The OSA Thin Films Technical Group Welcomes You

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https://www.osa.org/ThinFilmsTG

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Thin Films Technical Group at a Glance

- Focus
  - Optical thin films from fundamentals to applications
  - Our group serves over 1000 global members
- Mission
  - Connect people from academia, institutions and industries in the field
  - Bridge the fundamentals, the know-hows and the new developments
  - Promote networking and career development through continuous learning
- Find Us Here
  - OSA Technical Group Website: www.osa.org/ThinFilmsTG
  - LinkedIn: www.linkedin.com/groups/4783616

Interested in presenting your research?
Have ideas for our group activities/events?
Please contact us. Thank you!

Events of Thin Films Technical Group in 2019

- ***Optical Monitoring Systems for Optical Coatings***
  12 February 2019 by Dr. Binyamin Robin

- ***Quality Control and Thin Film Metrology for Future Optical Components***
  14 May 2019 by Dr. Lars Jensen

- **Meet and Greet at OIC 2019**
- *6 June 2019 by Dr. Jue Wang*

- ***High reflectance/transmittance measurements of laser optics with cavity ring-down (CRD) technique***
  24 September 2019 8:30 AM ~ 9:30 AM EDT
  by Prof. Bincheng Li

- ***Substrate-Transferable Single-Crystal Optical Coatings***
  12 November 2019 9:30 AM ~ 10:30 AM EST by Dr. Garrett Cole

You may find information on upcoming webinars and access the past presentations via on-demand webinars at
https://www.osa.org/en-us/get_involved/technical_groups/technical_group_webinars/#ondemand

Today’s Webinar

High reflectance/transmittance measurements of laser optics with cavity ring-down (CRD) technique

By Prof. Bincheng Li

Bincheng Li holds PhD in Analytical Chemistry from Wuhan University, China in 1995. He is a full professor at the School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China.

He has over 30 years of experience developing testing techniques for optical coatings and over 15 years of experience developing CRD for high reflectance/transmittance measurements. He is the writer of the international standard ISO 13142. He has co-authored over 240 technical papers.

电子科技大学
University of Electronic Science and Technology of China

High reflectance/transmittance measurements of laser optics with cavity ring-down (CRD) technique

Bincheng Li

School of Optoelectronic Science and Engineering
University of Electronic Science and Technology of China, Chengdu, China
and
Chengdu Extrema Optoelectronic Technologies Ltd. , China

光电系统工程实验室
Engineering Laboratory of Optoelectronic System

Outline

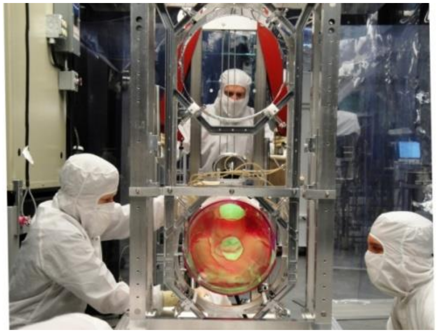
1. Introduction
2. History and Principle of CRD for high reflectance/ transmittance measurements
3. Recent technical developments of CRD for characterization of laser optics
4. ISO 13142: CRD for high reflectance/ transmittance measurements (Standard)
5. CRD Instrumentation
6. Conclusions

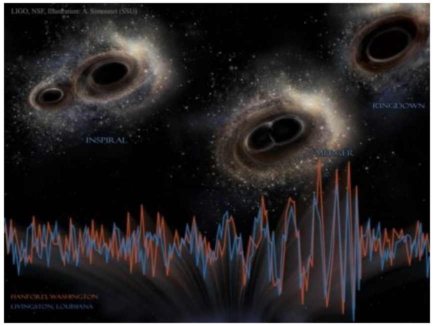
Introduction

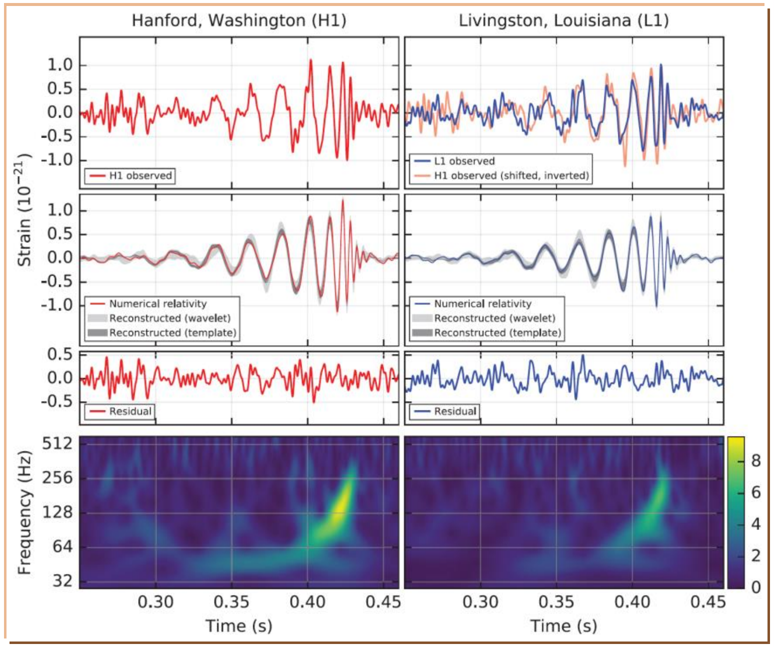
HR mirrors have been widely used in

- **High-power laser systems (NIF)**
- **Gravitational-wave detection (LIGO, VIRGO)**
- **Laser gyros**
- **Cavity-enhanced spectral analysis**

Precise and reliable measurements of high reflectance/transmittance (R/T > 99.9%) are required.







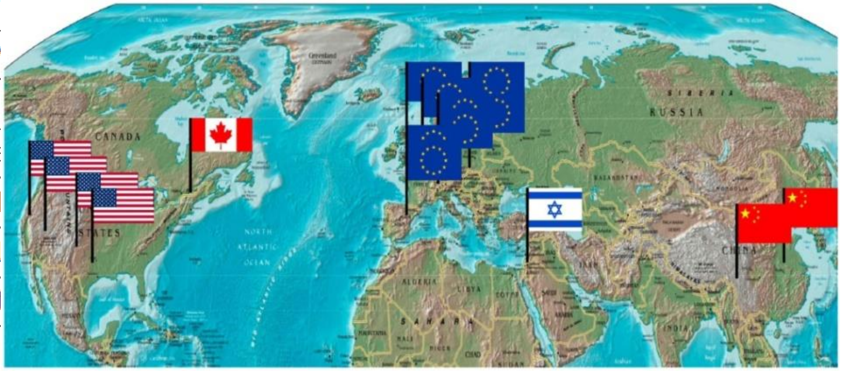
Gravitational wave detection with LIGO

Round Robin – Reflectance Measurement

Participating laboratories

Optical Interference Coatings 2010 Measurement Problem

Institution	Contact
Aerospace Cooperation, Los Angeles, USA	James D. Barrie
Chinese Academy of Sciences, Shanghai, China	Hongbo He
Chinese Academy of Sciences, Chengdu, China	Bincheng Li
Escuela Universitaria de Optica, Madrid, Spain	Juan Carlos Martinez Anton
Fraunhofer FEP, Dresden, Germany	Kerstin Täschner
Fraunhofer IST, Braunschweig, Germany	Michael Vergöhl
Institut f. Photonische Technologien, Jena, Germany	Christian Mühlig
JDSU, Santa Rosa, USA	Cliff Alapa
Laser Zentrum Hannover, Germany	Detlev
MLD Technologies, Eugene, USA	Sven
National Research Council, Ottawa, Canada	Daniel
Perkin Elmer, Rodgau-Jüdesheim, Germany	Ivo Ste
OMT Solutions, Eindhoven, The Netherlands	Ivo Sc
RAFAEL, Haifa, Israel	Shay
Raytheon Space & Airborne Systems, El Segundo, USA	Robert
University of the West of Scotland, Paisley, UK	Frank



OIC Measurement Problem, Tucson, June 10, 2010

LZH Fraunhofer IOF

Appl. Opt. 2011

Round Robin – Reflectance Measurement

Samples

LAYERTEC OPTICAL COATINGS · OPTICS

The samples (substrate polishing + coating) were manufactured & sponsored by LAYERTEC GmbH, Mellingen, Germany

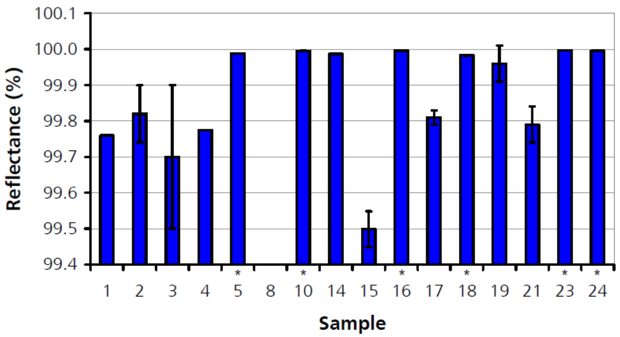
- Substrates: superpolished fused silica, 25 mm diameter,
- Coating process: magnetron sputtering
- Coating designs:
  quarterwave Ta_2O_5 / SiO_2 systems for 1064 nm, 0° AOI
  - sample type A: $(HL)^{16}$ H
  - sample type B: $(HL)^{10}$ H

Techniques used:
Spectrophotometry
Cavity Ring-down (CRD)
Laser Ratiometry

Sample type	av. loss (ppm)	st.dev. (ppm)	R (%)
A:	39.9	2.4	99.996
B	1216.5	73.9	99.878

Round Robin – Reflectance Measurement

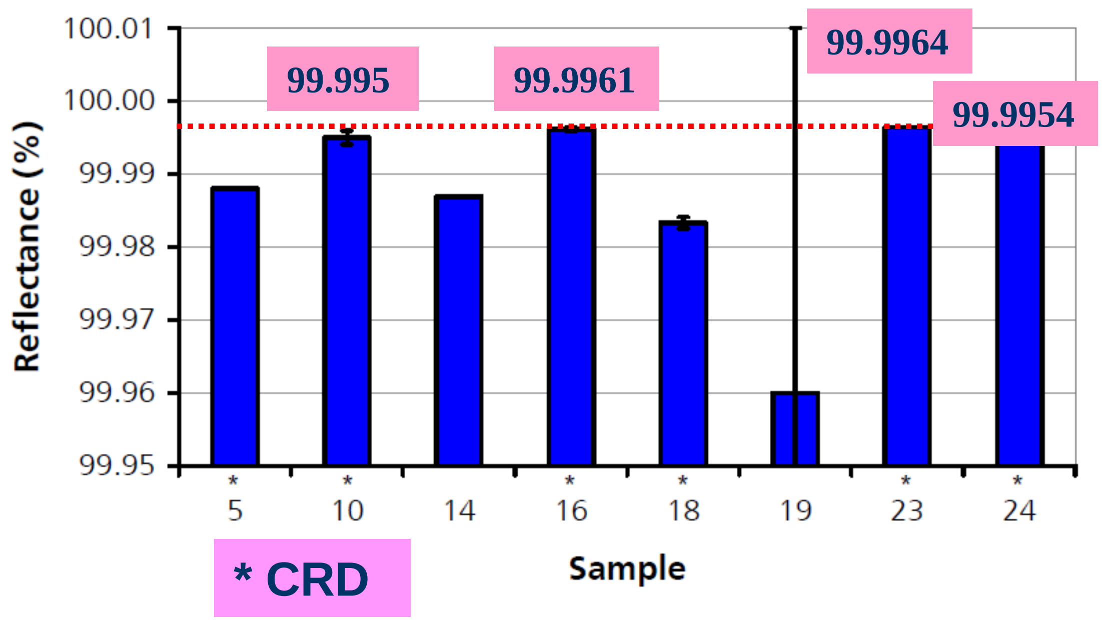
R results of participants
Sample type A (asterix: CRD measurement)



 # 8 A, result of spectrophotometric measurement: "Not possible to determine R within acceptable confidence. R probably higher than 99.95 % "

OIC Measurement Problem, Tucson, June 10, 2010

R results of participants
Sample type A zoom



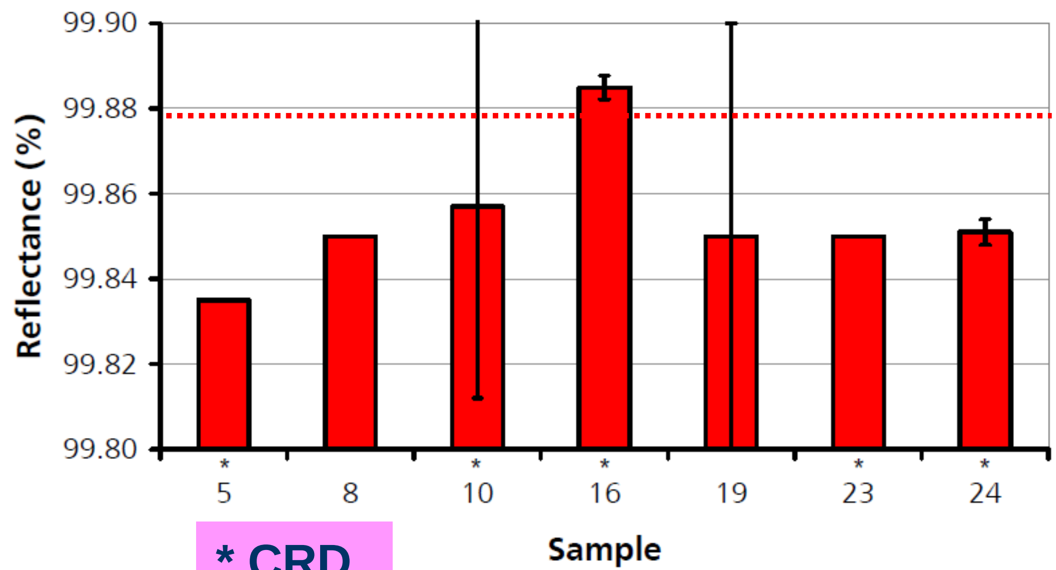
OIC Measurement Problem, Tucson, June 10, 2010

Reference value: 99.9960%

CRD is the only technique which can measure precisely reflectance (R) higher than 99.99%.

