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Optics and photonics — Lasers and laser-related equipment — Cavity ring-down method for high-reflectance and high-transmittance measurements

Optique et photonique — Lasers et équipement associé aux lasers — Méthode d'alternance de la cavité pour les mesurages du facteur de réflexion et du facteur de transmission

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by ISO/TC 172, *Optics and photonics*, Subcommittee SC 9, *Lasers and electro-optical systems*.

This second edition cancels and replaces the first edition ISO 13142:2015, which has been technically revised.

The main changes compared to the previous edition are as follows:

— addition of transmittance measurements into the document.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

With the development of film-deposition technology, the performance of optical thin films, especially the highly reflective (HR) and highly anti-reflective (AR) coatings which are widely used in large high-power laser systems, interferometric gravitational-wave detectors, laser gyroscopes, and cavity-enhanced and cavity ring-down spectroscopy applications, has been substantially improved in recent years. Laser-based optical systems require some optical components with extremely high reflectance or transmittance characteristic. It is necessary to be able to measure this reflectance or transmittance characteristic precisely. Up to now, the ISO standardized testing methods for reflectance/transmittance of optical laser components have the accuracy limit of approximately 0,01 % (for measurement of absolute reflectance/transmittance), which are not appropriate for measuring the reflectance /transmittance higher than 99,99 %, or in some cases measurement accuracy better than 0,01 % is required. The measurement procedures in this document have been optimized to allow the measurement of high reflectance or transmittance (larger than 99 %, theoretically up to 100 %) of optical laser components using the cavity ring-down technique which provides reflectance or transmittance data with high accuracy, high repeatability and reproducibility, and high reliability.

Optics and photonics — Lasers and laser-related equipment — Cavity ring-down method for high-reflectance and high-transmittance measurements

1 Scope

This document specifies measurement procedures for the precise determination of the high reflectance or high transmittance (>99 %) of optical laser components.

The methods given in this document are intended to be used for the testing and characterization of high reflectance of both concave and plane mirrors or high transmittance of plane windows used in laser systems and laser-based instruments. The reflectance of convex mirrors or transmittance of positive or negative lenses can also be tested by taking into consideration the radius of curvature of the mirror surface or the focal length of the lens. This document is complementary to ISO 15368 which specifies the measurement procedures for the determination of reflectance and transmittance of optical components with spectrophotometry. ISO 15368 is applicable to the measurements of reflectance and transmittance in the range from 0 % to 100 % with a typical accuracy of ±0,3 %, and is therefore not applicable to the precise measurements of reflectance and transmittance higher than 99,9 %.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 11145, *Optics and photonics — Lasers and laser-related equipment — Vocabulary and symbols*

ISO 14644-1, *Cleanrooms and associated controlled environments — Part 1: Classification of air cleanliness by particle concentration*

ISO 80000-7, *Quantities and units — Part 7: Light and radiation*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 11145 and ISO 80000-7 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
reflectance
<for incident radiation of given wavelength, polarization and angle of incidence> ratio of the reflected radiant or luminous flux to the incident flux in the given conditions

3.2
transmittance
<for incident radiation of given wavelength, polarization and angle of incidence> ratio of the transmitted radiant or luminous flux to the incident flux in the given conditions

4 Symbols used and units of measure

Table 1 — Symbols used and units of measure

Symbol	Term	Unit
c	speed of light in measurement environment	m/s
c_0	speed of light in vacuum	m/s
$h(t)$	impulse response of the ring-down cavity	
$h_0(t)$	Instrumental response function	
L_0	length of the initial cavity	m
L	length of the test cavity	m
ΔL_0	measurement error of the initial cavity length	m
ΔL	measurement error of the test cavity length	m
n	refractive index of air in measurement environment	
R	average reflectance of the concave cavity mirrors, equals square root of $R_1 \times R_2$	
R_s	reflectance of the test sample	
T_s	transmittance of the test sample	
R_1, R_2	reflectance of two concave cavity mirrors	
R_3	reflectance of the planar cavity mirror	
τ_{inst}	instrumental response time	s
t	time	s
$u(t)$	negative-step function	
α	the overall optical loss coefficient (absorption plus scattering) of the gases inside the cavity at the laser wavelength	m^{-1}
n_s	refractive index of the transmissive test sample substrate	
d	thickness of the transmissive test sample or central thickness of a lens to be tested	m
$\delta(t)$	delta function	
θ	angle of incidence of the test sample	rad
ρ	radius of curvature of concave surface of the cavity mirror	m
τ_0	decay time of the initial cavity	s
τ	decay time of the test cavity	s
$\Delta\tau_0$	measurement error of the decay time of the initial cavity	s
$\Delta\tau$	measurement error of the decay time of the test cavity	s

5 Test principles

5.1 General

The conventional reflectance/transmittance measurement techniques (spectrophotometry and laser ratiometry) are based on measuring the relative changes of light power reflected/transmitted by the test sample. The measurement accuracy is limited by the power fluctuations of the light sources. The cavity ring-down (CRD) technique, on the other hand, is based on the measurement of the decay rate of laser power trapped in a ring-down cavity consisting of at least two highly reflective mirrors. It is therefore totally immune to the power fluctuations of the light sources. The CRD technique can achieve a measurement accuracy that far exceeds the limit set by the power fluctuations of the light sources.

