Anamorphic Shaping of Laser Beams

How to Transforms a Collimated Laser Beam with Elliptical Cross-section into a Circular Beam or Vice Versa

by Ulrich Oechsner, Christian Knothe and Mats Rahmel

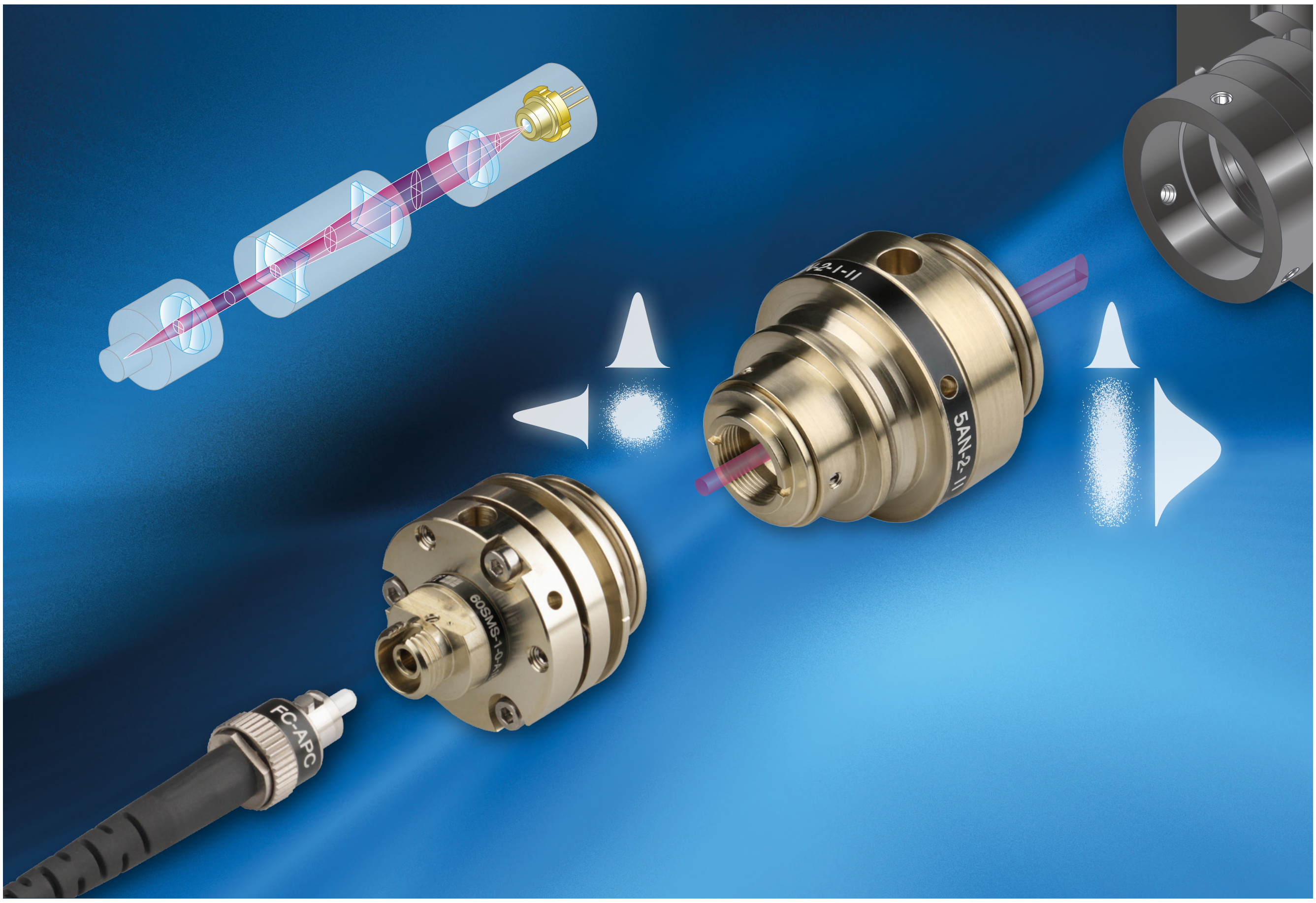

Fig. 1:
Anamorphic shaping of a laser diode beam. After collimation the beam is elliptical. A cylinder lens telescope like the 5AN shown transforms the beam to circular.

