OPTOELECTRONICS LETTERS Vol.19 No.1, 15 January 2023

Reflectivity measurement technology of special high reflective mirrors and uncertainty analysis of measurement results*

LIANG Xiaolin, ZHOU Songqing, LI Xiaowu, ZHOU Ling, and CHEN Huihuang**

College of Intelligent Manufacturing, Hunan University of Science and Engineering, Yongzhou 425199, China

(Received 21 July 2022; Revised 14 September 2022)

In order to meet the reflectivity measurement requirements of any incident angle at different points of the large size special high mirror, a rotating cavity ring-down spectroscopy high reflectivity measurement system was built, in which the rotation function of the resonant cavity was set, and the lifting and parallel travelling mechanism of the measured mirror was added. Furthermore, the uncertainty of the measurement results was analyzed and calculated. The results showed that the reflectivity of a high reflective mirror measured by the system was 99.979 5%, the measurement accuracy reached the order of 10^{-6}, and the combined standard uncertainty of reflectivity measurement was 0.002 8%. Collectively, these results provide a detection guarantee for the maintenance of the large size special high mirror, and provide ideas and methods for the uncertainty analysis of measurement results of similar equipment parameters.

Document code: A **Article ID:** 1673-1905(2023)01-0049-6

DOI https://doi.org/10.1007/s11801-023-2129-7

With the rapid development and application of laser technology, especially large-scale high-energy laser technology, laser gyroscope technology, laser shooting technology and high-precision spectral measurement technology, the coating technology with high reflectivity (>99.9%) has been promoted rapidly[1,2]. However, for special types of high reflectors with different reflection angles and large sizes in the application field of high-energy laser technology, the surface reflectivity directly determines the safety and stability of the optical system[3-6]. Therefore, how to accurately measure the reflectivity of these special high reflectors has become a key concern of researchers.

Cavity ring-down spectroscopy is one of the most commonly used methods for measuring the reflectivity of high reflective mirrors. This method has high measurement accuracy, and the measurement results are independent of the stability of the light source, so it has broad application prospects. In 1977, Virgil Sanders first proposed the idea of using optical resonator to measure the reflectivity of the lens. The accuracy of the lens reflectivity measured by combining the straight cavity and the folded cavity was better than ±0.000 1, which greatly improved the measurement accuracy compared with the traditional reflectivity measurement technology[7]. In 2010, SRIDHAR et al[8] developed a laser high-reflective mirror quality measurement device, the order of magnitude of the measurement accuracy was 10^{-4}, but the ring-down cavity completely depended on manual adjustment. Therefore, the device could only be used as a principle and technical verification experimental platform. In 2012, LÜ et al[9] reported that the average reflectivity of the straight cavity mirror at 635 nm was (99.959±0.001)%, the reflectivity of the sample to be measured was (99.917±0.003)%, and the measurement accuracy was 10^{-5}. In order to achieve accurate measurement of the reflectivity of high reflectors, relevant research institutes have carried out a variety of high reflectivity measurement methods. Among them, the cavity ring-down method is the only technical means that can accurately measure the reflectivity greater than 99.99%[10,11]. However, there are few studies on the direct methods to measure the reflectivity of special high reflective mirrors (large-size mirrors with different reflection angles and different reflection points), and the measurement accuracy of cavity ring-down high reflectivity, and the uncertainty of measurement results has not been comprehensively analyzed and evaluated by researchers.

In order to meet the measurement requirements of the reflectivity of special high reflective mirrors, especially large-size high-energy laser high reflective mirrors, a

* This work has been supported by the 2021 Annual Instructional Science and Technology Program of Yongzhou (No.2021-YZKJZD-009), the Outstanding Youth Foundation of Hunan Province (No.2020JJ2015), and the Science Research Project of Hunan Institute of Science and Technology (No.21xky040).

** E-mail: 122322855@qq.com

rotating cavity ring-down spectroscopy high reflectivity measurement system was built. In the system, the rotation function of the resonant cavity was set, and the lifting and parallel travelling mechanisms of the measured mirror were added. Accordingly, the reflectivity measurement of any incident angle and different points of a large-size mirror can be realized. In order to improve the stability of resonant cavity and the accuracy of reflectivity measurement, the system optical path debugging and accurate adjustment methods, and the uncertainty of reflectivity measurement results were given and analyzed in detail, respectively.

