Intra-cavity round-trip loss measurement of all-solid-state single-frequency laser by introducing extra nonlinear loss

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Received September 24, 2016; accepted December 6, 2016; posted online January 6, 2017

A scheme for measuring the intra-cavity round-trip loss of an all-solid-state single-frequency laser by inserting a type-I noncritical phase-matching nonlinear crystal introducing nonlinear loss into the resonator is presented. The intra-cavity round-trip loss is theoretically deduced by analyzing the dependence of the fundamental-wave (FW) and second-harmonic-wave (SHW) powers on the pump factor and the nonlinear conversion factor of the single-frequency laser and experimentally measuring them by recording different FW and SHW powers, which are decided by the temperature of the nonlinear crystal. The measured intra-cavity round-trip loss and pump factor are 4.84% and 6.91% W^{-1}, respectively. The standard deviations of the measured intra-cavity round-trip loss and the pump factor are 0.26% and 0.07%, respectively. This scheme is very suitable for measuring the intra-cavity round-trip loss of a high-gain solid-state single-frequency laser.

OCIS codes: 140.3410, 140.3515, 140.3570, 140.3580, 160.4330.

doi: 10.3788/COL201715.021402.

All-solid-state continuous-wave (CW) single-frequency lasers with high output powers pumped by laser diodes (LDs) have been extensively studied for various applications, including optical parametric oscillators[1], atomic trapping[2], microwave photonics[3], gravitation-wave detection[4], and quantum optics[5,6] due to their inherent advantages of a narrow linewidth, good beam quality, and high stability in conjunction with extremely low-intensity noise. In the production and maintenance of all-solid-state lasers, the intra-cavity round-trip loss is an important index, since it not only influences the pump threshold but also limits the output power of the laser[7–9]. It is necessary to precisely measure the intra-cavity round-trip loss of a resonator for the realization of a highly efficient and stable laser because the relationship between the intra-cavity round-trip loss and the net gain is the main factor in determining the running state of the laser. The precise measurement of the intra-cavity round-trip loss is also beneficial to the laser technology, such as Q-switching, mode selection, and frequency stabilization of solid-state lasers[10–12].

So far, a variety of methods for measuring the intra-cavity round-trip loss have been presented. The most popular one was proposed by Findlay and Clay and was named the F-C analyzing method[13]. By changing the transmission of the output coupler, the corresponding threshold pump powers were recorded, and the intra-cavity round-trip loss was obtained by numerically calculating the relationship between them. In order to improve the measurement precision, they had to replace a few sets of output mirrors with very different transmissivities. Even so, the process of replacing the output coupler still severely influenced the measurement precision of the intra-cavity round-trip loss. In 2008, Song *et al.* presented a method for obtaining the intra-cavity round-trip loss by numerically fitting the measured pump power and output power into rate equations[14]. However, this method was confined to high-gain solid-state lasers since the serious thermal effects of the laser were not considered[15–19]. In 2012, our group presented a new method based on the relationship between the frequency of the resonant relaxation oscillation (RRO), output power, and the intra-cavity round-trip loss. The intra-cavity round-trip loss was obtained by substituting the measured values of the RRO frequency and the output power into the equation, which can directly express the relationship among the intra-cavity round-trip loss, the RRO frequency, and the output power of the laser[8,20]. Nevertheless, this method cannot be applied to high-gain lasers where the serious thermal effects would move the RRO frequency[21]. Thus, it is necessary to find a novel and simple method to measure the intra-cavity round-trip loss of high-gain solid-state lasers.

In this Letter, we presented a simple method for accurately measuring the intra-cavity round-trip loss of solid-state lasers, which can be realized just by inserting a type-I noncritical phase-matching nonlinear crystal into the resonator. The different output power values of the fundamental-wave (FW) and second-harmonic-wave (SHW) powers were recorded with the changing of the phase-matching temperature of the nonlinear crystal.

By substituting these values into the deduced expression of the intra-cavity round-trip loss, the intra-cavity round-trip loss and the pump factor of the laser were directly obtained, respectively.

