Optical Design of Beam Delivery and Beam Forming Systems

ISO-Defined Beam Parameters Enable Quick and Easy Layout of Optical Systems in Real-Time

The layout of beam delivery and/or beam forming optical systems is a recurring task in development and application of laser systems and necessarily requires adequate simulation tools. Accurate and precise simulation of the propagation of laser beams through optical systems, with the aim of predicting the beam profile at desired locations, is challenging. It requires detailed characterization of the initial beam and application of sophisticated software, which usually can only be operated by highly qualified personal. Relaxing the requirements to the prediction of more general beam parameters like beam diameter, beam divergence, and Rayleigh length, important layout jobs can be accomplished by ease-to-use simulation tools based on a few beam parameters measured according to the well-known ISO 11146 standard.

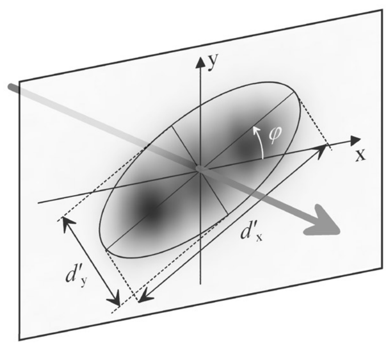

FIGURE 1: **Beam profile in a transverse plane plane and corresponding beam diameter d_x and d_y along the beams principal axes.**

Typical tasks in the design of beam delivery and beam forming systems are

- Collimating the beam to have a desired beam diameter or a given Rayleigh length
- Creating a focus with a desired beam waist diameter or Rayleigh length
- Converting the beam to a desired divergence
- Creating relay images with desired magnification at given locations
- Changing the beams transversal position or direction

In doing this the following restrictions or constraints may be important:

- Availability of off-the-shelf lenses
- Spatial constraints of the setup
- Misalignment sensitivity of optical elements
- Possible deviations of the properties of optical elements from their specifications
- Aberrations at spherical surfaces
- Dispersion

Variance Diameter

A very efficient approach to simulate the beam propagation through an optical system is based on the so-called variance diameter, a measure for the beams extent in a given plane perpendicular to the optical axis (Figure 1). The variance diameter is proportional to the root of the second order moment of the power density distribution in that plane. Hence, it expresses the width of a laser beam as the standard deviation of the light distribution from its center. For Gaussian profiles the variance diameter is identical to the well-known diameter defined by the $1/e^2$-drop of the intensity, but in contrast to this the variance definition is applicable to any other beam profile, too.

The property that makes this beam diameter definition outstanding amongst others is the general propagation law which is valid for virtually all kind of beams regardless of being Gaussian or non-gaussian, coherent or partially coherent. The free space evolution (Figure 2) of the variance diameter is in any case given by the simple hyperbolic expression

$$d(z) = d_0 \sqrt{1 + \left(\frac{z - z_0}{z_R}\right)^2} = \sqrt{d_0^2 + \theta^2 (z - z_0)^2} \qquad (1)$$

where $d(z)$ denotes the beam diameter at the location z along the optical axis, d_0 the beam waist, z_0 the beam waist location, z_R the Rayleigh length (the distance from the waist where beam diameter has increased by factor of $\sqrt{2}$), and θ the full beam divergence.

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Bernd Eppich, born in 1963, studied physics at the Technical University of Karlsruhe. He did his diploma thesis on resonators for solid state lasers at the Technical University of Berlin, where he later received his PHD for his research on laser beam characterization. In 2005 he joined the Ferdinand Braun Institut für Höchstfrequenztechnik, where he is responsible for beam characterization and development of optical systems for diode lasers.

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The well-known and very important beam propagation factor M^2 is proportional to the product of beam waist diameter and beam divergence and is invariant under propagation in aberration-free, lossless and passive systems.

As can be seen from the free space propagation law the propagation properties of the variance diameter can be defined by only three parameters, e.g. the beam waist diameter, the beam waist location and the divergence (or the Rayleigh length, or the beam propagation parameter).

