

# Optical feedback cavity ring-down technique for high reflectivity measurement

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An optical feedback cavity ring-down technique (OF-CRD), in which the retro-reflection of the ring-down cavity (RDC) is re-injected into the oscillator cavity of a Fabry-Perot diode laser and causes the spectral fluctuation of the diode laser, is developed for ultra-high reflectivity measurement of optical mirrors. Due to the optical feedback-induced spectral fluctuation, the spectral line of the diode laser is occasionally in resonance with one or more RDC modes, resulting in an enhancement of the coupling efficiency of the laser power into the RDC and the occurrence of resonance peaks in the amplitude of the CRD output signal. These resonance peaks are employed in a CRD experimental setup for high reflectivity measurement of optical mirrors at 1064 nm. In the CRD setup, a pair of cavity mirrors, with reflectivities higher than 99.99%, is used. The reflectivity of both cavity mirrors is determined to be 99.99606% with an uncertainty of only 0.00003%. With a folded cavity configuration, the reflectivities of three mirrors with incident angles of 0, 22.5, and 45 degrees, are measured, and the results are  $99.9459 \pm 0.0004\%$ ,  $99.9755 \pm 0.0005\%$ , and  $99.9621 \pm 0.0006\%$ , respectively.

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Optical mirrors with high reflectivities have been widely used in a variety of research fields, such as high-power laser systems, laser gyroscopes, gravitational-wave detectors, and so on<sup>[1-4]</sup>. Currently, the cavity ring-down (CRD) technique has been the most commonly used method for the measurement of reflectivities approaching unity ( $R > 99.9\%$ ). To date, various CRD experimental schemes have been developed<sup>[5]</sup>. Physically, the simplest one is the pulsed-CRD technique<sup>[6]</sup>, in which a pulsed laser with a high peak power and a TEM<sub>00</sub> mode is employed to produce a single exponential decay CRD signal. Exponential decay signals are recorded to determine the cavity decay time, from which the reflectivities of optical mirrors consisting of the ring-down cavity (RDC) are calculated. On the other hand, the continuous-wave (CW) CRD works with a CW laser as the optical source, which is switched off when the amplitude of the RDC output signal exceeds a predefined threshold. The CW-CRD has also been frequently used for high-reflectivity measurement<sup>[7]</sup>. With the CW-CRD technique, an ultra-high-reflectivity of 99.99984% of cavity mirrors has been determined with sub-ppm (part per million) accuracy<sup>[8]</sup>. However, the experimental arrangements of the conventional CW-CRD technique are relatively complicated.

Recently, an optical feedback cavity ring-down technique (OF-CRD) was developed in our laboratory for accurate measurement of high reflectivity<sup>[9,10]</sup>. In conventional CW-CRD techniques, narrow-band CW lasers, such as gas lasers, distributed-feedback (DFB) diode lasers, or extended cavity diode lasers (ECDLs), are normally employed as the light sources due to the fact that the use of a broadband laser source would result in a low

coupling efficiency of the laser power into the RDC. In the OF-CRD technique, on the other hand, a broadband Fabry-Perot (F-P) diode laser is used as the light source. Due to the optical feedback-induced spectral fluctuation, the spectral line of the diode laser is occasionally in resonance with one or more RDC modes, resulting in an enhancement of the coupling efficiency of optical power into the RDC and the occurrence of resonance peaks in the CRD signal. However, the physical mechanism of the resonance-peak formation in the OF-CRD signals has yet to be investigated. In this letter, the optical feedback(OF) effect is investigated in detail through experiments. An OF-CRD experimental setup is established to measure the reflectivities of cavity mirrors and of planar test mirrors with different angles of incidence. With this experimental setup, very high measurement accuracy can be achieved.

