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TIE-25 Striae in optical glass

Introduction

Optical glasses from SCHOTT are well known for their very low striae content. Even in raw production formats, such as blocks or strips, requirements for the most demanding optical systems are met. Since striae intensity accumulates over the affected volume, their effect can decrease to a low level for components with short optical path lengths. Striae with wave front distortions ≤ 30 nm do not have any significant negative influence on the image quality as Modulation Transfer Function (MTF) and Point Spread Function (PSF) analyses have shown (refer to Chapter 7).

This technical information shall help the customer to find the right specification for raw glass or blanks for optical elements, regarding measurement, classification, and assessment of striae and with reference to the regulations of ISO 10110 Part 4 "Inhomogeneities and Striae".

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1. Definition of Striae

An important property of optical glass is the excellent spatial homogeneity of the refractive index of the material. In general, one can distinguish between short- and long-range homogeneity of refractive index. Striae are spatially short-range variations of the homogeneity, i.e. variations over a distance of about 0.1 mm up to 2 mm, whereas the spatially long-range or global homogeneity of refractive index extends from cm-range to up the complete glass piece (up to approx. 1 m), see TIE-26 "Homogeneity of Optical Glass".

2. Root causes for striae

Striae mostly result from incomplete homogenization of the raw materials and dissolved refractory material of the tank during melting. The homogenization process is driven by convection in the tank and a stirrer in mixing pot to smoothen out the inhomogeneities further.

But striae can also be generated by detaching the old glass within the casting nozzle and by dropping the material on the cast surface during the cutting process, which is necessary to cut the glass melt from the cast glass.

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3. Metrology of striae – the shadowgraph method

The shadowgraph method (Figure 1) is suitable for striae detection due to its high sensitivity and ease of set up and handling [1]. The setup for the shadowgraph consists of the following elements: a 100 W Mercury high pressure short arc lamp (as a source) with a pinhole aperture without any imaging optics, a sample holder on a turn table and a white non-transparent projection screen. The light emitted from the lamp is divergent and partly coherent. Without a sample, the illumination pattern on the projection screen will show a constant bright area. By placing a sample with striae into the beam, the striae will become visible on the screen as a dark pattern (in general straight or curved lines), since the refractive index of the striae is different from that of the matrix material and thus, refracting the incident light slightly different.

The sensitivity of this method depends only on the geometrical setup. In theory, the highest sensitivity is achieved when placing the sample in the middle – between the lamp and the projection screen and maximizing the lamp-screen distance [2, 3]. In practice, due to rising geometric blur with shorter lamp-sample distances when utilizing a divergent light source, the optimum of sensitivity is found for the sample located approx. at 2/3 of the lamp-screen distance. Thus, SCHOTT uses an optimized geometrical setup with a lamp-screen distance of about 3 m, where the sample is placed about 1 m from the projection screen. With this setup, a sensitivity of about 10 nm optical path difference at 50 mm optical path lengths can be achieved.

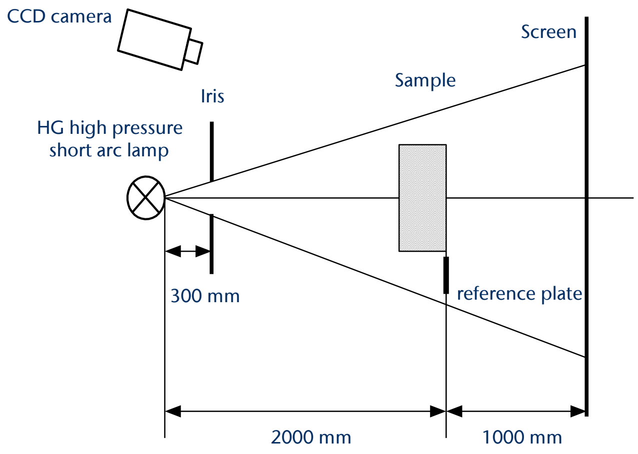

Figure 1: Shadowgraph setup with given distances of light source and iris, sample, and screen for displaying the striae.

Striae samples cut from standard strip glass have a defined optical path length of 50 mm in application direction. Block glass is inspected at ~ 200 mm optical path length. The sample must be rotated up to ± 45° with respect to the incident beam until the striae are most prominent. Furthermore, this rotation allows discrimination between surface flaws and internal striae. The surface flaw position would change with the rotating of the sample whereas the position of striae would remain almost constant. To further improve the contrast and the uniformity of the projection screen, the screen is also rotated during measurement. In addition, a CCD camera is installed for purpose of documentation.

The glass must be inspected in a room with subdued light (Figure 2). The glass sample needs to be polished for inspection on both sides. The surfaces along the optical path should be flat and almost parallel; otherwise, the interpretation of the results will be difficult due to imaging effects. The shadowgraph method is quite insensitive towards long-range homogeneity changes.

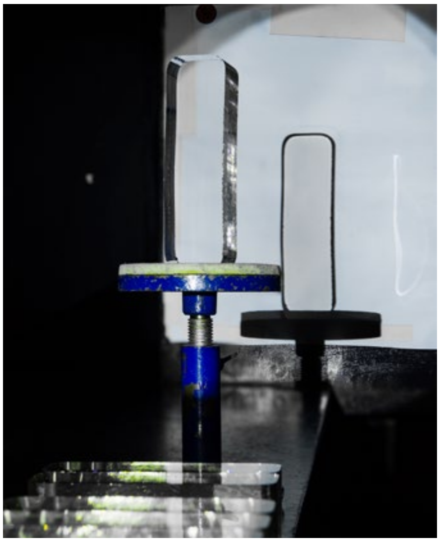

Figure 2: Striae testing using the shadowgraph method for glass strips with polished and parallel surfaces.

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4. Shape and appearance of striae

Striae can appear in the form of sharp, cord-like regions. This kind of striae can be found mainly in glasses produced by the clay-pot melting. Cord-like striae have a clear straight geometrical shape with sharp edges and can therefore be accurately localized (Figure 3 left).

The well-known but now invalid MIL specification for striae is based on reference samples made from the clay-pot melting process. More common today are band-like striae patterns produced by the continuous tank melting process. These striae do not exhibit sharp edges and their shape is similar to a frozen convection pattern (Figure 3 right). The MIL specification categorizes the striae in four different grades from low striae to high striae intensity with grade A to D, respectively (please refer to chapter 5).

