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Optical Feedback and Pulsed Cavity Ring-down Techniques for High-reflectivity Measurement: a Comparison Study*

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Abstract: An optical feedback cavity ring-down (OF-CRD) technique, based on the OF effect of diode laser, was developed for accurate high-reflectivity measurement of cavity mirrors. The amplitude of the OF-CRD signal was enhanced to be about two orders of magnitude larger than that without OF effect. The high-reflectivity of the cavity mirror, measured by the OF-CRD at four RDC lengths, is in excellent agreement and statistically determined to be 99.935 6 ± 0.000 8%. The OF-CRD and pulsed-CRD techniques, both based on the exponential decay measurement, were experimentally compared. The measurement accuracy of the OF-CRD is much higher than that of the pulsed-CRD, due to higher beam-propagation losses caused by mode-mismatching and mode beating effects in the pulsed-CRD experiment.

Key words: Cavity ring-down; Optical feedback; High reflectivity measurement; Pulsed laser
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0 Introduction

Highly reflective optical coatings have been employed to enhance the measurement sensitivity in gravitational-wave detection, spectroscopic studies of gases, etc. In the cavity ring-down (CRD) techniques, the high-reflectivity of the cavity mirrors can be calculated from the decay time of a linear empty cavity as if the diffraction and scattering losses can be neglected. To measure the reflectivity of a highly-reflective planar mirror, a folded cavity was constructed by inserting the planar mirror into the linear cavity. Both decay time values of the linear- and folded-cavity were measured and used to calculate the high-reflectivity of the planar mirror.

The CRD technique has been developed rapidly since the first application of pulsed CRD to absorption spectroscopy[1]. From then on, the pulsed-CRD has been intensively investigated as it has the advantages of simple optical arrangement and high sensitivity due to the high peak power of pulsed lasers. Recently the pulsed-CRD was employed for the high-reflectivity measurement in our lab[2].

On the other hand, the cw-CRD technique[3] has also been frequently used for high-reflectivity measurement. In the cw-CRD experiments, the frequencies of either a narrow-band laser or the RDC modes, or both, were controlled to make them in resonance with each other so that the transmittance of the laser power through the ring-down cavity (RDC) was greatly enhanced. With the cw-CRD technique, the ultra-high-reflectivity of cavity mirrors was determined to be 99.99984% with measurement accuracy at sub-ppm (part per million) level by Rempe et al[4]. However, the experimental arrangements of the cw-CRD technique were relatively complicated.

Most recently, an OF-CRD arrangement was developed for the accurate measurement of high-reflectivity in our lab, which differed from the previous ones mainly in the type of diode laser used as the light source and the way the diode laser was affected by optical feedback[5]. In this paper the reflectivity of cavity mirrors is selected so that the experimental setup is further simplified by eliminating the threshold circuit (TC). The OF-CRD is experimentally characterized in detail and compared with the conventional pulsed-CRD. It is indicated by the experimental results that the simple and low-cost OF-CRD is more accurate and reliable than pulsed-CRD.

1 OF-CRD for high-reflectivity measurement

The experimental OF-CRD setup was

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described in detail in reference [5]. In this paper, cavity mirrors with a moderately high reflectivity of ~99.93% are used in the CRD experiment. Although theoretically the measurement accuracy of reflectivity increases with an increasing reflectivity of cavity mirrors in CRD techniques, the signal-to-noise ratio of the cavity output signal is often largely reduced due to the ultra-low transmission of the cavity mirrors. In our previous paper, cavity mirrors with ultra-high reflectivity of about 99.996% was used[5]. Fig. 1 is the OF-CRD signals obtained using cavity mirror with modulation frequency being 100 Hz. Large resonant peaks in the cavity output signal appeared at a low frequency, as shown in Fig. 1(a). Therefore, a high-speed TC was necessary to switch off the diode laser at the right time of the peaks to obtain exponential decay signals. In this paper by using cavity mirrors with reflectivity of about 99.93%, the frequency of the occurrence of the resonant peaks in the CRD signals is so high that, at the negative step of the square-wave modulation signal where the diode laser is switched off, the amplitude of the OF-CRD signal is always sufficiently large, as shown in Fig. 1(b). Therefore, it is convenient to detect the cavity decay signal at the negative step of the modulation signal. The TC used in reference [5] is then eliminated. On the other hand,