The OF effect on both output power and spectrum of diode lasers has been intensively investigated due to the importance of line-width reduction and frequency stabilization of diode lasers in optical telecommunication<sup>[11]</sup>. The OF effect on diode lasers was classified into five regimes according to feedback strength<sup>[12]</sup>. In regime I, where OF is weak, the line-width was broadened or narrowed depending on the feedback phase. Rapid mode hopping was observed in regime II. The lowest line-width mode operation was obtained as the OF strength was increased to regime III. regime IV was well-known as the "coherence collapse" regime, in which the laser line-width was greatly broadened. In regime V, the laser regained stability and operated with a single longitudinal mode. The influence of filtered OF made from a high-finesse

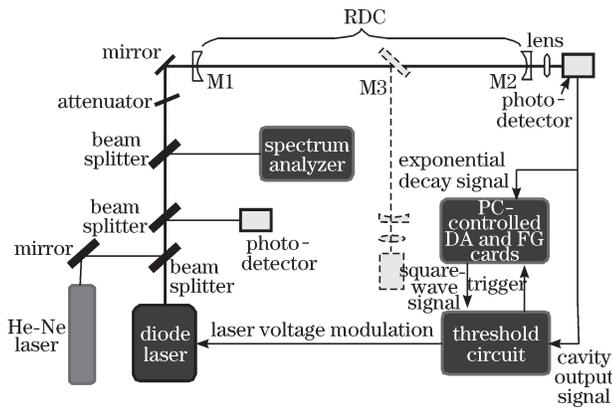


Fig. 1. Schematic diagram of the experimental OF-CRD setup.

resonator on diode lasers was also extensively investigated in order to achieve efficient noise suppression and frequency locking<sup>[13]</sup>.

To investigate the OF effect on the diode laser, the spectral changes of an F-P diode laser relative to a strong OF are experimentally investigated, including the direct reflection from the front mirror of a linear RDC, as well as the filtered frequency-selective OF from the RDC. A schematic diagram of the experimental setup is shown in Fig. 1. A CW F-P diode laser (Model IQ1A07(1060-10B)G2, Power Technologies) is used as the light source, whose wavelength is centered at about 1060 nm with an effective line-width of about 1.3 nm. A high-resolution spectrometer (Model 209, McPherson, 0.01-nm wavelength resolution, 0.05-nm wavelength accuracy) is used to measure the spectrum of the diode laser and monitor the spectral changes caused by the OF effect. The output power of the diode laser is square-wave modulated by a function generation card (Model UF2-3012, Strategic Test, Sweden), the output of which also serves as the excitation signal for a threshold circuit (TC). The laser output is monitored by a photodiode. The laser beam is coaxially coupled into the RDC. The light that leaks out of the cavity is focused into an InGaAs photo-detector module (Model 1811, New Focus), whose output is simultaneously sent to a

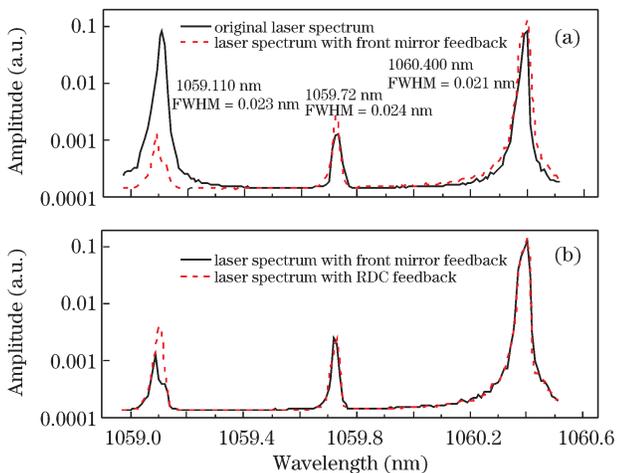


Fig. 2. Comparison of laser output spectra measured with and without OF effect: (a) with and without front mirror feedback; (b) with front mirror feedback and RDC feedback.

