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Research Article

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The design of f-θ-lenses for use in laser machining of glass

Abstract: At high power densities in excess of, say, 10^9 W/cm^2, such as may be created by focusing pulsed laser radiation of nanosecond pulse duration, optical glass is no longer transparent but absorbs the radiant power, resulting in stress and physical damage (cracks). While this is intended for certain techniques of machining glass and other normally transparent materials, secondary foci or 'ghost images' inside the focusing optics may also exceed the threshold for absorption and thereby cause damage to lenses if such ghost images fall inside an optical element. When designing optics for laser machining of glass, it is therefore important to control the formation of ghost images and to ensure that they are located outside all lens elements. This dominates the design process for such optical systems.

Keywords: f-θ-lens; ghost images; glass machining; high power density.

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1 Introduction

Among the many useful properties of the laser, its capability to create very high power densities in the focus of pulsed laser radiation is probably its most impressive single feature. Over just 50 years since the realization of the first laser by Maiman, techniques have evolved for the creation of laser pulses of ever shorter duration, allowing the controlled release of the energy stored in the laser medium through the pumping process in times down to the femtosecond regime. If that energy E (in Ws or Joule J) is fully converted into a laser pulse t seconds long, the peak pulse power is of the order of $P=E/t$ W. Even a laser of very moderate output of, say, 5 mJ per pulse and a pulse duration of, say, 5 ns (5×10^{-9} s), the properties readily available from commercial laser sources will thus deliver a peak power of 1 MW. If such radiation is then focused by suitable optics, this power can be concentrated onto a spot, the size of which depends on the quantity $M^2\lambda/(\pi*NA)$ where M^2 is the beam quality of the laser, λ its wavelength, and NA the numerical aperture of the focusing optics.

If the laser of the above numerical example is a typical solid state Nd-YAG-laser or Nd-YVO4-laser, with a beam quality of M^2=1.5, a wavelength of ~1060 nm, and is used with an aberration-free focusing optics of NA=0.05, it creates a diffraction image of about 25 μm radius, and the peak power density in that image will exceed 5×10^{10} W/cm^2. As the Gaussian shape of the laser beam will be preserved in such an image, the central peak power density will exceed 10^{11} W/cm^2. Higher power densities are accessible by the use of lasers of shorter wavelength, such as frequency-doubled Nd-lasers, where the typically somewhat lower power output is usually more than offset by the concentration of that power on a surface, smaller by a factor of 4.

2 Effects of high power densities

At the power densities computed above, the interaction of most materials with radiation no longer show the usual linear behavior as encountered at low power densities. Optical glass is no longer transparent but absorbs some radiation by dielectric breakdown due to non-linear refraction and multiphoton processes, which then causes stress and subsequent physical damage, such as cracks, inside the glass. There is a threshold for this type of process, which varies very widely for the different types of optical glass and which is also referred to as the laser damage threshold. In 1988, Schott [1] published a list of laser damage thresholds for some of its optical glasses, but that list has not since been updated or extended, and the units used for characterizing the phenomena are not easily translatable to practical applications. The manufacturing process of optical glasses, which typically involves melting and stirring in platinum vessels, also contributes to the laser damage threshold due to the inclusion of small absorbing particles. As a general rule, one has to be aware of possible damage by focused laser radiation, if the radiant power density exceeds, say, 10^9 W/cm^2.

It is useful to note for comparison that this is roughly 6 orders of magnitude higher than what we can ever achieve by focusing light from the sun, our most powerful natural radiation source.

3 Laser machining of glass

The combination of laser properties and associated focusing optics given in the above numerical example have been found to be well suited for processing optical glass and some other (normally) transparent materials, such as sapphire [2]. In by far the most popular application, processing here means the creation of many small cracks, which together form three-dimensional sculptures. Individual laser pulses should have energies in the lower milliJoule range, and numerical apertures should typically exceed 0.07 for a compromise between total power input (and risk of excessively spreading damage) and crack size, which typically runs at a few tenths of a millimeter. Although of generally irregular shape, the cracks are, on average, somewhat extended in the direction of the laser beam axis, and to avoid undue length, the power density must be set to just exceed the threshold, which is generally done by adjusting the laser pulse energy. The onset of damage – the formation of cracks – is audible. The shorter wavelength of a frequency-doubled Nd-laser will create proportionally smaller cracks and require less energy per pulse, which simultaneously reduces the risk of macroscopic damage. An example of the high quality of the resulting sculpture is shown in Figure 1.

A valuable technical application of laser damage in optical glass and other normally transparent materials is the drilling of long and narrow channels. Here, the process is initiated at the far end of the workpiece (Figure 2), so that there is a possibility for the heated glass material to escape without causing damage to the surrounding material. Thus the resulting bore has rather smooth walls, and by changing the location of the laser focus may vary in size over its length. The limit to this process is essentially set by the condition, where the debris is no longer expelled from the bore but starts to adhere to its lower end, but highly attractive length-to-diameter ratios are technically feasible if the process parameters are carefully chosen. An example is shown in Figure 3.