In order to improve the oscillating performance, the nonlinear loss is introduced into the resonator of a single-frequency laser with high gain[22,23]. In that case, the laser can achieve a high output with a single-frequency operation and dichromatic laser beams, and the intensity noises of the FW and SHW can be manipulated by tuning the nonlinear loss[24]. With feedback control of the nonlinear loss, the power and frequency stabilities can also be improved[25,26]. On this basis, a method for measuring the intra-cavity round-trip loss of a laser resonator by adjusting the nonlinear loss is proposed. According to the oscillation theory of the intra-cavity frequency-doubling laser, the intra-cavity FW intensity is expressed as[27]

$$I = \frac{\sqrt{(t+L-\eta I_0)^2 + 4\eta I_0 K P_{in}} - (t+L+\eta I_0)}{2\eta}, \quad (1)$$

where t is the transmissivity of the output coupler, L is the intra-cavity round-trip loss, I_0 is the saturation intensity, K is the pump factor, P_{in} is the pump power, and η is the nonlinear conversion factor. The output powers of the FW (P_f) and SHW (P_{sh}) are expressed as

$$P_f = tAI, \quad (2)$$

$$P_{sh} = \eta A I^2, \quad (3)$$

where A is the average transverse cross section of the laser beam in the gain medium. By substituting Eqs. (2) and (3) into Eq. (1), the intra-cavity round-trip loss L can be expressed as

$$L = \frac{\eta I_0 K P_{in} P_f^2 - (tP_{sh})^2 - tP_f P_{sh}(t+\eta I_0) - \eta I_0 t P_f^2}{\eta I_0 P_f^2 + tP_{sh}P_f}. \quad (4)$$

Equation (4) shows that the intra-cavity round-trip loss can be derived by precisely measuring the output powers of the FW and SHW when the other parameters are known. However, it is difficult to obtain the pump factor K of the high-power laser because the thermal lens effects of the intra-cavity elements, including the gain medium, optical diode, and so on, severely influence the output power characteristic of the laser[17,18]. As a result, we have to measure a few sets of output power values of the FW and SHW by tuning the temperature of the type-I noncritical phase-matching nonlinear crystal, and η is expressed as

$$\eta = \frac{8\pi^2 d_{\mathrm{eff}}^2 l^2 \omega_1^2}{\varepsilon_0 c \lambda_f^2 n^3 \omega_2^2} \operatorname{sinc}^2\left(\left[\frac{2\pi}{\lambda_f}\frac{dn_z}{dT} - \frac{\pi}{\lambda_{sh}}\frac{dn_y}{dT}\right] l\Delta T\right), \quad (5)$$

where d_{eff} and l are the effective polarization coefficient and the length of the nonlinear crystal, respectively, ε_0 is the vacuum permittivity, c is the velocity of light, n is the refractivity of the nonlinear crystal, λ_f and λ_{sh} are the wavelengths of the FW and SHW, respectively. ω_1 and ω_2 are the beam waists of the laser medium and the nonlinear crystal, respectively, $\frac{dn_z}{dT}$ and $\frac{dn_y}{dT}$ are the temperature coefficients of the refractive indexes of the FW and SHW in the nonlinear crystal[23,25], respectively, and ΔT is the temperature mismatch. Equation (5) denotes that the value of η is decided by ΔT when the material and the length l of the nonlinear crystal are chosen. When the temperature of the nonlinear crystal is detuned, η is changed, which results in the variation of the output powers of the FW and SHW. By measuring the output powers of the FW and SHW corresponding to the different nonlinear conversion factor η and solving Eq. (4), the intra-cavity round-trip loss of the single-frequency laser can be obtained. At the same time, the pump factor K of the laser is also acquired.

The presented method of measuring the intra-cavity round-trip loss was verified in a homemade single-frequency $Nd:YVO_4$ laser with a high output power, and a schematic diagram of the experimental setup is depicted in Fig. 1. The pumping source was a fiber-coupled LD with a center wavelength of 888 nm and a maximum output power of 80 W. Since the quantum defect of direct laser-level pumping with the pumping wavelength at 888 nm was lower than that of 808 nm, and the polarization-independent pumping characteristic of the pumping wavelength at 888 nm was realized, it was easier to inject a high pump power and improve the output power of the laser[28]. The diameter and the numerical aperture (NA) of the coupling fiber were 400 μm and 0.22, respectively. The pump radiation was focused into the gain medium by two lenses with focal lengths of 30 and 80 mm, respectively. M_1 and M_2 were concave-convex and plane-convex mirrors, both with a curvature radius of 1500 mm. Input coupler M_1 was coated with high-reflection (HR) films at 1064 nm and high-transmissivity (HT) films at 888 nm, and M_2 was coated with HR films at 1064 nm. M_3 and M_4 were two plane-concave mirrors, both with a curvature radius of 100 mm. M_3 was coated with HR films at 1064 nm. Output coupler M_4 was coated with partial transmission films at 1064 nm ($T_{1064\,\mathrm{nm}} = 20\%$) and HT films at 532 nm. The

