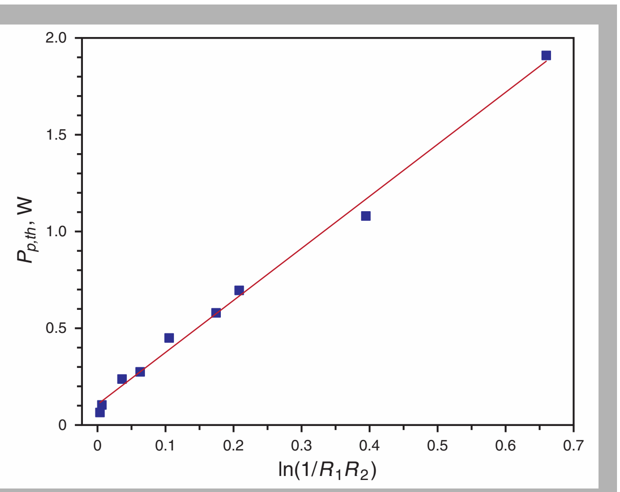
Abstract: The stimulated emission cross section of a 1.1-at.% doped Nd:$Gd_{3x}Y_{3(1-x)}Sc_2Ga_{3(1+\delta)}O_{12}$ ($x = 0-1$, $\delta = -0.2-0.2$) (Nd:GYSGG) crystal at 1.06 μm ($^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition) is measured at room temperature, using both the laser efficiency comparison method with an Nd:$Y_3Al_5O_{12}$ (Nd:YAG) laser and the threshold formula method, with their results of 1.59×10^{-19} and 1.50×10^{-19} cm^2, respectively. The measured results accord well with each other and they are of great use in designing a Nd:GYSGG laser system.



The relationship of $P_{p,th}$ and $\ln(1/R_1R_2)$ for the Nd:GYSGG laser

Stimulated emission cross section of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition of Nd:GYSGG

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1. Introduction

The Nd^{3+} doped garnet crystals such as Nd:$Y_3Al_5O_{12}$ (Nd:YAG), Nd:$Gd_3Ga_5O_{12}$ (Nd:GGG), Nd:$Gd_3Sc_2Ga_3O_{12}$ (Nd:GSGG), Nd:$Y_3Sc_2Ga_3O_{12}$ (Nd:YSGG), etc, have been regarded as the most excellent laser materials to achieve the 1.3, 1.06, and 0.9 μm near-infrared lasers and the frequency-doubled red, green and blue lasers [1–16]. Therefore, such materials have been developing incessantly for different laser properties these years. The Nd:$Gd_{3x}Y_{3(1-x)}Sc_2Ga_{3(1+\delta)}O_{12}$ ($x = 0-1$, $\delta = -0.2-0.2$) (Nd:GYSGG) crystal is a new laser material, which shows several good advantages compared with the other Nd^{3+} doped garnet crystals like Nd:YAG, such as high segregation coefficient, anti-radiation performance, large fluorescence branching ratio in the 0.9 μm wavelength band, etc. The continuous-wave (CW), Q-switched and mode-locked laser performance in

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the 1.06 μm band ($^4F_{3/2} \rightarrow {}^4I_{11/2}$) have been reported in several research works recently [17–19], in which the highest conversion efficiency reaches nearly 60%. As everyone knows, the stimulated emission cross section is one of the most important parameters in determining the maximum gain, saturation power, and optimum output mirror reflectivity, etc, in a well-designed laser system. However, this parameter still keeps blank in open published journal papers up to now. Although the stimulated emission cross section can be measured using the Füchtbauer-Ladenburg (F-L) formula [20–22], too many special equipments are needed to obtain a lot of parameters like the fluorescence spectra, fluorescence life time, fluorescence branching ratio and so on.

In this paper, we report the measurement of the stimulated emission cross section of Nd:GYSGG crystal emanating from the $^4F_{3/2}$ state and terminating on the $^4I_{11/2}$ state at room temperature using two much simpler and more effective methods: laser efficiency comparison method (Tucker's method of comparing laser efficiency) [23] and the threshold formula method [24]. The results are 1.59×10^{-19} and 1.50×10^{-19} cm^2, respectively, which is in good accordance with each other.

