Experimental determination of the thermo-optic coefficient \( \frac{dn}{dT} \) and the effective stimulated emission cross-section \( \sigma_e \) of an \( a \)-axis cut 1.3-at.\% doped Nd : GdVO\(_4\) crystal at 1.06 µm wavelength

1 Diode Pumped Solid State Laser Group, Center for Advanced Technology Indore, M.P. 452013, India
2 Biomedical Applications section, Center for Advanced Technology, Indore, M.P. 452013 India

Received: 6 January 2003 / Revised version: 3 April 2003
Published online: 30 July 2003 © Springer-Verlag 2003

ABSTRACT In this paper, we report the experimental determination of the thermo-optical coefficient \( \frac{dn}{dT} \) and the effective stimulated emission cross-section \( \sigma_e \) at 1064 nm for an \( a \)-axis cut 1.3-at.\% doped Nd : GdVO\(_4\) crystal in a monolithic laser configuration. The pump-power-induced thermal lensing effect in the monolithic laser was used to determine these parameters. While measuring the \( \frac{dn}{dT} \) parameter, we also took into consideration the effect of pump-power-induced thermal expansion of the crystal. The \( \frac{dn}{dT} \) values obtained were 2.64 – 6 and \( 4.87 \times 10^{-6} \) K\(^{-1} \), respectively, for directions parallel and perpendicular to the \( c \)-axis of the crystal. We show that the neglect of pump-power-induced thermal expansion of the crystal can overestimate the value of \( \frac{dn}{dT} \) by 30%–50%. With the measured variation of the focal length of the thermal lens as a function of the absorbed pump power, we also computed the overlap integrals at the threshold pump power. These overlap integral values were used to estimate the product of the effective stimulated emission cross-section \( \sigma_e \) and the excited state lifetime \( (\tau) \) of the Nd : GdVO\(_4\) crystal, which was found to be \( 1.476 \times 10^{-22} \) cm\(^2\)s. With the reported values of \( \tau \) for a 1.3-at.\% doped Nd : GdVO\(_4\) crystal, we estimated the value of \( \sigma_e \) to be in the range \( 14.76 \times 10^{-19} \) to \( 16.4 \times 10^{-19} \) cm\(^2\). The value of the effective stimulated emission cross-section measured in this way was found to be around two times higher in magnitude than earlier reported values measured by spectroscopic methods.

PACS 42.60.Lh; 42.60.Da; 42.60.By; 42.55.Rz

1 Introduction

In recent years Nd\(^{3+}\)-doped gadolinium vanadate (Nd : GdVO\(_4\)) has proven to be an efficient solid-state laser material due to its good laser properties, such as its high stimulated emission cross-section at a wavelength of 1.06 µm and its suitability for diode pumping, which results from its large absorption coefficient and large absorption bandwidth at the diode emission wavelength around 808 nm [1–8]. Some experiments have shown that it is a more efficient LD-pumping solid-state laser material than Nd : YVO\(_4\) crystals [3, 4]. Studies of thermal properties of Nd : GdVO\(_4\), such as thermal conductivity, thermal expansion, and specific heat [5, 6, 8], have shown that it is suitable for high-power laser systems. However, accurate measurements of some important parameters for this crystal, like the thermo-optic coefficient \( \frac{dn}{dT} \) and the effective stimulated emission cross-section \( \sigma_e \) at the lasering wavelength of 1.06 µm, are not available.

The thermo-optic coefficient of a laser crystal is an important parameter, since it directly influences the pump-power-induced thermal lensing effect, which in turn limits the scaling-up of the output power [9]. In the case of a solid-state laser material, a fraction of the absorbed pump power is dissipated in the form of heat, which leads to a variation of the refractive index through the \( \frac{dn}{dT} \) parameter and a variation of the thickness through the thermal expansion coefficient \( \alpha_T \). The combination of these two effects creates a phase variation for a paraxial beam passing through such a thermally loaded gain medium, which ultimately leads to thermal lensing and thermal aberration. Recently Zhang et al. [8] measured the \( \frac{dn}{dT} \) parameter of a Nd : GdVO\(_4\) crystal, by measuring the focal length of the thermal lens as a function of the absorbed pump power. However, in their measurements, the effect of thermal expansion was neglected. Also, in their experiment only the \( \frac{dn}{dT} \) parameter in the direction parallel to the \( c \)-axis of the Nd : GdVO\(_4\) crystal was considered.

However, a knowledge of the \( \frac{dn}{dT} \) parameter in directions both along and perpendicular to the \( c \)-axis of an anisotropic crystal like Nd : GdVO\(_4\) is necessary, because it influences the intra-cavity-generated second harmonic (SH) conversion efficiency by depolarizing the fundamental and SH beams passing through the gain medium [10].