Anamorphic beam shaping optics are, e.g., used to transform elliptical laser beams to a round shape before coupling them to single-mode optical fibers. Conversely, there are cases where originally round laser beams need to be transformed into an elliptical shape.

The article describes some sample applications and discusses several concepts of anamorphic beam shaping and their respective advantages and disadvantages.

Schäfter+Kirchhoff GmbH | Kieler Str. 212 | 22525 Hamburg, Germany | +49 40 85 39 97-0 | info@sukhamburg.de | www.sukhamburg.com

Examples of laser sources which emit elliptical beams (Fig. 1) are laser diodes and tapered amplifiers.
In both cases, the beam shape is due to the flat structures of their active semiconductor layers.

Laser Diodes

Laterally single-mode laser diodes emit a diverging beam with an elliptical and approximately Gaussian intensity distribution. The larger divergence is oriented perpendicular and the smaller parallel to the light emitting layer (Fig. 2).

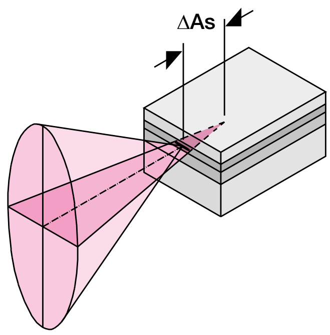

Fig. 2:

Laser diode with astigmatism ΔAs.

Additionally, laser diodes often have two virtual emission sources of the s- and p-directions, i.e. astigmatism, characterized by the axial displacement, ΔAs (Fig. 2), which is usually referred to as astigmatism of the laser diode. Typical laser diode aspect-ratios are 1:2 to 1:3, typical laser diode astigmatisms are in the order of 5 to 50 microns, the latter of both being quite seldom with current laser diodes.

When these laser beams are collimated by a lens, the elliptical shape is conserved (Fig. 1). Collimation along both principal axes at the same time is only possible if the astigmatism is negligible.

Tapered Amplifiers

Tapered amplifiers are optical active semiconductor devices which are used to amplify the power of laser beams by a factor of 100 or more. This is a non-linear process, where the amplifier operates as a laser which is „seeded“ by the input laser. Properties like wavelength and polarization are preserved.

The input or seeding laser beam is coupled into the input facet of the Tapered Amplifier.

In the amplifier, the active region is elongated in one direction, resulting in a rectangular output facet with a large aspect-ratio. Due to this elongation, the area of the output facet is much enlarged, and output powers of several Watts are possible, which would destroy the facet of a normal laser diode. But this also results in a strongly elliptical and astigmatic output beam, which has to be reshaped and astigmatically corrected.

Also, if a laser diode is used for seeding, anamorphic beam shaping and astigmatic correction is also required on the input side. On the output side, tapered amplifiers can have aspect-ratios and astigmatisms similar to laser diodes, but often have aspect-ratios above 1:6 and astigmatic differences of several 100 microns.

The elliptical shape and the astigmatism of a laser beam are both a problem when the beam is to be coupled to a single-mode fiber.

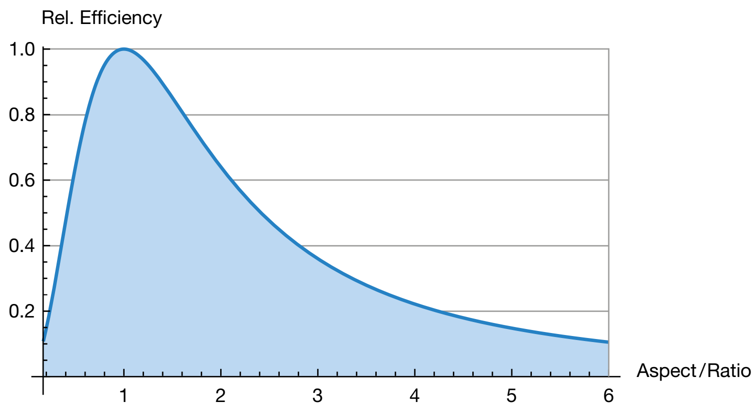

Fig. 3:

Relative coupling efficiencies for elliptical beams with varying aspect-ratio to a single-mode fiber. An aspect-ratio of 2, e.g., reduces the efficiency to about 64%.

Single-mode Fibers

Single-mode fibers are specialized fibers that transmit light in the transverse fundamental mode LP01 only. The field distribution (mode field) of the light exiting the fiber is close to Gaussian. Polarization maintaining single-mode fibers are available which preserve the linear polarization of the laser source.

For laser sources with inferior beam quality, single-mode fibers have a cleansing effect, they act as a spatial filter. Also, for measurements which require an extremely stable setup, single-mode fibers can serve as a defined interface between a laser source and the more sensitive environment of the measurement. The coupling of an incoming Gaussian laser beam to a single-mode fiber is optimal when the (focussed) beam's field distribution at the fiber entrance is the best possible match to the fiber's mode field.

Single-mode fibers have a circular – or in case of some polarization maintaining single-mode fibers – close to circular mode field. Also there is no astigmatism. Therefore, elliptical or astigmatic beams are coupled with reduced efficiency.

To determine the coupling efficiency, the overlap between the fiber's mode field and the laser beam's field distribution at the fiber entrance is calculated. Figure 3 shows example results for an elliptical beam with an aspect ratio varying between 6:1 and 1:6, and Fig. 4 for a circular, but astigmatic beam. Usually, both effects are present simultaneously, which makes matters worse.

Therefore, if a high coupling-efficiency is required, both beam shape and astigmatism need to be corrected. There are several approaches to anamorphic beam shaping. All are able to reshape an elliptical beam, but only two are able to correct for varying astigmatism.

Anamorphic Prism Pair

One of the oldest and simplest methods is first to collimate the laser beam, if necessary, and then to use a pair of wedged prisms which magnify the beam in one direction (Fig. 5a). This setup does change the beam shape, but any astigmatism present cannot be corrected without additional optics. The lateral displacement of the optical axis caused by the prisms is often a drawback.

Anamorphic Cylinder Telescope

Another method is to use two cylinder lenses acting in as a Galileo's telescope in one direction. Fig. 5b shows how this is used in case of a laser diode.
The collimating lens produces a collimated elliptical beam with a Gaussian intensity profile. If there additionally is an astigmatic difference, ΔAs, the beam is collimated in only one of the principal axes and diverging in the other. The cylinder telescope contains a positive and a negative cylinder lens, scaling down the longer elliptical axis to that of the shorter axis. To compensate for divergence induced in one direction, the distance between of the cylinder lenses

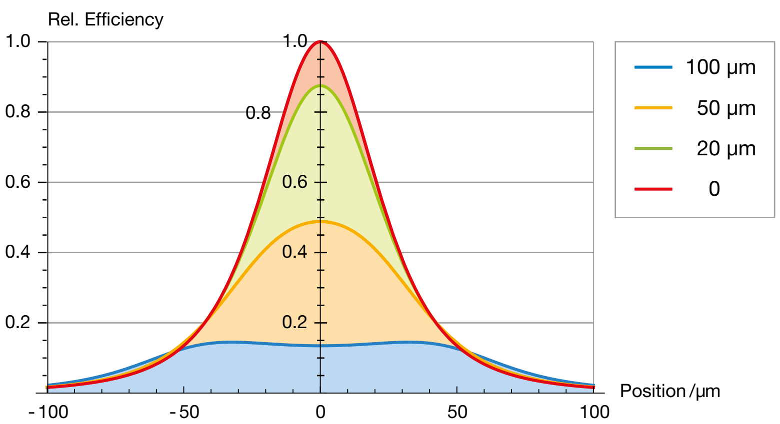

Fig. 4:

Relative coupling efficiencies for circular, but astigmatic beams, with astigmatic focus distances 0, 20, 50, and 100 µm. Shown is an example for wavelength 660 nm and a mode field diameter of 4 µm.

a) b) c)

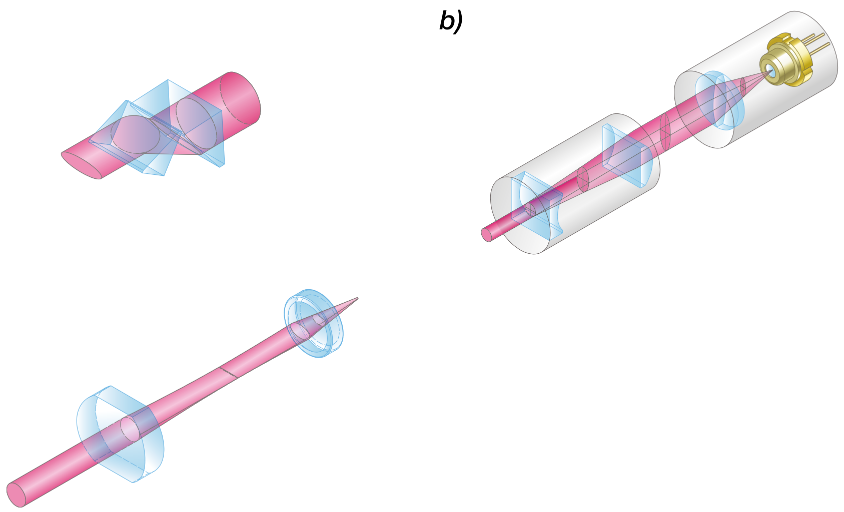

Fig. 5

Some methods for anamorphic beam shaping: a) Anamorphic prism pair, b) Anamorphic cylinder telescope, c) Combination of Spherical and cylinder lens.

is changed. When the beam is refocused in this way, the spot is not only circular but also has plane wave fronts.

Due to the two-element design, it is possible to achieve excellent beam quality while using simple plano-convex and plano-concave cylinder lenses. Lens curvatures and glasses are selected so that the aberrations of both lenses cancel each other resulting in an overall diffraction limited design

Monolithic Cylinder Telescope

Anamorphic cylinder telescopes are sometimes offered as monolithic, single glass, element. The beam is reshaped in the same way as described for the cylinder telescope, but it is not possible to change the distance or the surfaces. A fixed astigmatism could be corrected, but not a varying astigmatism as it is present with laser diodes. The monolithic design has another drawback, there is only one glass, and to achieve diffraction limited performance, a pure cylinder shape usually is not sufficient. “Acylinder” shapes are used, where the cross section is not circular, but a more complicated, aspheric curve.

Combination of spherical and cylindrical lenses

When both aspect-ratio and astigmatism are very large, as e.g. at the exit of some tapered amplifiers, a prism or telescope setup is not adequate. Here, either two crossed positive cylinder lenses, or a combination of spherical collimation optics with a single positive cylinder lens are used (Fig. 5c). Both setups are able to reshape high aspect-ratios and to correct large astigmatisms. But especially with the use of stock lenses, the resulting beam quality often is a problem.

Advantages and disadvantages

Prism pairs and monolithic designs lack the possibility to correct the varying astigmatism present in many elliptical laser beams. This is a disadvantage when not only spherical, but also plane wave fronts are required as in high-efficiency fiber coupling. Regarding costs, the prism setup has the simplest optical elements, but due to the offset optical axis, the mechanics tends to be more complicated.

All in all the cylinder lens telescope setup seems to be good regarding both costs and performance, providing optimum beam quality, as well as shape and astigmatism correction. Diffraction limited and even achromatic performance is possible with a balanced optical design of “simple” cylinder lenses. Acylinder (aspheric) lenses are not required.

