

# Fundamentals of Beam Profiling and Beam Measurement

As a laser beam propagates, its width and spatial intensity distribution will change in space and time owing changes in the laser cavity, divergence, and interaction with optical elements. Spatial intensity distribution is one of the fundamental parameters that indicates how a laser beam will behave in an application. Laser printing, material processing, fiber optic coupling, optical data storage, laser pumping, and photochemistry are some of the applications whose efficiency depends on a laser's spatial intensity profile and beam width. Theory can sometimes predict the behavior of a beam, but manufacturing tolerances in lenses and mirrors, and ambient conditions affecting the laser cavity, necessitate verification. Consequently, it is crucial for researchers, system designers, and laser manufacturers to be able to measure accurately these parameters. ISO standard 11146 defines approaches to be used in measuring such beams. All CVI Melles Griot products are in full conformance with this standard.

## DEFINING BEAM WIDTH

The boundaries of optical beams are not clearly defined and, in theory at least, extend to infinity. Consequently, the dimensions of a beam cannot be defined as easily as the dimensions of hard physical objects. The commonly used definition of beam width is the width at which the beam intensity has fallen to  $1/e^2$  (13.5%) of its peak value when measured in a plane that is orthogonal to the optical axis. This is derived from the propagation of a Gaussian beam and is appropriate for lasers operating in the fundamental TEM<sub>00</sub> mode (see figure 11.33).

Many lasers, however, exhibit a significant amount of beam structure, and applying this simple definition leads to problems. Therefore, the ISO 11146 standard specifies the beam width as the  $1/e^2$  point of the second moment of intensity, a value that is calculated from the raw intensity data and which reduces to the common definition for a Gaussian beam.

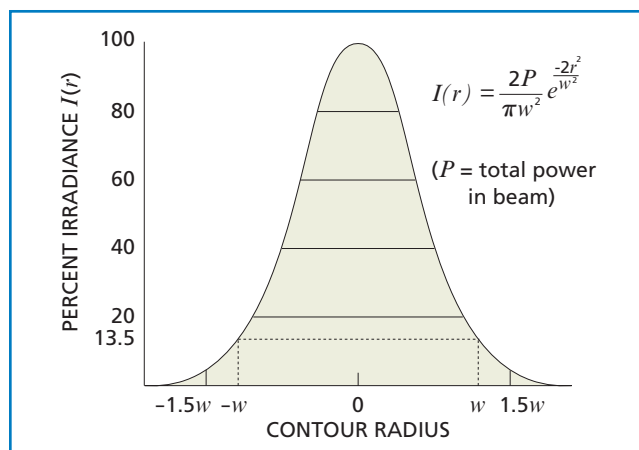


Figure 11.33 **Gaussian profile of a TEM<sub>00</sub> mode** (note the beam radius  $w$  at the  $1/e^2$  (13.5%) intensity level)

## METHODS OF MEASURING BEAM WIDTH

There are four main types of beam-profiling instrumentation: camera-based systems, knife-edge scanners, slit scanners, and pinhole scanners. Each has specific advantages and disadvantages. Different measurement techniques may result in slightly different results; therefore, it is critical that comparative measurements be made with the same technique.

### Camera-Based Profilers

Camera-based profilers use a two-dimensional array of square or rectangular pixels as the imaging device, which, much like photographic film, instantly record and display the entire optical pattern that impinges on the camera surface. The intensity distribution of a laser beam is recorded pixel by pixel and displayed as either a topographic or three-dimensional contour plot. The advantage of such profilers is that they can detect and display any structure that may exist on the profile. They can display two- and three-dimensional plots of profiles, and they can be used with both cw and pulsed lasers. The chief disadvantage of these instruments is that their measurement resolution is limited by pixel size (usually between 5 and 10  $\mu\text{m}$  on a side), which, in general, limits their use to measuring beams greater than  $\sim 60 \mu\text{m}$  in width. A new class of camera-based profiler, the  $\mu\text{Beam}^{\text{TM}}$ , overcomes this size limitation by magnifying the laser beam, in a calibrated manner, by a factor of up to  $100\times$ . This allows profiling of beams less than 5  $\mu\text{m}$  in diameter but limits the maximum beam diameter to about 50  $\mu\text{m}$ . Another disadvantage is limited spectral range.

