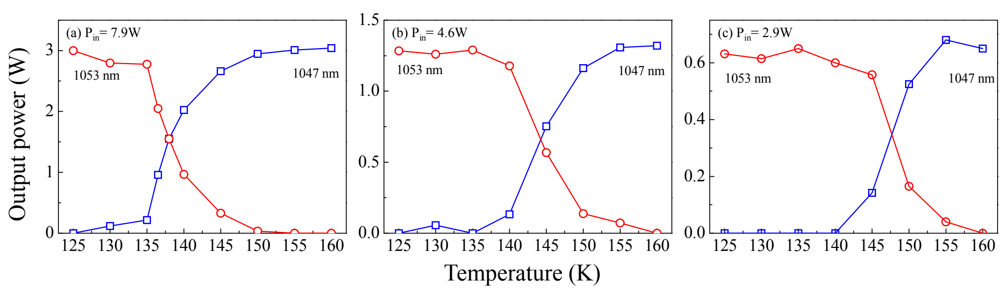

Fig. 4. Output powers of the Nd:YLF laser at 1047 nm and 1053 nm with respect to the temperature at incident powers of (a) 7.9 W, (b) 4.6 W and (c) 2.9 W.

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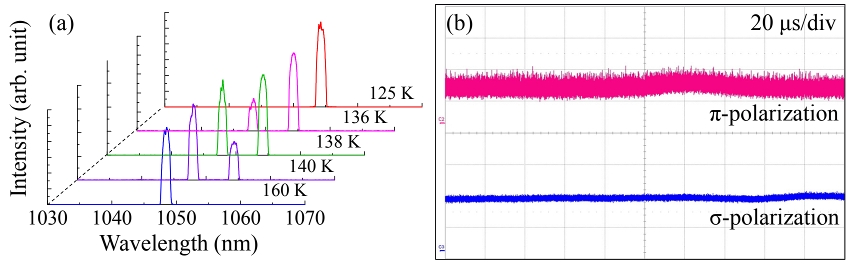

Fig. 5. (a) Stimulated emission spectra of the cryogenic Nd:YLF laser at the incident pump power of 7.9 W with cooling temperatures of 160 K, 140 K, 138 K, 136 K and 125 K. (b) The temporal dynamics of the cryogenic Nd:YLF laser at 1047 nm and 1053 nm with the optimal temperature and the incident pump power of 7.9 W.

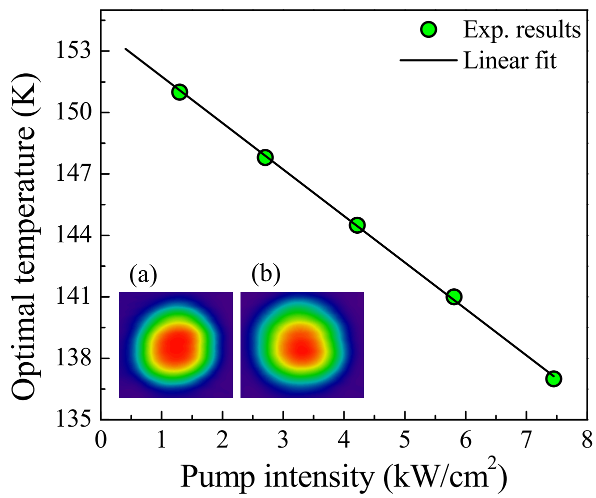

Fig. 6. Experimental results of the optimal temperature for balancing output powers of two emission wavelengths for the orthogonally polarized Nd:YLF laser with respect to the pump intensity and the linear fitting curve of the experimental data. The inset: Transverse distribution of the dual-polarization Nd:YLF laser at the optimal temperature and the pump power of 7.9 W for (a) 1047 nm and (b) 1053 nm.

4. Conclusion

In conclusion, we have demonstrated an efficient cryogenic Nd:YLF laser with orthogonal polarized simultaneous emission at 1047 nm and 1053 nm. The feasibility for achieving equal output powers of two emission wavelengths has been confirmed by exploring the temperature dependence of the fluorescence spectra and the absorption coefficient for the Nd:YLF crystal in a temperature range from 110 K to 290 K. Due to the local heating arising from the pump absorption, the optimal temperature for balancing output powers at tow polarizations varies with the incident pump intensity. At the optimal temperature of 138 K, output powers of the Nd:YLF laser at each wavelengths reaches 1.55 W with an incident pump power of 7.9 W. The optical to optical conversion efficiency is 39% and the slope efficiency is up to 43%. To the best of our knowledge, it is the highest conversion efficiency for a orthogonally polarized Nd:YLF laser with simultaneous emission at 1047 nm and 1053 nm.

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