INVITED PAPER

Optical systems for high-power laser applications: principles and design aspects

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Starting from the optical properties of laser beams, the requirements of optical systems for manipulating laser radiation in industrial applications are derived. The relevant parameters, relations to the diffraction limit and the state-of-the-art design techniques are discussed. The three important types of lasers for use in industrial materials processing operate at wavelengths ranging from the infrared (10.6 μm, CO₂ laser; 1.06 μm, Nd : YAG) to the ultraviolet region (excimer lasers). Each wavelength range is associated with specific design challenges. The scarcity of suitable refractive materials for the 10 μm wavelength range and the ultraviolet below 300 nm is a major constraint. Reflective systems are used widely at the longer wavelength, but some designs suffer from coma. The 1.06 μm radiation from the Nd: YAG laser can make use of many well-developed optical means for handling visible light. Energy transport by optical fibres is commonly used. Optical systems for excimer laser applications are specific in that they image a mask onto a workpiece, and use the high photon energy and the high definition possible with the short wavelength for precision micro-machining.

1. Introduction

1.1. Radiance of a laser

Over the last two decades, the industrial use of lasers in the lower kilowatt power range has grown steadily, in particular for such applications as drilling, cutting and welding. From an industrial standpoint, the laser is a thermal tool, and its usefulness stems from the exceptionally high radiance of the laser radiation source. A (rotationally symmetrical) laser which generates a radiation beam of radius w₀ (or radiating surface A = πw₀²) at the point of smallest beam diameter, or beam ‘waist’, will radiate its power P into a cone of angular radius θ = λ/(πKw₀), where K is the beam quality, which is equal to or smaller than 1. This corresponds to a solid angle of ω = πθ², so that the radiance of the laser N = P/(Aω) is found to be P(K/λ)². Note that this is an average and that the radiance will be even higher in a central peak of the beam or in pulsed mode.

1.2. Focusability

Since radiance is a quantity invariant to (loss- and aberration-free) optical manipulation, optical
systems allow the transformation of laser radiation such that very high power densities \( P/A' = N \omega' \) are achieved by choosing a suitable value of the solid angle \( \omega' \) at which the laser radiation impinges on a surface \( A' \). An alternative parameter, more commonly used in optics, is the numerical aperture \( n \sin U' \), which is related to the solid angle by \( \omega' = \pi \sin U' \).

Apparently then, proper choice of the numerical aperture of the optics which focus the laser radiation onto the workpiece is a major factor for the applications mentioned above.

1.3. Some numerical examples
A quantitative evaluation of the above relations may be helpful for putting things into perspective. Consider a CO\(_2\) laser of 1 kW with a beam quality \( K = 0.5 \). Its radiance is approximately \( 2.2 \times 10^8 \) W cm\(^{-2}\) sr\(^{-1}\), and it is noteworthy that this level corresponds to blackbody radiation at a temperature of \( 1.05 \times 10^5 \) K. It is obvious that power densities well in excess of \( 1 \) MW cm\(^{-2}\), as required for processes such as drilling and cutting, are readily achievable even at moderate numerical apertures. As a second example, take a high-power solid-state (Nd:YAG) laser which delivers 1 kW of power into an optical fibre. Its poorer beam quality — the beam quality \( K \) will typically be about 0.012 — is only partially compensated by the ten times shorter wavelength, and the radiance is down to approximately \( 1.4 \times 10^7 \) W cm\(^{-2}\) sr\(^{-1}\), but still at an impressive and highly useful level.

As seen from the above examples, laser radiation constitutes a very powerful thermal tool, but it is also a costly source, and optimum use of its inherent capabilities is mandatory for successful competition with other technologies. For any given laser and application, this largely boils down to a proper choice and design of the optical train which transports and ultimately focuses the radiation on to a workpiece, and this is the subject of the present paper.

1.4. Importance of laser beam quality
From the above relations it will also be apparent that beam quality is a controlling factor for the efficient use of laser radiation in all cases where power density is the essential quantity for the process, in that a laser of higher beam quality will allow either a higher power density for the same optical layout or a reduction in power level or numerical aperture. The continuous drive towards lasers of better beam quality is largely fuelled by the demand for higher process efficiencies. It goes without saying, that the design of suitable optics has to accompany, and preferably anticipate, these trends.

2. Optical properties of laser radiation
2.1. The Gaussian beam
Although laser radiation can be relayed, manipulated or focused by optical means just like any other optical radiation, there are important differences rooted in the spatial coherence of laser radiation. In the special case of a Gaussian beam profile, the beam, while propagating along its longitudinal axis \( z \), changes its radius in a nonlinear fashion according to

\[
w(z) = w_0 \left[ 1 + \left( \frac{\lambda z}{\pi w_0^2} \right)^2 \right]^{1/2}\]

so that the beam boundaries do not form straight lines analogous to the rays in classical optics. Instead, the beam radius attains a minimum of \( w_0 \) at \( z = 0 \), referred to as the beam waist, and fans out, in accordance with the above equation, to a cone of radiation with a limiting half-angle

\[
\theta_{z=\infty} = \frac{\lambda}{\pi w_0}
\]
The distance over which the beam has grown to $\sqrt{2}$ times its size at the waist is known as the Rayleigh range $z_R$, and

$$z_R = \frac{\pi w_0^2}{\lambda} \quad (3)$$

At the site of the waist, the beam phasefront is flat, and its radius of curvature $R(z)$ changes along the axis of propagation according to

$$R(z) = z \left[ 1 + \left( \frac{z_R}{z} \right)^2 \right] \quad (4)$$

### 2.2. Relation to classical optics

The above relations are quite different from those for classical ray optics; yet the concept of optical rays retains some usefulness when treating laser beams, provided they are strictly seen as the normal to the phasefront of the beam, which is exactly what they are in noncoherent optics. The well-established methods for optical design, which are essentially based on ray-tracing, can, with some modifications, be applied to optics for laser beam handling; these modifications concern the nonlinear change of wavefront curvature in transfer from one optical surface to the next, in accordance with the above relation, but the correction is very small in most cases. The laws of refraction and reflection apply unchanged.