Round Robin – Reflectance Measurement

R results of participants
Sample type B zoom



*** CRD**

OIC Measurement Problem, Tucson, June 10, 2010

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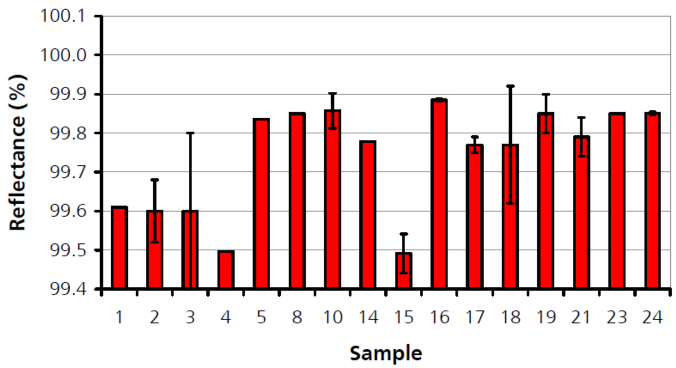
R results of participants
Sample type B



OIC Measurement Problem, Tucson, June 10, 2010

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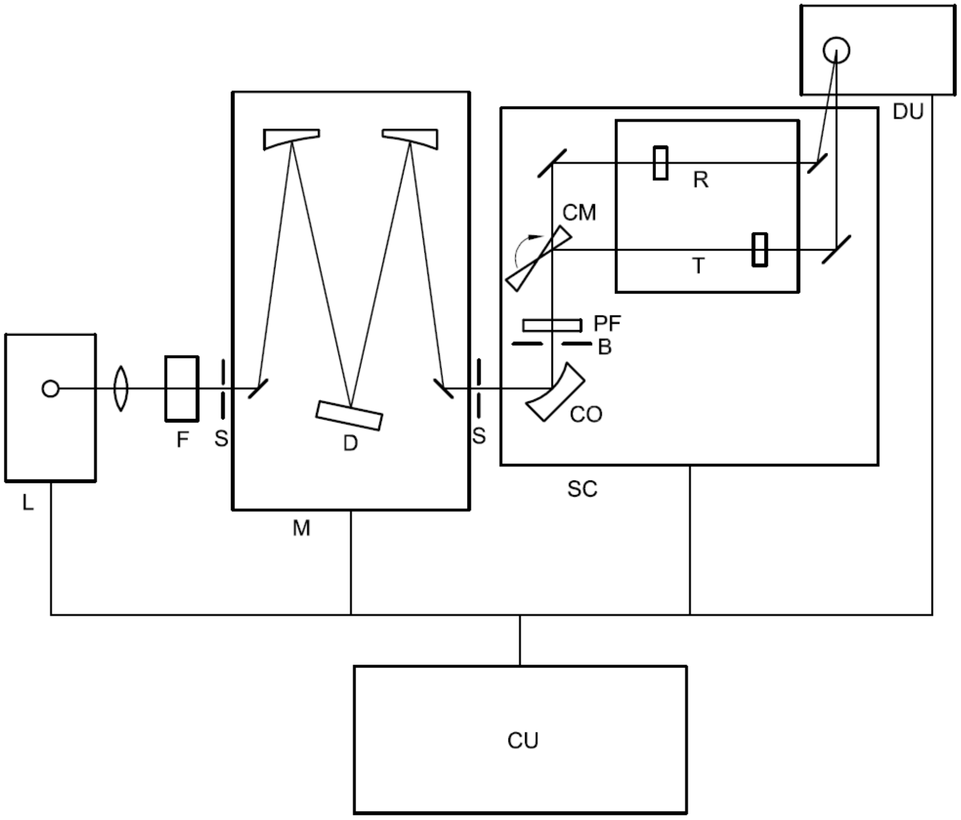
Reference value： 99.878%

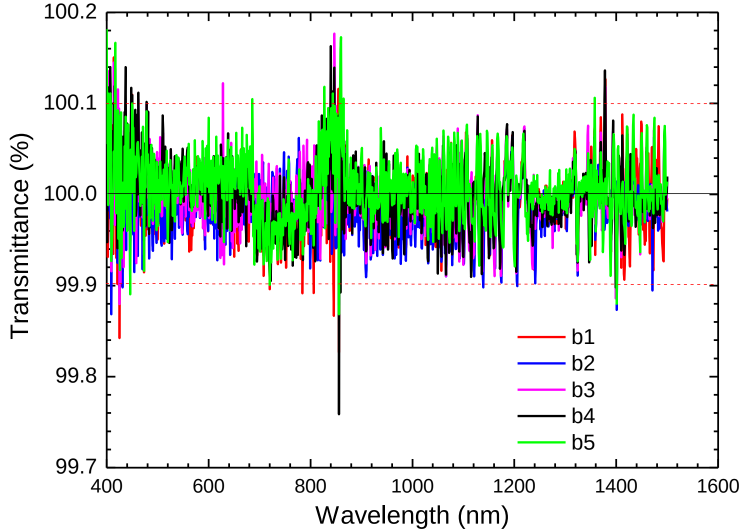
For R ~ 99.8%, CRD shows better accuracy.

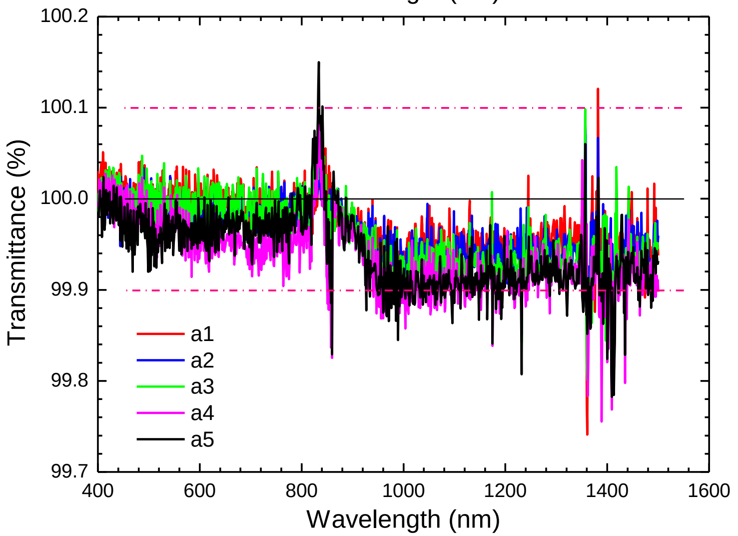
Spectrophotometry

100%-transmittance line of a typical spectrophotometer



Standard arrangement of a spectrophotometer





Typical repeatability of a spectrophotometer for R/T measurement: ±0.1%

Comparison

Testing technique	Spectrophotometry	Laser ratio	Cavity Ring-down
Typical measurement range (%)	0 – 100	0 – 100	99.0 - >99.99999
Maximum measurable Reflectance (%)	99.9	99.99	> 99.99999
Measurement sensitivity (%)	0.01	0.01	< 0.00001
Typical Reflectance measurement accuracy (%)	±0.3	> ± 0.01	< ± 0.0001
System configuration	Simple	Complex	Simple
Calibration	Yes	Yes	No
Alignment	Easy	Difficult	Easy
Operation	Easy	Difficult	Easy

CRD is capable of measuring reliably R > 99.9%

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5. CRD Instrumentation
6. Conclusions

Phase-shift - CRD technique

J M Berbelin [Aerospace Corporation, USA] Appl. Opt. 19, 144(1980)

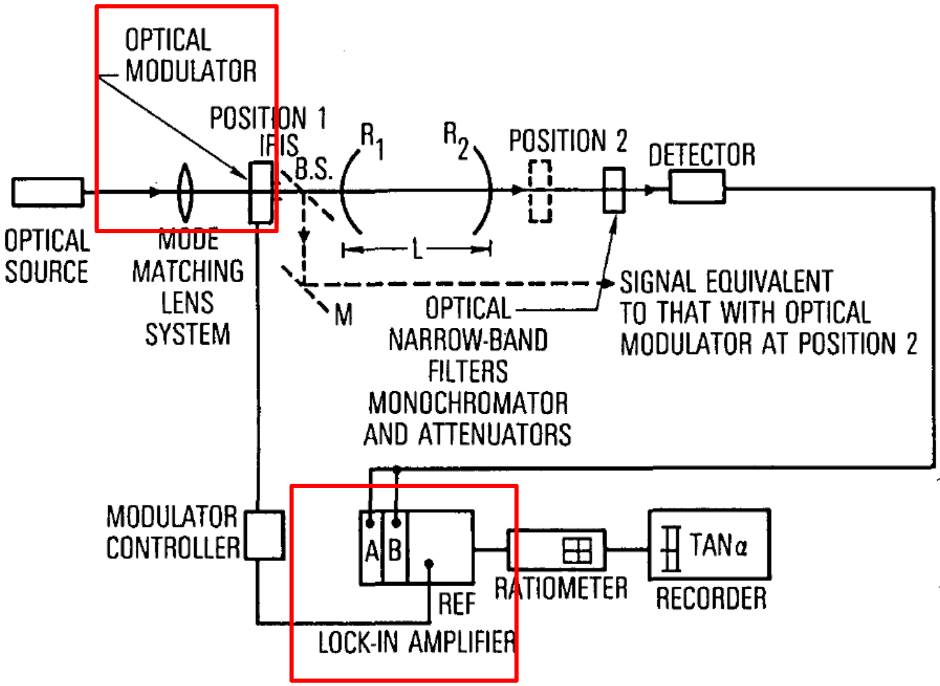


Fig. 1. Photon-lifetime measurement method.

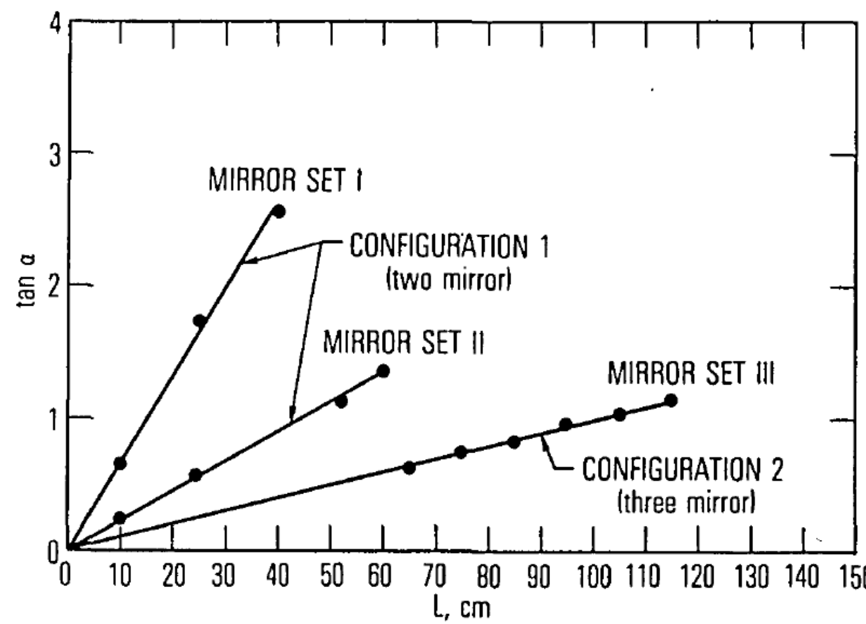


Fig. 2. Tanα vs intracavity distance.

$$\tan(\alpha) = 4\pi f \tau$$

Phase shift **Decay time**

Accuracy achieved: ~ 100ppm

Continuous wave (cw) - CRD technique

Z A Anderson [California Institute of Technology, USA]   Appl. Opt. 23, 1238(1984)

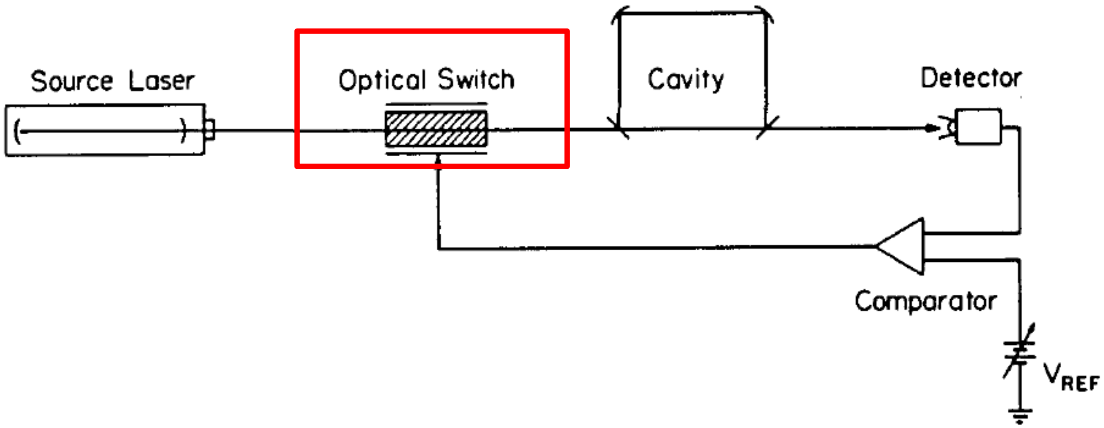
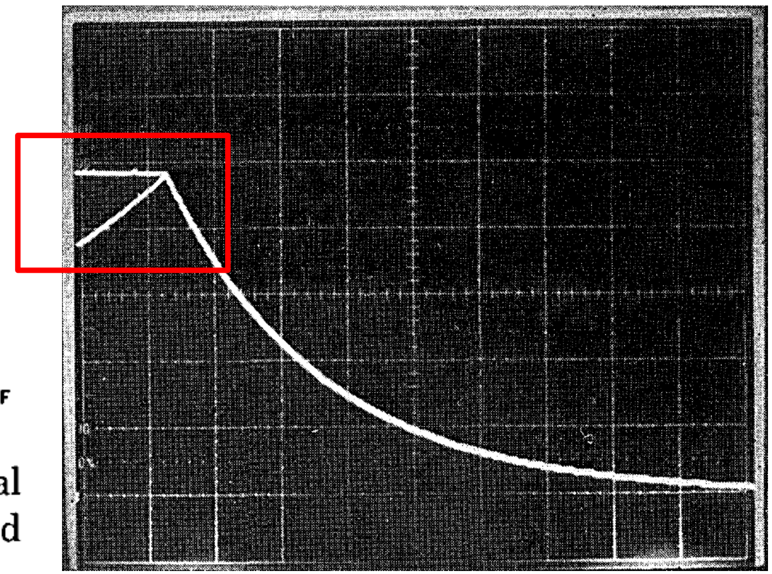


Fig. 1. Conceptual schematic of decay measuring device. Optical switch shuts off light when detector output reaches a preset threshold level.



