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LETTER

A cryogenically cooled Nd:YAG monolithic laser for efficient dual-wavelength operation at 1061 and 1064 nm

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Abstract
We experimentally explore the fluorescence spectra of the Nd:YAG (YAG: yttrium aluminum garnet) crystal at cryogenic temperatures to confirm the feasibility of dual-wavelength operation at 1061 and 1064 nm. Furthermore, a cryogenically cooled Nd:YAG crystal with coating to form a monolithic cavity is employed to investigate the performance of the dual-wavelength operation. At an incident pump power of 20 W, the output powers for each wavelength can simultaneously reach 6.0 W at the optimally balanced temperature of 152 K. The optimal temperature for balancing the output powers of the two wavelengths is experimentally determined as a function of the incident pump power intensity.

(Some figures may appear in colour only in the online journal)

1. Introduction

Dual-wavelength lasers have attracted much interest due to the many potential applications including laser spectroscopy, holography, LiDAR, medical instrumentation, and nonlinear optical mixers [1–5]. Neodymium-doped laser materials have been identified as prospective candidates for realizing simultaneous dual-wavelength emission because they possess many sharp fluorescent lines with the transitions of $^4F_{3/2} \rightarrow {}^4I_{9/2}$, $^4F_{3/2} \rightarrow {}^4I_{11/2}$, and $^4F_{3/2} \rightarrow {}^4I_{13/2}$ [6–10]. Nd-doped dual-wavelength lasers with a small wavelength separation [11–15] are particularly desirable in generating coherent terahertz (THz) radiation by difference frequency generation [16].

Recently, Nd-doped mixed scandium garnet (Nd:YSAG) ceramics have been demonstrated to simultaneously operate at the two wavelengths of 1061 and 1064 nm which are the two strongest emission peaks in the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition [17, 18]. It was also found that the relative intensity of the two wavelengths of 1061 and 1064 nm depends on the operation temperature and the pump power intensity. Actually, the balance between the rates of spontaneous emissions at 1061 and 1064 nm has earlier been observed in Nd:YAG crystals and ceramics at cryogenic temperatures [19]. Nevertheless, the performance of dual-wavelength Nd:YAG lasers at 1061 and 1064 nm has so far not been explored.

In this work, we first investigate the fluorescence spectra of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition in Nd:YAG crystals in a temperature range between 70 and 300 K under low-level pumping. Experimental results confirm that the rates of spontaneous emissions at 1061 and 1064 nm can be nearly balanced at a temperature of approximately 210 K. We further employ a coated Nd:YAG crystal forming a monolithic cavity to explore the dual-wavelength operation

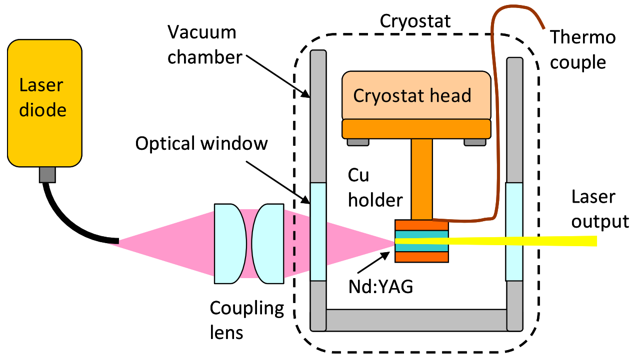

Figure 1. Schematic diagram of the experimental setup at cryogenic temperatures.

at cryogenic temperatures. We experimentally obtain the optimal temperature for balancing the output powers of the two wavelengths. It is found that the optimal temperature considerably decreases with increasing pump power intensity due to the local heating. At an incident pump power of 20 W, the output powers for each wavelength can be up to 6.0 W at the optimally balanced temperature of 152 K, corresponding to an optical conversion efficiency of nearly 60%.