The analogy with noncoherent radiation may be extended to the generation of an image, which is the formation of a diffraction pattern from a converging phasefront at some point in space, and which may be simulated by calculation of the (Huygens) diffraction integral. Quantitative differences with respect to the noncoherent case result from differences in amplitude and phase distribution over the phasefront, however, and affect the position as well as the size and shape of the spot of highest energy concentration. Most marked is the absence of outer rings, characteristic of the Airy pattern, in the case of an untruncated beam with a Gaussian profile.

### 2.3. Real laser beams

The above applies to purely Gaussian, or fundamental mode (TEM$_{00}$), laser beams and has to be modified for real beams which are characterized by higher and mixed modes.

A difference of practical importance and rather far-reaching consequences, is related to the definition of the beam size. While incoherent beams are usually limited by hard aperture stops to well-defined beam widths, the definition of that quantity for laser beams is much less obvious. For pure Gaussian beams, the level at which the power has dropped to $1/e^2$ of its central peak is quite generally used for describing the beam width, but for higher and mixed mode beams this level is no longer meaningful and must be replaced by a more rigorous and fundamental definition. A suitable and generally applicable description of the beam width is based on the second moments of the power density distribution function of the beam [1–3] and this quantity has also been adopted for the proposed ISO and CEN standards [4].

It should be noted, that the 'beam quality' $K$, already introduced above, is based on this beam size definition, and enables us to apply the formulae for the Gaussian beam also to real beams, if the wavelength $\lambda$ is replaced by the quantity $\lambda' M^2$

$$\frac{\lambda}{K} \equiv \lambda' M^2 \quad (5)$$
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which could be looked at as an ‘effective’ wavelength. Not only does the introduction of $K$ (or $M^2$) allow us to express the beam quality by a single number, but also the quantity is seen to be directly related to the product of the beam diameter and the full beam divergence [5]:

$$4\theta w_0 = \frac{4\lambda}{\pi K} = \frac{4\lambda M^2}{\pi}$$

This quantity is also known as the beam parameter product [6]; it is invariant throughout the beam propagation, as long as aberration-free optics are involved. Both $K$ and $M^2$ are used (interchangeably) in the literature, but in what follows we will use $K$ exclusively.

2.4. Effect of aberrations

Inasmuch as aberrations of an optical system can be seen as deformations of a source phase-front, such aberrations will alter the power distribution within the focal spot, generally associated with an increase of the spot diameter. This, in turn, can be expressed by a decreased $K$ value. As in consideration of optics for noncoherent radiation, the effects of aberrations on the quality of the image become negligible if the wavefront aberrations are small.

What is to be considered small here is somewhat arbitrary. The well-known Rayleigh quarter-wave criterion refers to the peak to valley phase difference in a smoothly varying phasefront, and translates to an RMS phasefront error of somewhere between 1/14 and 1/20 wavelengths for more irregular phasefronts and those including random fabrication errors [7]. In the noncoherent case, the corresponding Strehl ratio is 0.8, and this still qualifies as excellent image quality. A similar argument and criterion will suffice for most laser applications as well. At the other end, diffraction effects are essentially wiped out if the RMS phasefront error exceeds a few wavelengths.

2.5. Transition from diffraction to aberration limitation

Between the limits of pure diffraction and predominant aberrations, the spot size and power distribution within the focal spot will gradually change from those determined by diffraction to those controlled by the aberrations of the system at hand. For coherent beams, the precise effects of the phasefront aberrations in that intermediate range cannot be calculated by straightforward methods, except for simple cases [8], and various simplifying approaches have been in use or proposed for ‘adding up’ diffraction and aberration quantities [9, 10]. Such approaches may typically be based on the reasoning that a simple algebraic sum of the diffraction and aberration contributions will be on the safe side for quantifying the actual focal size, or that the root of the sum of the squares of each contribution is an apparently reasonable proposition. Undoubtedly, the former, worst case, assumption will at least give a rough indication of which level of aberration will cause a sensible reduction of performance. If the parameters of the optical system and the beam amplitude and phase distribution are fully known, a calculation of the diffraction integral by numerical methods is probably the most reliable method for obtaining quantitative data on the expected size and power distribution of the focal spot.

2.6. Diffraction spot size

While the differences in power roll-off towards the limits of the beam led to the need for different size definitions for laser beams and for noncoherent (i.e. hard truncated) beams, as discussed above, a similar difficulty pertains to the definition of the size of the diffraction image. In the noncoherent case, the quantity of choice is the diameter of the first dark ring of the Airy pattern, which occurs at $1.22\lambda/(n' \sin U')$ where $U'$ is the limiting angle of the
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cone of the converging radiation beam, and $n'$ is the refractive index of the medium in which the image is formed.

In a Gaussian focus, there is, of course, no 'first dark ring' and the size definition becomes arbitrary. Using the $1/e^2$ limit discussed above, the full width of a Gaussian beam focus is $d = 2\lambda/(\pi n \sin U')$, or $0.64\lambda/(n \sin U')$. Although the two definitions are of necessity incompatible, in that the optical diameter needed to ensure that the Gaussian beam is not truncated at the $1/e^2$ level requires a substantially larger $\sin U'$, the coherent image is easily seen to be smaller than its noncoherent counterpart. It will further be noted that in both cases roughly 15% of the energy falls outside the diffraction diameter, albeit with quite different shape, the Gaussian image being much more compact as much more than 99% of the energy falls within two diffraction diameters.