Figure 1 Three-dimensional image of a fly, sculptured in a block of glass. This image consists of more than 50 000 microcracks. Reproduced by friendly permission of the Institute for Laser Technology, Aachen (D).

4 Required lens properties

To generate a three-dimensional pattern in glass by focused pulsed laser radiation, it is common practice to process the workpiece in subsequent layers perpendicular to the direction of the laser radiation, while the workpiece is gradually moved from layer to layer. Within each layer, the beam is scanned rapidly as allowed by the pulse repetition rate, which for lasers corresponding to

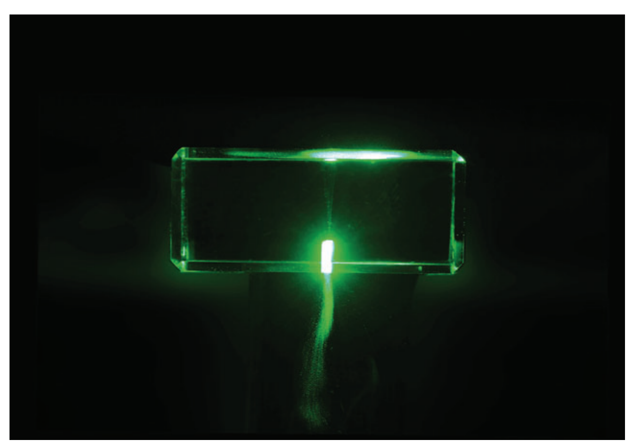

Figure 2 Using high power density Nd:YVO4-laser radiation for drilling high aspect ratio bores in glass. The process is started at the rear side of the workpiece so that debris can escape through the bore. Picture courtesy of Edgewave GmbH, Wuerselen, Germany.

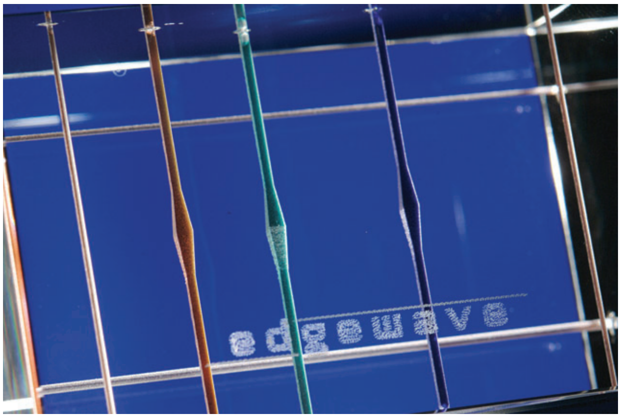

Figure 3 The size and cross-section of bores drilled by non-linear absorption of high power density laser radiation can be varied along the bore. Picture courtesy of Edgewave GmbH, Wuerselen (D).

the above used numerical examples will typically run in the lower kilohertz range. The overall productivity can be quite high with good quality images obtainable in just tens of seconds. The optical setup for this procedure consists of rapidly deflecting scan mirrors – usually computer controlled – followed by a focusing optics in the form of a scan lens. A scan lens is characterized by having its entrance pupil well in front of the refracting elements and is thus always strongly non-symmetrical. Scan lenses are often required by the application to have an off-axis focal position, which is proportional to the angle (‘θ’) under which the (collimated) beam (emanating from the scan mirrors) enters the system, rather than the tangent of that angle as is typically required for photography. It is then referred to as an ‘f-θ-lens’ and is characterized by a strong negative (barrel-type) distortion. The linear speed of the focus in the lateral direction is then proportional to the angular deflection speed of the scan mirrors. For the applications discussed in this paper, where pulse durations are smaller than the pulse temporal separation by some three orders of magnitude, there is only negligible movement of the focal position during pulse time, and the exact position of each laser focal spot will typically be solely governed by computer control of the scan mirrors and thus not depend on f-θ-type linear movement of the focus with scan angle, yet the use of a true f-θ-lens will somewhat simplify the translation of the desired machining pattern to the scan mirror positions and thus may save costs.

For constant process behavior over the full machining area, the scan lens must be aberration free over the total field to the point of diffraction limitation at the chosen numerical aperture. As in all laser applications, the numerical aperture of the optics must well exceed that of the laser beam at $1/e^2$ of its waist radius to avoid beam aperturing and associated broadening of the focus. A factor of 1.5 is generally considered appropriate. In practice, a numerical aperture of 0.07 is a reasonable value for applications in glass machining, offering, as the above numerical data show, diffraction image radii near 25 μm for Nd-laser radiation, and half that value for the frequency-doubled Nd-laser radiation, while, as will be seen below, allowing still rather unsophisticated lens designs.