The cavity ring-down spectroscopy uses folded cavity, which makes the measurement process relatively simple and easy to adjust. It can measure the reflectivity of the lens at any angle, and calibrate the high precision reflectivity by using low precision reflectivity[12,13]. The reflectivity measurement system of cavity ring-down spectroscopy usually needs three parts, namely, light source, ring-down cavity, data acquisition and processing. Mirrors M1 and M2 constitute an optical resonator, and the reflectivity is generally required to be more than 99%. Assuming that the reflectivities of the cavity mirrors M1 and M2 are respectively R_1 and R_2, the initial energy of the optical pulse entering the ring-down cavity is I_0, and the attenuation of the optical pulse energy in the resonant cavity with time can be expressed as

$$I(t) = I_0 \exp(-\frac{\tau}{t}). \tag{1}$$

Without considering other losses such as cavity absorption, τ is completely determined by the cavity mirror reflectivities R_1 and R_2. τ can be expressed as

$$\tau = t_r / \ln\left(R_1 R_2\right)^{-1}, \tag{2}$$

where t_r=2L/c represents the time required for the light to travel to and from within the cavity, L is the cavity length of the resonant cavity, c is the speed of light, and τ represents the time when the optical pulse energy drops to 1/e of the initial value I_0. Assuming that the cavity mirror reflectivities R_1 and R_2 are equal, the cavity mirror reflectivity R can be calculated by measuring τ, and can be expressed as

$$R = \sqrt{R_1 R}_2 = \exp(-\frac{t_r}{2\tau}). \tag{3}$$

For any high reflective mirror to be measured, the actual measurement process is divided into two steps. Firstly, the straight cavity is used to calibrate the reflectivity of the cavity mirror, and then the folded cavity is used to measure the reflectivity of the mirror to be measured. The reflectivity of the mirror to be measured is calculated with

$$R = \exp\left[\frac{L}{c}\left(\frac{1}{\tau_0} - \frac{1}{\tau}\right)\right], \tag{4}$$

where τ_0 is the ring-down time of the straight cavity and τ is the ring-down time of the folded cavity.

According to the reflectivity measurement principle of cavity ring-down method, a rotating cavity ring-down spectroscopy reflectivity measurement system was designed as shown in Fig.1. The system consists of light sources, a ring-down cavity, a detector, a digital oscilloscope and a computer. The main laser is IRRB-1319 lamp pumped pulse laser, the output wavelength is 1.319 μm, the pulse energy is 15 mJ, and the pulse width is 7 ns. The guiding light is 1.2 mW He-Ne laser coaxial with the main laser, the output wavelength is 632.8 nm, which is used to solve the problems such as the invisibility of the main laser in the measurement system and the difficulty in adjusting the optical path. M3 and M4 are both reflective mirrors of the 1 319 nm laser. They are used to adjust the 1 319 nm main laser path to ensure that the main laser and guide light path was in the same axis. M5 is a lens with high transmittance at 1 319 nm and high reflectivity at 632.8 nm. M1 and M2 are concave high reflective mirrors with curvature radius of 0.6 m and reflectivity of 99.95%. M2 has high-precision rotation function, and the length of the resonant cavity does not change when the straight cavity rotates to the folded cavity. M is the mirror to be measured, which is placed on the adjustable structure with the lifting and parallel travelling functions, and its central position does not change during the adjustment process. The purpose is to meet the reflectivity measurement requirements of special high reflective mirrors. M6 is a focusing lens. The detector adopted the Det410 InGaAs detector of Thorlabs Company, whose response time is 1 ns, and the detection diameter is 1 mm. The signal is recorded by the TDS3044B digital oscilloscope, the sampling frequency used is 400 MHz, and the signal is used for real-time acquisition of ring-down waveform and accurate adjustment of ring-down cavity.

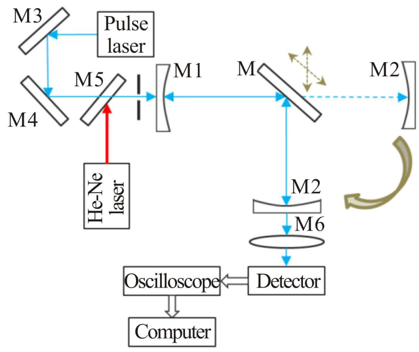

Fig.1 High reflectivity measurement system with the cavity ring-down method

The optical path debugging of the measurement system mainly has three key steps, namely, height fixing, coaxial adjusting and cavity adjusting. (1) Height fixing. Since the main laser at 1.319 μm is invisible to the naked eye, He-Ne light is used as the guiding light in the experiment. Therefore, the first step of the experiment was to make two different wavelengths of light at the same height. (2) Coaxial adjusting. The He-Ne light as the guiding light must be coaxial with the main laser. The

