第 37 卷　第 12 期
2010 年 12 月

中　国　激　光
CHINESE JOURNAL OF LASERS

Vol. 37, No. 12
December, 2010

文章编号：0258-7025(2010)12-3075-06

Loss Measurement of High-Finesse Fabry-Perot Cavities

Liufeng Li (李刘锋)　Yan Li (李　艳)　Lisheng Chen (陈李生)*

(*Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan, Hubei* 430071, *China*)

Corresponding author: *lchen@wipm.ac.cn*

Received March 30, 2010; *Revised April* 26, 2010

Abstract　The loss of a high-finesse Fabry-Perot cavity was measured using frequency scan and cavity ring-down techniques. Different transverse modes were examined by sweeping the frequency of the laser across the corresponding resonances. In addition, cavity ring-down technique was used to measure the loss of the Fabry-Perot cavity and a simple model was employed to remove the influence of finite response time of the optical switch and the detection circuit.

Key words　high-finesse Fabry-Perot cavity; loss measurement; cavity ring-down; frequency scan

CLCN: TN247　　**Document Code**: A　　**doi**: 10.3788/CJL20103712.3075

1　Introduction

Low-loss highly-stable Fabry-Perot (F-P) cavities are of interest in many research fields such as laser cooling of mechanical oscillators[1,2], cavity quantum electrodynamics (QED)[3,4], laser interferometers[5,6], and optical frequency standards[7~9]. The benefits of long storage time, adjustable quality factor, and small frequency pulling make the F-P cavity an ideal component to enhance and engineer the matter-field interaction. Low vibration sensitivity and low noise F-P cavities are currently under development to fully realize these features.

Optical loss of an empty cavity is largely determined by the quality of the mirror coatings. We are developing cavities with various geometries and supporting structures[10]. These cavities will be used in our future experiments on optical frequency standards, precision laser spectroscopy, and the test of Lorentz invariance. Currently these cavities have a finesse of 70000～80000, and are still under development. In this process, both techniques of frequency sweeping and cavity ring-down are used to measure the loss of F-P cavities. Information from loss measurement is used for developing low-loss high-reflection cavity mirrors.

Usually the finesse of a cavity is first measured and the cavity loss is directly inferred from it. With a knowledge of the free spectral range (FSR, R_{FS}) of the cavity, the finesse can be estimated by sweeping either the cavity length or the frequency of the input light. Although it is widely used in low-finesse (about 100) cavities, this technique is limited when the resonances of the cavity become too narrow. Many sophisticated methods have been used to measure the loss of high-finesse cavities, such as cavity ring-down[11~13], frequency response function[14], and cavity ringing effect[15].

In this work, we use both frequency sweep and cavity ring-down to measure the finesse of an F-P cavity. With the frequency sweeping technique, we examine the loss associated with different cavity modes. Mode-dependent cavity loss provides useful information for optimizing the mirror coating. The maximum finesse that can be measured with the current experimental setup is investigated with this method. The loss of the same cavity is also measured with the cavity ring-down technique. A simple model is used to remove the contribution of the finite falling times produced by the optical switch and detector.

2　Methods

The finesse of a cavity is defined as

$$F = R_{FS}/\Delta\nu, \tag{1}$$

where $\Delta\nu$ is the width of the cavity resonance (full-width at half-maximum, FWHM). Cavity resonances can be observed by sweeping the frequency of the input light and monitoring the transmitted signal on an oscilloscope. When the width of the resonance is comparable to the FSR of the cavity, it can be directly estimated on the oscilloscope with the FSR deduced from the length of the cavity [$R_{FS} = c/(2L)$], where L is the cavity length, c is the speed of light. For high-finesse cavities, this task

Supported by Bureau of Comprehensive Planning, Chinese Academy of Sciences.

becomes less practical because the resonance becomes too narrow to be measured on the oscilloscope. Also, the accuracy of the measurement is limited by the nonlinearity of the frequency sweeping that is usually performed with the help of a piezoelectric transducer (PZT).