The list of properties of a lens for use in machining of glass discussed, so far, is not yet complete. A flat image surface is desirable although not strictly necessary, as (1) slightly (and homogeneously) bent machined surfaces are hardly visible in practice and (2) any such effect could be compensated for by a suitably advanced software for the adaptation of the computer modeling of the object to slightly curved surfaces, corresponding to a curved image. A further issue is telecentricity of the focused beams in image space. For most of what follows, it will be assumed, that the exiting beams are near telecentric, noting that strict telecentricity is not possible, if there is an axial separation between the scan mirrors for the two mutually perpendicular directions, but this is not normally harmful.

F-θ-lenses with specifications similar to the above are available on the market from a number of vendors, and it is tempting to try them for use in glass machining. This has sometimes resulted in catastrophical lens damage and inner breakdown. To understand this problem, one has to return to the above discussion of the power density aspects of pulsed laser radiation. While the components of a focusing lens system cooperate to generate a final focus, each lens surface will also reflect a small yet significant portion of the incident radiation, and this can create an image, which is called a secondary focus, also referred to as a ‘ghost image’, somewhere in front of that surface. If the reflected beam converges, that image is real. The power associated with such an image will, of course, be only a small fraction of the incident power, determined largely by the quality of the antireflection coatings applied to the optical surfaces, but may well run around 1% of the incident power. Both the exact location of such a ghost image as well as its optical quality play a crucial role in what happens at such an image. If a ghost image is inside (or even worse at the surface of) a lens, and if the ghost image is associated with an enhanced numerical aperture and low aberrations, the threshold for laser damage is often easily exceeded even under normal operating conditions. To play it safe, it is therefore mandatory to design a scan lens for use in laser machining by high peak power pulsed radiation such that all the ghost images are outside the optical components by a reasonable margin. This additional requirement has turned out to dominate the design of such lenses, as it unexpectedly severely restricts the common design options [3].

5 The Hopkins laser diode scan lens

As an example of a lens design from the literature, Figure 4 shows a lens taken from Warren Smith's book 'Modern Lens Design' [4], a design by Hopkins. It uses the classical structure of a scan lens, with a low index of negative lens in front, followed by two high index positive lenses. The performance is excellent, i.e., the lens is diffraction limited at f/5 with a field of view of ±30 mm. A closer inspection reveals, however, a ghost image inside the first lens, created by the reflection from the rear surface of lens 3. This makes the design, as is, unsuitable for the purpose discussed in this paper. The question then arises, what needs to be changed to move the ghost image into an air space, and how this will affect the performance. It goes without saying that a reoptimization of the total lens structure is unavoidable in this situation, where diffraction-limited performance has to be unconditionally maintained. The rather compact structure of the Hopkins lens suggests, that a substantial increase of the axial separation between the first and the second lens might create enough space for accommodating the current ghost image caused by the rear surface of lens 3.

6 Trying to modify the Hopkins lens

Three options of a modified Hopkins lens are shown in Figure 5, all with an intentionally increased axial distance between the front negative lens and the pair of positive rear lenses. All three are the result of reoptimisation, which includes (and rather strongly depends on) bending of the first and second lenses. The upper system has the ghost image from the third lens in a desirable position, but there is now a new real ghost image from the rear surface of the second lens, which happens to fall just inside lens 1. For the middle system, that ghost image has moved into the big air space as well, but now the ghost image from the front side of lens 2 occurs just inside lens

