Specification at LASER COMPONENTS

The International Standards Organization (ISO) has issued guidelines to help specify optics in a uniform manner; therefore, laser optical components can fulfill their tasks to the user's fullest expectations.

Based on the DIN ISO 10110 norm, this guideline will summarize and explain the correct handling of laser optics. In addition to the choice of substrate material – which is dependent on the application – this guideline states the most important specifications (e.g. for material imperfections) and their classifications, which play a central role when verifying optics. This summary also lists important criteria for examination.

Choice of Material

LASER COMPONENTS obtains the material for laser optics exclusively from reputed manufacturers.

The most important substrate criteria are:

- Absence of bubbles and striae
- Homogeneity
- Spectral absorption behavior
- Polishability
- Index of refraction n
- Hardness
- Thermal expansion coefficient

The optimal application area for each material can be derived from its fluorescence and spectral absorption behavior.

Quality Levels

Laser optics are often used inside laser resonators. Therefore the demands on the surface figure and the ability of the components to withstand high power levels are extremely high. Nevertheless, a standard material like BK7 is sufficient in most cases.

04/21 / V03 / HB:IF / lc-optics/tipps/specs_lc

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The following table lists typical applications of the most common substrate materials.

Material \ Application	UV 190 nm - 400 nm	Vis/NIR 400 nm - 1800 nm	IR up to 2.1 µm	IR up to 3 mm	Extreme Power	Extreme Surface Figure	At Temp. Application > 80° C
BK7 n = 1.51 at 1064 nm		■	♦				
B270 n = 1.52 at 550 nm		♦					
Floatglass n = 1.52 at 550 nm		♦ (low power e.g. protect. window)					
Sapphire (Random) n = 1.75 at 1064 nm		♦	♦	■			♦
UV-quartz[1] n = 1.45 at 1064 nm	■		♦ (2.1 µm - 2.9 µm)		♦ (super polished 5/4 x 0.01)	♦	♦
OH-free Quartz[2] n = 1.45 at 1064 nm			■	❍	♦ (super polished 5/4 x 0.01)		
CaF_2 Monocrystalline n = 1.45 at 550 nm	♦			❍			
MgF_2 Monocrystalline n = 1.38 at 550 nm	♦			❍			
Zerodur® n = 1.46 at 550 nm						■	♦

■ Main application; ♦ Possible application; ❍ Application with limitations

[1] e.g. Suprasil® 1, Suprasil® 311, Suprasil® 312, C7980, Q0, Q1, Q2

[2] Infrasil® 301, Suprasil® 300

Classifications of Bubbles and Striae

Bubbles
Bubbles are cavities with a circular cross section inside the substrate which can occur during the manufacture of the glass.

Striae
Spatial inclusions that differ from the base material are called striae.

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Bubble Classes

Nomenclature

According to DIN ISO 10110, "bubbles and inclusions" are specified as "NxA," where A is the measure of maximum permissible inclusion size in mm and N denotes the total number of allowable inclusions at maximum size. A is defined as the square root of the projected area of the largest bubble and/or inclusion.

1/N x A 1: Code number for bubbles and inclusions
N: Number of bubbles and inclusions
A: Maximum permissible inclusion size [mm]

The correct specification according to DIN ISO 10110 is demonstrated by the example 1/3 x 0.16. The first digit indicates the type of specification. A "1" stands for bubbles and inclusions. Accordingly, a bubble specification is introduced in our example. "3 x 0.16" means that not more than 3 bubbles with a maximum size of 0.16 are permitted. These are so-called preferential values.

The following table states the separation factors for bubbles and inclusions.

Preferential Values	1	2.5	6.3	16
Size A in mm	0.006			
	0.010	0.006		
	0.016	0.010	0.006	
	0.025	0.016	0.010	0.006
	0.040	0.025	0.016	0.010
	0.063	0.040	0.025	0.016
	0.10	0.063	0.040	0.025
	0.16	0.10	0.063	0.040
	0.25	0.16	0.10	0.063
	0.40	0.25	0.16	0.10
	0.63	0.40	0.25	0.16
	1.0	0.63	0.40	0.25
	1.6	1.0	0.63	0.40
	2.5	1.6	1.0	0.63
	4.0	2.5	1.6	1.0

Calculation of the Substrate Quality

If the sum of the projected areas of the bubbles and inclusions is smaller than the maximum total area N x A^2, it is possible to state a higher number of bubbles and/or inclusions that have a smaller size via the table.