2.7. Real spot size
From the above, the size of a focused real laser 'spot', actually the diameter of an (image) beam waist, for a laser of beam quality $K$ is seen to be

$$W_w = \frac{2\lambda}{\pi K \sin U'}$$

Since $\lambda$ and $K$ are determined by the choice of the laser used, the only parameter left to the user for control of the spot size is the numerical aperture of the focusing optics - quite in analogy to classical optics. It is also apparent that a laser of superior beam quality ($K$ approaching 1) allows one to achieve a desired spot size at lower numerical aperture. This is important for three reasons: a higher numerical aperture generally requires optics which (1) are more sophisticated, (2) will typically have a shorter back focus (i.e. the last optical surface will be closer to the workpiece), and (3) have a shorter depth of focus, quantified by the Rayleigh range associated with the radiation cone at the image, $Z_R$, where

$$Z_{R1} = \frac{\pi K W_w^2}{\lambda}$$

or, with Equation 7,

$$Z_{R1} = \frac{W_w}{\sin U'}$$

which shows that, for any given spot size $W_w$ the Rayleigh range will be proportional to $K$ (Equation 8) or, equivalently, inversely proportional to the numerical aperture that was required to achieve that spot size (Equation 9).

2.8. Low-beam-quality sources
For laser beams with a beam quality $K$ well below 1, as is typical for most high-power solid-state lasers, the focal size approaches that of the classical image of an extended object. This is easily demonstrated for the case of the radiation output from, for instance, a Nd: YAG laser, which is delivered via an optical fibre of diameter $D$. The fibre output forms a source of diameter $D$, or radiating surface

$$A = \frac{\pi D^2}{4}$$
and if the beam quality is $K$, it will radiate all power into a cone of angular radius

$$\sin U = \frac{\lambda}{\pi KD/2} \quad (11)$$

Now let this radiation beam enter an optical system of magnification $m$; then the exiting radiating cone will have an angular radius of $\sin U' = (1/m) \sin U$, and the geometrical image diameter will be $d = mD$. The diffraction image of a Gaussian source, however, would have a diameter of

$$d_{\text{diff}} = \frac{2\lambda}{\pi \sin U'} = \frac{2\lambda m}{\pi \sin U} \quad (12)$$

and with the above relation between $K$ and $\sin U$, we find

$$d_{\text{diff}} = mKD \quad (13)$$

that is, it would be $K$ times smaller. In other words, with decreasing $K$, the diffraction contribution is only a fraction $K$ of the diameter of the image. Apparently, a corresponding argument applies to the level of acceptable aberrations. Conversely, with the trend towards lasers of improved beam quality, a concurrent drive for improved optics is mandatory.

3. Optical system aspects of industrial lasers
3.1. Which laser is fit for industrial use?

For a laser to be fit for industrial application in materials processing, we require that it has a reasonable energy efficiency and that it can be scaled up to the power level needed for the intended application. Very few laser types satisfy these quite straightforward requirements. In today’s practice we encounter only the following.

1. The $CO_2$ laser, a gas laser radiating at 10.6 $\mu$m wavelength. With an efficiency up to 15%, it is the only laser that has been built for (continuous) power levels of 10 kW and beyond, although by far the largest number of presently installed industrial $CO_2$ lasers operate below 3 kW.

2. The $Nd: YAG$ laser, a (preferred) member of a family of solid-state lasers based on ions of rare-earth elements dissolved in a host crystal selected for its high thermal conductivity. It radiates at 1.06 $\mu$m, has less than 3% efficiency and is mostly built for (average) powers of several hundred watts, often delivered in pulses (peak powers typically 1–10 kW, but up to 1000 kW if operated in $Q$-switched mode). Continuous powers up to 3 kW have become available recently.

3. The family of excimer lasers, gas lasers based on excited dimers formed by a halogen (F, Cl, etc.) and a noble gas (Ar, Kr, etc.), and operating in the ultraviolet spectral region with an efficiency of 2–4%. The radiation is always emitted in short pulses (tens of nanoseconds duration) and thus at very high peak powers (above $10^7$ W). The emitted wavelength depends on the gas composition, with KrF (248 nm) and ArF (193 nm) being of particular interest and value.

In addition to the above, the semiconductor (or diode) laser offers interesting prospects, mainly owing to its excellent efficiency (up to 50%) and attractive principle of operation (solid state, direct electrical activation). It lacks scalability, and if powers of more than a few watts are needed the output from a number of individual units must be combined by some optical means. Some design problems associated with this task will be discussed briefly below. These lasers operate in or near the visible spectrum.
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Each of the spectral regions associated with the above lasers has its specific problems and calls for quite different approaches. Details of each of the three lasers mentioned will be discussed in subsequent sections.

3.2. Common aspects of laser optics
It should also be noted that there are some common aspects that apply to all high-power laser optics. First, all optical surfaces have to be kept very clean and damage-free to avoid warm-up, thermal stress and eventual rupture. Second, and in particular when dealing with CO₂ lasers in the kilowatt class, the (unavoidable) residual absorption by optical components requires carefully designed cooling schemes and cooling geometries. Third, to minimize the risk of undue absorption of radiation at lens rims and mounts, etc., the clear optical diameters have to be carefully chosen and, wherever there is a chance for a laser beam to hit the rim of an optical device, a (cooled) diaphragm must be placed in front of (and outside) that device.

All designs for manipulating high-power laser radiation should avoid intermediate loci and the use of optical surfaces at (much) reduced beam diameters. While it is always recommended to try to achieve the required system performance with a minimum of optical elements, extra emphasis should be given to this aspect in view of the complexity (cooling) and cost (materials) of laser optics.

3.3. CO₂ laser optics
3.3.1. Beam transport and relaying
The scarcity and high cost of suitable refractive optical materials for wavelengths around 10 μm have important consequences for the layout of optical systems for high-power lasers. Mirrors are the primary means for transport, positioning and manipulation of the high-power beam. This beam typically emanates from a stationary source and may initially have a diameter of a few centimetres. It is often necessary to bridge long and varying path lengths of the order of ten metres to the actual site of material processing.

