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Electro-optical systems — Cavity ring-down technique for high-reflectance measurement

Systèmes électro-optiques — Technique d'alternance de la cavité pour le mesurage du facteur de réflexion

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Foreword

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The committee responsible for this document is ISO/TC 172, *Optics and photonics*, Subcommittee SC 9, *Electro-optical systems*.

Introduction

With the development of film-deposition technology, the performance of optical thin films, especially the highly reflective 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 characteristic. It is necessary to be able to measure this reflectance characteristic precisely. The measurement procedures in this International Standard have been optimized to allow the measurement of high reflectance (larger than 99 %, theoretically up to 100 %) of optical laser components using the cavity ring-down technique which provides reflectance data with high accuracy, high repeatability and reproducibility, and high reliability.

Electro-optical systems — Cavity ring-down technique for high-reflectance measurement

1 Scope

This International Standard specifies measurement procedures for the precise determination of the high reflectance of optical laser components. Up to now, the ISO standardized testing methods for reflectance of optical laser components have the accuracy limit of approximately 0,01 % (for measurement of absolute reflectance) which are not appropriate for measuring the reflectance higher than 99,99 % or, in some cases, measurement accuracy better than 0,01 % is required. The range of application of this standardized test method is reflectance 99 % and higher (theoretically up to 100 %).

The methods given in this International Standard are intended to be used for the testing and characterization of high reflectance of both concave and plane mirrors used in laser systems and laser-based instruments. The reflectance of convex mirrors can also be tested by taking into consideration the radius of curvature of the mirror surface.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. 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*

3 Terms and definitions

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

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

4 Symbols used and units of measure

Table 1 — Symbols used and units of measure

Symbol	Unit	Term
c	m/s	speed of light in measurement environment
c_0	m/s	speed of light in vacuum
$h(t)$		impulse response of the ring-down cavity
$h_0(t)$		instrumental response function
L_0, L	m	lengths of the initial and test cavities
ΔL_0, ΔL	m	measurement errors of the initial and test cavity lengths
n		refractive index of air in measurement environment

Table 1 *(continued)*

Symbol	Unit	Term
R		average reflectance of the concave cavity mirrors, equals square root of R_1*R_2
R_s		reflectance of the test sample
R_1, R_2		reflectance of two concave cavity mirrors
R_3		reflectance of the planar cavity mirror
T_0	s	instrumental response time
t	s	time
$u(t)$		negative-step function
α	cm^{-1}	the overall absorption coefficient of the gases inside the cavity at the laser wavelength
$\delta(t)$		delta function
θ	rad	angle of incidence of the test sample
ρ	m	radius of curvature of concave surface of the cavity mirror
τ_0, τ	s	decay time of the initial and test cavities
$\Delta\tau_0$, $\Delta\tau$	s	measurement errors of the decay time of the initial and test cavities

5 Test principles

5.1 General

The conventional reflectance measurement techniques (spectrophotometry and laser ratiometry) are based on measuring the relative changes of light power reflected 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):

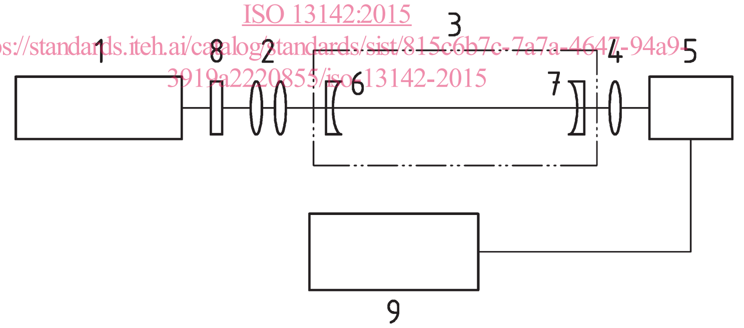
$$\mathrm{c} = \frac{c_0}{n} \tag{3}$$

When at test laser wavelength the absorptance of gases inside the ring-down cavity is 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):