The declaration of the inclusions according to DIN 10110 always states the values with the largest size. The bubbles and/or inclusions, however, can occur in higher numbers - but smaller sizes - in the specified substrates. This is calculated as follows.

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Example:

The specification 1/2 x 0.040 means that a maximum of two bubbles (N) of size 0.040 (A) can occur. A look at the preferential values listed in the first column of the table shows the desired size in mm. The multiplication column "2.5" to the right of the preferential values depicts the size 0.025.
Accordingly nearly 2 x 2.5 = 5 bubbles and/or inclusions have the size 0.025. Following this principle, more values up to the multiplication factor 16 can be calculated. For the given substrate nearly 2 x 16 = 32 bubbles of size 0.010 are also permissible.

House Norm at LASER COMPONENTS

The standard BK7 material of normal quality possesses the exceptional values 1/3 x 0.025.

Inhomogeneity and Striae Classes

The definition of striae classes was changed in the new DIN ISO 10110 norm and expanded by the term "inhomogeneity classes."

The nomenclature of the specification now reads "2/A;B". The first digit is the code number for inhomogeneity and striae. "A" denotes the inhomogeneity class and "B" the striae class.

2/A;B 2: Code number for inhomogeneity and striae
A: Inhomogeneity class
B: Striae class

Inhomogeneity

A change in the refractive index of the optical component caused by a change in the chemical makeup of the material is called inhomogeneity.

The permissible deviation in the refractive index of an optical component is divided into six inhomogeneity classes.

Inhomogeneity Classes	Maximum Permissible Deviation in the Refractive Index of the Component 10^{-6}
0	± 50
1	± 20
2	± 5
3	± 2
4	± 1
5	± 0.5

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Striae

Striae are defined as spatially short-range variations of homogeneity which occur as well-defined thread-like inclusions.

The specification of the striae class not only serves the selection of raw material but also allows examination as to whether the final part matches the specifications.

Classes 1 to 4 regard striae, which vary the optical path by at least 30 nm. Class 5 is used for components that satisfy the highest quality expectations. Here the difference in the optical path is significantly lower than 1 %.

Striae Classes	Striae Density Which Varies the Optical Path by at Least 30 nm [%]
1	10
2	5
3	2
4	1
5	Extremely high absence of striae; the limitation to striae exceeding 30 nm is obsolete

House Norm at LASER COMPONENTS

The house norm for BK7 and fused silica is 2/5;5.

Surface Figure Error (Surface form tolerance)

The surface figure error is also called surface deviation. It denotes a mismatch between the actual and the ideal surface. The surface figure error is calculated from the following formulas:

Peak-to-Valley Difference

The difference between the maximum distance a_{max} and the minimum distance a_{min} between the surfaces is called the peak-to-valley difference (PV difference).

Total Surface Figure Error Function

The theoretical surface which is defined by the difference between the actual surface and the ideal surface is called total surface figure error function.

Best Fit Sphere

The so-called best fit sphere is derived from the total surface figure error function. The best fit sphere function describes the sphere for which the rms value of the difference between the sphere and the total surface figure error function is minimized (rms: root mean square).

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Irregularity Function

Irregularity function denotes the difference between the total surface figure error function and the best fit sphere.

Determination of the Surface Figure Error

In order to determine the surface figure error the surface to be examined is compared to a high precision reference glass. Interference fringes result from the difference between the test surface and the projection of the reference wavefront (reference surface).

Tolerances of the Surface Figure Error

If tolerances of the surface figure error are to be determined it is necessary to separate the measured surface figure error into different error types. These are for spherical surfaces

- Sagitta Error
  The sagitta error is the peak-to-valley difference between a best fit sphere and a surface.
- Irregularity
  Irregularities are defined as the peak-to-valley difference between the irregularities function and its best fit surface.

All maximum allowable values of the mentioned error types have to be stated in units of interference fringes. The green mercury line (e line) with λ = 546.07 nm is used as a reference wavelength for declarations of the surface figure error.