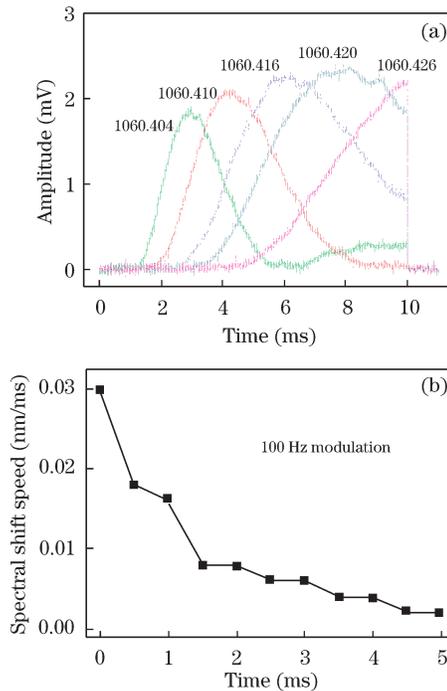


Fig. 3. (a) Temporal behaviors of laser output at different wavelengths and (b) spectral shift speed within one modulation period. The values in (a) indicate the wavelength in nm.

data-acquisition (DA) card (Model UF2-6021) and the TC. The TC is used to switch off the F-P diode laser when the amplitude of the RDC output signal exceeds a predefined threshold and to simultaneously trigger the DA card, which records the exponential decay signal immediately after switching off the diode laser. A variable attenuator is used to adjust the OF strength. A He-Ne laser is employed for aligning the cavity mirrors.

The original spectrum of the diode laser without the influence of the OF effect is presented by the solid line in Fig. 2(a), which consists of three longitudinal modes centered at 1059.1, 1059.7, and 1060.4 nm. The laser output power is contributed mainly by the 1059.1 and 1060.4-nm lines and only negligibly by the 1059.7-nm line. The spectral width of each longitudinal mode is approximately 0.2 nm. When the OF from the front mirror of the RDC is present, most laser power previously emitted at 1059.1 nm is shifted to the 1060.4 nm line, and the 1060.4-nm line is slightly broadened, as represented by the dotted line in Fig. 2(a). In this case, the frequency-selective feedback from the RDC is eliminated by blocking the retro-reflection from the back mirror of the RDC. On the other hand, no significant spectral change is observed when the frequency-selective OF from the RDC is added to the strong OF from the front mirror (Fig. 2(b)). This is done by un-blocking the retro-reflection from the back mirror of the RDC. It is worth mentioning that due to the resolution limitation of the spectrometer, spectral changes within 0.01 nm can not be measured. This might be the case when the frequency-selective feedback is present, as the line-width of the RDC is typically in the range of 10 to 100 kHz. However, without any doubt, the results presented in Fig. 2 show the strong effect of the OF on the spectrum

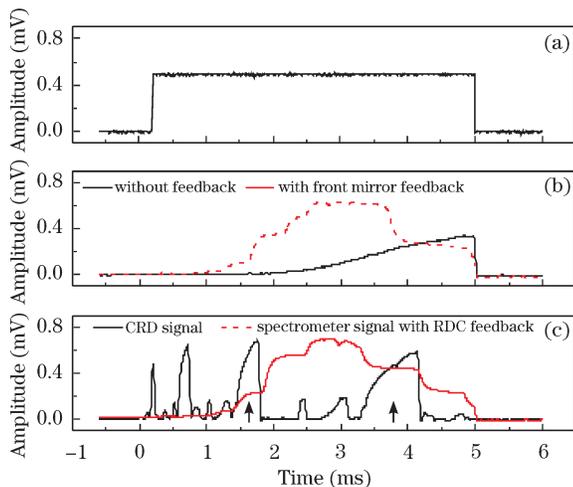


Fig. 4. (a) Output power of the laser within one modulation period; (b) the spectrometer signals at a fixed wavelength, without and with optical feedback from the front mirror of the RDC; (c) the spectrometer signal at a fixed wavelength with feedback from the RDC and the corresponding CRD signal.

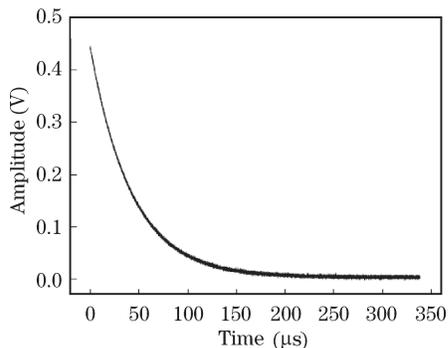


Fig. 5. A typical exponential decay signal immediately after the diode laser is switched off by the threshold circuit in the OF-CRD experiment.

of the laser beam coupled into the RDC.

