Laser Beam Propagation

The output beam from modern lasers can be of very high quality. Even an ideal laser beam, however, does not propagate unaltered through space. Laser beams change their size as they propagate, and beam delivery systems must be designed to take this into account.

For example, the beam from a popular industrial CO_2 laser has a diameter of 7 mm at the laser and a divergence of 2.3 milliradian. If a moving beam system were made using this laser, the beam diameter would vary considerably with axis travel. With the focusing lens 1 meter from the laser, the beam would be 7.4 mm in diameter. If the lens were moved to 3 meters from the laser, the beam size on the lens would increase to 9.8 mm. This change nearly doubles the power density in the focused spot and would have a severe effect on many processes.

For a moving beam system to maintain consistent performance throughout its range of axis travel, the beam from the laser must be expanded and collimated. Common ratios of expansion are 2:1 or 3:1. Note that, with 3:1 expansion, the original 7 mm beam diameter is 21 mm. Since the clear aperture of all optical components should be at least 1.5 times the beam diameter (twice the diameter is preferable), a 3X expanded beam requires 32 mm (1.25") optics. With a 2X expander, the more common 1" optics are large enough.

If we take our initial example of beam size change and install a 2X expander, we can get a beam size of 13.9 mm at both 1 and 3 meters from the expander by setting the beam waist at 2 meters. The diameter at the waist it 13.86 mm, so there is a negligible change through the axis travel.

Calculating beam propagation

The calculation of laser beam diameters as the beam propagates through space and is focused by lenses may be done by using equations developed by S.A. Self. Fundamentally, any circularly symmetric laser beam can be described by its waist diameter D_0 and its divergence Θ, as indicated in the sketch titled “Characteristic Dimensions of a Laser Beam”. The beam diameter D_Z at any distance Z from the waist can then be calculated by:

$$D_Z^2 = D_0^2 + z^2 \cdot \Theta^2$$

Calculating focal spot size and distance

When a laser beam is sent through a lens, it is transformed into a new beam whose characteristics depend on the incident beam and the lens's focal length. The focus of the lens is actually the waist of this transformed beam. We shall use the following terminology for a laser beam being focused by a lens as in the second sketch, titled "Focusing of a Laser Beam":

D_{01}	=	waist diameter of the original beam
D_{02}	=	waist diameter of the focused beam
z_1	=	distance from D_{01} to the lens
z_2	=	distance from the lens to D_{02}
f	=	focal length of the lens
Θ_1	=	divergence of the original beam
Θ_2	=	divergence of the focused beam

Then the distance z_2 from the lens to waist, which is not always the lens's focal length, is:

$$z_2 = f + \frac{(z_1 - f) \cdot f^2}{(z_1 - f)^2 + D_{01}^2 / \Theta_1^2}$$

and the focused spot diameter D_{02} is found by:

$$\frac{1}{D_{02}^2} = \frac{1}{D_{01}^2} \cdot \left(1 - \frac{z_1}{f}\right)^2 + \frac{1}{f^2 \cdot \Theta_1^2}$$

The divergence of the focused beam is:

$$\Theta_2 = \Theta_1 \cdot \frac{D_{01}}{D_{02}}$$

The above equations are sufficient for calculating the propagation of laser beams through any unaberrated optical system