PRAMANA
— journal of
physics

Vol. 75, No. 6
December 2010
pp. 1233–1239

Cavity ring-down technique for measurement of reflectivity of high reflectivity mirrors with high accuracy

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Abstract. A simple, accurate and reliable method for measuring the reflectivity of laser-grade mirrors ($R > 99.5\%$) based on cavity ring-down (CRD) technique has been successfully demonstrated in our laboratory using a pulsed Nd:YAG laser. A fast photomultiplier tube with an oscilloscope was used to detect and analyse the CRD signal. The cavity decay times were measured for three cavities formed by a combination of three mirror pairs. The absolute reflectivities R_1, R_2, R_3 were determined to be 99.94%, 99.63%, 99.52% at normal incidence. The reflectivity of mirrors is measured to an accuracy of 0.01%.

Keywords. Cavity ring-down method; reflectivity measurement; optical resonator.

PACS Nos 42.79.-e; 42.60.Da; 42.62.-b

1. Introduction

In high-power laser master oscillator power amplifier (MOPA) chains [1], a large number of high-reflectivity (HR) mirrors with reflectivity approaching unity are utilized for beam routing and beam transport. To minimize the loss of photons, the mirrors should have high values of reflectivity ($R > 99.5\%$). An equally important requirement is to establish an accurate technique for measuring reflectivity of HR mirrors used in the laser chain. Cavity ring-down (CRD) technique is an effective technique [2–5] to measure reflectivity of high reflectivity mirror (HR) with an accuracy better than 0.01%. Another advantage is, its immunity towards intensity fluctuation of laser source, as the measurement relies upon relative change in intensity of the pulse. The accuracy of the reflectivity of HR mirrors measured by spectrophotometer is limited to 1% and by power meters are limited by 3%.

CRD technique as a tool for R-measurement is preferably applied for high-reflectivity (HR > 96%) mirrors to get good measurement accuracy and measurable cavity decay time. The spectral region in which CRD can be applied has no principal limitation, as long as the mirrors are highly reflective at the wavelength region of interest and a tunable laser source available. In cw-CRD the scanning ranges of wavelength available is relatively limited compared to pulsed CRD technique, because pulsed laser sources such as dye lasers and OPOs can operate over large wavelength region and their higher peak power allows one to extend the wavelength region from UV to IR via non-linear frequency conversion.

The laser beam inside a cavity formed by two or more mirrors decays because of the various reflective and absorptive losses in each round trip. For minimum absorption ($\alpha \sim 0$), the losses in the bare cavity are essentially due to the mirror reflectivity losses. As the reflectivity of the mirror is not 100%, the intensity of laser beam launched in the cavity decreases in each round trip after reflection from mirrors. The decrease in intensity is monitored and the data are used to calculate the reflectivity of mirrors. This technique is known as cavity ring-down technique.

Let I_0 be the intensity at time $t = 0$ when the laser beam is launched into the cavity of length d. After one round trip, beam intensity I can be written as $I = I_0 R_1 R_2$ where R_1, R_2 are the reflectivities of the cavity mirror.

Here, absorption inside the cavity due to air molecules is assumed to be negligible. After k number of round trips, i.e. after time $t = k^* t_{\rm r}$, where $t_{\rm r}$ is the cavity round trip time ($t_{\rm r} = 2d/c$), intensity I can be written as

$$I = I_0 R_1^k R_2^k \tag{1}$$

$$k = \frac{t}{t_{\rm r}} = \frac{ct}{2d}. \tag{2}$$

Equation (1) can be written in the following form:

$$I(t) = I_0 {\rm e}^{-t/\tau} \tag{3}$$

$$\tau = -\frac{2d}{c \ln R_1 R_2}. \tag{4}$$

When $R_1 = R_2 = R \sim 1$ with approximation $\ln R = -(1 - R)$, eq. (4) becomes

$$\tau = \frac{d}{c(1-R)}, \tag{5}$$

where τ is the cavity ring-down time, which will be experimentally measured. For a combination of two mirrors out of the total three mirrors, eq. (4) can be solved to get

$$\ln R_i + \ln R_j = -\frac{2d}{c\tau_{ij}}, \quad \text{for } i \neq j = 1, 2, 3. \tag{6}$$

We will have three equations for three combinations of mirrors and three unknown reflectivities. The reflectivity of mirror 1 can be calculated as

$$\ln R_1 = -\frac{d}{c}\left[\frac{1}{\tau_{12}} + \frac{1}{\tau_{13}} - \frac{1}{\tau_{23}}\right]. \tag{7}$$

Similarly, we can get R_2 and R_3. Using eqs (6) and (7), reflectivity of each mirror can be evaluated by measuring the corresponding cavity decay times.