To avoid undue losses and beam quality deterioration in the numerous mirrors for beam redirection, the requirements for reflectivity and surface flatness increase with the number of reflective surfaces and the distance to be bridged. Telescopes are often included in the beam-relaying optics for two reasons: (1) to reduce angular beam shift, and (2) to expand the beam for less dependence of the beam diameter on the axial distance, and more specifically, to create an expanded beam waist near the centre of the range of operation in the axial direction. A wider beam may also be desirable as it leads to focusing with a larger back focus for a given numerical aperture. This, of course, has to be weighed against the size, cost and weight of larger focusing optics, and may call for a beam-narrowing telescope just in front of the focusing optics.

3.3.2. Telescopes
In applications with lasers, telescopes are often referred to as beam expanders, since adaptation of the beam diameter to the requirements of the system setup is their main function. Of the two well-known types of telescopes, the Keplerian and the Galilean, the latter, which uses a positive-negative combination of optical elements, is preferred in laser applications because it avoids an intermediate focus and is shorter. Lenses can be used at the lower powers, but in CO₂ laser applications mirrors are more commonly used. If these mirrors are of paraboloidal shape, the ingoing and outgoing beam axes will be parallel (Fig. 1a); if spherical mirrors are applied, the angles of deflection must be different at the two mirrors (Fig. 1b) in order to
Figure 1  Galilean telescope designs for beam expansion and waist relocation of a CO\textsubscript{2} laser beam, using off-axis paraboloidal mirrors (a) or spherical mirrors (b). Note the different tilt angles in the latter case, required to compensate for astigmatism. Mirror separation is adjusted to control the position of the image beam waist. The associated lateral beam shift is offset by synchronously moving a third, flat, mirror, often arranged for a total deflection of 90° (c).

compensate for astigmatism. By slightly varying the separation between the two mirrors, the telescope can be adjusted to control the beam waist position. This is, of course, associated with a lateral beam shift, which must be compensated by a third mirror, which is often arranged such that the total unit has a 90-degree deflection (Fig. 1c).

3.3.3. Lenses for CO\textsubscript{2} lasers
At power levels up to, say, 3 kW, CO\textsubscript{2} laser radiation can be conveniently focused by lenses [11, 12]. In applications such as cutting or welding, the lens simultaneously serves as a pressure window for the gas that assists in the process. These lenses are almost exclusively made from ZnSe, which is the only environmentally stable material with the required low bulk absorption [13]. High-quality (sometimes referred to as ‘laser grade’) ZnSe is available from several vendors with a bulk absorption coefficient of <0.0005 cm\textsuperscript{-1} [10, 14] at the wavelength of the CO\textsubscript{2} laser. Including the losses in a (high-quality) antireflection coating, a good new ZnSe lens will absorb less than 0.15% of the incident radiation [5].

The refractive index of ZnSe (2.4028) is comfortably high enough to allow a single lens to achieve diffraction-limited performance on-axis at moderate numerical apertures. The limit is somewhat arbitrary and depends on how much the focal spot is allowed to exceed the minimum spot size due to diffraction alone. The latter was seen above to be

\[ W_w = \frac{2\lambda}{\pi K \sin U'} \]  \hspace{1cm} (14)

The spot contribution due to spherical aberration of the lens can be approximated by

\[ W_s = \frac{hD^3}{f^2} \]  \hspace{1cm} (15)

where \( D \) is the lens diameter, \( f \) is its focal length, and \( h \) is a (dimensionless) constant depending
on refractive index and lens shape. Its numerical value, for ZnSe, is 0.0286 for a plano-convex
lens, and 0.0187 for a meniscus-shaped lens. Using the approximation $D/2f = \sin U'$, we can
write

$$W_s = 4hD \sin^2 U'$$  \hfill (16)$$

The ratio of the two contributions to the spot size is

$$\frac{W_s}{W_w} = \frac{2\pi K}{\lambda} Dh \sin^3 U'$$  \hfill (17)$$

and is seen to depend strongly on the numerical aperture. To meet a given ratio of $W_s/W_w$ for a
given beam quality $K$ and beam diameter $D$ at the lens, the numerical aperture may not exceed

$$\sin U' = \left( \frac{W_s}{W_w} \frac{\lambda}{2\pi K Dh} \right)^{1/3}$$  \hfill (18)$$

For a beam of 25 mm diameter, and a CO$_2$ laser with $K = 0.5$, this limiting aperture is 0.106
($f/4.8$) and 0.122 ($f/4.1$) for a plano-convex and a meniscus lens, respectively, if we require
that $W_s$ is less than 25% of $W_w$. We can rewrite Equation 18 in terms of the focal length and
find

$$\sin U' = \left( \frac{W_s}{W_w} \frac{\lambda}{4\pi K fh} \right)^{1/4}$$  \hfill (19)$$

a relation which allows one quickly to evaluate the suitability of a single lens of given focal
length $f$ for an intended application.

Even if we tolerate a larger aberration contribution than was used in the above example, the
high power at which $\sin U'$ enters the formulae makes for a rather hard limit of operation of the
single, spherically shaped lens.

3.3.4. Extending the limit of the single lens

There are several options for operation beyond that limit. One is the use of diffractive optics;
this is obviously favoured by the relatively long wavelength, and diffractive optical elements
with the required high diffraction efficiency have recently become commercially available
[15]. A second option is to aspherize one of the lens surfaces, which, in principle, allows
one to fully remove spherical aberration. Still another is to use more complex designs based
on multiple lenses. Such designs may be of the retrofocus type [16], which has the advantage
of allowing excellent aberration correction while simultaneously enlarging the back focus
(Fig. 2).