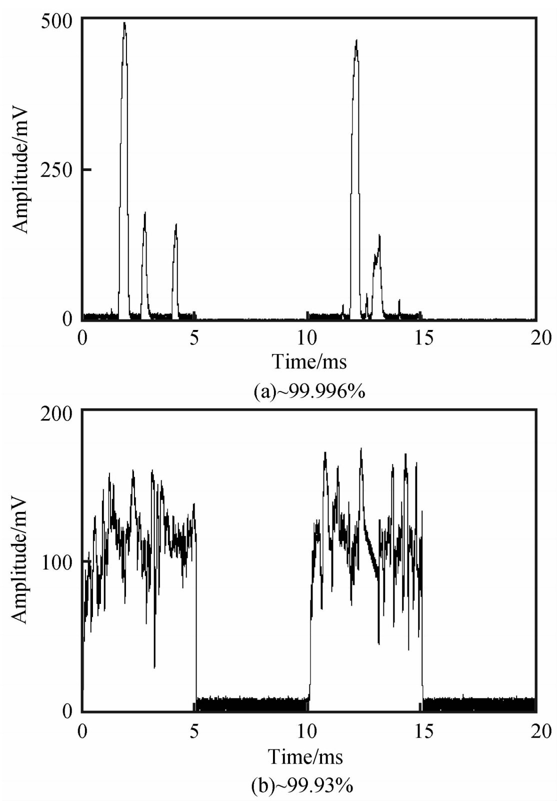
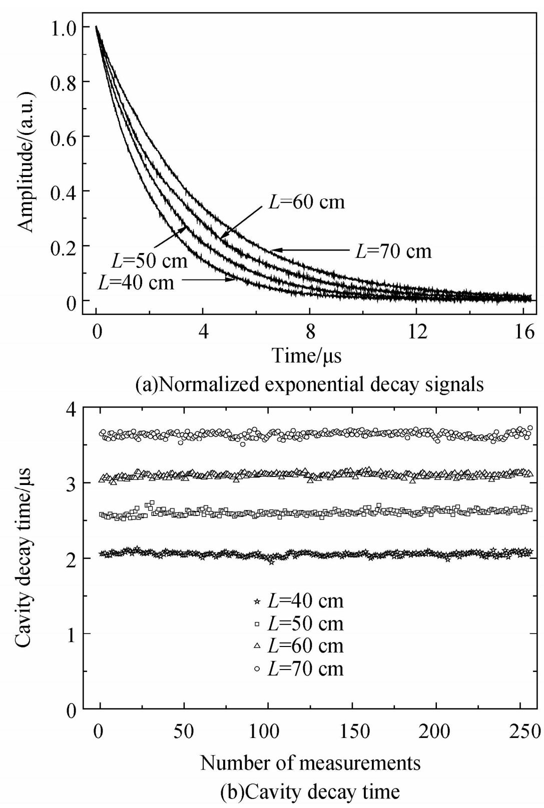


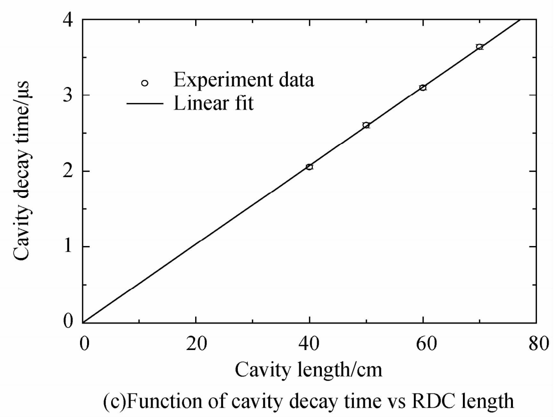
Fig. 1 The OF-CRD signals obtained by using cavity mirrors with reflectivity of ~99.996% and ~99.93%

the reflectivity measurement of highly-reflective planar mirrors can become more convenient when using cavity mirrors with reflectivity of about 99.93% instead of that of about 99.996%.