An improved technique can be used to extend the range covered by frequency sweeping. The laser is first phase modulated before entering the cavity and the two frequency sidebands are developed after the phase modulation[16]. When the laser frequency is swept by a saw-tooth signal across the resonance, two additional small peaks appear in the transmitted signal. These two components serve as accurate frequency markers because they are separated from the carrier by a distance equal to the frequency of the phase modulation, which is much smaller than FSR. More specifically, one uses an oscilloscope to measure the ratio of the linewidth to the distance between the carrier and one of the sidebands. Then the modulation frequency times this ratio gives the linewidth of the resonance from which the finesse can be obtained according to Eq.(1). Note that the linewidth of the laser should be at least one order of magnitude smaller than that of the resonance of the cavity. With a prior knowledge of its linewidth, the laser's contribution can be removed from the measured line profile.

As the loss of the cavity decreases, the resonance becomes narrower. It will be difficult to resolve the narrow resonance in frequency domain. Whereas in time domain light field stored in a high-finesse cavity has a relatively long decay time, which can be readily measured by the cavity ring-down technique. This method is of advantage for measuring ultra-low-loss cavities, but a fast optical switch with small falling times (about 100 ns) is required. After the field inside the cavity reaches a steady state, the light incident on the cavity is switched off and the transmitted light decays exponentially, with a time constant determined by the round-trip loss in the cavity[11]. A digital storage oscilloscope records the transmitted signal and an exponential curve fit gives the decay time. The relationship between the decay time and the cavity finesse has been deduced in Ref.[11]:

$$F = 2\pi \frac{c}{2L}\tau, \tag{2}$$

where τ is the cavity decay (storage) time. The loss of the cavity is related to the finesse by

$$F = 2\pi/\alpha, \tag{3}$$

where α is the round-trip loss. Note that Eq.(2) and (3) have been derived in the limit of high finesse (low loss).

3 Experimental Setup

Figure 1(a) illustrates the experimental setup. Before entering the cavity, the laser was phase modulated by an electro-optic modulator (EOM). A resonance circuit was used to drive the EOM crystal at the fixed frequency of 2.5 MHz. To increase the resolution, a high voltage amplifier working at a lower frequency was used. A saw-tooth signal swept the frequency of the laser. The transmitted light from the cavity hit onto a photo detector. Resonances of the cavity and their sidebands were displayed on an analog oscilloscope for the measurement of the linewidth.

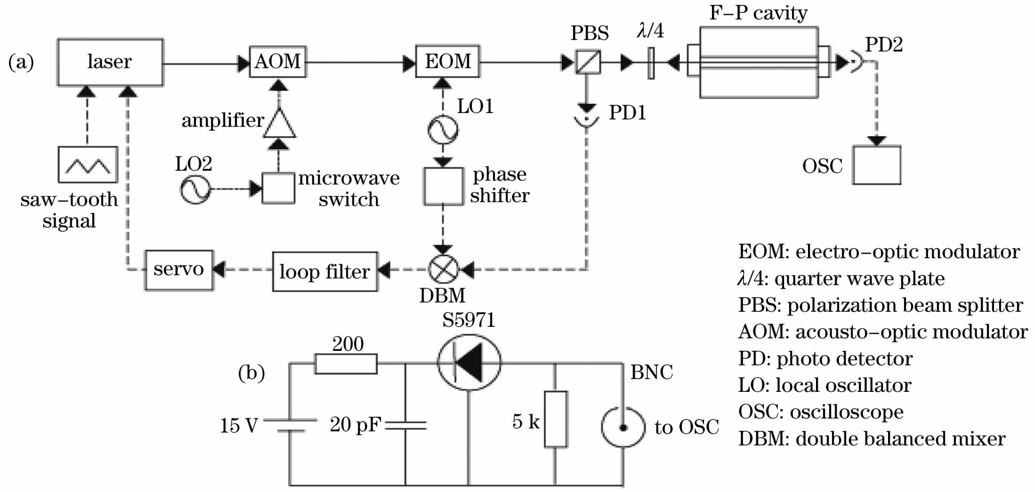

Fig.1 (a) Apparatus for loss measurement of F-P cavity, (b) circuits of PD2.