He-Ne light can be seen in the experiment, but the main laser is not visible. The phase paper can be used to determine its specific location. Firstly, the He-Ne light determines the guiding light path through M5. Secondly, the two kinds of light were coaxial by adjusting M3 and M4. The specific method is to make the main laser and the He-Ne light overlap before M1, and then make the two light sources overlap before M6. According to the principle of determining a straight line by two points, the guiding light and the main laser are coaxial. (3) Cavity adjusting. The resonant cavity composed of M1 and M2 is the key to the success of measurement. First, the He-Ne light passes through the lens centers of M1 and M2 respectively, then the light returned by M2 passes through the center of M1, and finally the light returned by M1 passes through the center of M2. Since the main laser and the guiding light are coaxial, the oscillation of the main laser in the resonant cavity composed of M1 and M2 can be roughly judged.

The stability of ring-down cavity is very important[14]. The slight misalignments of the cavity length or the cavity mirror angle will cause the ring-down waveform distortion, leading to the failure of the measurement. In 2006, YI et al[15] carried out the waveform simulation of ring-down cavity misalignment. Through numerical calculation, the variation of ring-down waveform under different cavity length misalignments or cavity mirror tilts was simulated. This paper selected the above experimental system parameters in the Matlab environment for modeling and simulating, and the simulation results acquired from the model were consistent with the former. When the resonator is stable, the ring-down signal decreases exponentially. With the increase of offset, the amplitude modulation of ring-down signal is more obvious, and the ring-down time is also gradually advanced. With the increase of the misalignment of the cavity mirror angle, the even pulse amplitude gradually decreases to disappear. Therefore, according to the simulation results, with the ring-down curve of the stable cavity as the criterion, the digital oscilloscope is used to collect the ring-down waveform in real time to accurately adjust the ring-down cavity. The cavity length and the cavity mirror angle of the resonant cavity are accurately adjusted according to the amplitude strength law of the ring-down signal and the amplitude change of the odd and even pulse signal, which is conducive to improving the stability and measurement accuracy of the ring-down cavity.

A straight cavity with a cavity length of 1.2 m was made up of M1 and M2 mirrors. The ring-down curve obtained in one measurement is shown in Fig.2. The ring-down curve was fitted exponentially according to Eq.(1), and the ring-down time of this measurement was 6.351 μs, as shown in Fig.3.

With the cavity length unchanged and M2 rotating, the straight cavity was changed into a folded cavity, and a 45° total-reflection mirror was inserted at the beam turning point. Under the same conditions, 10 measurements were carried out, a ring-down curve obtained in one measurement, as shown in Fig.4. The ring-down curve of the exponential fitting of the folded cavity is shown in Fig.5. The ring-down time of the straight cavity and the folded cavity measured for 10 times, as shown in Fig.6. The average values were 6.356 4 μs and 4.553 9 μs, respectively. According to Eq.(4), the reflectivity of the 45° total-reflection mirror was 99.979 5%, and the measurement accuracy reached the order of 10^{-6}.

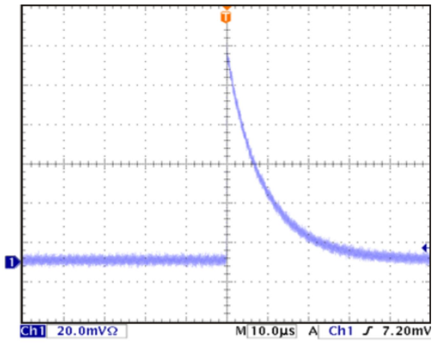

Fig.2 The ring-down curve of the straight cavity

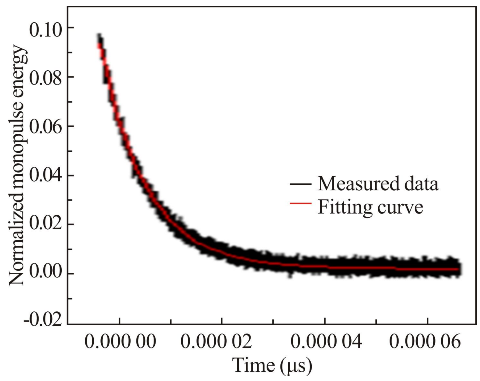

Fig.3 The ring-down curve of exponential fitting for the straight cavity

According to Eq.(4), the influencing factors of the uncertainty u_R of reflectivity measurement mainly include the uncertainty u_1 of the cavity length measurement, the uncertainty u_2 of the ring-down time measurement in the straight cavity and the uncertainty u_3 of the ring-down time measurement in the folded cavity, as shown in Fig.7.