In the present CRD experiment, the light that leaks out of the RDC is attenuated to avoid saturation on the photo-detector. A modulation frequency of 100 Hz is used, which can be set at 1 kHz or even higher to enhance the measurement speed as long as the CRD amplitude is sufficiently high for sensitive measurement of the cavity decay time. The cavity decay signals at the negative step of the modulation signal are recorded by the data-acquisition card and fitted to an exponential decay curve to determine the cavity decay time, which is then used to calculate the reflectivity of the cavity mirrors.

The high-reflectivity measurement is repeated at four RDC lengths. The exponential decay measurement is repeated 256 times at each RDC length. The typical exponential decay signals at each RDC length are recorded and normalized to their maximum amplitude, as shown in Fig. 2(a). The signals are averaged 16 times in the present experiment. Each signal is fitted to a single exponential decay function, $a\exp(-t/\tau)+b$, with a the amplitude factor, b the dc offset of the signal amplitude and τ the cavity decay time, respectively, to determine the cavity decay time. The fitted cavity decay time values are shown in Fig. 2(b).





(c)Function of cavity decay time vs RDC length

Fig. 2 Normalized exponential decay signals and corresponding fitted cavity decay time values at different RDC lengths, and the function of cavity decay time vs RDC length

The high-reflectivity is calculated from the cavity decay time via $R=1-L/c\tau$, with L the RDC length and c the speed of light. The high-reflectivity of cavity mirrors are statistically determined to be 99.935 0±0.000 8%, 99.936 0±0.000 8%, 99.935 5±0.000 6%, 99.935 9±0.000 7%, with RDC lengths of 40 cm, 50 cm, 60 cm, and 70 cm, respectively. The excellent consistency of the high-reflectivity values determined at different RDC lengths indicates that the beam-propagation loss in a stable RDC can be neglected when the RDC is under the cw diode laser excitation. The beam-propagation loss means the part of the cavity loss introduced by the light escaped from the side of the RDC (i. e, mode-mismatching induced diffraction loss) after several reflections. Overall, the high-reflectivity of the cavity mirrors is statistically determined to be 99.935 6±0.000 8% from all 1 024 measured values. On the other hand, the cavity decay time values measured at four RDC lengths are plotted as a function of the RDC length in Fig. 2(c). The error bar denotes the standard deviation. The cavity decay time is linearly proportional to the RDC length via $\tau=kL$, with k the slope of the linear fit. The high-reflectivity is calculated to be 99.935 7% by $R=1-1/ck$.

The high reproducibility of the OF-CRD based high-reflectivity measurement is experimentally verified with a RDC length of 50 cm. The exponential decay signals are recorded 256 times and each time the cavity decay time is determined and used to calculate the high-reflectivity. The high-reflectivity of the cavity mirror, statistically determined by the 256 measured high-reflectivity values, is denoted by one of the data point in Fig. 3. The error bar denotes corresponding standard deviation. The exponential decay signals are not averaged in this experiment. 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 7 times to obtain all data points in Fig. 3. The cavity decay time and the high-reflectivity are statistically determined to be 2.592 μs and 99.935 7% with standard deviations of 0.025 μs and 0.0007%, respectively.