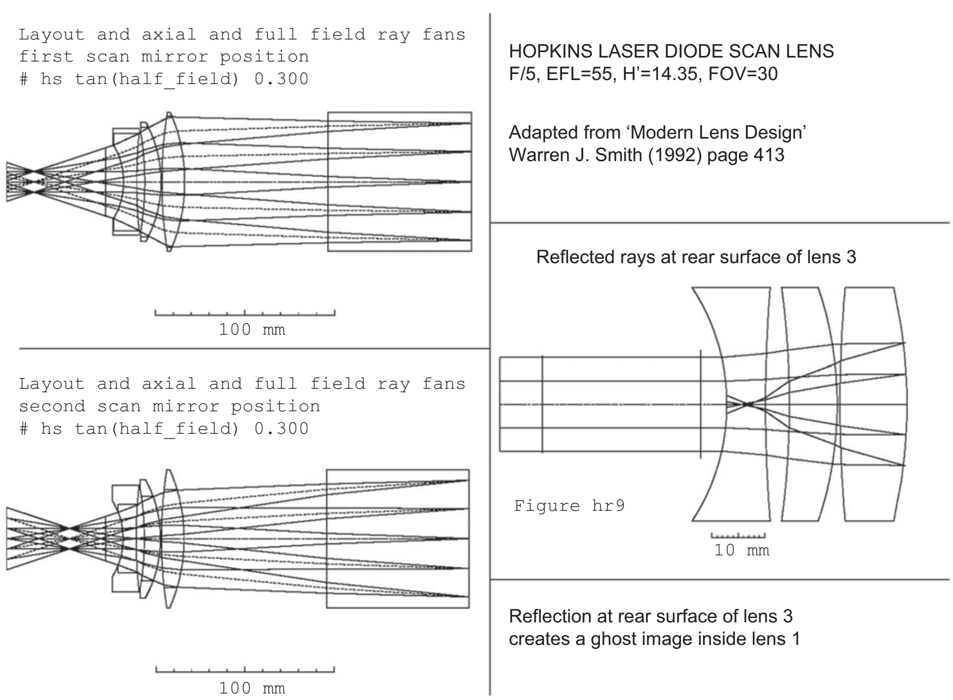

Figure 4 This scan lens design, adapted from the lens shown on page 412 of Warren Smith's book 'Modern Lens Design' [4], a design by Hopkins, has a ghost image inside lens 1, caused by reflection at the rear side of lens 3.

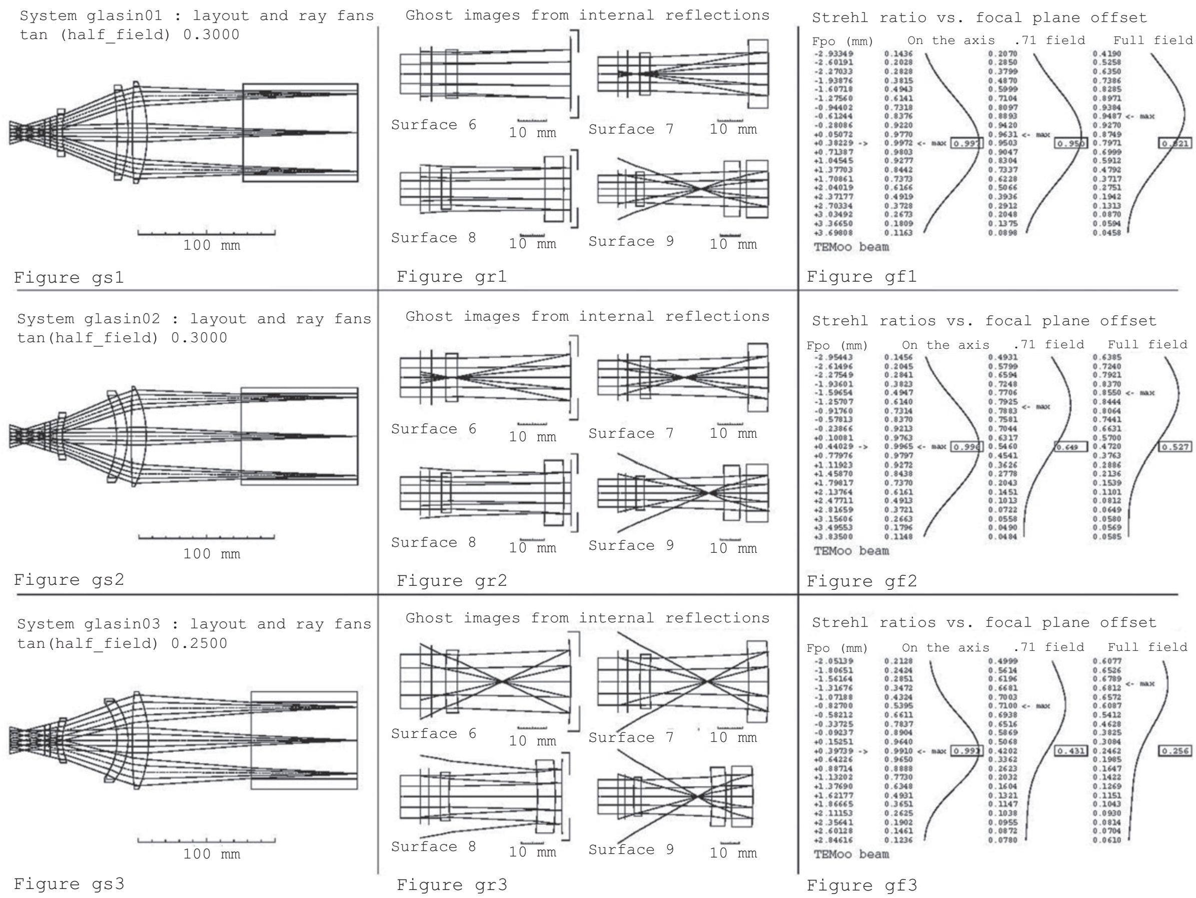

Figure 5 Three lens designs with extended distance between the first (negative) lens element and the positive lens group. Ghost images from the reflection at the rear side of lens 3 are all in air, but the upper system suffers from a ghost image from the rear side of lens 2, the middle system from a ghost image from the front side of lens 2. All ghost images are in the air for the lower system, but field curvature is excessive, and the strong meniscus shapes of lenses 1 and 2 are undesirable. For the meaning of the rightmost column, see text.