FIGURE 2: **Free Space propagation of the variance beam diameter.**

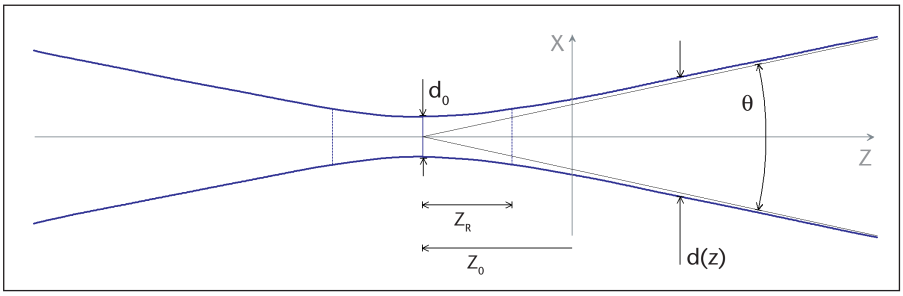
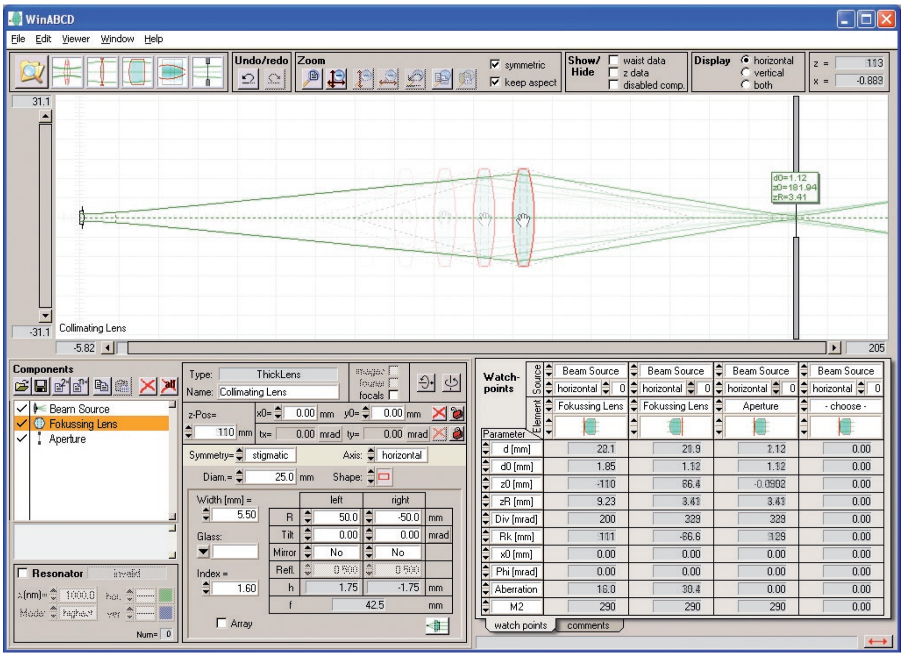


FIGURE 3: **A screenshot of WinABCD.**



THE COMPANY

The Ferdinand-Braun-Institut für Höchstfrequenztechnik (FBH) is one of the leading institutes in Europe for applied research in microwaves and optoelectronics. In the optoelectronic field, it develops high-power diode lasers and laser systems (0.6–1.2 µm) with excellent beam quality and high reliability. Applications are in e.g. materials processing, sensor technology, medical technology and high precision metrology. The FBH has a staff of 225 employees and a budget of 17.1 million Euros.

This generality of the propagation law was the reason why the variance definition has been chosen as the fundamental definition for the beam characterization standard ISO 11146. This document describes in detail, how the beam propagation parameters mentioned above are measured. Devices for such measurements are commercially available.