Pre-set threshold circuit and optical switch for CRD signal recording

Accuracy achieved:
R = 0.999820±3ppm
R = 0.998730±7ppm

Continuous wave (cw) - CRD technique

G Rempe [California Institute of Technology, USA Opt. Lett. 17, 363(1992)

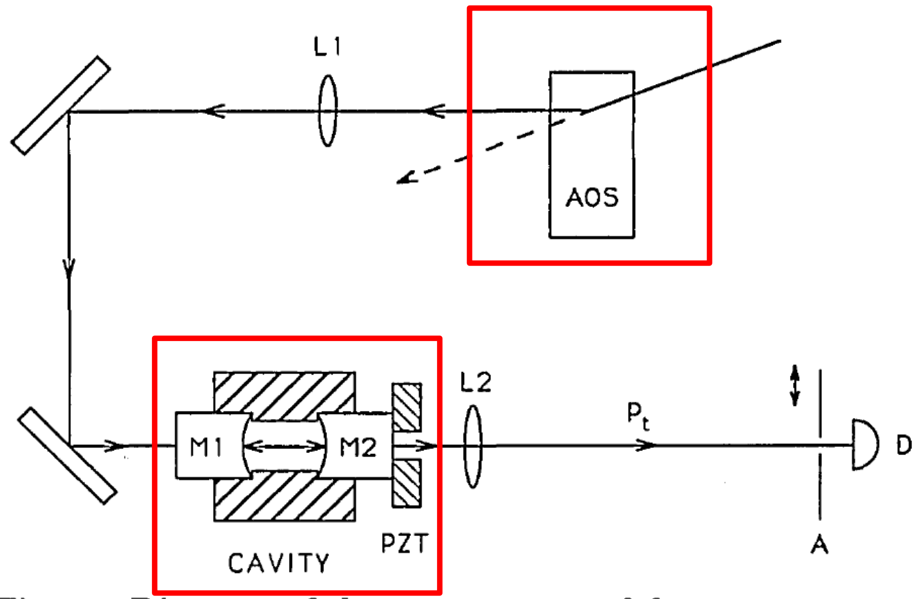
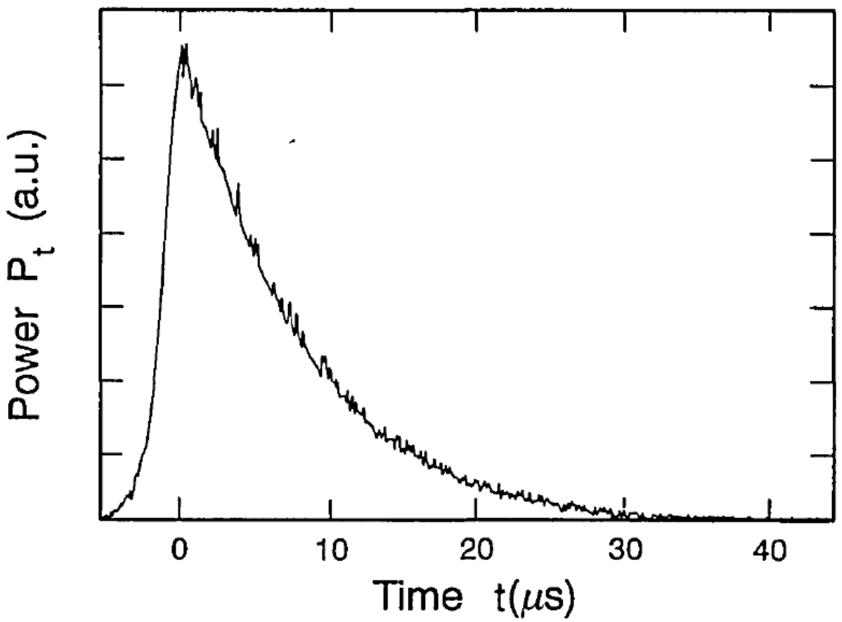


Fig. 1. Diagram of the apparatus used for measurement of cavity-decay time and finesse.



Cavity length modulation for optical coupling;
Pre-set threshold circuit and optical switch for CRD signal recording.

Accuracy achieved:
R = 0.9999984±0.15ppm

Narrow band cw - CRD technique

N Uehara [U of Electro-Communications, Japan, Opt. Lett. 20, 530(1995)

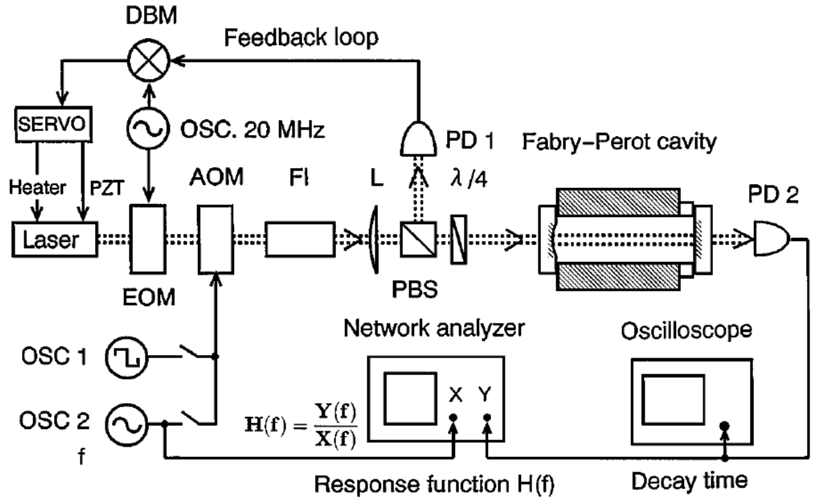
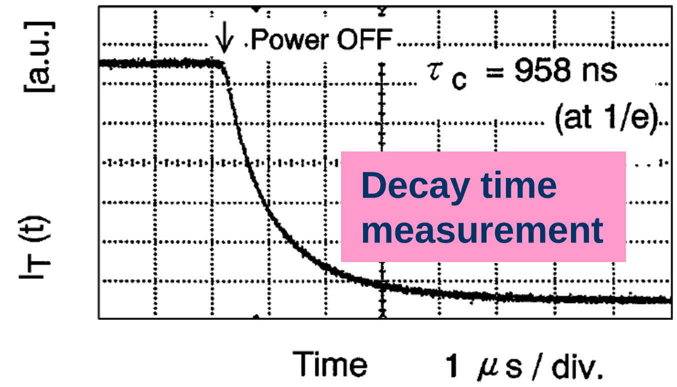
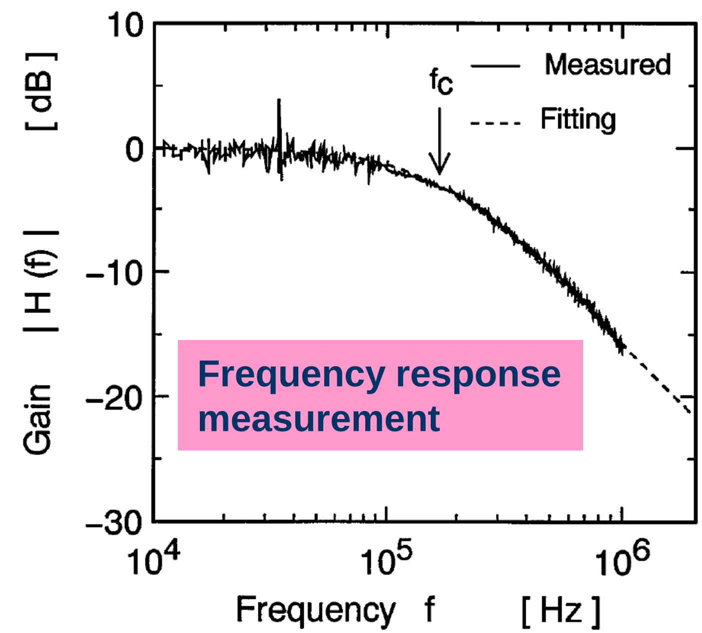


Fig. 1. Experimental setup of measurements of cavity decay time and response function of a Fabry–Perot cavity. A cw laser is frequency stabilized to the TEM_{00} longitudinal mode by the Pound–Drever–Hall technique. DBM, double-balanced mixer; PZT, piezoelectric transducer.

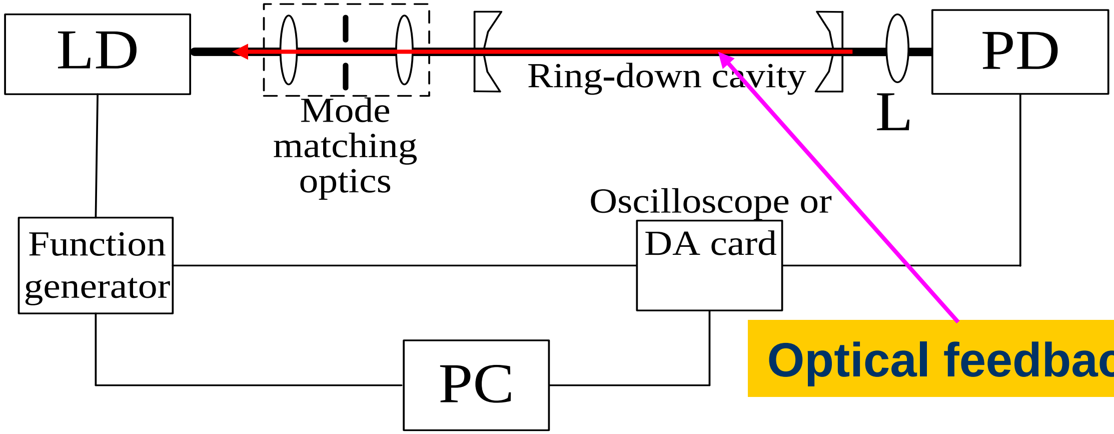




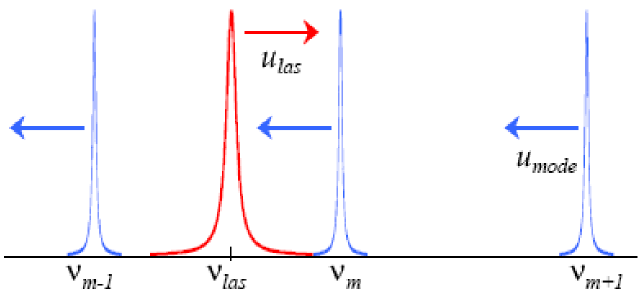
Single-frequency laser with frequency stabilized to F-P cavity Dual frequency modulation employed to generate FM sidebands

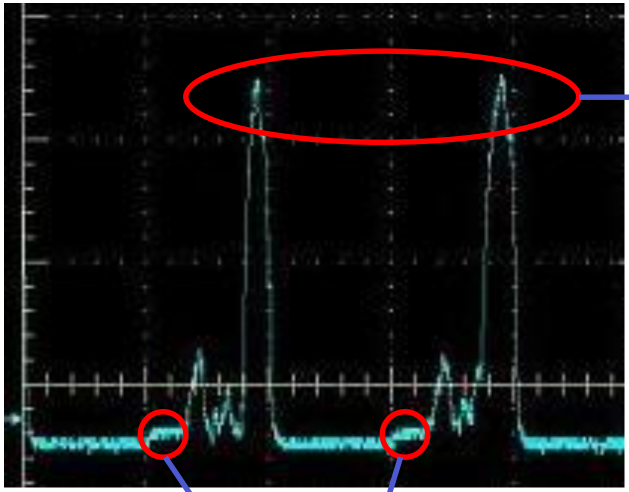
Optical feedback - CRD technique

Y Gong [IOE, CAS, China, Appl. Phys. B93, 355(2008)



Optical feedback





No resonance

Resonance peaks due to optical feedback are used to record CRD signals, results in strong SNR enhancement .

