

# The Misunderstood $M^2$

Understanding the measurement and following proper procedure will yield accurate results.

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**M**<sup>2</sup> describes the deviation of a laser from a purely fundamental TEM<sub>00</sub> mode structure, where M represents the factor by which the purely fundamental theoretical beamwidth is multiplied to determine the actual beamwidth. A laser producing a purely fundamental mode beam, for example, has an M<sup>2</sup> of 1.0; a laser with an M<sup>2</sup> of 1.2 will produce a spot width 9.5% larger than theoretical. It is not surprising, then, that the parameter is widely used to characterize beam quality. What is surprising is that many laser researchers and test engineers do not seem to know how this important parameter is measured.

A common misunderstanding is that a sensor can be simply inserted into a laser beam path to instantly “read out” M<sup>2</sup>. This is not possible since M<sup>2</sup> is determined through a process of beam-size measurements along the beam path—a process that is not always intuitive. M<sup>2</sup> determination requires mapping the beam propagation in space and taking beamwidth parameters along this path to determine the deviation from the theoretical. Some standards call for 10 or more measurements at specified positions along the beam path and fitting functions to determine beam propagation.

This sounds like a difficult task, but a simple yet reliable measurement process exists called the Rayleigh method. The method is easy to implement for many lasers and can be performed in less than a minute, even when it is done manually. The test uses a test lens, an optical rail, and a beam profiler or beam-size measurement tool, and requires only three beam measurements.

The Rayleigh method involves directing the laser beam through the test lens to create a beam waist. A profiling tool mounted on the optical rail measures the beam size along the optical path of this beam waist.

First, measure the beam diameter at the beam waist  $D_{\min}$ . Next, determine the Rayleigh distance  $Z_{\min}$  of the beam waist by moving the profiling tool along the optical rail from the beam waist toward the laser to the point at which the measured beam diameter is the Rayleigh diameter

$\sqrt{2} D_{\min}$ . The position of the profiling tool on the optical rail is recorded as  $Z_{\min}$ . Finally, determine the Rayleigh distance  $Z_{\max}$  to the other side of the beam waist by moving the profiling tool from the beam waist away from the laser to the point at which the beam diameter is again the Rayleigh diameter.

We obtain M<sup>2</sup> using

$$M^2 = \pi D_{\min}^2 / (2\lambda |Z_{\min} - Z_{\max}|)$$

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where  $\lambda$  is the laser wavelength.

Some simple guides exist for selecting the test lens in order to generate a convenient beam-waist dimension and Rayleigh length. We can approximate the beam waist using  $D_{\text{waist}} = f\theta$ , where  $f$  is the focal length of the test lens and  $\theta$  is the beam divergence. For a lens with a focal length of 100 mm and a beam divergence

of a milliradian,  $D_{\text{waist}}$  is approximately  $D = 100 \text{ mm} (1 \times 10^{-3}) = 100 \mu\text{m}$ , which is easily measured by most profiling equipment. We can estimate the Rayleigh distance  $Z$  of the 100- $\mu\text{m}$  spot using

$$Z = \pi D_{\text{waist}}^2 / 4\lambda$$

$Z$  is 10 to 20 mm for visible wavelengths ( $\lambda = 400\text{--}750 \mu\text{m}$ ). For accurate results, the test lens diameter should be at least twice the input beam diameter to prevent clipping of the beam. If the lens is smaller than this, it will begin to act as a limiting aperture, creating diffraction effects that will propagate with the beam and distort the results. The laser should be stable during the course of the measurements; if mode hopping occurs during the M<sup>2</sup> measurement, the results will be invalid.

In just a few short steps, M<sup>2</sup> can be determined using the Rayleigh method and the mystery of the often-misunderstood parameter vanishes. **oe**

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