Exploring optical properties of Nd-doped vanadates with intracavity self-mode locking

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ABSTRACT

We employ an intracavity self-mode-locked laser to systematically measure the group refractive indices and the thermo-optic coefficients for Nd:GdVO4, Nd:YVO4 and Nd:LuVO4 crystals at 1064 nm. We further make a detailed comparison between the present results and those currently reported in the literature. All the experimental results can be found to be fairly consistent with the recent reported data

Keywords: self-mode locking, group refractive indices, thermal-optic coefficient

1. Introduction

In the past decade, Nd-doped rare-earth vanadate crystals such as yttrium orthovanadate (YVO4), lutetium vanadate(LuVO4) and gadolinium vanadate(GdVO4), have been identified to be promising laser materials because of their significant advantages that include high stimulated emission cross-sections at 1.06 μm and wide absorption bandwidths for the diode-pumping scheme [1-5]. The thermal-optic coefficient dn/dT of a laser crystal is explicitly associated with the thermally induced lensing effect that significantly influences the cavity stability, the oscillation mode size, the maximum achievable average power, and the output beam quality [6,7]. There are some reported values of dn/dT obtained by different methods for Nd:GdVO4, Nd:YVO4 and Nd:LuVO4 crystals near 1064 nm [8-14]. However, the reported data are found to differ considerably from each other. Therefore, it is highly desirable to precisely clarify the values of thermo-optic coefficients for various vanadate crystals.

Recently, an intracavity scheme in a self-mode-locked laser is proposed to measure the temperature dependence of the group refractive index with great precision [15]. In this work we employ this intracavity method to systematically measure the group refractive indices and the thermo-optic coefficients for Nd:GdVO4, Nd:YVO4 and Nd:LuVO4 crystals at 1064 nm. We make a detailed comparison between the present results and those currently reported in the literature. Measured results reveal that the LuVO4 crystal has an obviously smaller value than the GdVO4 and YVO4 crystals for the thermo-optic coefficient in the direction parallel to the c-axis. On the other hand, the GdVO4 crystal has a somewhat smaller value than the LuVO4 and YVO4 crystals for the thermo-optic coefficient in the direction perpendicular to the c-axis. On the whole, experimental results are found to agree very well with the data reported by Zelmon et al. [13,14].

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2. Experimental setup

Recently, it has been experimentally demonstrated that under the condition of eliminating the internal and external unwanted reflection, diode-end-pumped Nd-doped crystal lasers could be spontaneously operated in the state of self-mode-locking [16,17]. Here we setup a self-mode-locked Nd:YVO4 laser to measure the group refractive indices and the temperature dependence of refractive index with the intracavity scheme for Nd:GdVO4, Nd:YVO4 and Nd:LuVO4 crystals at 1064 nm. Figure 1 depicts the experimental setup that is a compact concave-plano configuration. The gain mediums were a-cut 0.2 at.% Nd:YVO4 crystal with a length of 10 mm. Both end surfaces of the Nd:YVO4 crystals were antireflection coated at 1064nm and wedged at 0.5° to suppress the Fabry–Perot etalon effect. The gain crystal was wrapped with indium foil and mounted in a water-cooled copper holder. The water temperature was maintained around 20 °C to ensure stable laser output. The input mirror was a 100 mm radius-of-curvature concave mirror with antireflection coating at 808 nm on the entrance face and with high-reflectance coating at 1064 nm (>99.8%) and high transmittance coating at 808 nm on the second surface. The flat wedged output coupler with 15% transmission at 1064nm was used throughout the experiment. The pump source was a 2.5 W 808 nm fiber-coupled laser diode with a core diameter of 100 μm and an NA of 0.16. A focusing lens with 25 mm focal length and 85% coupling efficiency was used to reimage the pump beam into the laser crystal. The average pump size was approximately 150 μm, which was appropriate for mode-size matching. The mode-locked pulses were detected by a high-speed InGaAs photodetector (Electro-optics Technology Inc. ET-3500, with rise time 35 ps), whose output signal was connected to a digital oscilloscope (Agilent, DSO 80000) with 12 GHz electrical bandwidth and sampling interval of 25 ps. At the same time, the output signal of the photodetector was also analyzed by an RF spectrum analyzer (Advantest, R3265A) with bandwidth of 8.0 GHz.

