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# Lasers and laser-related equipment — Test method for angle resolved scattering

*Lasers et équipements associés aux lasers — Méthodes d'essai pour déterminer la dispersion avec résolution angulaire*

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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*.

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# Introduction

In 2004, increasing demands from industry for qualified angle resolved scattering (ARS) measurements led to a discussion note to start activities for a completely new standard on ARS measurements of optical components in SC 9/WG 6, which was later discussed again in 2008. This new attempt was in particular driven by, but not limited to, the development of optical components for the deep ultraviolet spectral region, where scatter losses by material and surface imperfections cause critical limitations. It was then agreed to support the development of a new working draft.

Since then, there has been an increased interest in a standard procedure that is easy to apply for practical applications ranging from high-end surfaces, coatings, and materials, structured components like diffraction gratings, to radiation shaping elements like display foils and diffusors used at wavelengths ranging from the EUV and DUV to the IR spectral regions.

Two standards exist that describe measurements of angle resolved scattering:

— ASTM E 2387-19[15];

— SEMI ME 1392-0116[16].

Another related document is ISO 13696 which describes procedures to measure the Total Scattering (TS) of optical components.

Radiation scattering caused by imperfections of optical components can critically affect the performance of optical systems. Radiation scattered into large angles usually means a loss of radiant power and thus reduced throughput. Radiation scattered into smaller angles can lead to image degradation. Knowledge of the angular distribution of scattered radiation is thus essential in order to assess the quality of optical components.

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This standard describes a testing procedure for the corresponding quantity, the angle resolved scattering (ARS), which is defined by the measured scattered intensity (scattered radiant power normalized to incident radiant power and solid angle of detection) as a function of the scattering angles.

Angle resolved scattering data can be used as input for stray-radiation calculations in optical design software. Other information like the Total Scattering (defined in ISO 13696) or other integrated scattering quantities can be derived from angle resolved scattering by numerical integration. In addition, although not covered in this document, analysing angle resolved scattering can provide information about the origins of scattering such as interface roughness, particles, defects, sub-surface damage, and bulk inhomogeneities.

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# Lasers and laser-related equipment — Test method for angle resolved scattering

## 1 Scope

This document describes procedures for the determination of the angle resolved scattering by optical components such as coated or uncoated optical elements, photonic structures, and materials that can be transparent, translucent, or opaque. It comprises scattering into the scattering sphere around the specimen usually separated into the backward and forward hemispheres. The procedures apply to wavelengths of radiation ranging from 5 nm in the extreme ultraviolet to 15 µm in the infrared spectral ranges.

## 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*

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## 3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 11145 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**
**scattered radiation**
fraction of the incident radiation that is deflected from the specular optical path

[SOURCE: ISO 13696:2002, 3.1.1]

**3.2**
**detector solid angle**
$\Delta\Omega_s$
solid angle of the detector aperture with respect to the origin of coordinates

**3.3**
**angle resolved scattering**
**ARS**
radiant power $\Delta P_s$ scattered into a direction ($\theta_s$, $\phi_s$) relative to the incident radiant power $P_i$ and the *detector solid angle* (3.2) $\Delta\Omega_s$:

$$\tilde{f}(\theta_s,\phi_s)=\frac{\Delta P_s(\theta_s,\phi_s)}{P_i\Delta\Omega_s}$$

Note 1 to entry: ARS can be transformed into the bidirectional reflectance, transmittance, or scattering distribution function, BRDF, BTDF, or BSDF $(f_\mathrm{r})$ respectively, by dividing ARS by $\cos\theta_\mathrm{s}$:

$$f_\mathrm{r}(\theta_\mathrm{s},\phi_\mathrm{s})=\frac{\tilde{f}(\theta_\mathrm{s},\phi_\mathrm{s})}{\cos\theta_\mathrm{s}}$$

Note 2 to entry: The total scattering[1] defined in ISO 13696 can be derived from ARS through numerical integration within the corresponding scattering hemispheres. For normal incidence and reflective scattering, the integral is:

$$\sigma_\mathrm{TS}=\int_0^{2\pi}\int_{\leq 2^\circ}^{\geq 85^\circ}\tilde{f}(\theta_\mathrm{s},\phi_\mathrm{s})\sin\theta_\mathrm{s}\,\mathrm{d}\theta_\mathrm{s}\,\mathrm{d}\phi_\mathrm{s}$$

### 3.4

**diffuse reflectance standard**

diffuse reflector with known, preferably Lambertian, *ARS* (3.3)

### 3.5

**instrument signature**

intrinsic contribution to measured *ARS* (3.3) produced by the instrument itself, usually estimated by measuring *ARS* (3.3) without any specimen