The propagation of the variance diameter through compound optical systems consisting of aberration free lenses and mirrors (spherical and cylindrical lenses, GRIN lenses, spherical und cylindrical mirrors) is based on the so-called Gaussian matrices (also called ABCD matrices) representing such systems in paraxial geometrical optics. The underlying equations are almost as simple as equation (1) and therefore simulation can be very fast and efficient.

As an example, WinABCD (Figure (3), a software product from the FBH, uses this technique to enable real-time optical design. This means that the user can grab, move, tilt and alter all optical elements (lenses and sources) in the graphical interface with the mouse device and immediately gets the resulting beam propagation both in the graphical representation and as numerical values of desired beam parameters.

The following parameter can be obtained at any axial position within the system, separately for the horizontal and vertical direction:

- Transversal beam position
- Beam diameter
- Beam divergence
- Beam waist position
- Beam waist diameter
- Rayleigh length
- Radius of phase front curvature
- Spherical aberration parameters
- Beam propagation factor M^2 (e.g. for incoherently compound sources)

Furthermore, including additional a-priori information or assumptions on the shape of the beam profile, e.g. considering the profile shape as being Gaussian or top-hat, the degree of transmission through apertures in the system and coupling efficiencies in multi mode fibers can be estimated. Restricting to fundamental Gaussian beams the coupling efficiency into mono-mode fibers as a function of the beam size, position, orientation and phase front curvature at the fiber entry can be obtained.

Chromatic Effects

In optical systems designed for sources with a broad spectrum or for many sources with different wavelengths the wavelength dependency of the refractive index of the lens materials has to be considered. As an example the chromatic shift of the waist position of a collimated beam focused by single plano-convex lens is presented. Neglecting other chromatic aberrations the method of propagating the variance diameter easily delivers the amount of focus shift and how it can be reduced by use of an achromatic doublet (Figure 4).

Misalignment Sensitivity

In many optical design tasks misalignment sensitivity is an important issue. Even small errors in the positioning of optical elements may decrease the desired performance, e.g. reduce the coupling efficiency into a fiber.

The following example shows a diode stack consisting of more than hundred independent emitters. Each plane of the stack is collimated by an individual FAC (fast axis collimator) micro lens. Three conventional cylindrical lenses are used to form the beam separately in horizontal and vertical direction, such that the coupling conditions of a multi mode fiber at the system exit are met. In spite of the large number of beam sources the method of propagating the variance diameters allows even in this case a real-

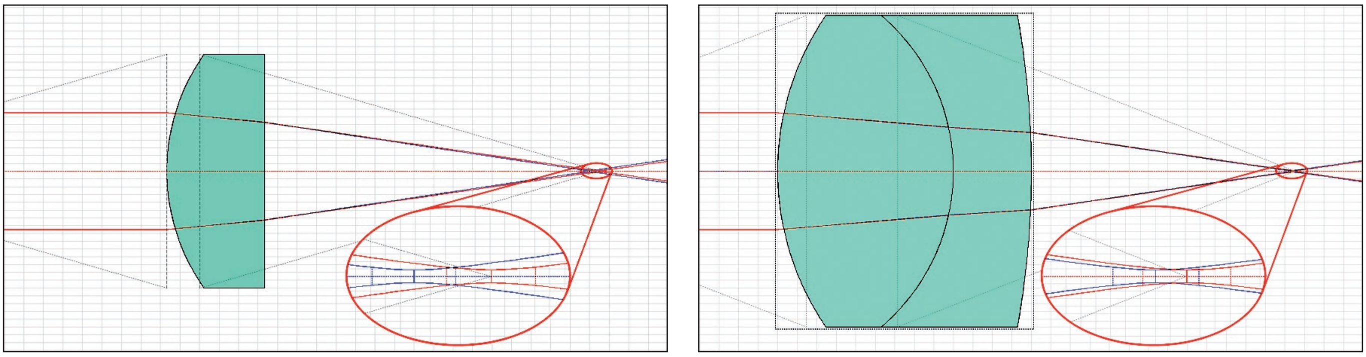


FIGURE 4: **Chromatic focus shift introduced by a single lens (left) and its improvement by an achromatic doublet (right). The red and blue lines indicate the beam propagation of sources with longer and short wavelengths.**