The diffraction limited setup is also mandatory for the “inverse” problem of transforming an originally round laser beam to an elliptical shape, as in case of the elliptical fiber collimators for two-dimensional dipole

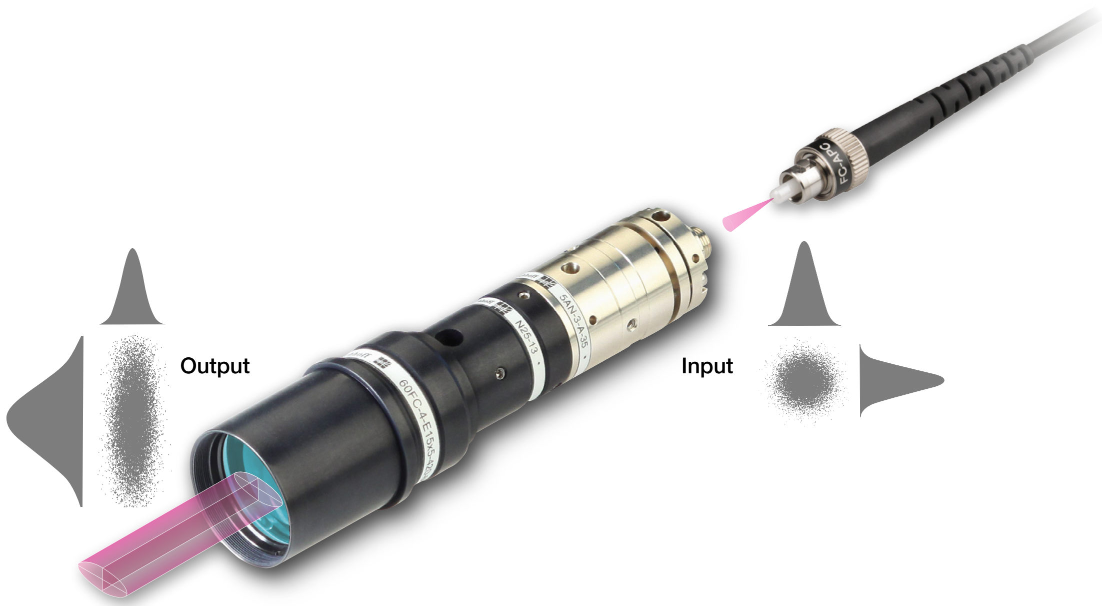

Fig. 6

Elliptical fiber collimator for use in two-dimensional magneto-optical traps (2D-MOTs). A cylinder lens telescope of type 5AN is used to expand the beam to an aspect-ratio of 1:3.

traps mentioned earlier in this article. On the other hand, the telescope design is limited to aspect-ratios of about 1:3. It is possible to cascade two or even more telescopes, but there are more compact and simpler solutions for these cases.

Availability and Applications

The anamorphic beam shaping optics series 5AN, which is based on the cylinder telescope principle is commercially available from Schäfter+Kirchhoff with aspect ratios ranging from 1:1.6 to 1:3. Typical applications are fiber coupling of beams from laser diodes or tapered amplifiers with aspect-ratios up to 1:3.

Elliptical Beams for Traps

But there is also series of specialized fiber collimators which combines a fiber collimator, an anamorphic beam shaping optics 5AN and a beam expander to generate a large beam with elliptical cross-section (Fig. 6). Atoms and even larger molecules can be trapped in the focus of a laser beam. This is used to move them around with the laser beam acting as “optical tweezer”, or to hold them in place.

With a combination of laser beams and a magnetic field, atoms can also be cooled and trapped for quantum-optical experiments (magneto-optical trap, MOT). For two-dimensional magneto-optical traps (2D-MOTs) or in mirror magneto-optical traps, an elliptical shape of the laser is preferred. The laser beams used in these experiments often have a round shape, e.g., because they are originating from a single mode fiber. Anamorphic beam shaping is used to generate the required elliptical beam shape.

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