Focusing and optical imaging in applied laser technologies

Beam characteristics of both methods

In the field of laser material processing the knowledge of the intensity distribution in the processed volume is of considerable importance. Both, manageable algorithms as well as some information about parameters that influence the beam profile, including limiting factors, are relevant for the practical application. This article compares the approach of focusing laser beams with the method using an imaging optical system. Different algorithms are described and practical consequences are discussed.

Focusing of laser beams

General case

Basically, the focusing of a laser beam is achieved by using a single- or multi-lens laser optic, that is mainly characterized by its focal length and the diameter of the free aperture. Figure 1 shows the transformation of a laser beam through an ideal optical lens with a focal length *f*. Based on the properties of the primary beam, the parameters of the secondary beam can be calculated with the help of the equations in Table 1. In praxis, as long as the free aperture of the lens is approximately twice the size of the diameter of the beam, diffraction at the edge of the lense is of no relevance. Focusing the beam leads to a characteristic waist, which is refered to as the beam focus. Knowing the parameters of the primary beam given in Equations (1) and (2) is necessary to calculate the secondary beam properties. Even if the Rayleigh length of the primary beam is unknown, it can be traced back following the general wave optical relations given in (3), when w_0 is the radius of the waist of the primary beam, λ is the wavelength and k is the beam propagation factor, which is calculated using the relation $k = 1/M^2$. It is 1 for ideal Gaussian beams. However, the actual M^2-factor of a laser is provided by the laser company and can be subject to heavy deviations compared to the ideal factor of 1.

Special case: Focusing a parallel beam

Above equations are appropriate for divergent laser beams approaching a focusing optic. The waist diameter of the primary beam and the position of the waist after the optic, respectively, can be determined, if the position of the primary waist was given or measured before. However, if the primary waist radius w_0 is far beyond the dimension of the wavelength, the laser beam can, to some extent, be considered parallel. In this case, Equations (1) and (2) change over to the following forms (4) and (5), as commonly refered to in literature. In this special case the distance of the secondary waist s' from the principal plane of the optical element is equal to the focal length *f*. The size of the secondary waist does then only depend on the radius of the primary parallel beam w_P, the focal length f of the optic, the wavelength λ and the beam propagation factor k of the laser beam.

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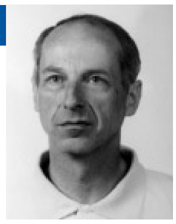

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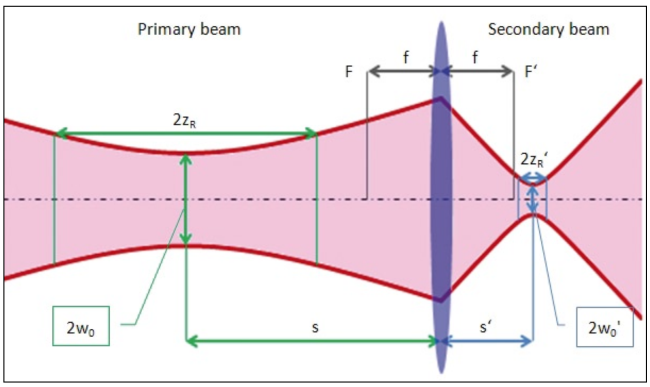

FIGURE 1: **Transformation of a beam using an ideal optical lens with a focal length *f*.**

Properties of the primary beam	*Secondary beam*	
Waist position s	$w_0' = w_0 \cdot f \cdot \sqrt{\frac{1}{(s-f)^2 + z_R^2}}$	(1)
Beam radius w_0	$s' = f + \frac{f^2 \cdot (s-f)}{(s-f)^2 + z_R^2}$	(2)
Rayleigh length z_R		
Wavelength λ	$z_R = \frac{k \cdot w_0^2 \cdot \pi}{\lambda}$	(3)

TABLE 1: **Laser beam parameters.**

$$w_0' = \frac{\lambda \cdot f}{\pi \cdot k \cdot w_p} \quad (4)$$

$w_p = w_0$ Radius of the parallel beam

$$s' = f \quad (5)$$

Determining the beam properties outside the focus position

The knowledge about the achievable focus diameter itself cannot satisfactorily be used to estimate the impact of the laser beam while material is being processed. Furthermore, the different beam radii near the focus can be particularly important. In this regard the Rayleigh length of the secondary beam can be estimated as soon as its waist radius w_0' and the beam propagation factor k are known parameters.