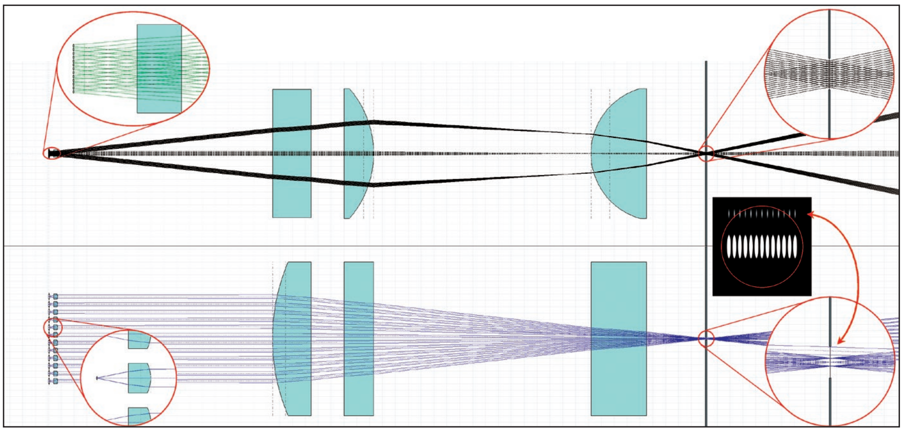


FIGURE 5: **Impact of misaligning a single FAC lens by 8 µm. The misalignment in the vertical lens position causes coupling losses of about 4%. Top graph: top view. Bottom graph: side view. Center inlet: beam profile at fiber entry.**

time design. The impact of moving and/or tilting any optical element or beam source is displayed instantaneously, including the coupling efficiency under the assumption of Gaussian shaped beam profiles. The simulation suggests that for the FAC lenses an vertical positioning error of 8 µm a coupling loss of approximately 4% results (Figure 5). In this way mounting tolerances can be quantified fast and easy.