In the cavity ring-down measurement, an optical switch was inserted before EOM to turn off the input light with high speed. The optical switch consisted of an acousto-optic modulator (AOM, Brimrose EF-200-50) and a microwave circuit that can switch off the driving microwave of the AOM with the time constant of 10 ns. The laser was first locked to a longitude mode of the cavity using the Pound-Drever-Hall (PDH) technique[16]. When the field inside the cavity reached a steady state, the laser beam was switched off by the AOM and the transmitted light was detected by a PIN photodiode (PD2). The PD2 (Hamamatsu S5971) had the cut-off frequency of 100 MHz and was connected as shown in Fig. 1(b). The output of PD2 was directly sent to a digital oscilloscope (TDS 2014B) and the decaying waveform was stored by the oscilloscope with its single-trigger function.

The F-P cavity used in the measurements was a cylindrical cavity whose geometry was detailed shown in Ref. [10]. Two fused silicon plano-concave mirrors with the curvature radius of 2 m were optically contacted to a cylindrical spacer to form an F-P cavity. The nominal length of the cavity is 10 cm, corresponding to an FSR of 1.5 GHz. The cavity was placed inside a temperature-controlled vacuum chamber and supported by a V block. Four teflon strips were inserted beneath the spacer to provide damping and thermal isolation. The windows of the vacuum chamber were wedged (20′) and anti-reflection (AR) coated to prevent parasitic etalons.

The used continuous-wave (CW), single-frequnency, diode-laser-pumped, was a Nd:YAG ring laser developed at the National Institute of Metrology (NIM). The nonplanar ring resonator of the Nd:YAG laser was temperature controlled and enclosed by a hermetic sealed aluminum box to further improve the stability. A thin PZT plate was cemented to the top of the ring resonator. The frequency of the laser could be swept by the PZT. The free running linewidth of the laser was about 2.1 kHz, independently verified by heterodyne beat against another Nd:YAG laser.

4 Results and Discussions

4.1 Frequency Scan

Resonances associated with different transverse modes were displayed on an analog oscilloscope by sweeping the frequency of the laser. One of the two sidebands was used as the frequency marker from which the width of the resonance was determined. Figure 2 shows the resonances of four modes with the modulation frequency of 80 kHz. The corresponding FWHM is also indicated in the figure. Table 1 lists the linewidth of each mode.

Table 1 Diagnostic measurement of the cavity loss

Node	FWHM /kHz	F /10^4
$n=0$	20(1.5)	7.50(56)
$n=1$	16.7(1.0)	9.00(54)
$n=2$	20.5(1.6)	7.30(57)
$n=3$	18.5(1.8)	8.10(79)
$n=4$	17.4(1.8)	8.60(89)

FWHM of the resonance of the transverse mode is obtained by sweeping the frequency across the resonances of the cavity. Modulation frequency is 80 kHz. The cavity has an FSR of 1.5 GHz.

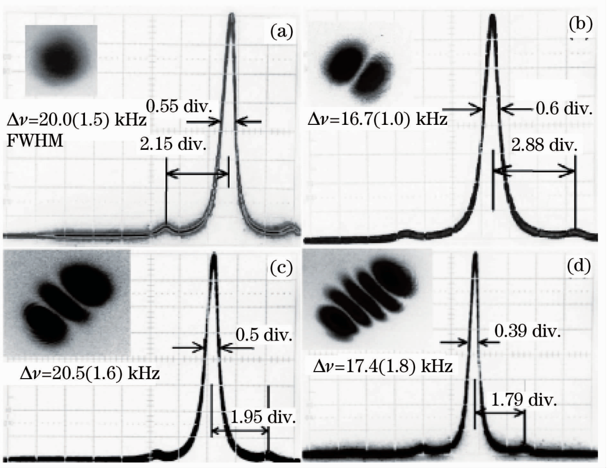

Fig. 2 Resonances of F-P cavity recorded on an oscilloscope by sweeping the frequency of laser. Phase modulation of the EOM in front of the cavity generates two sidebands, which are used to calibrate the horizontal scale of the oscilloscope. Insets are corresponding mode distributions. Modulation frequency of the EOM is 80 kHz. Sweep rate is 10 Hz.