1. A further bending of both lens 1 and lens 2 shifts all the previous ghost images into the big air space, but at the expense of (1) a rather large field curvature and (2) quite strong meniscus shapes of both lens 1 and lens 2, which are undesirable, as that makes them relatively expensive to manufacture. The curves at the right in Figure 5 are plots of the dependencies of the Strehl ratios on the axial image plane positions for beams on axis at 0.7 field and at full field; they thus show the field curvatures for the best (=diffraction limited) focus. Note that **not** the (absolute) numbers but the trend towards increased field curvature when going from the upper towards the lower system is of interest and importance here. The rather simplistic line of reasoning, which led to the systems in Figure 5, is clearly unsatisfactory. Obviously both air spaces need to cooperate with the individual surface power contributions for steering the location of the – basically unavoidable – ghost images. This implies, that the design process has to be steered, such as to put restrictions on not only air spaces but also on lens shapes during optimization, while carefully observing their effects and selecting free parameters accordingly. This is a tedious and thus time-consuming process.

7 The structure of a satisfactory design

An example of a rather satisfactory solution is shown in Figure 6. Its structure bears no similarity any more to the previously discussed systems. Both real ghost images, caused by reflections at the rear surfaces of lenses 2–3, are in the air, yet the system is quite compact, and the field curvature is fair, with a sag of the image surface of under 0.5 mm up to an image diameter of 55 mm, running up to 1.2 mm at full image diameter of 75 mm. While this may be acceptable for most applications, it

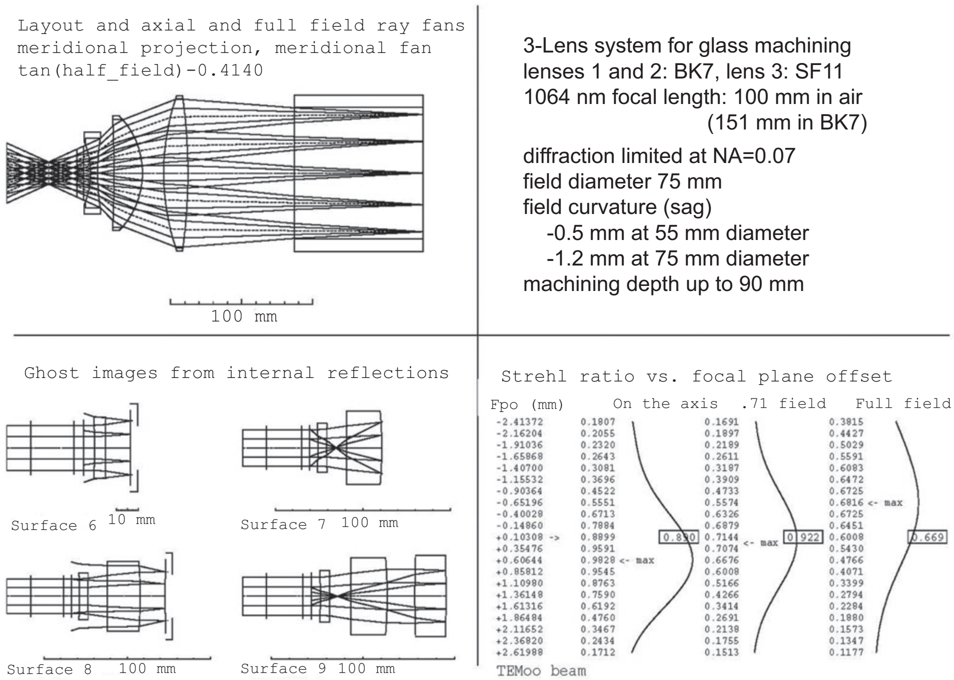

Figure 6 This design uses BK7 glass for lenses 1 and 2 and SF11 for lens 3. Ghost images are all in air, but the field curvature is just a bit too large, as seen by the plots of the Strehl ratios as a function of the axial positions (i.e., the focal plane offsets) of the planes of intersection with beams on axis, at 0.7 field and at full field.

can be improved by a different choice of glasses for both the negative and the positive lenses, as shown in Figure 7 with a similar overall structure. The new glasses are Schott FK5 and N-SF8, and the sag of the image plane is under 0.1 mm for the central 55 mm field and <0.6 mm at full field.