To further understand the resonance peaks that occurred in the CRD signal, the temporal behavior of the laser spectrum is also investigated within one modulation period. The waveforms of the laser output power measured by the spectrometer at wavelengths 1060.404, 1060.410, 1060.416, 1060.420, and 1060.426 nm within the 1060.4-nm laser line and within one modulation period are shown in Fig. 3(a). Even though the output power of the diode laser is kept approximately constant during the modulation period, the output power at the beginning is mostly contributed by emissions from shorter wavelengths within the laser spectrum. As time passes by, the contribution to output power is replaced by the emissions from longer wavelengths as emissions from shorter wavelengths die down. In this time scale, the central wavelength of the laser spectrum shifts towards longer wavelengths within the modulation period and finally stabilizes to a certain wavelength in approximately 5 ms. The speed of the spectral shift as a function of time is shown in Fig. 3(b). The laser spectrum shifts rapidly at the beginning of the driving period of the laser and then slows down gradually. No significant

spectral shift is observed after 5 ms (not shown). The temperature modulation caused by the driving current modulation is believed to be the reason for the spectral shift, as it is well known that the spectrum of a diode laser shifts with temperature.

To establish correlations between the resonance peaks of the OF effect and the spectral shifts caused by the OF effect, the spectrometer signals at a certain wavelength, which represents the laser power at that wavelength, and the CRD signals within one modulation period are simultaneously recorded. The results are presented in Fig. 4. The waveform of the overall output power, which is the spectrometer signal integrated over the whole spectral range, of the diode laser is shown in Fig. 4(a). The constant power level indicates that the laser power is not affected by the spectral shifts and OF effect within the whole modulation period. The influence of the OF effect on the spectrometer signal recorded at a fixed wavelength is shown in Fig. 4(b). Without the OF effect, the spectrometer signal at the fixed wavelength increases gradually with time, until the driving current is abruptly switched off. When the strong feedback from the front mirror of the RDC is present, the spectrometer signal at that fixed wavelength largely fluctuates. The addition of the frequency-selective feedback from the RDC to the OF effect further changes the temporal behavior of the spectrometer signal at a fixed wavelength (Fig. 4(c)), as well as the waveform of the CRD signal. From Fig. 4(c), it is clear that occasionally, there are correlations between the temporal behaviors of the spectrometer signal and of the CRD signal at a fixed wavelength. The two arrows in Fig. 4(c) indicate the time periods in which the resonance peaks of the CRD signal are correlated with the amplitude changes of the spectrometer signal, while other resonance peaks might be

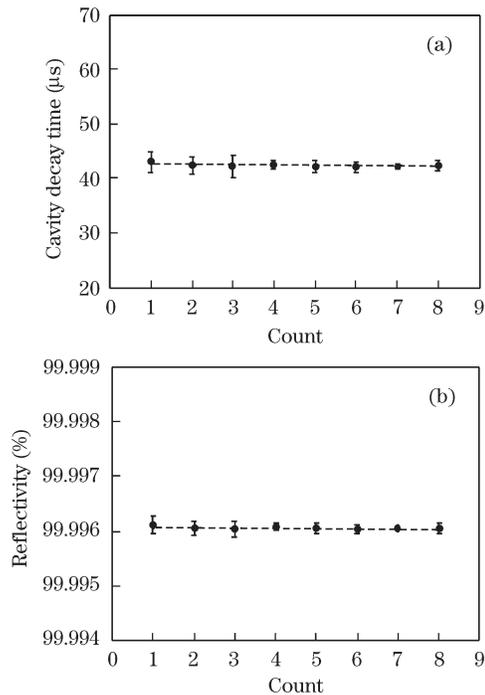


Fig. 6. Reproducible results of the measured cavity decay time (a) and determined reflectivity (b) of a pair of cavity mirrors with reflectivity of  $\sim 99.996\%$ .