Both the modulation frequency and the linewidth of the laser limit the highest finesse that can be accessed by using the frequency sweeping. Decreasing the modulation frequency and sweeping range around the resonance increases the resolution of the measurement. For example, the resonances of a cavity with the finesse of 200000 and FSR of 1.5 GHz exhibits the linewidth of 7.5 kHz (FWHM). With the modulation frequency of 1.25 MHz the resonance had a width less than 0.1 divisions, which was barely resolved. When the modulation frequency reduced to 80 kHz, the width would be on the order of 1 division, providing a quick estimation of the linewidth of the resonance.

Current results given in Table 1 do not take into account the influence of the finite linewidth of the laser, which leads to an underestimate of the finesse of the cavity. As the loss of the cavity drops, the finite linewidth of the laser eventually becomes a limiting factor of the resolution in frequency domain. Ideally, if the lineshape of the laser is known, a deconvolution will extract the width of the resonance from the lineshape obtained by frequency sweep. Figure 3 shows the beat note between two similar Nd:YAG lasers, one of which was used in the loss measurement. The beat note has the linewidth of 3 kHz, indicating a 2.1-kHz free-running linewidth of the laser. However, a reliable correction of the spectral impurity of the laser is complicated in that the free-running Nd:YAG laser also exhibits frequency jittering. Thus we do not tend to directly remove the 2.1-kHz linewidth of the Nd:YAG laser from the results listed in Table 1. The finesse in Table 1 should be interpreted as their corresponding lower boundaries. Nevertheless, a coarse estimate of the frequency jittering is possible by setting the single-shot time of the spectrum analyzer similar to the period of the frequency sweeping and performing repeated beating measurements. In this way, the contribution of the frequency jittering to the linewidth of the resonances is estimated as 1～3 kHz.

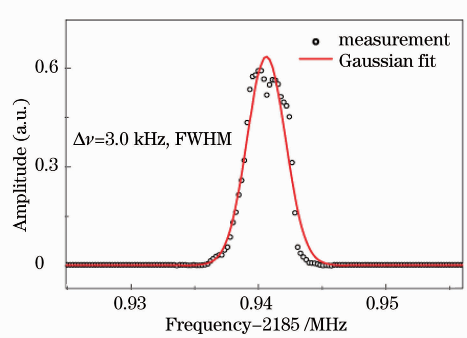

Fig. 3 Beat note between two free-running Nd:YAG lasers. The resolution bandwidth of the spectrum analyzer is 1 kHz.

4.2 Cavity Ring-down

The speed of the optical switch was first investigated in the cavity ring-down experiment. Ring-down measurement was not affected by the time delay of the AOM that was related to the propagating time of the sound wave inside the AOM. But the driving circuit, the finite size of the light within the light-sound interacting region, and detection circuit produced a finite falling time, which modified the decay of the cavity field. Figure 4 shows the light intensity of the first-order diffraction of the AOM when the cavity was removed and the radio frequency (RF) power driving the AOM was switched off. The intensity could be well fitted to an exponential decay function $y(t) = A\exp[-(t-t_0)/\tau_1] + y_0$, with the time constant τ_1 of 1.073(5) μs.

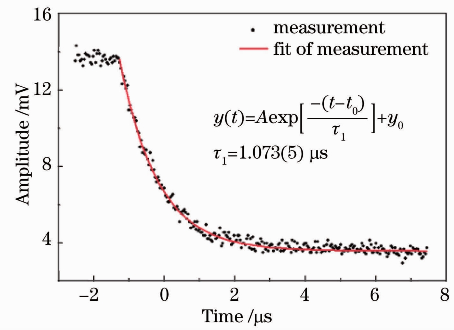

Fig. 4 First-order diffraction of AOM after RF driving signal is switched off. Solid curve is an exponential fit of experimental data (dots).

We use a simple model to remove the contribution from the finite switching time of the AOM. When the input light is switched off abruptly without any falling time, the decay of the field inside the cavity will be exponential provided that the loss is small and the round trip is not very long (far shorter than that light can travel in one storage time). But the real decay process inside the cavity is more complicated with a finite switching time. In control theory the unit-step response function of a first-order system in time domain is an exponentially growing function. We model the current process to be two independent first-order systems that are connected in series. It is straightforward to derive the unit-step response function of this composite system in time domain[17]. A transformation from exponential increase to decay then gives the decay of the cavity field with finite switching time, which can be written as

$$y(t) = \frac{\tau_1\exp(-t/\tau_1) - \tau_2\exp(-t/\tau_2)}{\tau_1 - \tau_2}, \quad (4)$$

where τ_1 and τ_2 are the time constants of the optical switch and the cavity, respectively. From this expression, it is clear that if the switching time is much smaller than the cavity decay time ($\tau_1/\tau_2 < 10$), it has a negligible contribution.

