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Precise measurement of the thermo-optical coefficients of various Nd-doped vanadates with an intracavity self-mode-locked scheme

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Abstract

We employ an intracavity self-mode-locked laser to precisely measure the group refractive indices and thermo-optic coefficients for Nd-doped vanadates at 1064 nm. The samples include Nd:$GdVO_4$, Nd:YVO_4 and Nd:$LuVO_4$ crystals. We make a detailed comparison between the present results and those currently reported in the literature. We confirm that the present results are in good agreement with the currently available data with the best precision.

Keywords: thermo-optical coefficient, Nd-doped vanadates, self-mode-locking

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

1. Introduction

In the past decade, Nd-doped rare-earth vanadate crystals such as yttrium orthovanadate (YVO_4), lutetium vanadate ($LuVO_4$) and gadolinium vanadate ($GdVO_4$) 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 $\mathrm{d}n/\mathrm{d}T$ 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 quality of the output beam [6, 7]. There are some reported values of $\mathrm{d}n/\mathrm{d}T$ obtained by different methods for Nd:$GdVO_4$, Nd:YVO_4 and Nd:$LuVO_4$ 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 the thermo-optic coefficients for various vanadate crystals.

Recently, an intracavity scheme in a self-mode-locked laser has been proposed for measuring 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:$GdVO_4$, Nd:YVO_4 and Nd:$LuVO_4$ 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 $LuVO_4$ crystal has an obviously smaller value than the $GdVO_4$ and YVO_4 crystals for the thermo-optic coefficient in the direction parallel to the c-axis. On the other hand, the $GdVO_4$ crystal has a somewhat smaller value than the $LuVO_4$ and YVO_4 crystals for the thermo-optic coefficient in the direction perpendicular to the c-axis. On the whole, our experimental results are found to agree very well with the data reported by Zelmon *et al* [13, 14].

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 self-mode-locking state [16, 17]. Here we set up a self-mode-locked Nd:YVO_4 laser

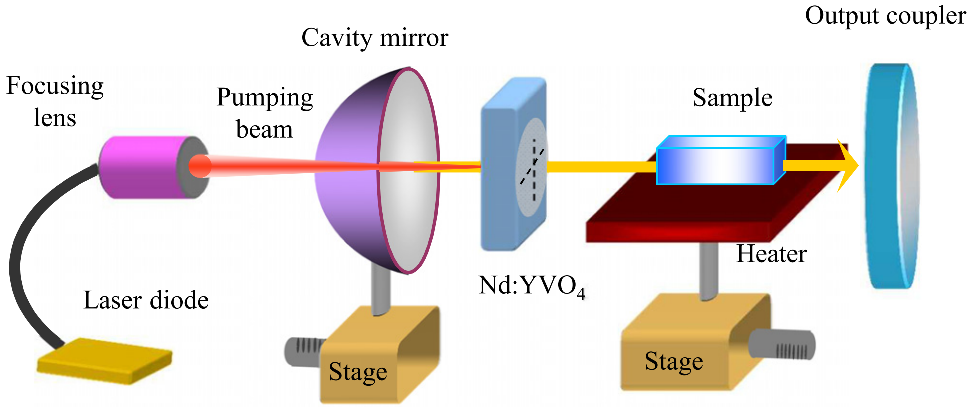

Figure 1. Experimental setup of a self-mode-locked Nd:YVO_4 laser for measuring the group refractive indices and thermo-optic coefficients.

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

Group refractive index	Nd:$GdVO_4$ n_o	Nd:$GdVO_4$ n_e	Nd:YVO_4 n_o	Nd:YVO_4 n_e	Nd:$LuVO_4$ n_o	Nd:$LuVO_4$ n_e
This work	2.012 34	2.249 30	1.998 22	2.222 02	2.034 86	2.254 72
Zelmon *et al* [13, 14] (at $T = 23$ °C)	2.012 35	2.249 11	1.998 35	2.222 06	2.034 90	2.254 56