$$z_R' = \frac{w_0'^2 \cdot \pi \cdot k}{\lambda} \quad (6)$$

The spatial dimension of the waist is reached at the point, where the beam radius has enlarged by the factor of √2 compared to the radius at the center of the waist. For the calculation of the beam radius at any other position along the direction of propagation z, the following equation is appropriate.

$$w'(z) = w_0' \cdot \sqrt{1 + \left(\frac{z}{z_R'}\right)^2} \quad (7)$$

$z = 0$ Position of the secondary waist

Defining the beam radius

The beam radius w, which has turned up in the equations used so far, has not been specified yet. Considering an ideal Gaussian beam, this parameter is the Gaussian radius, which is defined as the value where the intensity has declined to the factor of $1/e^2$ of its maximum. For laser beams whose beam quality is unequal to 1 but show a rotational-symmetrical beam shape, the beam radius can be calculated according to the second-order moments of the Wigner distribution or the method of enclosed power, further described in current ISO-standards. Technically speaking, the specified equations are only suitable for the beam radius w_σ of the second-order moment. If the demand for exact results is not too high, the rather available beam radii obtained with the method of enclosed power can be applied as initial values for the equations.

Determining the beam profile

The equations for the determination of the beam properties discussed so far only provide information about the obtained beam radius whereas no evidence is given about the beam profile itself. No further calculation is required if the beam profile is a Gaussian one since it remains ideal along the axis of propagation, even if the laser beam is focused by a high grade optic that does hardly derogate the quality of the beam. However, every beam profile differing from an ideal Gaussian profile is liable to modifications while propagating along the z-axis. An additional experimental set up or even computational methods are required to further describe the obtained beam caustic.

Aberrations and diffractional effects caused by the focusing optics

The explanations above describe the transformation of laser beams assuming ideal optical lenses, which is not particularly fulfilled in praxis. All plano-convex focusing lenses show spherical aberrations, which increase the more the lens is illuminated by the laser beam. According to Equation (4) the smallest focus diameter can be expected in case of the lens being fully illuminated. This is the reason why beam expanders are placed first in front of the optical element. Beam expansion has detrimental effects on spherical aberrations, though, and therefore should not be exaggerated. The maximum value of tolerable expansion to achieve the smallest possible focus needs to be determined in praxis or with a waveoptical numerical approach. Lensing arrays and aspherical lenses could help to compensate aberrations. Nevertheless, the beam profile deteriorates due to diffractional effects that occur because of the finite geometry of the lenses. In practical applications diffractional effects are minimized if the diameter of the laser optic is at least twice the size of the diameter of the laser beam. Again, the adverse effect of diffraction on the beam profile needs to be quantified in measurements and waveoptical calculations.

Optical Imaging

Scope

The effort of laser material processing is not invariably to achieve a maximum power density on the material by focusing the laser beam. The demand for a specific power density distribution at the processing point and to realize this distribution using given patterns and geometries occurs even more frequently. A top-hat distribution can be achieved fairly easy when a circular geometry is irradiated with a constant power density instead of a Gaussian one. In the field of laser micro processing arbitrary geometries, also referred to as masks, are applied to localize the effective laser radiation used for the processing and to transfer it to the material. The mask is placed in front of the laser optic. This leads to an imaging laser process. The differences between this approach compared to the method of focusing a laser beam are described more in detail subsequently.

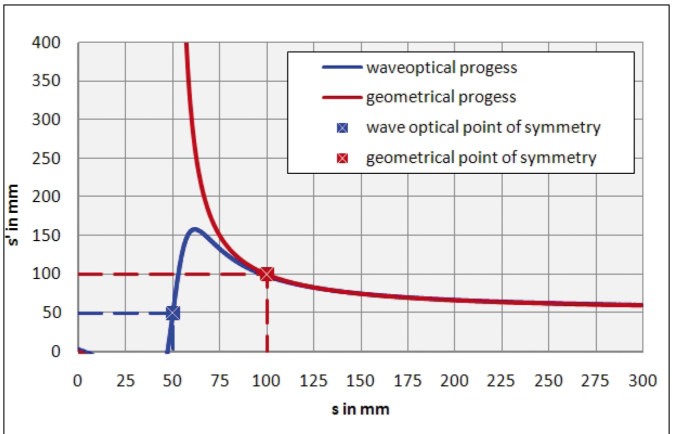

FIGURE 2: **Comparison of the geometrical and waveoptical progress of s' ($w_0 = 0.1$ mm, $\lambda = 1.06$ µm, $k = 0.8$, $f = 50$ mm).**