Figure 5 shows the decay of the field stored in the cavity when the input light is switched off by the AOM. The experimental data is fitted by the model described by Eq. (4), with τ_1 fixed to 1.073 μs. The cavity decay time from this fit is $\tau_2 = 10.39(5)$ μs, corresponding to the finesse of $F = (9.79 \pm 0.05) \times 10^4$. We also fit the experimental data to a simple exponential decay function and get the time constant of $\tau = 10.48(4)$ μs, with only 0.1-μs difference from the model that takes into account the finite switching time. The small difference is in agreement with our model since the switching time in this experiment is one order of magnitude smaller that the cavity decay time.

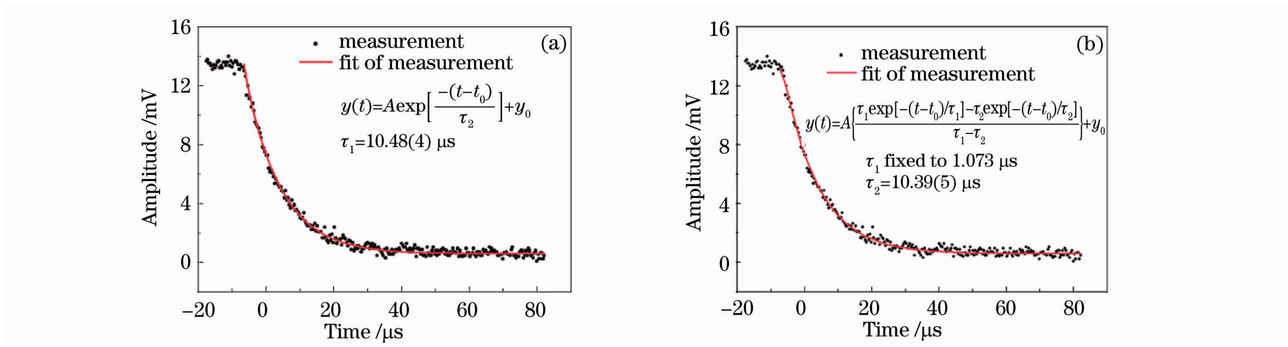

Fig. 5 Cavity ring-down signal fitted by (a) a simple exponential function and (b) a model takes into account the finite falling time of AOM and detection circuit. See text for details.

4.3 Discussions

Both techniques of frequency sweeping and cavity ring-down can be used to measure the loss of optical cavities. For cavities with moderate finesse less than 100000, the resonances of the cavity can be resolved by frequency scan. The cavity ring-down at time domain is more suitable for measuring high-finesse cavities with $F > 10^5$. In the range of F from 50000 to 2000000 both methods can be adopted, providing a diagnostic check of the measurement.

5 Conclusions

The loss of an F-P cavity is measured with both frequency sweeping and cavity ring-down. The lower boundary of the finesse of the cavity is estimated as 75000 using frequency sweep while the cavity ring-down gives a value of $F = (9.79 \pm 0.05) \times 10^4$. The difference of the two results is attributed to the spectral linewidth and frequency jittering of the free-running Nd : YAG laser. Several high-order transverse modes are also examined with the help of frequency sweeping. In the current experimental setup, decreasing the modulation frequency of EOM to 80 kHz can extend the measurable finesse up to 200,000. A finite switch-off time of the AOM is a major limiting factor in our cavity ring-down measurement. To correct for the finite falling time of the input light, we develop a simple model, which suggests that the switch time has a negligible influence when it is one order of magnitude smaller than the decay (storage) time of the cavity.

Acknowledgement

Equipment loans from Kelin Gao, Baolong Lu, Mingsheng Zhan, and Jin Wang at Wuhan Institute of Physics and Mathematics (WIPM) are highly appreciated.