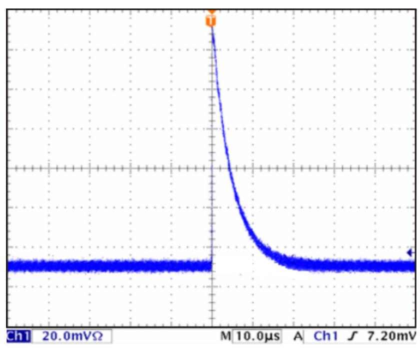

Fig.4 The ring-down curve of the folded cavity

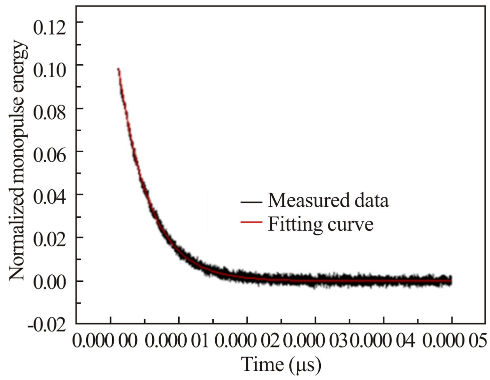

Fig.5 The ring-down curve of exponential fitting for the folded cavity

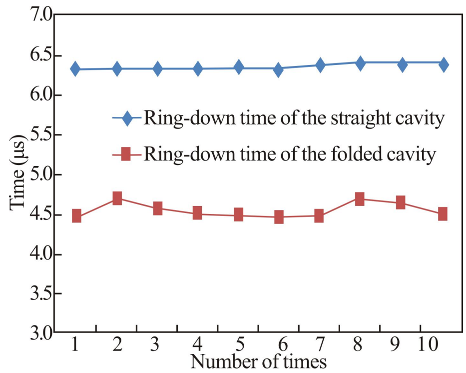

Fig.6 Measurement results of ring-down time

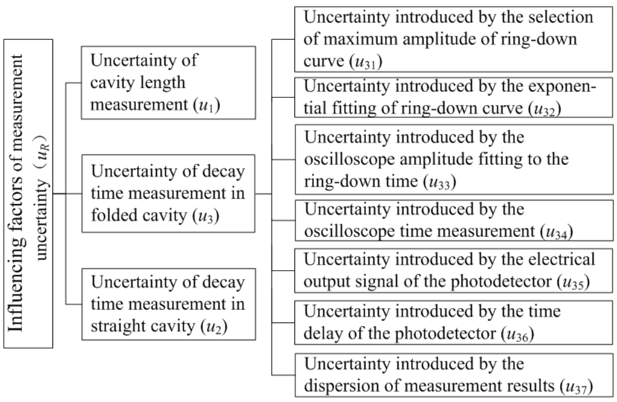

Fig.7 Influencing factors of measurement uncertainty

The source of cavity length measurement uncertainty was mainly introduced by the cavity length measurement equipment. The indication error of the common meters is ±0.5 mm. According to the uniform distribution, the standard uncertainty u_1 of the cavity length measurement is

$$u_1 = 0.5 / \sqrt{3} \approx 0.288\,7 \text{ mm}. \tag{5}$$

The sources of the uncertainty of the ring-down time measurement in the folded cavity mainly include the uncertainty introduced by the selection of the maximum amplitude of the ring-down curve, the uncertainty introduced by the exponential fitting of the ring-down curve, the uncertainty introduced by the oscilloscope amplitude fitting to the ring-down time, the uncertainty introduced by oscilloscope time measurement, the uncertainty introduced by the electrical output signal of the photodetector, the uncertainty introduced by the time delay of the photodetector and the uncertainty introduced by the dispersion of measurement results.

The uncertainty u_{31} is introduced by the selection of maximum amplitude of ring-down curve.

For the same ring-down curve, 10 points were selected at the head of the curve as the maximum amplitude to intercept the ring-down curve. The ring-down time after the fitting was shown in Tab.1.

