Spectral index of optical coating – Cavity ring-down spectroscopy

1. Cavity ring-down spectroscopy

1.1 Optical cavity

Optical cavity is also called optical resonance (the phenomenon of amplitude enhancement due to the same frequency). It is usually an optical cavity structure formed by two mirrors. In cavity ring-down spectroscopy, both mirrors are high reflective mirrors, one is the reference mirror and the other is the measured mirror. The light wave will be limited to multiple reflections in the cavity.

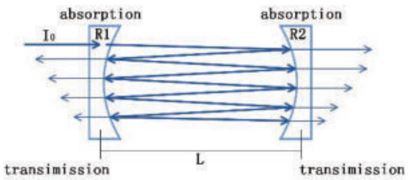

Fig. 1 Schematic diagram of light propagation in optical cavity

1.2 Cavity ring-down/CRD

A beam of light shines into the optical cavity composed of the reference mirror and the measured mirror, and the light will be reflected many times in the optical cavity. Since the mirror is not 100% reflective, it has the influence of transmission and absorption losses. The energy of light will decay over time. This process is called cavity ring-down.

1.3 Cavity ring-down spectroscopy/CRDS

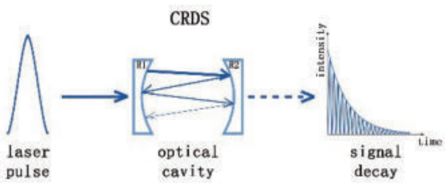

Fig. 2 Schematic diagram of ring-down spectrum of optical cavity

Cavity ring-down spectroscopy is a highly sensitive spectral technology, which can accurately determine the reflectivity of the mirror through the total loss of light. Cavity ring-down spectroscopy is also known as cavity ring-down laser absorption spectroscopy (CRLAS).

Cavity ring-down spectroscopy is generally divided into pulse cavity ring-down spectroscopy and continuous wave cavity ring-down spectroscopy.

2. Spectrometer

Spectrometer is a scientific instrument used to separate and measure the spectral components of physical phenomena. The measured variable is usually the intensity of light, but it can also be, for example, the state of polarization. The spectrometer is mainly composed of light source, dispersion component (prism or grating) and detector. A spectrometer that receives dispersion signals with a photodetector is also called a spectrophotometer.

In the reflectivity measurement of general optical elements, commercial spectrometer is often used to directly measure the reflection spectrum, and the measurement accuracy often depends on the accuracy of the instrument itself.

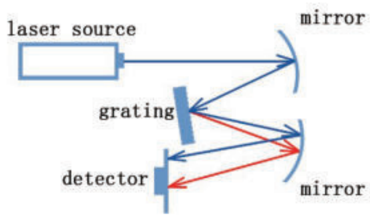

Fig. 3 Schematic diagram of simple spectrometer

3. Equipment of cavity ring-down spectroscopy

The equipment used in the measurement of cavity ring-down spectroscopy is called cavity ring-down spectrometer.

There are some differences between cavity ring-down spectrometer and general spectrometer. It includes a laser light source for high-precision cavity, two high reflective mirrors and detectors.

The cavity ring-down spectrometer measures the time required for the light intensity to decay to 1/e of the initial intensity. This time is called" ring-down time "and can be used to calculate the total loss of the system.

4. Test method of cavity ring-down spectroscopy

- The two mirrors of the optical cavity are respectively set as the reference mirror and the measured mirror;
- The laser (pulse / continuous) of the laser is introduced into the optical cavity. Through the reflection of the mirror, the round-trip light is rapidly enhanced due to multiple phase length interference (superposition enhancement of light with the same frequency, the same vibration direction and constant phase difference);
- After that, the laser is quickly cut off, and the attenuation degree of light intensity escaping from the cavity is detected by a detector placed behind the mirror;
- Calculate the total loss of the corresponding laser round trip through the ring-down time;
- Change the reference mirror for multiple measurements to confirm the loss of the measured mirror, so as to obtain the reflectivity and reflection spectrum of the measured mirror.

5. Technical principle of cavity ring-down spectroscopy

Pulse cavity ring-down spectroscopy is used as an explanation. The pulsed light is limited to multiple reflections in an empty optical cavity. The attenuation of beam energy is caused by absorption and scattering. The total loss has been proved to be an exponential function related to time.

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

In the above formula, I (t) is the light intensity at time t; I_o is the initial light intensity; t is the time when the beam is limited to reflection in the cavity at the moment when the laser is cut off; e is the natural constant, and its value is about 2.718; τ is the decay time constant, which is expressed as the time required for I (t) to decay to 1 / e of I_o. Its value depends on the loss of the mirror in the cavity and some other optical losses, such as scattering. The mathematical expression of τ can be expressed as:

$$\tau=n/c\cdot 2L/\alpha$$

In the above formula, n is the refractive index of the cavity, generally, it is air, that is n=1; c is the speed of light in vacuum, and its value is 3×10^8 m/s； L is the length of the cavity, that is, the distance between the centers of the two mirrors; α is the total round trip loss of the system (including transmission loss, absorption loss, scattering and other optical losses of two mirrors), that is, the value we are concerned about.

The total loss includes transmission loss, absorption loss, scattering and other optical losses of two mirrors.