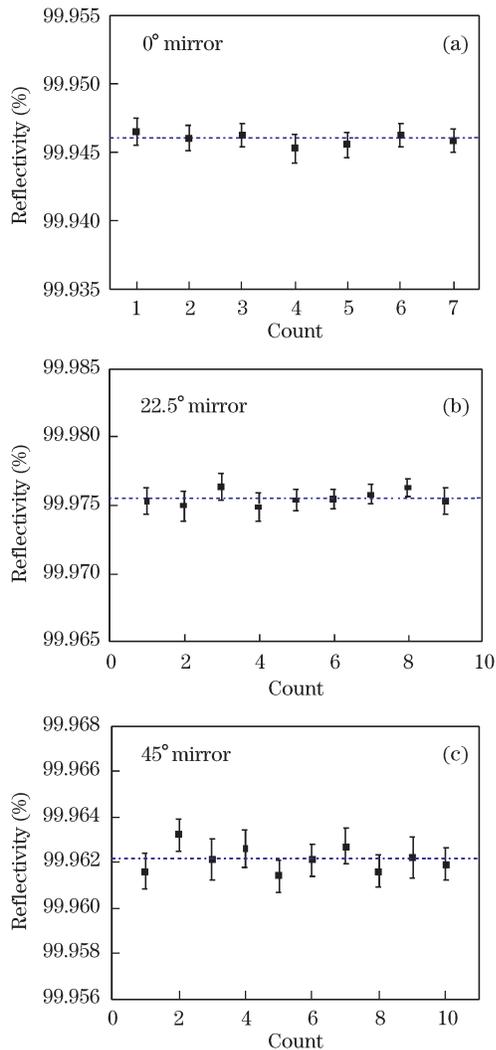


Fig. 7. Determined high reflectivity of the planar test mirrors with an angle of incidence (a)  $0^\circ$ , (b)  $22.5^\circ$ , and (c)  $45^\circ$ .

correlated to spectrometer signals at other wavelengths. Clearly, the results presented in Fig. 4 show the correlation between the resonance peaks of the CRD signal and the spectral shifts that occurred in the laser spectrum, with the spectral shifts partially caused by the OF effect.

In the OF-CRD technique, the resonance peaks of the CRD signal are used to determine the cavity decay time and therefore, the reflectivity of the mirrors consisting of the RDC. When the amplitudes of the resonance peaks exceed a predefined threshold, the TC is triggered to switch off the laser power, and an exponential decay signal is recorded. A typical exponential decay signal immediately after switching off the diode laser is shown in Fig. 5. The reflectivity of the cavity mirror is about 99.996%, and the cavity length is 50 cm. The OF-CRD decay signal in Fig. 5 is fitted to a single exponential decay function,  $a \exp(-t/\tau) + b$ , with  $a$  as the amplitude factor and  $b$  as the dc offset of the signal amplitude. The cavity decay time is determined to be  $42.36 \mu\text{s}$ . The instrumental response time of the OF-CRD arrangement including the TC is about 20 ns, and it can be neglected in the decay time determination. The fitted decay time is then used to determine the reflectivity of the cavity

mirrors in the linear cavity configuration.

The OF-CRD technique is first used to determine the reflectivity of the cavity mirrors. In the experimental setup presented in Fig. 1, a pair of cavity mirrors with a similar reflectivity of approximately 99.996% is used to construct a linear RDC and to investigate the sensitivity and reproducibility of the OF-CRD technique. The cavity decay time measured by the OF-CRD technique and the corresponding reflectivity of the cavity mirrors are shown in Fig. 6. The exponential decay signals are repeatedly detected 256 times, and the cavity decay time is determined from each signal. The 256 cavity decay times is statistically averaged to determine the reflectivity. The error bars indicate the statistical errors. To repeat the measurement, the cavity alignment is destroyed by arbitrarily moving the cavity mirrors and then restored by re-adjusting the mirrors to their optimal positions. The measurements are repeated 8 times to obtain all data points. The reflectivity of the cavity mirror is statistically determined to be  $99.99606 \pm 0.00003\%$ . The result is in good agreement with the data given by the manufacturer (with a reflectivity higher than 99.995% and a transmission coefficient of about 0.002%). The results show that the present OF-CRD technique is highly sensitive and reproducible for ultra-high reflectivity measurement.