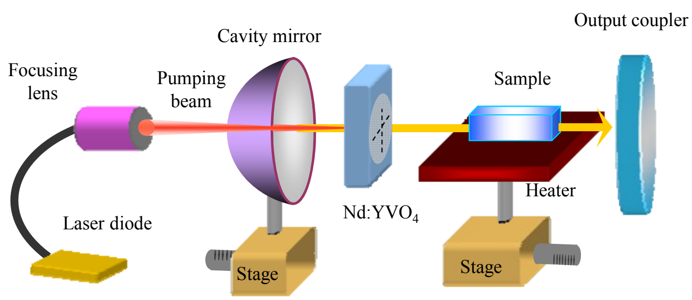

Fig. 1. (Color online) Experimental setup of a self-mode-locked Nd:YVO4 laser for measuring the group refractive indices and thermo-optic coefficients.

3. Experimental results and discussion

First of all, we set up the cavity without inserting the sample to be approximately 6.49 cm, corresponding to free spectral range of 2.313 GHz. As reported in the earlier study [16,17], the laser cavity could be optimized to exhibit stable mode locking by finely adjusting the cavity with the help of monitoring the real-time pulse train. After optimizing the self-mode-locked laser, the sample crystal was inserted into the cavity to measure the change of the pulse repetition rate. The sample crystals are a-cut 0.2 at.% Nd:GdVO4 crystal with a length of 10.04 mm, a-cut 0.1 at.% Nd:YVO4 crystal with a length of 12.39 mm, and a-cut 0.5 at.% Nd:LuVO4 crystal with a length of 8.22 mm. We set the a-axis and c-axis of the sample crystals to be along the output polarization separately, and the optical path difference can be precisely calculated from the variation of the pulse repetition rate. Since these crystals are positive uniaxial crystals with $n_o = n_a = n_b$ and $n_e = n_c$, we set the *c*-axis of the sample crystal to be along the output polarization, and the group refractive index for n_e can be determined by measuring the optical path difference. In addition, the group refractive

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index for n_o can be determined by turning the sample crystal 90° around the longitudinal axis. Table 1 shows the experimental results for the group refractive indices for n_o and n_e at the wavelength of 1064 nm. Numerical calculations based on the models developed by Zelmon *et al.* [13,14] are also listed in table 1 for comparison. The group refractive index n_g for the wavelength can be calculated mathematically from the phase refractive index n_p by use of [18]

$$n_g = n_p - \lambda \frac{\partial n_p}{\partial \lambda} \cdot \tag{1}$$

Recently, Zelmon *et al.* [13,14] reported new measurements of the phase refractive indices for the $Nd:GdVO_4$, $Nd:YVO_4$ and $Nd:LuVO_4$ crystals and fitted the Sellmeier equation of the form

$$n_p^{\ 2} = A + \frac{B\lambda^2}{\lambda^2 - C} + \frac{D\lambda^2}{\lambda^2 - E} \cdot \tag{2}$$

The five parameters in Eq. (2) for the $Nd:GdVO_4$, $Nd:YVO_4$ and $Nd:LuVO_4$ crystals can be found in the refs. [13,14]. With Eqs. (1) and Eqs. (2), the group refractive indices for n_o and n_e at the wavelength of 1064 nm are calculated and shown in table 1. It can be seen that the deviations between the present results and the numerical calculations are generally less than 2×10^{-4}.

Table 1. Experimental results for the group refractive indices for n_o and n_e at the wavelength of 1064 nm.

	$Nd:GdVO_4$		**$Nd:YVO_4$**		**$Nd:LuVO_4$**	
Group refractive index	n_o	n_e	n_o	n_e	n_o	n_e
This work	2.01234	2.24930	1.99822	2.22202	2.03486	2.25472
Zelmon *et al.* [13,14] (at T=23°C)	2.01235	2.24911	1.99835	2.22206	2.03490	2.25456

The measurement for the thermo-optic coefficient of a laser crystal is practically important for scaling up the output power because this parameter is directly related to the thermally induced lensing effect. To measure the temperature dependences of refractive indices, we employ an oven and a temperature controller to steadily adjust the temperature of the sample crystal between 50 °C and 170 °C. The variation of the temperature ΔT leads to an optical path difference ΔL that is given by $\Delta L = [(dn/dT) + \alpha_T \times (n-1)] \times l_c \times \Delta T$, where l_c is the length of the sample crystal and α_T is the linear thermal expansion coefficient. The thermally induced optical path difference results in a variation of the pulse

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repetition rate Δf to be given by $\Delta f = -[\ 2\times f^2/c\ ]\times\Delta L$. Figure 2 depicts experimental results for the frequency shift versus the temperature change for the light polarization in directions along and perpendicular to the *c*-axis of the Nd:$GdVO_4$, Nd:YVO_4 and Nd:$LuVO_4$ crystals. We subsequently exploited the experimental data of the temperature dependence of the pulse repetition rate and the information of the thermal expansion coefficient α_T to determine the temperature dependence of the group refractive index.