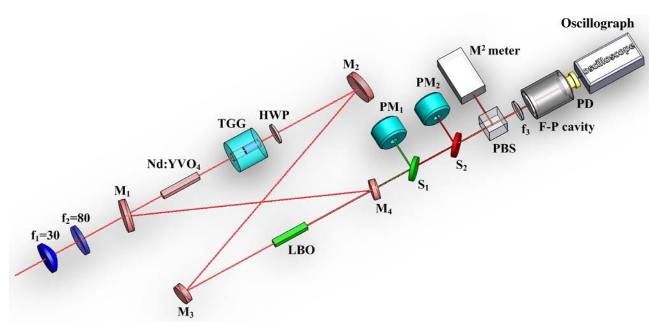

Fig. 1. Schematic diagram of the experimental setup. S_1, S_2: beam splitter; f_1, f_2: coupling lens; f_3: lens; PBS: polarization beam splitter; PD: photodiode detector.

gain medium was an α-cut composite 3 mm × 3 mm × (3 + 20) mm YVO_4/Nd:YVO_4 rod that included an undoped end cap of 3 mm and an Nd-doped part of 20 mm with a concentration of 0.8% and a wedge angle of 1.5° at the second end face to keep the polarization stable. The front end face of the Nd:YVO_4 crystal was coated with anti-reflection (AR) films at 1064 and 888 nm, and the second end face was coated with AR films at 1064 nm. An optical diode comprised of an 8 mm long terbium gallium garnet crystal and a half-wave plate was applied to eliminate the spatial hole burning effect and realize the unidirectional operation of the laser. The nonlinear crystal was a type-I noncritical LiB_3O_5 (LBO) crystal with dimensions of 3 mm × 3 mm × 18 mm, and both faces were coated with AR films at 1064 and 532 nm. It was placed at the beam waist between M_3 and M_4, and its temperature was controlled by a homemade temperature controller with a precision of 0.01°C. The output beams of the FW and SHW were split by mirror M_5 (HR at 1064 nm and HT at 532 nm) and monitored by a power meter (LabMax-Top, Coherent).

When the temperature of the LBO crystal was controlled at the optimal phase-matching temperature of 149.0°C, the output powers of 1064 and 532 nm of the laser were 22.32 and 1.239 W, respectively. The long-term stabilities of the 1064 nm laser and 532 nm laser for 5 h were measured, the fluctuations (peak-to-peak) of which were ±0.48% and ±0.62%, respectively, as shown in Fig. 2. The longitudinal-mode structure of the laser was monitored by a scanned Fabry–Perot cavity with a free spectral range of 750 MHz and a finesse of 120. The transmission curve depicted in Fig. 3 proves that the laser was stably running in the single-longitudinal mode (SLM). The beam quality of the laser was measured by an M^2 meter (M2SETVIS, Thorlabs), and the measured values of M_x^2 and M_y^2 for 1064 nm were 1.04 and 1.03, respectively. The measured caustic curve and corresponding spatial beam profile were shown in Fig. 4.

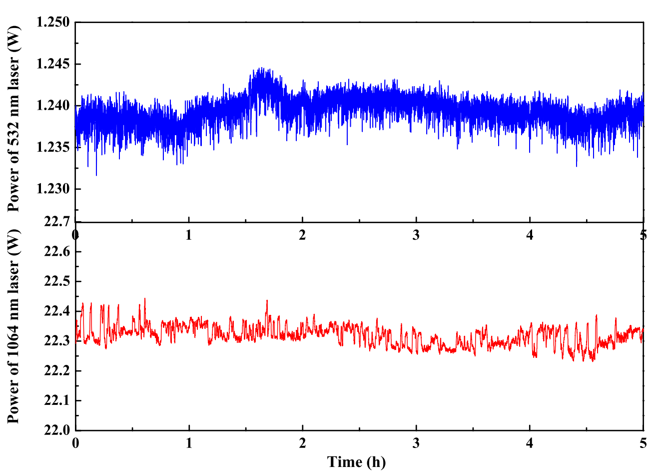

Fig. 2. Long-term power stabilities of 1064 nm laser and 532 nm laser for 5 h.