The nomenclature according to DIN ISO 10110 is "3/A (B)." The first digit "3" indicates surface figure errors. "A" denotes the maximum permissible sagitta error (in units of interference fringes) and "B" the maximum permissible irregularity.

3/A (B/C)
- 3: Code number for surface figure error
- A: Maximum permissible sagitta deviation
- B: Maximum permissible irregularity (deviation from sphere)
- C: Fine surface figure error (rotational symmetry irregularities)

Example:

The declaration 3/0.5 (0.25/–) refers to the following:
Error type: 3 Surface figure errors
Sagitta error: 0.5 interference fringe (λ/4)
Irregularity: < 0.25 interference fringe (λ/8)
Fine surface figure error: no specification

In the in-house norm for spherical surfaces A is not specified on a standard basis. The maximum permissible deviation is given as tolerance of the radius of curvature (typically ± 0.5%).

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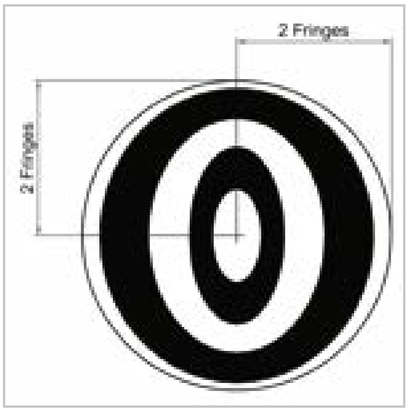
Interferometric Determination of the Error

The interferometric determination of the sagitta error and the irregularity can both be done with and without tilting the test surface.

Testing for large surface figure errors is performed without tilting. Here the sagitta error creates an interference pattern of circular fringes. Asymmetrical abnormalities can be identified by elliptically or even hyperbolically distorted fringes.

To determine the shares of sagitta errors and irregularities of an interference pattern both the maximum (m) and minimum (m') number of fringes are counted along two directions. In the case of elliptical fringes, the sagitta error is (m + m')/2 and the irregularity is |m - m'|.

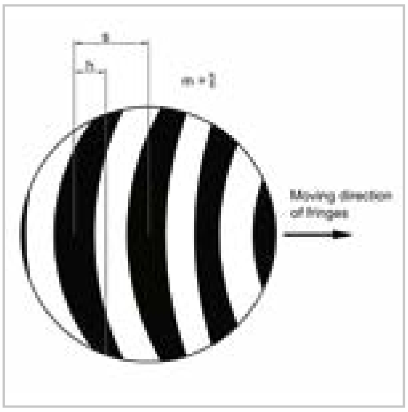


Test surface with sagitta error and irregularities of 2 fringes each.

The mainly occurring small surface figure errors are measured via tilting. Scope of the measurement is the quotient of the fringe bending h and the fringe width s.

The distance between two fringes of the same color corresponds to a path difference Δs of a wavelength Δs = λ. For a surface figure requirement of λ/4 the ratio m between the bending h and the fringe spacing s must not be bigger than 1:4.
In the example above it is assumed that the substrate meets a surface figure requirement of 3/0.5.

By moving the test surface towards the reference surface the precision optician can determine whether the substrates features a concave or a convex form. If the fringes with the large curvature move away from the center, the test surface is convex (see figure). If, on the other hand, they move towards the center, the test surface possesses a concave shape.



Applications and Requirements

Optics that are used inside the resonator of a laser must have a spherical surface figure of λ/10. To achieve this, a certain ratio between diameter and thickness must not exceed.

Substrate	Diameter / Thickness
BK7	≤ 5 : 1
Fused Silica	≤ 10 : 1

This rule of thumb saves the setup from substrates that are too thin and thereby becoming deformed during coating or assembly. Thinner substrates can reach a surface figure of λ/10 only if they are optically contacted.

Using thinner substrates without any problems is only possible for applications in transmission, such as windows. This is possible because the sagitta errors of both the entrance and exit surface work in the same direction, reducing the transmitted wavefront error.

House Norm at LASER COMPONENTS

With regard to a flat 1" substrate the house norm for BK7 and fused silica is 3/0.2 (0.1).

