

## Mode Quality ( $M^2$ ) Measurement Improves Laser Performance

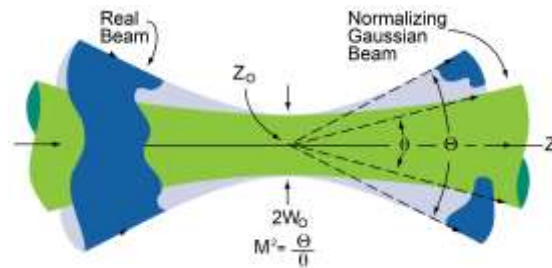
The laser mode quality factor ( $M^2$ ) provides a highly useful means of predicting laser beam propagation and focusing characteristics for both laser manufacturers and systems integrators. The Coherent ModeMaster PC enables rapid, accurate measurement of  $M^2$  for a wide range of CW and quasi-CW lasers with output from the ultraviolet to near infrared spectral range.

### Introduction and Overview

Two of the most important advantages of lasers over other light sources is their ability to propagate over long distances without spreading significantly (that is, to be highly collimated), and their capacity for being focused to small spots so as to deliver very high optical power densities. The easiest way to characterize how well a real world laser beam can be collimated or focused is through the use of the beam propagation factor ( $M^2$ ). Unfortunately,  $M^2$  is not readily measured using traditional laser beam diagnostic instruments such as power meters or beam profilers. This whitepaper reviews how  $M^2$  is used to calculate actual (rather than theoretical) laser beam properties, and then presents a practical instrument that enables rapid  $M^2$  measurement.

### What is $M^2$ ?

The beam propagation factor ( $M^2$ ) was specifically created to enable accurate calculation of the properties of laser beams which depart from the theoretically perfect TEM<sub>00</sub> beam. This is important because it is quite literally impossible to construct a real world laser that achieves this theoretically ideal performance level.



**Figure 1**  $M^2$  is defined as the ratio of actual beam divergence ( $\theta$ ), shown in blue, to the divergence ( $\theta_0$ ) of a perfect Gaussian beam, shown in green, having the same waist size and location. The waist location ( $Z_0$ ) and the waist diameter ( $2W_0$ ) must coincide for this calculation.

$M^2$  is defined as the ratio of a beam's actual divergence to the divergence of an ideal, diffraction limited, Gaussian, TEM<sub>00</sub> beam having the same waist size and location. Specifically, beam divergence for an ideal, diffraction limited beam is given by:

$$\theta_{theoretical} = \frac{\lambda}{\pi w_0},$$

Where the divergence of an actual beam is given by:

$$\theta_{actual} = M^2 \frac{\lambda}{\pi w_0}.$$

Where:  $\theta$  is the beam divergence half angle  
 $\lambda$  is the laser wavelength  
 $w_0$  is the beam waist radius (at the  $1/e^2$  point)  
 $M^2$  is the beam propagation factor

This definition of  $M^2$  allows us to make simple modifications to optical formulas by multiplying by the  $M^2$  factor to account for the actual beam divergence. This is the reason why  $M^2$  is also sometimes referred to as the "times diffraction limit number".

The  $M^2$  factor is used in the manner as follows to develop actual beam radius and focus spot size formulas.

### Actual Beam Radius

The Gaussian beam propagation formula used to calculate beam radius at any location is (in air or vacuum):

$$w(z)_{theoretical} = w_0 \sqrt{1 + \left( \frac{\lambda z}{\pi w_0^2} \right)^2}$$

Where the radius  $w(z)$  is a function of  $z$  distance (along the optical axis) from the beam waist.

Applying the  $M^2$  factor to the diffraction limit number changes this equation to:

$$w(z)_{actual} = w_0 \sqrt{M^2 + M^2 \left( \frac{\lambda z}{\pi w_0^2} \right)^2} =$$

$$M w(z)_{theoretical}$$

As a result, it provides a beam diameter formula that accounts for the actual divergence of the beam.

This formula can be further refined by substituting in the Rayleigh Range,  $z_R$ , a very common and useful beam metric defined as the distance over which the beam diameter increases by a factor of  $\sqrt{2}$ , and its cross sectional area doubles. By substituting  $z_R$ , defined as:

$$z_R \equiv \frac{\pi w_0^2}{\lambda}$$

The formula then becomes:

$$w(z)_{actual} = w_0 \sqrt{M^2 + M^2 \left( \frac{z}{z_R} \right)^2}$$

### Actual Spot Size at Focus

Similarly,  $M^2$  can be applied to the formula used to calculate the size of a focused Gaussian beam. The equation for calculating the spot size of a perfect Gaussian beam focused by an aberration free lens is given by:

$$w_{theoretical} = \frac{\lambda f}{\pi w_0}$$

Where:  $f$  is the lens focal length

$w_0$  is the input beam radius at the lens

$w$  is the radius of the focused spot

With the inclusion of the  $M^2$  term, this now becomes:

$$w_{actual} = \frac{M^2 \lambda f}{\pi w_0}$$

Therefore,  $M^2$  provides a simple means for accurately calculating the most commonly required parameters of real world laser beams, namely, divergence angle, propagation characteristics over a distance, and the size of focused spots.