Tab.1 The fitting results of the ring-down time after the interception of the ring-down curve (μs)

No.	1	2	3	4	5
Ring-down time τ	4.565 7	4.546 3	4.551 0	4.515 2	4.529 6
No.	6	7	8	9	10
Ring-down time τ	4.480 8	4.483 6	4.490 6	4.471 7	4.509 4

The uncertainty u_{31} can be calculated as

$$u_{31} = \sqrt{\frac{1}{n(n-1)}\left[\sum_{k=1}^{n}\left(\tau_k - \bar{\tau}\right)^2\right]} = 0.009\,8 \text{ μs}. \tag{6}$$

The uncertainty u_{32} is introduced by the exponential fitting of the ring-down curve.

The first-order exponential ring-down fitting was performed on the ring-down curve obtained from one measurement. The standard deviation between the data point and the fitting function is 2.316×10^{-6}, and the uncertainty of the ring-down time is 1.05×10^{-5} μs. Compared with u_{31}, this value is small and can be ignored.

The uncertainty u_{33} is introduced by the oscilloscope amplitude fitting to the ring-down time.

The relationship between the fitted amplitude V and the time t is

$$V = 0.128\,67\mathrm{e}^{-t/\left(4.508\,9\times10^{-6}\right)}. \tag{7}$$

Considering the oscilloscope calibration certificate, the uncertainty of calibration results was 0.2% when the amplitude range was 20.0 mV/div. According to the uniform distribution, the uncertainty of the amplitude measurement was 0.12%. The uncertainty u_{33} can be expressed as

$$u_{33} = \frac{\partial t}{\partial V}u_{\mathrm{v}} = 1.082\times10^{-7} \text{ μs}. \tag{8}$$

Compared with u_{31}, u_{33} was small and can be ignored.

The uncertainty u_{34} is introduced by the oscilloscope time measurement.

The time range given by the oscilloscope calibration certificate is 10 μs, and the uncertainty of calibration results was 0.045%. According to the uniform distribution, the uncertainty of the oscilloscope time measurement was

0.026%, and the uncertainty u_{34} of the ring-down time measurement was 0.001 2 μs.

The uncertainty u_{35} is introduced by the electrical output signal of the photodetector.

The uncertainty introduced by the electrical output signal of the photodetector can be expressed by the amplitude fitting of the oscilloscope to the uncertainty introduced by the ring-down time. According to the technical specification, the uncertainty of the electrical output signal of the photodetector used in the measurement system is 0.5%, which was equivalent to the uncertainty of the oscilloscope amplitude. The uncertainty u_{35} of the ring-down time introduced by the electrical output signal of the photodetector was calculated as

$$u_{35}=\frac{\partial t}{\partial V}u_{\mathrm{v}}=5.591\times10^{-7}\,\mu\mathrm{s}. \tag{9}$$

Compared with u_{31}, u_{35} was small and can be ignored.

The uncertainty u_{36} is introduced by the time delay of the photodetector.

According to the technical specification, the response time of the photodetector is 1 ns, so the uncertainty u_{36} introduced by the time delay of the photodetector is about 0.001 μs.

The uncertainty u_{37} is introduced by the dispersion of measurement results.

Under the same measurement conditions, 10 measurements were carried out to fit the measured ring-down curve. The ring-down time was shown in Tab.2.

Tab.2 The fitting results of the ring-down time under the same measurement conditions (μs)

No.	1	2	3	4	5
Ring-down time τ	4.487 7	4.702 2	4.568 0	4.508 9	4.484 4
No.	6	7	8	9	10
Ring-down time τ	4.460 5	4.479 3	4.697 6	4.662 2	4.488 6

Then the uncertainty u_{37} introduced by the dispersion of measurement results can be calculated as

$$u_{37}=\sqrt{\frac{1}{n(n-1)}\left[\sum_{k=1}^{n}\left(\tau_k-\bar{\tau}\right)^2\right]}=0.030\ 6\ \mu\mathrm{s}. \tag{10}$$

Based on the above analysis, the combined standard uncertainty u_3 of the ring-down time measurement in the folded cavity to be measured is shown as

$$u_3=\sqrt{u_{31}{}^2+u_{34}{}^2+u_{36}{}^2+u_{37}{}^2}=0.032\ 2\ \mu\mathrm{s}. \tag{11}$$

The influencing factors of uncertainty u_2 were consistent with the influencing factors of uncertainty u_3, and the analysis method is the same. The calculated value of u_2 was 0.028 0 μs.