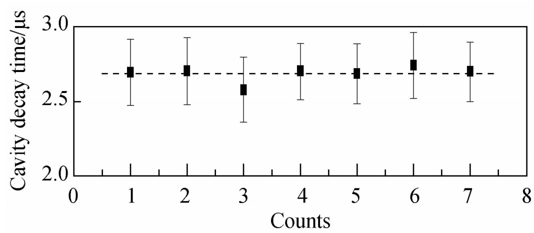


Fig. 3 Reproducible cavity decay time measured by the OF-CRD

2 Comparison of OF-CRD with pulsed-CRD

In this paper, the pulsed-CRD technique is also used for the high-reflectivity measurement and compared with the OF-CRD technique. A schematic diagram of the experimental pulsed-CRD setup is shown in Fig. 4. A flash-pumped pulsed Nd:YAG laser (Model Precision 8 000, Continuum) with a multi-transverse-mode output, whose wavelength is also centered at 1 064 nm, is used as the light source. The pulse duration is approximately 10 ns. In the pulsed-CRD experiment, the CRD signal is sensitive to the mode-matching (or mode-mismatching) between the laser beam and the RDC, due to the multi-modes of the laser beam. The RDC mirrors used in this experiment are identical to that used in the OF-CRD experiment. The light that leaks out of the RDC is focused into a high-speed photo-detector (with a rise time of 1 ns, Model 1 623, New Focus), whose output is sent to a digital oscilloscope (Model TDS5054B, Tektronix). This photo-detector has a lower gain factor than that used in the OF-CRD as the peak power of the pulsed laser is sufficiently high.

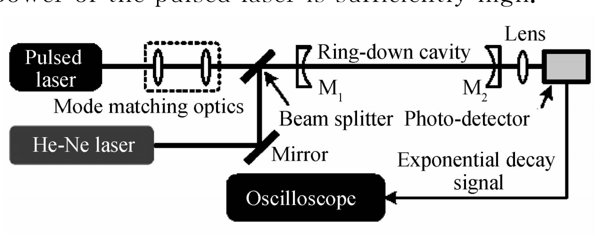


Fig. 4 Schematic diagram of the experimental pulsed-CRD setup

Schematically, the RDC output should be a sequence of laser pulses with a temporal interval of the RDC round-trip time and with an exponentially decayed intensity envelop when an ultra-short laser pulse is coupled into the RDC. However, the laser pulse overlaps with itself when the pulse duration is longer than the RDC round-trip time. In the present experiment with RDC lengths between 30 cm and 80 cm, the round-trip time is between 2.0～5.3 ns, the laser pulse overlaps with itself several times in the RDC, making the discrete pulses unobservable. Meanwhile, the longer pulse duration than the round-trip time of the RDC may result in interference and mode-beating effects. In the pulsed-CRD experiments, the effects of mode-beating and mismatching usually cause periodic fluctuations and non-exponential decays of the pulsed-CRD signals[6], which make the accurate pulsed-CRD measurement more difficult.

Fig. 5(a) shows an example of the pulsed-CRD signals obtained with a RDC length of 80 cm. The pulsed-CRD signal apparently deviates from the single exponential decay at the beginning portion of the signal. A parameter, t_0, is introduced to analyze the high-reflectivity determined from different segments of the pulsed-CRD signal. The data points from $t=t_0$ to the end of the pulsed-CRD signal are fitted to a single exponential decay function, $a\exp(-t/\tau)+b$, to determine the cavity decay time. As shown with empty circles in the inset of Fig. 5(a), the cavity decay time decreases with an increasing t_0 and becomes nearly constant (3.92 μs) when $t_0>1$ μs. The logarithmic value of the pulsed-CRD signal is calculated after subtracting the dc amplitude offset and then linearly fitted. In our previous paper the linear fitting method was used to make an accurate pulsed-CRD measurement in the mode-mismatching condition[6]. In the present pulsed-CRD, the data points from $t=t_0$ to $t=6$ μs of the pulsed-CRD signal are used in the linear fitting. Data points with low signal-to-noise ratio ($t>6$ μs) are eliminated. The cavity decay time obtained by the linear fitting decreases very slowly as t_0 increases and is much more accurate than that obtained by the exponential decay fitting, as shown with solid circles in the inset of Fig. 5(a). The cavity decay time obtained by the linear fitting remains approximately constant (3.92 μs) when $t_0>1$ μs, which is in agreement with that obtained by the single exponential decay fitting.