2. The temperature dependence of the spontaneous fluorescence

Figure 1 shows a schematic diagram of the experimental setup at cryogenic temperatures. The laser crystal was wrapped with indium foil and mounted in an oxygen-free copper holder. The copper holder with the laser crystal was placed in a vacuum chamber and attached to the cold finger of the temperature-controlled cryostat (VPF-100, Janis Research Co.). We utilized a calibrated Kp–Au thermocouple on the material surface with a nano-voltmeter (Lake Shore 331) to measure the temperature.

The laser crystal is a 1.1 at.% Nd:YAG crystal with a length of 5 mm and a diameter of 3 mm. The Nd:YAG sample used for the measurement of temperature-dependent spontaneous fluorescence spectra was antireflection (AR) coated at 808 nm and 1030–1100 nm ($R < 0.2\%$) on both end facets. The pump source was a 24 W 808 nm fiber-coupled laser diode with a 600 μm fiber core diameter and a numerical aperture of 0.16, reimaged into the laser crystal through a pair of focusing lenses with a focal length of 50 mm and 85% coupling efficiency. The pump spot radius was approximately 300 μm. The spectral information was monitored by using an optical spectrum analyzer (Advantest Q8381A) that employs a diffraction grating monochromator with the resolution of 0.1 nm.

Figure 2 shows experimental results for the fluorescence spectra in the range between 1060 and 1070 nm at a low pump power intensity of 0.2 kW cm^{-2} for different temperatures of 170, 190, 210, and 230 K. The spectra display two dominant peaks near 1061 and 1064 nm, which are mainly contributed by the transitions of $^4F_{3/2}$ (R$_1$) → $^4I_{11/2}$ (Y$_1$) and $^4F_{3/2}$ (R$_2$) → $^4I_{11/2}$ (Y$_3$), respectively. It is confirmed that the

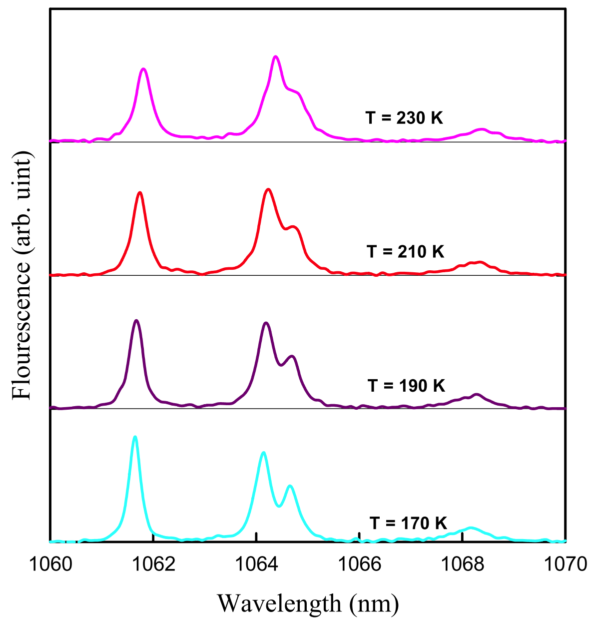

Figure 2. Experimental results for the fluorescence spectra in the range of 1060–1070 nm at a low pump power intensity of 0.2 kW cm^{-2} for different temperatures of 170, 190, 210, and 230 K.

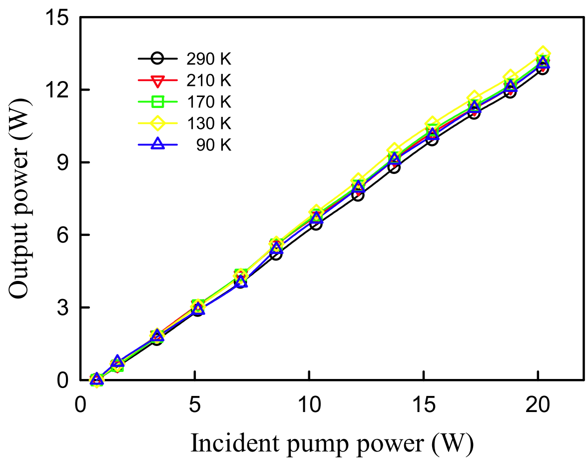

Figure 3. Output power with respect to the incident pump power for different temperatures of 90, 130, 170, 210, and 290 K.