to measure the group refractive indices and the temperature dependence of the refractive index with the intracavity scheme for Nd:$GdVO_4$, Nd:YVO_4 and Nd:$LuVO_4$ crystals at 1064 nm. Figure 1 depicts the experimental setup that is a compact concave-plano configuration. The gain medium was *a*-cut 0.2 at.% Nd:YVO_4 crystal with a length of 10 mm. Both end surfaces of the Nd:YVO_4 crystals were antireflection coated at 1064 nm and wedged at 0.5° to suppress the Fabry–Pérot etalon effect. The gain crystal was wrapped with indium foil and mounted in a water-cooled copper holder. The water temperature was maintained at around 20 °C to ensure a 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 a 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 1064 nm 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 a numerical aperture of 0.16. A focusing lens of focal length 25 mm 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 a 12 GHz electrical bandwidth and sampling interval of 25 ps. At the same time, the output signal of the photodetector was also analyzed by a RF spectrum analyzer (Advantest, R3265A) with bandwidth of 8.0 GHz.

3. Experimental results and discussion

First of all, we set up the cavity length without inserting the sample to be approximately 6.49 cm, corresponding to a 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 alignment with 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 in the pulse repetition rate. The sample crystals are *a*-cut 0.2 at.% Nd:$GdVO_4$ crystal with a length of 10.04 mm, *a*-cut 0.1 at.% Nd:YVO_4 crystal with a length of 12.39 mm and *a*-cut 0.5 at.% Nd:$LuVO_4$ crystal with a length of 8.22m̃m. 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 index for n_o can be determined by turning the sample crystal by 90° around the longitudinal axis.

Table 1 shows the experimental results for the group refractive indices for n_o and n_e at a 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]