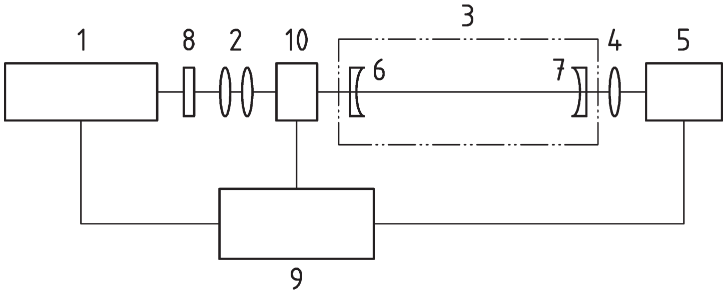
$$R = \sqrt{R_1 R_2} = \exp\left(\frac{-L_0}{c\tau_0}\right) \tag{5}$$



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
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

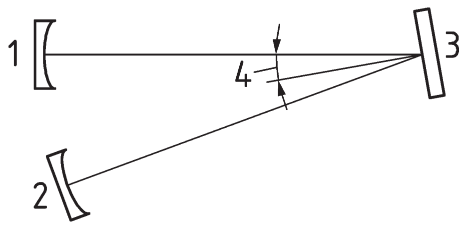
5.3 Decay time of test cavity and reflectance of test sample

If a planar test sample is to be measured, a test ring-down cavity is formed by inserting this test sample into the initial cavity as shown in Figure 3. The incident angle of the laser beam on the test sample follows the required incident angle of the test sample. In this case, the decay time of the folded test cavity can be expressed as Formula (6):

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

Therefore, combining Formula (4) and Formula (6), the reflectance R_s of the test sample can be calculated as Formula (7):

$$R_s = \exp\left(\frac{L_0}{c\tau_0} - \frac{L}{c\tau}\right) \qquad (7)$$



Key

1 input cavity mirror, concave high reflectance mirror
2 output cavity mirror, concave high reflectance mirror
3 test sample
4 angle of incidence of test sample

Figure 3 — Schematic of optical arrangement for test cavity

5.4 High reflectance measurement with an optical feedback CRD technique

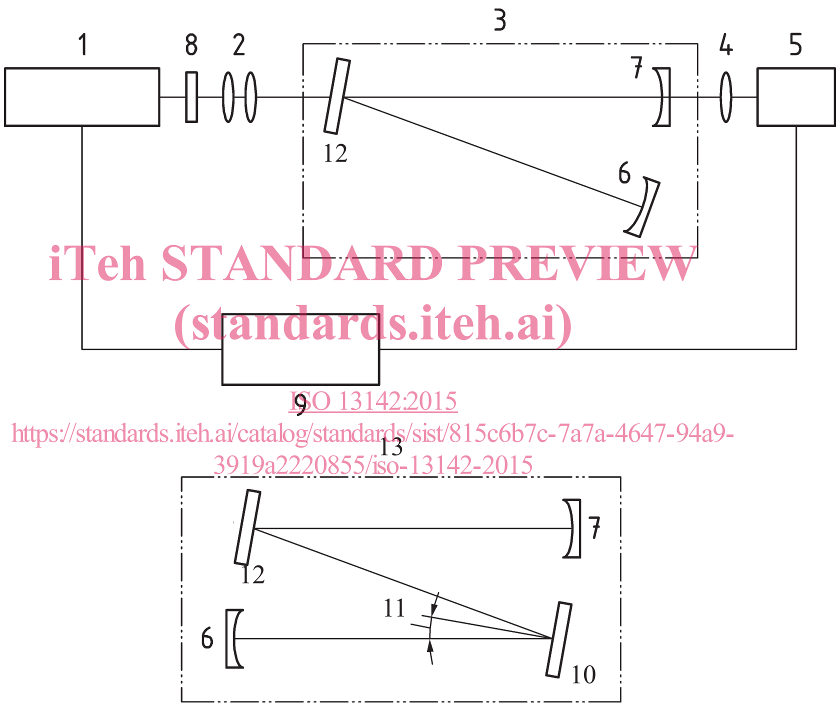
In the cw-CRD case, an optical feedback CRD (OF-CRD) scheme employing a semiconductor laser as the light source (shown in Figure 4) can be used for the reflectance measurement with an improved signal-to-noise ratio in the CRD signals. In OF-CRD scheme, the initial cavity consists of three cavity mirrors:

two concave mirrors and one planar mirror. The beam from the semiconductor laser is coaxially coupled into the ring-down cavity from 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 Formula (2) to Formula (6) 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 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.



Key

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

Figure 4 — Schematic of optical arrangement for OF-CRD technique for high reflectance measurement