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COLLIMATED LIGHT'S NON-ZERO BEAM DIVERGENCE



INSIGHTS

Does collimated light maintain a constant beam diameter out to infinity?

Ideally, collimated light would have a constant diameter from the lens out to infinity, but no physical collimated beam maintains exactly the same diameter as it propagates. The collimated beam's divergence, which is the rate at which the beam's diameter changes, depends on the properties of both the light source and the collimator. Due to this, the collimated beam from a broadband-wavelength source, such as a lamp or light emitting diode (LED), behaves differently than the collimated beam from a narrowband-wavelength source, like a laser.

Collimated Lamp or LED Light

An ideal point source emits light uniformly in all directions, and a positive spherical lens placed one focal length (f) away collimates the light it collects into a beam with zero divergence. This ideal model can be adapted for use with a broadband-wavelength source, like a lamp or LED. Physical sources like these resemble groupings of multiple point sources. An adapted model for these sources takes into account the diameter (d) of the physical light source, as well as the distance (i.e. the focal length) between the light source and the lens. The ratio of these values provides an estimate of the full divergence angle (θ),

$$\theta \sim d / f,$$

of the collimated beam. The better the physical source resembles a single ideal point source, the lower the divergence angle of the collimated beam (Figure 1.1). The resemblance is closer when the physical source is very small, far away from the lens, or both.

A Lamp or LED as a Good-Enough Point Source

A physical source adequately resembles an ideal point source when the divergence of the collimated output beam meets the application's requirements. If the divergence is too large, one option is to increase the focal length of the collimating lens, so the source can be moved farther away. However, this can have the negative effect of reducing the amount of light collected by the lens and output in the collimated beam.

In Figure 1.1, light emitted from each point on the source fills the lens' clear aperture. Rays traced from different points on the source show the output beam's diameter is smallest at the lens, and the beam appears to diverge from the clear aperture of the lens. If light from each point on the source filled only a fraction of the lens' clear aperture, the beam waist would be displaced from the lens.

Laser Point Sources

The point source model can also be adapted for laser light, but in this case the source is defined as the input beam waist. The source size is the waist diameter ($2W_0$). Typical sources include a focal spot, an optical fiber's end face, and the facet of a single-mode laser diode.

There are similarities between point source model adaptations for lasers and broadband sources. For example, laser sources should also be placed one focal length away from the lens to minimize the divergence of the collimated beam. In addition, the smaller the laser source (input beam waist diameter), the lower the collimated beam's divergence.

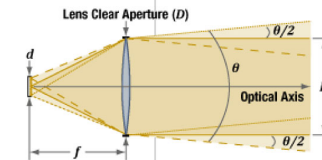
Unlike LEDs and lamps, laser sources do not emit light uniformly in all directions, although the laser light's divergence can be large. If the light comes from a single-wavelength laser, there's a good chance its intensity cross section resembles a Gaussian function. The collimated beam's behavior can then be described using Gaussian beam equations, and the equations describing beam divergence would need to include the wavelength.

Collimated Laser Light

The laser source's size helps determine the properties of the collimated beam. Size is typically referenced to the beam waist radius (W_0) or diameter ($2W_0$), often through its Rayleigh range (z_R).

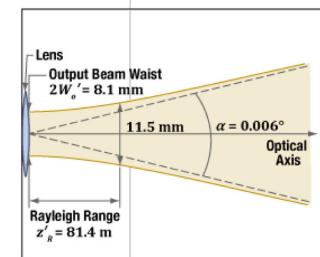
$$z_R = \pi W_0^2 / \lambda,$$

in which (λ) is the wavelength. When the input beam's waist and Rayleigh range are smaller, the collimated output beam has a lower divergence. (See Figures 1.2 and 1.3 for an example.) The divergence along the entire collimated beam can be reduced by shrinking the input



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Figure 1.1 If a broadband-wavelength source, like a lamp or LED, is placed one focal length (f) away from a lens, light from each point on the source is individually collimated. The full divergence angle ($\theta \sim d / f$) of the output beam depends on the focal length and source diameter (d).



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Figure 1.3 The input parameters in Figure 2 create a collimated output beam with a waist located a distance one focal length (50 mm) from the lens. Note that this figure's scale is larger than the scale in Figure 1.2. Close to the beam waist ($\ll z_R$), the beam diameter is approximately constant. Far from the waist ($\gg z_R$), the beam's divergence can be

source beam's waist diameter.

If the source waist is one focal length away from the lens, the collimated beam's waist is located one focal length away from the lens' opposite side. The beam's divergence increases with distance from the waist, and generalizations about the beam divergence can be made for regions close to and far from the waist.

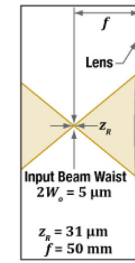
Near the waist, the output beam best resembles an ideally collimated beam. In this region, the beam divergence is lowest, and the beam diameter stays close to the output beam waist diameter ($2W'_o$). But, since the beam diameter increases with distance from the waist, the extent over which the beam is considered collimated is limited. The application determines the limit, which is typically referenced to the output beam's Rayleigh range (z'_R),

$$z'_R = \pi W'^2_o / \lambda.$$

Some applications specify a distance $\ll z'_R$, others tolerate a region that extends a full Rayleigh range from the waist, and some just require the beam diameter to stay below a certain maximum. It can be helpful to note that the beam diameter is a factor of $\sqrt{2}$ (~41%) larger than the waist diameter at a distance one Rayleigh range away from the beam. Examples of different relationships between z_R and z'_R , the input and output beam's Rayleigh ranges, respectively, are plotted in Figure 1.4.

Far from the output beam waist ($\gg z'_R$), the beam divergence is comparatively larger. The divergence in this region is reduced when the output beam waist diameter (and Rayleigh range) are increased. Here, the beam has an approximately constant full divergence angle,

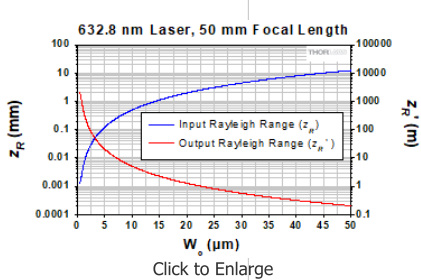
$$\alpha \approx 2\lambda / \pi W'_o.$$



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Figure 1.2 A 632.8 nm laser source, which has a 5 μm diameter waist (W_o) and a 31 μm Rayleigh range (z_R), is collimated by a 50 mm focal length (f) lens.

described by a full divergence angle (α). A wavelength of 632.8 nm was assumed.



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Figure 1.4 The input laser light better resembles a point source when it has a smaller beam waist (W_0), and therefore a shorter input Rayleigh range (z_R). The collimated output beam has a Rayleigh range (z_R') that depends on W_0 , focal length, and wavelength. Increasing the focal length, or decreasing the wavelength, increases z_R' and decreases the overall output beam divergence. The values plotted above were calculated for a 632.8 nm wavelength and a focal length of 50 mm. For comparison, values for a wavelength of 1550 nm and a focal length of 25 mm have also been calculated.

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