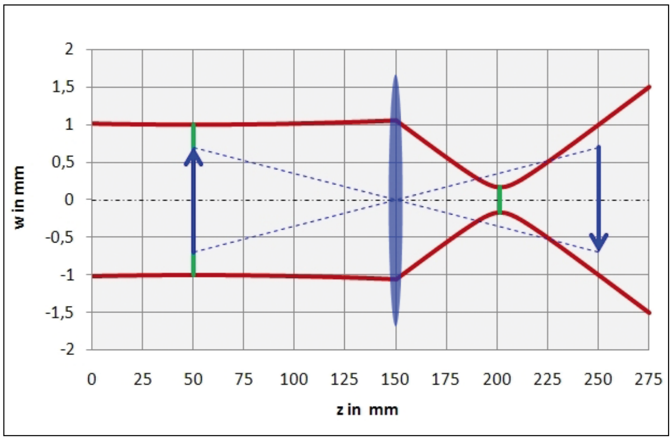

FIGURE 3: **A parallel incident beam leads to different positions of beam focus (green) and image (blue) ($w_0 = 1$ mm, $\lambda = 1.06$ µm, $k = 0.1$, $f = 50$ mm).**

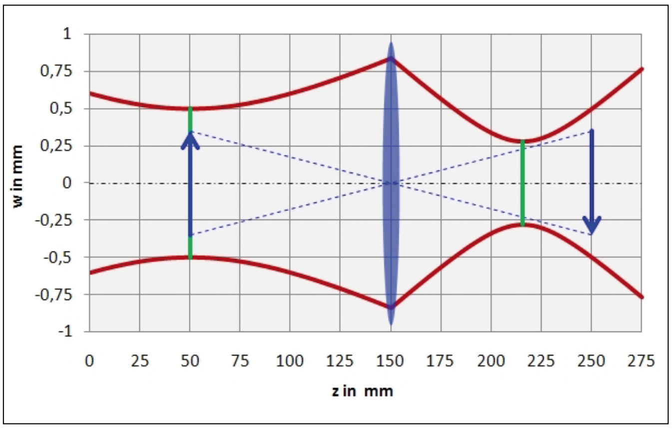

FIGURE 4: **A divergent incident beam leads to a secondary beam waist at a further distance compared to Figure 3 (w_0 = 0.5 mm, λ = 1.06 µm, k = 0.1, f = 50 mm).**

Imaging position

Equation (2) specifies the position of the waist s' of the secondary beam according to the one s of the primary beam if an initial waist radius w_0 and Rayleigh length z_R are given. The determined waveoptical progress can be compared to the well-known geometrical approach. s symbolizes the object distance and s' the image distance, respectively. Equation (8) relates both.

$$s' = \frac{s \cdot f}{s - f} \quad (8)$$

In Figure 2 both, the geometrical and waveoptical approach are contrasted. A growing distance to the laser optic leads to an equal progress of s' whereas this changes formidably with a closer distance of s to the focal length f. In the geometrical approach the focus is shifted to an infinite distance the more the object distance approaches the focal length f. The distance of the focus, which is the secondary waist in the waveoptical model, however, remains finite and after it reaches a reversal point, turns around. At a certain distance, when $s = f$, the image distance s' is also equal to the focal length f, which is refered to as the waveoptical point of symmetry. To align masks along the direction of beam propagation leads to the practical consequence shown in Figure 3 and 4. The image behind the laser optic is situated at a different position compared to a free propagating incident parallel beam. To illustrate the differences Figure 3 shows a mask object at a distance $s = 2f$ in front of the optical element, which is set directly within the parallel beam of the laser. Based on the theorems of geometrical optics, the mask is imaged at that point after the optic where s' is equal to $2f$, whereas the beam focus of the incident parallel beam occurs at the point, where $s' = f$. Figure 4 visualizes the different positions of the beam focus and image in case of a strongly divergent primary beam as it could derive from an additional focusing.

