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

*Optiques et photoniques — Lasers et équipement associé aux lasers
— Méthode d'alternance de la cavité pour le mesurage du facteur de
réflexion et de transmittance*
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Contents

Page

Foreword	iv
Introduction	v
1 Scope	1
2 Normative references	1
3 Terms and definitions	1
4 Symbols used and units of measure	2
5 Test principles	2
5.1 General.....	2
5.2 Decay time of initial cavity and reflectance of cavity mirrors.....	2
5.3 Decay time of test cavity and reflectance/transmittance of test sample.....	4
5.4 High reflectance/transmittance measurement with an optical feedback CRD technique ...	5
6 Preparation of test sample and measurement arrangement	6
6.1 Test sample.....	6
6.2 Laser source.....	6
6.3 Ring-down cavity.....	7
6.4 Detection unit.....	7
6.5 Data acquisition and processing.....	7
6.6 Environment.....	8
7 Test procedure	8
7.1 General.....	8
7.2 Measurement of decay time of initial cavity.....	8
7.3 Calculation of reflectance of cavity mirrors.....	9
7.4 Measurement of decay time of test cavity.....	9
7.5 Calculation of reflectance/transmittance of test sample.....	9
7.6 Assessments of the measurement.....	9
8 Main error factors	10
8.1 Influence of the instrumental response time on reflectance/transmittance measurement.....	10
8.1.1 General.....	10
8.1.2 Multi-parameter fitting method.....	10
8.1.3 Data truncation method.....	11
8.2 Measurement error of the reflectance of cavity mirrors.....	11
8.3 Measurement error of the reflectance/transmittance of test sample.....	12
9 Test report	12
Annex A (informative) Reflectance/transmittance reliability check experiment	14
Annex B (informative) Test report	15
Bibliography	17

Foreword

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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.

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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 $\pm 0,3$ %, 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 transmitted test sample substrate	
d	thickness of the transmitted 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 radiometry) 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 \(2\)](#):

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

With [Formula \(3\)](#):

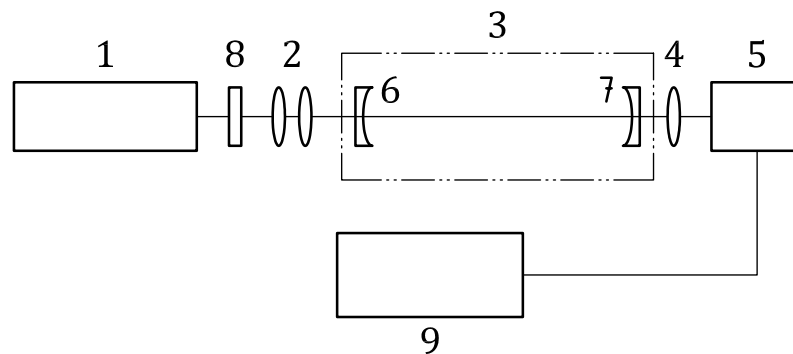
$$c = \frac{c_0}{n} \tag{3}$$

When 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. [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 \(5\)](#):

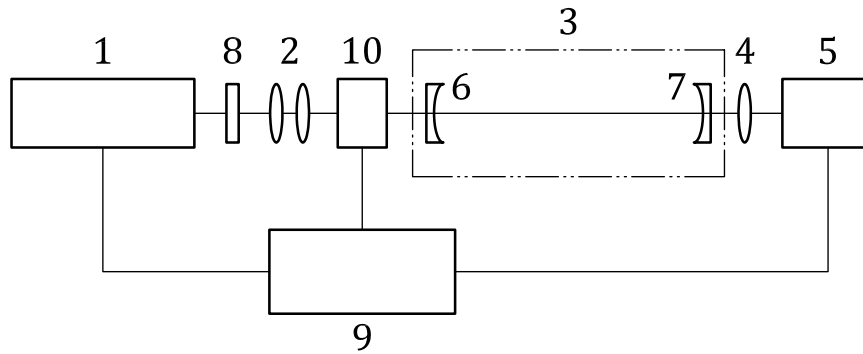
$$R = \sqrt{R_1 R_2} = \exp\left(\frac{-L_0}{c\tau_0}\right) \tag{5}$$



Key

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

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



Key

- | | | | |
|---|----------------------|----|---|
| 1 | laser | 6 | input cavity mirror, concave high reflectance mirror |
| 2 | mode matching optics | 7 | output cavity mirror, concave high reflectance mirror |
| 3 | initial cavity | 8 | polarizer |
| 4 | focusing lens | 9 | control and data-processing unit |
| 5 | photo-detector | 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/transmitted planar test sample or a lens is to be measured, a test ring-down cavity is formed by inserting this reflective/transmitted test sample or lens into the initial cavity as shown in [Figure 3](#) (for reflective sample) or [Figure 4](#) (for transmitted 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 \(6\)](#):

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

for the reflective sample, and as [Formula \(7\)](#):

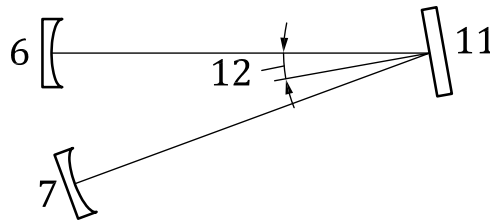
$$\tau = \frac{-[L + (n_s - 1)d]}{c \ln(T_s \cdot \sqrt{R_1 R_2})} \tag{7}$$

for the transmitted sample or lens. Therefore, [Formulae \(4\)](#) and [\(6\)](#), the reflectance, R_s , of the reflective test sample can be calculated as [Formula \(8\)](#):

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

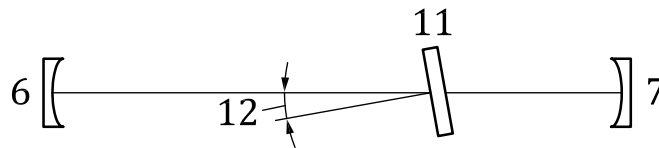
And, combining [Formulae \(4\)](#) and [\(7\)](#), the transmittance, T_s , of the transmitted test sample or lens can be calculated as [Formula \(9\)](#):

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

**Key**

- 6 input cavity mirror, concave high reflectance mirror 11 reflective test sample
 7 output cavity mirror, concave high reflectance mirror 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 11 transmitted test sample or lens
 7 output cavity mirror, concave high reflectance mirror 12 angle of incidence of test sample

Figure 4 — Schematic of optical arrangement of test cavity for transmittance measurement
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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 time for the three combinations, separately. From the three measured decay time 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;