Precise measurement of group refractive indices and temperature dependence of refractive index for Nd-doped yttrium orthovanadate by intracavity spontaneous mode locking

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We report on a novel method based on intracavity spontaneous mode locking to precisely measure the group refractive indices and temperature dependence of refractive index of Nd : YVO_4 crystal at the wavelength of 1064 nm. All the experimental results are found to agree very well with the most recent measured values. We also confirm that the developed method is applicable to measuring the group refractive indices and the temperature dependence of the refractive indices of other vanadate crystals, as well as nonlinear crystals. © 2011 Optical Society of America

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Phase and group refractive indices are among the most important properties of optical materials. The former and the latter are the ratios of the vacuum velocity of light to its phase and group velocities in the material, respectively. For dispersive media, these indices may differ substantially. Different approaches for measuring the phase refractive indices of various materials have been reviewed [1]. The group refractive index n_g for the wavelength can be calculated mathematically from the phase refractive index n_p by use of [2]

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

Alternatively, the group refractive index of a material can be measured directly by measuring the time of propagation of short pulses over a known distance. White-light interferometry based on the use of a white-light source in combination with a standard Michelson or Mach–Zehnder interferometer is by far the most widely used method for measuring the group refractive indices for different optical materials [3–5].

The temperature dependence of refractive index, dn/dT, is also an important physical quantity of an optical material [6]. In solid-state lasers, the temperature dependence of refractive index of the laser gain media explicitly determines the focal power of the thermally induced thermal lens that significantly influences the cavity stability, the oscillation mode size, the maximum achievable average power, and the output beam quality [7]. Therefore, precise measurement of the temperature dependence of refractive index for laser gain media is practically important for designing high-power solid-state lasers.

In the past decade, Nd^{3+}-doped vanadate crystals have been confirmed to be promising gain medium due to their good laser properties, such as their large stimulated emission cross section and high absorption over a wide pumping wavelength bandwidth [8–11]. Recently it was verified that, under the condition of eliminating the internal and external unwanted reflection, a diode-end-pumped Nd:YVO_4 laser could exhibit remarkable spontaneous mode locking [12,13]. In this work, we develop a novel method based on intracavity spontaneous mode locking to precisely measure the group refractive indices and the temperature dependence of refractive index of Nd:YVO_4 crystal at the wavelength of 1064 nm. The experimental results are found to be in good agreement with the most recent measured values [14]. The developed method is also confirmed to be applicable to measuring the group refractive indices and temperature dependence of refractive index of other vanadate crystals, as well as nonlinear crystals.

Figure 1 depicts the experimental setup for measuring the group refractive indices and the temperature dependence of refractive index. We used a simple concave-plano configuration to construct the laser cavity and obtained stable spontaneous mode locking by avoiding all unwanted reflection. 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 crystal were antireflection coated at 1064 nm 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.

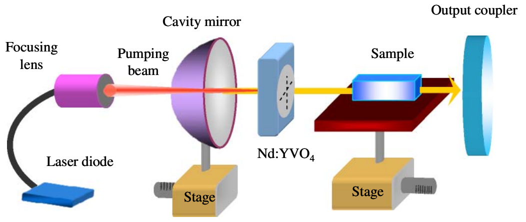

Fig. 1. (Color online) Experimental setup for measuring the group refractive indices and temperature dependence of refractive index.

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A 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 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.

First of all, we set up the cavity without inserting the sample to be approximately 4.5 cm, corresponding to free spectral range of 3.337 GHz. As reported in the earlier study [12], 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 and the power spectrum. Figures 2(a) and 2(b) show the pulse trains on two different time scales, one with time span of 10 μs, demonstrating the amplitude stability, and the other with time span of 10 ns, demonstrating the mode-locked pulse train. It can be seen that the pulse train displays full modulation and complete mode locking is achieved. The corresponding power spectrum is depicted in Fig. 2(c). The frequency deviation of the power spectra, $\Delta\upsilon/\upsilon$, is experimentally found to be significantly smaller than 10^{-4}, where υ is the center frequency of the power spectrum and $\Delta\upsilon$ is the frequency deviation of FWHM. The small frequency deviation enables us to measure the change of the optical path length with precision. More importantly, the self-mode-locked emission is linearly polarized because the Nd:YVO$_4$ gain medium is a uniaxial crystal with a large birefringence.

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 crystal was an a-cut Nd:YVO$_4$ crystal with a doping concentration of 0.2 at.% and length of 12.4 mm. We initially set the c axis of the sample crystal to be along the output polarization. Figure 3 depicts the experimental results for the pulse repetition rate before and after inserting the sample crystal. The optical path difference can be precisely calculated from the variation of the pulse repetition rate.

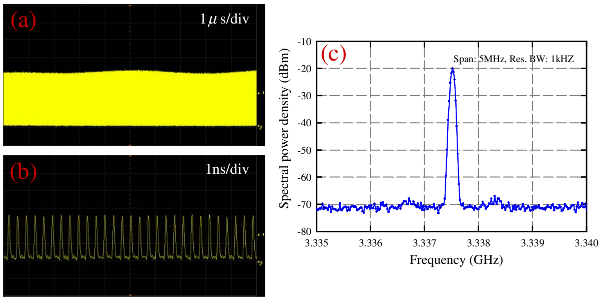

Fig. 2. (Color online) Pulse trains on two different time scales: (a) time span of 10 μs, demonstrating mode-locked pulses; (b) time span of 10 ns, demonstrating the amplitude oscillation. (c) Corresponding power spectrum.