$$n_g = n_p - \lambda \frac{\partial n_p}{\partial \lambda}. \quad (1)$$

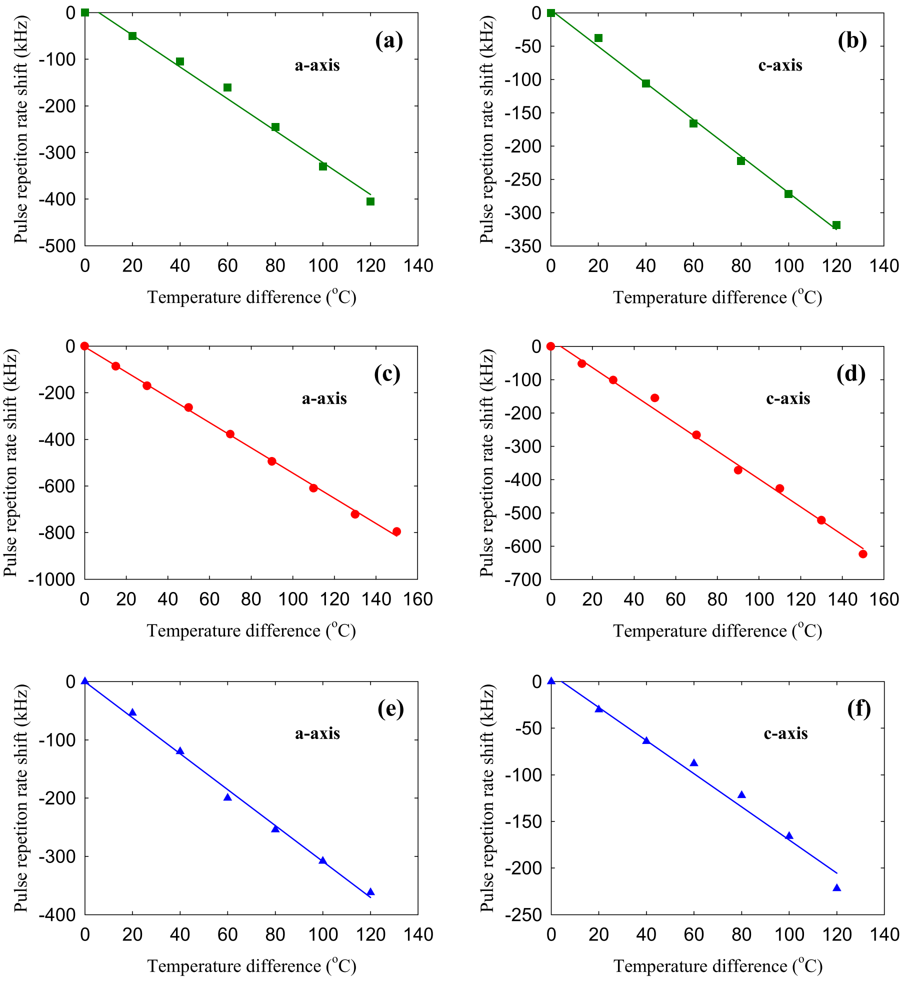

Figure 2. Experimental results for the frequency shift versus the temperature change at 1064 nm for the laser polarization in directions along and perpendicular to the *c*-axis of the ((a), (b)) $Nd:GdVO_4$, ((c), (d)) $Nd:YVO_4$ and ((e), (f)) $Nd:LuVO_4$ crystals.

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

$$n_{\mathrm{p}}^2 = A + \frac{B\lambda^2}{\lambda^2 - C} + \frac{D\lambda^2}{\lambda^2 - E}. \quad (2)$$

The five parameters in equation (2) for the $Nd:GdVO_4$, $Nd:YVO_4$ and $Nd:LuVO_4$ crystals can be found in [13, 14]. Using equations (1) and (2), the group refractive indices for n_{o} and n_{e} at a 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}.

Measurement for the thermo-optic coefficient of a laser crystal is of practical importance 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 employed an oven and a temperature controller to steadily adjust the temperature of the sample crystal between 50 and 170 °C. The variation of the temperature ΔT leads to an optical path difference ΔL that is given by $\Delta L = [(\mathrm{d}n/\mathrm{d}T) + \alpha_{\mathrm{T}} \times (n-1)] \times l_{\mathrm{c}} \times \Delta T$, 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 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 light polarization in the 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 for the temperature dependence of the pulse repetition rate and information about the thermal expansion coefficient α_{T} to determine the temperature dependence of the group refractive index. The α_{T} values used in the calculation are $1.5 \times 10^{-6}\ \mathrm{K}^{-1}$ [10], $4.43 \times 10^{-6}\ \mathrm{K}^{-1}$ [19] and $1.7 \times 10^{-6}\ \mathrm{K}^{-1}$ [4] for the $Nd:GdVO_4$, $Nd:YVO_4$ and $Nd:LuVO_4$ crystals, respectively. Figure 3 depicts the calculated results of the group refractive indices versus the temperature at a wavelength of 1064 nm for light polarization in the 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 in an oven with a temperature controller. The effects of thermal expansion and the temperature dependence of the refractive index are considered in the measurement of the optical path difference. However, if the sample crystal were heated locally, the effects