5.2 Decay time of initial cavity and reflectance of cavity mirrors

When a laser beam is coupled into the ring-down cavity, it will gradually leak out of the cavity as a small fraction of the light is transmitted through the cavity mirrors at each reflection. The temporal behaviour of the cavity output signal immediately after the laser pulse (in the pulsed case, as shown in Figure 1) or immediately after the laser power is switched off [in the continuous wave (cw) case, as shown in Figure 2, or at the falling edge of a square-wave modulated power] can be expressed as an exponentially decay function of time according to the following decay route given in Formula (1):

$$I(t) \propto I_0 \exp\left(\frac{-t}{\tau_0}\right) \tag{1}$$

Where I_0 is the initial light intensity of the cavity output signal, τ_0 can be expressed as given in Formula (2):

$$\tau_0 = \frac{L_0}{c\left(\alpha L_0 - \ln\sqrt{R_1 R_2}\right)} \tag{2}$$

With Formula (3):

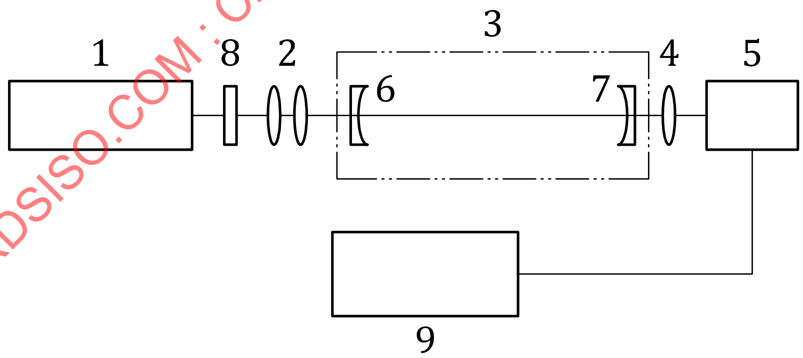
$$c = \frac{c_0}{n} \tag{3}$$

For the case where at test laser wavelength the absorptance and scattering loss of gases inside the ring-down cavity are negligible, the empty cavity ring-down time, τ_0, is only dependent upon the cavity length and the reflectance of the cavity mirrors and Formula (2) reduces to Formula (4):

$$\tau_0 = \frac{-L_0}{c \ln\sqrt{R_1 R_2}} \tag{4}$$

By experimentally measuring the decay time, τ_0, the average reflectance of the cavity mirrors can be calculated as Formula (5):

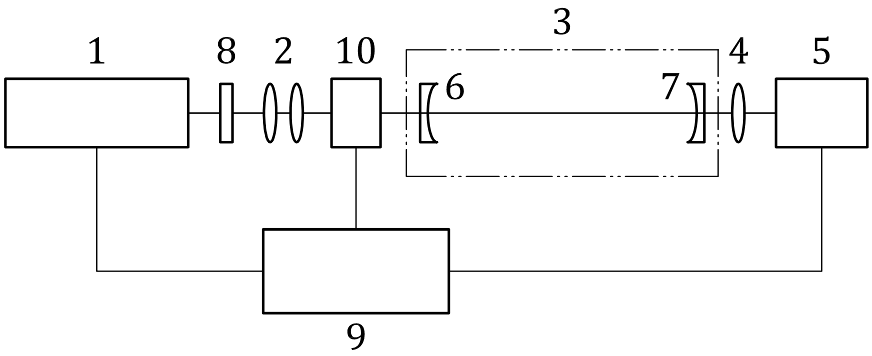
$$R = \sqrt{R_1 R_2} = \exp\left(\frac{-L_0}{c\tau_0}\right) \tag{5}$$



Key

1 laser
2 mode matching optics
3 initial cavity
4 focusing lens
5 photo-detector
6 input cavity mirror, concave high reflectance mirror
7 output cavity mirror, concave high reflectance mirror
8 polarizer
9 control and data-processing unit

Figure 1 — Schematic of optical arrangement for pulsed-CRD technique for high reflectance measurement



Key

1 laser
2 mode matching optics
3 initial cavity
4 focusing lens
5 photo-detector
6 input cavity mirror, concave high reflectance mirror
7 output cavity mirror, concave high reflectance mirror
8 polarizer
9 control and data-processing unit
10 optical switch