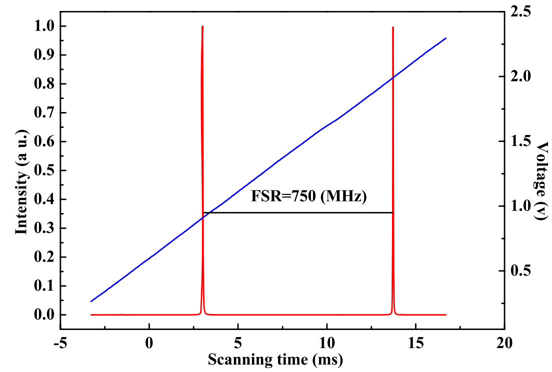

Fig. 3. Longitudinal-mode structure of the laser by scanning the confocal Fabry–Perot cavity.

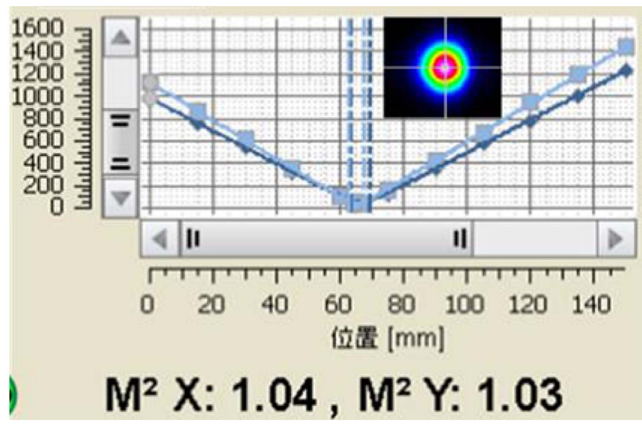

Fig. 4. Measured result of the beam quality.

In order to verify the method for measuring the intra-cavity round-trip loss, the temperature of the LBO crystal was detuned by 0.4°C each time around the optimal phase-matching temperature. Simultaneously, the output powers of 532 and 1064 nm were also recorded, as shown in Figs. 5(a) and 5(b), respectively. It can be noted that the laser can operate in the SLM, while the temperature of the

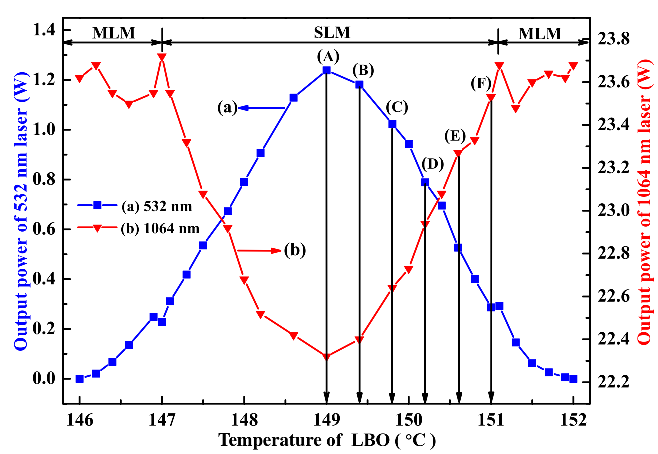

Fig. 5. Output powers of 1064 and 532 nm versus the temperature of the LBO crystal and the relevant temperature values for measurement of the intra-cavity round-trip loss.

