How to (Maybe) Measure Laser Beam Quality

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Abstract

The objectives of this tutorial are to introduce the most important concepts and define some of the common terms involved in laser beam quality; to review briefly some of the beam quality definitions and measurement schemes employed to date; to describe some of the problems associated with various approaches and with standardization efforts for beam quality measurement; and finally to express a few of the author's personal prejuduces on this subject. The "Maybe" in the title of this tutorial is intended to convey that measuring, or even rigorously defining, any single all-inclusive measure of laser beam quality is still a controversial and unsettled topic—and may remain so for some time.

1. Background: Some "Ideal" Beam Profiles

To gain some insight into the concept of laser beam quality, let us consider three elementary near-ideal laser beam profiles such as the examples shown in Figure 1. If for example the near-field and far-field profiles of a uniform slit beam are given by

$$u_0(x) = \frac{1}{2a}, \quad -a \le x \le a \qquad \text{and} \qquad u(x,z) \approx \frac{\sin(2\pi ax/z\lambda)}{2\pi ax/z\lambda}, \quad z \to \infty$$

then we can define a near-field far-field product for this beam, based on its half width at the input plane and first null at the output plane, to be

$$\Delta x_0 \times \Delta x(z) = 0.5 \times z\lambda \ .$$

The far-field beam between the first nulls in this case contains 84.5% of far-field power for a square input aperture. If we consider instead a circular "top hat" beam with near-field and far-field profiles given by

$$u_0(r) = \left(\frac{1}{\pi a^2}\right)^{1/2}, \quad 0 \le r \le a \qquad \text{and} \qquad u(r) \approx \frac{2J_1(2\pi ax/z\lambda)}{2\pi ax/z\lambda}, \qquad z \to \infty$$

then the near-field far-field product based on the input radius and the first null in the output beam is given by

$$\Delta r_0 \times \Delta r(z) = 0.61 \times z\lambda$$

and far-field beam within this first null also contains $\approx 84\%$ of the total power in the beam. Finally, if we consider an ideal TEM_0 beam in one transverse dimension with waist and far-field profiles given by

$$u_0(x) = \left(\frac{2}{\pi w_0^2}\right)^{1/4} \exp\left[-x^2/w_0^2\right] \qquad \text{and} \qquad u(x,z) = \left(\frac{2}{\pi w^2(z)}\right)^{1/4} \exp\left[-x^2/w^2(z)\right]$$

then the variation of the gaussian spot size $w(z)$ with distance is given by

$$w^2(z) = w_0^2 + \left(\frac{\lambda}{\pi w_0^2}\right)^2 (z - z_0)^2$$

where z_0 is the location of the gaussian beam waist. Expressed in terms of the near-field and far-field beam widths w, which correspond to half-widths at $1/e^2$ intensity, the near-field far-field product for this case is

$$w_0 \times w(z) = 0.32 \times \lambda z$$

and this width contains $\approx 86\%$ of the total power in a circular gaussian beam.

The general conclusion is that the product of the near-field and far-field beam widths for a number of elementary near-ideal beam profiles is given by $z\lambda$ times a numerical factor on the order of unity, depending on just how the beam width is defined. The size of this numerical factor might be taken as a measure of "beam quality" (the lower the better), since one can suspect (and easily confirm) that less ideal beam profiles will have substantially larger near-field far-field products than these elementary examples.

"Nongaussian Gaussians"

From the above results, as well as the extensive literature on stable optical resonator modes, it may appear that a gaussian beam represents the best or one of the best possible profiles for a laser beam. This semi-correct idea is sometimes extended however to the more dangerous conclusion that if one observes a nicely shaped gaussian beam in the laboratory, one therefore has a near-ideal or single-mode or TEM_0-mode laser. This is not necessarily the case. As a warning example, Figure 2 shows a highly accurate gaussian beam profile which is in fact a totally "nongaussian gaussian" beam. This particular profile, which has an almost perfectly gaussian shape, is in fact synthesized from an incoherent superposition of higher-order Laguerre-gaussian modes, specifically 44% of the TEM_{01} mode, 17% TEM_{10}, 19% TEM_{11}, 11% TEM_{20}, and 6% TEM_{21}, and absolutely no TEM_{00} at all. This beam will remain almost perfectly gaussian as it propagates but since it has an M-squared value as defined below of $M^2 \approx 3.1$, it will diverge $\approx$3.1 times as rapidly with distance as a true TEM_{00} beam.