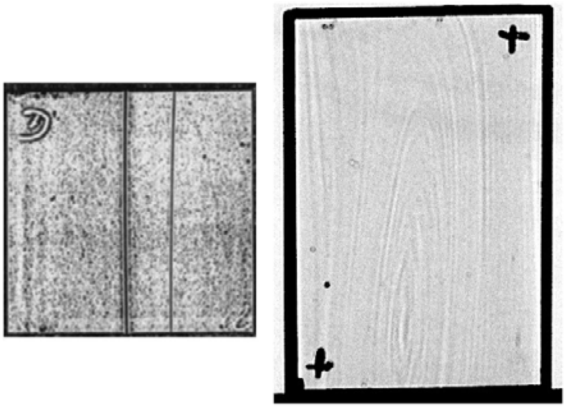

Figure 3: Cord-like striae according to MIL grade D (left) and band-like striae grade D (right).

Band-like striae may affect large volumes of the glass parts, but the effect of striae decreases with decreasing optical path length. Figure 4 shows a comparison of the striae intensity inside glasses of various thickness and their respective optical path lengths.

In the given example, the striae intensity decreases from grade C at 50 mm optical path length to grade B at 10 mm optical path length. This is an important observation. The standard measurement thickness for striae testing is 50 mm whereas the final lens thickness in consumer applications is often not larger than 10 mm. This suggests that standard grade C striae within the glass will be almost unidentifiable in the final lens.

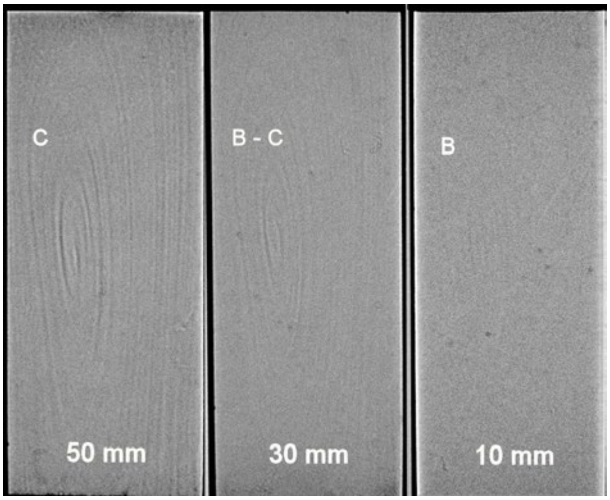

Figure 4: Striae intensity as a function of the thickness of the glass.

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Striae and the resulting wave front distortion are also highly directional dependent (Figure 5). The striae visibility in the shadowgraph setup almost disappears when the samples are rotated ±5° around the vertical axis.

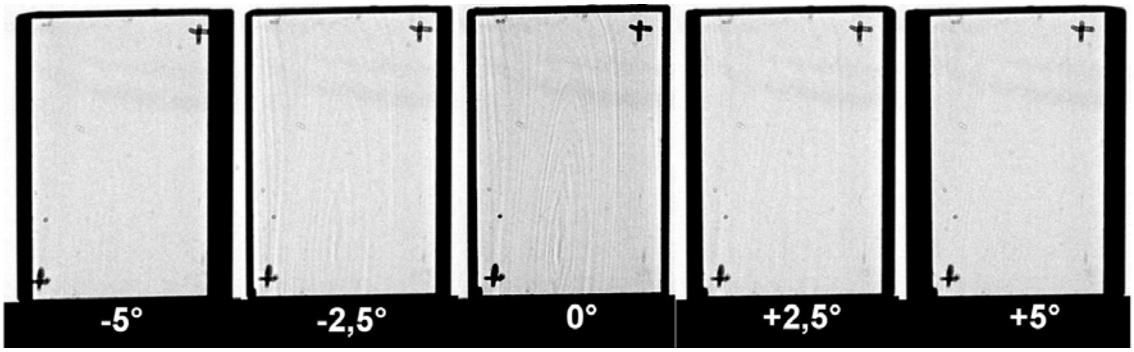

Figure 5: Influence of the viewing angle on the striae intensity along the optical path.

Figure 6 shows the shadowgraphs of a rectangular glass sample in three perpendicular directions. The striae intensity in the first direction is C grade whereas the striae intensity in the remaining two directions ranges between A and B grades.

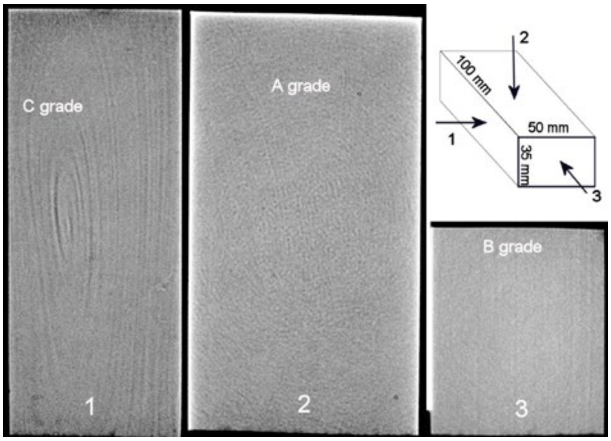

Figure 6: Striae intensity in three perpendicular directions of one sample as shown in the sketch on the upper right.

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5. Specification of Striae: Comparison of different standards

The most prominent standards for striae are the ISO 10110 part 4 and the expired MIL-G-174 B. This chapter explains the differences between the two standards and the interpretation of the SCHOTT catalogue definitions with respect to these standards.

Striae are characterized by two main properties: Their intensity or wave front deviation and the geometrical area of the striae. For striae that are not localized the thickness of the sample has an important influence on the intensity of the striae. As a rule of thumb, reducing the thickness will reduce the intensity of striae, if its shape is band-like and extends through parts of the glass volume.

The MIL-G-174 B [4] categorizes striae in a piece of raw glass according to its intensity but without any reference to the striae area and sample thickness. The striae are categorized by four reference samples of cord-like striae into four classes A to D. These reference samples are older than 25 years.

The intensities of the MIL reference striae have been measured externally using an interferometer with a very high spatial resolution. From this a wave front, deviation can be assigned for each class. The old SCHOTT striae specification uses this definition (Figure 7).

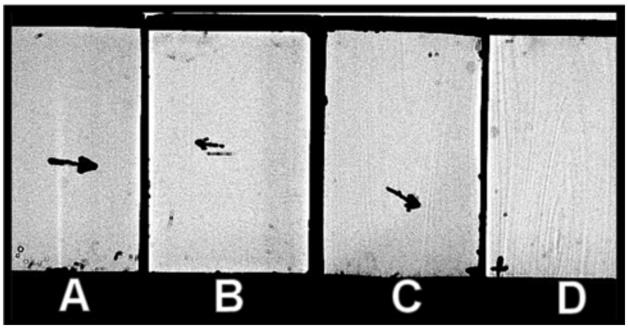

Figure 7: Striae grade A to D according to the old SCHOTT specification (based on MIL-G-174 B).