## 4 Symbols and abbreviated terms

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| | |
|---|---|
| $\tilde{f}$ | angle resolved scattering, ARS |
| $\Delta\Omega_\mathrm{s}$ | detector solid angle |
| $\Delta P_\mathrm{s}$ | scattered radiant power |
| $P_\mathrm{i}$ | incident radiant power |
| $\phi_\mathrm{s}$ | azimuthal scattering angle |
| $\theta_\mathrm{i}$ | angle of incidence |
| $\theta_\mathrm{r}$ | angle of specular reflection |
| $\theta_\mathrm{s}$ | polar scattering angle |

## 5 Scattering geometry

The scattering geometry is defined in spherical coordinates with respect to the specimen normal as shown in Figure 1. The origin of coordinates lies at the specimen as follows:

- for measuring reflective scattering, the origin lies at the entrance surface;
- for measuring transmissive scattering, the origin lies at the exit surface;
- for thin specimens (specimen thickness small compared to the field of view of the detector), the origin can be either at the entrance or the exit surface;
- for certain applications, it may be useful to place the origin at other locations, for example in the specimen.

The exact location of the origin shall be documented.

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[1] In ISO 13696:2002, total scattering is currently described by the symbol TS. This will be changed to the symbol, $\sigma_\mathrm{TS}$, in the upcoming revision.

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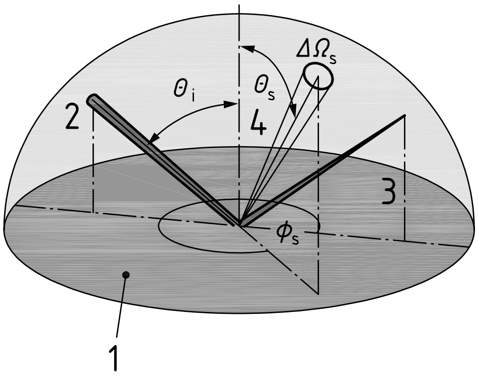

**Key**

| | | | |
|---|---|---|---|
| 1 | specimen under test | $\theta_i$ | angle of incidence |
| 2 | incident beam | $\theta_s$ | polar scattering angle |
| 3 | specularly reflected beam | $\phi_s$ | azimuthal scattering angle |
| 4 | scattered radiation at $(\theta_s, \phi_s)$ | $\Delta\Omega_s$ | detector solid angle |

NOTE The angle of the specular reflection ($\theta_r$) is equal to the angle of incidence ($\theta_i$).

Figure 1 — Scattering geometry

The scattering geometry is shown in Figure 1. The azimuthal scattering angle is zero for measurements within the incident plane containing both the incident and specularly reflected beams. In addition, a specimen orientation angle should be defined and documented. The direction of incidence and the surface normal define the incident plane.

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# 6 Test method

## 6.1 Principle

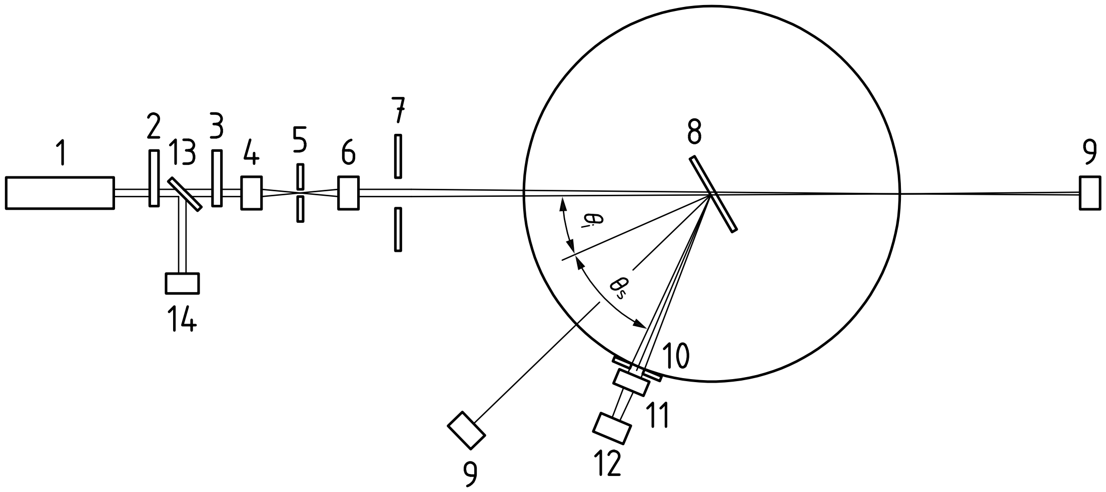
The fundamental operating principle of the instrument for ARS measurements (see Figure 2) is based on measuring the radiant power scattered from the specimen as a function of the scattering angles using a detector with a small but finite aperture that is scanned along a defined trajectory on or within the full scattering sphere about the specimen. The simplest type of measurement is a detector scan with the plane of incidence (in-plane scan).

The angle of incidence is kept constant during a single measurement. The ARS is either measured by rotating the detector with respect to the specimen and the illumination system, or, alternatively, the detector is fixed and the illumination system and the specimen are rotated with respect to the detector.