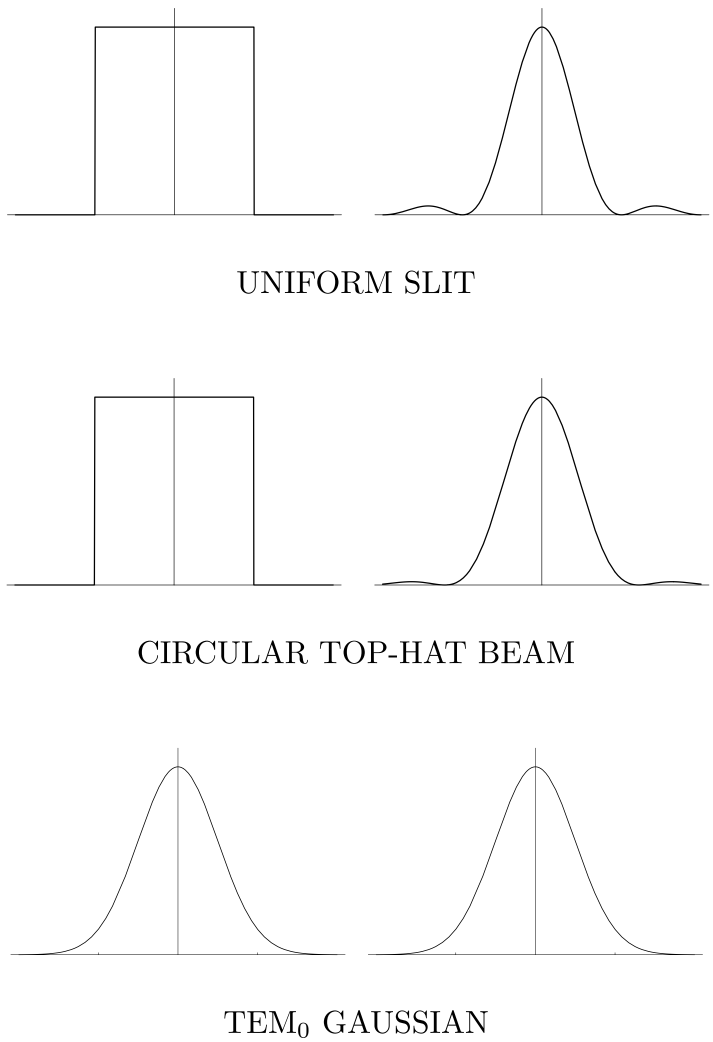

Figure 1. A few examples of idealized optical beam profiles.