fluorescence intensities of the two wavelengths $I_{1061\ \mathrm{nm}}$ and $I_{1064\ \mathrm{nm}}$ can nearly be balanced at a temperature of 200 K. The balance of the fluorescence intensities at 1061 and 1064 nm indicates the feasibility of dual-wavelength operation in a cryogenically cooled Nd:YAG laser. Moreover, the peaks can be found to shift toward the shorter wavelengths with decreasing temperature. The shifting rates are approximately 3.1×10^{-3} and 3.4×10^{-3} nm K^{-1} for the peaks at 1061 and 1064 nm, respectively.

3. Cryogenically cooled Nd:YAG monolithic lasers

We employed a Nd:YAG sample with coating to form a monolithic cavity to explore the performance at cryogenic

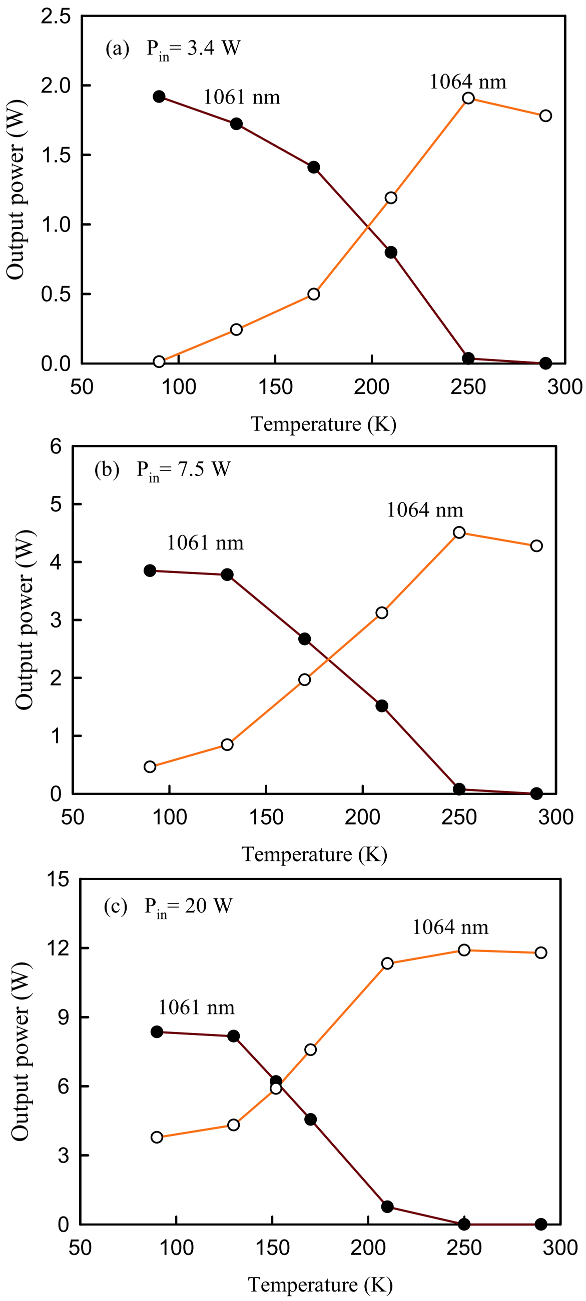

Figure 4. Temperature dependence of the output powers at 1061 and 1064 nm for three different pump powers of 3.4, 7.5, and 20 W.