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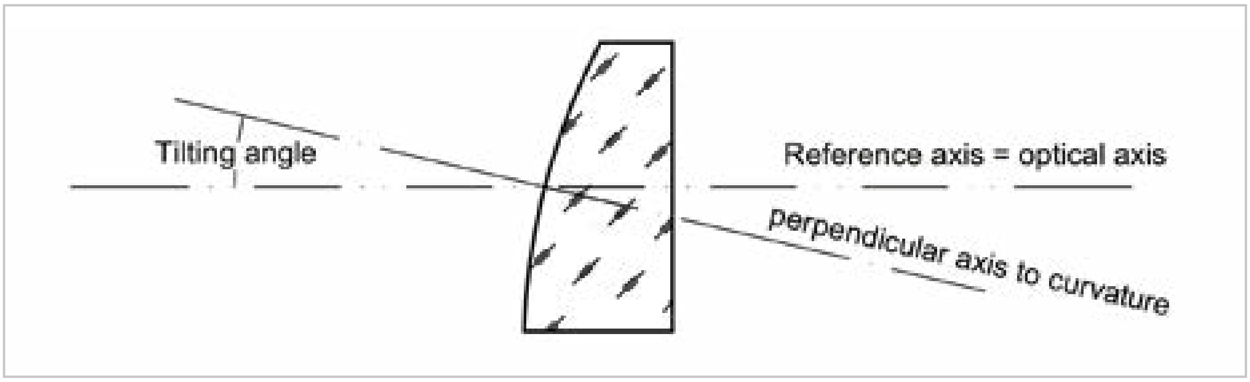
Centering Accuracy

DIN ISO 10110-6 is the basis for the centering accuracy of rotationally symmetric optical systems containing spherical and aspherical surfaces. In there, specifications of centering tolerances for optical elements and systems are described. The digit "4" is assigned to this specification.

If individual spherical surfaces are considered, the centering error equals the wedge angle of the surface, where the wedge angle denotes the angle between the reference axis and the surface normal.

The specification of the centering error of spherical surfaces must follow the nomenclature "4/σ" where σ denotes the maximum permissible wedge angle.

In addition to σ the lateral offset (L) has to be stated as well for single aspherical surfaces. The lateral offset denotes the distance from the vertex of the aspherical surface to the reference axis. The specification of an aspherical surface must be 4/σ (L).



If certain optical parts are cemented together, a wedge angle tolerance for the cement layer is given. Nomenclature: 4/Δτ.

Single Lens

4/σ (L) 4: Code number for centering accuracy
σ: Maximum permissible wedge angle
L: Lateral offset (for aspheres)

Cemented Lens

4/ Δτ 4: Code number for centering accuracy
Δτ: Wedge angle tolerance of the cement layer

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Surface Quality

The surface quality describes errors in an optical surface caused during the manufacturing process or by improper handling.

This includes the following errors:

- Scratches / smears
- Holes
- Hair cracks
- Polishing pimples

The specification is performed according to DIN ISO 10110-7. The most common nomenclature is "5/N x A". The first digit "5" indicates the surface quality whereas "N" denotes the number of permissible surface imperfections with maximum size "A".

5/N x A   5: Code number for surface quality
N: Number of permissible surface imperfections with maximum size
A: Maximum permissible size [mm]

<u>House Norm at LASER COMPONENTS</u>

With regard to a 1" diameter uncoated substrate the house norm is 5/4 x 0.025. With this, the maximum total area of imperfections is defined and not exceeded. The number of imperfections N varies with size A. If A is reduced, the number of imperfections increases. Therefore, 5/10 x 0.016 would also fulfill the house norm.

Additional Errors

If more errors occur, that is in addition to surface imperfections, they can be recognized by the extended specification.

Coating imperfections 5/N x A, CN' x A'
C: Coating quality
N':Number of permissible quality with maximum permissible size
A': Size (regarding coating quality)

Scratches 5/N x A; LN" x A"
L: Scratches of arbitrary length
N": Number of permissible scratches with maximum permissible size
A": Size (regarding scratches)

Edge chips 5/N x A; EA'"
A'": Maximum permissible chip size from the physical edge of the surface

Complete nomenclature of the surface quality

5/N x A; CN' x A'; LN" x A"; EA'"

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Determination of Surface Quality

In order to inspect a part for surface quality light is shone on the sample. Surface imperfections will cause the light to scatter. This scattering is compared to the background illumination. In practice, the size of the surface imperfections is determined with a comparison chart.