CRD signals recorded at negative edges of square-wave intensity modulation

Typical CRD configurations

- **Phase-shift CRD**

  Low coupling efficiency leads to limited measurement range

- **Continuous wave (cw) CRD**

  Optical switching, cavity length modulation or frequency modulation or frequency stabilization, and preset threshold are employed for CRD measurements

- **Optical feedback CRD**

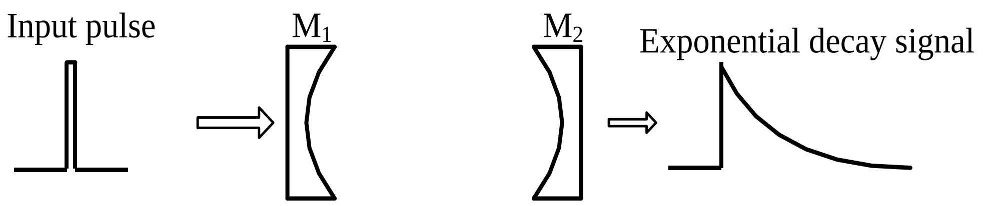
  improved coupling efficiency leads to higher SNR, therefore higher accuracy

- **Pulsed CRD**

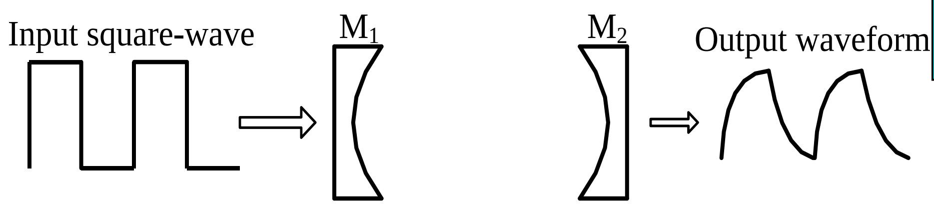
  simple, relatively high cost, limited measurement accuracy: ~10^{-5} - 10^{-6} (depends on beam quality)

Basic Principle of CRD

In CRD, the cavity decay time rather than the absolute intensity is measured, making the reflectance measurement independent of the power fluctuation of the light source.



$$I(t) \propto \exp(-t/\tau)$$



Time domain

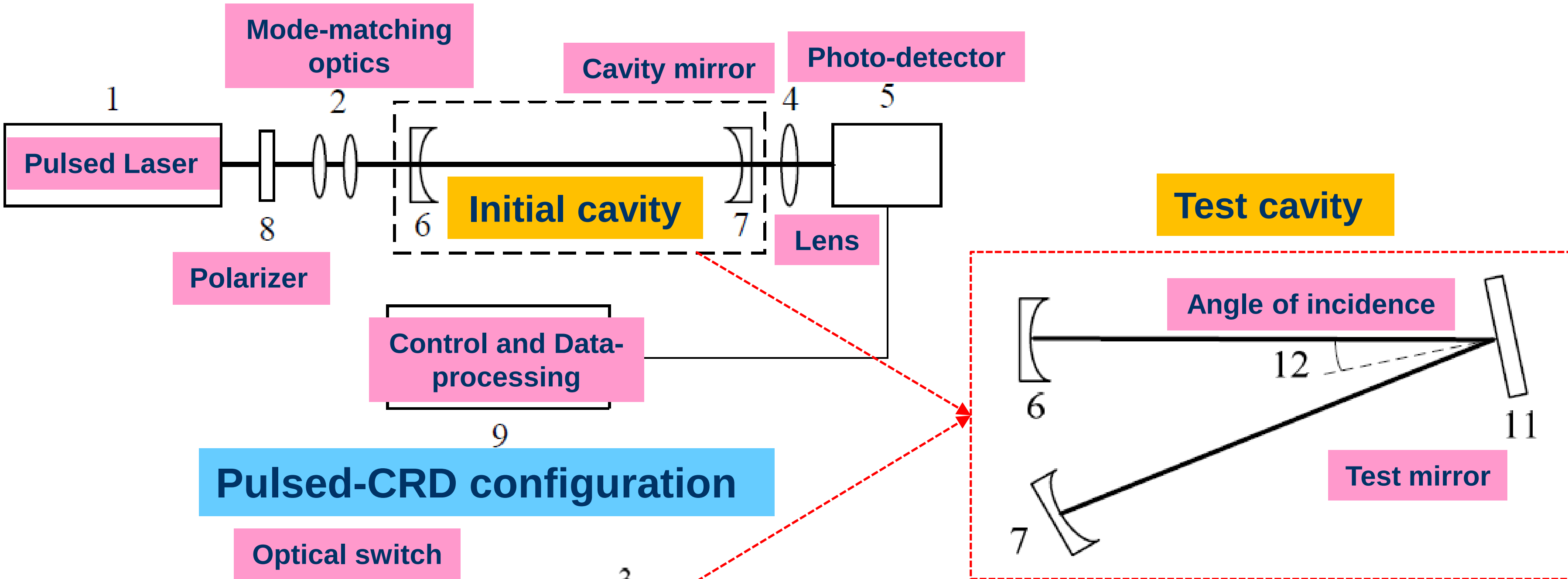
$$I_{CRD}(t) \propto \begin{cases} 1 - \dfrac{\exp(-t/\tau)}{1+\exp(-T/2\tau)} & \left(0, \frac{T}{2}\right) \\ \dfrac{\exp\left[\left(\frac{T}{2}-t\right)/\tau\right]}{1+\exp(-T/2\tau)} & \left(\frac{T}{2}, T\right) \end{cases}$$

Frequency domain

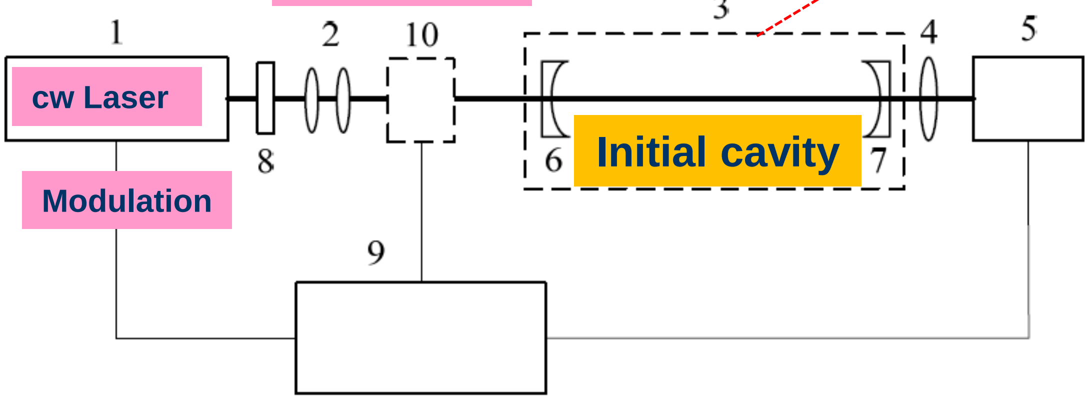
$$I_k(\omega) = \left(1 + k^2\omega^2\tau^2\right)^{-1/2}, \tan\phi_k(\omega) = -k\omega\tau$$

Key parameter: decay time constant

CRD Arrangement – *R* Measurement



Pulsed-CRD configuration



cw-CRD configuration

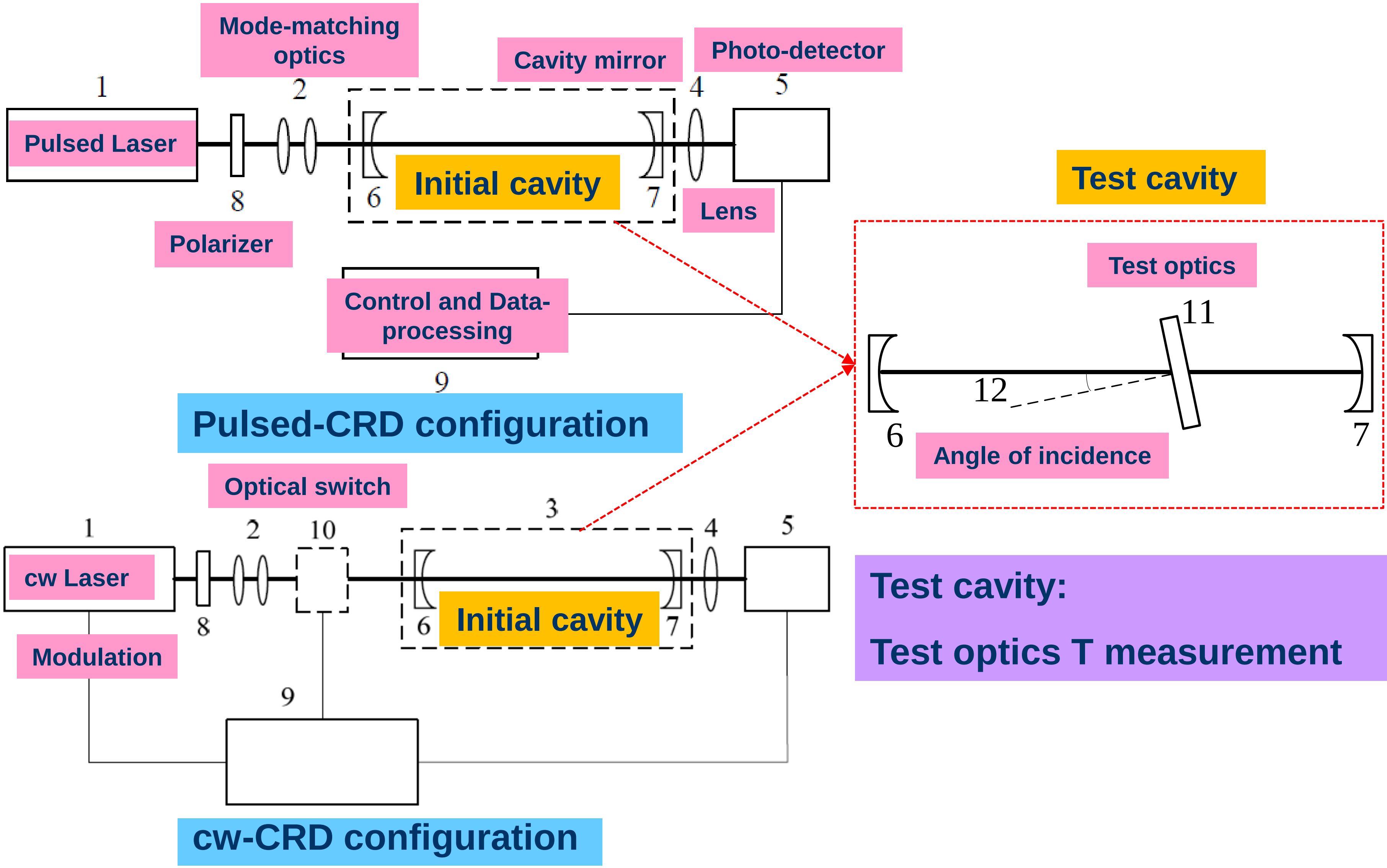
Initial cavity:

Cavity mirror R measurement

Test cavity:

Test mirror R measurement

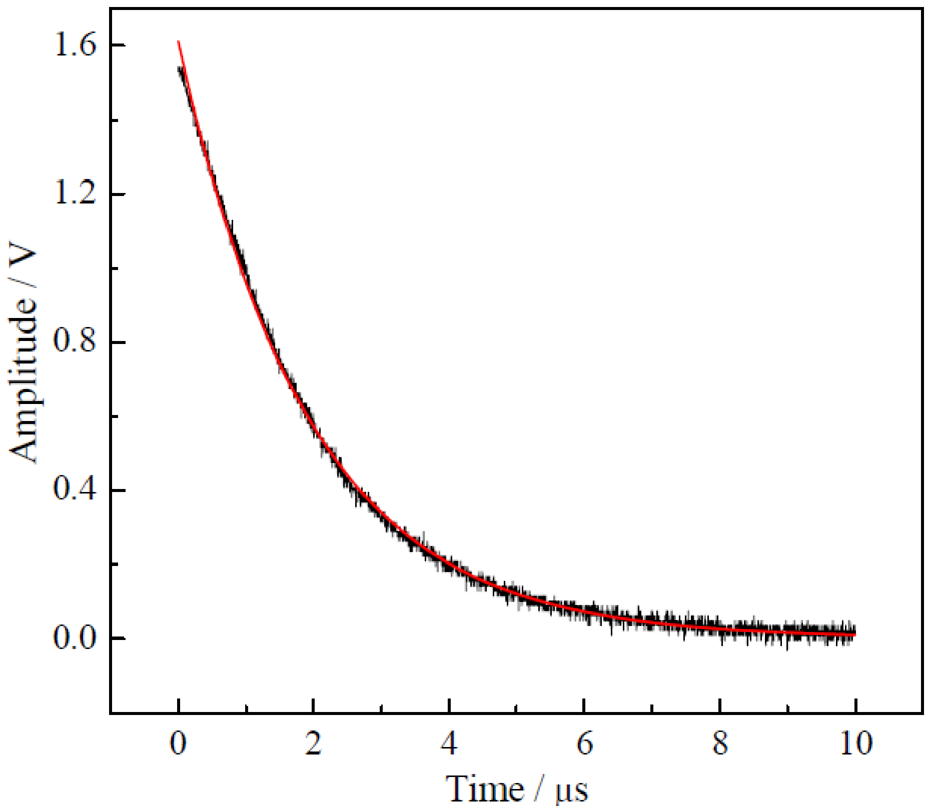
CRD Arrangement – *T* Measurement



Test cavity:

Test optics T measurement

CRD signal and R/T calculations



A typical CRD decay signal – single exponential function

Cavity mirror R:

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

***L_0*: Initial cavity length**

***τ_0*: Initial cavity decay time**

Test mirror R:

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

***L*: Test cavity length**

***τ*: Test cavity decay time**

Test optics T:

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

***n_s*: Refractive index of test optics**

***d*: Thickness of test optics**

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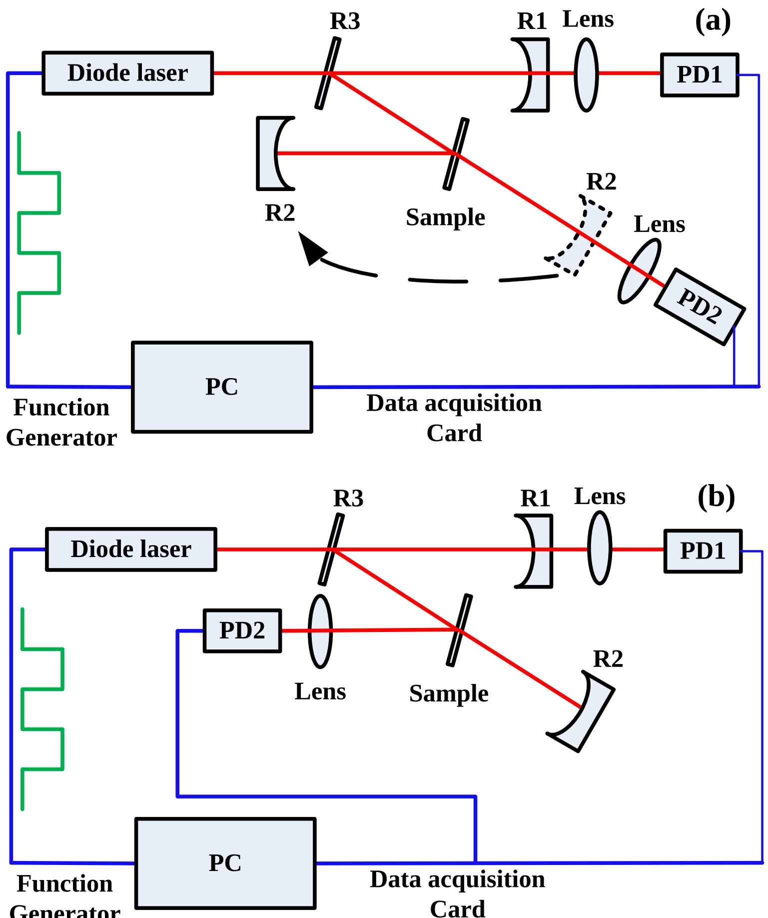
Recent Technical Development