Figure 2 — Schematic of optical arrangement for cw-CRD technique for high reflectance measurement

5.3 Decay time of test cavity and reflectance/transmittance of test sample

If a reflective/transmissive planar test sample or a lens is to be measured, a test ring-down cavity is formed by inserting this reflective/transmissive test sample or lens into the initial cavity as shown in Figure 3 (for reflective sample) or Figure 4 (for transmissive sample or lens). The incident angle of the laser beam on the test sample follows the required incident angle of the test sample. In case of a lens, the laser beam should propagate through the centre of the lens. In this case, the decay time of the test cavity can be expressed as Formula (6):

$$\tau = \frac{-L}{c \ln\left(R_s \cdot \sqrt{R_1 R_2}\right)} \tag{6}$$

for the reflective sample, and as Formula (7):

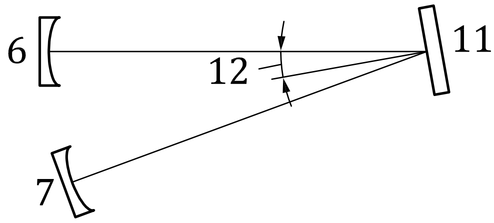
$$\tau = \frac{-\left[L + \left(n_s - 1\right) d\right]}{c \ln\left(T_s \cdot \sqrt{R_1 R_2}\right)} \tag{7}$$

for the transmissive sample or lens. Therefore, from Formulae (4) and (6), the reflectance, R_s, of the reflective test sample can be calculated as Formula (8):

$$R_s = \exp\left(\frac{L_0}{c\tau_0} - \frac{L}{c\tau}\right) \tag{8}$$

And, combining Formulae (4) and (7), the transmittance, T_s, of the transmissive test sample or lens can be calculated as Formula (9):

$$T_s = \exp\left[\frac{L_0}{c\tau_0} - \frac{L + \left(n_s - 1\right) d}{c\tau}\right] \tag{9}$$



Key

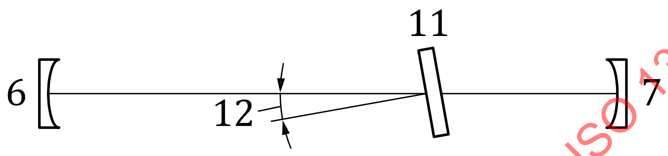
6 input cavity mirror, concave high reflectance mirror

7 output cavity mirror, concave high reflectance mirror

11 reflective test sample

12 angle of incidence of test sample

Figure 3 — Schematic of optical arrangement of test cavity for reflectance measurement



Key

6 input cavity mirror, concave high reflectance mirror

7 output cavity mirror, concave high reflectance mirror

11 transmissive test sample or lens

12 angle of incidence of test sample

Figure 4 — Schematic of optical arrangement of test cavity for transmittance measurement

NOTE Reflectances of HR mirrors with 0° angle of incidence (AOI) are normally measured at AOI of 3° to 8°, which is considered sufficient. However, if required, the reflectance measurement at 0° AOI is possible. This can be done by pairing the test mirror and two cavity mirrors separately (that is, separate pairs of two cavity mirrors, of one cavity mirror and the test mirror, and of another cavity mirror and the test mirror) to form three stable straight cavities and measure three decay times for the three combinations, separately. From the three measured decay times the reflectance of the test mirror, as well as the reflectances of the two cavity mirrors can be determined via Formula (4), respectively.