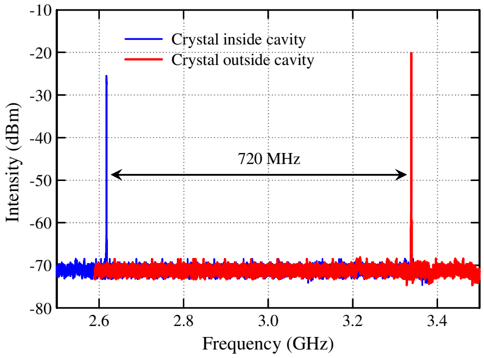

Fig. 3. (Color online) Experimental results for the pulse repetition rate before and after inserting the sample crystal.

The measured optical path difference was then employed to determine the group refractive index for n_e. Since the YVO$_4$ crystal is a positive uniaxial crystal with $n_o = n_a = n_b$ and $n_e = n_c$, the group refractive index for n_o can be determined by turning the sample crystal 90° around the longitudinal axis. It was found that the group refractive indices for n_o and n_e are 1.9987 and 2.2222, respectively. Recently, Zelmon *et al.* [14] reported new measurements of the phase refractive indices for the Nd:YVO$_4$ crystal and expressed the Sellmeier equation as

$$n_o^2 = 2.3409 + \frac{1.4402\lambda^2}{\lambda^2 - 0.04825} + \frac{1.8698\lambda^2}{\lambda^2 - 171.27}, \qquad (2)$$

$$n_e^2 = 2.7582 + \frac{1.853\lambda^2}{\lambda^2 - 0.056986} + \frac{3.0749\lambda^2}{\lambda^2 - 195.06}. \qquad (3)$$

With Eqs. (1)–(3), the group refractive indices for n_o and n_e are calculated to be 1.9984 and 2.2221, respectively. The differences between our and Zelmon *et al.*'s results are as significantly small as 0.0003 and 0.0001 for the group refractive indices of n_o and n_e, respectively. The principal sources of error in the measurements are from the frequency uncertainty of the pulse repetition rate. The frequency uncertainty is estimated to be approximately ±50 kHz. Consequently, the errors induced by the frequency uncertainty in the measurement of group refractive indices are generally less than $\pm 10^{-4}$.

Zelmon *et al.* [14] recently measured the temperature dependences of refractive indices of the Nd:YVO$_4$ crystal and found the values to be $dn_o/dT = 14.0 \times 10^{-6}\,\mathrm{K}^{-1}$ and $dn_e/dT = 9.0 \times 10^{-6}\,\mathrm{K}^{-1}$. Their values are larger by a factor of 3 for dn_o/dT and a factor of 2 for dn_e/dT at 1064 nm than those often cited in the literature [15]. This large discrepancy deserves further investigation. To measure the temperature dependence of refractive index, we employ a heater and a temperature control to vary the temperature of the sample crystal between 30 °C and 200 °C. The optical path difference ΔL caused by the temperature change ΔT can be expressed as $\Delta L = [(dn/dT) + \alpha_T \times (n - 1)] \times l_c \times \Delta T$, where l_c is the length of the sample crystal and α_T is the linear thermal expansion coefficient. The optical path difference leads to a variation of the pulse repetition rate $\Delta\upsilon$ to be

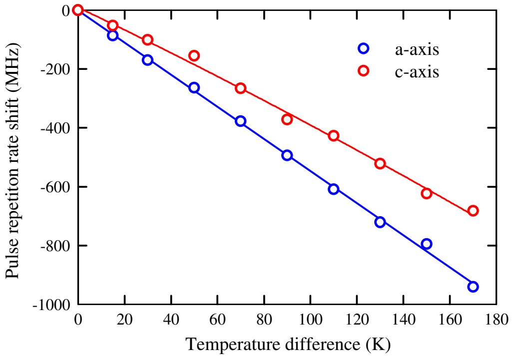

Fig. 4. (Color online) Pulse repetition rate shift versus temperature.

given by $\Delta v = -[2 \times v^2/c] \times \Delta L$. As a consequence, the temperature dependence of refractive index can be determined by recording the variation of the pulse repetition rate as a function of the temperature change. Figure 4 shows the experimental results for the frequency shift versus the temperature change. With the experimental data and $\alpha_T = 4.43 \times 10^{-6}\,\mathrm{K}^{-1}$, the temperature dependences of refractive indices are derived to be $dn_o/dT = 14.6 \times 10^{-6}\,\mathrm{K}^{-1}$ and $dn_e/dT = 9.0 \times 10^{-6}\,\mathrm{K}^{-1}$. Our results can be found to agree very well with those Zelmon *et al.* reported [14]. Furthermore, we confirmed that the present method can be used to measure the temperature dependences of refractive indices for other laser crystals.

In conclusion, we have exploited intracavity spontaneous mode locking to measure the group refractive indices and the temperature dependence of refractive index of Nd:YVO_4 crystal at the wavelength of 1064 nm with high accuracy. All the experimental results are found to be in good agreement with the most recent measured values. This method can be further employed to measure the group refractive indices and temperature dependences of refractive indices of other laser crystals, as well as nonlinear crystals.

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