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Optics and photonics — Laser and laser-related equipment — Photothermal technique for absorption measurement and mapping of optical laser components

Optique et photonique — Lasers et équipements associés aux lasers — Technique photothermique pour le mesurage et la cartographie de l'absorption des composants laser optiques

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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~~www.iso.org/directives).

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

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~~www.iso.org/members.html.

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Introduction

With the rapid development of high-power/energy laser technology, laser-induced damage to optical laser components and laser-induced thermal distortion in laser components become the most important limiting factors for the operation and applications of high-power/energy laser systems. Normally, the laser-induced damages to optical laser components are caused by absorbing defects on the surface or within the laser components which result in thermal stress or melting of the laser components and lead to damage. The thermal distortions, which induce wavefront distortions and therefore beam quality deteriorations to the laser beam, are caused by non-uniform thermal expansion or refractive index change due to absorption irregularities (such as absorbing defects) inside the laser components. To improve the laser-induced damage threshold (LIDT) and reduce the laser-induced thermal distortion of laser components used in high-power/energy laser systems, there are needs not only to measure precisely the absorptance of the laser components, but also to detect various absorbing defects on/within the laser components, therefore to improve the performance of these laser components via optimizing fabrication/coating processes.

Currently, the ISO 11551 standardized testing method - laser calorimetry for absorptance measurements of optical laser components can only measure test samples with small sizes (normally less than 50 mm in diameter and 10 mm in thickness) and has almost no capability to measure the absorptance of large-sized laser components (100 mm in diameter and over) widely used in high-power/high-energy laser systems. In addition, laser calorimetry has only limited capability to map the absorptance distribution of an optical laser component.

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The measurement procedures in this document have been optimized to allow the mapping of absorbing defects of optical laser components and measurement of absolute absorptance of large-sized laser optics actually used in high-power/energy laser systems using photothermal techniques which provide absorption measurement/mapping with high sensitivity, high spatial resolution, and high reliability.

In addition to absorption measurement/mapping of optical laser components with photothermal amplitude, the photothermal phase measurement/mapping can also find applications in thermo-physical characterization of laser optics, which will be helpful for a better understanding of defect properties of laser optics and laser-defect interaction that would lead to a better understanding of laser-induced damage mechanism of laser optics.

Optics and photonics — Laser and laser-related equipment — Photothermal technique for absorption measurement and mapping of optical laser components

1 Scope

This document specifies procedures for the absorption measurement and high spatial-resolution two-dimensional or three-dimensional absorption mapping of optical laser components, and upon calibration, the measurement of absolute absorptance of laser optics.

The methods given in this document are intended to be used for the two-dimensional or three-dimensional absorption mapping of optical laser components, that is, measurement of absorption as a function of position, as well as absorption/absorptance measurement and mapping of laser optics used in high-power-/high-energy laser systems.

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.

<std>ISO 11145, *Optics and photonics — Lasers and laser-related equipment — Vocabulary and symbols*</std>

<std>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*</std>

<std>ISO 80000-7, *Quantities and units — Part 7: Light and radiation*</std>

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 terminologicalterminology databases for use in standardization at the following addresses:

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

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

3.1
absorption
radiant flux absorbed by the optical laser component

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3.2
absorptance
ratio of the radiant flux absorbed to the radiant flux of the incident radiation

3.3
absorption map
absorptance map
measured *absorption* (3.1)/*absorptance* (3.2) as a function of sample position

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Note 1 to entry: The definition of absorptance used for this document is limited to absorptance processes which convert the absorbed energy into heat. For certain types of optics and radiation, additional non-thermal processes may result in absorption losses which will not be detected by the test procedure described here.

4 Symbols used and units of measure

Table 1 — Symbols used and units of measure

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Symbol	Term	Unit
A	Absorptance of test sample	
A_0	Absorptance of calibration sample	
S	Photothermal amplitude of test sample	
S_0	Photothermal amplitude of calibration sample	
P, P_0	Pump laser power	W
ΔI, I_0	Probe beam intensity change and dc probe intensity detected in photothermal lensing	
I_1, I_2	Probe beam intensity detected by the two photo-detectors of a bi-cell photo-detector in photothermal deflection	
D	Thermal diffusion coefficient of test sample	m^2s^{-1}
$\Delta\varphi(x, y)$	Photothermally induced optical phase shift to probe beam	
α_{th}	Linear thermal expansion coefficient of test sample	K^{-1}
dn/dT	Temperature coefficient of refractive index of test sample	K^{-1}
ν	Poisson ratio of test sample	
f	Modulation frequency of pump laser power	Hz
μ_{th}	Thermal diffusion length of test sample	m
a	Pump beam radius in test sample	m
λ	Probe laser wavelength	m
z	Detection distance	m
$T(x, y, z)$	Photothermally induced temperature rise distribution inside test or calibration sample	K
B, C	Proportional coefficients	
β	Slope of linear fit of the measured absorptance dependence of the power-normalized photothermal amplitude of calibration samples	