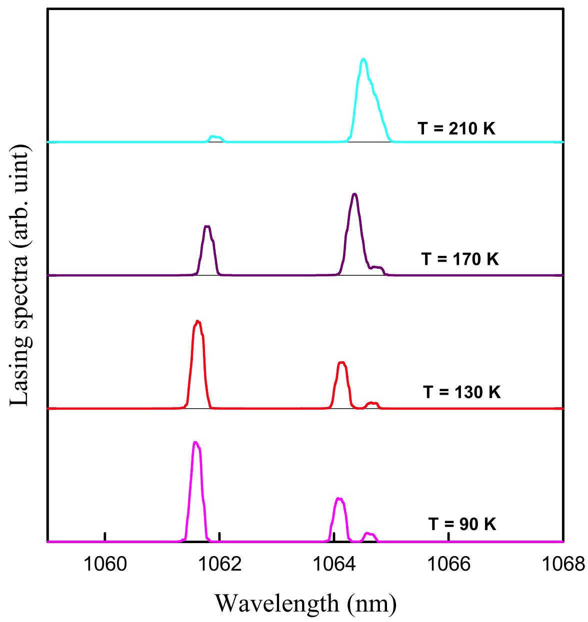

Figure 5. Temperature dependence of the lasing spectra at a pump power of 20 W.

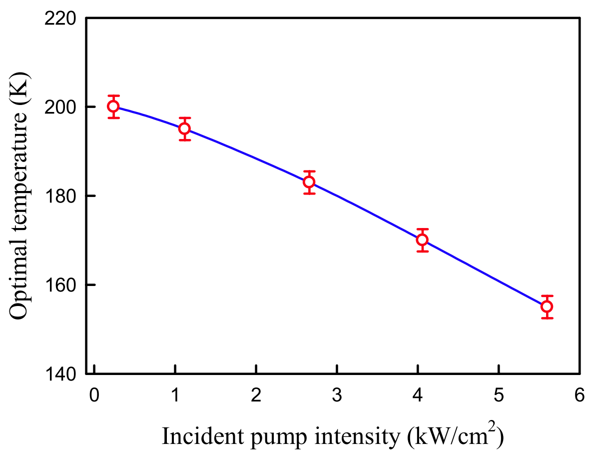

Figure 6. Optimal temperature for balancing the dual-wavelength output powers as a function of the incident pump power intensity.

temperatures. The monolithic Nd:YAG crystal was high-reflection coated at 1030–1100 nm ($R > 99.8\%$) and high-transmission coated at 808 nm ($T > 95\%$) on the front surface and was partially reflection coated at 1060–1070 nm ($R = 95\%$) on the output surface. Figure 3 shows the output power with respect to the incident pump power for different temperatures of 90, 130, 170, 210, and 290 K. The overall performance is found to be nearly independent of temperature and the optical-to-optical conversion efficiency is up to 60%.

In contrast, the lasing spectra were found to be significantly dependent on the temperature and to display two peak wavelengths located at 1061 and 1064 nm for temperature below 250 K. Figure 4 depicts the temperature dependence of the output powers at 1061 and 1064 nm for three different pump powers of 3.4, 7.5, and 20 W. It is observed that the optimal temperature for balancing the dual-wavelength output powers shifts toward lower values with increasing pump power due to the local heating. With an incident pump power of 20 W, the output powers for each wavelength can reach 6 W at the optimally balanced temperature of 152 K. The temperature dependence of the lasing spectra at a pump power of 20 W is shown in figure 5. As observed in the spectra of spontaneous emission, the central peaks slightly shift toward the shorter wavelengths with decreasing temperature. Finally, the optimal temperature for balancing the dual-wavelength output powers is experimentally determined as a function of the incident pump power intensity, as shown in figure 6.

4. Conclusion

The fluorescence spectra of the Nd:YAG crystal at cryogenic temperatures have been experimentally investigated to verify the feasibility of dual-wavelength operation at 1061 and 1064 nm. We further utilized a cryogenically cooled Nd:YAG crystal with coating to form a monolithic cavity to explore the performance of the dual-wavelength operation. At an incident pump power of 20 W, the output powers for each wavelength can simultaneously reach 6.0 W at the optimally balanced temperature of 152 K. The optimal temperature for balancing the output powers of the two wavelengths was found to shift toward lower temperatures with increasing pump power due to the local heating. We have experimentally determined the optical temperature as a function of the incident pump power intensity.

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