The ISO 10110 part 4 [5] introduces 5 classes of striae grades for finished optical parts. In grades 1–4, only striae with intensities greater than 30 nm optical path difference are categorized. The grades 1–4 differ by the area of the striae as compared to the complete area of the part. Striae with intensities less than 30 nm are categorized in class 5. The main challenge with this standard is that it is defined only for finished optical parts.

The previous SCHOTT specification used internally adhered to the nomenclature of the MIL specification. The reference samples are characterized according to their wave front deviation. The MIL specification characterizes only cord-like striae and therefore does not depend on thickness. The SCHOTT specification refers to a thickness of 50 mm takes into account the behavior of band-like striae that are most common in the optical glass production process.

The specification in the current SCHOTT catalogue [6], in general, excludes striae with grades higher than C. This is because such striae are prevented during the production process, except for a thin layer (< 2 mm) lying directly below the fire polished surfaces which originates from the evaporation of constituents during casting. These layers are eliminated in the subsequent machining process steps. SCHOTT's normal quality is always class C or better per 50 mm path length, corresponding to about 30 nm optical path difference. Thus, SCHOTT standard optical glass fulfills the requirements of the ISO 10110 class 1–4.

As mentioned before, striae in optical glass are mainly band-like striae due to the production process and their intensity depends on the thickness of the glass parts, while the inspected length is often much longer than the thickness of the finished parts. Hence, the standard quality of the finished parts, which have a reduced thickness, is equal or better

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grade B (corresponding to about 15 nm optical path difference). Taking this consideration into account, it is even possible to fulfill the need of grade A striae for a finished optical component from a glass block with a higher striae grade.

For more stringent requirements, SCHOTT offers VS1 quality with less than 10 nm optical path difference due to striae. VS1 quality for fine annealed pre-shaped glasses is valid only with respect to the inspection direction. In this category, no striae must be visible with the shadowgraph method. SCHOTT also offers VS2 and VS3 quality which meets the requirements of VS1 in two or three directions, respectively, perpendicular to one another. For pressings using VS quality glass, we use pre-inspected raw glass since inspections of the pressings themselves is not possible.

The main implications of the SCHOTT specifications for the customer are summarized as follows:

- SCHOTT optical raw glass always fulfills MIL-G-174B grade C (< 30 nm wave front deviation) and ISO 10110 part 4, class 1–4. Striae in optical glass, if present, are band-like striae. The intensity (wave front deviation/class) depends on the thickness of the glass.
- Raw optical glass is inspected at greater optical path length compared to finished parts, therefore, finished parts exhibit striae class B (according MIL-G-174 B) or better.
- Raw optical glass of Schott standard quality might be even suitable for finished parts with grade A striae quality, if the optical path length of the raw glass is much larger than the finished part.
- VS quality is only valid for fine annealed glass with respect to the inspection direction and available up to three dimension.

	MIL-G-174B	ISO 10110	SCHOTT old (Only internal use)	SCHOTT new
Valid for:	Raw glass	Finished glass	Raw glass	
Characterized by:	Intensity without sample thickness	Area of striae (density)	Intensity with sample thickness (50 mm)	
Striae grades	**D** (no quantification)	≥ 30 nm **1:** ≤ 10 % **2:** ≤ 5 % **3:** ≤ 2 % **4:** ≤ 1 %	**D:** ~ 60 nm	
	C (no quantification)		**C:** ~ 30 nm	< 30 nm: **normal** quality of raw glass
	B (no quantification)	**5:** extreme low striae content Further details have to be marked in the drawings	**B:** ~ 15 nm	~ < 15 nm: finished glass
	A (no quantification)		**A:** < 10 nm	
			VS: no striae visible	**VS1/VS2:** no striae visible in one/two directions

Table 1: MIL and ISO standards for striae as compared to the SCHOTT specification

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6. A simple striae model

The influence of striae on optical imaging depends on their size, shape and the difference between the refractive indices of glass and the striae area.

The difference in refractive index generates a wave front deviation, which is proportional to the optical path length. For a better understanding, imagine striae with the shape of a straight half sheet paper introduced into a glass block (see Figure 8). The striae have a different refractive index (n_2) than the rest of the material (n_1). For this theoretical review, it is assumed that the difference in refractive index between the striae and the remaining material is $\sim 3 \cdot 10^{-7}$. Therefore, a plane wave front passing through the glass block in different directions will be distorted in different ways.

A wave front in view direction 1 will pass half of the striae length and therefore be distorted by $(n_2 - n_1) \cdot 100$ mm = $3 \cdot 10^{-7} \cdot 100$ mm = 30 nm, which can be observed using the shadowgraph method, since a projection of the striae will become visible. The striae will appear as a medium dark solid line. The darker the striae appear, the higher the wave front deviation. The term intensity is often used to express the wave front deviation.

A wave front traveling in view direction 2 will be distorted only by the thickness of the striae. As mentioned before, striae are very localized homogeneity deviations, therefore the wave front deviation introduced into a plane wave passing striae in thickness direction is very low $(n_2 - n_1) \cdot 2$ mm. Striae of intensities less than 10 nm cannot be observed with the shadowgraph. Hence, no striae would be observed in view direction 2.

In view direction 3, the plane wave front passes the striae over the complete length of 200 mm. Therefore, the wave front deviation and the intensity of the striae on the shadowgraph screen is high – the striae appear dark. In addition, the shadowgraph screen displays the projection of the striae shape. According to the overview, the striae appear to be a solid half lines reaching to the middle of the screen.

It is important to keep in mind that the striae assumed here is only a model. In reality, striae are of more complicated shapes, especially band-like striae are difficult to determine. Nevertheless, there are some points that can be learnt from this simple model:

1) Striae can generally be characterized by their intensity, in terms of wave front deformation, and their area. The visibility of striae depends on the view direction.

2) The intensity of striae depends on the length of the striae in the view direction. Therefore, striae viewed in thickness direction are invisible and do not affect any optical application.

In the next chapter, simulations of the effects of sinusoidal model-shaped striae inside a lens will be discussed.