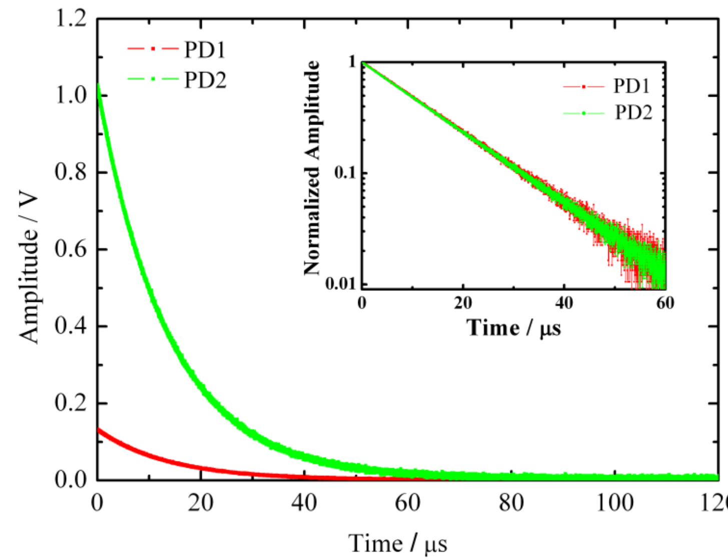
Simultaneous measurement/mapping of reflectance (*R*), transmittance (*T*) and optical loss (*K*)



Reflectance measurement

Transmittance measurement

Experimental Configuration



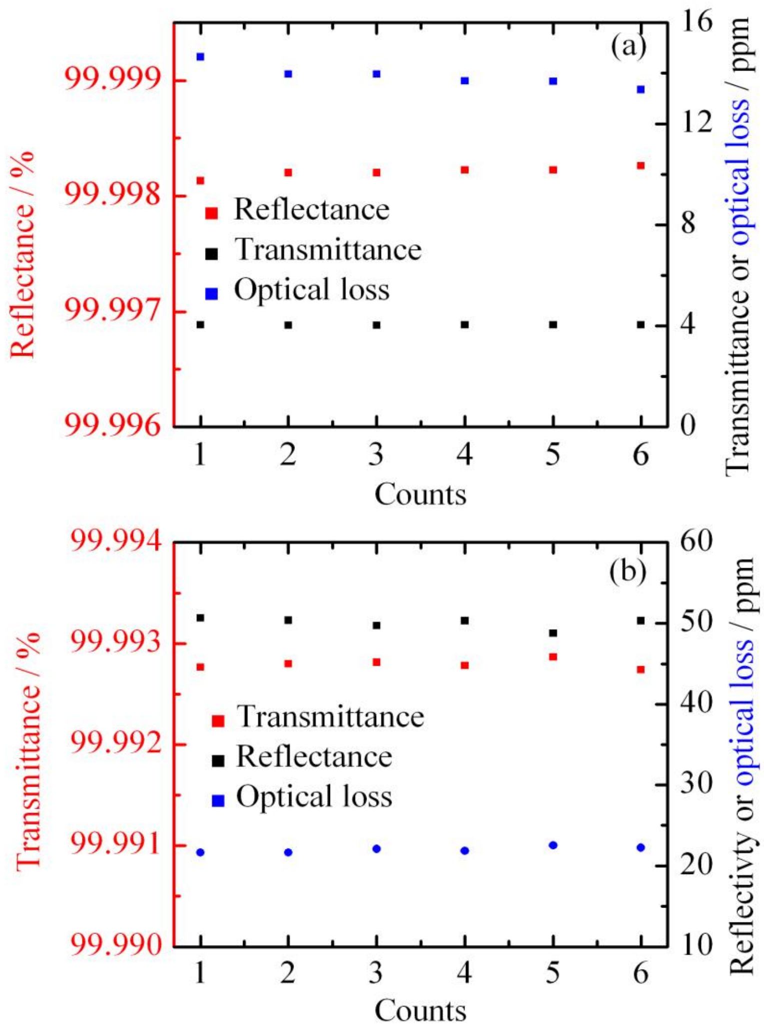
CRD signal

Ring-down time for high *R*/*T* determination;

Amplitude ratio for residual *T*/*R* determination

Optical loss $K = 1 - R - T$

Simultaneous measurements of *R*, *T*, and *K*



HR sample

R **= 99.99821%±0.4ppm**

T **= 4.042±0.008 ppm**

K **= 13.9±0.4 ppm**

sub-ppm precision

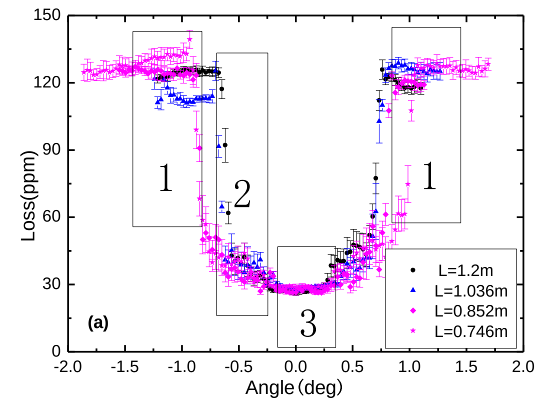
Important: Accurate determination of transmittance of output cavity mirror, which can be fulfilled with angle-resolved CRD technique

AR sample

T = 99.99279%±0.4ppm

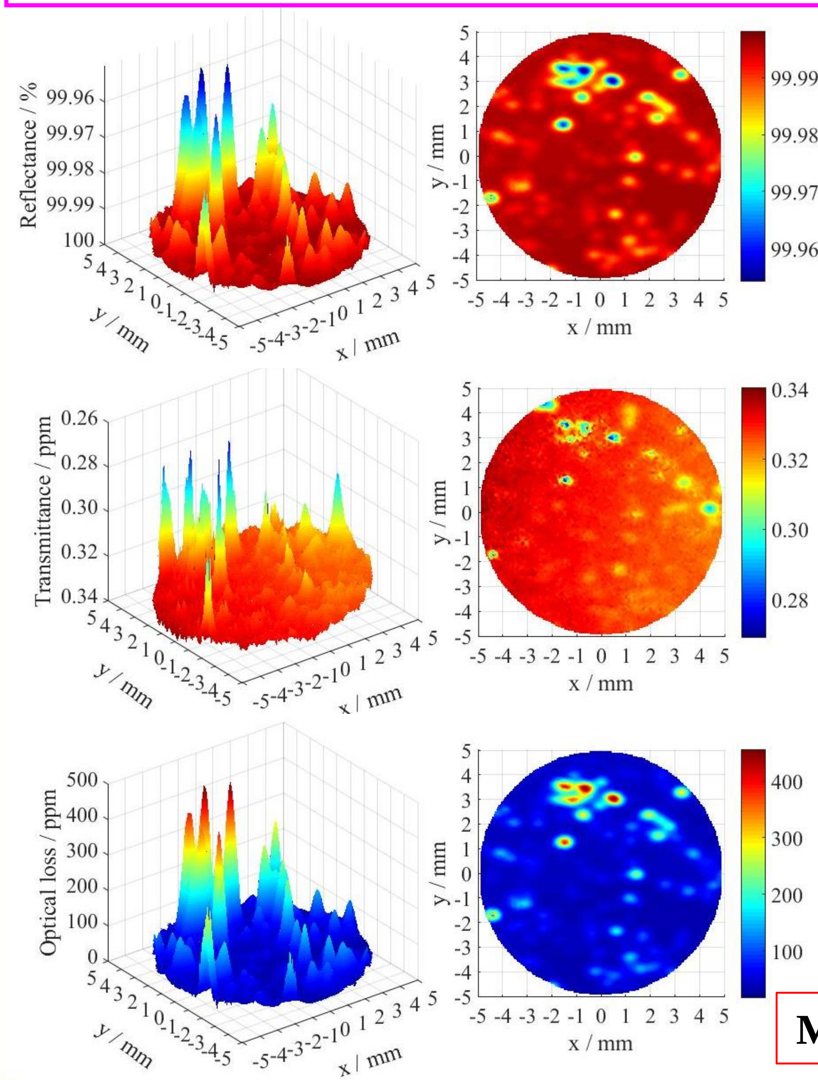
R = 50.0±0.7 ppm

K = 22.0±0.4 ppm



Opt. Express 22: 29135(2014)

Simultaneous mapping of *R*, *T*, and *K* (HR)

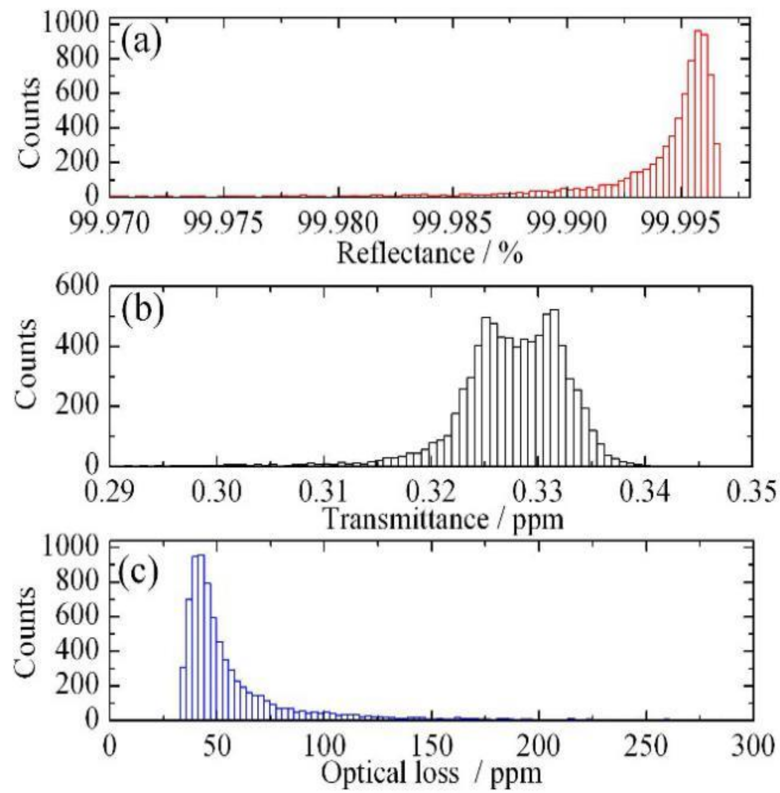


99.9936%
±0.0046%

0.327ppm
±0.005ppm

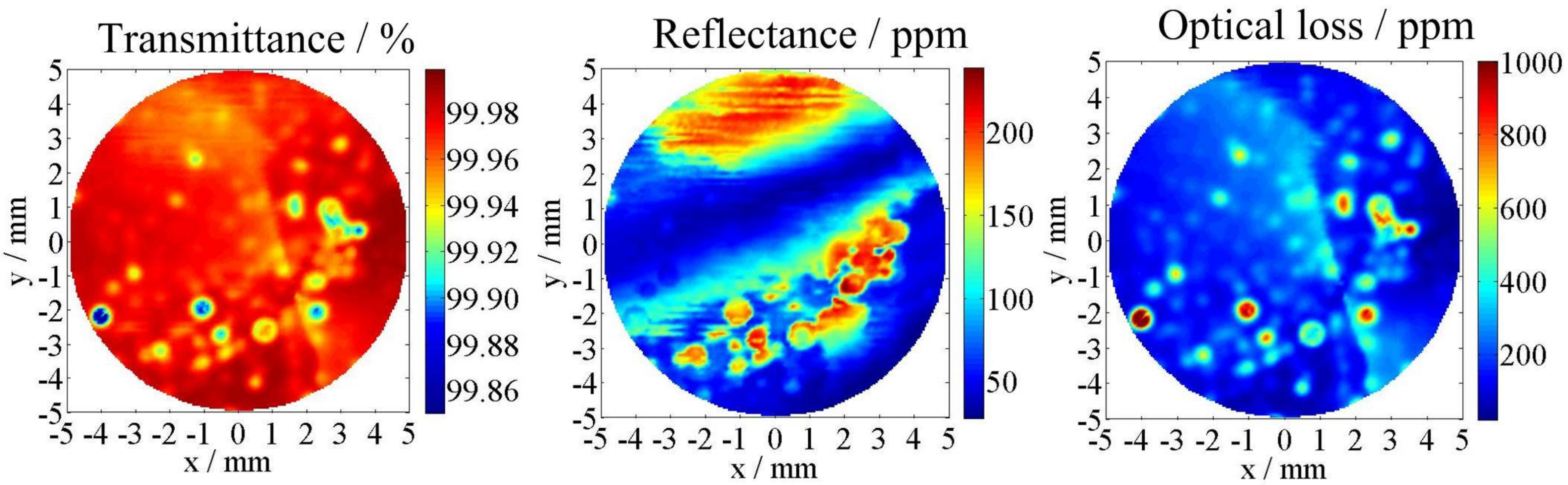
63.69ppm
±46.27ppm

Maps



Histograms

Simultaneous mapping of *R*, *T*, and *K* (AR)



T = 99.9704±0.0144%

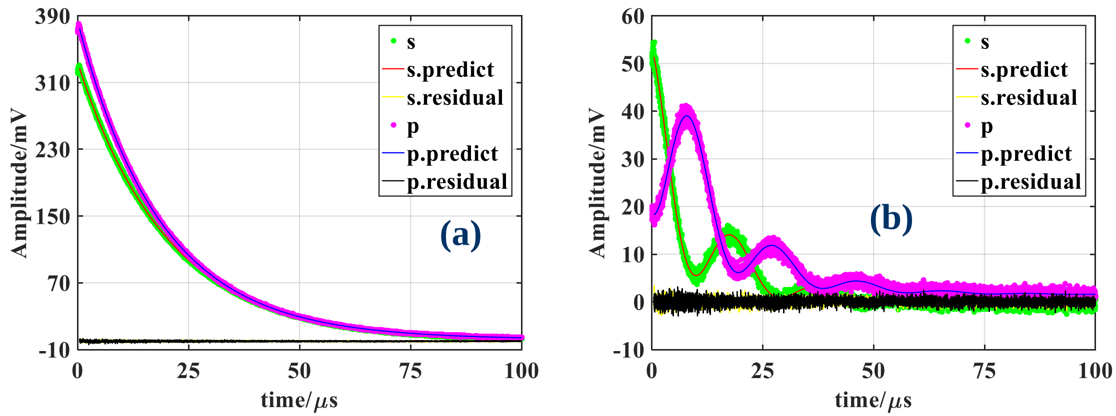
R = 92.1±51.4ppm

K = 203.7±119.7ppm

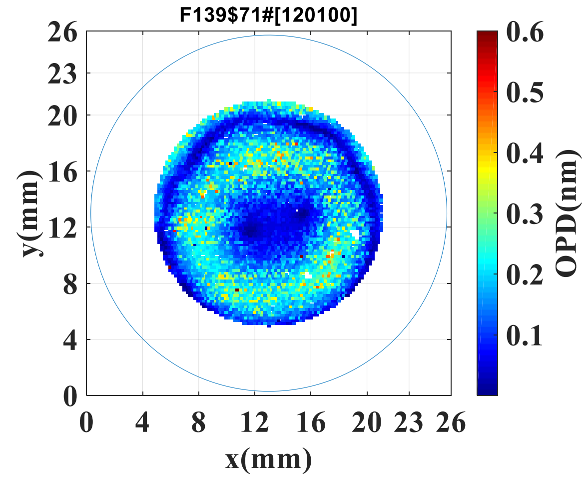
Simultaneous mapping of reflectance, transmittance and optical loss provides useful information on defect characterization and coating performance optimization of laser optics.

