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Real Beam Propagation

The Propagation Constant

The propagation of a pure Gaussian beam can be fully specified by either its beam waist diameter or its far-field divergence. So, in principle, full characterization of a beam can be made by simply measuring the waist diameter ($2w_0$), or by measuring the diameter ($2w_z$) at a known and specified distance (z) from the beam waist, using the equations

$$w(z) = w_0 \left[1 + \left(\frac{\lambda z}{\pi w_0^2} \right)^2 \right]^{1/2}$$

and

$$R(z) = z \left[1 + \left(\frac{\pi w_0^2}{\lambda z} \right)^2 \right]$$

where λ is the wavelength of the laser radiation, and $w(z)$ and $R(z)$ are the beam radius and wavefront radius, respectively, at distance z from the beam waist.

In practice, however, this approach is fraught with problems - it is extremely difficult, in many instances, to locate the beam waist; relying on a single-point measurement is inherently inaccurate; and, most importantly, pure Gaussian laser beams do not exist in the real world. The beam from a well-controlled helium neon laser comes very close, as does the beam from a few other gas lasers. However, for most lasers (even those specifying a fundamental TEM₀₀ mode) the output contains some component of higher order modes that do not propagate according to the formula shown above. The problems are even worse for lasers operating in high-order modes.

The need for a figure of merit for laser beams that can be used to determine the propagation characteristics of the beam has long been recognized. Specifying the mode is inadequate, because, for example, the output of a laser can contain up to 50% higher order modes and still be considered TEM₀₀.

The concept of a dimensionless beam propagation parameter was developed in the early 1970s to meet this need, based on the fact that, for any given laser beam (even those not operating in the TEM₀₀ mode) the product of the beam waist radius (w_0) and the far-field divergence (θ) is constant as the beam propagates through an optical system, and the ratio

$$M^2 = \frac{w_{0R} \cdot \theta_R}{w_0 \cdot \theta},$$

where w_{0R} and θ_R are the beam waist and far-field divergence of the real beam, respectively, is an accurate indication of the propagation characteristics of the beam. For a true Gaussian beam, $M^2 = 1$

Embedded Gaussian

Diagram illustrating the evolution of a Gaussian beam in a tapered fiber. The beam starts at $z=0$ with waist $2w_0$ and propagates to $z=R$ where the waist is $2w_R(R)$. The diagram shows the beam's cross-sections at different points, with labels for "EMBEDDED GAUSSIAN", "MIXED MODE", and $2w_0R = M(2w_0)$. The beam is shown as a yellow shaded region expanding as it moves along the z -axis.

A mixed-mode beam that has a waist M (not M^2) times larger than the embedded Gaussian will propagate with a divergence M times greater than the embedded Gaussian. Consequently the beam diameter of the mixed-mode beam will always be M times the beam diameter of the embedded Gaussian, but will have the same radius of curvature and the same Rayleigh range ($z=R$).

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