LBO was changed by ±2°C around 149.0°C. Once the temperature of the LBO changed more than ±2°C, the laser will operate in multi-longitudinal-mode. Both output powers of 532 and 1064 nm around the optimal phase-matching temperature were symmetrical while tuning the temperature of the LBO crystal. Six sets of output powers of 532 and 1064 nm with the temperature of the LBO at (A), (B), (C), (D), (E), and (F) were chosen to obtain the intra-cavity round-trip loss, as recorded in Table 1. The nonlinear conversion factors (η) with the temperature of the LBO at the six temperature points were calculated by inserting the laser parameters (in Table 2) and the mismatch temperatures ΔT into Eq. (5), as also listed in Table 1. Fifteen sets of equations, including the intra-cavity round-trip loss and the pump factor, can be obtained by substituting every two sets of output powers into Eq. (4). An intra-cavity round-trip loss of 4.84% as well as a pump factor of 6.91% W^{-1} were obtained by solving the fifteen sets of equations. The obtained standard deviations of the intra-cavity round-trip loss and the pump factor were 0.26% and 0.07%, respectively, as shown in Table 3. It is worth noting that the measured intra-cavity round-trip loss included the resonator loss as well as the insertion loss of the nonlinear crystal.

Table 1. Output Powers of 1064 and 532 nm and the Nonlinear Conversion Factors with the Temperature of the LBO Crystal at (A), (B), (C), (D), (E), and (F)

Number	T/°C	ΔT/°C	P_f/W	P_{sh}/W	$\eta/(\mathrm{m}^2/\mathrm{W})$
A	149.0	0	22.32	1.239	6.5×10^{-11}
B	149.4	0.4	22.40	1.182	6.166×10^{-11}
C	149.8	0.8	22.64	1.023	5.662×10^{-11}
D	150.2	1.2	22,94	0.789	3.957×10^{-11}
E	150.6	1.6	23.27	0.527	2.582×10^{-11}
F	151.0	2.0	23.53	0.287	1.379×10^{-11}

Table 2. Parameters of the Experimental Laser

t	19%
I_0	8.30827×10^6 W/m^2
P_{in}	74 W
l	18 mm
d_{eff}	1.16×10^{-12} V/m
ε_0	8.85×10^{-12} F/m
c	3×10^8 m/s
n	1.56
λ_f	1064 nm
λ_{sh}	532 nm
ω_1	390 μm
ω_2	84 μm

Table 3. Calculated Results for the Intra-Cavity Round-Trip Loss and the Pump Factor Value, Average Value, and the Standard Deviation Value

Eqs	L (%)	K (%. W^{-1})
(A,B)	6.85	7.47
(A,C)	4.29	6.75
(A,D)	3.99	6.67
(A,E)	4.9	6.92
(A,F)	4.97	6.94
(B,C)	3.49	6.53
(B,D)	3.48	6.57
(B,E)	4.74	6.88
(B,F)	4.86	6.91
(C,D)	3.65	6.58
(C,E)	5.18	7
(C,F)	5.19	7
(D,E)	6.66	7.42
(D,F)	5.19	7.01
(E,F)	5.21	7.01
Average value	4.84	6.91
Standard deviation	0.26	0.07

In conclusion, a simple method for measuring the intra-cavity round-trip loss is proposed and demonstrated by means of introducing nonlinear loss. The theoretical expression of the intra-cavity round-trip loss is presented by analyzing the dependence of the output powers of the FW and SHW on the pump factor and the nonlinear conversion factor of an intra-cavity SHG single-frequency laser. By tuning the temperature of the LBO crystal of a homemade Nd:$\mathrm{YVO_4}$ laser, output powers of 1064 and 532 nm are measured. The high-precision intra-cavity round-trip loss and the pump factor of the high-gain single-frequency laser are obtained by solving fifteen sets of equations at six different temperatures of the LBO in the single-frequency region and are 4.84% and 6.91% W^{-1}, respectively. The obtained standard deviations of the intra-cavity round-trip loss and the pump factor are 0.26% and 0.07%, respectively. The presented method is suitable to measure the intra-cavity round-trip loss of FW lasers as well as the intra-cavity frequency-doubling lasers owing to its intrinsic advantages, including simplicity, convenience, and precision. In particular, it can be used to evaluate the intra-cavity round-trip loss and the pump factor of the lasers under high pump powers.

This work was supported by the Key Project of the Ministry of Science and Technology of China

(No. 2016YFA0301401) and the National Natural Science Foundation of China (Nos. 61405107, 61227902, and 61227015).