CRD for Stress Birefringence Measurement

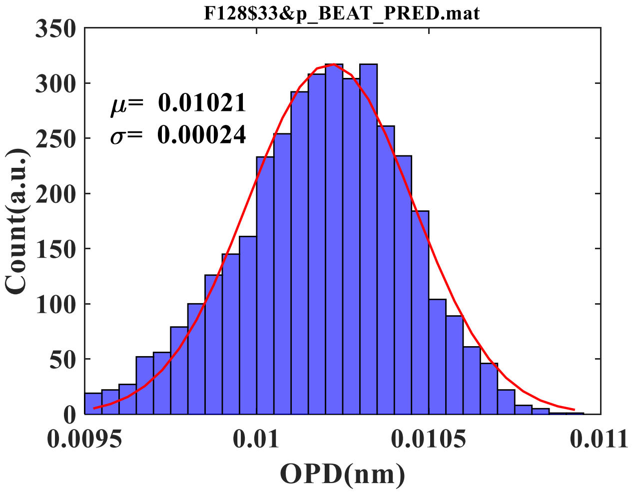
Sample: fused silica plate with thickness 2mm



Typical CRD signals：(a) empty cavity；(b) *OPD*= 0.0354nm



Stress Birefringence

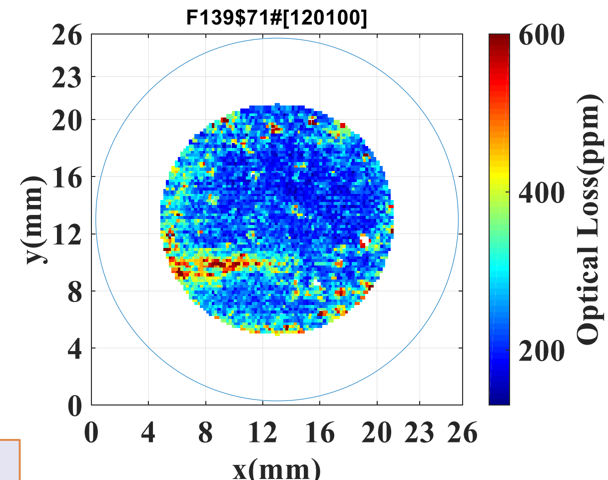


Repeatability:

$\sigma_{OPD}=2.4\times10^{-4}$ nm

$\sigma_{\delta}=2.38\times10^{-6}$ rad

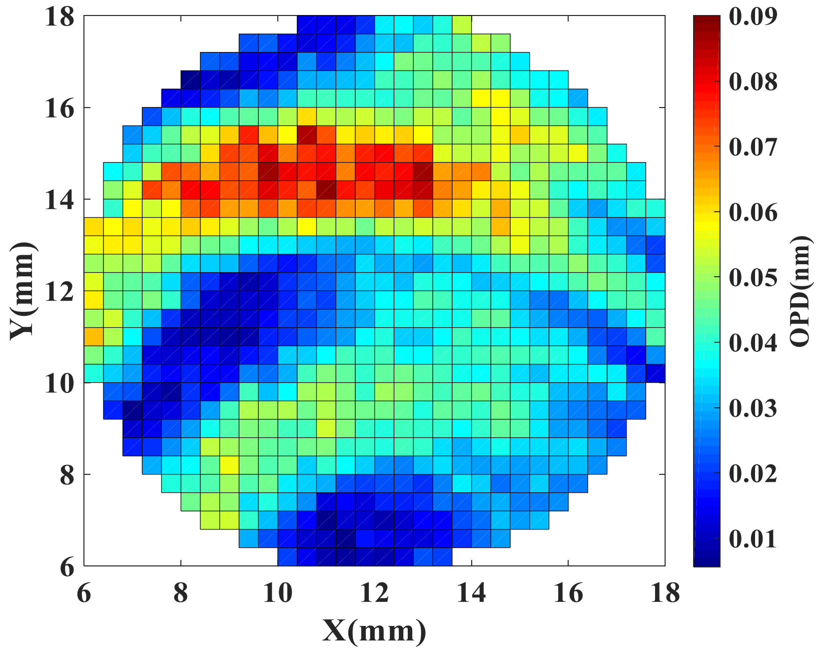
OPD: optical phase difference



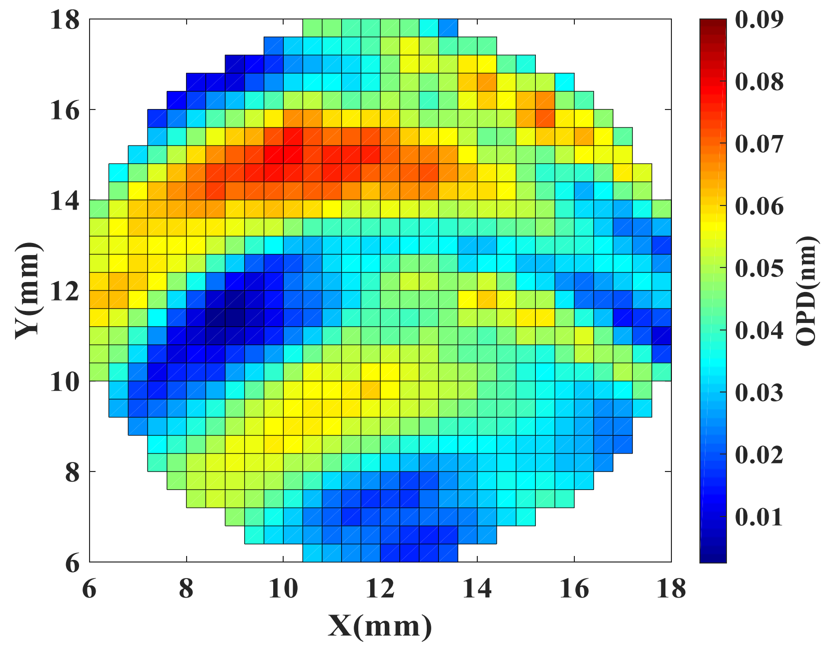
Optical Loss

Comparison

Sample: fused silica plate



(a) CRD birefringence map



(b) Hinds Exicor 300 birefringence map

The measurement sensitivity of CRD is over two orders of magnitude better than the commercial instruments for birefringence measurements

Outline

1. **Introduction**
2. **Principle of CRD for high reflectance/ transmittance measurements**
3. **Recent technical developments of CRD for characterization of laser optics**
4. **ISO 13142: CRD for high reflectance/ transmittance measurements (Standard)**
5. **CRD Instrumentation**
6. **Conclusions**

CRD Standardization

International Standard ISO 13142

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

ISO TC 172 / SC 9 / WG 1

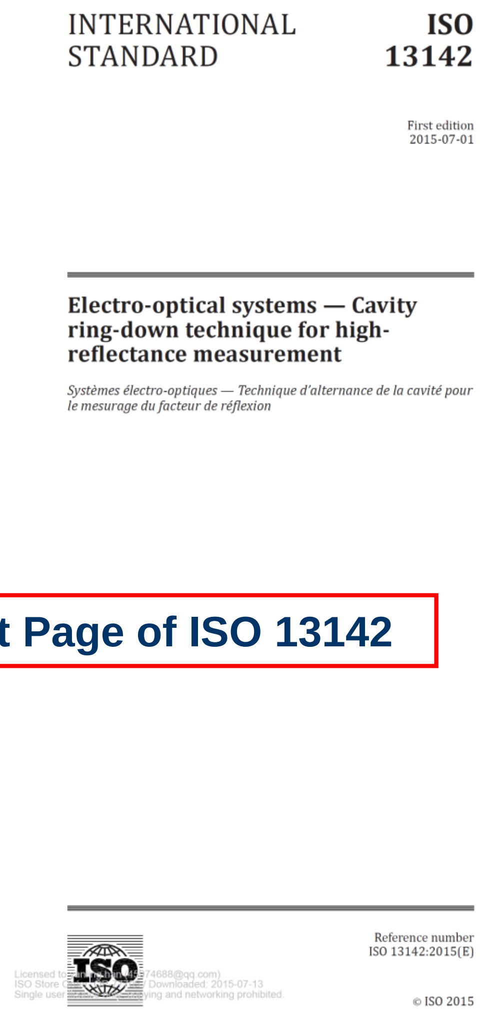
Project: CRD for high reflectance measurements

Project initialized: Nov. 2008

NWIP approved: Feb. 2012

Publish: June 2015

Revision approved: November 2018 (to include high transmittance measurement)



INTERNATIONAL STANDARD

ISO 13142

First edition
2015-07-01

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

Reference number
ISO 13142:2015(E)

First Page of ISO 13142

Typical CRD configurations recommended in ISO 13142

- **Pulsed CRD**

  Simple, relatively high cost, limited measurement accuracy

- **Continuous wave (cw) CRD**

  Experimentally complex due to the use of AOM (optical switching), PZT (cavity length modulation), etc.

- **Optical feedback CRD**

  Improved coupling efficiency leads to higher SNR, therefore higher accuracy

Remarks

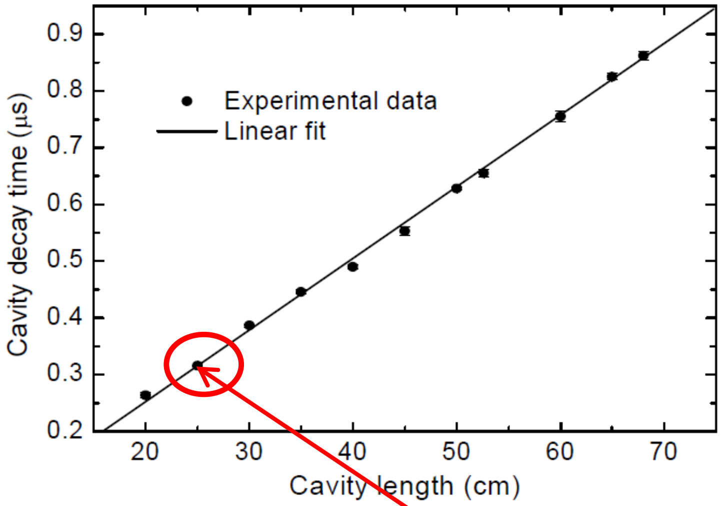
➢ Stable cavity condition is required to eliminate the impact of diffraction loss.

➢ Finite instrumental response time has to be taken into consideration (unless a fast detector is used)

➢ It is recommended to use the same cavity length for both initial cavity and test cavity to minimize environmental impact

➢ The measurement accuracy may be checked via the independence of the reflectance on the cavity length, or the linear dependence of the decay time on the cavity length.