5.4 High reflectance/transmittance measurement with an optical feedback CRD technique

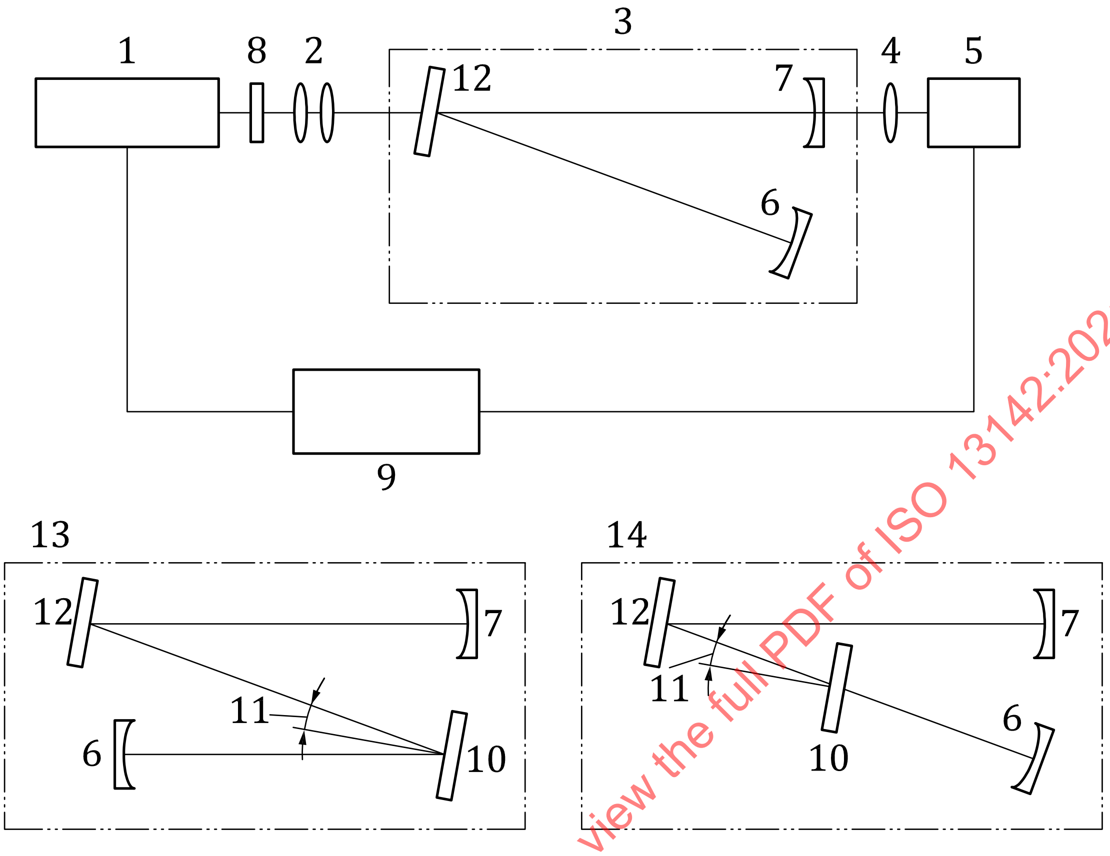
In the cw-CRD case, an optical feedback CRD (OF-CRD) scheme employing a semiconductor laser as the light source (shown in Figure 5) can be used for the reflectance/transmittance measurement with an improved signal-to-noise ratio in the CRD signals. In OF-CRD scheme, the initial cavity consists of three cavity mirrors – two concave mirrors and one planar mirror. The beam from the semiconductor laser is coaxially coupled into the ring-down cavity through the high-reflectance planar cavity mirror. The optical feedback (back-reflection of the laser beam) from the ring-down cavity is retro-reflected into the oscillator cavity of the semiconductor laser. Due to the self-mixing effect of the semiconductor laser, the spectral linewidth of the laser is significantly reduced by the frequency selected optical feedback, resulting in significant enhancement of the coupling efficiency of the laser power into the ring-down cavity and therefore a large increase of the CRD amplitude. When the laser power is modulated by a square wave signal, the cavity decay signal can be obtained at the falling edge of the square wave signal. The test principle is the same as that presented in 5.2 and 5.3. The item $\sqrt{R_1 R_2}$ in Formulae (2) to (7) should be substituted by $\sqrt{R_1 R_2} \cdot R_3$ in OF-CRD scheme.

The following two measurements are necessary to determine the reflectance/transmittance of the test sample:

a) τ_0 and L_0 are measured with the initial cavity;

b) τ and L are measured with the test cavity.

For transmittance measurement, the thickness and refractive index of the test sample substate are required. In case of a lens as the test sample, the thickness is the central thickness of the lens.



Key

1	semiconductor laser	8	polarizer
2	mode matching optics	9	control and data-processing unit
3	initial cavity with three mirrors	10	test sample
4	focusing lens	11	angle of incidence of the test sample
5	photo-detector	12	input cavity mirror, plane high reflectance mirror
6	cavity mirror, concave high reflectance mirror	13	test cavity with four mirrors, for reflectance measurement
7	output cavity mirror, concave high reflectance mirror	14	test cavity for transmittance measurement

Figure 5 — Schematic of optical arrangement for OF-CRD technique for high reflectance/transmittance measurements

6 Preparation of test sample and measurement arrangement

6.1 Test sample

Storage, cleaning and preparation of the test samples shall be carried out in accordance with the instructions of the manufacturer on the test samples for normal use.

6.2 Laser source

Wavelength of the laser source, angle of incidence and state of polarization shall correspond to those specified by the manufacturer for the use of the test sample. The state of polarization (*p* or *s*) of the laser beam shall be selected by the polarizer. If the value ranges are accepted for these three quantities, any combination of the wavelength, angle of incidence and state of polarization may be chosen within these ranges.

Transverse mode matching between the laser beam mode and the mode of the ring-down cavity is important and absolutely required in CRD techniques, especially in the pulsed-CRD systems. Mode matching optics (i.e., beam shaping lenses) are helpful to improve the beam quality of the laser and, further, to reduce the impact of mismatching on the CRD measurements. The impact of mode beating effect on the CRD measurements can be avoided by applying a single-mode (TEM_{00} mode) excitation in the cavity. In this case a single exponentially decay signal could be obtained.