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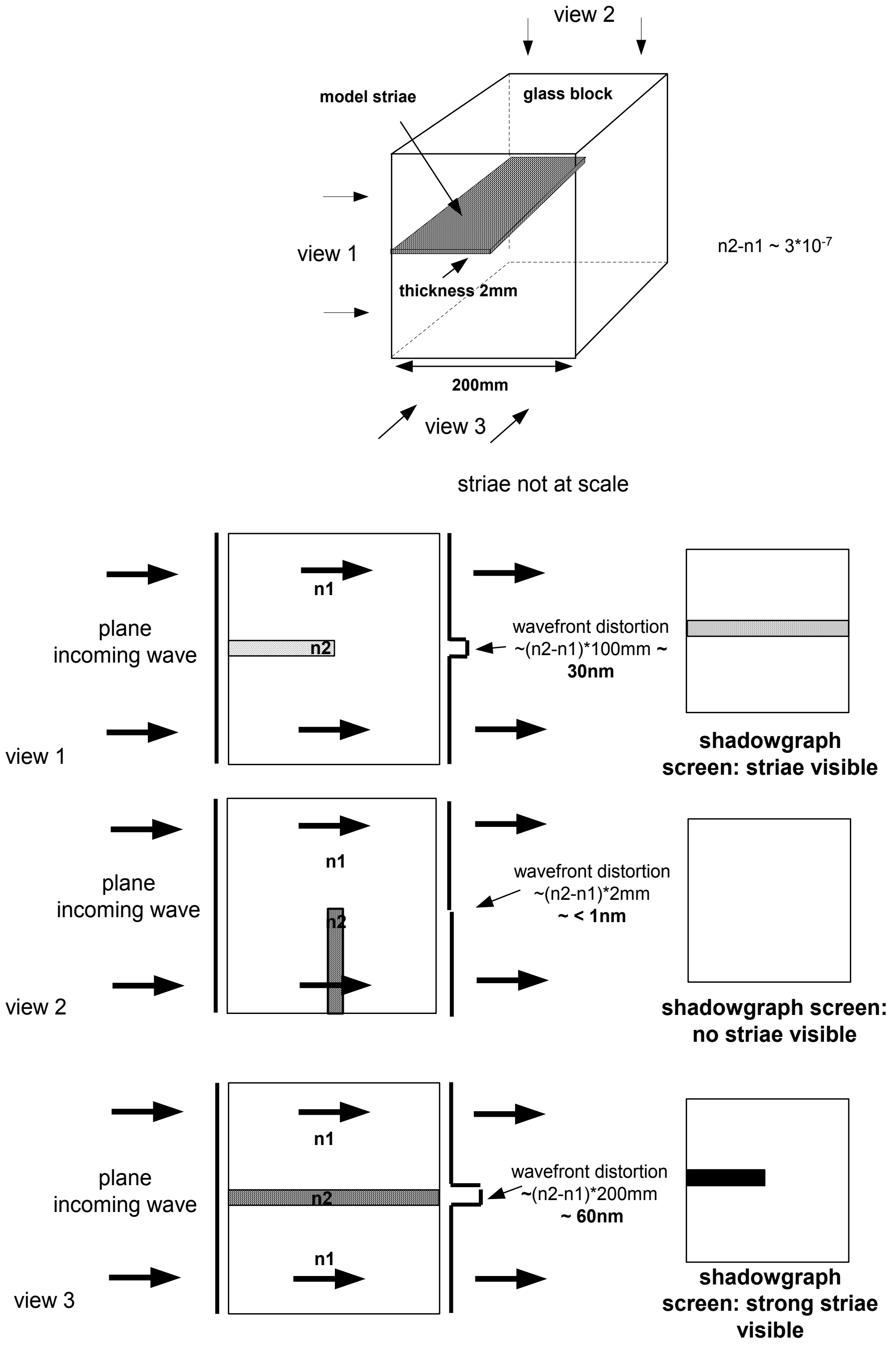

Figure 8: Influence of different view directions on the shadowgraph of model striae.

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7. Influence of striae in application

An ideal optical system is defined by its ability to focus a point-like object without any aberrations to a point-like image. Normal optical systems are, in general, not free of aberrations. Depending on their position, striae may produce aberrations within optical systems. In the wave optical theory, the point-like object emits waves with ideal constant spherical wave fronts and phases.

The aperture of an optical system is given by the element in the system that limits the beam diameter and therefore the amount of light exiting the system. This can be a separate iris or the lens itself. The image of the aperture is called entrance and exit pupil.

Striae near pupils introduce a phase shift and therefore change the shape of the wave front. In practice, this means that the striae broaden the intensity distribution of a picture from an ideal point source (Figure 9). It has been shown that striae intensities below λ/10 have no significant effect on the image quality [7]. For wavelength λ = 535 nm this would compare to striae intensity less than 54 nm, which is worse than striae grade C, please refer to [7].

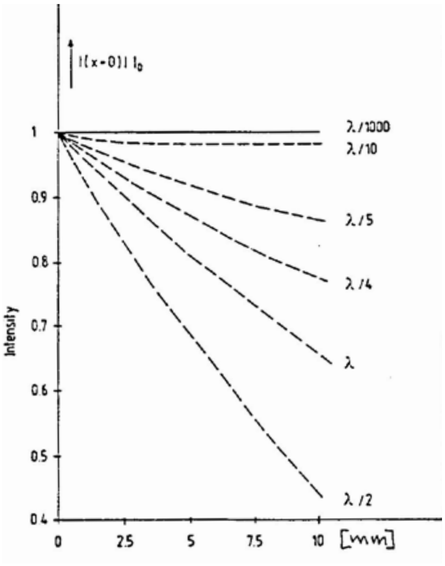

Figure 9: Central intensity of a picture of an ideal point source dependent on striae size and wave front deviation (intensity of the striae) [7].

In the following sections, the results of the striae simulation using Zemax optical design software are discussed. Artificial striae with different intensities have been built into an ideal optical setup and in a real double Gauss lens system to analyze the influence on the image quality.

7.1. Influence of striae on the point spread function (PSF) and modulation transfer function (MTF) in an ideal aberration free optical system

For the simulation of the effect of striae on an ideal aberration free imaging system, a setup of a lens with a focal length of 500 mm and an aperture of 50 mm diameter (f/10) is used. In front of this lens, a plane plate with sinusoidal structures in one direction is placed. This sinusoidal structure introduces a phase modulation with a spatial frequency of 0.2 mm^{-1} and a variable peak-to-valley (PV) amplitude (60 nm, 30 nm, 15 nm, 8 nm). This structure is a worst-case model of striae in an ideal system. Figure 10 shows the setup of the model. The calculations are carried out for a wavelength of λ = 500 nm.