2. The laser efficiency comparison method

2.1. Theoretical analysis

The gain per pass is exactly equal to the internal and external losses when a laser is in a steady-state operation. Therefore, the conditions of laser operation at threshold can be expressed as

$$R_1 R_2 \exp\left[2l(g - L_i)\right] = 1\,, \tag{1}$$

whereR_1 and R_2 are the effective mirror reflectivities of the laser cavity, l is the length of the laser crystal, g is the single pass gain coefficient at threshold and L_i is the total internal losses per centimeter (exclusive of transmission losses by the mirror transmittance), which includes losses introduced by scattering losses, diffraction losses, excited-state absorption and optical inhomogeneity, etc. The format of Eq. (1) can be changed into

$$\ln(1/R_1R_2) = 2l(g - L_i)\,. \tag{2}$$

The single pass gain coefficient g is related to the population density of the upper laser level N_u and the stimulated emission cross section σ when the laser operates at threshold. The relationship can be described by

$$g = \sigma N_u\,. \tag{3}$$

Substituting Eq. (3) into Eq. (2), we can get

$$\ln(1/R_1R_2) = 2l(\sigma N_u - L_i)\,. \tag{4}$$

For a four-level laser material, the upper level population density N_u is related to the absorbed pump power in CW operation at threshold according to Eq. (5):

$$N_u = \frac{\tau \eta_p f_B P_a}{h v_p V}\,, \tag{5}$$

where τ is the fluorescence lifetime, η_p is the pump quantum efficiency, P_a is the absorbed pump power by the laser crystal at threshold, hv_p is the pump photon energy, V is the pumped volume, and f_B is the fractional number of Nd^{3+} ions in the appropriate laser sublevel of the $^4F_{3/2}$ state.

The pumping efficiency η_p represents the fraction of the absorbed pump photons producing population inversion. For the Nd^{3+} doped four-level laser materials, it is considered that each absorbed pump photon leads to an Nd^{3+} ion in the $^4F_{3/2}$ state, and therefore to a close approximation $\eta_p = 1$ [23]. This conclusion has been proved experimentally and in all subsequent equations η_p will be taken to be unity.

Ignoring the overlap of the sublevels of the $^4F_{3/2}$ state, f_B will be

$$f_B = \frac{1}{1 + \exp(hc\Delta\bar{v}/KT)}\,, \tag{6}$$

where h is Planck's constant, c is the velocity of light, K is Boltzman's constant, T is the Kelvin temperature, and $\Delta\bar{v}$ is the level splitting in wave numbers between the upper and lower sublevels of the $^4F_{3/2}$ state. For Nd:YAG, $\Delta\bar{v} = 88$ cm^{-1} so that $f_B = 0.40$. For Nd:GYSGG, $\Delta\bar{v} = 52.54$ cm^{-1}, then $f_B = 0.44$. However, considering the overlap between the sublevels of the$^4F_{3/2}$ state of Nd:YAG, there is a small correction ($\sim 6\%$) for f_B [25], and for Nd:GYSGG it is of the same case.

If the laser operates at threshold, $P_a = P_{th}$. Combining Eq. (4) and Eq. (5) we obtain

$$\ln(1/R_1R_2) = \frac{2l\sigma f_B \tau}{h v_p V} P_{th} - 2lL_i\,. \tag{7}$$

From Eq. (7) we can get the stimulated emission cross section of the crystal through plotting the $P_T \sim \ln(1/R_1R_2)$ graph. Defining its slope as M_p

$$M_p = \frac{d\left[\ln(1/R_1R_2)\right]}{dP_{th}} = \frac{2lf_B\tau\sigma}{hv_pV} \tag{8}$$

then we get

$$\sigma = M_p \frac{hv_pV}{2lf_B\tau}\,. \tag{9}$$

However, it is difficult to determine the pumped volume V accurately. If the stimulated emission cross section of a particular crystal is known, and the experiments of two crystals have the same procedure and are pumped in an identical geometrical arrangement, it is convenient to

