Comparing M^2 of an actual laser beam to a pure TEM_{00} Gaussian beam allows beam-propagation characteristics to be accurately predicted.

Propagation factor quantifies laser beam performance

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Laser Focus World

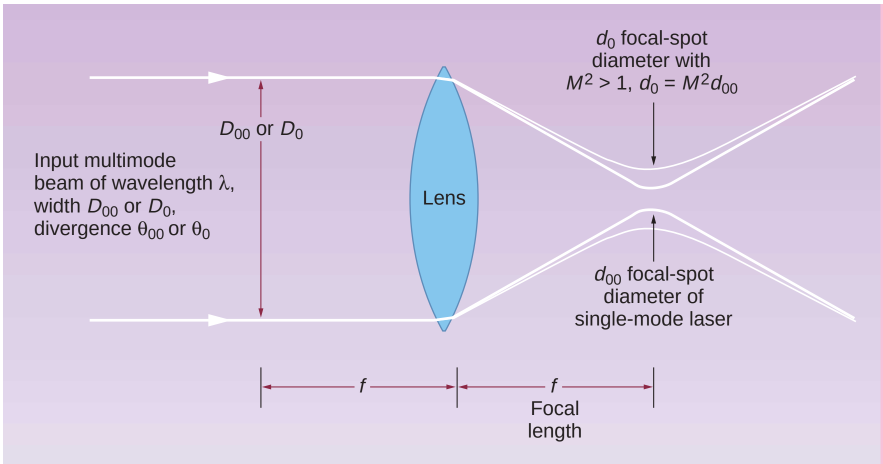

FIGURE 1. Two equivalent input beams that are equal in all other respects will focus to two different waist sizes if the M^2 of each beam is different.

Many emerging applications of lasers require extremely high TEM_{00} Gaussian mode quality. These range from scientific experiments—in which the beam must be focused to a very high intensity (or irradiance) for nonlinear processes—to industrial processes in which a beam must be focused to the smallest possible spot for such applications as drilling holes in stainless steel.

In the past, a Gaussian fit to the beam profile has been used to evaluate how close the beam is to TEM_{00}. It was shown more than 10 years ago, however, that a multimode combination of beams can have a nearly perfect Gaussian shape.[1–3] Thus, a Gaussian fit can deceive a user into assuming propagation properties of a laser beam that will not exist in practice. The Gaussian fit then becomes not only a meaningless measurement, but also one that is deceptive—giving the user a false sense of laser performance.

If a Gaussian fit does not adequately provide the mode characteristics of a laser beam, what measurement does? The answer is the beam-propagation factor M^2. With today's beam-profile-analysis equipment and software, it is easy to identify this parameter, which quantitatively compares the propagation characteristics of the real beam to those of a pure TEM_{00} Gaussian beam. For a given input beam width and lens focal length, this comparison allows the exact focused spot size to be predicted, as well as the irradiance of a focused spot, the Rayleigh range over which the beam is relatively collimated, and the far-field divergence of the beam. While the M^2 concept has been known for many years, the popularity of making this measurement has only recently been catching on in both scientific and industrial communities.

The theory of M^2

A common use of the M^2 concept is in determining the size of a focused spot when a focusing lens is used (see Fig. 1), as

$$d_0 = M^2\, 4\lambda f / \pi D_0$$

where λ is the wavelength, f is the focal length of the lens, and D_0 is the waist width of the input multimode laser beam at the focal length of the lens. This equation shows that the focused spot size d_0 is M^2 times larger than it would be for a pure TEM_{00} Gaussian beam of the same input width D_0. Thus, for a beam of $M^2 = 2$, the focused spot size is two times larger than would be obtained with a TEM_{00} beam. The irradiance, which is proportional to the beam width squared, would be only one-fourth of that achieved with a pure TEM_{00} Gaussian beam.

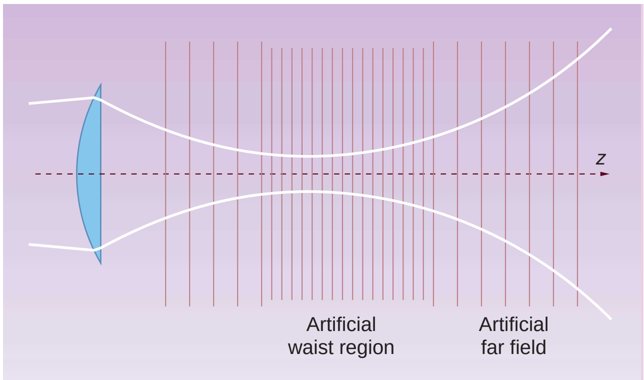

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FIGURE 2. The ISO standard defines the method required to accurately measure M^2, which is based on a fixed-position lens and multiple beam-width measurements made through the waist.