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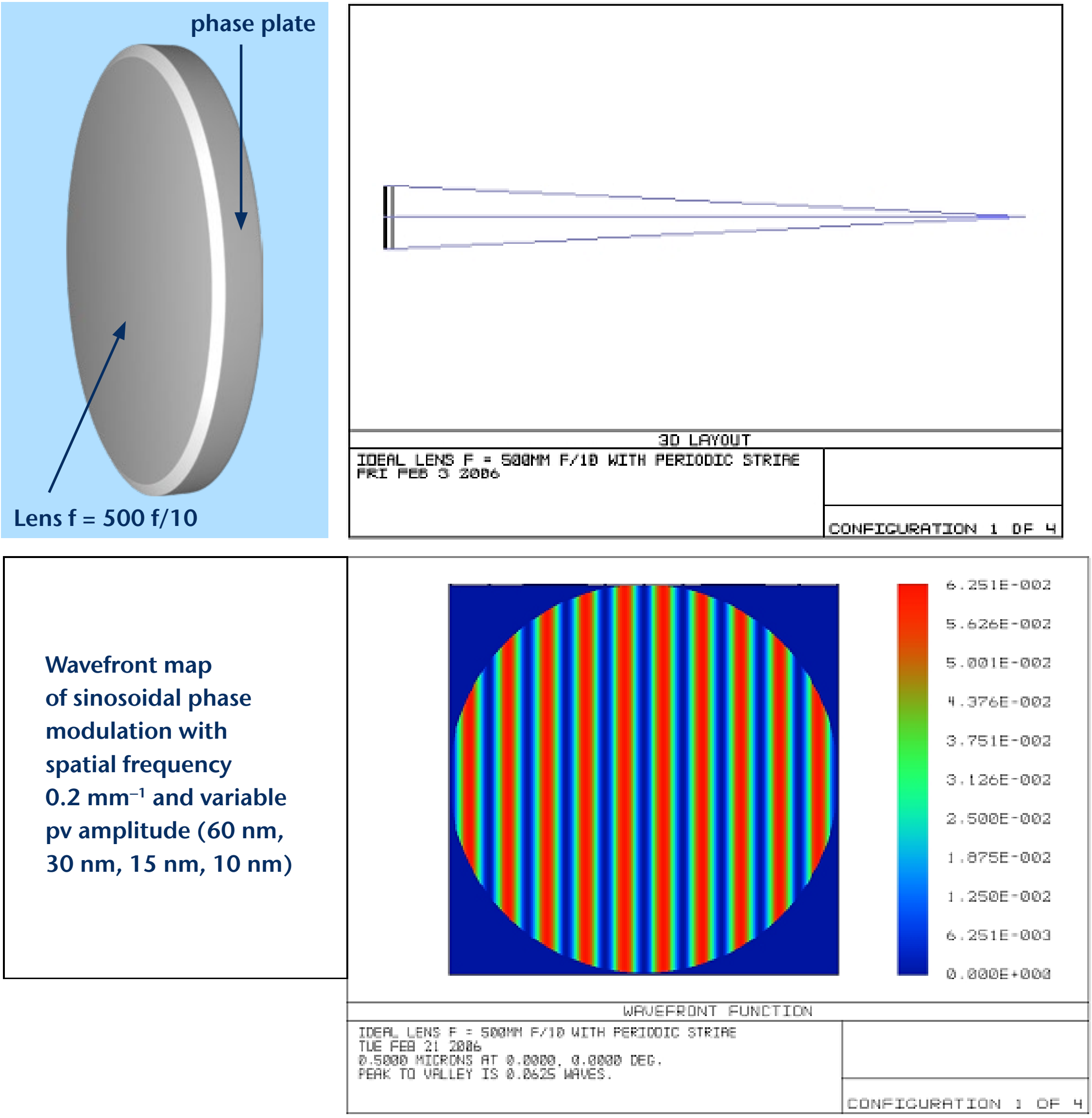

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3D LAYOUT
IDEAL LENS F = 500MM F/10 WITH PERIODIC STRIAE
FRI FEB 3 2006
CONFIGURATION 1 OF 4
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Wavefront map of sinosoidal phase modulation with spatial frequency 0.2 mm^{-1} and variable pv amplitude (60 nm, 30 nm, 15 nm, 10 nm)

```
WAVEFRONT FUNCTION
IDEAL LENS F = 500MM F/10 WITH PERIODIC STRIAE
TUE FEB 21 2006
0.5000 MICRONS AT 0.0000, 0.0000 DEG.
PEAK TO VALLEY IS 0.0625 WAVES.
CONFIGURATION 1 OF 4
```

Figure 10: Setup of a Zemax model for the simulation of the effect of striae on an ideal optical system