When using measurement devices the sample can be inspected via both transmission and reflection measurement.

Optical surfaces which are used for high power optics cannot have any traversing scratches. The utmost care is therefore required during quality inspection of substrates.

The substrates are not examined using a microscope. It can be said from experience that errors which can only be recognized under a microscope do not have any influence on the damage threshold and the quality of the laser beam.

To determine surface imperfections a template for size comparison is available.

Surface Finish

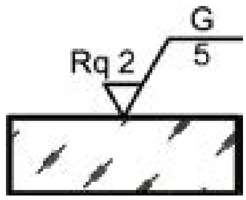
The surface finish is a global, statistical characteristic pertaining to the roughness profile of an optical surface. The characteristics and structure are the same at every location of the test surface. There are matt and reflective surfaces. For reflective surfaces irregularities in the form of micro defects can occur.

Fine Grind Surfaces (matt)

Fine grind surfaces are characterized by a difference in height that does not significantly differ from the wavelength of visible light.

They are described using the quadratic average roughness Rq [µm]. It is defined as the quadratic average of the absolute values of the distances between the roughness profile and the median within the measured section. Hence, Rq is dependent on the measuring length. At the very least, the lower boundary of the measuring length has to be given for the measurement.

The following figure shows the correct nomenclature of the surface finish specification for matt surfaces.



The number next to “Rq” is the maximum permissible average roughness in µm. The letter “G” signifies a grinded surface. The digit “5” below the G is the minimum measuring length (5 mm) necessary to determine Rq.

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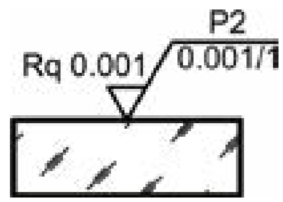
Reflective Surfaces

The difference in height is far less for reflective surfaces than for matt surfaces. There are three ways to measure the error of reflective surfaces.

- Average Roughness Rq
  In most cases stating the average roughness Rq is sufficient.
- Mechanical Scanning
  Microdefects are detected using a mechanical profilometer. It is crucial how often the profilometer needle deviates from the otherwise smooth surface.
- PSD Function
  For the finest polished surfaces, which have to live up to the highest expectations, the spectrum of spatial frequencies of the surface roughness is examined.



Reflective surface with a maximum of 80 micro-defects per 10 mm measuring length and surface roughness Rq ≤ 0.001 µm at a measuring length between 0.001 mm and 1 mm.

To denote a reflective surface without any quantitative statements the letter "P" is simply used. P stands for polished.

The maximum permissible number of micro-defects with a size of < 1 µm is determined for each size by the polishing grade P1 - P4. The following table shows the correlation between polishing grade and micro-defects.

Polishing Grade	Number N of Microdefects per 10 mm of Measuring Length
P1	80 ≤ N ≤ 400
P2	16 ≤ N ≤ 80
P3	3 ≤ N ≤ 16
P4	N < 3

In addition to the average roughness Rq a certain measuring length range can be set. The statement follows the example of matt surfaces. The measuring length range of Rq (nomenclature x mm / y mm) is stated below the polishing grade (see figure).

House Norm at LASER COMPONENTS

The house norm is polishing grade P4.

Labelling of Coatings

The performance requirements of a coating are stated only for a few parameters directly in the drawing.

The following symbols are used:

- τ: Permeance of radiant fluxes
- ρ: Reflection of radiant fluxes
- α: Absorption of radiant fluxes
- (λ): Optically coated surfaces

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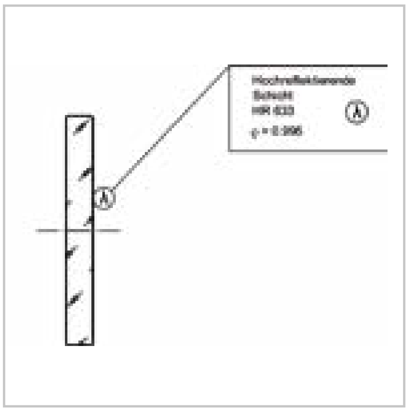
The description of the optical characteristic is done in a box (see figure). If functional coatings are applied to cement layers it has to be stated whether the specification applies before or after cementing.