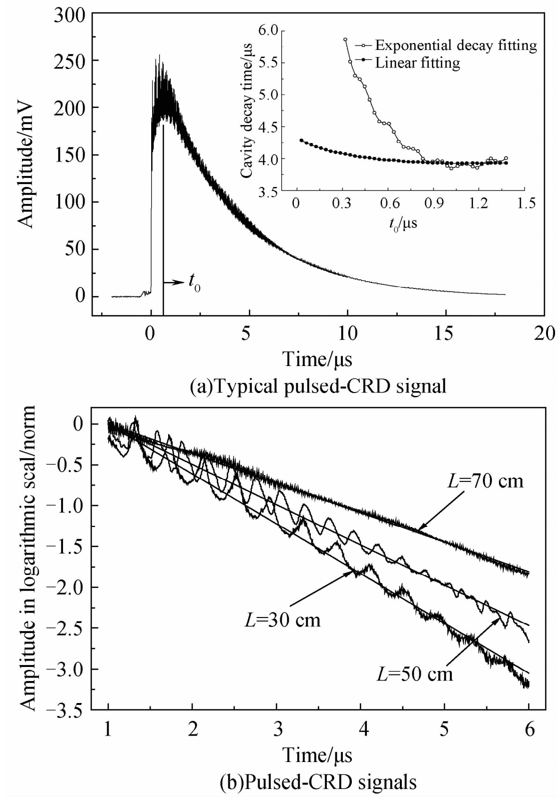


Fig. 5 A typical pulsed-CRD signal and pulsed-CRD signals in logarithmic scale and corresponding theoretical best-fits

The logarithmic values of the pulsed-CRD signals and corresponding best-fits, with RDC lengths of 30 cm, 50 cm, and 70 cm, are shown in Fig. 5(b), respectively. The pulsed-CRD signals obtained at the other three RDC lengths (40 cm, 60 cm, and 80 cm) are not shown to make the figure legible. The signals are averaged 32 times and the measurement is repeated 8 times at each RDC length to measure the cavity decay time. The mode-beating effect at low frequencies (megahertz level) are observed at RDC lengths of ～30 cm and ～50 cm, respectively, because the RDC modes are degenerate at ～29.3 cm and 50 cm and low-frequency mode beating appears when the RDC length deviates slightly from its mode-degeneration values.

The cavity decay time values measured by the pulsed-CRD are plotted as a function of the RDC length in Fig. 6 and the corresponding linear fit is also shown. The high-reflectivity is calculated to be 99.925 4% via $R=1-1/ck$, with k the slope of the linear fit. On the other hand, the high-reflectivity is statistically averaged from all the reflectivity values measured at six RDC lengths to be 99.926±0.009%, which is smaller than that measured by the OF-CRD method (99.935 6%), due to a higher beam-propagation loss inside the RDC in the pulsed-CRD experiment. Meanwhile, the measurement error (standard deviation) of the reflectivity in the pulsed-CRD experiment is approximately one order of magnitude larger than that in the OF-CRD experiment, due to the strong mode- mismatching and beating effects in pulsed CRD.

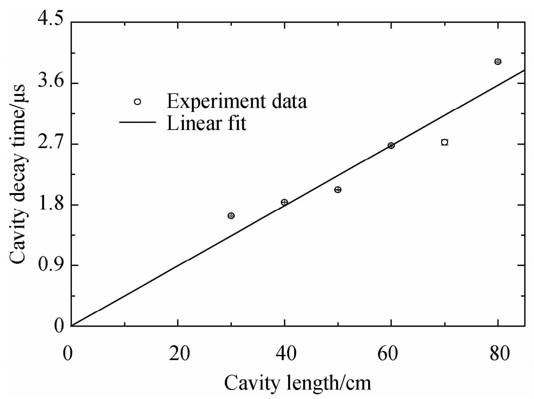


Fig. 6 Cavity decay time measured by the pulsed-CRD as a function of the RDC length