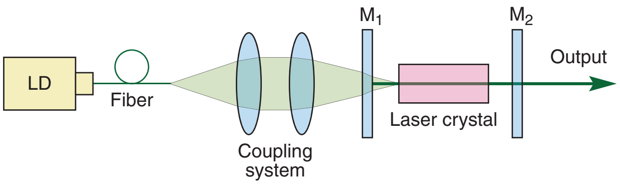

Figure 1 (online color at www.lphys.org) Schematic diagram of the experimental setup

measure an unknown cross section of another crystal relative to the "standard". Consequently,

$$\frac{\sigma_x}{\sigma_{STD}} = \frac{(M_p/f_B\tau)_x}{(M_p/f_B\tau)_{STD}} . \tag{10}$$

If the Nd:YAG crystal is chosen as the "standard", then Eq. (10) can be written as

$$\frac{\sigma_{GYSGG}}{\sigma_{YAG}} = \frac{(M_p/f_B\tau)_{GYSGG}}{(M_p/f_B\tau)_{YAG}} . \tag{11}$$

The emission cross section σ of Nd:GYSGG can be obtained if we know the slope M_p of the Nd:GYSGG crystal and the Nd:YAG crystal. And from Eq. (7) we can also obtain the internal losses L_i from the ordinate intercept at $P_{th} = 0$.

2.2. Experimental results and discussions

The schematic of the experimental setup is shown in Fig. 1. The pump source is a fiber coupled diode laser with the central wavelength of 808 nm at room temperature. The fiber numerical aperture is 0.22 and its core diameter is 400 μm. A plane parallel cavity with the length of 26 mm is used. The rear mirror (M_1) is coated for anti-reflection (AR) around 808 nm and high-reflection (HR) around 1.06 μm ($R > 99.94\%$), while the output mirror (M_2) is part-transmission (PT) coated. The pump wave is focused by the coupling system into the laser crystal at a spot radius of about 160 μm. The Nd:GYSGG crystal is 1.1-at% doped, grown by the Czochralski method and cut along the $\langle 111 \rangle$ direction with the dimension of $3\times3\times6$ mm^3. Both sides of the Nd:GYSGG crystal are polished and AR coated around 808 nm and 1.06 μm for diode end pumping. Another 1.1-at.% doped Nd:YAG crystal which is also 6-mm long and AR coated on both ends is used as the reference sample.

Several output couplers are used in the experiment with their reflectivities of 99.4, 96.5, 93.9, 90.0, 84.0, 81.2, 67.4, and 51.7% around 1.06 μm. For each output mirror, the absorbed pump power at laser resonating threshold ($P_{th,a}$) is measured. Data are collected both for Nd:GYSGG and Nd:YAG crystals. The relationships of

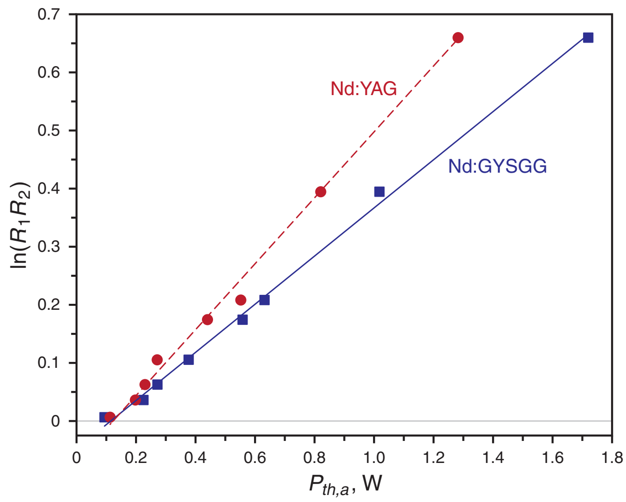

Figure 2 (online color at www.lphys.org) The relationship of $ln(1/R_1R_2)$ and $P_{th,a}$ for Nd:GYSGG and Nd:YAG lasers

$\ln(1/R_1R_2)$ and $P_{th,a}$ for are shown in Fig. 2, where the total internal losses L_i and the slopes can be obtained according to Eq. (7).