Two types of image detectors are used in CVI Melles Griot beam camera-based profilers—charge-coupled device (CCD) detectors and complementary metal-oxide semiconductor (CMOS) detectors. In general, CCD detectors have a greater dynamic range and lower noise than CMOS detectors, but they are somewhat slower and require much more complex circuitry. In camera-based beam profilers, the performance differences are minor. One clear advantage of a CMOS detector is that the failure of pixel can shut down a complete row because of the way in which charge travels through the detector.

### Knife-Edge, Slit, and Pinhole Profilers

All three of these instruments generate a profile by mechanically moving an aperture across the beam in a plane orthogonal to the optical axis. The light passing through the aperture is measured by a detector and correlated with the position of the aperture as it crosses the beam. Unlike camera-based scanners, which measure a profile in three dimensions ( $x$ ,  $y$ , intensity), scanners measure only two dimensions at a time ( $x$  and intensity or  $y$  and intensity). Consequently, three-dimensional representations generated by these systems are calculated, not measured, and the accuracy or the reconstruction depends upon basic assumptions made about the beam characteristics and the algorithms used in the reconstruction.

### Scanning Pinhole Profilers

Pinhole profilers use a small pinhole as the aperture and plot the transmitted power vs position. The resolution of the profile is determined by the size of the aperture. The chief advantage of a pinhole profiler is its ability, within the resolution, to create an exact profile of a plane through a portion of the beam. The disadvantages are that the transmitted power through the pinhole is very small, aligning the pinhole is extremely difficult, and multiple positional measurements are needed to generate a profile of the entire beam.

### Scanning Slit Profilers

Slit profilers use a long narrow aperture which encompasses the full width of the beam in a direction perpendicular to the travel of the slit. It then plots the transmitted power through the slit vs position. Unlike the pinhole scanner, the slit scanner scans through the entire beam, not just a single plane. However, unless the beam is circularly symmetric and near Gaussian, the profile may not be an exact representation of the intensity profile. Like pinhole scanners, the resolution of the scan is a function of the width of the slit, and the narrower the slit, the less light reaches the detector, decreasing the signal-to-noise ratio.

### Scanning Knife-Edge Profilers

Knife-edge profilers use an aperture large enough to pass the entire beam. The aperture has one sharp, straight edge (knife edge). As the aperture traverses the beam, the system measures the portion of the beam that is not blocked by the blade (see figure 11.34) and plots the differential (rate of change in intensity) vs position of the power through the aperture.

This has several advantages when compared to a slit or pinhole scans: The beam intensity is not limited by the size of the pinhole or slit width, so the signal-to-noise ratio is very high; resolution is not limited by the size of the aperture, allowing beams of a few microns in diameter to be measured; and because, at some point in the scan the full beam strikes the detector, accurate power and noise measurements can be taken. Like the slit scanner, the accuracy of a scan depends upon the geometry of the beam. For best results, the beam should be circularly symmetric and near Gaussian.