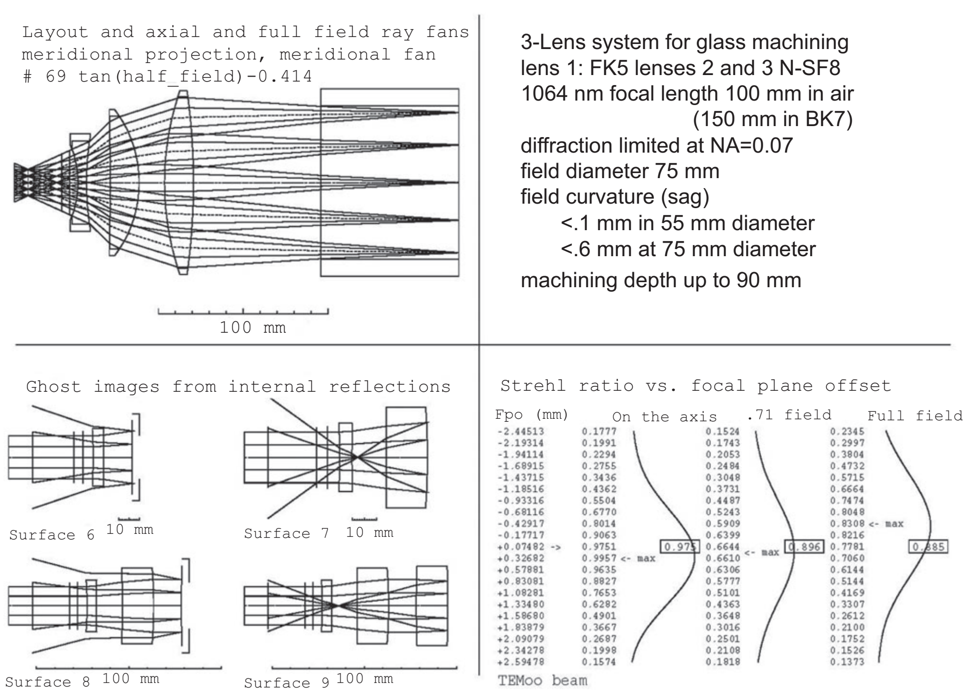

Figure 7 A satisfactory scan lens design for 1064 nm wavelength, using FK5 and N-SF8 glasses. It covers a field of 75 mm diameter with low field curvature.

8 Optimization for frequency-doubled Nd-laser radiation

All lenses discussed, so far, have strong chromatic aberrations, and no effort was made for these designs to compensate for the dependencies of the monochromatic aberrations on wavelength. Consequently, these lenses will not be suitable for use at half the Nd-laser wavelength without substantial reoptimisation, which typically results in possibly undesirable relocations of the ghost images. A version of the lens in Figure 7, adapted to other glasses and reoptimised for frequency-doubled Nd-laser radiation, is shown in Figure 8. Here, the ghost image from the reflection at the rear surface of lens 3 has moved to a position just in front of the first lens.

9 Four-element lens with increased focal length and field coverage

To satisfy the higher demands on field size and field flatness, as well as enhanced image size and depth of machining of glass, it appears necessary to add another lens element. The preferred configuration will spread the positive lens power over three rather than two lens elements. It may be noted, that this approach is quite in line with the design of the rear part of the typical (photographic) double Gauss-type lenses of enhanced performance. Adding a lens will necessarily add two more reflections at those refracting surfaces, which, in the light of the above discussions, might give rise to difficulty in controlling additional ghost images. The system of Figure 9, a design for frequency-doubled Nd-laser radiation has not only excellent diffraction limited performance (see Figure 10) as well as field flatness, but also has only two real ghost images, resulting from reflections at the rear surfaces of the second and the third lens element, the first of which being located well in front of the first lens and the second in the air space between the first and the second lens. All other reflected beams are divergent and the ghost images thus imaginary (Figure 11).

10 Scaling

Like most optical systems, the lens in Figure 9 is scalable within reasonable limits. As all lateral aberrations increase with scale, the diffraction performance will deteriorate with scale, while simultaneously, the individual lens elements become larger and thus more expensive to manufacture with the required ever tighter tolerances.