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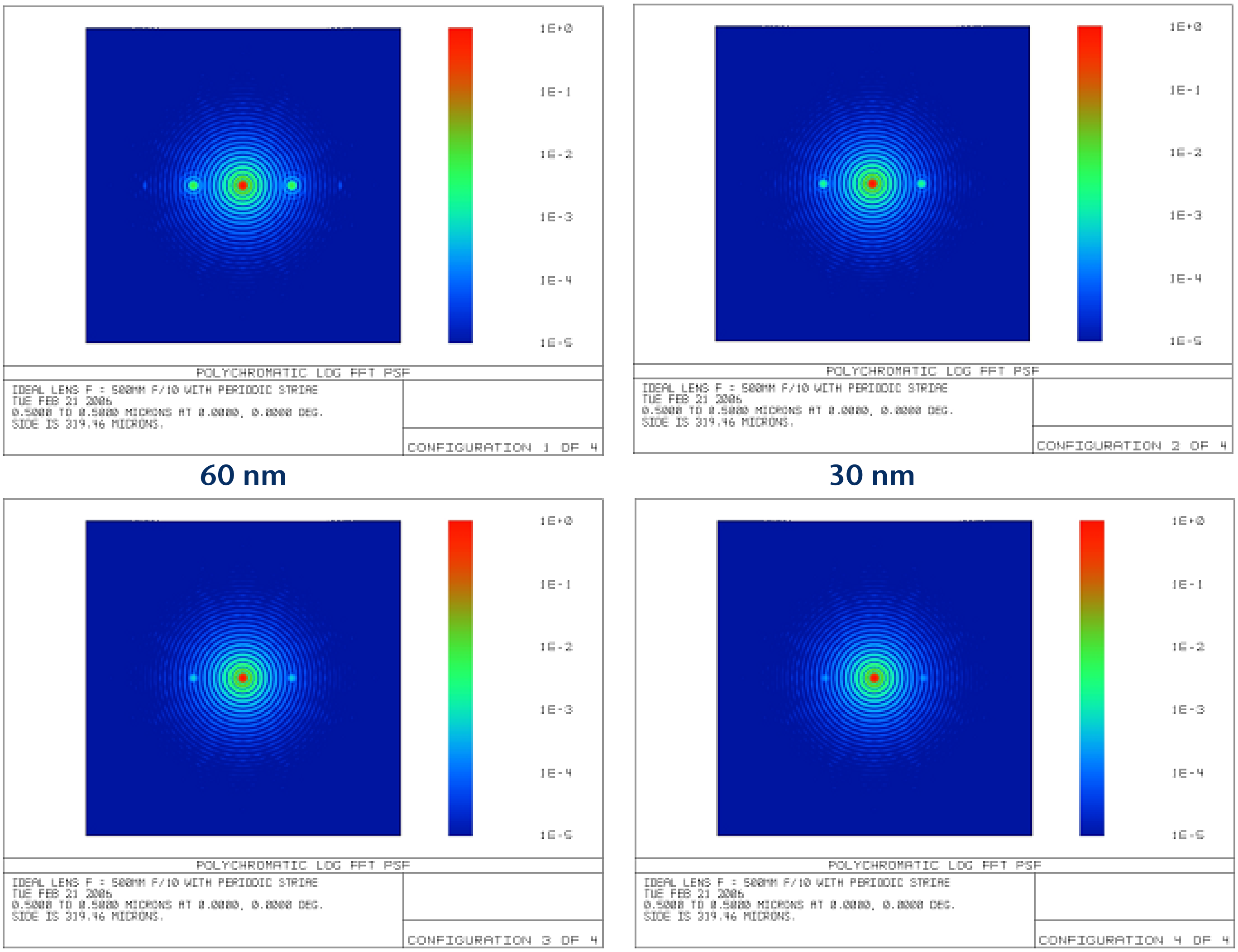
The following figures show the influence of the model striae on the PSF of the system. An ideal aberration free system would show a diffraction limited point image with no side intensity maxima.

The striae in the system generates side maxima in the PSF. The intensity of the side maxima depends on the striae intensity.

Figure 11 shows the log-scaled area plot of the intensity distribution and figure 12 shows the log-scaled intensity distribution along the x-axis.



60 nm

30 nm

15 nm

8 nm

Figure 11: PSF of an ideal system with different wave front deviations, ranging from striae grade D (60 nm) to A (8 nm).

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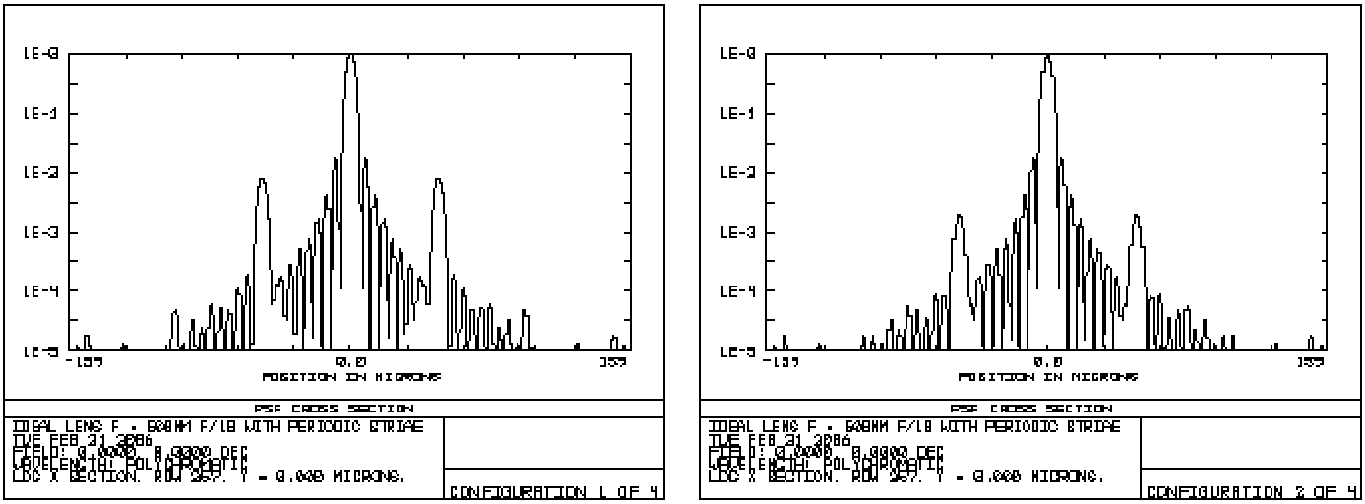
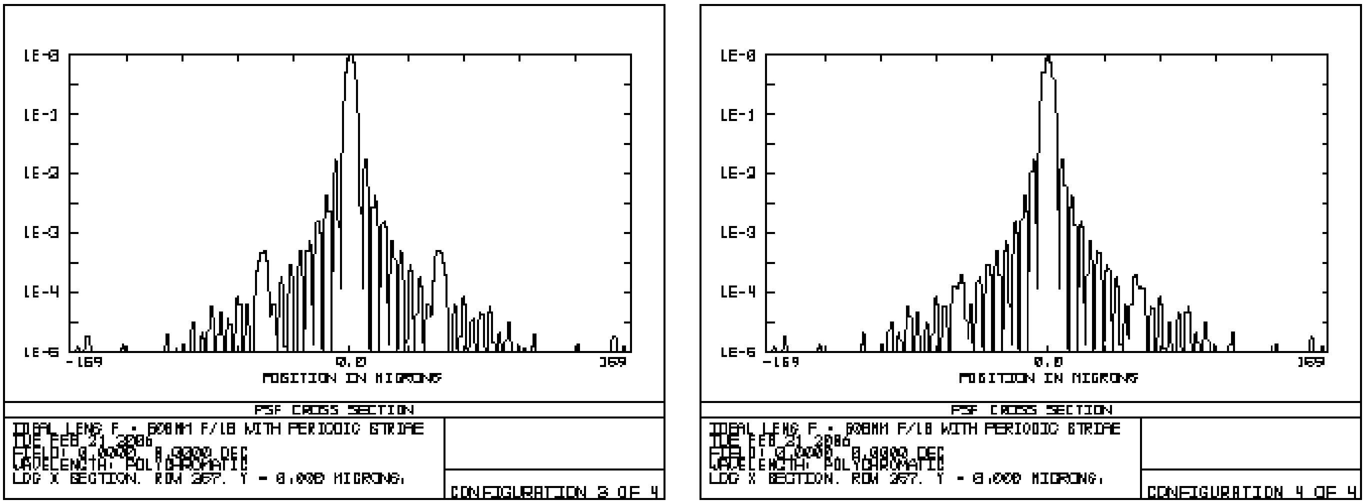


60 nm **30 nm**



15 nm **8 nm**

Figure 12: Two-dimensional plot of the PSF of an ideal system with different wave front deviations, ranging from striae grade D (60 nm) to A (8 nm).