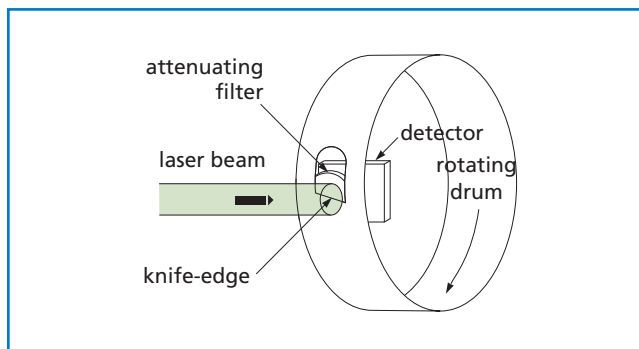


Figure 11.34 **Simplified mechanics of a knife-edge beam profiler**

### Tomographic Scanning

As discussed above, scanning slit and knife-edge scanners cannot generate truly accurate three-dimensional reconstructions of laser beam profiles. Reasonable approximations can be made, however, by using tomographic techniques—the same techniques used with MRI and CAT scanners to create three-dimensional images of internal organs. The key to making these reconstructions is to scan the beam in as many different directions as possible. For useful tomographic analysis, scans from at least three different directions are needed. If scans could be made from 10 or more directions, the three-dimensional reconstruction would be highly accurate.

CVI Melles Griot offers two knife-edge systems that use tomographic algorithms to construct three-dimensional profiles. The BeamAlyzer™ system has a three-blade scan, and the Super BeamAlyzer™ has a seven-blade scan (see figure 11.35). For most beams, the Super BeamAlyzer's reconstructions rival those measured directly with a camera-based scanner.

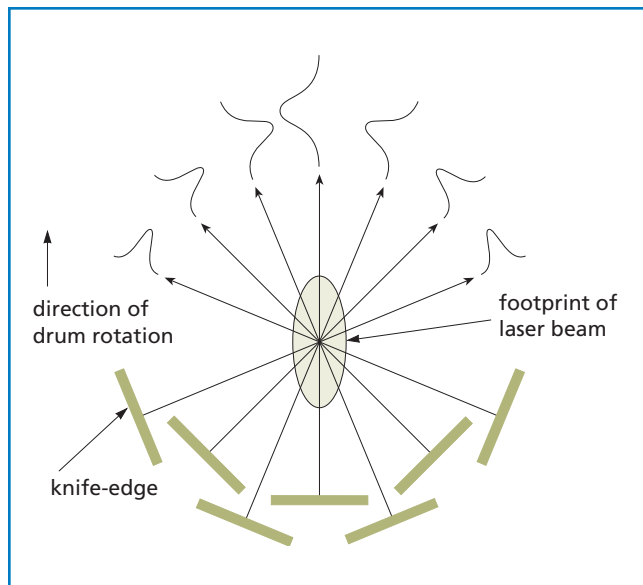


Figure 11.35 **Orientation of the knife edges on the 7-blade Super BeamAlyzer™ tomographic beam profiler**

### BEAM PROPAGATION FACTOR AND $M^2$

The propagation factor  $k$  is given by the equation

$$k = \frac{1}{M^2} = \frac{\lambda}{\pi W_0 \theta} \quad (11.28)$$

where  $\lambda$  is the wavelength of the beam,  $W_0$  is the beam waist, and  $\theta_0$  is the far-field divergence of the beam. The propagation factor is an invariant that describes the relationship of a non-Gaussian beam to a Gaussian beam as it passes through an optical system. If  $k=M=1$ , the beam is Gaussian. If  $k < 1$  ( $M^2 > 1$ ), the beam is not Gaussian, but all of the standard Gaussian propagating formulas may be used with appropriate modifications (e.g.,  $W_0 = M \times w_0$ ,  $\theta_0 = M \times \theta_0$  where  $w_0$  and  $\theta_0$  are the corresponding Gaussian parameters). Indeed, the concept of an "embedded Gaussian" has been introduced as a construct to assist with both theoretical modeling and laboratory measurements (see figure 11.36).

### $M^2$ Measurement

A variety of instruments have been developed to measure the propagation factor and  $M^2$  in the laboratory. Most are based on the same fundamental operating principle; the incoming laser beam is focused by a lens. This creates a beam that has a beam waist at the focal point, a near-field divergence region (within the Rayleigh range), and a far-field region (many, many times the Rayleigh range) all within a distance of a few inches. Using a beam profiler, the beam diameter at the waist and the diameters at near-field and far-field points on either side of the waist are measured. A computer then fits a hyperbolic curve to the data and, using the fundamental Gaussian formulas, calculates the beam waist and divergence of the embedded Gaussian,  $M^2$ , the location of the beam waist in the incoming laser beam, and other critical parameters. A schematic diagram of a simple  $M^2$  moving lens device is shown in figure 11.37.