Decay time versus cavity time



$$R = \exp(-1/ck)$$

Slope of the linear dependence of the decay time on the cavity length

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Key issues in CRD instrument development

1 Laser source

operation mode: pulsed or cw
pulse energy or output power (SNR)
pulse duration (with respect to round-trip time)
bandwidth: broad band or narrow band (power coupling)
beam quality: TEM_{00} or milti- modes (mode matching)

2 Cavity configuration

initial cavity: straight or folded (“V”)

3 Photo- detector

high response speed, high sensitivity, low noise

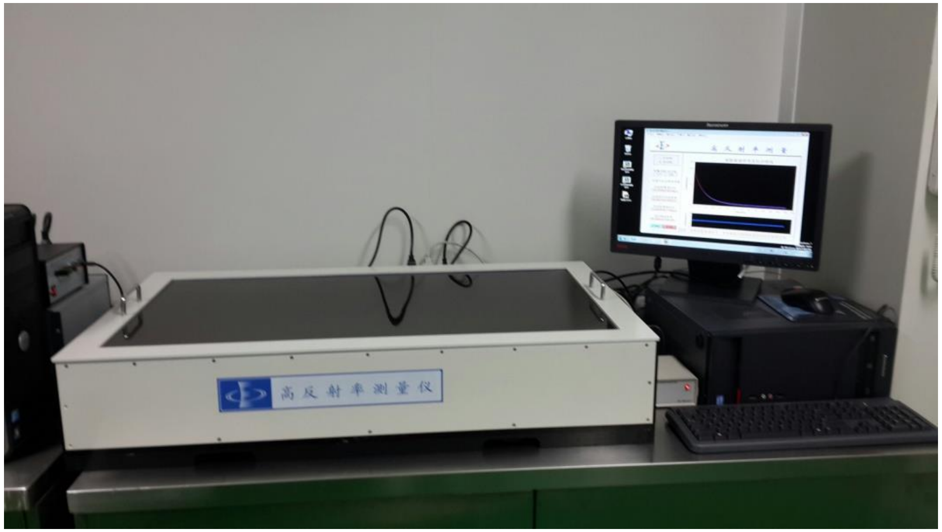
4 Instrumental response time

Effect of overall response time on CRD decay time determination

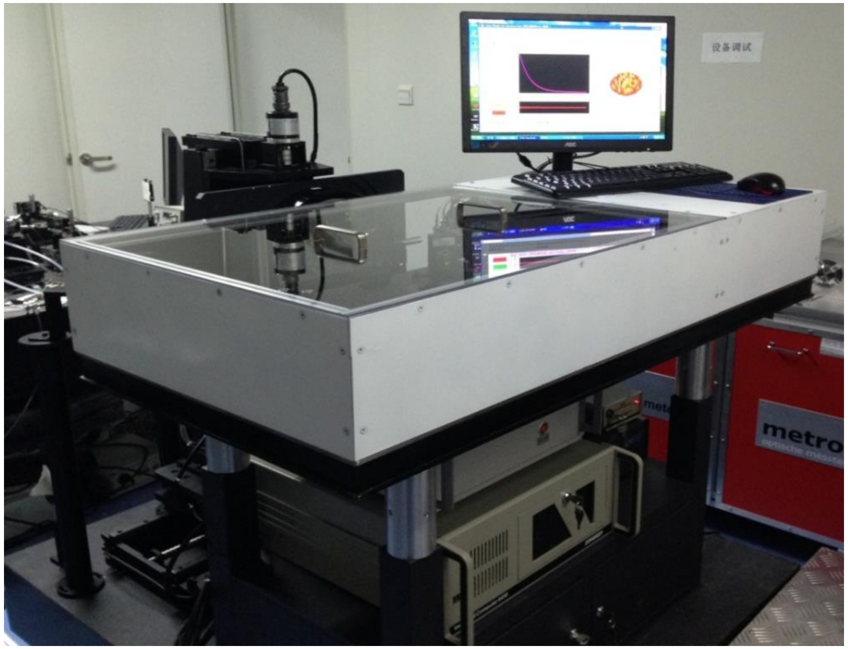
CRD Instrument Development

CRD Instrumentation

CRD instruments have been developed at several wavelengths for reflectance/transmittance measurements and mapping



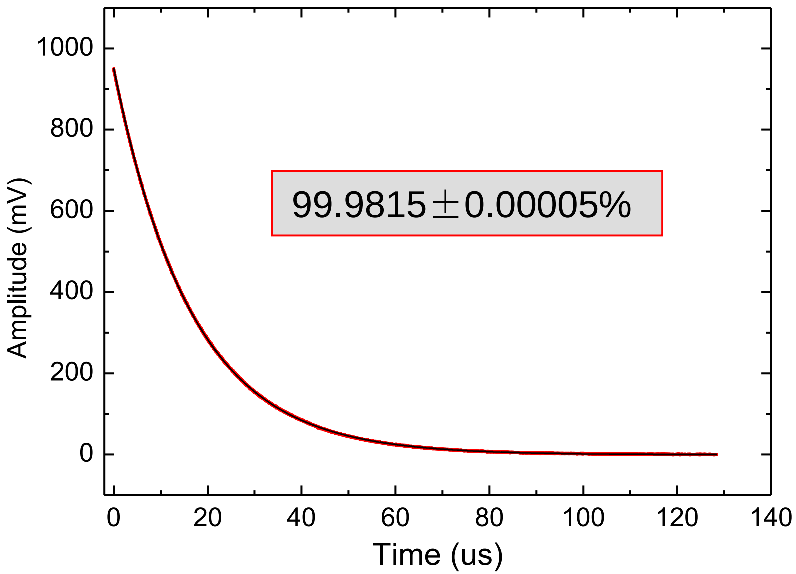
Developed CRD instrument at 635nm for reflectance/transmittance measurements of laser optics used in laser gyros.



Developed CRD instrument at 1064nm for reflectance mapping of large-aperture mirrors used in high-power laser systems

CRD Instrument Development

Instrument Performance



Typical CRD signal

Higher SNR in CRD signal and therefore higher measurement precision due to the use of patented optical feedback CRD technique.

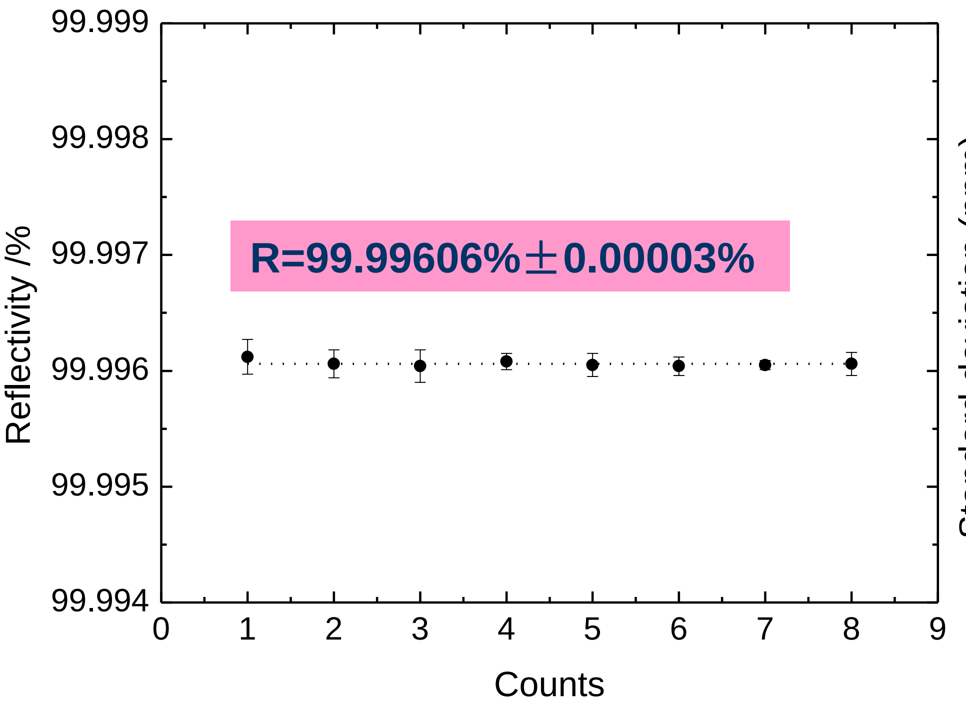
Key Function

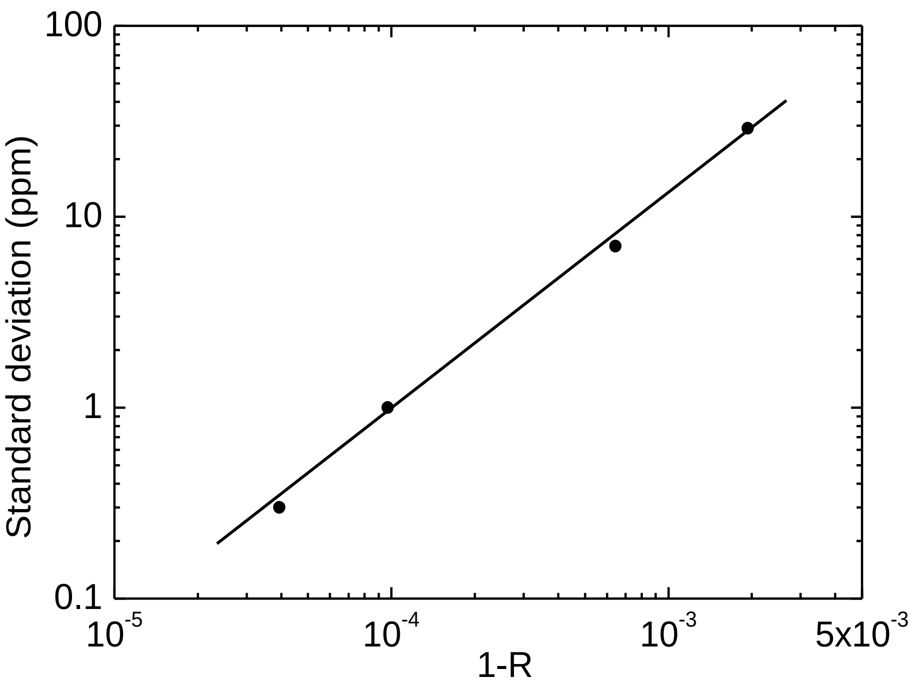
Separate or simultaneous high-precision measurements and/or mapping of reflectance, transmittance and optical loss of HR and AR laser optics

Key Specifications

R / T **range: 99.5% - 99.9999%**
Optical loss range: 0.5% - 0.0001%
Measurement sensitivity: <0.1ppm
Measurement repeatability: <1ppm
Sample size: up to diameter 500mm

HR measurement of cavity mirrors (1064nm)

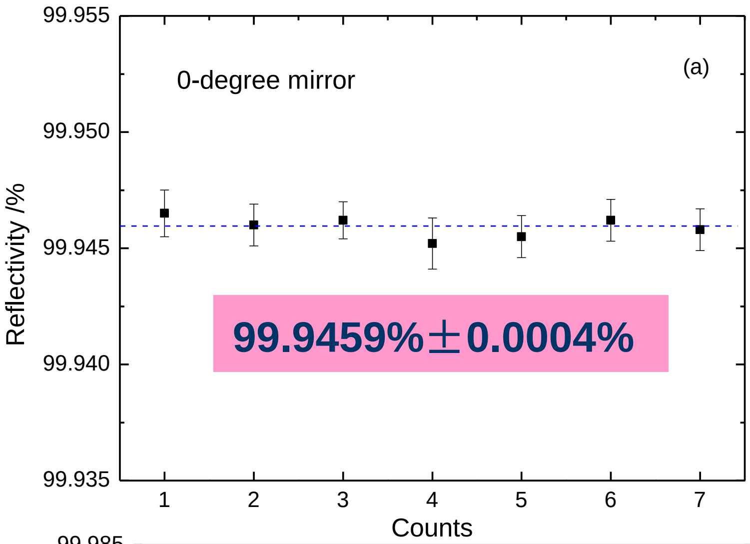


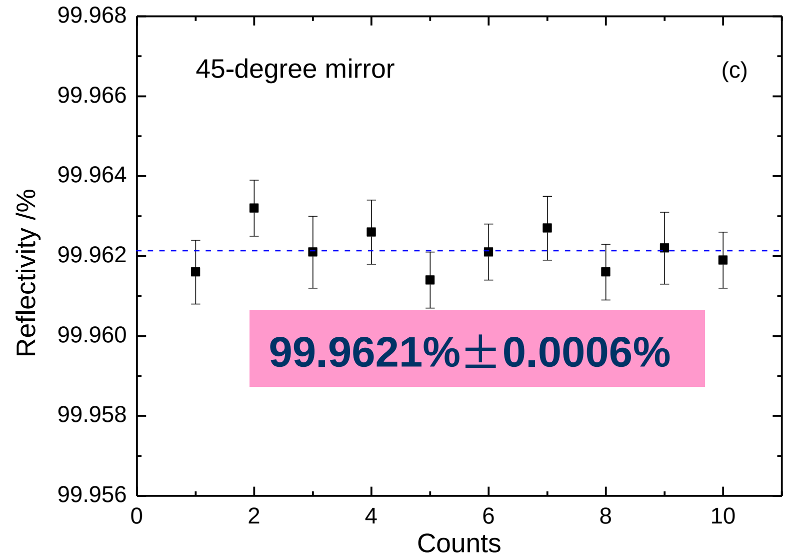


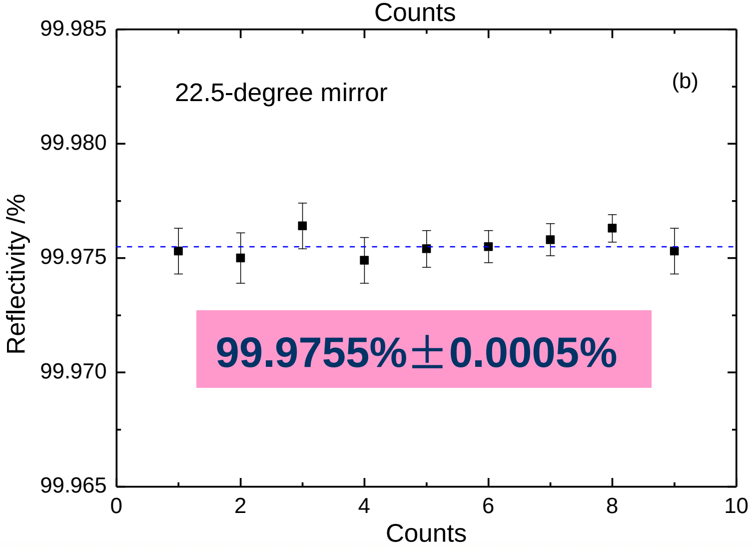
$$\left|\frac{\Delta R}{R}\right| = (1-R)\left(\left|\frac{\Delta L}{L}\right| + \left|\frac{\Delta \tau_1}{\tau_1}\right|\right)$$

For cavity mirrors with reflectance R > 99.99%, the measurement error is < 0.0001%, or 1ppm.