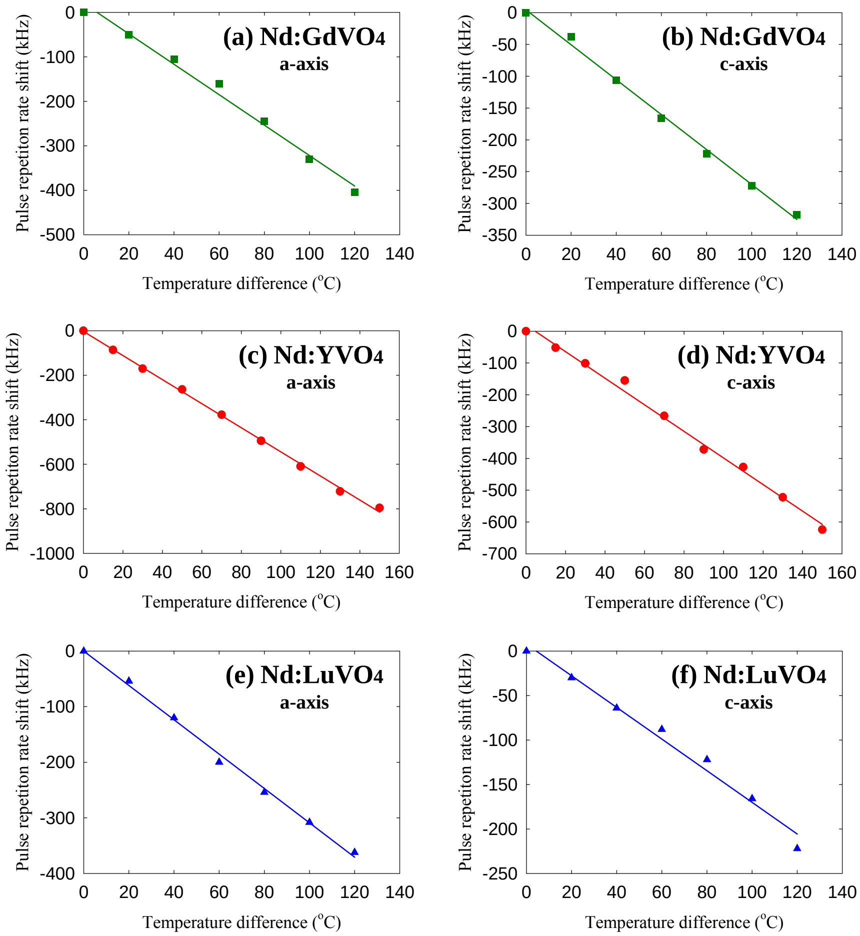

Fig. 2. (Color online) Experimental results for the frequency shift versus the temperature change at 1064 nm for the laser polarization in directions along and perpendicular to the c-axis of the Nd:GdVO4, Nd:YVO4 and Nd:LuVO4 crystals.

Figur The α_T values used in the calculation are 1.5×10^{-6} K^{-1} [10], 4.43×10^{-6} K^{-1} [19], and 1.7×10^{-6} K^{-1} [4] for the Nd:$GdVO_4$, Nd:YVO_4, and Nd:$LuVO_4$ crystals, respectively. Figure 3 depicts calculated results of the group refractive indices versus the temperature at the wavelength of 1064 nm for the light polarization in directions along and perpendicular to the *c*-axis of the Nd:$GdVO_4$, Nd:YVO_4 and Nd:$LuVO_4$ crystals. In this work the sample crystal was heated uniformly with an oven and a temperature controller. The effects of thermal expansion and temperature dependence of refractive index are considered in measurement of the optical path difference. However, if the sample crystal was heated locally, the effects such as refractive index change, bulging, and stress optical birefringence may be more complicated [20]. A detailed comparison between the present results and those currently reported in the literature is shown in Table 2. Our experimental results can be found to be fairly consistent with the data reported by Zelmon et al. [13,14]. The method adopted by Zelmon et al. is believed to be still the most accurate way to measure the refractive indices of materials. As seen in table 2, the value of the thermo-optic coefficient dne/dT of the LuVO4 crystal is obviously smaller than those of the GdVO4 and YVO4 crystals. On the other hand, the value of the thermo-optic coefficient dno/dT of the GdVO4 crystal is somewhat smaller than those of the LuVO4 and YVO4 crystals.