In the pulsed-CRD system, the interval between two adjacent pulses shall be much larger than the cavity decay time. It is recommended that the duration of the laser pulse be shorter than the cavity round trip time ($2L/c$).

In the cw-CRD system, the laser power can be switched off by an optical switch. If a semiconductor laser which is modulated by square wave is employed, the laser is switched off at the falling edge of the square wave, so that the optical switch can be eliminated. The modulation frequency has to be experimentally optimized to maximize the CRD amplitude at the falling edge of the square wave.

6.3 Ring-down cavity

Both initial and test cavities are optically stable cavities, which are defined by $0<\rho<2L_0$, $0<\rho<2L$. The reflectance of a convex mirror can also be measured if the test cavity consisting of cavity mirrors and the convex test mirror is optically stable. Similarly, the transmittance of a lens can also be measured if the test cavity consisting of cavity mirrors and the test lens is optically stable. In this case, the focal length of the test lens should be within a certain range which is determined by the stable cavity condition for the test cavity.

It is recommended to use cavity mirrors with reflectance higher than 99,9 %. Cavity mirrors with higher reflectance are preferable as the reflectance/transmittance measurement accuracy improves with the increasing reflectance of the cavity mirrors. It is important to use cavity mirrors with higher reflectance when measuring high reflectance of test mirrors. When the reflectance of the test mirror is expected to be higher than 99,99 %, it is recommended to use cavity mirrors with reflectance also higher than 99,99 %. In some cases a set of cavity mirrors with different reflectances should be prepared for measurements of test mirrors with reflectances in a wide range. In all cases reflectance (R_1, R_2 and R_3) of each cavity mirror shall not be lower than 99,5 %.

6.4 Detection unit

The detection unit consists of a focusing lens, a photo-detector, both appropriate for the laser wavelength at which the measurement is to be performed, and an oscilloscope or a fast data-acquisition card.

To ensure that the laser power exiting the output cavity mirror is fully collected, the numerical aperture (NA) of the focusing lens and the active area of the photo-detector shall be optimized carefully. The focusing lens shall be coated with an anti-reflective coating at the laser wavelength.

A fast-speed photo-detector with a rise time much shorter than the decay time of the cavity should be used, so that the impact of the instrumental response time on the reflectance measurement can be neglected. In the case of a photo-detector with a rise time comparable to the decay time of the cavity, the influence of the rise time on the reflectance measurement has to be eliminated via data processing, see 8.1.

6.5 Data acquisition and processing

A certain number of ring-down signals are acquired by an oscilloscope or a data-acquisition card and averaged to determine the decay time of the initial cavity and of the test cavity. The number of acquired ring-down measurements should be sufficient to provide an acceptable signal-to-noise ratio. The number of ring-down signals shall be documented.

6.6 Environment

The environment of the testing place shall consist of dust-free filtered air with 40 % to 60 % relative humidity. The residual dust shall be reduced in accordance with the clean-room Class 7 as specified in ISO 14644-1. To minimize the impact of the environmental fluctuations on the test results, it is recommended that the overall length of the test cavity is kept the same as that of the initial cavity.