To test the capability of the OF-CRD technique for the reflectivity measurements of planar mirrors, a folded RDC with a cavity length of 80 cm is constructed by inserting a high-reflective test mirror with a required angle of incidence into the linear RDC, which comprises two cavity mirrors with a reflectivity of 99.99606%, as shown in Fig. 1. The planar mirrors used in the measurements are three highly reflective mirrors with incident angles of  $0^\circ$ ,  $22.5^\circ$ , and  $45^\circ$ . Similarly, for each measurement, the cavity decay time is measured 256 times and statistically averaged to determine the reflectivity. For each planar mirror, the measurement is repeated 7 or 9 times by destroying and then restoring the cavity alignment. The reflectivities, shown in Fig. 7, are determined to be  $99.9459 \pm 0.0004\%$  for the  $0^\circ$  mirror,  $99.9755 \pm 0.0005\%$  for the  $22.5^\circ$  mirror, and  $99.9621 \pm 0.0006\%$  for the  $45^\circ$  mirror. The low standard deviations of the determined results indicate the high measurement accuracy and reproducibility of the OF-CRD technique for high reflectivity measurement. The measurement accuracy can be further enhanced with higher-reflectivity cavity mirrors or test mirrors.

In conclusion, a simple and sensitive OF-CRD technique has been developed for the high reflectivity measurement of both cavity mirrors and planar test mirrors. The spectral fluctuations of the laser line caused by the OF from the retro-reflection of the RDC result in the spectral resonance between the laser line and the RDC modes, which further leads to large resonant peaks in the RDC output signals. These resonance peaks have been used to determine the cavity decay time and the reflectivities of cavity mirrors and planar test mirrors. The reflectivity of cavity mirrors has been measured to be 99.99606% with a standard deviation of only 0.00003%. By establishing a folded RDC, the reflectivity of three planar test mirrors with incident angles of  $0^\circ$ ,  $22.5^\circ$ , and  $45^\circ$  have been measured to be  $99.9459 \pm 0.0004\%$ ,

$99.9755 \pm 0.0005\%$ , and  $99.9621 \pm 0.0006\%$ , respectively. The high measurement accuracy has proven that the OF-CRD is a highly precise and reliable technique for high reflectivity measurement.

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## References

1. A. Abramovici, W. E. Althouse, R. W. P. Drever, Y. Gürsel, S. Kawamura, F. J. Raab, D. Shoemaker, L. Sievers, R. E. Spero, K. S. Thorne, R. E. Vogt, R. Weiss, S. E. Whitcomb, and M. E. Zucker, *Science* **256**, 325 (1992).
2. P. Elleaume, M. Velghe, M. Billardon, and J. M. Ortega, *Appl. Opt.* **24**, 2762 (1985).
3. S. T. Cole, R. L. Fork, D. J. Lamb, and P. J. Reardon, *Opt. Express* **7**, 285 (2000).
4. L. H. J. F. Beckmann and D. Ehrlichmann, *Opt. Quantum. Electron.* **27**, 1407 (1995).
5. G. Berden, R. Peeters, and G. Meijer, *Int. Rev. Phys. Chem.* **19**, 565 (2000).
6. L. F. Gao, S. M. Xiong, B. C. Li, and Y. D. Zhang, *Proc. SPIE* **5963**, 59632F (2005).
7. D. Romanini, A. A. Kachanov, N. Sadeghi, and F. Stoeckel, *Chem. Phys. Lett.* **264**, 316 (1997).
8. G. Rempe, R. J. Thompson, H. J. Kimble, and R. Lalezari, *Opt. Lett.* **17**, 363 (1992).
9. Y. Gong, B. Li, and Y. Han, *Appl. Phys. B* **93**, 355 (2008).
10. Y. Gong, B. Li, Y. Han, and M. Liu, *Proc. SPIE* **7132**, 71320U (2009).
11. R. W. Tkach and A. R. Chraplyvy, *J. Lightwave. Tech.* **LT-4**, 1655 (1986).
12. E. A. Viktorov and P. Mandel, *Phys. Rev. Lett.* **85**, 3157 (2000).
13. G. P. Agrawal and C. H. Henry, *IEEE J. Quantum. Electron.* **24**, 134 (1988).