3.3.5. Use of zoom optics

Since numerical aperture is the quantity of choice for matching the beam focus and the depth of
focus to a given application, lens systems which allow continuous adjustment of the numerical
aperture would seem to be of high practical value. These are zoom systems, comparable to the
zoom lenses which are widely used in, for instance, photography, except that they are operated
at constant entrance pupil diameter rather than exit pupil diameter, and the $f$-number varies
accordingly, which is here the reason for zooming. A 3 : 1 range of focal lengths (and $f$-numbers)
can be covered with relatively unsophisticated, yet diffraction-limited, optics using just three
lenses (all spherical) or even only two (one aspheric surface). Note that the appropriate variation
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Figure 2  ZnSe lenses for focusing CO\textsubscript{2} laser radiation at different numerical apertures, all drawn to the same scale. (a) Planoconvex lens at f/3.5; (b) meniscus lens at f/2.8; (c) retrofocus two-lens system at f/2.4; (d) retrofocus two-lens system at f/2.0; (e) retrofocus three-lens system at f/1.4; (f) single lens with aspheric front surface at f/1.4. All lenses are diffraction-limited (Strehl ratio >0.95) for a beam of up to 23 mm diameter. Note that retrofocus designs (c, d, e) allow maintenance of a large back focus.

in depth of focus (Rayleigh range) is nearly one order of magnitude. There has been surprisingly little activity in this area, although the feasibility and usefulness of the approach has been well demonstrated [17].

3.3.6. Thermal effects in (ZnSe) lenses

The residual absorption of CO\textsubscript{2} laser power in ZnSe lenses, a substantial part of which occurs in the antireflection coatings, causes lens heating and radial temperature gradients in the lens if cooling is, as usual, by heat conduction to the lens rim [18–20]. In a new and perfectly clean lens made from highest-quality material, the effect is small, but it increases strongly for a contaminated and/or (lightly) damaged lens surface. The primary result is a shortening of the focal length, and by far the largest contribution to that is caused by ray bending due to the thermally induced gradient of the refractive index. A simple model, which describes the situation in thermal equilibrium, has been shown to match experimental data within 10% [20]. A more sophisticated model, based on finite-element calculations, leads to similar results and, in addition, covers the time dependency of the effect [21]. In an example situation of a lens absorbing 20 W (1% of a 2 kW beam) the lens centre will attain a temperature 25 K higher than the rim, and the focus shift after reaching thermal equilibrium — which typically takes half a minute — is of the order of one Rayleigh range. For an application like cutting, this is normally beyond acceptable limits, and thus puts a limit on lens absorption of, say, 10 W at most if serious deterioration of cutting quality is to be avoided. Interestingly, the heating of the lens centre hardly affects the aberrations; in fact, the spherical aberration is even slightly reduced. Lens heating and the associated focal shift have so far attracted surprisingly little attention in
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the literature on laser materials processing, and probably have been largely underestimated as a source of poor process reproducibility.

3.3.7. Mirror systems for use with CO2 lasers

For the focusing of laser powers in excess of, say, 3 kW, but under certain conditions also at lower power levels, mirror systems are preferable to refractive optics. Owing to the excellent thermal conductivity of relevant mirror substrate materials, notably copper, and owing to efficient cooling geometries, which are essentially independent of the mirror size, reflective optics can withstand both high power levels and power densities (in excess of 10 kW cm\(^{-2}\)) without suffering from undue distortion. For the larger beam diameters, associated with high-power beams and ranging occasionally up to 80 mm diameter, mirrors also offer substantial cost advantages over refractive optics.

Material aspects

High thermal conductivity, high reflectivity at the CO2 laser wavelength (>99%), which can be further enhanced by suitable coatings, and suitability for precision machining, have made copper the most popular substrate material for mirrors used with CO2 lasers. Its only drawback is its low hardness and consequent susceptibility to scratching during cleaning. Thus, occasionally, and in applications where a mirror is subject to spatters or fumes, a material of higher durability and hardness is preferred, notably (bare) molybdenum, which has a reflectivity of typically 98%. Mirrors for CO2 laser applications are often delivered with cooling water channels integrated into the mirror body.

Angular field requirements

Since laser beam focusing is normally by the use of an optical system within a very small angular field centred about the axis, it is tempting to consider only the axial aberrations of such systems. It must be borne in mind, however, that mirror optics for laser beam handling are of necessity applied in some off-axis arrangement to avoid central obscurations, and that such systems are notoriously difficult to align so that they are truly operating with the ingoing beam parallel to the actual optical axis. As a consequence, the focusing system should tolerate angular deviations from the true optical axis of, say, one or two milliradians, and it is important to consider the possibility of aberrations at these field angles, small as they may seem to be.

Off-axis paraboloids and coma

A case in point is the off-axis paraboloid, which has been quite popular among users of high-power lasers because it is known to have no spherical aberration. Paraboloids do suffer, however, from very large coma, owing to the impossibility of fulfilling the optical sine condition. Its magnitude is often underestimated or even neglected in system considerations [22], yet it is the primary source of concern for paraboloidal mirrors, particularly when these are used at large off-axis angles (90-degree off-axis paraboloids are not uncommon). The disappointingly poor performance often seen in practice is nearly always due to alignment inaccuracies and associated coma.

Figure 3 is a comparison of the alignment sensitivity of off-axis paraboloids at, respectively, 40° and 90° with that of several other mirror systems, all operating at the same numerical aperture, and shows the dramatic deterioration of the quality of the focus of a 90-degree off-axis paraboloid at a field angle as small as 1 milliradian.