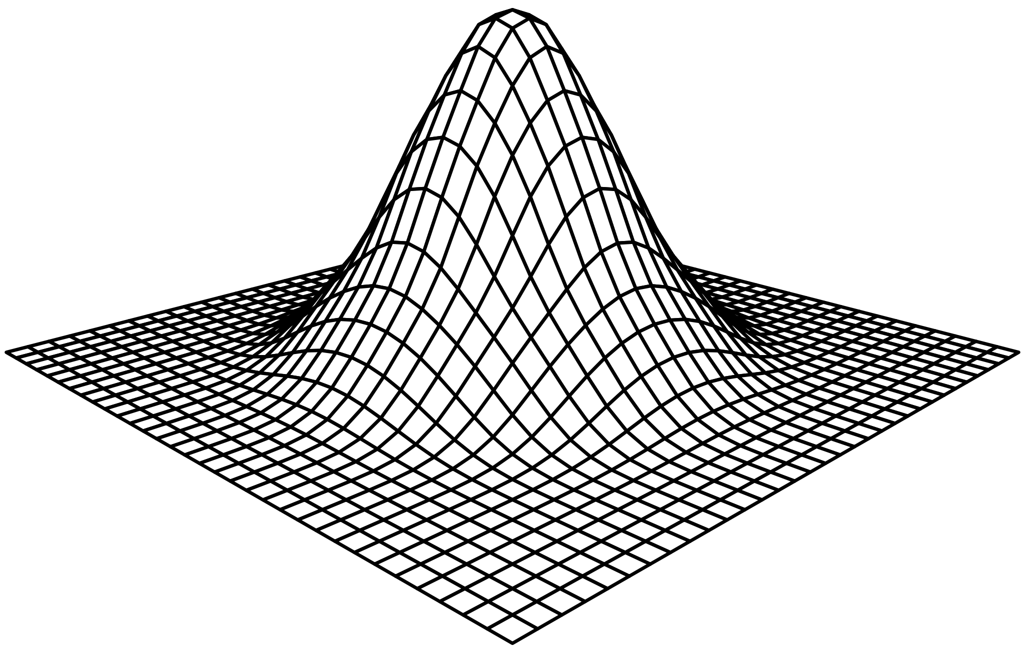

Figure 2. A “nongaussian gaussian”, having zero actual TEM_{00} mode content.

2. The Basic Problem: Defining Beam Width

The core question in developing a meaningful measure of "beam quality" for routine use with real, everyday, spatially coherent or incoherent laser beams is simply: What is a meaningful, practical, readily measurable definition for the "width" of a beam, given its time-averaged intensity profile $I(x, y)$ at any given plane z? (The correct term here is really 'irradiance profile" rather than 'intensity profile", but old habits die hard.) We're not concerned with the beam's phase profile in these discussions, even though the phase profile will have major effects on beam propagation, for two reasons: first of all, phase profiles are much harder to measure than intensity profiles, and second and more important, incoherent or multimode beam do not even have meaningful stationary phase profiles.

Suppose then that the transverse intensity profile of a real beam at a given plane looks something like Figure 3. As Mike Sasnett has remarked, "trying to define a unique width for an irregular beam profile like this is something like trying to measure the width a ball of cotton wool using a calipers". Possible definitions of beam width that have been suggested or used for optical beams in the past include:

- Width (or half-width) at first nulls.
- Variance σ_x of the intensity profile in one or the other transverse direction.
- Width at $1/e$ or $1/e^2$ intensity points.
- The 'D86" diameter, containing 86% of the total beam energy.
- Transverse knife edge widths between 10%–90% or 5%–95% integrated intensities.
- Width of a rectangular profile having the same peak intensity and same total power.
- Width of some kind of best fit gaussian fitted to the measured profile.

and any number of other definitions. Note that the above definitions applied to different beam profiles can give very different width values, and in fact some of them cannot even be applied to certain classes of profiles. It's also important to understand that in general there are no universal conversion factors between the widths produced by different definitions; the conversion from one width definition to another depends (strongly in some cases) on the exact shape of the intensity profile.

One of the major conclusions of this tutorial is that there is, at least as yet, no single universally applicable and universally meaningful definition of laser beam quality that can be expressed in a single number or a small number of parameters. One reason is that the "quality" of a given beam profile depends on the application for which the beam is intended. But at a more fundamental level, the inability to even define a single rigorous and universal measure of laser beam width means that there is no single universal way in which one can evaluate the product of near-field and far-field widths for an arbitrary laser beam as we did in Section 1, and then use the scalar factor in front of the $z\lambda$ product as a measure of the quality of the beam.

Figure 3. Example of a not unrealistic transverse irradiance profile.