The side maxima intensity generated by striae of 60 nm wave front deviation is about 1/100 of the intensity of the main peak. For standard C grade striae with 30 nm optical path difference, the side maxima intensity is less than ~ 1/500 of the intensity of the main peak. For B grade striae with 15 nm, this fraction goes down to less then ~ 1/1,000 and for A grade striae, the effect is nearly a magnitude smaller in the range of ~ 1/10,000.

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glass made of ideas

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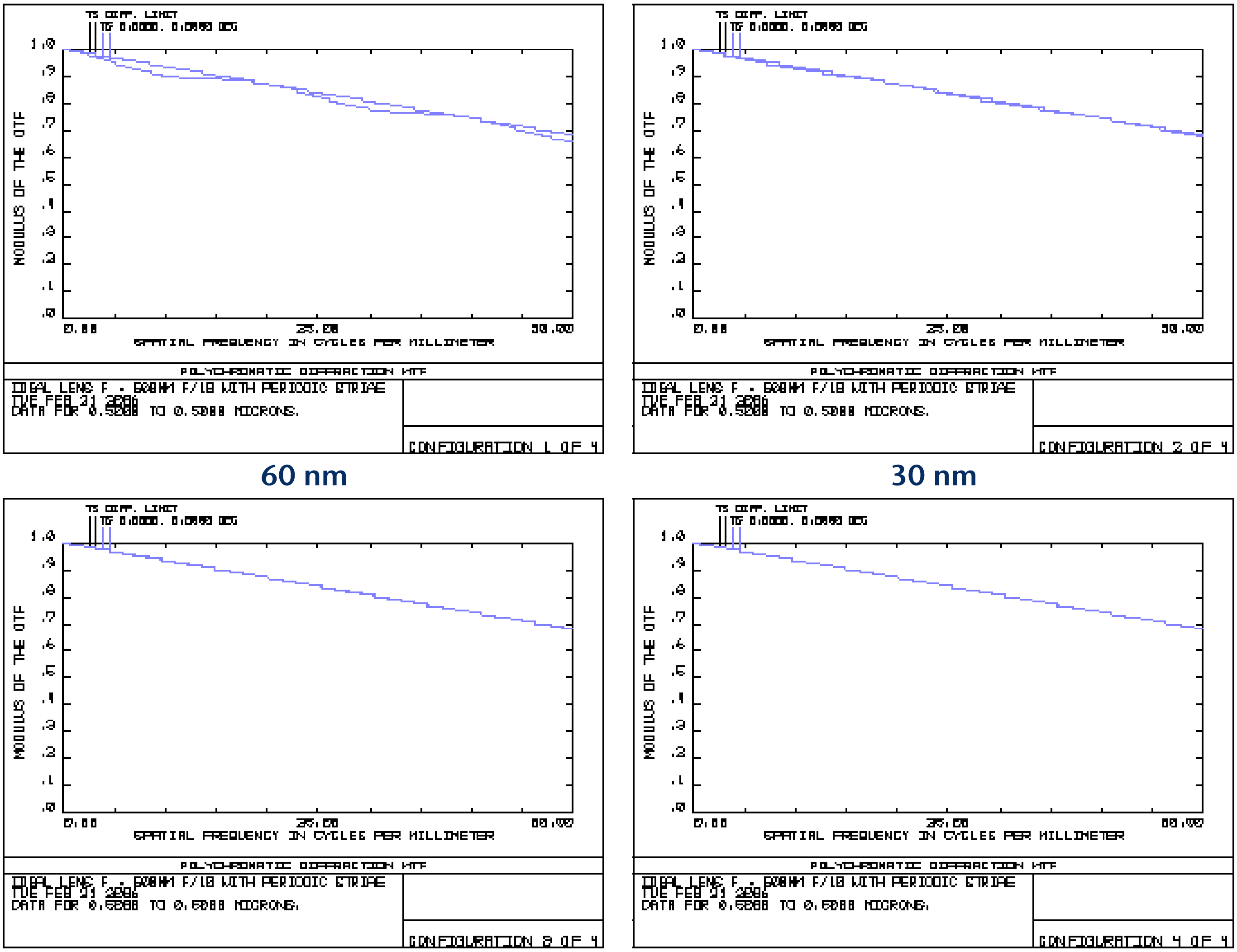
Considering that the displayed striae represent a worst-case scenario, the PSF deviations visible are negligible for standard applications.

This becomes even more apparent if we display the corresponding MTF for the striae grades A to D (Figure 13). A striae of 60 nm wave front deviation results in clearly visible effects in the MTF curve of the ideal system. Below 30 nm wave front deviation (striae grade C or better), the effects are nearly invisible and hence negligible.



60 nm

30 nm

15 nm

8 nm

Figure 13: MTF of an ideal system with different wave front deviations, ranging from striae grade D (60 nm) to A (8 nm).

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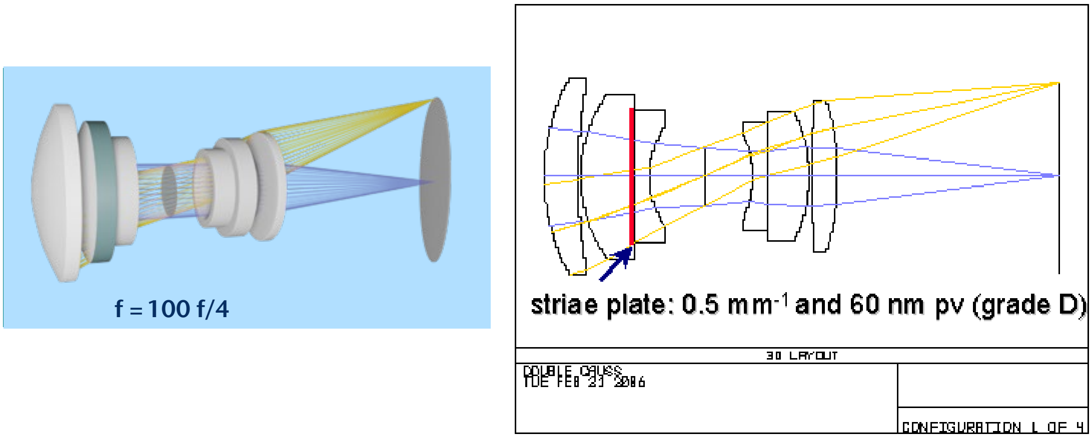
In general, it can be concluded that the standard grade striae equal or below 30 nm wave front deviation shows no recognizable degradation of the image quality in an ideal system.