In actual practice the situation is complicated by the fact that the comatic image changes its
Figure 3  Comparison of the alignment sensitivity of different off-axis mirror systems. The central part of the figure shows the geometrical aberrations (diameters of the blur circles) in relation to the deviation from the system axis. The systems on the left side use paraboloidal surfaces under $90^\circ$ and $40^\circ$, respectively. The systems on the right side are based on spherical mirrors [25].

shape with increasing off-axis angle. This is caused by the shape of the comatic wavefront, which is symmetrical about a plane which contains the axis and the chief ray, but has central symmetry about the intersection with the axis [23]. As we move off-axis, we only take a section of that wavefront, in which the centrally symmetrical component becomes increasingly unbalanced, and in which the component with planar symmetry predominates more and more. As a result, the section of the aberrated wavefront actually used attains a more and more cylindrical shape, which is the characteristic of astigmatism. Accordingly, line foci show up in planes in front of, and behind, the best axial image. There is no cure for coma of single mirrors other than the use of designs involving two (or more) curved surfaces. This has, of course, been well known to optical scientists for a long time, and led to designs such as the Ritchie–Chretien system which dominates modern astronomical telescopes. Unfortunately, this and other related systems do not lend themselves well to off-axis derivatives, in that (1) the numerical aperture of an off-axis cutout will typically be much too small for laser focusing applications and (2) the back focus will of necessity be much shorter than the focal length. It is easily seen that all two-mirror systems with a concave–convex sequence of curved surfaces suffer from these two drawbacks, regardless of their precise shape.

Alternative mirror configurations
A straightforward conclusion is that a convex–concave sequence of mirrors, i.e. the well-known Schwarzschild design [24] is better suited to meet the specific needs of laser focusing optics. This is indeed true, yet an off-axis section of the basic Schwarzschild mirror system requires a secondary (concave) mirror which has roughly five times the diameter of the incoming beam, which makes it cumbersome and expensive. An obvious cure to this problem is the addition of a third curved mirror, that is, a concave mirror up front, and systems based on this
philosophy are highly promising for applications at high laser powers. Surprisingly little research has been done so far on these designs, and an exploratory study has only recently been published [25]. Such systems can easily achieve diffraction-limited performance (at 10.6 μm) for field angles well in excess of 5 milliradians for focal length up to 300 mm, and at numerical apertures up to 0.125 (or f/4). These systems use spherical surfaces throughout. The systems shown on the right side of Fig. 3 are typical examples.

Aspheric mirrors – some general aspects
A word of caution about the use of aspheric mirror surfaces in general may be in order here. In the past, aspheric surfaces were known to be costly to produce by classical grinding and polishing techniques and were accordingly avoided by designers, if possible. Metal mirrors using copper substrates are, however, currently fabricated mainly by single-point diamond turning on numerically controlled machines, and the generation of aspheric shapes of high precision is well within the capability of these machines at only little higher cost. This, in turn, has created the impression that, now that the realm of affordable aspherics has been opened up to broader applications, full use should be made of this capability.

There are, however, two basic difficulties associated with the use of aspheric surfaces in off-axis systems. One derives from the fact that the mirror sections actually used have no rotational symmetery, which makes both shape measurement or shape verification and alignment difficult and time-consuming. The second problem is that aspheric surfaces perform as part of a system involving multiple optical surfaces. Thus, in a telescope system based on two aspherics, coma may be cancelled; one stand-alone aspheric surface, however, does not offer enough degrees of freedom to correct more than one aberration, for instance spherical aberration, and leaves us with strong uncorrected coma, which drastically limits the angular field. This was demonstrated above for the case of the paraboloid but applies equally well to the ellipsoid or the hyperboloid, which might be used in conjunction with divergent or convergent beams.

The role, and adequate use, of aspherics in optical design has been the subject of numerous studies in the last two decades. The *Optics Index*, which covers publications in the various journals of the Optical Society of America, lists 52 references on aspherics for the period of 1985 to 1989, and 38 for the period from 1990 to 1993. A doctoral thesis [26] published in 1986 (in German) covers an in-depth study of the subject.

3.3.8. Nonimaging beam shaping of CO₂ laser beams
In addition to applications for cutting and welding, CO₂ laser radiation is also used in various surface treatment techniques such as transformation hardening, cladding and alloying. A distinguishing feature of these applications is that the surface must be scanned by a beam of intense radiation but with a (laterally) homogeneous intensity distribution so as to attain a uniform temperature distribution over the scanned width. This is, of course, in sharp contrast to the circular beam profile which is supplied by most CO₂ lasers. Optical devices which transform a (circular) laser beam into a rectangular spot are referred to as beam homogenizers or beam integrators if they perform this task by spatial manipulation. Clearly, an alternative approach is to use high-speed lateral scanning of a (partially) focused beam.

Laser beam integrators typically split the original beam into more or fewer parts, which are recombined in 'reversed' order for proper overlap in some given plane. One approach uses a kaleidoscope-type cavity, which may have adjustable convergence in one direction for varying the size of the final spot. Incoupling of the radiation by means of an axicon is helpful in minimizing the number of internal reflections needed to achieve a given homogeneity. This is
important in view of the high losses due to reflection at large angles of incidence, which could in this way be brought down to about 15% [27].

The splitting of a laser beam with subsequent recombination is invariably associated with interference between the recombining beamlets, which shows up as a modulation of the power density in the ‘integrated’ spot. The best method for bringing this modulation down to acceptable levels is to have the beams recombine under large angles, which increases the spatial frequency of the interference pattern. Intentional introduction of aberrations in the recombining optics may also help.

3.4. Nd:YAG laser and visible laser optics

3.4.1. Material aspects

The wavelength of 1.06 μm at which the Nd:YAG laser operates is sufficiently close to the visible spectrum to allow full use of the wide range of optical glasses that have become available in high quality and at low cost. Yet, if operated in conjunction with a Q-switched laser, where power densities well above $10 \times 10^9 \text{ W cm}^{-2}$ can be achieved, the possibility of laser damage to optical glasses has to be considered. There are two mechanisms which cause internal damage: one is due to foreign particles, such as platinum, which have entered the glass during the manufacturing process, and the other is self-focusing of a laser beam due to an increase of the effective index of refraction with the local power density of the laser beam and characterized by the nonlinear refractive index $n_2$ of the glass. A further concern is surface damage, which is largely independent of the chemical composition and thus the type of glass, but is related to the polishing agent and, of course, surface cleanliness. Schott publishes a list of optical glasses, for which damage-related quantities have been measured [28].

