

What is M²

For a laser beam propagating through space the equation for the divergence, Θ , of a pure Gaussian unfocused beam is given by

$$\Theta_{00} = 4\lambda/\pi D_{00} \quad (1)$$

where D_{00} is the waist size of the beam, and λ is the wavelength. Actual beams with additional modes often start with a larger beam waist, D_0 , and/or have a faster divergence Θ_0 . In this case equation (1) becomes

$$\Theta_0 = M^2 4\lambda/\pi D_0 \quad (2)$$

where Θ_0 and D_0 are the divergence and width of a non Gaussian beam and M^2 is greater than 1 and is named the “Beam Propagation Ratio” per the ISO 11146 standard. When a pure Gaussian laser beam is focused, the width of the focused spot is defined by:

$$d_{00} = 4\lambda f/\pi D_{00} \quad (3)$$

where d_{00} is the ideal focused spot width, f is the focal length of the lens, and D_{00} is the width of the input beam waist and is placed one focal length from the lens as shown in Figure 1.

However, when a distorted, or multimode beam is focused, the equation demonstrated in Figure 1 becomes:

$$d_0 = M^2 4\lambda f/\pi D_0 \quad (4)$$

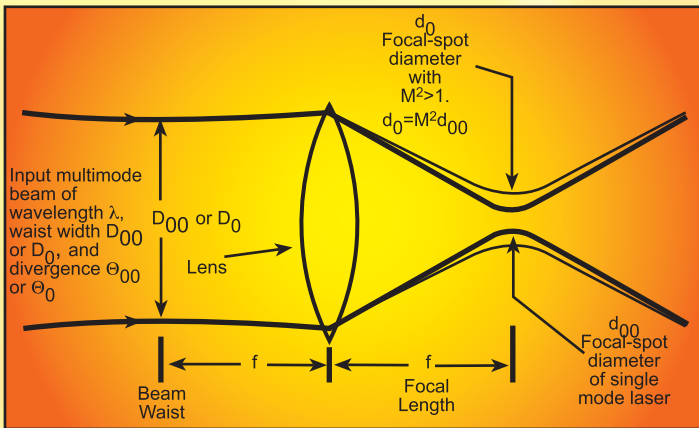


Figure 1. Characteristics of a laser beam as it passes through a focusing lens.

The real focused spot width is M^2 larger than expected for a pure Gaussian beam! The energy intensity is thus M^4 times less than for a pure beam. Therefore, knowing M^2 is essential in knowing the intensity, or beam width, of a focused beam.

Note: If the lens is not exactly one focal length from the beam waist then Figure 1 does not apply. See reference 3.

How is M² Measured?

You can not determine M^2 from a single beam profile measurement. The ISO/DIS 11146 requires that M^2 be calculated from a series of measurements as shown in Figure 2. M^2 is measured on real beams by focusing the beam with a fixed position lens of known focal length, and then measuring the characteristics of the artificially created beam waist and divergence. The important characteristics to be measured are:

1. The width of the smallest focused spot in X and Y
2. The position of the focused spot relative to the focal length of the lens
3. The beam width at the focal length of the lens (which is usually different than the smallest spot)
4. The divergence angle of the beam beyond focus

To provide an accurate calculation of M^2 , it is essential to make more measurements in the focused beam waist region, and a number of measurements in both the far fields. The multiple

measurements ensure that the minimum beam width is found. In addition, the multiple measurements enable a “curve fit”

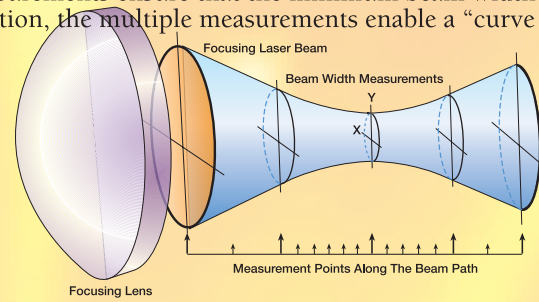


Figure 2. Multiple beam width measurements made by M²-200

that improves the accuracy of the calculations by minimizing measurement error at any single point. An accurate calculation of M^2 is made by using the data from the multiple beam width measurements at known distances from a lens, coupled with the known characteristics of the focusing lens.

What About Accuracy?

There are a number of sources of potential error in M^2 measurements. Spiricon engineers have gone to great lengths to minimize these errors. One of the greatest errors in measuring M^2 comes from measurement of the beam widths. The beam width measurement method is prone to significant errors if the “background” or “baseline” of the camera is not adjusted correctly. For example, if the baseline is set too high, as in Figure 3a, the beam width as measured by the instrument will be larger than the actual beam width.

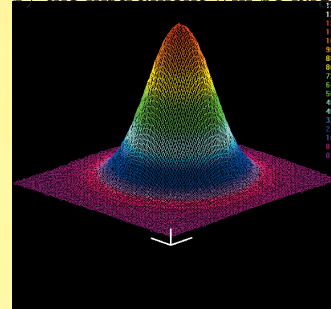


Figure 3a. Baseline too high results in a measured width too large.

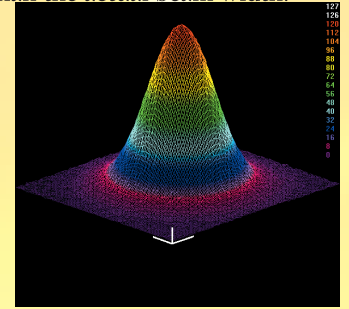


Figure 3b. Baseline corrected with Ultracal results in a correct beam width measurement.