The following parameters are used for determining σ_{GYSGG}: the fluorescent lifetime of Nd:GYSGG and Nd:YAG are 220 μs [26] and 230 μs [27]; the stimulated emission cross section of Nd:YAG $\sigma_{YAG} = 2.3\times10^{-19}$ cm^2 [28]; the slopes of the $\ln(1/R_1R_2) \sim P_{th,a}$ curves for Nd:GYSGG and Nd:YAG are 0.4144 and 0.5675, respectively. It is easy to obtain $\sigma_{GYSGG}/\sigma_{YAG}$ equals to about 0.69 according to Eq. (8) and Eq. (11), which indicates that the stimulated emission cross section of Nd:GYSGG is about 1.59×10^{-19} cm^2. Considering the sources of errors introduced in our experiments the inaccuracy of this value could be 20%.

Calculated from the curve intercept value of 0.048 in Fig. 2, the total internal loss coefficient L_i of Nd:GYSGG at 1.06 μm is 0.04 cm^{-1}, and the single-pass total internal loss is about 2.4% for the 6-mm long Nd:GYSGG. The large loss may be caused by crystal quality, coatings, and experimental errors, etc. However, the internal loss coefficient does not affect the measurement of stimulated emission cross section.

3. The threshold formula method

3.1. Theoretical analysis

The stimulated emission cross section σ can also be obtained from the formula shown as follows:

$$\sigma = \frac{\pi h\nu_p (w_c^2 + w_p^2)^2}{4\eta_p P_{th,a}\tau}(L_i + T) , \tag{12}$$

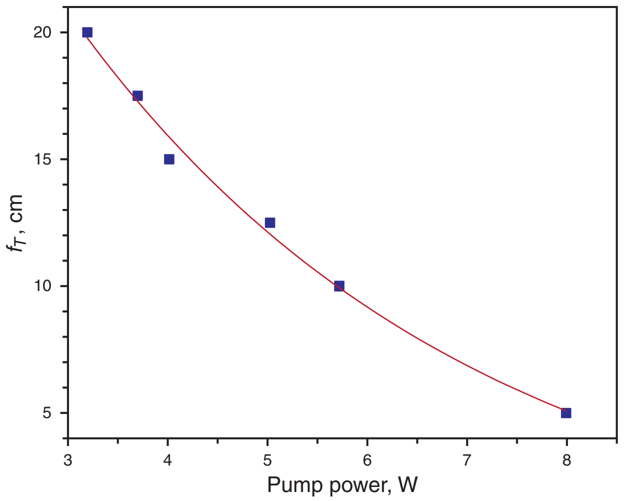

Figure 3 (online color at www.lphys.org) Thermal focal lengths of the Nd:GYSGG laser at different pump powers

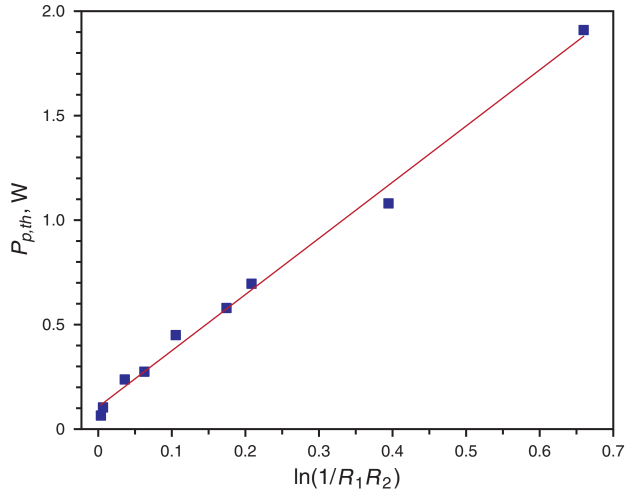

Figure 4 (online color at www.lphys.org) The relationship of $P_{p,th}$ and $\ln(1/R_1R_2)$ for the Nd:GYSGG laser