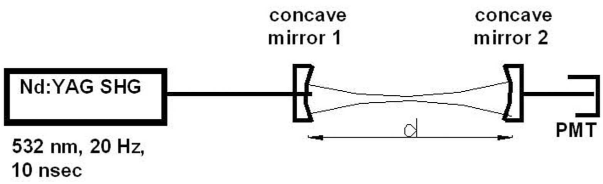

Figure 1. CRD set-up for measuring reflectivity of test mirror at 0° AOI.

Table 1. Decay time measurement for three cavities formed by mirrors Mi and Mj.

Mirror combination	Decay time (μs)
Mirrors 1&2	2.69
Mirrors 1&3	2.17
Mirrors 2&3	1.381

2. Experimental set-up

A stable cavity was formed using concave HR test mirrors as shown in figure 1. The pulsed Nd:YAG laser beam at 532 nm, with a repetition rate of 20 Hz and a pulse width of 10 ns was launched into the cavity. The laser beam transmitted from the cavity was attenuated and monitored using a PMT of fast response time. The pulse shape of the transmitted beam from the cavity was monitored by the oscilloscope (500 MHz, 1 GS/s). PMT signal was further processed with exponential decay fitting program to estimate the decay time τ. Using three HR mirrors, three different combinations were made and the corresponding data were processed to get the decay time, i.e. $\tau_{12}, \tau_{23}, \tau_{31}$. Using these values in eq. (6), the reflectivity of each mirror was calculated unambiguously.

The detector used in the experiment was a highly sensitive PMT which could detect weak CRD signal. Use of PMT avoids the necessity of mode matching optics to match the laser beam with fundamental transverse (TEM_{00}) cavity mode.

The cavity ring-down signal measured by PMT is shown figure 2. Figure 3 shows the exponential curve fitting results of the cavity ring-down signal of figure 2. The cavity length d during the experiment was 173 cm. Decay time of each mirror combination is listed in table 1. By solving decay equations of (6), the value of reflectivity of individual mirror was evaluated accurately without using any additional reference mirror. The value of reflectivies of each mirror is listed in table 2.

Table 2. Reflectivities of individual mirrors.

Reflectivity of mirror 1 (R_1)	99.9364
Reflectivity of mirror 2 (R_2)	99.6281
Reflectivity of mirror 3 (R_3)	99.5241

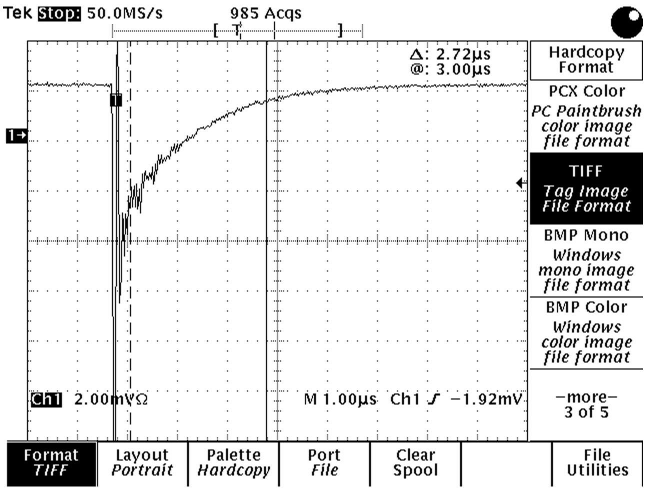

Figure 2. CRD signal as seen by the oscilloscope.