The combined standard uncertainty u_{R} of reflectivity measurement is

$$u_{\mathrm{R}}=\sqrt{\left(\frac{\partial R}{\partial L}\right)^2u_1{}^2+\left(\frac{\partial R}{\partial \tau_0}\right)^2u_2{}^2+\left(\frac{\partial R}{\partial \tau}\right)^2u_3{}^2}=0.002\,8\%. \tag{12}$$

The expanded uncertainty U to be measured is

$$U=2u_{\mathrm{R}}=0.005\ 6\%,\quad (k=2). \tag{13}$$

Compared with the time attenuation method, the cavity ring-down spectroscopy uses a folded cavity, which makes the measurement process relatively simple and the adjustment more convenient. Compared with the resonator fineness method, it can measure the reflectivity at any angle of the mirror, and also calibrate the high-precision reflectivity by using the low-precision reflectivity. The design and construction of the high reflectivity measurement system for rotary cavity ring-down spectroscopy can meet the measurement requirements of special high reflective mirrors. The measurement accuracy was up to 10^{-6}. The measurement uncertainty is independent and closely related to the measurement result. It is a parameter that indicates the dispersion of the measurement result, and it is important to analyze the measurement result.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

References

[1] YANG J B, ZONG S G, CHEN L F. Developments and trends of laser weapons[J]. Laser and infrared, 2021, 51(06)：695-704. (in Chinese)

[2] CHEN C, LI G P, ZHANG B, et al. High energy laser far-field irradiance distribution measurement technology and its developments[J]. Journal of applied optics, 2020, 41(04)：675-680. (in Chinese)

[3] HU P, ZHANG J Z, ZHANG F Z. Modeling and analysis of inner thermal effects in high energy laser system[J]. High power laser and particle beams, 2022, 34(01)：119-129. (in Chinese)

[4] ZHANG Z, SHI L X, LI H T. Reliability evaluation of optical lenses transmittance and reflectance measurement system[J]. Journal of Changchun University of Science and Technology (natural science edition), 2019, 42(01)：41-44. (in Chinese)

[5] FAN F, XU X, XU Q, et al. Progress on ultra-precision manufacturing technology of large-aperture high-power laser optics[J]. Opto-electronic engineering, 2020, 47(08)：5-17. (in Chinese)

[6] WANG X L, WEI Z, WANG R, et al. High-accuracy self-mixing interferometer based on multiple reflections using a simple external reflecting mirror[J]. Optoelectronics letters, 2018, 14(03)：161-163.

[7] WU Y X, YUE H M, LIU Y. High-precision measurement of low reflectivity specular object based on phase measuring deflectometry[J]. Opto-electronic engineering, 2017, 44(08)：772-780.

[8] SRIDHAR G, SANDEEP K, AGARWALL A. Cavity ring-down technique for measurement of reflectivity of high reflectivity mirrors with high accuracy[J]. Pramana journal of physics, 2010, 75(6)：1233-1239.

[9] LV X N. Construction of cavity ring-down spectrometer and its application in reflectivity measurement of high reflective mirrors[D]. Dalian：Dalian University of Technology, 2012：45-51. (in Chinese)

[10] NING K, HOU L, FAN S T, et al. An all-polarization-maintaining multi-branch optical frequency comb for highly sensitive cavity ring-down spectroscopy[J]. Chinese physics letters, 2020, 37(06)：30-34.

[11] WU X W, LI C, FENG C L, et al. Time-resolved measurements of NO_2 concentration in pulsed discharges by high-sensitivity cavity ring-down spectroscopy[J]. Plasma science and technology, 2017, 19(05)：055506.

[12] WANG X P, ZHAO G, JIAO K, et al. Uncertainty of optical feedback linear cavity ringdown spectroscopy[J]. Acta physica sinica, 2022, 71(12)：49-57. (in Chinese)

[13] BAI Y, YAN F P, TAN S Y, et al. Ring cavity fiber laser based on Fabry-Pérot interferometer for high-sensitive micro-displacement sensing[J]. Optoelectronics letters, 2015, 11(06)：421-425.

[14] ZHANG X, JIAN J W, ZHENG Y G, et al. An optic fiber sensor for multiple gases based on fiber loop ring-down spectroscopy and microring resonator arrays[J]. Optoelectronics letters, 2016, 12(04)：312-315.

[15] YI H Y. Misalignment simulation of cavity ring-down waveform[J]. Chinese journal of lasers, 2006, 3(33)：399-404. (in Chinese)