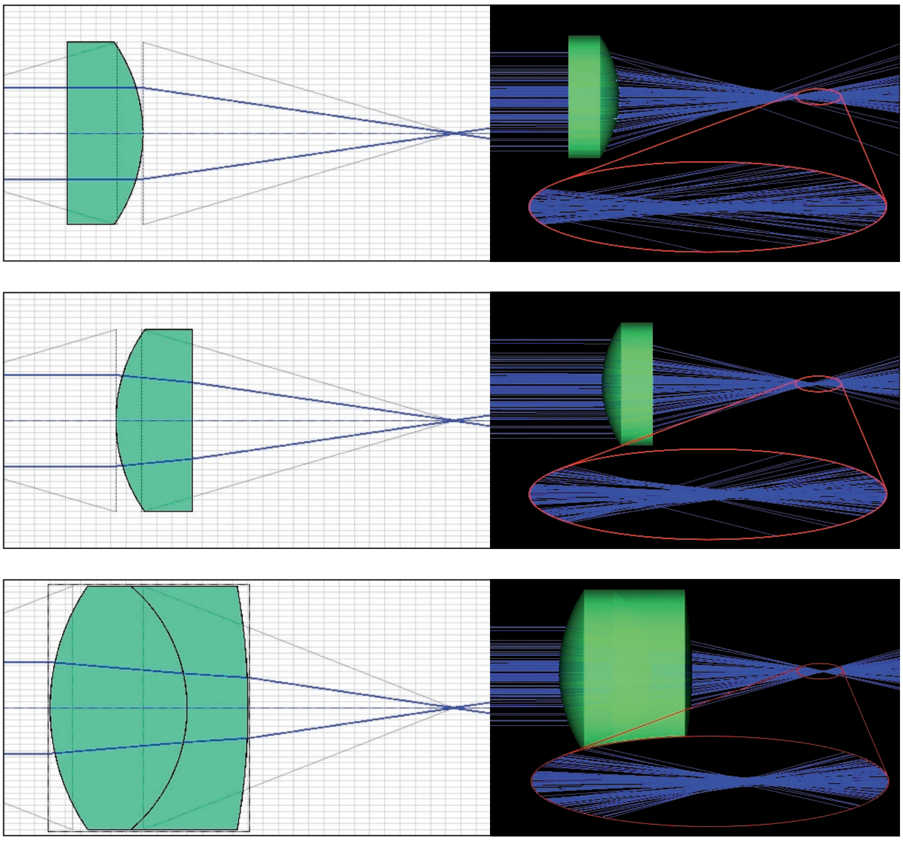


FIGURE 6: **Influence of aberrations while focusing of a collimated beam. From top to bottom aberrations decrease, which can be calculated with method of propagating the variance diameter. Simulation with a raytracing software demonstrates how the focal spot is increased due to the aberrations (right column).**

Aberrations

Although the method of propagating the variance diameters cannot take into account aberrations, it can be utilized to detect optical elements which may introduce significant aberrations and hence severe beam quality degradation.

For coherent Gaussian beams the surfaces of constant phase are spherical and the radius of phase curvature at a given axial position is only a function of the distance from the beam waist and the Rayleigh length. For arbitrary beams the phase surfaces may show deviations from pure spheres, but the same relation applies for the radius of curvature of the **best-fitting** spherical surface. Hence, the propagation of the variance diameter delivers this information, too.

A beam transmitting a lens with spherical surfaces may suffer from aberrations which can significantly degrade beam quality (increase the beam propagation parameter M^2). The main contribution to this aberrations is a function of the radius of phase curvature of the beam, the radius of curvature of the lens surface and the beam diameter only and therefore can be derived from the propagation of the variance diameter. The expected amount of aberrations can be expressed as a dimensionless number giving the deterioration of the wavefront in times the wavelength at the border of the beam profile. A value of unit or higher suggests the presence of aberrations and should attract attention. To obtain the complete impact of a lens the aberration values of both surfaces of the single lens must be added (they may even cancel out each other).

Figure 6 shows the focusing of a collimated beam with a plano-convex lens in two different orientations and with a compound achromatic lens with the same effective focal length. The aberration values calculated for these three examples are ~5, ~1.3, and ~0.43, respectively, unveiling the degradation due to a badly oriented single plano-convex lens and the possible improvement by correct orientation or use of an achromatic doublet.

If aberrations cannot be reduced to negligible values, more sophisticated simulation tools should be consulted. If the optical system is designed for coherent beams, a coherent field propagation method may be used to analyze the impact of aberrations. But this is only possible if measurements or reliable a-priori assumptions on the source field are available. Otherwise and in the case of partially coherent sources a useful approach is to model the beam as a source of geometric-optical rays with Gaussian spatial and angular distribution corresponding to the size and divergence of the beam. Analysis is then accomplished by conventional ray tracing. For this purpose WinABCD offers a direct access to the well-known raytracing software ZEMAX (Figure 6), exporting all optical elements and sources for external analysis at push of a button.

Conclusion

The method of propagating the variance diameter enables a very quick and efficient layout of optical beam forming and beam delivery systems. It is based on simple beam characterization as defined in the international standard ISO11146. Software based on this approach offer the possibility of real-time design, instantaneously displaying graphically the beam propagation through the system and relevant numerical beam parameters at any desired position while the user inserts, moves or tilts optical elements. Requirements on special knowledge and training for users are relaxed. Although aberrations and diffraction at apertures cannot be handled, the method can at least unveil where such problem may appear. If they cannot be avoided, more sophisticated simulation tools should be applied to the setup designed so far.