7 Test procedure

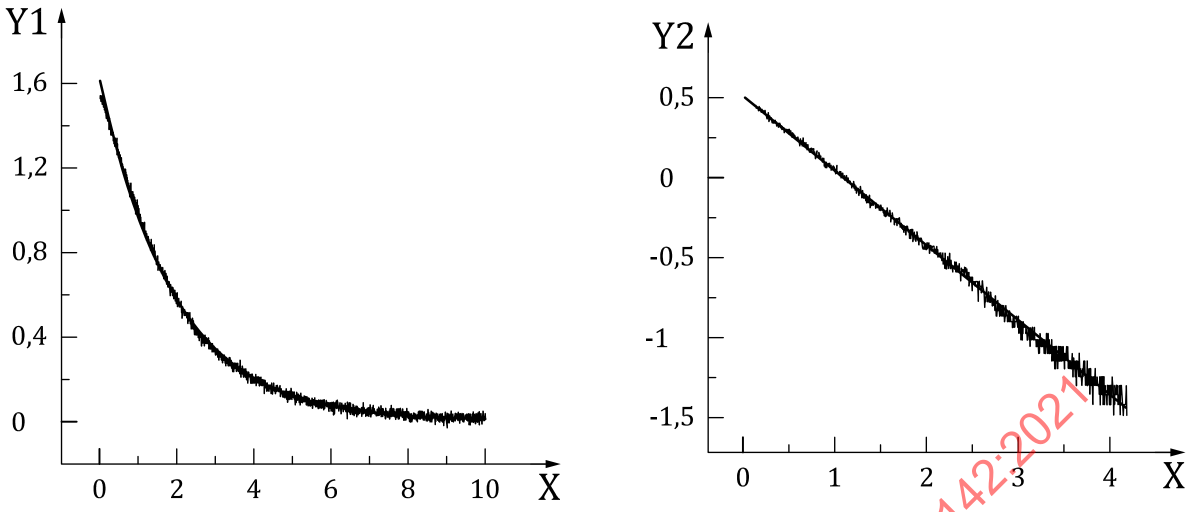
7.1 General

One of the pulsed-CRD method, the cw-CRD method or the cw OF-CRD method shall be chosen to measure the reflectance/transmittance. The decay time of both the initial cavity and the test cavity shall be measured to determine the reflectance/transmittance of the test sample.

The incident angle of the test sample shall be set according to the manufacturer's instruction. Reflectance of a sample aligned at normal incidence usually cannot be measured directly and instead for normal incidence the incident angle is set in between 3° to 8°, which shall be documented. For transmittance measurement, in the case of normal incidence the incident angle of the test sample should be set as small as possible providing that the reflected beams by the two surfaces of the test sample are totally out of the ring-down cavity. Care shall be taken to avoid, eliminate, or take into account the influence of interferometric effect of the two reflected beams on the transmittance measurement. This could be done by using a laser source with a short coherent length, or by using a slightly wedged substrate, or by slightly adjusting the incident angle to minimize the interferometric effect.

7.2 Measurement of decay time of initial cavity

Set up the initial ring-down cavity experiment. Record the initial cavity output signal immediately after the laser pulse (in the pulsed-CRD), or immediately after the laser power is switched off, or at the falling edge of the square-wave modulation (in the cw-CRD). Subtract the dc offset using the output signal when the laser light is blocked or shut off. As shown in Figure 6, this dc offset-subtracted signal is then fitted to a single exponentially decay function, $a\exp(-t/\tau_0)$, in the linear scale, with a being the amplitude factor, or fitted to a linear function in the logarithmic scale, $\log(a)-t/\tau_0$, to determine the initial cavity decay time τ_0. When it is fitted, eliminate the first part of the data corresponding to the time period twice the instrumental response, or eliminate a certain number of data points at the beginning of the recorded signal until the fit becomes insensitive to the number of data points eliminated.



Key

X time, in µs

Y1 amplitude, in V

Y2 log (amplitude), in a.u.

Figure 6 — Typical decay signal of the initial cavity and corresponding exponential fit in linear scale or linear fit in logarithmic scale

7.3 Calculation of reflectance of cavity mirrors

Calculate R using Formula (5), as described in 5.2.

7.4 Measurement of decay time of test cavity

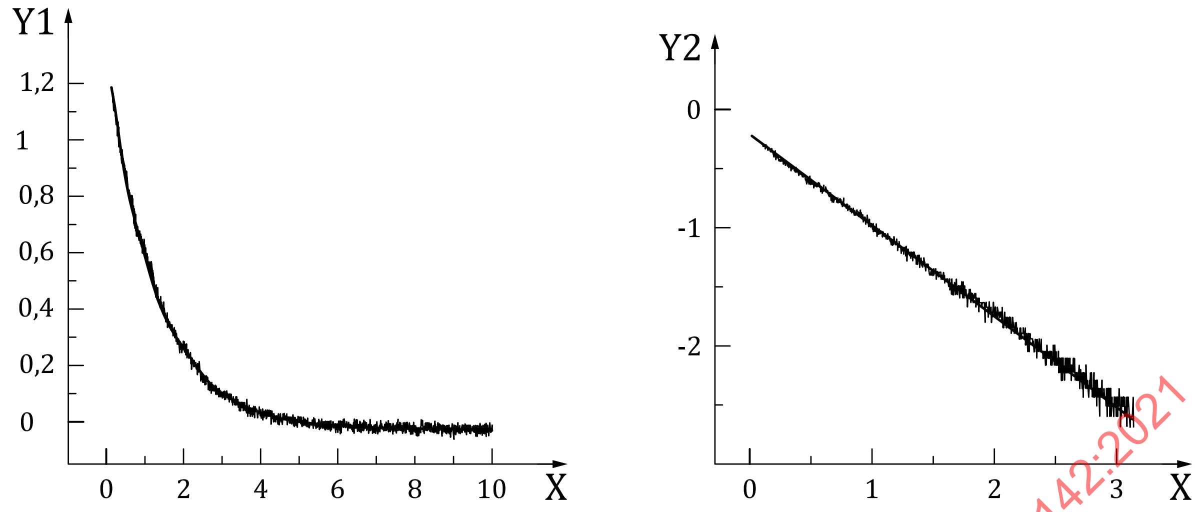
Set up the test ring-down cavity experiment. Test cavity decay time τ is measured in the same way as described in 7.2. The decay signal of the test cavity and corresponding exponential fit in linear scale or linear fit in the logarithmic scale is shown in Figure 7.