Spiricon’s M^2 -200 beam propagation analyzer uses a very sophisticated, patented Ultracal™ calibration method to ensure that the background is set properly as in Figure 3b. Thus background errors do not contribute to beam width measurement errors. This Ultracal is extremely important because at the beam focus, or waist, the beam may cover only a few pixels of the camera. A slight error in background over the many non-illuminated pixels could generate a response equal to, or greater than the real signal, and create significant error.

Besides baseline level, baseline noise can contribute to significant errors in beam width measurement. Spiricon’s patented Ultracal incorporates all noise components in a manner that tends to cancel noise by averaging positive and negative going fluctuations. Competitive systems truncate negative going noise fluctuations to zero, leaving only positive noise components. This tends to create a net positive DC offset. This is similar to having a positive DC baseline offset which would contribute to beam width measurement errors.

The ISO 11146 method of M^2 measurements specifies that a lens shall be placed at a fixed position in the beam path, and then the measurements made a specified distance from the lens. Not all commercial M^2 measuring instruments employ a fixed position lens and moving detector. Instead, some manufacturers use a

fixed position detector and a moving lens. If the laser beam is diverging or changing in some other way over the travel range of a moving lens, the reported M^2 value and other results can be significantly compromised.

Finally, Spiricon engineers have developed a proprietary method of using software apertures to exclude noise beyond the wings of the laser beam. This contributes greatly to beam width measurement accuracy, especially when the beam is focused to a small waist and covers only a small number of pixels.

Automatic M^2

The M^2 -200 Optical Train uses a fixed position lens, and automatically translates the camera through the near field and the far field beam waist. Both the lens and the camera are mounted at fixed positions on one end of the instrument housing. The mirrors which direct the focused beam onto the camera are mounted on a table, as shown in Figure 4. The table is connected to a very precise lead screw and stepper motor to translate the table in known increments. This generates a series of beam width measurements along the path of the focused beam as illustrated in Figure 2. All of these measurements and translations, as well as incremental beam attenuation, are automatically controlled by the M^2 -200 software. A new, high speed USB interface allows use even with laptop computers.

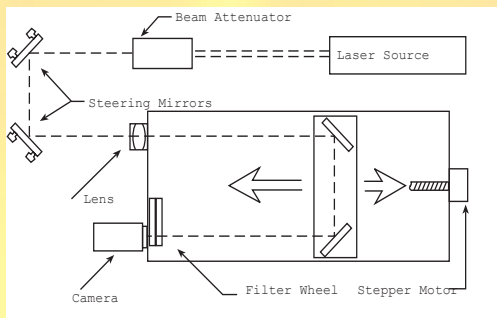


Figure 4. M^2 -200 Optical Train to enable automatic measurement of M^2 on lasers from the Near UV to Near IR (Steering Mirrors and Beam Attenuator not included)

Manual M^2

The M^2 -200 software and framegrabber can be purchased without the Automatic Optical Train shown in Figure 4. This enables manual measurements for lasers having wavelengths incompatible with the optics and camera of the Optical Train. In this case a user would set up their own optical rail as shown in Figure 5 on the back cover. This enables measurement of UV and IR lasers from 157 to 248nm and 1 μ m to 1000 μ m using Spiricon's Pyrocam III camera, or lasers with beams too large or too small for the Optical Train, etc. The user manually positions the camera on the rail, adjusts the attenuation to match the camera's dynamic range, and captures each frame individually, with each step prompted by the M^2 -200 software. The software then computes M^2 just as it would for the Automated Optical Train.

M^2 Results

The measurements of beam width vs. position for a given run are shown in Figure 6. After a few points are measured the software calculates an extrapolated curve fit. It then uses this curve to double the frequency of measurements in the waist region, following the ISO 11146 procedure, which improves the accuracy. The X's and Y's are the individual points measured. The solid lines are the best fit hyperbola of the beam propagation equation to the measured points. The M^2 and other laser parameters are computed from the best fit hyperbola since it provides a smoothing of the data points.

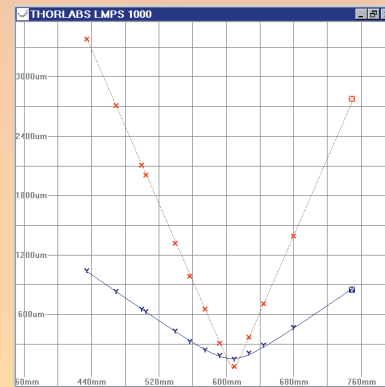


Figure 6. Plotted results of an M^2 run.

Figure 7 shows the displayed results of the measured laser parameters. These include the X and Y beam widths, M^2 or K , the divergence angles, the Rayleigh range, and other parameters as shown.

	Current	Units
---Quantitative---4 Sigma---		
Total	3.518.787	
Peak	5.965e+02	
Min	-7.531e+00	
Width X	2.773e+03	um
Width Y	8.486e+02	um
Z Location	750.00	mm
---Laser---		
Waist Width X	2.701e+02	um
Waist Width Y	7.043e+02	um
Divergence X	4.216e+00	mrad
Divergence Y	1.304e+00	mrad
Waist Loc X	501.78	mm
Waist Loc Y	624.51	mm
M^2 X	1.41	
M^2 Y	1.14	
Rayleigh X	64.06	mm
Rayleigh Y	540.06	mm
Astigmatism	0.40	
Asymmetry	2.61	

Figure 7. M^2 200 measurement results.

The 2D beam profile of the currently measured point in the beam propagation curve of Figure 6 is shown on the front cover. This image enables visual intuitive verification of the beam profile behavior through focus. After each run the user can click to any individual measured point and observe the beam profile. Outlying or anomalous points can be automatically or manually excluded from the curve fit calculations for more accurate results.

References:

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