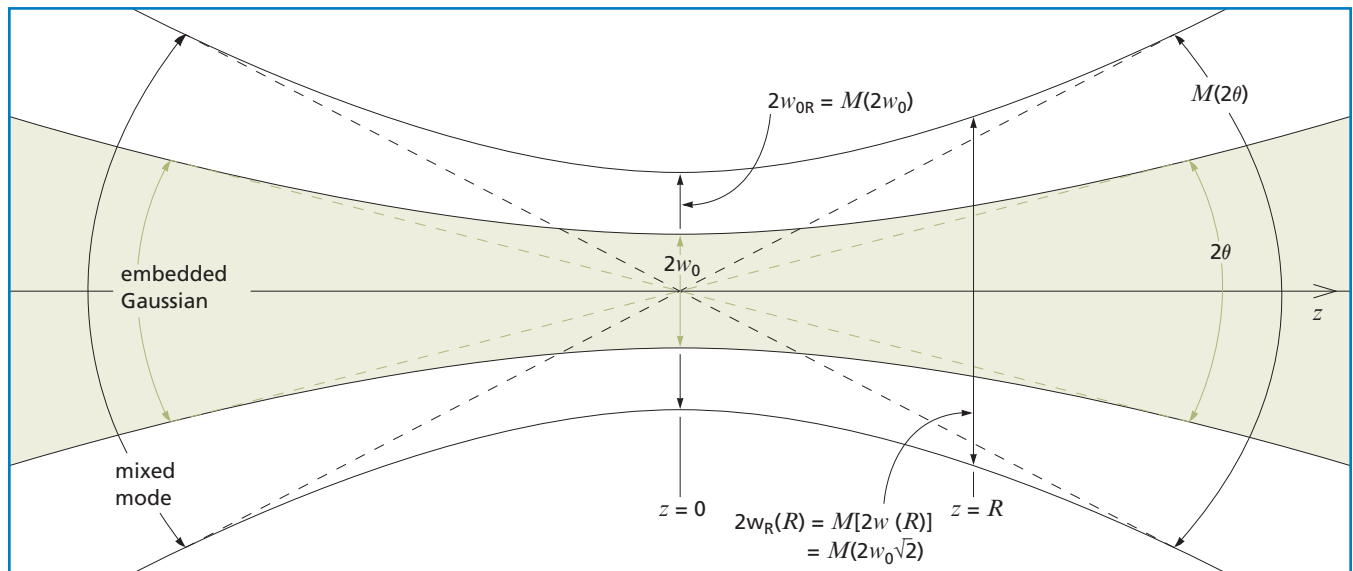


Figure 11.36 **The embedded Gaussian concept** A mixed-mode beam which has a waist  $M$  (not  $M^2$ ) times larger than the embedded Gaussian will propagate with a divergence  $M$  times greater than the embedded Gaussian, and the mixed-mode width will always be  $M$  times the embedded Gaussian width, but will have the same radius of curvature and the same Rayleigh range

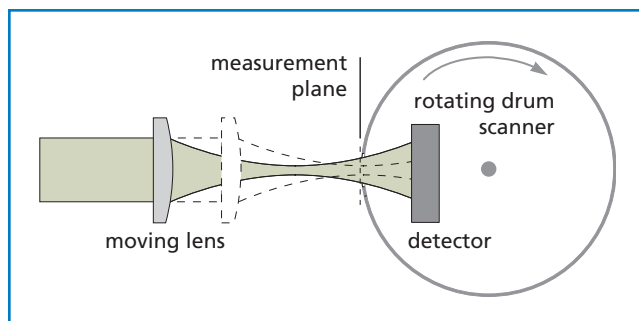


Figure 11.37 **A simple moving-lens  $M^2$  setup**