5 Test method

5.1 Test principle

5.1.1 General

Based on photothermal effects, photothermal techniques are highly sensitive for the measurement of weak absorptance of optical laser components. In a typical photothermal experiment, a continuous-wave or highly repetitive pulsed excitation laser (pump laser) beam is used to irradiate the sample under test, heat is created within the sample due to optical absorption, and a temperature rise distribution within the sample is formed. For optical laser components, a displacement is induced on the sample surface due to thermal expansion, and a refractive index gradient is formed within the sample due to the temperature dependence of refractive index. By employing photothermal techniques to detect the surface displacement or refractive index gradient with a second probe laser beam, the absorptance (absorption) of the sample can be determined. The absolute absorptance can be obtained by calibrating the photothermal amplitude. By measuring the absorption/absorptance as a function of position, the absorption/absorptance map of a laser component is obtained.

Photothermal lensing (or thermal lens - TL) and photothermal deflection (PTD) are appropriate detection schemes for absorption measurement and mapping of optical laser components. Two detection schemes, both reflected and transmitted probe beam detections, can be used to measure the photothermal signal amplitude, which is linearly proportional to the absorption/absorptance of optical laser components under test when the photothermally induced optical phase shift to the probe beam is relatively small as compared to the probe beam wavelength (small signal approximation).

5.1.2 Photothermal lensing (TL)

In a typical TL scheme, an unfocused probe beam irradiates the pump laser-induced surface displacement zone or the refractive index gradient zone which acts as a negative (or positive) lens. The photothermal signal is represented by the intensity change at the centre of either the reflected probe beam (in surface TL – STL scheme) or the transmitted probe beam (in transmitted TL – TTL scheme). This probe beam intensity change can be detected by a pinhole photodetector (a photodetector with a pinhole in front of it).

5.1.3 Photothermal deflection (PTD)

In a typical PTD scheme, a tightly focused probe beam irradiates the pump laser-induced surface displacement zone or the refractive index gradient zone, the reflected probe beam is deflected due to the slope of the surface displacement in a reflected PTD configuration, or the transmitted probe beam is deflected due to the refractive index gradient in a transmitted PTD configuration. The photothermal signal is represented by the probe beam deflection, which can be easily detected by a position-sensitive photodetector (for example, a bi-cell photodetector).

5.1.4 Rules for selecting reflected and transmitted photothermal detection schemes

Selecting between the reflected or transmitted photothermal detection schemes (both TL and PTD) should be considered as follows. As a general rule, the detection scheme with a higher detection sensitivity should be selected for more sensitive and precise absorption measurement. For an optical laser component with a (much) larger linear thermal expansion coefficient so that the photothermally induced optical phase shift to the probe beam by the thermal expansion caused surface displacement is large, a reflected photothermal detection scheme is preferable. On the other hand, a transmitted photothermal detection scheme should be selected if the temperature coefficient of refractive index of the component is much larger so that the optical phase shift to the probe beam caused by the temperature rise induced refractive index change is much larger than that caused by the surface displacement.

However, if the sample under test is opaque to the probe beam, the reflected photothermal detection scheme should be selected.

For photothermal absorption measurement of bulk samples and separation of surface absorption and bulk absorption, the transmitted photothermal detection scheme is preferable. The reflected photothermal detection scheme may be used for measurement of bulk samples only when the bulk sample is homogeneous and has negligible surface absorption.

5.2 Measurement arrangement and test equipment

5.2.1 Photothermal detection arrangement

There are four photothermal detection arrangements that may be used to measure and map the absorption of optical laser components. That is, surface thermal lens (STL), transmitted thermal lens (TTL), reflected photothermal deflection (or photothermal displacement) (reflected PTD), and transmitted photothermal deflection (transmitted PTD).

Figures 1 to 4 show typical experimental arrangements for the STL, TTL, reflected PTD, and transmitted PTD detection schemes, respectively.