### Practical $M^2$ Measurement

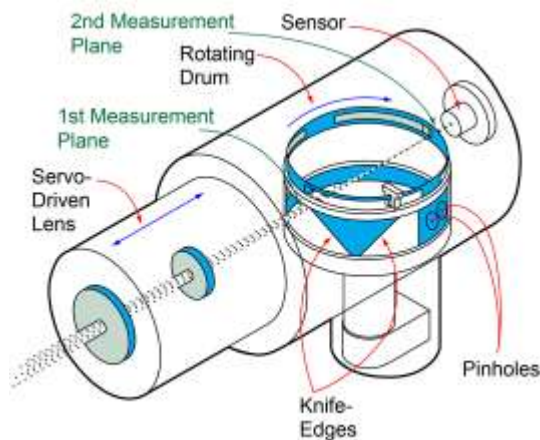
While knowledge of a laser's  $M^2$  parameter clearly enables computational simplicity, it is only of practical use if it can readily be determined for real world laser beams. It is possible to determine  $M^2$  using traditional beam profiling equipment, however, this approach is tedious and time consuming. Specifically, it involves making measurements at several different points along the axis of the beam (which each require highly accurate optomechanical alignment of the measurement head) and then performing a series of calculations to reduce the data and derive  $M^2$ .

To create a practical alternative for obtaining  $M^2$  measurements in both laboratory and production environments, Coherent developed the ModeMaster PC as shown in Figure 2. This is a turnkey instrument that integrates all of the necessary beam measurement, optomechanical alignment and data reduction hardware and software into one, easy to use product.



**Figure 2. The Coherent ModeMaster integrates a measurement head, precision optomechanical alignment hardware, a computer interface box, and alignment, data acquisition and data analysis software to deliver rapid, accurate  $M^2$  measurements.**

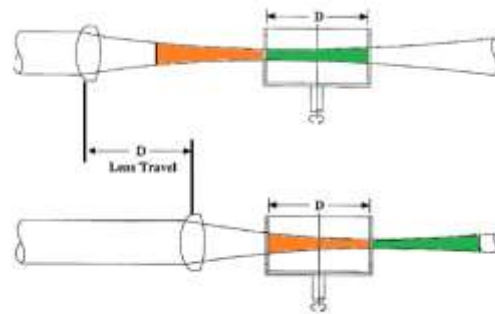
The ModeMaster PC measurement head contains a two axis beam profiler mated with an automated, focusing lens assembly, as shown schematically in figure 3. Specifically, the profiler utilizes two knife edges oriented at  $90^\circ$  to each other on a rotating drum, together with a single element detector. As the drum spins, the knife edges rapidly scan the beam in orthogonal directions, and the transmitted light is measured. This signal data is sent to the computer which derives the beam profile in each axis.



**Figure 3. Schematic of the ModeMaster PC measurement head, which includes a servo driven focusing lens assembly, dual axis knife edge scanners and a detector. The knife edges provide the beam diameter data, while the pinholes provide an intensity profile by which the ModeMaster is aligned. This head is mounted on a five axis precision positioner.**

Note, for each rotation of the drum, the beam profile is measured in two different planes, namely, where the knife edges cut the beam nearer the focusing lenses,

and where they cross the beam nearer the detector. In operation, the diffraction limited, precision focusing lens assembly first serves to place the internal focused beam waist midway between these two planes. This is accomplished by adjusting focus until the beam diameters at both planes are essentially equivalent, as shown in figure 4. Once this position is reached, the lens is then translated along the beam propagation axis to measure the beam profile at 256 different planes.



**Figure 4. The lens scans across one drum diameter,  $D$ , but the system acquires two diameters worth of data by taking measurements on both planes of the drum.**

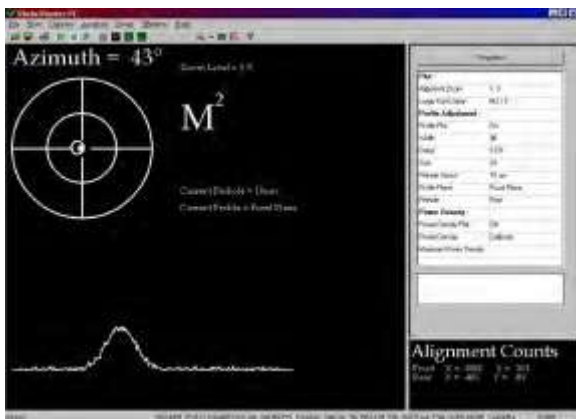
From these profile measurements, the powerful ModeMaster PC software then derives the  $M^2$  factor, the size and location of the beam waist, the far-field divergence angle, astigmatism, asymmetry (of both diameter and divergence angle) and the Rayleigh Range of the input laser source. Measurements also include ISO  $D4\sigma$ , second moment, knife edge, slit and  $D86$  beam diameters, as well as pointing stability. This entire measurement and data reduction process occurs in less than 30 seconds. The ModeMaster PC also provides special weighting functions to help eliminate effects on measurement accuracy due to intermittent beam noise, vignetting or other transients during the focus scan.