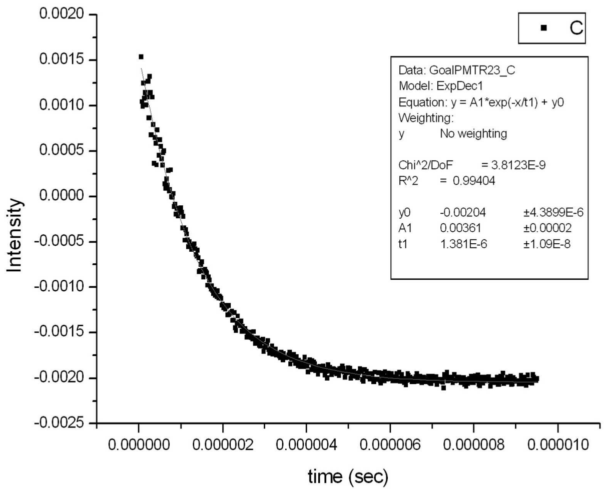

Figure 3. Exponential fitting of decay curve for mirrors 2 and 3.

3. Measurement of reflectivity of plane mirror at 45° angle of incidence (AOI)

Figure 4 shows the typical set-up for measuring the cavity decay time for the test mirror for 45° angle of the mirror. To measure the reflectivity of test mirror at 45° AOI, the following procedure was carried out. Initially cavity decay time (3.9 μs) for a reference cavity formed by a pair of concave mirrors ($f = 1.3$ m) as shown in figure 1 and the corresponding R_1, R_2 (0.9975) values were evaluated. Figures 5 and 6 show the cavity ring-down signal and the results of the exponential decay fitting of the reference cavity.

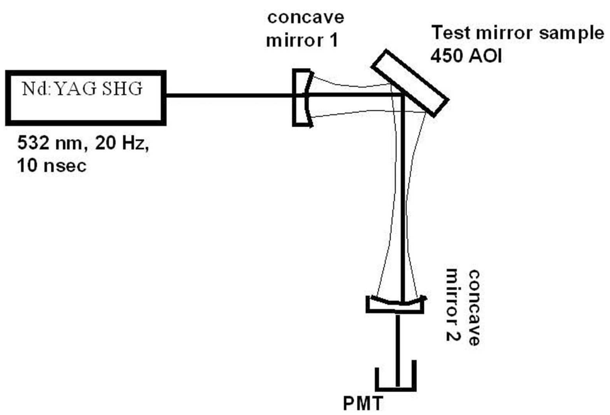

Figure 4. CRD set-up for measuring reflectivity of the test mirror at 45° AOI.

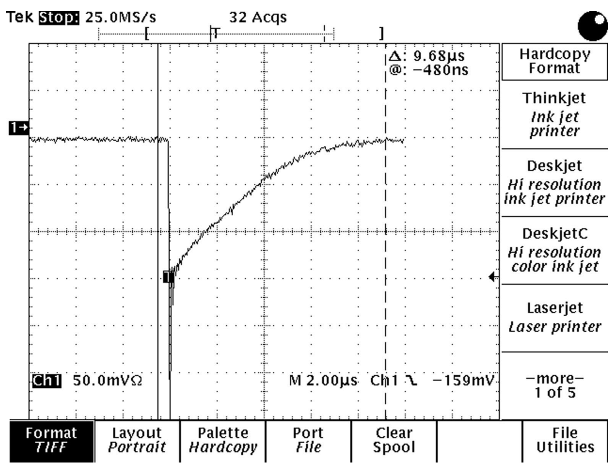

Figure 5. CRD signal of the reference cavity.

Test mirror was kept inside the reference cavity as shown in figure 4. Angle of incidence of the test mirror was maintained at the desired value of 45°. Cavity was aligned to get decay time (0.76 μs) and the corresponding $R_1R_2R_3$ value was deduced. Using these data, the value of reflectivity of the test mirror ($R_3 = 98.92$) was evaluated. Figure 7 shows the decay fitting results of the L-shaped cavity with a test mirror coated for 45° angle of incidence.

4. Effect of pulse energy on reflectivity measurement

We have measured the cavity decay time of reference cavity for three different values of pulse energies of 0.15, 0.4 and 0.9 mJ respectively and the results are listed in table 3.