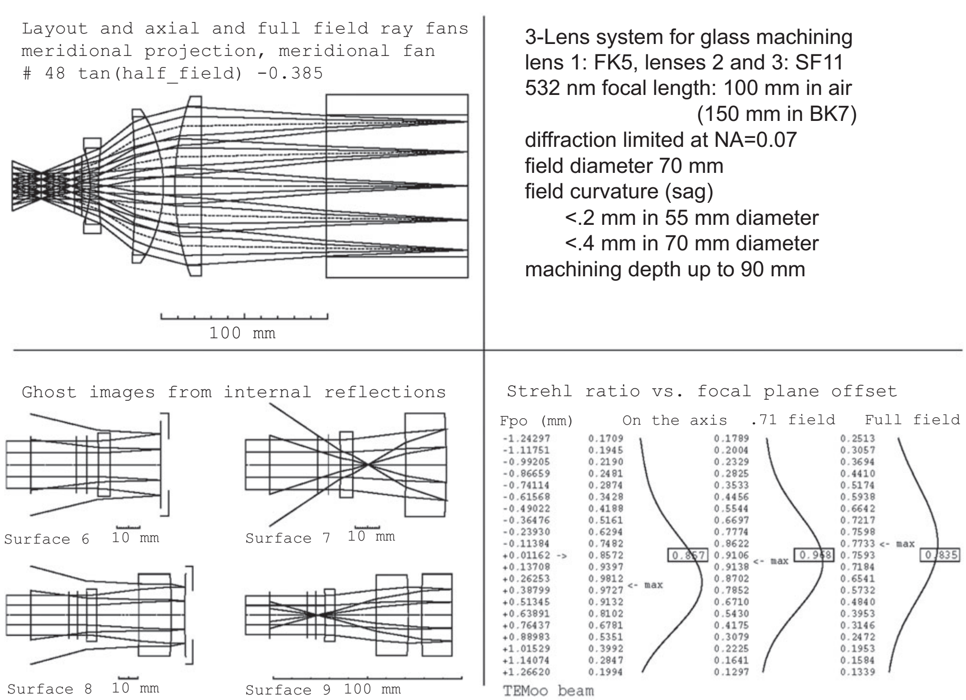

Figure 8 A scan lens design for the 532 nm wavelength, using FK5 and SF11 glasses. It covers a field of up to 70 mm diameter.

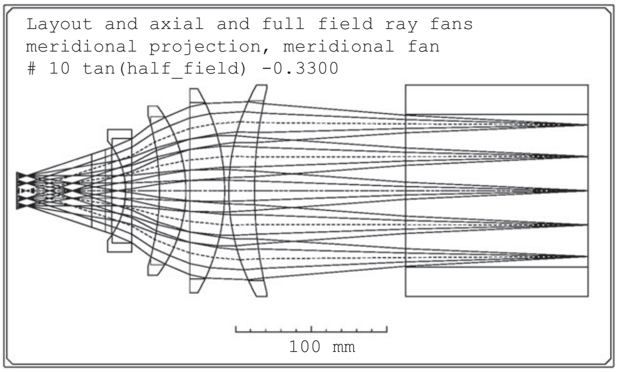

Figure 9 A high-performance four-element scan lens design for 139 mm focal length in air at 532 nm wavelength. It is diffraction limited (Strehl ratio >0.9) at NA=0.07 and covers a field of 90 mm diameter, flat to better than 0.1 mm.

The system in Figure 9 is still diffraction limited if scaled up to a focal length of 200 mm, roughly a factor of 1.4, and will then cover a field of up to 130 mm diameter and allow machining depths of up to 185 mm. The diameter of the largest lens has by then, however, grown to 200 mm, which makes the system huge, heavy and expensive. This is essentially the price to pay for telecentricity. In view of this, some tests have been done with a lens, which was specifically designed for somewhat divergent field ray beams, such as to limit the lens diameters to just 100 mm for a diffraction-limited field coverage of 130 mm diameter. Sculptures in glass were created with this lens, but they did not satisfy the aesthetic demands and expectations of the viewer. As the individual cracks are slightly elongated in the direction of the focused

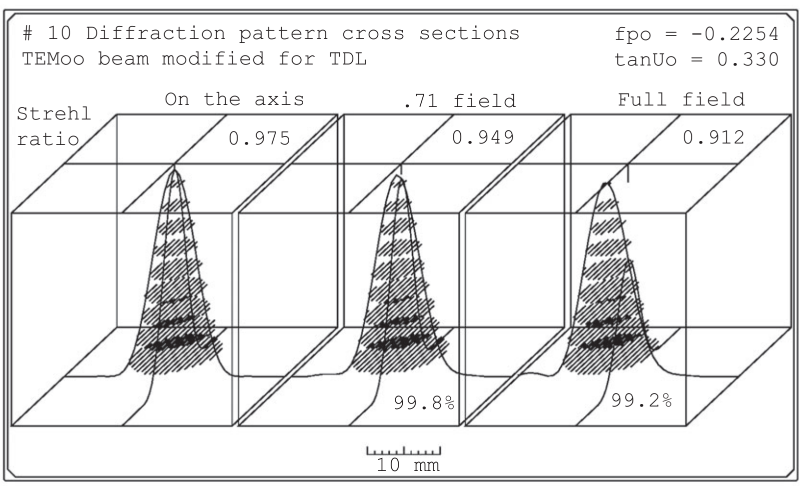

Figure 10 Diffraction patterns for the lens shown in Figure 9. The full field image is laterally offset by a small amount of coma, which is not harmful for the application.