where w_p and w_c are the pump and the cavity beam spot size, respectively, hv_p is the pump photon energy, T is the output coupler transmission at 1.06μm, L_i is the total internal losses, $P_{th,a}$ is the absorbed threshold pump power, τ is the fluorescence lifetime, and η_p is the pumping efficiency. If we know all the parameters of the equation on the right, the stimulated emission cross section can be calculated.

Here the Findlay-clay method [29] is used to obtain the total internal losses L_i. For a four-level laser system, Eq. (5) can also be written as

$$N_u = AP_{p,th}\,, \quad (13)$$

where $P_{p,th}$ is the incident pump power at threshold, A is a constant including the absorption coefficient, pump energy and the distribution of the pump light in the laser medium.

Combining Eq. (4), and Eq. (13), we can get

$$P_{p,th} = \frac{1}{A\sigma}\left[\frac{1}{2l}\ln(1/R_1R_2) + L_i\right]. \quad (14)$$

While $R_1 = R_2 = 1$, Eq. (14) becomes

$$P_{p,th,o} = \frac{L_i}{A\sigma}\,, \quad (15)$$

where $P_{p,th,o}$ is the pump power at threshold for zero output coupling. Substitute Eq. (15) into Eq. (14), we finally obtain:

$$P_{p,th} = \frac{P_{p,th,o}}{2L_il}\ln(1/R_1R_2) + P_{p,th,o}\,. \quad (16)$$

Eq. (16) shows that the threshold incident pump power is a linear function of $\ln(1/R_1R_2)$. Therefore by varying the reflectivity of the output mirror and measuring the incident pump power at threshold, the internal losses L_i can be determined from the slope and intercept of the $\ln(1/R_1R_2) \sim P_{p,th}$ plotting.

3.2. Experimental results and discussions

We use Eq. (12) to calculate the stimulated emission cross section of Nd:GYSGG crystal. The basic parameters needed for the calculation are $w_p = 160$ μm, $\tau = 220$ μs, $T = 10\%$, and $\eta_p = 1$ as mentioned above. Before the cavity beam waist w_c is obtained, the thermal focal length f_T is measured using the method in [30]. Fig. 3 shows the experimental results (in squares) and the exponentially fitted curve, from which the thermal focal length at threshold incident pump power can be determined to be 410 mm and the cavity beam waist w_c is calculated to be about 174 μm for the plane parallel resonator we used.

The internal losses L_i is measured through Eq. (16) using the experimental setup exactly the same as that in Fig. 1. The relation curve of $P_{p,th}$ and $\ln(1/R_1R_2)$ is plotted in Fig. 4.

The internal loss coefficient L_i is about 0.045 cm^{-1}, and thus the single-pass internal loss of the Nd:GYSGG laser is 2.7%. It is in good accordance with the value of our earlier result. For accuracy, an average value $L_i = 2.54\%$ is adopted and the stimulated emission cross section is calculated to be 1.50×10^{-19} cm^2 from Eq. (12). However, since the error introduced in measuring the thermal focal length at threshold may be quite large, the cavity beam waist and the last calculated stimulated emission cross section should differ from the actual value. A departure of 0.50×10^{-19} cm^2 for σ is considered reasonable.

4. Conclusion

The stimulated emission cross section for the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition at 1.06 μm of an 1.1-at.%

doped Nd:GYSGG crystal is measured at room temperature by both the laser efficiency comparison method and the threshold formula method, with their values of about 1.59×10^{-19} and 1.50×10^{-19} cm^2, respectively. These values are of great consistency for similar experimental results. As the error causation of laser efficiency comparison method is less than that of the threshold formula method, the former value is believed to be more accurate. The measurement of stimulated emission cross section is of great importance in a well designed Nd:GYSGG laser system.

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