In the pulsed-CRD experiment a multi-transverse-mode beam is used. The pulsed laser beam is coupled through two mode-matching lenses into the high-finesse RDC and reflected back and forth in the RDC. Although the mode matching in the pulsed-CRD can be optimized by monitoring non-degenerate transverse mode beating[7], the perfect mode matching is difficult as the mode-matching lens, as shown in Fig. 4, has to be very precisely adjusted[6]. The mode-matching is not optimized in the present pulsed-CRD experiment, as neither in the OF-CRD experiment. The resulted mode-mismatching causes a considerable error in the high-reflectivity determination. The cavity decay time values measured by the pulsed-CRD at six RDC lengths show an approximately linear dependence on the RDC length, with moderate errors around the linear fit, due to the fact that the mode beating and mismatching effects are different at six RDC lengths. The measurement accuracy of the present pulsed-CRD can be improved by filtering the multi-transverse-mode laser beam and carefully optimizing the mode-matching between the pulsed laser beam and the RDC. However, even if a pulsed laser with a perfect TEM_{00}-mode beam profile is used and the modes of the laser and RDC are perfectly matched, it is still expected that the accuracy of the pulsed-CRD for the high-reflectivity measurement to be lower than that of the OF-CRD, due to the mode beating effect in the pulsed-CRD experiment.

The beam quality of the cw diode laser used in the OF-CRD is better than that of the pulsed laser. Thus, in the OF-CRD experiment with a stable cavity configuration, the cavity decay time can be accurately determined without the use of mode-matching optics, as long as all the laser power exiting the RDC is collected by the photo-detector[6]. On the other hand, for most highly reflective mirrors, the width of the reflection band normally covers several tens of nanometers and the reflectivity within this band remains approximately constant. Therefore, the influence of the limited spectral width (for a FP diode laser, the spectral bandwidth is around 3 nm) of the laser line and that of the OF induced spectral fluctuations on the high reflectivity measured at the laser wavelength is negligible. It is indicated by the experimental results presented in section 2 that the OF-CRD is reliable and accurate for high-reflectivity measurement.

3 Conclusions

The high-reflectivity of cavity mirrors has been measured by both OF-CRD and pulsed-CRD techniques. The simple OF-CRD arrangement has been further simplified by eliminating the high-speed threshold circuit. The high-reflectivity of cavity mirrors, measured at four RDC lengths, has been in excellent agreement and statistically determined to be 99.935 6 ± 0.000 8%. On the other hand, the high-reflectivity of the same cavity mirrors has also been measured by the pulsed-CRD technique. Compared to the pulsed CRD technique, the improvement of the measurement accuracy of over one order of magnitude with the OF-CRD technique has clearly demonstrated that the simple and low-cost OF-CRD is a highly accurate and reliable technique for high-reflectivity measurement.

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光反馈光腔衰荡和脉冲光腔衰荡技术测量腔镜高反射率的对比研究

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摘　要：基于半导体激光器的光反馈效应，提出了光反馈光腔衰荡技术用于测量腔镜的高反射率。相对于没有光反馈的情况，光腔衰荡信号振幅提高了两个数量级，从而大大提高了高反射率测量精度。在四个衰荡腔长采用光反馈光腔衰荡技术测量得到的腔镜反射率非常一致，统计平均值为 99.9356±0.0008%。通过实验比较了光反馈光腔衰荡和脉冲光腔衰荡技术。结果表明，光反馈光腔衰荡技术的测量精度比脉冲光腔衰荡技术高。

关键词：光腔衰荡；光反馈；高反射率测量；脉冲激光

GONG Yuan was born in 1981. He received his Ph. D degree from the Institute of Optics and Electronics, Chinese Academy of Sciences in 2008. His current research interests focus on the cavity ring-down techniques and fiber-optic biochemical sensors.