For protective layers a broad dash-dot-dash line (according to ISO 128) is drawn next to the outlined part.



Example of specifying optically coated surfaces.

Concrete Example

After an introduction to the theoretical principles of specifying laser optics a plano-convex AR lens is discussed in detail according to DIN ISO 10110. Please note also the drawing on page 19.

Technical Drawing

The noticeable element of the specification in the drawing is the scale drawing. The lens is drawn to a scale of 1:1 and again magnified by a factor of 4.

Center Thickness and Diameter

The measurement on top is the edge thickness of 2.49 mm. The value is closed off by parentheses; this means that size and tolerance are determined using other dimensions. In this case, they are determined by the center thickness of 4.9 ± 0.2 mm (stated below the lens) and the radius of curvature.

The diameter is given on the plane side of the lens and measures 15 mm with a minimum size of 14.8 mm.

Generally, center thickness and diameter are stated with tolerances.

Surface

In the drawing the surface quality is symbolized by "P4". It follows from the table on page 15 that the polished surface must have less than three micro-defects per 10 mm of measuring length.

Coating

Specifications regarding the AR layers can be found in the box on the lower right next to the drawing. According to these specifications the reflection per surface must not exceed 0.2 % for light with a wavelength of λ = 1064 nm.

At this location a possibly requested angle of incidence has to be stated if it differs from 0°. A missing statement will always be interpreted as 0°. Below these declarations the requirements for wipe and scratch resistance according to MIL specs are given if necessary.

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MIL-48497A has guidelines on how substrates are to be tested for abrasion resistance. Such tests can, for example, be performed with an eraser. In addition, MIL-675-C has procedures on how to test optics for their adhesiveness and moisture resistance.

Material Properties

The material properties of the glass are flanked on the left and right by the substrate properties regarding radius of curvature, test range, and surface accuracy.

The left column ("left surface") states the radius of curvature of the lens surface in the first row with the symbol "∞", which denotes a plane surface.

For the "right surface" the radius of curvature is stated as R = 12.91 mm CX (for convex) with tolerance.

The test range (or optically effective diameter) is denoted by the symbol Øe and measures 85 % of the coated surface for both sides.

Protective Chamfer

Below the following line a statement regarding the protective chamfer can be found. In both cases its width has to measure between 0.2 mm and 0.4 mm at an angle of 45°.

Surface Figure Error

Afterwards, the surface figure errors (code number "3") are specified. The sagitta error for a plane surface is 0.2 interference fringes (= λ/10), while (0.2) denotes the maximum permissible irregularity at 0.2 interference fringes (= λ/10).