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The focused spot size and irradiance of a laser beam have profound effects in both science and industry. In science, nonlinear processes are typically proportional to the irradiance squared or cubed. Thus, a beam with an M^2 of 1.4 (and an irradiance of one-half that of the Gaussian) would have a nonlinear output of 0.25 to 0.125 of a beam with an M^2 of 1, all other characteristics being equal.

In the industrial process of very fine hole drilling, a beam with an M^2 of 1.4 would drill holes 1.4 times larger than would a beam that was pure TEM_{00}. With the beam irradiance one-half that of a Gaussian beam, the hole may not be drilled to the expected depth.

In both scientific and industrial cases, it is essential for the user to know what to expect from the process. While experimentation is often used to obtain this information, by knowing the M^2 of the laser beam, a scientist or production manager can make accurate predictions.

Measurement of M^2

One reason the concept of M^2 has not been particularly popular is the difficulty of making an accurate measurement. It cannot be determined with a single calculation, as would be possible with a Gaussian fit, for example.

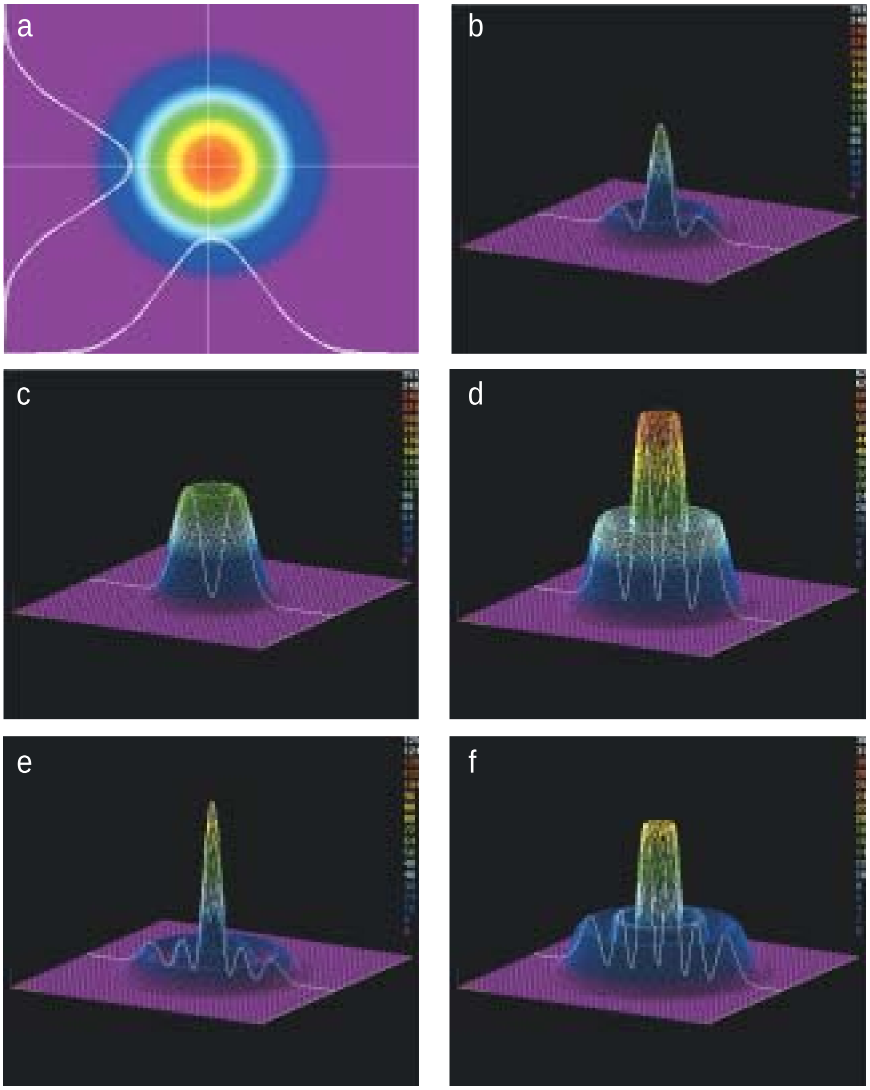

FIGURE 3. Simulated composite laser beam (a; $M^2 = 3.3$) composed of 0% TEM_{00}, 16% TEM_{*10}, 44% TEM_{*01}, 20%TEM_{*11}, 12% TEM_{*20}, and 8% TEM_{*21} appears Gaussian (fit = 0.97) even though it is composed entirely of higher-mode laser beams The two white cross-section profiles are that of the beam and of the Gaussian fit, which are seen to be almost indistinguishable (b is $TEM_{*1,0}$, c is $TEM_{*0,1}$, d is $TEM_{*1,1}$, e is $TEM_{*2,0}$, and f is $TEM_{*2,1}$).