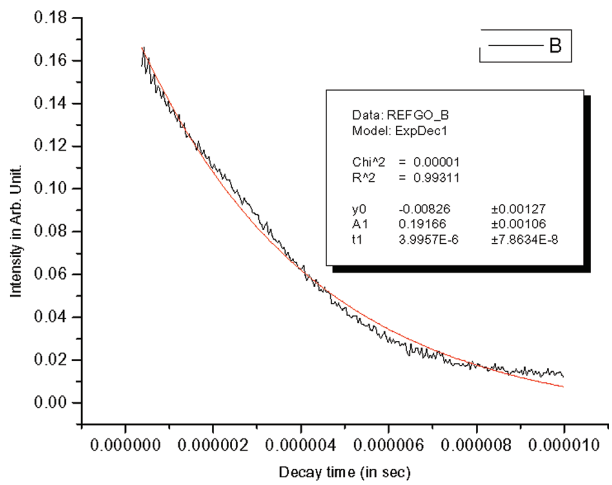

Figure 6. Exponential fitting of decay curve for the reference mirror.

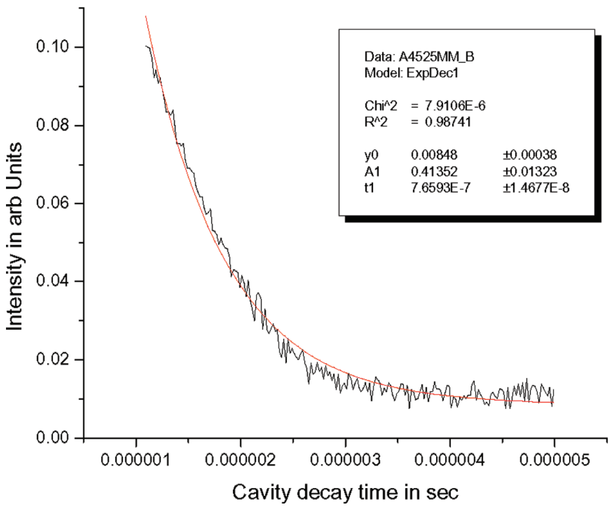

Figure 7. Exponential fitting results for L-shaped cavity containing the test mirror of 45° AOI.

The variation of pulse energy of Nd:YAG laser from 0.15 to 0.9 mJ affects only the second decimal of the reflectivity values for six times variation in the power. This shows that the error in the reflectivity measurement using CRD technique with reference to power variation of the laser is minimal.

The accuracy of the reflectivity measurement using CRDT can be estimated using the following error analysis from eq. (2) with $R_1 = R_2 = R$.

$$\frac{\Delta R}{R} = -\frac{1}{c}\left[\frac{\tau \Delta l_{\mathrm{c}} - l_{\mathrm{c}} \Delta \tau}{\tau^2}\right]. \tag{8}$$

Table 3. Decay time and reflectivity measurement for different laser pulse energies.

Pulse energy (mJ)	Cavity decay time (μs)	Reflectivity (%)
0.15	1.75	99.66
0.4	1.80	99.67
0.9	1.59	99.63

Equation (8) shows the correlation of the error measurement of the cavity length (Δl_c) and the decay time ($\Delta\tau$) fitting error on the reflectivity measurement error. In our experiment maximum error of Δl and $\Delta\tau$ are measured to be 1 cm and 100 ns respectively. For $\tau = 2$ μs and $l_c = 173$ cm, $\Delta R/R = 1.275 \times 10^{-4}$. Hence the accuracy of reflectivity measurement of the HR mirror with our set-up is better than 0.01%.

5. Conclusion

The CRD technique for measuring reflectivity of the laser grade mirrors to an accuracy of 0.01% was successfully demonstrated. Reflectivity measurements of mirrors in two configurations were carried out. We have also studied the effect of pulse energy variation on the cavity decay time and the corresponding reflectivity measurement. Presently we are optimizing cavity parameters to make a compact reflectometer for qualifying laser grade mirrors.

References

[1] I L Bass, R E Bonanno, R P Hanckel and P R Hammond, *Appl. Opt.* **31**, 6993 (1992)
[2] D H Lee, Y Yoon, B Kim, J Y Lee, Y S Yoo and J W Hahn, *Appl. Phys.* **B74**, 435 (2002)
[3] Y Gong, B Li and Y Han, *Appl. Phys.* **B93**, 355 (2008)
[4] Piotr Zalicki and Richard N Zare, *J. Chem. Phys.* **102(7)**, 2708 (1995)
[5] G Berden, R Peeters and G Meijer, *Int. Rev. Phys. Chem.* **19(4)**, 565 (2000)