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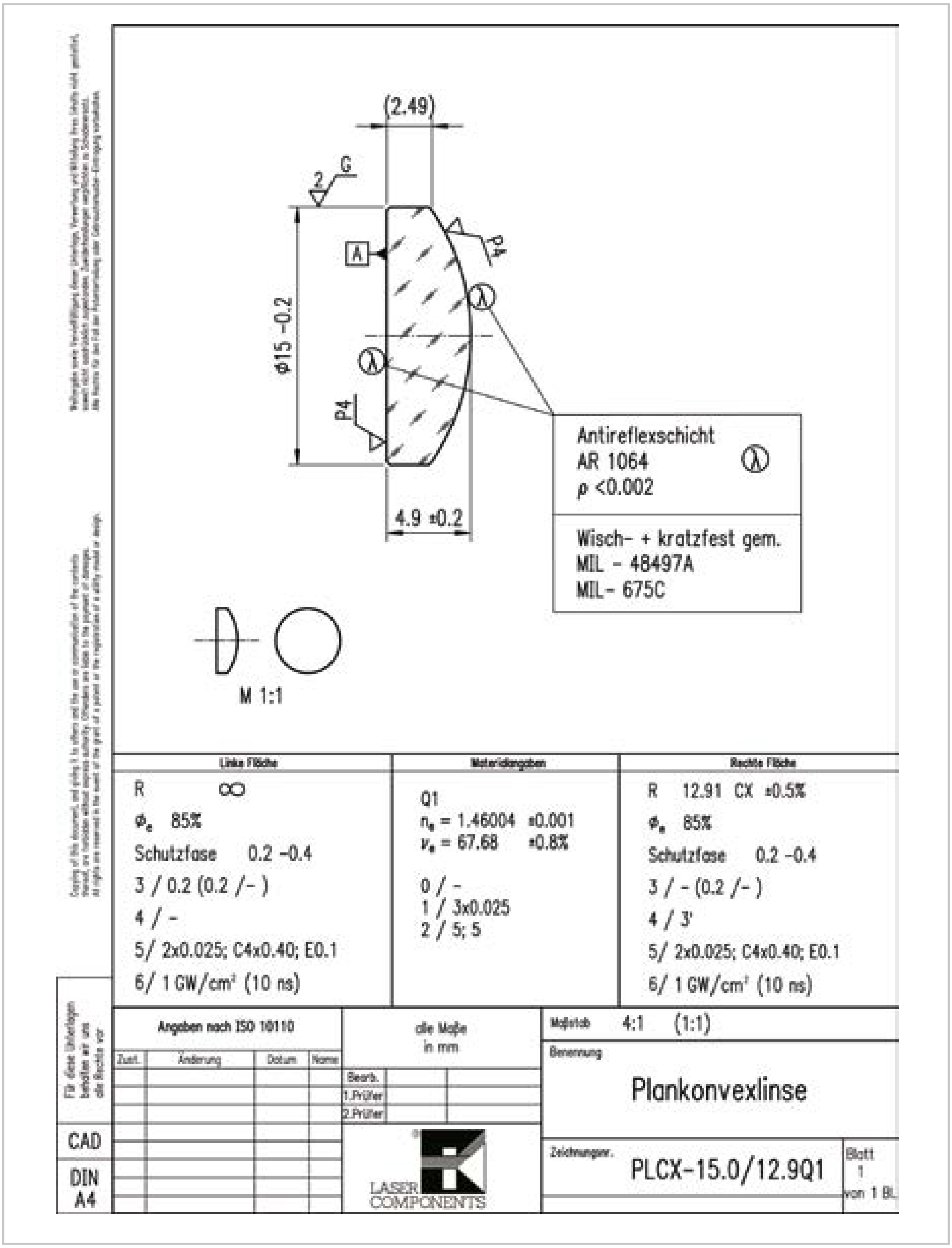

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Centering Tolerance

A specification of the centering tolerance (code number "4") is not given for the left surface since it acts as a reference surface. This can be recognized by the black reference triangle with the box "A". The reference surface normal (dash-dot-dash line) serves as a reference axis for the centering tolerance of the right lens surface. According to this, the maximum permissible wedge angle for the spherical surface is three arc minutes.

Surface quality

In the next line the specifications of the surface imperfections are stated for both sides. Here 2 x 0.025 refers to a maximum of two surface imperfections with a maximum permissible size of 0.025. For coating imperfections a maximum of four imperfections with a maximum permissible size of 0.40 are allowed. The maximum permissible protrusion of edge chips from the physical edge is stated as 0.1 mm.

Damage Threshold

The digit "6" states the damage threshold as being 1 GW/cm^2. The value in parentheses, i.e. (10 ns), indicates that the damage threshold refers to pulsed laser operation at 10 ns.

Raw Material

The first row of the middle column indicates the type of raw material. In this case it is quartz "Q1" (name given by the manufacturer). It is followed by the index of refraction n_e at the e line of mercury (λ = 546.07 nm) which is 1.46004 ± 0.001.

Optical Dispersion

The optical dispersion of the lens is defined using the Abbe number ν_e. In this example it is 67.68 ± 0.8 %.

A statement regarding strain-induced double refraction ("0") is not made. 1/3 x 0.025, on the other hand, indicates that three bubbles with a maximum size of 0.025 are permitted.

Inhomogeneities

Because of the use of high quality material, the specification of inhomogeneities in substrates usually falls in the highest inhomogeneity class 5. Therefore the maximum permissible deviation from the refractive index is ± 0.5 x 10^{-6}.

Striae Class

The last row of the middle column states the striae class which, in this case, is "5". As a result the substrate has to be extremely free of stria. The limitation of striae >30 nm becomes irrelevant.

Additional Specifications

Sometimes the user also needs data regarding the lens shape such as position of the primary plane, back focal lengths, etc. In this case they are listed separately in the upper right corner of the specification sheet.

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