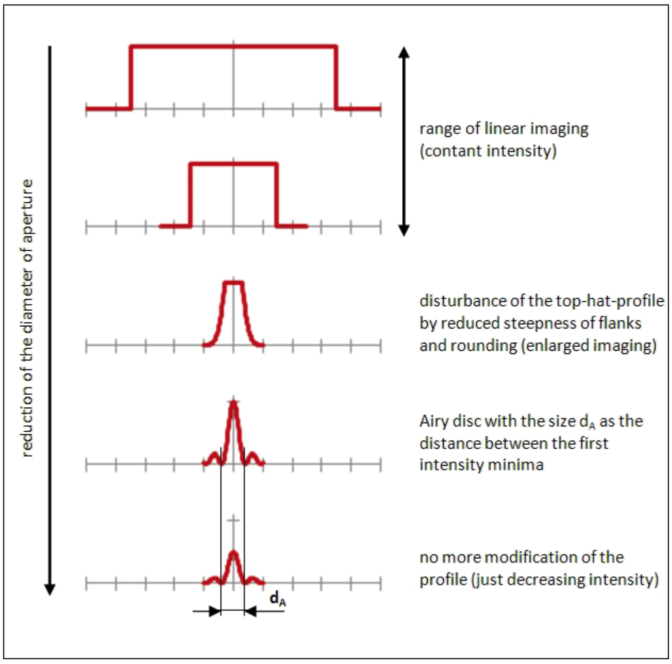

FIGURE 5: **The reduction of the hole diameter of an aperture placed in front of the optical element leads to a change of the intensity distribution within the image.**

Image ratio and optical resolution

The geometrical image ratio *m,* as defined in Equation (9), is the relation between the image size compared to the object size.

$$m = \frac{f}{s-f} = \frac{s'}{s} \qquad (9)$$

There is a linear coherence between image size and object size. Apart from that, the image size does only depend on the focal length *f* and the object distance *s*. In contrast, the focus diameter according to Equation (4) is influenced by the wavelength of the laser radiation, the beam quality factor k and the radius of the primary beam w_P. These are limiting factors concerning an any desired miniaturization of a focus. An assumption could be, that imaging carried out with apertures with small hole diameters, that operate as the mask, leads to smaller focal spots on the material than the waveoptical focusing. Admittedly, the geometrical approach does not apply for arbitrarily chosen image ratios and miniaturizations of apertures. As soon as the hole diameter of the aperture, placed first in front of the optic, falls below a certain size diffraction occurs and affects the intensity distribution in the imaging plane. This intensity distribtion would not match the mask pattern. Figure 5 shows how the intensity distribution is modified as a result of a reduction of the aperture hole in front of the optic. The characteristic Airy pattern is obtained at very small aperture diameters and it illustrates the intensity distribution in the imaging plane. It can be quantified by the distance of the 2 innermost minima and gives the limiting value for the resolution. A further reduction of the hole diameter of the aperture only affects the intensity values of the image whereas the shape and radial extent of the Airy disc are not influenced.

The size of the Airy disc d_A' is determined in the following way:

$$d_A' = 2.44 \cdot \frac{\lambda \cdot s'}{D} \qquad (10)$$

D Diameter of the laser optic (free aperture)
s' distance between optical element and imaging plane

The achievable resolution is predefined by the wavelength of the laser radiation and the aperture of the optical element. The comparison between the diameter of the Airy disc and the focus diameter, used Equation (4), that are both obtained at comparable optical parameters leads to a deviation of 1.92. This factor merely results from different definitions to describe the focal spot size on the material. A further focusing of the laser beam goes along with an increase of the intensity distribution on the processed material whereas it remains constant if apertures with different hole diameters are applied and the hole size does not fall below a certain value. If so, higher laser output powers are required if the object is imaged using a mask. The knowledge about the size of the Airy disc allows to estimate the focal spot size on the processed material. Furthermore, the quality of the imaged mask on the material is determined by this waveoptical parameter. Especially in the field of laser micro processing it is particularly essential to gain information about how detailed a mask can be imaged. The degree of that deviation, caused by limited steepness and rounds of the edges, is determined by the Airy disc. Namely, the real image is obtained by the superposition of a variety of Airy patterns. To project the Airy disc in the image plane onto the object plane, that is equivalent to the mask position in front of the optic results in the optical resolution with regard to the patterned mask. It can be calculated according to the equation:

$$d_A = \frac{d_A' \cdot s}{s'} \qquad (11)$$

Elements on the mask with a smaller dimension than d_A cannot be imaged on the material with a given laser optic because of a limited resolution.

THE INSTITUTION

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The Laser Institute of the University of Applied Sciences in Mittweida (LHM) emerged in 2010 from the formerly founded Laser Applications Center (LAZ, founded in 1987) and Laserinstitut Mittelsachsen e.V. (1997). Several professors, postgraduates, scientific employees and students work on different laser applications and the development of new laser components.

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