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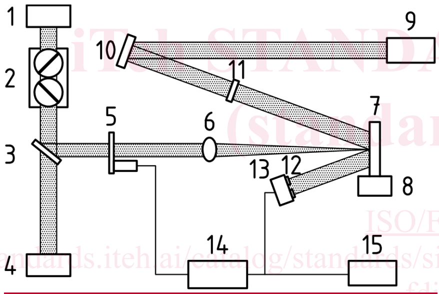

Key

1	pump laser	9	probe laser
2	variable attenuator for pump beam	10	mirror
3	beam-splitter	11	attenuator for probe beam
4	power meter	12	pinhole
5	mechanical chopper	13	photo-detector
6	lens	14	lock-in amplifier
7	sample under test	15	oscilloscope
8	translation stage		

Figure 1 — Typical experimental arrangement for the STL detection scheme

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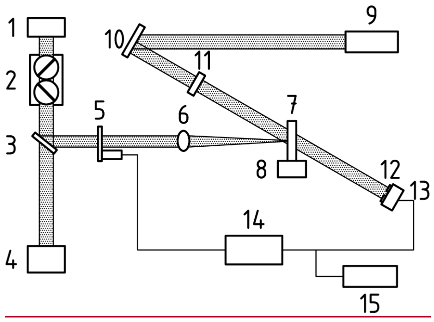

Key

1	pump laser	9	probe laser
2	variable attenuator for pump beam	10	mirror
3	beam-splitter	11	attenuator for probe beam
4	power meter	12	pinhole
5	mechanical chopper	13	photo-detector
6	lens	14	lock-in amplifier
7	sample under test	15	oscilloscope
8	translation stage		

Figure 2 — Typical experimental arrangement for the transmitted TL detection scheme

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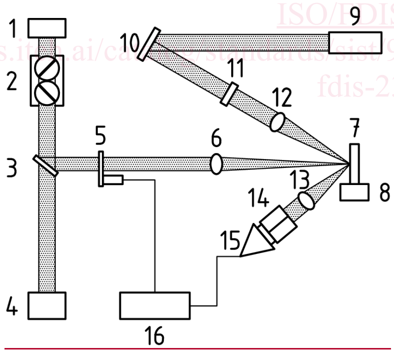

Key

1	pump laser	9	probe laser
2	variable attenuator for pump beam	10	mirror
3	beam-splitter	11	attenuator for probe beam
4	power meter	12, 13	lens
5	mechanical chopper	14	bi-cell photo-detector
6	lens	15	differential amplifier
7	sample under test	16	lock-in amplifier
8	translation stage		

Figure 3 — Typical experimental arrangement for the reflected PTD detection scheme

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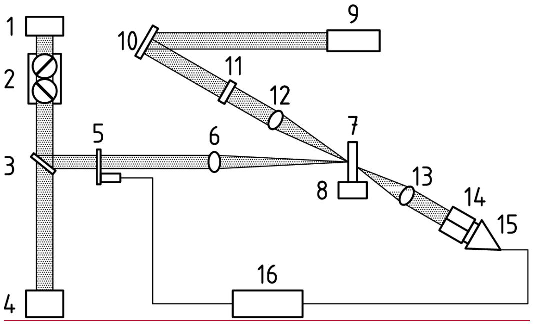

Key

1	pump laser	9	probe laser
2	variable attenuator for pump beam	10	mirror
3	beam-splitter	11	attenuator for probe beam
4	power meter	12, 13	lens
5	mechanical chopper	14	bi-cell photo-detector
6	lens	15	differential amplifier
7	sample under test	16	lock-in amplifier
8	translation stage		

Figure 4 — Typical experimental arrangement for the transmitted PTD detection scheme

5.2.2 Pump laser

The pump laser is a continuous-wave or highly repetitive pulsed laser used to heat the test sample. 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 acceptable for these three quantities, any combination of the wavelength, angle of incidence and state of polarization may be chosen within these ranges.

The (average) power of the pump laser should be sufficiently high so that the surface displacement or refractive index gradient created by the pump beam absorption of the test sample is highly detectable. The pump laser power should be adjustable via a variable attenuator which should not create any change to the beam profile of the pump beam during power adjustment. The pump beam profile shall be the same at all times, during the calibration and during the photothermal measurement at each adjusted power. The pump laser power is periodically modulated by a mechanical chopper or an acoustic-optic modulator. The modulation frequency is selected for optimal signal-to-noise ratio (SNR) of the photothermal signal.

For absorption mapping performed longer than several minutes, the power stability of the pump laser shall be monitored by a power meter or photo-detector as shown in Figures 1 to 4, and if needed its influence on the absorption mapping shall be eliminated by normalizing the photothermal amplitude with the monitored output power.

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The pump beam is focused into the test sample to create enough temperature rise inside the test sample. The beam size of the pump beam on/inside the test sample is optimized taking into account the SNR of