7.2. Influence of striae on the point spread function (PSF) and modulation transfer function of a double-Gauss lens

The influence of the striae on an ideal optical system is shown in this chapter for a 6-element double-Gauss system as a model of choice since the double-Gauss design form has dominated the class of photographic lenses for many years. There are literally thousands of adaptations of this form, which has an apt combination of aperture, field, and design complexity. They are most used in the 50 mm lens with wide apertures.

Figure 14 shows the used double-Gauss system. The focal length is 100 mm at f/4. The striae plate was introduced between the second and the third element. The striae plate consists of sinusoidal phase modulations with a spatial frequency of 0.5 mm^{-1} and D grade striae intensity of 60 nm peak-to-valley. The wave front map shows that the double Gauss system is dominated by zonal errors with a maximum of 500 nm at a field angle of 0°. The striae plate structures are not visible in this plot due to the large-scale. All calculations are based on a wavelength of $\lambda = 500$ nm.



Wavefront map dominated by zonal errors at field angle 0°

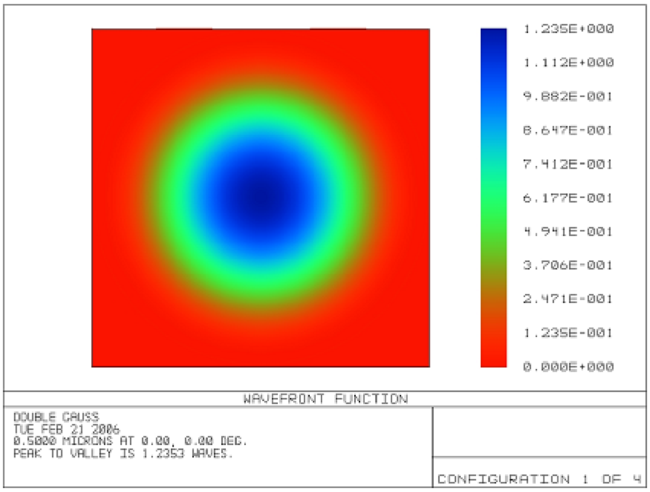


Figure 14: Setup of a Zemax model for the simulation of the effect of striae on a double-Gauss system.

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Figure 15 shows the results of the PSF for this system. The two-dimensional intensity plot shows that the peak is broadened due to the aberration of the double-Gauss system. No side maxima introduced by striae are visible. The aberrations of the double-Gauss system dominate the influence of the striae.

The domination of aberration effects for parallel beams becomes even more apparent in the MTF given in Figure 16. The aberrations lead to a strong decrease of the curve at higher spatial frequencies. The striae have no recognizable influence on the shape of the MTF curve.

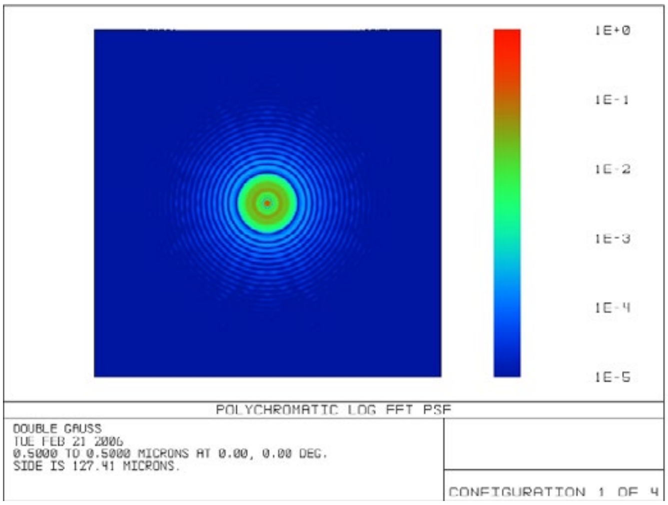

Figure 15: PSF of the double Gauss system with a wave front deviation of 60 nm, striae grade D.

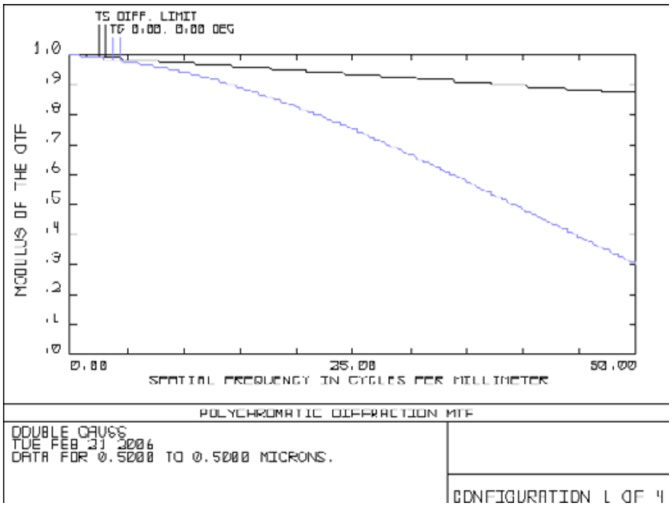

Figure 16: MTF of an ideal system with wave front deviation of 60 nm, striae grade D.

8. Conclusions

As shown in chapter 7.1, a striae intensity below 30 nm shows no significant influence on the image quality of an ideal diffraction limited system. And the calculations of the PSF and MTF curve clearly reveal that striae with intensities less then 60 nm have no effect on the image quality of a standard double-Gauss lens system as it is used in many photographic systems. The inherent aberrations of the optical system override the effect that striae have on the image quality significantly.

Thus, standard C grade striae quality (causing 30 nm optical path difference) inspected with samples with 50 mm thickness is adequate for consumer optics, and even many industrial grade applications. For prisms with longer optical path lengths, C grade quality is also recommended when verified with an inspected path of 200 mm at minimum.

In optical systems with the highest demands on image quality, especially in the microscopy and lithography industries, SCHOTT offers VS quality with less than 10 nm intensity as shown in chapter 5 for one to three dimensions.

For more theoretical details on the influence of striae in optical systems we advise [7–9].

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9. Literature

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