## 6.2 Measurement arrangement and test equipment

### 6.2.1 General

The instrument employed for the determination of ARS is divided into four functional sections which are described in detail in Figure 2.



**Key**

| | |
|---|---|
| 1 | radiation source |
| 2 | chopper (optional) |
| 3 | variable attenuator (optional) |
| 4 | focussing element 1 |
| 5 | pinhole |
| 6 | focussing element 2 |
| 7 | baffles (optional) |
| 8 | specimen |
| 9 | beam dump |
| 10 | detector entrance aperture |
| 11 | field lens (optional) |
| 12 | detector |
| 13 | beam splitter (optional) |
| 14 | reference detector (optional) |

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Figure 2 — Instrument for ARS measurements

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If radiant power fluctuations or drifts of the radiation source of more than 5 % are expected over the time scale comprising calibration and measurements, an additional reference channel shall be implemented into the setup shown in Figure 2. The back reflection of a tilted superpolished substrate of a material transparent in the relevant spectral region of the laser and positioned before the spatial filter as well as an appropriate detector, preferably similar to the actual scatter detector, should be used for this purpose.

### 6.2.2 Environmental conditions

The instrument should be located in a clean room environment or under a laminar flow system to prevent scattering from dust particles. Some applications, in particular in the UV range, require operation in vacuum or specific gas atmospheres to avoid absorption of radiation in air or to suppress Rayleigh scattering from air molecules. The environmental conditions during measurements shall be documented.

### 6.2.3 Radiation source

Excellent beam quality and sufficiently high incident radiant power are essential for ARS measurements of optical components. Therefore, lasers, laser diodes or narrow or broad band sources may be used as radiation sources. The source used shall be documented.

The temporal radiant power variation of the radiation source shall be measured and documented. This comprises long-term drifts as well as short-term fluctuations. Drifts and fluctuations smaller than 5 % are below the overall uncertainty of measurement and can be accepted. Larger drifts and fluctuations should be monitored and taken into account accordingly. For this purpose, a reference signal should be measured using a beam splitter and a reference detector.

An attenuator based on a combination of neutral density filters or other means is used to adjust the incident radiant power.

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### 6.2.4 Beam preparation system

The beam preparation system consists of a spatial filter to generate a clean beam and, if necessary, additional baffles to suppress stray radiation from the illumination system. The beam profile should be a rotationally symmetric Gaussian. Other profiles, for example a top-hat profile can also be used provided that the instrument signature, particularly at scatter angles close to the specular directions, is not affected.

The last focussing element images the pinhole onto the plane of the detector aperture. That is, the specularly reflected or normally transmitted beam shall be focused on the detector aperture when the detector is viewing that direction and when the specimen being measured is in place.

If the focal point of the illumination system is at the specimen, at infinity (collimated beam) or at any other position other than the detector aperture, the user shall check, document, and quantify to which extent this affects the near-specular instrument signature and the compatibility with results obtained from TS measurements according to ISO 13696.

The focal length of the beam preparation system shall be adjustable so that the refractive power of the specimen can be compensated.

Single surface mirrors are preferred as optical components, because they usually produce less scattering and thus enable better (lower and narrower) instrument signatures to be achieved. Ideally the ARS of the mirrors should be lower than the ARS of the specimen to be measured.

If spherical mirrors are used, the angles of incidence should be as small as possible to reduce aberrations that can critically affect the instrument signature in the near-specular regions.

The beam diameter on the specimen shall be documented. It shall be smaller than the field of view of the detector at the specimen position. Typical diameters are between $D$ = 0,4 mm and 10 mm. The field of view shall be adapted to the beam diameter.

NOTE Some applications require focussing onto the specimen. Thus, substantially smaller beam diameters down to the micrometre range can be achieved, but the larger beam size at the position of the detector aperture makes scattering into small angles close to the specular directions inaccessible. The actual near-angle limit can be assessed by inspecting the instrument signature.

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Beam traps surrounding the instrument shall be used and positioned to absorb all specularly reflected and normally transmitted beams. Additional beam traps might be necessary to absorb off-specular diffraction peaks from diffractive specimens.

### 6.2.5 Goniometer

Typically, a goniometer is used to measure the ARS.

The inner goniometer contains the specimen mount and allows for adjusting the angle of incidence. The angle of incidence shall be documented.

The specimen mount shall allow for adjusting the specimen in all three dimensions as well as its tilt. Motorized stages are preferred for performing automated specimen scans and scattering maps.

The outer goniometer arm carries the detector system.

Instruments with one degree of freedom allow for scanning in one plane – usually the plane of incidence. These measurements are referred to as “in-plane ARS measurements”.

The range of scatter angles shall be documented. For constant step size, this can be done by stating the minimum and maximum scatter angles as well as the step size.

More advanced instruments allow for scanning the detector within the entire sphere or along arbitrary paths around the specimen. The measurements are referred to as “3D ARS measurements” or “out-of-plane ARS measurements”, respectively.