References

1. E. V. Kovalchuk, D. Dekorsy, A. I. Lvovsky, C. Braxmaier, J. Mlynek, A. Peters, and S. Schiller, Opt. Lett. **26**, 1430 (2001).
2. K.-K. Ni, S. Ospelkaus, D. Wang, G. Quemener, B. Neyenhuis, M. H. G. Miranda, J. L. Bohn, J. Ye, and D. S. Jin, Nature **464**, 1324 (2010).
3. T. M. Fortier, M. S. Kirchner, F. Quinlan, J. Taylor, J. C. Bergquist, T. Rosenband, N. Lemke, A. Ludlow, Y. Jiang, C. W. Qates, and S. A. Diddams, Nat. Photon. **5**, 425 (2011).
4. B. Willke, Classical Quantum Gravity **24**, S389 (2007).
5. P. Li, Y. J. Li, and K. S. Zhang, Laser Phys. Lett. **12**, 045401 (2015).
6. J. Qiu, J. H. Shi, Y. S. Zhang, S. S. Han, and Y. Z. Gui, Photon. Res. **3**, 82 (2015).
7. X. L. Yu, Z. Y. Li, B. J. Yang, and L. Yu, Laser **26**, 21 (2005).
8. H. D. Lu, Chin. J. Lasers **40**, 7 (2013).
9. S. G. Sabouri and A. Khorsandi, Chin. Opt. Lett. **10**, 061405 (2012).
10. B. Lu, L. Yuan, X. Qi, L. Hou, B. Sun, P. Fu, and J. Bai, Chin. Opt. Lett. **14**, 071404 (2016).
11. Z. Yu, M. Wang, X. Hou, and W. Chen, Chin. Opt. Lett. **13**, 071403 (2015).
12. W. Liu, Y. Ju, T. Dai, L. Xu, J. Yuan, C. Yang, B. Yao, and X. Duan, Chin. Opt. Lett. **14**, 091401 (2016).
13. D. Findlay and R. A. Clay, Phys. Lett. **20**, 277 (1996).
14. F. Song, H. Cai, S. J. Liu, T. Li, and J. G. Tian, "A method to measure the intracavity losses of LD-pumped solid-state laser," Chinese Patent: 200710058008 (2008).
15. J. Q. Zhao, Y. Z. Wang, B. Q. Yao, and Y. L. Ju, Laser Phys. Lett. **7**, 135 (2010).
16. D. Y. Chen, X. D. Li, Y. Zhang, X. Yu, F. Chen, R. P. Yan, Y. F. Ma, and C. Wang, Laser Phys. Lett. **8**, 46 (2011).
17. Q. W. Yin, H. D. Lu, and K. C. Peng, Opt. Express **23**, 4981 (2015).
18. Q. W. Yin, H. D. Lu, J. Su, and K. C. Peng, Opt. Lett. **41**, 2033 (2016).
19. E. Ji, Q. Liu, Z. Hu, P. Yan, and M. Gong, Chin. Opt. Lett. **13**, 121402 (2015).
20. H. D. Lu, J. Su, and K. C. Peng, "A method to measure the intracavity losses of all-solid-state laser," Chinese Patent: 201210094396.1 (2012).
21. J. Zhang, K. S. Zhang, Y. L. Chen, T. C. Zhang, C. D. Xie, and K. C. Peng, Acta Opt. Sin. **20**, 1311 (2000).
22. S. Greenstein and M. Rosenbluh, Opt. Commun. **248**, 241 (2005).
23. H. D. Lu, J. Su, Y. H. Zheng, and K. C. Peng, Opt. Lett. **39**, 1117 (2014).
24. H. D. Lu, Y. R. Guo, and K. C. Peng, Opt. Lett. **40**, 5196 (2015).
25. P. X. Jin, H. D. Lu, J. Su, and K. C. Peng, Appl. Opt. **55**, 3478 (2016).
26. X. Chen, N. Jiang, Y. Lv, and K. Qiu, Chin. Opt. Lett. **14**, 091404 (2016).
27. C. W. Zhang, H. D. Lu, Q. W. Yin, and J. Su, Appl. Opt. **53**, 6371 (2014).
28. Y. J. Wang, Y. H. Zheng, Z. Shi, and K. C. Peng, Laser Phys. Lett. **9**, 506 (2012).