3. Second Moments and the M-squared Method

Among the various beam width definitions mentioned above the variance definition perhaps comes the closest to a universal and mathematically rigorous formulation, however. As a result, this definition has become the basis of the so-called "M-squared" method for characterizing laser beams, which we will attempt to explain in this section. This formulation starts by evaluating the second moment of the beam intensity profile $I(x,y)$ across the rectangular coordinate x (or alternatively across the y coordinate) in the form

$$\sigma_x^2 = \frac{\int_\infty^\infty (x-x_0)^2\, I(x,y)\, dx\, dy}{\int_\infty^\infty I(x,y)\, dx\, dy}$$

where x_0 is the center of gravity of the beam (which, as a side note, travels rigorously in a straight line as the beam propagates). One can then find that this second moment obeys a universal, rigorous, quadratic free-space propagation rule of the form

$$\sigma_x^2(z) = \sigma_{x0}^2 + \sigma_\theta^2 \times (z-z_0)^2$$

where σ_{x0} is the variance at the beam waist; σ_θ is the variance of the angular spread of the beam departing from the waist; and z_0 is the location of the beam waist along the z axis. Of primary importance is the fact that this quadratic propagation dependence holds for any arbitrary real laser beam, whether it be gaussian or nongaussian, fully coherent or partially incoherent, single mode or multiple transverse mode in character. Moreover, at least so far as anyone has proven, this quadratic dependence of beam width is rigorously true only for the second-moment width and not for any other of the width definitions listed above. In fact, with some of the width definitions listed above not only can there be multiple minima or waists along the axis, but the beam width may make discontinuous jumps at certain locations along the beam.

General Beam Width Definition

Now it so happens that for a gaussian beam profile of the form $I(x) = \exp[-2x^2/w_x^2] \equiv \exp[-x^2/2\sigma_x^2]$, the very widely used gaussian beam spot size parameter w is just twice the variance, i.e. $w_x \equiv 2\sigma_x$. Therefore for any arbitrary, real, potentially nongaussian beam it is convenient to adopt the spot-size or beam-width definitions

$$W_x \equiv 2\sigma_x \qquad \text{and} \qquad W_y \equiv 2\sigma_y$$

where we use capital W as a general beam width notation for arbitrary real beams, with this definition being coincident with the gaussian beam parameter w for ideal gaussian TEM_0 beams. As a side note, one can then discover that for virtually all but the most pathological beam profiles an aperture having full width or diameter of $D \approx 3W$ or $D \approx \pi W$ will have $\geq 99\%$ energy transmission through the aperture.

The second-moment-based beam widths W_x and W_y defined above will then propagate with distance in free space exactly like the gaussian spot size $w(z)$ of an ideal gaussian beam, except for the insertion of an M^2 multiplication factor in the far-field spreading of the beam. That is, for any arbitrary beam (coherent or incoherent) and any choice of transverse axes, one can write using the second-moment width definitions

$$W_x^2(z) = W_{0x}^2 + M_x^4 \times \left(\frac{\lambda}{\pi W_{0x}}\right)^2 (z - z_{0x})^2$$

and

$$W_y^2(z) = W_{0y}^2 + M_y^4 \times \left(\frac{\lambda}{\pi W_{0y}}\right)^2 (z - z_{0y})^2$$

where M_x and M_y are parameters characteristic of the particular beam. As a result, using these definitions one can write the near-field far-field product for an arbitrary beam in the form

$$W_{0x} \times W_x(z) \approx M_x^2 \times \frac{z\lambda}{\pi} \quad \text{and} \quad W_{0y} \times W_y(z) \approx M_y^2 \times \frac{z\lambda}{\pi} \quad \text{as } z \to \infty\,.$$

In other words the parameters M_x^2 and M_y^2 give a measure of the "quality" of an arbitrary beam in the sense defined in Section 1. General properties of these M^2 values include:

- The values of M_x^2 and M_y^2 are ≥ 1 for any arbitrary beam profile, with the limit of $M^2 \equiv 1$ occurring only for single-mode TEM_0 gaussian beams
- The M^2 values evidently give a measure of "how many times diffraction limited" the real beam is in each transverse direction.