The effective stimulated emission cross-section \( \sigma_e \) of the laser crystal is another important parameter for evaluating the laser system parameters, such as the maximum gain, saturation power, and optimum power reflectivity [11]. Measurements of the value of \( \sigma_e \) of a 1.3-at.\% doped Nd : GdVO\(_4\) crystal by a spectroscopic method are reported in [2]. However, the spectroscopic technique for the measurement of \( \sigma_e \) requires the determination of fluorescent branching ratios and the fluorescent quantum efficiency of the \( ^{4}F_{3/2} \) level, which are usually difficult to determine. The laser-pumped laser
technique [12] is an easier method for the determination of $\sigma_e$, but in this method, optical and laser properties of the reference material must be known very accurately. Moreover due to the pump-power-induced thermal lensing effect, it is very difficult to ensure identical mode volumes for the sample and the reference material. The method described in [13] directly provides the value of the product $\sigma_e \tau$ of the laser crystal and also takes into account the influence of the pump-power-induced thermal lensing effect on the effective mode volume and the overlap efficiency. To the best of our knowledge, measurements of $\sigma_e$ of Nd : GdVO$_4$ crystals at a wavelength of 1.06 $\mu$m by considering the influence of thermal lensing effects on the overlap integrals under lasing conditions have not yet been reported.

In this paper we report the experimental determination of the thermo-optic coefficient (dn/dT parameter) of a 1.3-at% doped a-axis cut Nd : GdVO$_4$ crystal, both along and perpendicular to the direction of the c-axis of the crystal, in a monolithic laser configuration. For this measurement we took into account the pump-power-induced thermal expansion of the crystal. We also measured the value of $\sigma_e$ for the Nd : GdVO$_4$ crystal in the same laser configuration. In this method, with the measured variation of the focal length of the thermal lens as a function of the absorbed pump power, we computed the overlap integrals at the threshold pump power. These overlap integral values were used to estimate the product of the effective stimulated emission cross-section ($\sigma_e$) and the excited state lifetime ($\tau$) of the Nd : GdVO$_4$ crystal, which was found to be 1.476 $\times$ 10$^{-22}$ cm$^2$ s. With the reported values of $\tau$ for the 1.3-at% doped Nd : GdVO$_4$ crystal, we estimated the value of $\sigma_e$ to be in the range $14.76 \times 10^{-19} - 16.4 \times 10^{-19}$ cm$^2$. The value of the effective stimulated emission cross-section of the Nd : GdVO$_4$ crystal measured in this way was found to be around 2.0 times higher in magnitude than earlier reported values measured by spectroscopic methods [2].

2 Experimental setup

The schematic of the experimental setup is shown in Fig. 1. The pump source used was a fiber-coupled diode-laser (Coherent F-81–1000C) that delivered a maximum output power of 1 W. The wavelength of maximum emission at 25 °C was 809 nm with a 1.2 nm spectral width (FWHM). The fiber-tip had a diameter of 100 $\mu$m and a numerical aperture of 0.18. The spatial intensity profile of the output beam from the fiber was circular in shape with a maximum at the center and a far-field divergence (FWHM) of around $9^\circ$.

The output beam was collimated and focused using two plano-convex lenses (f = 50 mm). Since the quality of the pump beam ($M^2$ parameter) and the actual focused spot-size are important parameters for accurate measurements of the focal length of the thermal-lens, we measured these parameters for this setup. For this purpose, the spot-radius of the pump beam at several locations after the focusing lens and around the focused position were estimated with the help of a knife-edge with a 10% clip-level criterion [14]. The variation of the diode-beam spot size was plotted as a function of distance from the secondary principal plane of the focusing lenses, and the focused spot-radius and $M^2$ parameter were estimated by least-squares fitting of the usual multi-mode beam propagation law given by [15]

$$w_p^2(z) = w_{po}^2 \left\{ 1 + \left[ \frac{\lambda_p M_p^2}{n \pi w_{po}^2} (z - z_o) \right]^2 \right\},$$

where $w_{po}$ is the radius at the waist, $\lambda_p$ is the pump wavelength, $M_p^2$ is the pump beam propagation factor, $z_o$ is the waist location from the focusing lens, and $n$ is the refractive index of the medium. The beam propagation factor and the focused spot-radius estimated in this way were 26 and 70 $\mu$m, respectively, at the maximum operating current (Fig. 2).

The laser-diode junction temperature was kept at the value corresponding to the optimum pump radiation absorption inside the crystal. The diode output power was varied by using neutral density filters while keeping the diode operating current at its maximum value. This was done to avoid shifts of the laser wavelength with the current. In OEM packaged laser diodes there is some thermal resistance between the diode junction and the temperature sensor; with increasing thermal loads, the temperature difference between the two increases.