3.4.2. Power transport by optical fibres

One of the most notable developments of the last decade is the increased use of optical fibres for relaying the power output from industrial Nd:YAG lasers to the site of application [29]. In terms of the user interface this means that the user deals with a source of precisely defined size – the fibre diameter – and well-specified radiating cone – the numerical aperture at the fibre output. Quite often, and particularly at powers in the kilowatt range, the output of the fibre is already recollimated to a specified beam diameter and beam divergence as part of the system as supplied by the source manufacturer. Although some of the beam quality of the original laser source is unavoidably lost in the process, this approach has some important advantages for the laser user, in that critical components can be well sealed off from the environment, and in that the application can rely on a source of excellent homogeneity.

3.4.3. Some system aspects

The higher absorption of Nd:YAG laser radiation by metals in comparison with CO₂ laser radiation has made the Nd:YAG laser the preferred source for drilling and (micro-)welding. This is further enhanced by the numerous ways in which this type of radiation can be manipulated by well-developed optical means. Mechanical or electrooptical deflectors can be used to deflect or to multiplex a beam to several locations; dielectric beam splitters allow the energy to be split for simultaneous action; all in combination with the use of optical fibres for relaying the (sub-)beam to the place of work. Simultaneous spot welding by laser has found wide use in the electronics industry; it is highly efficient and has the inherent advantage of minimizing distortion and stress in the finished product.
3.4.4. Focusing optics
In the Nd:YAG laser spectral region, focusing optics can make use of a wide range of optical glasses and rely on established design techniques. These optical systems will normally be used only in a small angular field, where relatively unsophisticated designs are satisfactory. Care should be taken to avoid foci due to secondary reflection being created inside lenses. All lenses should be somewhat oversized to ensure that no appreciable amounts of power can be trapped in the lens mount. Cemented lenses are better avoided at the higher powers.

System requirements may demand that an optical system for manipulating Nd:YAG laser radiation be colour-corrected so that, for instance, it has the same focal position for the wavelength of the Nd:YAG laser and a pilot laser emitting visible light, often a HeNe laser. In this case, the classical and well-established methods for correcting colour by suitable choice of glass come into play and, under certain circumstances, reflective optics may be preferable. If there is no such requirement, however, the glasses can be selected for optimum correction of the monochromatic aberrations, notably spherical aberration and coma.

3.4.5. Some examples
An example of the first situation mentioned in Section 3.4.4 is shown in Fig. 4, where the radiation from a 1-kW Nd:YAG laser had to be focused at a distance of 8–12 m, and where radiation from a HeNe laser, in conjunction with a closed-cycle TV circuit, served to monitor the focusing and to locate the focal spot position. To obtain the required small focus diameter of <3 mm, an optical system of large diameter was mandatory, and an axially symmetric two-mirror system was chosen in spite of its unavoidable central shadow, which, in the present situation causes a loss of just over 1% (the mirror diameter ratio is about 10:1). The system was successfully used for decommissioning land mines by using the laser to drill a hole into the shell and subsequently burn off the explosive charge, a process which, for obvious reasons, called for a fairly large stand-off distance and which, nevertheless, proved to be highly repeatable.

Figure 4 (a) Optical system for focusing a collimated beam of 1 kW Nd:YAG radiation to a spot <3 mm in diameter at a distance of 8–12 m from the optics. The convex mirror (C) is coated for high reflectivity at the 1.06 μm wavelength of the Nd:YAG laser and for high transmission of the radiation from a HeNe pilot laser, which enters from the right. The large mirror (M) to the left (400 mm diameter) is moved axially for simultaneous focusing of both beams at the desired distance. The HeNe focus is monitored by a TV camera (not shown). (b) A photograph of the system (courtesy of Thyssen Lasertechnik GmbH Aachen).
and low-risk. The second case is exemplified by the optical system of Fig. 5a; this shows a focusing system for application in cutting of thin materials at high speed, which calls for a diffraction-limited focal spot at $f/1.6$. The design has three lens elements and uses normal glasses (BK7, SF11). By adding an aplanatic lens element, the numerical aperture can be further increased, if so desired, without sacrificing diffraction-limited performance (Fig. 5b).

### 3.4.6. Prospects

The availability of loss-free and stable materials, combined with the applicability of established design methods, puts all lasers operating in or near the visible spectrum into a relatively advantageous position, which, although difficult to quantify, tends to strengthen the future prospects for the Nd: YAG laser and related solid-state lasers, provided the steady improvements in beam quality and cost reduction which have been achieved over the last years can be continued.

### 3.4.7. Optics for diode lasers

Of all lasers, the diode laser is produced in, by far, the largest numbers, and this is due to its broad use in information processing technologies, including its best-known application in the compact disc player. The diode laser, actually a family of lasers utilizing the properties of semiconductor diodes, which allow lasing action at sufficiently high current densities, has some inherently advantageous properties which should give it a bright future in materials processing applications as well. Most notable is the relatively high efficiency of this type of laser, which has already established its place as a pumping source for solid-state lasers where waste heat input is to be kept at minimum (such as in Nd: YAG lasers of low power yet excellent beam quality). The logical extension is the direct application of diode laser radiation to processes requiring high powers, thereby avoiding the losses associated with the above process. This obviously necessitates shaping and combining the radiation emanating from numerous individual diode laser sources, each of which is highly unsymmetrical and afflicted with severe astigmatism. The challenge is largely optical, and is complicated by the small size — and consequently large angle of divergence — of the diode laser source in the direction perpendicular to the diode junction. A thorough discussion of the state of the art is beyond the scope of this contribution, but it is felt that diffractive optics, and microoptics in general,
may be in a position to provide an answer and/or technological breakthrough, and should be carefully watched in the future.