### System Considerations

The first step in actually performing a measurement with the Coherent ModeMaster PC is to align the system's optical axis with that of the input laser beam. This is necessary in order to achieve accurate results. Two tools are built into the product to enable simple, rapid alignment to a very high degree of accuracy. The first is a software screen that displays the position of the center of each of the beam profiles (measured at the front and back planes of the rotating drum) in real time; these are represented as a circle and a dot, superimposed over a crosshairs. The second is a set of coarse and fine alignment positioners on the

measurement head itself that enable its adjustment in five degrees of freedom (rotation in all three axes, and translation in both directions perpendicular to the optical axis).

To align the system, the user simply makes an adjustment with one of the positioners, and then observes the results on the screen. The goal is to align the head so both the circle and dot are close to the center of the crosshairs. Precisely overlapping the circle and dot at the center of the target can cause reflections inside the ModeMaster, or back into the laser, that can increase noise during a focus run; therefore, slight misalignment of the circle and dot is the best practice for collecting accurate focus run data. Following a consistent alignment procedure can help achieve the most accurate and repeatable  $M^2$  measurements.



**Figure 5. The ModeMaster PC includes a screen that simplifies optomechanical alignment of the measurement head with the input laser beam.**

Any given lens system within the Coherent ModeMaster PC can only achieve internal focus at the necessary location for a limited range of input beam waist locations, sizes and divergences. For this reason, two different, modular lens systems are offered. The first, called the “low divergence” optics, operates with input beams of up to 25 mm in diameter and divergences of under 2 mrad. The second, called “high divergence” optics are optimized for beams of 12 mm diameter or less, and beam divergences as high as 4 mrad. For both sets of optics, the measurement head must be positioned between one and three Rayleigh ranges away from the original laser beam waist. For most lasers, the waist location is at or near the output coupler.

Two different sensor modules are also available for the Coherent ModeMaster PC to enable measurement over a wide spectral range. Specifically, a silicon sensor is used for lasers in the 220 nm to 1000 nm range, while a germanium sensor is available for lasers in the 800 nm to 1800 nm spectral band. All of these optics and sensor modules can easily be swapped out by the user, thus enabling measurement over a wide range of input conditions.

Another important thing to note about the Coherent ModeMaster PC is that the laser output must appear constant over the time that it takes to make a single scan of the beam, otherwise spurious results will occur. The rate of drum rotation and the sensor response time limits the system to measuring beams that are either true continuous wave (CW), or pulsed at repetition rates of greater than 10 MHz.

This combination of beam size and divergence, wavelength and repetition rate factors means the Coherent ModeMaster PC is best suited for characterizing the output of ultraviolet to near infrared, CW and quasi-CW lasers. Typical examples of these are gas lasers (e.g. HeNe’s, ion lasers and HeCd’s), collimated diode lasers, optically pumped semiconductor lasers (OPSLs), collimated fiber lasers, and mode locked solid-state lasers.

### Applications

Typically, there are two classes of users that can benefit the most from the rapid, high precision  $M^2$  measurements delivered by the Coherent ModeMaster PC. The first of these are laser manufacturers. Specifically, laser builders can take advantage of the fast, real time data display possible with the instrument to enable peaking or adjustment of units in production for minimum  $M^2$  or divergence, maximum power density, or to achieve specific far-field beam profiles and pointing angles. Laser producers can also use the system as a final quality check on completed products to assess these same parameters. The fast, 30 second measurement time, combined with the ModeMaster’s compact size, makes it particularly convenient for use in these types of manufacturing environments.

System integrators incorporating the types of lasers mentioned previously can also make use of the Coherent ModeMaster PC. In particular, the instrument can be used to perform incoming inspection on purchased lasers to verify output parameters and assess adherence to specifications. Checking these beam parameters assures that a laser can be

successfully integrated into a system that incorporates an optical assembly designed to function with expected laser characteristics.

### **Conclusion**

In conclusion, the beam propagation factor ( $M^2$ ) is a highly useful metric for characterizing the optical quality of real world laser beams. Currently, the Coherent ModeMaster PC is the only truly integrated, turnkey solution for performing  $M^2$  measurements, and the only instrument that is sufficiently automated and simple enough to use for production line applications. The system delivers accurate measurements of  $M^2$  and several other parameters in accordance with ISO standards; in fact, the ISO standard that defines  $M^2$  is based on the measurement approach implemented in the Coherent ModeMaster PC.