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The International Organization for Standardization (ISO; Geneva, Switzerland) committee has defined a methodology that provides for reliable measurement of M^2 so that this parameter can be used with confidence by anyone making the measurement.[4] The method involves placing a lens of a known focal length in a laser beam, then making a series of measurements through the focused waist of the beam (see Fig. 2). Measurements that are usually essential include the width of the spot at the smallest focus, the position of the spot at focus, the width of the beam at the focal length of the lens—which may not be the same place as the smallest spot—and the divergence of the beam beyond focus. Typically, a more-reliable and consistent measurement is obtainable when the equipment end user makes a series of measurements and then performs a curve fit to the measured data to calculate the M^2 parameters from the fit.

Examples illustrating the contrast between Gaussian fit and M^2 are shown in Figs. 3 and 4. In Fig. 3, a computer-generated beam is shown that is composed of several modes.[3,5] The beam shape provides an almost perfect Gaussian fit at 0.97, yet the M^2 of the beam is 3.3.

Equipment perspectives

Certain steps are essential to making a reliable and consistent measurement of M^2. The first is to perform the measurement as specified in the ISO standard. That is, the lens must be stationary and the sensor moved through the waist of the beam. In some cases, the user finds it easier to hold the sensor stationary, and move the lens in the incoming beam (see Fig. 5 on p. 122). This method is typically reliable when the input beam is well collimated over the range of motion of the focusing lens. If, however, the beam is either diverging or converging over the travel length of the lens, then the M^2 measurement can be incorrect and very misleading.

A second part of the ISO definition is that the width of the laser beam must be measured by the Second Moment method. Spiricon Inc. (Logan, UT) software uses proprietary algorithms to calculate the Second Moment width, which is difficult to do because of nonlaser background signal and off-axis laser light. While there are many other definitions of laser-beam width, including the $1/e^2$ points and 14% of peak, none reliably provides an accurate evaluation of M^2. Some suggestions have been made to enable other types of measurements to approximate the Second Moment width.[6] Nevertheless, only the Second Moment beam-width measurement conforms to the laser-beam-propagation equation and is, therefore, the only measurement that provides reliable and consistent measurements of M^2.

There are several commercial instruments for measuring the M^2 of laser beams. Some use the stationary-detector/moving-lens method described here. Some users are satisfied with these instruments, while others report the results to be inconsistent. As noted, the difference may be whether or not the beam is measured through a collimated section. Some manufacturers report that they have special algorithms to correct for errors in the case of high-divergence beams. Others provide instrumentation that holds the lens stationary and moves the detector, as mandated in the ISO standard. Spiricon provides the fixed-lens type of instrumentation.

For unusual lasers that have extremely large beams or wavelengths incompatible with the optics and cameras of commercial instruments, a user typically has to make the M^2 measurement manually. In this case, software is available that provides a detailed step-by-step process for making consistent measurements and calculating M^2.

Commercial application

The concept of M^2 measurement enables both laser manufacturers and laser users to have greater confidence in their ability to predict the performance of the laser beam. In some cases, OEM users are requiring laser manufacturers to measure the M^2 on each laser shipped and hold a very tight specification on this parameter.

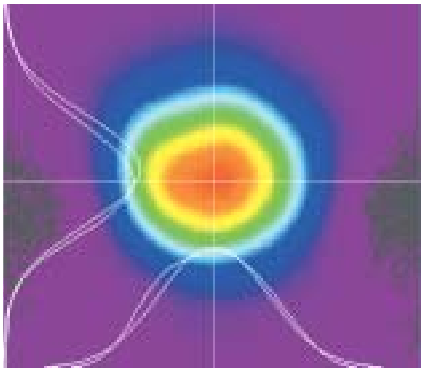

FIGURE 4. Real multimode laser beam has M^2 of 4.8 but its Gaussian fit is 0.91, so in an industrial application this beam would not perform as well as one with a smaller M^2 parameter.

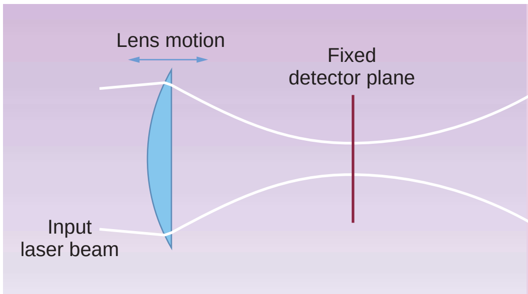

FIGURE 5. Alternative M^2 measurement method, which involves moving the lens instead of the detector, can be reliable if the input beam is well collimated over the range of motion of the focusing lens.

Commercial instrumentation is now readily available for M^2 measurement, which makes it much easier for the end user to accurately evaluate this important parameter. Hence, experiments come much closer to meeting the expectations of the laser scientist, and industrial users are much better able to predict what a laser will do in a given application. ❑

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