7.5 Calculation of reflectance/transmittance of test sample

Calculate R_s of reflective test sample or T_s of transmissive test sample using Formula (8) or (9), as described in 5.3.

7.6 Assessments of the measurement

The measurement error is assessed by evaluating the quality of the fits to the measurement data, as presented in Figures 6 and 7. The deviation of the measurement data from the exponential fit in the linear scale, or from the linear fit in the logarithmic scale, shows the error of the measurement. Typically, the measurement error of the reflectance is about a few percent of (1-R) or (1- R_s), and that of the transmittance is about a few percent of (1- T_s).



Key

X time, in µs

Y1 amplitude, in V

Y2 log (amplitude), in a.u.

Figure 7 — Typical decay signal of the test cavity and corresponding exponential fit in linear scale or linear fit in logarithmic scale

8 Main error factors

8.1 Influence of the instrumental response time on reflectance/transmittance measurement

8.1.1 General

The instrumental response time, τ_{inst}, consists mainly of the response time of the laser source, the photo-detector and the oscilloscope or data-acquisition card. The effect of the finite response time of the experimental apparatus on the CRD signal has to be accounted for in order to achieve precise reflectance/transmittance measurements. In case of $\tau_{inst} << \tau_0$ (and τ), the influence of the instrumental response time on the reflectance/transmittance measurement is small and can be neglected. However, in the case that the instrumental response time becomes comparable to the decay time, the CRD signal deviates significantly from the single exponential decay function, leading to significant error in the determination of the decay time as well as the calculation of the reflectance/transmittance. Two methods, that is, multi-parameter fitting and data truncation method, can be employed to eliminate or minimize the influence of the instrumental response time on the reflectance/transmittance measurement. In any case, the instrumental response time, τ_{inst}, shall be always smaller than the decay time τ_0 (and τ) in the testing.

8.1.2 Multi-parameter fitting method

In CRD measurements, the CRD signal is proportional to the convolution of the input signal, which is the input pulse (here a delta function is assumed) $\delta(t)$ in the pulsed case or the negative-step function $u(-t)$ in the cw case, with the impulse response of the ring-down cavity $h(t)$, and the instrumental response function $h_0(t)$. The impulse response of the ring-down cavity $h(t)$ and the instrumental response function $h_0(t)$ can be expressed as Formula (10) and Formula (11), respectively:

$$h(t) \propto \exp\left(-\frac{t}{\tau}\right) \tag{10}$$

and

$$h_0(t) \propto \exp\left(-\frac{t}{\tau_{inst}}\right) \tag{11}$$

The CRD signals are given in both pulsed- and cw-CRD schemes as Formula (12) and Formula (13), respectively,

$$I_{pulse}(t)/I_0 = \delta(t) \cdot \exp\left(-\frac{t}{\tau}\right) \cdot \exp\left(-\frac{t}{\tau_{inst}}\right) = \left[\exp\left(\frac{-t}{\tau}\right) - \exp\left(\frac{-t}{\tau_{inst}}\right)\right] \tag{12}$$

$$I_{cw}(t)/I_0 = u(-t) \cdot \exp\left(-\frac{t}{\tau}\right) \cdot \exp\left(-\frac{t}{\tau_{inst}}\right) = \left[\exp\left(\frac{-t}{\tau}\right) - \frac{\tau_{inst}}{\tau}\exp\left(\frac{-t}{\tau_{inst}}\right)\right] \tag{13}$$

where I_0 is the initial signal amplitude at time $t = 0$.

The instrumental response time, τ_{inst}, should be smaller than the cavity decay time, τ, in order to make the CRD signal applicable to determine the cavity decay time. By applying a multi-parameter estimation technique to determine simultaneously the cavity decay time and the overall response time of the experimental apparatus via fitting the experimental CRD signal to the corresponding theoretical model [Formula (12) or (13)], the influence of the instrumental response time on the reflectance measurement can be eliminated.

8.1.3 Data truncation method

Due to the finite instrumental response time, the deviation between the experimental CRD signal and the corresponding best-fit is most significant at the beginning part of the decay signals. The CRD signal gradually approaches the exponential decay in the linear scale or the linear decay in the logarithmic scale with the increasing time. Therefore, the impact of the instrumental response time on the reflectance/transimittance measurement can be diminished by intentionally removing the data points at the beginning part of the CRD signal from being fitted. However, care has to be taken when deleting the data points at the beginning duration to reduce the influence of the instrumental response time, because the CRD amplitude as well as the signal-to-noise ratio of the CRD signal also decreases as the time increases. In general, the removed data points should be within the fitted decay time τ_0 (and τ) from the beginning.