HR measurement of test mirrors (1064nm)







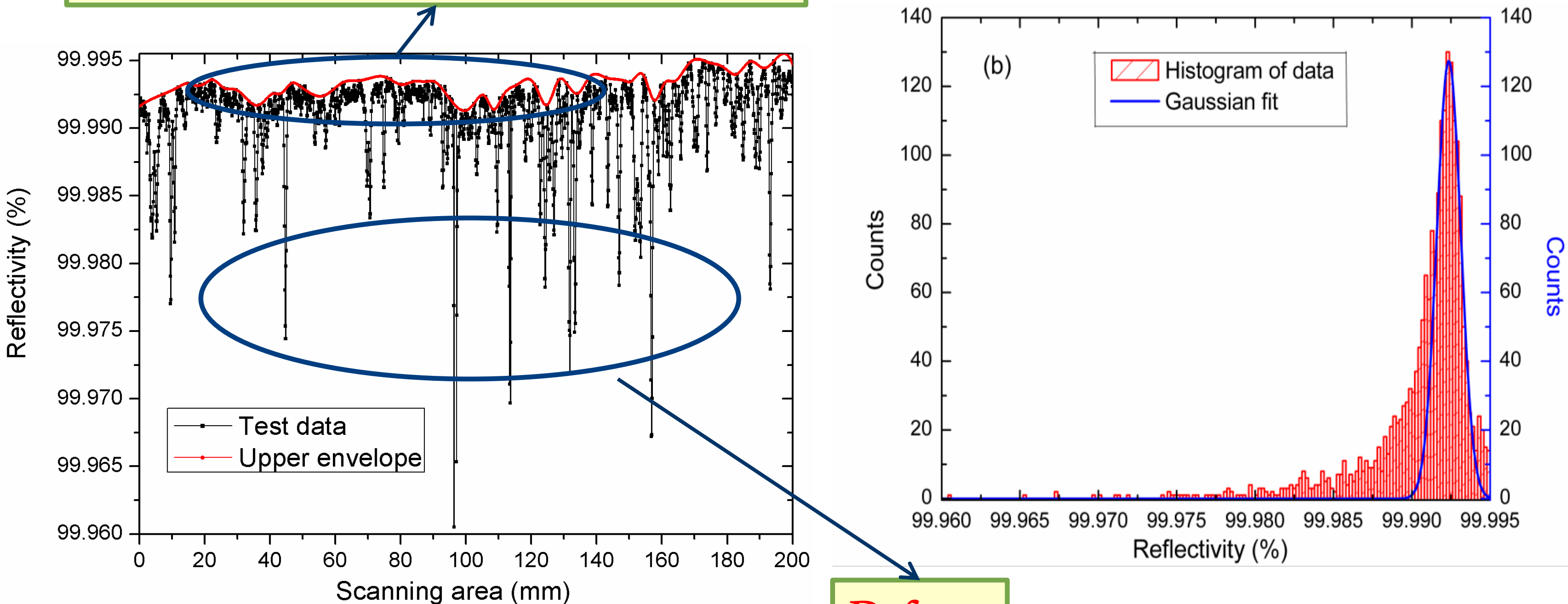
$$\left|\frac{\Delta R_3}{R_3}\right| = \left|\frac{\Delta R}{R}\right| + (1-RR_3)\left(\left|\frac{\Delta L}{L}\right| + \left|\frac{\Delta \tau_2}{\tau_2}\right|\right)$$

For test mirror R measurement, the first two numbers following the last "9" of the reflectance value can be always accurately determined.

Example: 1D scan of 200mm in length

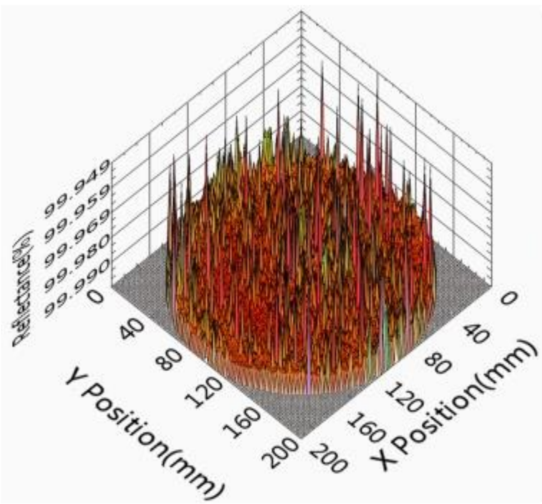
Sample: Diameter 240mm, AOI 22.5° for 1064nm
Scan step: 0.1mm

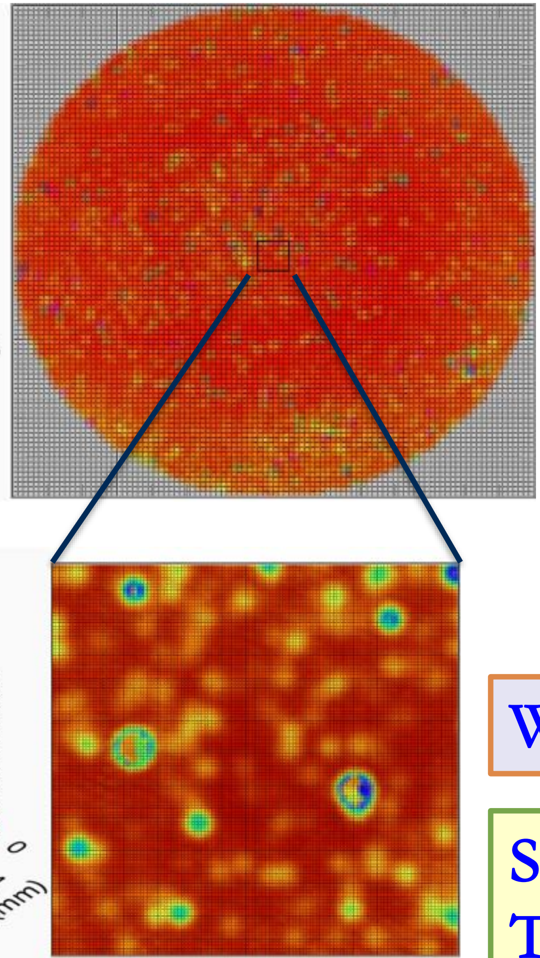
Non-uniformity caused by coating process

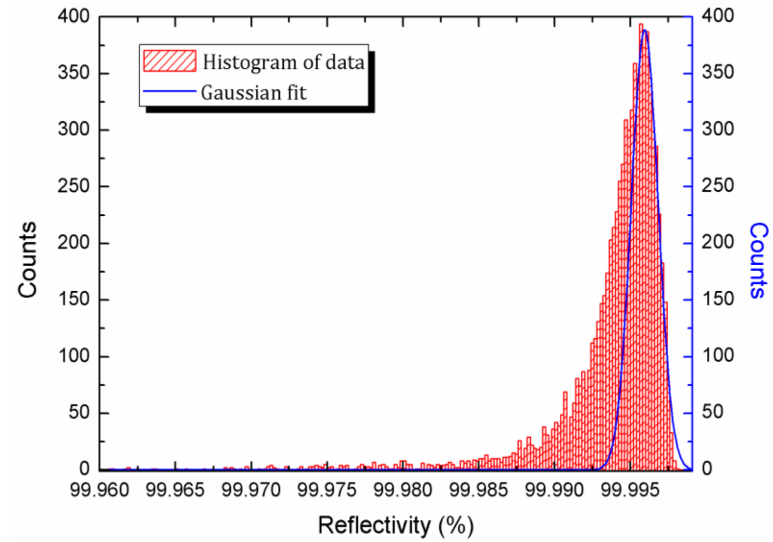


Defects

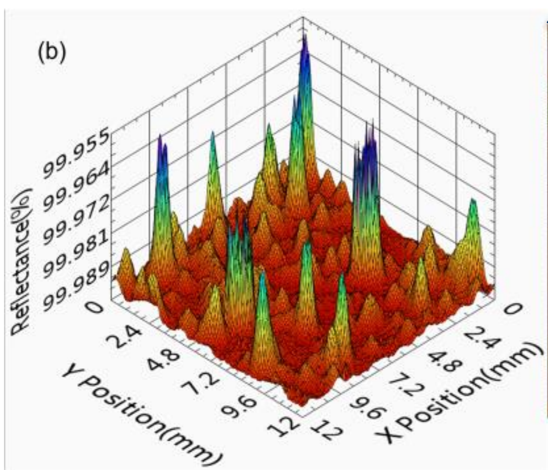
Example: 2D mapping area of 200mm in diameter







Histograms



Wavelength: 1064nm

Scan speed: 1145 points/hour
Time to finish： 408 minutes

Example: high-resolution mapping of small area

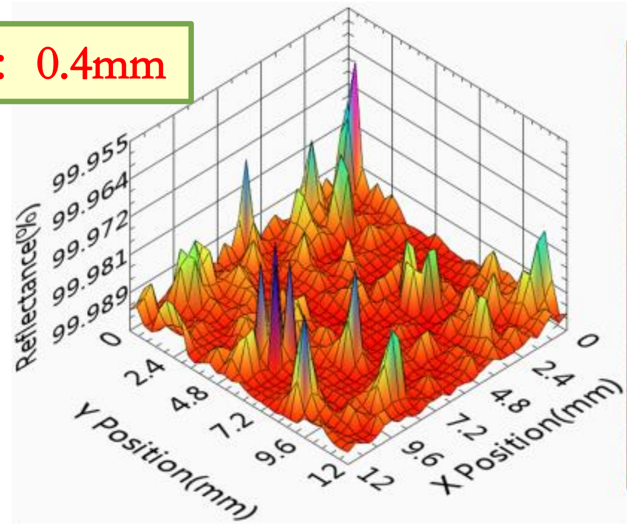
Scan area
12mm×12mm

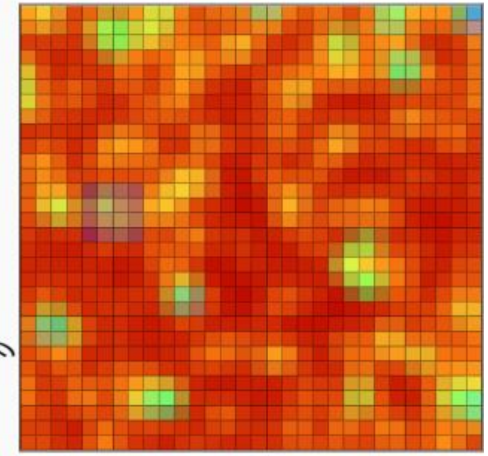
Beam diameter：
0.4mm

Spatial resolution is determined by beam diameter and scan step

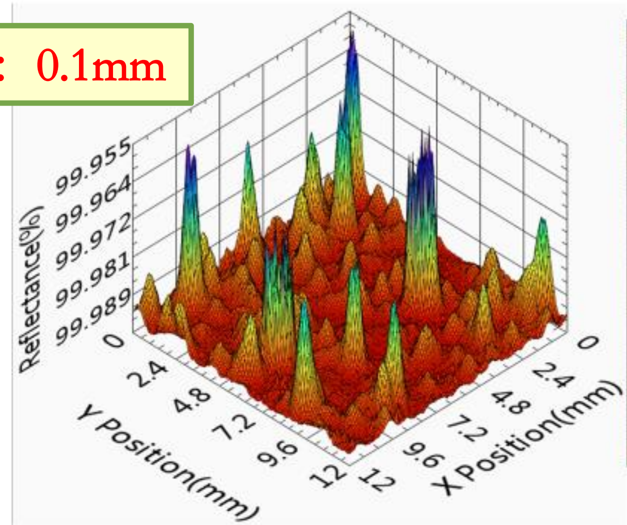
Spatial resolution could be improved by data processing

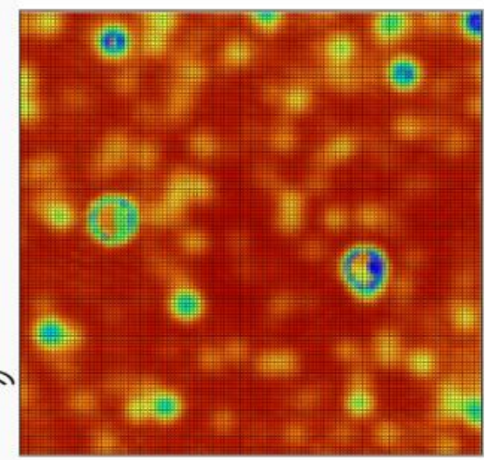
Scan Step： 0.4mm





Scan Step： 0.1mm





Wavelength: 1064nm

Conclusions

- CRD is the technique of choice for the measurements of reflectance/transmittance higher than 99.9%.
- CRD can measure and map simultaneously reflectance, transmittance, and optical loss of HR/AR laser optics with up to sub-ppm precision.
- Low-cost, easy-operation and nearly maintenance-free CRD instruments have been developed for high reflectance/transmittance/optical loss measurements and mapping, which provide useful information for defect characterization and performance optimization of laser optics.

References

[1] S. Xiao, B. Li, H. Cui, and J. Wang, Sensitive measurement of stress birefringence of fused silica substrates with cavity ring-down technique, Opt. Lett. 43(4):843(2018)

[2] Y. Han, B. Li, L. Gao, and S. Xiong, Reflectivity mapping of large-aperture mirrors with cavity ringdown technique, Appl. Opt. 56(4):C35(2017)

[3] H. Cui, B. Li, S. Xiao, Y. Han, J. Wang, C. Gao, and Y. Wang, Simultaneous mapping of reflectance, transmittance and optical loss of highly reflective and anti-reflective coatings with two-channel cavity ring-down technique, Opt. Express 25(5):5807(2017)

[4] B. Li, H. Cai, Y. Han, L. Gao, C. Gao, and Y. Wang, Simultaneous determination of optical loss, residual reflectance and transmittance of highly anti-reflective coatings with cavity ring down technique, Opt. Express 22(23): 29135(2014)

[5] H. Zu, B. Li, Y. Han, and L. Gao, Combined cavity ring-down and spectrophotometry for measuring reflectance of optical laser components, Opt. Express 21(22): 26735(2013)

[6] Z. Qu, B. Li, and Y. Han, Measuremnt of losses in optical components using filtered optical feedback cavity ring-down technique, Proc. SPIE 8206: 82061M(2012)

[7] Y. Gong, B. Li, and Y. Han, Optical feedback cavity ring-down technique for accurate measurement of ultra-high reflectivity, Appl. Phys. B 93: 355(2008)

[8] Y. Gong and B. Li, High reflectivity measurement with a broadband diode laser based cavity ring-down technique, Appl. Phys. B 88(3): 477(2007)

Thank you for your attention

Any suggestions or comments,

or need more technical details,

or interested in CRD instruments for your applications,

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