Arbitrary non-twisted real laser beams can then be fully characterized, at least in this second-order description, by exactly six parameters, namely W_{0x}, W_{0y}, z_{0x}, z_{0y}, M_x^2, M_y^2.

The "embedded gaussian" picture

One of the most useful features of the M^2 parameter is that the M^2 values and their associated W_0 and z_0 parameters can be directly applied in the design of optical beam trains for real laser beams as follows. Given the M^2 parameters for an optical beam in either transverse direction, one can envision an "embedded gaussian" beam with waist size w_0 and in general with spot size $w(z)$ given by

$$w_0 = W_0/M \quad \text{at } z = 0 \qquad \text{and} \qquad w(z) = W(z)/M \quad \text{at any } z\,.$$

This embedded gaussian beam does not necessarily have any physical reality, i.e., it does not necessarily represent the lowest-order mode component of the real beam. One can however carry out beam propagation or design calculations in which one propagates this hypothetical embedded gaussian through multiple lenses and paraxial elements, finding the focal points and other properties of the embedded gaussian. One can then be assured that the real optical beam will propagate through the same system in exactly the same fashion, except that the spot size $W(z)$ of the real beam at every plane will be exactly M times larger than the calculated spot size $w(z)$ of the hypothetical embedded gaussian beam at every plane along the system.

Practical Problems With M^2

The concept of a real-beam spot size based on twice the variance of the intensity profile, and the resulting M^2 parameters, are thus very useful as well as mathematically rigorous. There are also some significant practical problems associated with this approach, however, including:

- The second moments of real intensity profiles can be difficult to measure accurately, and so the associated beam width or M^2 measurements are subject to sizable errors unless carefully done.
- In particular, if intensity profile measurements are made using for example CCD cameras, background noise, baseline drift, camera nonlinearity and digitization can cause measurement errors.
- The second-moment-based beam width definition heavily weights the tails or outer wings of the intensity profile, where the beam intensity is likely to be low and difficult to measure accurately. As a result, beams having a significant fraction of their energy contained in a widespread background or "pedestal" will have second-moment widths substantially larger than their central lobe widths. (On the other hand beams with this characteristic are in fact not particularly good beams.)
- Finally there is a still unsolved conceptual problem with the second moment approach in that idealized beams having discontinuous steps in their intensity profiles, including slit or top hat beams, appear to have infinite second moments in the far (and even in the near) fields, and thus appear to have infinite M^2 values. This is not in fact a practical problem for real beam measurements, but the fact that an ideal slit beam appears to have an infinite M^2 value is understandably confusing.

The bottom line is that M^2 values based on the variance approach are both mathematically rigorous and definitely useful, but by no means tell the whole story. In recognition of this, it is strongly recommended that the M^2 value for a real beam be referred to, not as the "beam quality" for that beam, but as the **beam propagation factor**, since this parameter does give a rigorous and very useful measure of how the beam will propagate through free space or indeed through any kind of paraxial optical system.

4. Twisted Beams

The second-moment method and the 6 beam parameters described in the preceding section give a straightforward and complete description of any optical beam which has a fixed set of principal transverse axes along its direction of propagation. Such a beam can be referred to as a "simple astigmatic beam". The waist sizes W_{0x} and W_{0y} then give a measure of the assymmetry of the beam size at the x and y waists; the axial spacing between the waist locations, z_{0x} and z_{0y} gives a measure something like the conventional astigmatism of the beam; and the M_x^2 and M_y^2 values characterize what can be viewed as a second kind of astigmatism or a "divergence assymmetry" for the beam in the two transverse directions. The formulas for $W_x(z)$ and $W_y(z)$ given above remain correct in fact for any choice of transverse x and y axes across the beam, although the values of the 6 beam parameters will change as the coordinate system is rotated. The waist sizes will take on their minimum values, however, the waist locations will be separated by the maximum amount, and the M^2 values will be most meaningful if the coordinate axes x and y are chosen to be coincident with the principal axes of the optical beam itself.