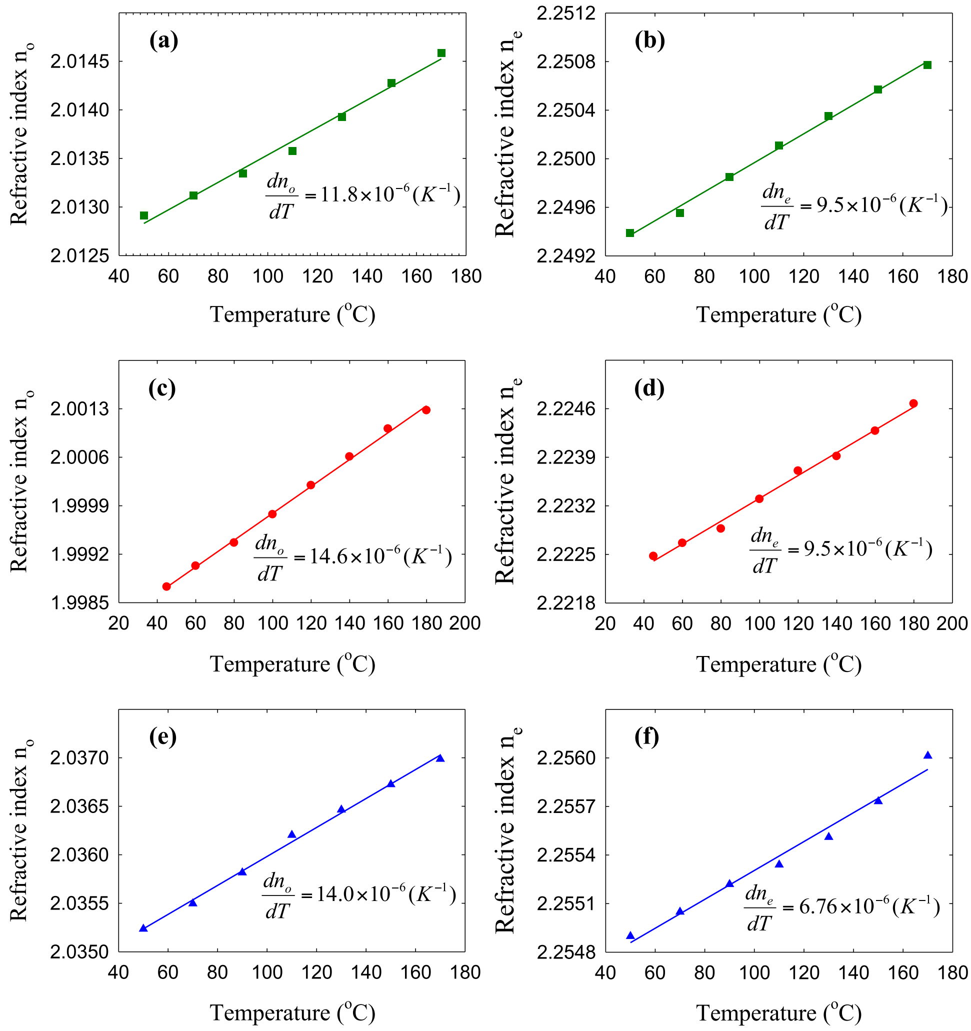

Figure 3. Calculated results of the group refractive indices versus the temperature at 1064 nm for the laser polarization in directions along and perpendicular to the *c*-axis of the ((a), (b)) $Nd:GdVO_4$, ((c), (d)) $Nd:YVO_4$ and ((e), (f)) $Nd:LuVO_4$ crystals.

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 ($\times10^{-6}$ K^{-1})	dn_e/dT	dn_o/dT ($\times10^{-6}$ K^{-1})	dn_e/dT	dn_o/dT ($\times10^{-6}$ K^{-1})	dn_e/dT
This work (at 1064 nm)	11.8	9.5	14.6	9.5	14.0	6.7
Zelmon *et al* [13, 14] (at 1064 nm, $T = 23\,°C$)	11.8	9.0	14.0	9.0	15.6	6.76
Loiko *et al* [12] (at 632.8 nm)	5.5	4.3	8.2	3.1	—	—
Mukhopadhyay *et al* [11] (at 1064 nm)	4.87	2.64	—	—	—	—
Zhang *et al* [10] (at 1064 nm)	—	4.7	—	2.7	—	—

such as refractive index change, bulging and stress optical birefringence might 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 seen to be fairly consistent with the data reported by Zelmon *et al* [13, 14]. The method adopted by Zelmon *et al* is still believed to be the most accurate way to measure the refractive indices of materials. As seen in table 2, the value of the thermo-optic coefficient dn_e/dT of the $LuVO_4$ crystal is obviously smaller than those of the $GdVO_4$ and YVO_4 crystals. On the other hand, the value of the thermo-optic coefficient dn_o/dT of the $GdVO_4$ crystal is somewhat smaller than those of the $LuVO_4$ and YVO_4 crystals.

4. Conclusion

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:

$GdVO_4$, Nd:YVO_4 and Nd:$LuVO_4$ crystals at 1064 nm. Measured results reveal that the value of the thermo-optic coefficient of the $LuVO_4$ crystal is obviously smaller than those of the $GdVO_4$ and YVO_4 crystals in the direction parallel to the c-axis. On the other hand, the value of the thermo-optic coefficient of the $GdVO_4$ crystal is somewhat smaller than those of the $LuVO_4$ and YVO_4 crystals in the direction perpendicular to the c-axis. In general, experimental results are found to be in good agreement with the recent measured values with the best precision.

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