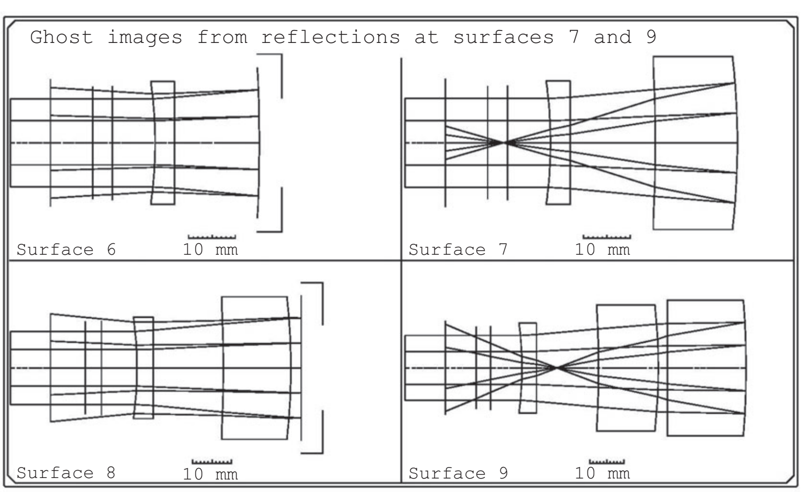

Figure 11 There are only two real ghost images for the lens in Figure 9, both in air.

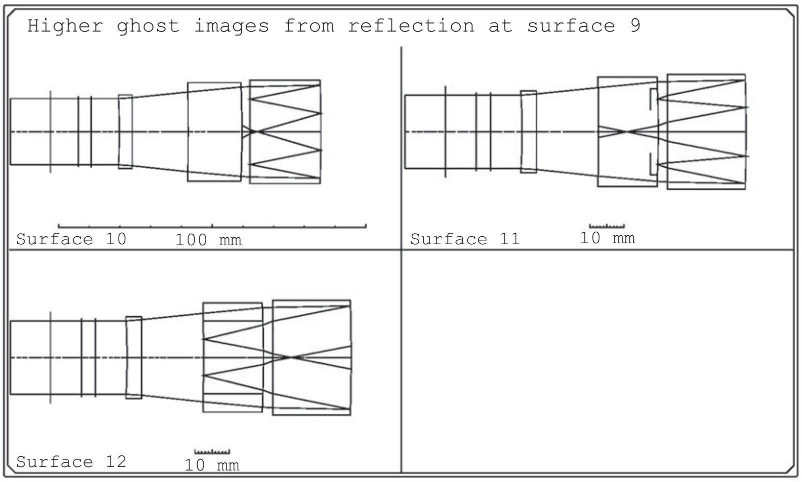

Figure 12 Light reflected from the rear surface of lens 3 of the system shown in Figure 9 creates a secondary ghost by a second reflection at the front side of lens 2, and which is inside lens 3 (below). There are also two tertiary ghosts, both in glass (above).

beams, the overall visual appearance varies undesirably over the field and thus depends strongly on the direction of viewing. Thus, it appears, that three-dimensional sculpturing, such as exemplified by Figure 1, needs telecentric optical beam processing in image space if only for aesthetic reasons.

11 Secondary and higher ghost images

In all the above, we have considered and dealt with only such ghost images, which result from a single reflection at one lens surface. The beams created by such reflections will, of course, be again partly reflected by the surfaces they encounter on propagation, and this causes what may be aptly called secondary ghost images. There will then also be tertiary ones and so on. With decent antireflection coatings, the intensities of each such higher-order ghost image will typically be some two orders of magnitude lower while, of course, also depending on the associated numerical aperture. Figure 12 shows the secondary ghost images for the four-element lens in Figure 9 associated with the primary ghost image caused by the reflection at the rear side of lens 3, as well as two tertiary ghost images, all of which are inside lenses. Fortunately, when reasonably decent antireflection coatings are applied, the risk of laser damage due to these foci is very low. On close inspection, it becomes quite clear, that there is no way of assuring that secondary ghost images stay outside glass elements, let alone any higher-order ghosts. In practice, no problems have been encountered from such ghosts.

12 Summary

While it may be stated that the design of the optical systems for laser applications will generally follow approaches, which have been used and proven for well-known and established optical tasks, the specific properties of lasers, notably their potential for creating very high power densities, add to the specifications. This, in turn, requires specific – and for classical lens design tasks uncommon and/or unnecessary – attention to the axial positions of ghost images, to the point that this will often dominate the design process [3]. That, in summary, is the message of this paper.

Acknowledgments: The machining of optical glass by high power density laser radiation was pioneered by scientists of the 'Fraunhofer Institute for Laser Technology' (ILT) in Aachen, Germany, which is one of the most important development and contract research institutes in its specific field. Special credit is due to Dipl. Ing. Dieter Hoffmann. This work was strongly supported by the development of Q-switch-pulsed, diode laser pumped, frequency-doubled Nd:YVO4-slab lasers with high beam quality, also pioneered at the ILT [5, 6]. These lasers are presently manufactured by Edgewave GmbH, Wuerselen, Germany. Special credit is due to Dr. Keming Du [2].

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