If the reflectivity of two mirrors is $R_1=R_2=R\sim1$, the total loss can be confirmed by the $I(t)=I_0(R_1R_2)^{2nL/c}$:

$$\alpha=-\ln(R_1R_2)\approx2(1-R)$$

But we have a more accurate test.

Suppose there are three mirrors, M_1、M_2 and M_3. M_1 and M_2 is the reference mirror, M_3 is the measured mirror. Through the above method, we can obtain the total loss α13 of M_1 and M_2, total loss α_{23} of M_2 and M_3, total loss α_{13} of M_1 and M_3. From this, it can be easily concluded that the single mirror loss of the measured mirror is:

$$\alpha_3=1/2(\alpha_{23}+\alpha_{13}-\alpha_{12})$$

From the above formula, we can obtain a highly accurate reflectivity and reflection spectrum.

6. How accurate can cavity ring-down be measured?

The high reflectivity and transmittance values in the range of 99.5-99.9999% are determined by cavity ring-down time measurement. The error range can be minimized by this method, for example, R = 99.995% ± 0.001% (the resolution is 10^{-5} cm^{-1}). By setting, the resolution of pulse method can reach 10^{-6} - 10^{-9} cm^{-1}. The continuous method is better than the pulse method, and can reach 10^{-7} - 10^{-12} cm^{-1}. Under the same method, the higher the reflectivity of the mirror, the higher the measurement accuracy.

7. Why is cavity ring-down spectroscopy so sensitive?

7.1 Long optical path

Optical path is the path of light propagation in optical medium. Due to the action of two high reflective mirrors, the effective optical path length in the optical cavity can reach several kilometers. In mirror measurement, the minimum amount that can be detected is positively correlated with the length of light passing through the optical cavity. Thus, the loss measurement accuracy with high sensitivity can be obtained with a shorter optical cavity.

7.2 Determined only by the ring-down time

The measurement of cavity ring-down spectrum is only related to the ring-down time without paying attention to the pulse (continuous) laser characteristics of the light source. In the general spectral measurement, the intensity fluctuation of the light source will affect the accuracy of the spectrum to a certain extent. However, in the cavity ring-down spectrum test, the ring-down presents the form of e-index, which is independent of the light source intensity.

8. Why can't direct spectroscopy be used for reflective film?

If a spectrometer (spectrophotometer) is directly used for reflection spectrum measurement, the error range of the measurement results depends on the resolution of the instrument. The error range of reflectance directly measured by common spectrometer is about ± 0.5%. If a better spectrometer is used with very low interference, the error range can be reduced to about ± 0.1%. Generally, the general error is about ± 0.2%. It is enough for low reflectivity mirrors, but for high reflective mirrors with 99.5% or more reflectivity, even 0.1% is a great difference. The difference between penetration and non-penetration may be less than 0.1%. The difference may lead to the decline of instrument performance and safety problems, and even the irreparable damage of the whole system.

Therefore, for high reflectance mirrors with reflectivity above 99.5%, high-precision spectral measurement methods, such as cavity ring-down spectroscopy, should be used to measure the reflectivity iinstead of low-precision spectral measurement methods.

9. What are the limitations of cavity ring-down spectroscopy?

9.1 Slow acquisition of spectra

Cavity ring-down spectroscopy uses a monochromatic laser source to measure the reflectivity after ring-down for a certain time. For the reflection spectrum in the continuous wavelength range, cavity ring-down spectroscopy cannot be obtained quickly. However, it must be noted that some teams are developing the use of broadband LED light source or supercontinuum light source for measurement, which has been partially proved in the near ultraviolet to mid infrared range. In addition, frequency agile fast scanning (FARS) spectroscopy has been used to improve the mechanical or thermal frequency tuning affecting the acquisition rate of cavity ring-down spectroscopy, which improves the acquisition efficiency of cavity ring-down spectroscopy by two orders of magnitude.

9.2 Limited by wavelength

Cavity ring-down spectroscopy is limited both by the availability of wavelength-tunable lasers, and by the availability of high reflective mirrors at these wavelengths.

9.3 High cost

Because cavity ring-down spectroscopy requires high reflective mirrors and high standard laser systems, it is several orders of magnitude more expensive than other methods.

9.4 It can only be used for high reflective mirror measurement

For low reflectivity mirrors, resonance may not even occur in the optical cavity. The reflectivity below 99.5% cannot be determined by cavity ring-down spectroscopy.

10. What should we pay attention to when using cavity ring-down spectroscopy?

10.1 Cleanliness

For cavity ring-down spectroscopy, the reflectivity of cavity mirror is very important, which affects the accuracy of the system. The cleanliness will seriously affect the mirror or system, reduce its reflectivity and increase its loss. Therefore, the measurement of cavity ring-down spectroscopy usually needs to be carried out in a dust-free laboratory.

10.2 Reflectivity high enough

Because the low reflectivity mirror may lead to the failure of the optical cavity ring-down process, the reflectivity of measured mirror needs to be greater than 99.5%. If it is lower than 99.5%, it is recommended to directly use direct spectroscopy for measurement. In addition, the reference mirror also needs as high reflectivity as possible to improve the accuracy of the system.

10.3 Multiple reference mirror

Because the data measured in a single time is the common loss of two mirrors, in order to ensure the accuracy of the data, at least two reference mirrors are required to participate in the measurement of cavity ring-down spectrum.

Reference

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