References

1 D. Kleckner, D. Bouwmeester. Sub-kelvin optical cooling of a micromechanical resonator [J]. *Nature*, 2006, **444** (7115): 75～78

2 C. H. Metzger, K. Karrai. Cavity cooling of a microlever[J]. *Nature*, 2004, **432**(7020): 1002～1005

3 J. Ye, H. J. Kimble, H. Katori. Quantum state engineering and precision metrology using state-insensitive light traps [J]. *Science*, 2008, **320**(5884): 1734～1738

4 Xiao Xiaoqi, Yang Lianhua. Remote preparation of qubit via tripartite entangled W state in cavity QED [J]. *Acta Optica Sincia*, 2008, **28**(9): 1812～1815
肖骁琦,杨联华. 利用三原子 W 类纠缠态在腔量子电动力学体系中实现单原子态的远程制备[J]. 光学学报, 2008, **28**(9): 1812～1815

5 T. Akutsu, S. Kawamura, A. Nishizawa *et al*.. Search for a stochastic background of 100-MHz gravitational waves with laser interferometers [J]. *Phys. Rev. Lett.*, 2008, **101** (10): 1101～1104

6 Sun Xutao, Liu Jiqiao, Zhou Jun *et al*.. Confocal Fabry-Perot interferometer for frequency stabilization of laser[J]. *Chinese J. Lasers*, 2008, **35**(7): 1005～1008
孙旭涛,刘继桥,周 军 等. 激光稳频的共焦法布里-珀罗干涉仪[J]. 中国激光, 2008, **35**(7): 1005～1008

7 M. Takamoto, F.-L. Hong, R. Higashi *et al*.. An optical lattice clock[J]. *Nature*, 2005, **435**(7040): 321～324

8 A. D. Ludlow, T. Zelevinsky, G. K. Campbel *et al*.. Sr lattice clock at 1×10^{-16} fractional uncertainty by remote optical

evaluation with a Ca clock[J]. *Science*, 2008, **319**(5871): 1805～1808

9 W. H. Oskay, S. A. Diddams, E. A. Donley *et al*.. Single-atom optical clock with high accuracy[J]. *Phys. Rev. Lett.*, 2008, **97**(2): 801～804

10 L. Chen, J. L. Hall, J. Ye *et al*.. Vibration-induced elastic deformation of fabry-perot cavities[J]. *Phys. Rev. A*, 2006, **74**(5): 3801～3813

11 D. Z. Anderson, J. C. Frisch, C. S. Masser. Mirror reflectometer based on optical cavity decay time[J]. *Appl. Opt.*, 1984, **23**(8): 1238～1245

12 Li Zhigang, Zhang Yuchi, Zhang Pengfei *et al*.. Measurement of ultra-low loss mirrors by cavity ring-down technique with laser frequency sweeping[J]. *Acta Optica Sincia*, 2009, **29**(3): 718～722
李志刚,张玉驰,张鹏飞 等. 用扫描激光频率腔衰荡对超低损耗镜片的测量[J]. 光学学报, 2009, **29**(3): 718～722

13 Tan Zhongqi, Long Xingwu, Huang Yun. High sensitivity CW-cavity ring-down spectroscopy of tuning wavelength[J]. *Acta Optica Sincia*, 2009, **29**(3): 747～751
谭中奇,龙兴武,黄 云. 高灵敏度调谐式连续波腔衰荡光谱技术[J]. 光学学报, 2009, **29**(3): 747～751

14 N. Uehara, K. Ueda. Accurate measurement of ultralow loss in a high-finesse fabry-perot interferometer using the frequency response functions[J]. *Appl. Phys. B*, 1995, **61**(1): 9～15

15 J. Poirson, F. Bretenaker, M. Vallet *et al*.. Analytical and experimental study of ringing effects in a Fabry-Perot cavity. Application to the measurement of high finesses[J]. *J. Opt. Soc. Am. B*, 1997, **14**(11): 2811～2817

16 E. D. Black. An introduction to Pound-Drever-Hall laser frequency stabilization[J]. *Am. J. Phys.*, 2001, **69**(1): 79～87

17 D. E. Seborg, T. F. Edgar, D. A. Mellichamp. Process Dynamics and Control[M]. Hoboken NJ: John Wiley Sons, 2004. 106～108