8.2 Measurement error of the reflectance of cavity mirrors

From Formula (5), the measurement error of the reflectance of the cavity mirrors can be expressed as Formula (14):

$$\left|\frac{\Delta R}{R}\right| = (1-R)\left(\left|\frac{\Delta L_0}{L_0}\right| + \left|\frac{\Delta \tau_0}{\tau_0}\right|\right) \tag{14}$$

where

$\Delta L_0 / L_0$ is the measurement error of the initial cavity length;

$\Delta \tau_0 / \tau_0$ is the measurement error of the decay time of the initial cavity.

The reflectance measurement error decreases as the reflectance increases. It is recommended to use cavity mirrors with reflectance higher than 99,9 % or even above 99,99 %. For example, assume the overall measurement error for the cavity length and decay time is 1 % (For a CRD instrument, a measurement error of the cavity length of 0,1% or less can be easily achieved, as the cavity length is normally in the range from 0,5 m to 1,0 m), the measurement error for the reflectance of the cavity mirrors is 0,001 % when the reflectance is 99,9 %, and reduces to 0,000 1 % and 0,000 01 % when the reflectance is 99,99 % and 99,999 %, respectively. On the other hand, the reflectance of the cavity mirrors has to be optimized as the coupling efficiency of the laser power to the ring-down cavity decreases as the reflectance of the cavity mirrors increases.

8.3 Measurement error of the reflectance/transmittance of test sample

Similarly, the measurement error of the reflectance/transmittance of the test sample can be expressed as Formula (15) and Formula (16), respectively:

$$\left|\frac{\Delta R_s}{R_s}\right| = \left|\frac{\Delta R}{R}\right| + (1 - RR_s)\left(\left|\frac{\Delta L}{L}\right| + \left|\frac{\Delta \tau}{\tau}\right|\right) \quad (15)$$

$$\left|\frac{\Delta T_s}{T_s}\right| = \left|\frac{\Delta R}{R}\right| + (1 - RT_s)\left(\left|\frac{\Delta L}{L}\right| + \left|\frac{\Delta \tau}{\tau}\right|\right) \quad (16)$$

In Formula (16) the contributions of uncertainties of refractive index and thickness of transmitted sample substrate to the measurement error of the transmittance are negligible and therefore not considered. The use of cavity mirrors with a higher reflectance improves the measurement accuracy of the reflectance/transmittance of the test sample. Assume the average reflectance of the cavity mirrors is 99,99 %, according to Formulae (14) to (16), the typical values of measurement uncertainty of high-reflectance/high-transmittance test sample are shown in Table 2.

Table 2 — Typical uncertainty of reflectance/transmittance measurement of test sample

Reflectance/transmittance %	Uncertainty %
$99{,}0 < R_s/T_s < 99{,}5$	< ±0,02
$99{,}5 < R_s/T_s < 99{,}9$	< ±0,01
$99{,}9 < R_s/T_s < 99{,}99$	±0,002
$R_s/T_s > 99{,}99$	±0,000 2

The measurement accuracy for the reflectance/transmittance can be further improved by reducing the measurement error of the decay time, which can be done by a better mode-matching between the laser modes and the ring-down cavity modes, a longer cavity length, and a more sensitive and lower-noise detection method.

If required, the reliability of the reflectance/transmittance measurement results can be experimentally verified. The experimental method is described in Annex A.

9 Test report

The following information shall be documented in the test report:

a) information on the test organization:

   1) testing organization;

   2) date of test, time;

   3) examiner;

b) information concerning the test sample:

   1) manufacturer of test sample;

   2) type of test sample;

   3) part ID, date of production;

   4) specifications of manufacturer for normal use (wavelength, polarization, angle of incidence, purpose of use, etc.);

c) information concerning the test facility:

   1) laser source (wavelength, operating mode cw/pulsed, pulse duration and repetition rate, modulation frequency for cw source, state of polarization, spectral linewidth);

   2) parameters of the detection system and data acquisition (instrumental response time, number of signals recorded for averaging);

   3) description of other relevant test equipment;

   4) environmental conditions (temperature, degree of cleanliness when clean room is used, humidity, etc.);

d) information concerning testing and evaluation:

   1) initial and test cavity lengths;

   2) location size of beam on the sample;

   3) ring-down time of the initial and test cavities;

e) error budget:

   1) errors of decay time;

f) test results:

   1) graphs of cavity decay signals for both initial and test cavities and corresponding best-fit curves;

   2) reflectance or transmittance of test sample;

   3) reflectance or transmittance uncertainty of test sample;

g) a reference to this document, i.e. ISO 13142:2021.

An example of test report is given in Annex B.