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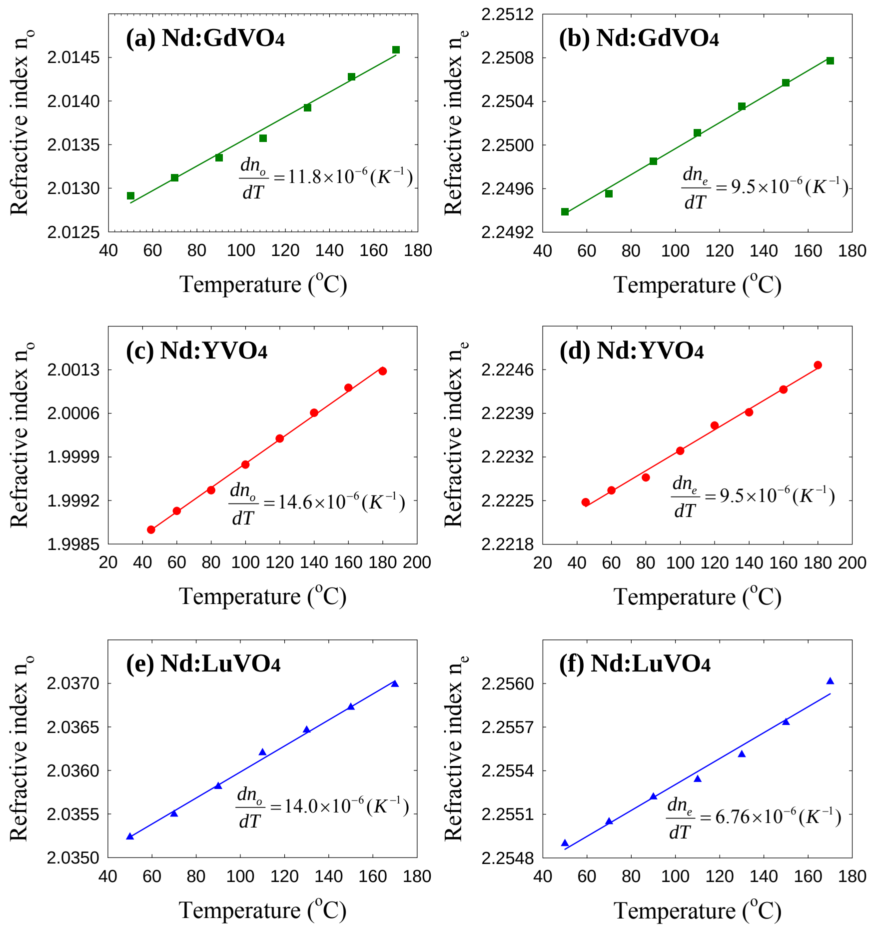

Fig. 3. (Color online) Calculated results of the group refractive indices versus the temperature at 1064 nm for the laser polarization in directions along and perpendicular to the c-axis of the Nd:GdVO4, Nd:YVO4 and Nd:LuVO4 crystals.

Table 2. Experimental results and those currently reported in the literature for temperature dependences of refractive indices.

	$Nd:GdVO_4$		$Nd:YVO_4$		$Nd:LuVO_4$	
	dn_o/dT ($\times 10^{-6}$ K^{-1})	dn_e/dT	dn_o/dT ($\times 10^{-6}$ K^{-1})	dn_e/dT	dn_o/dT ($\times 10^{-6}$ K^{-1})	dn_e/dT
This work (at 1064nm)	11.8	9.5	14.6	9.5	14.0	6.7
Zelmon *et al.* [13,14] (at 1064nm, T=23°C)	11.8	9.0	14.0	9.0	15.6	6.76
Loiko *et al.* [12] (at 632.8nm)	5.5	4.3	8.2	3.1	---	---
Mukhopadhyay *et al.* [11] (at 1064nm)	4.87	2.64	---	---	---	---
Zhang *et al.* [10] (at 1064nm)	---	4.7	---	2.7	---	---

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4. Conclusions

In conclusion, we employed the intracavity scheme in a self-mode-locked laser to systematically measure the group refractive indices and the thermo-optic coefficients for Nd:GdVO4, Nd:YVO4 and Nd:LuVO4 crystals at 1064 nm. Measured results reveal that the value of the thermo-optic coefficient of the LuVO4 crystal is obviously smaller than those of the GdVO4 and YVO4 crystals in the direction parallel to the c-axis. On the other hand, the value of the thermo-optic coefficient of the GdVO4 crystal is somewhat smaller than those of the LuVO4 and YVO4 crystals in the direction perpendicular to the c-axis. In general, our experimental results are found to be in good agreement with the recent measured values.

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