3.5. Optics for excimer lasers

3.5.1. Unique properties of excimer lasers

Excimer lasers are distinct from the types of lasers discussed so far in that they are powerful sources of ultraviolet radiation at wavelengths determined by the combination of gases used, such as KrF (248 nm) or ArF (193 nm). The correspondingly high photon energy allows largely nonthermal interaction with matter and thereby opens up novel and unique applications [30]. At the same time there are a number of optical consequences and challenges not found elsewhere, which fall into three categories: material aspects, imaging, and beam homogenization.

3.5.2. Material aspects

The wavelength region below 300 nm and down to, say, 190 nm is known for the very small number of available transparent optical materials [30, 31]. Fused synthetic silica is most widely used, as are some crystalline fluorides, mainly CaF₂ and LiF and, to a lesser extent, MgF₂, as it suffers from birefringence. The material problems are further compounded by the very short pulse duration of excimer laser radiation and accordingly high peak powers. All materials undergo irreversible changes under irradiation from excimer laser sources, the mechanisms of which are not yet fully understood [31]. Thus the user must be prepared for the optical systems used in excimer laser applications to have a limited lifetime. Aside from being scarce, the materials mentioned above all have low refractive indices, which compounds the design challenge; there is sufficient difference in dispersion to allow correction at two wavelengths. Durable antireflection coatings are also available [32].

3.5.3. Imaging

The excimer laser typically emits an approximately rectangular beam with a length-to-width ratio of 2:3, and low beam quality K (<0.01) in both directions. This is not the type of beam which lends itself to focusing to a small spot, for instance for an application in (micro-)machining. Instead, the laser beam is used to illuminate a mask, which is then imaged onto the workpiece. In this way, the very high definition which is possible owing to the short wavelength can be fully utilized, although at a price: only a small fraction of the (valuable and expensive) radiation is actually used for material processing, and the quality of the machining process now depends critically on the quality of the imaging optics, which not only have to meet diffraction criteria at a very short wavelength but also over an extended angular field.

Aperture requirements are dictated by the energy density (J cm⁻²) needed for an intended process. Material removal by excimer laser radiation is characterized by a well-defined threshold, which for polymers is often of the order of 0.1–0.3 J cm⁻², but an order of magnitude higher for typical ceramics. At much higher energy densities, saturation of the removal process is a common feature, so that the actual working conditions have to be chosen carefully.

3.5.4. Need for long back focus

To protect the optics from condensation of ablated material, the imaging optical system has to have as large a back focus as possible, and this, together with the requirement for numerical aperture, puts a heavy burden on the design. Figure 6 is an example of a lens for material processing by an ArF (193 nm wavelength) excimer laser. The lens is designed for 10:1 imaging of a mask on a workpiece at f/4; it has a focal length of 83 mm and the back focus is just under
Figure 6  Optical system for 10:1 imaging of a mask using 193 nm radiation from an ArF excimer laser, with \( f = 83 \) mm at \( f/4 \), and designed such that it has the same focal position for the HeNe laser radiation from a pilot laser. The system is used for micro-machining.

The lens is of the Petzval type, which is known for its good definition over a small field (less than 2° for the example lens). The lens is achromatized such that it has the same focal position for 193 nm and for the radiation of a HeNe laser which is used for focusing. Performance is excellent on-axis (Strehl ratio \( >0.8 \)) but reduced in the field. Structures smaller than 4 \( \mu \)m are resolved over most of the field.

3.5.5. Photolithography
Photolithography is a key technology for fabricating large-scale integrated circuits in the electronics industry. It depends on the use of ultraviolet radiation to locally changing the chemical properties of a material (photoresist) and is currently the most important application of excimer lasers. As there is no material removal, a large back focus of the imaging optics is no longer a limiting factor, but there are very high demands on resolution, numerical aperture and field (including flatness of field and low distortion), which puts optics for photolithography into a class of their own.

3.5.6. Beam homogenization
As was discussed above, the role of an excimer laser in materials processing is typically that of a radiation source which illuminates a mask, where the actual processing is done by the small amount of radiation which passes through the mask. Needless to say, the homogeneity of the illumination becomes a critical factor in this type of operation. The excimer laser source, on the other hand, emits a strongly inhomogeneous beam, more or less flat (or ‘rectangular’) in the elongated beam direction, and of a shape which resembles a Gaussian in the direction of small beam width.

Devices which transform the original excimer laser beam into a desired shape are generally referred to as beam homogenizers. In direct analogy to the beam integrators for use in surface treatment with CO\(_2\) lasers and discussed above, they typically rely on splitting the aperture and recombining the beamlets by refracting or reflecting them into one common plane. Materials aspects may dictate different approaches though. It should be noted that interference effects are of less concern here owing to the much shorter wavelength and rather poor spatial coherence of the typical excimer laser beam. The main problem is to achieve the desired result with a minimum of radiation losses caused by absorption or incomplete reflection. The patent literature should be consulted for more detailed information on these, sometimes ingenious, devices.

When larger areas of a workpiece need to be treated by an excimer laser, effective beam homogenization is already achieved, at least in one direction, by moving the mask and the workpiece during the processing in opposite directions and at speeds corresponding to the
magnification of the optics. This, of course, assumes that the processing is averaged over a large number of laser radiation pulses. It also requires that the optics have very low distortion.

4. Conclusion

The design of optical systems for use with high-power lasers is in many respects comparable to that for other applications in optics, but there are additional requirements and challenges, sometimes subtle, which derive from the peculiar nature of laser beams, the high power level, and/or materials problems. A thorough understanding of these aspects is needed to properly apply the wealth of knowhow that has accumulated in the field of optical system design over several centuries (!) to the relatively new area of high-power lasers. The authors feel that the potential of optical devices in applications of high-power lasers is not yet fully utilized or even sufficiently recognized. Close, or closer, cooperation between optical designers and laser system designers and users appears to be urgently required.

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