There do exist more general kinds of "twisted" optical beams in which the principal axes for either the phase or intensity profiles can rotate ("twist") by 180 degrees as the beam propagates from $z = -\infty$ to $+\infty$. As a simple example of one such twisted optical beam one might think of a beam consisting of two identical TEM_{00} beams pointed parallel but with one beam positioned just slightly above the other at their common waist plane. Now turn the upper beam in the horizontal plane to point slightly to the right, and the lower beam to point slightly to the left. The result is an intensity profile consisting of two spots which are oriented vertically at the waist plane, but which twist or rotate in a clockwise direction as they propagate forward in z (and the reverse as they propagate backward from the waist). There are many other more complicated examples of such beams having either intensity or phase twists, or both together. Such beams require in general **ten** parameters to describe them fully to second order, including all the second moments and cross-moments and their axial variation. A number of papers by Nemes describe their properties in more detail.

5. Further Methods for Characterizing Beam Quality

Recognizing the difficulties associated with the second-moment method, are there other useful extensions or alternatives to the second-moment method for characterizing the "quality" of a laser beam? A first answer is that rather than measuring the second moment from a complete beam intensity profile measured using a CCD camera or comparable technique, it is often much more convenient and reasonably accurate to make knife-edge measurements in two transverse directions across a beam. One can in principle manipulate a complete and carefully measured knife-edge profile to determine the second moment quite accurately, but it is often convenient to measure only a single knife-edge width, e.g., between 10% and 90% points, and then convert this into an approximate variance using suitable conversion formulas.

One way to gain additional information about a beam profile beyond the second moment or M^2 value is to also determine the so-called kurtosis parameter, which brings in the fourth moment of the beam profile and gives additional information about the sharpness of the beam profile. As a practical matter, however, if the second moment is difficult to determine accurately on a real beam, the fourth moment is even more so.

Another potential beam parameter which seems to be often cited but seldom clearly defined is the Strehl ratio, based on the on-axis (or peak) value of the real beam in the far field compared to the same quantity for some ideal beam. Unfortunately, the ideal comparison beam is often not clearly identified—for example, is the ideal beam a beam with the same intensity profile but a uniphase output (in which case the Strehl ratio is really not a particularly good measure for a beam with a messy intensity profile), or is it the same beam power distributed uniformly over the output aperture of the laser (which may not be a particularly meaningful comparison)?

Perhaps the most useful way of characterizing a laser beam if one wishes to go beyond simply the M^2 parameter and give a larger set of numbers is to give a "power in the bucket" (PIB) curve, i.e. a plot of fractional power within a given beam diameter or beam width versus the diameter or width. As we will illustrate in the following section such a curve can be more informative than even a complete beam intensity profile because it clearly displays how much of the total beam power is really in the central beam lobe, and how much of the beam power may be distributed in a weak but large-area background or pedestal extending far outside the main portion of the beam. Even a few accurately measured points along such a PIB curve can give an substantially increased understanding of the quality of a laser beam.

6. Phased Arrays and "Power in the Bucket" Curves

The larger and more powerful a laser oscillator, in general the more difficult it is to make it oscillate in a single transverse mode, or provide an output beam having good beam quality. It is not surprising, therefore, particularly with microwave phased-array systems in mind, that proposals frequently arise for optical phased arrays—systems in which one starts with an array of small to medium sized lasers having good individual beam quality, and then combines the outputs of these lasers into a single beam which yields the total power of the array with the good beam quality of each individual laser.

This idea may not, however, be as practical or useful as it seems, even if one can solve the always difficult problems of locking the individual laser oscillators into a single coherent array, and then combining the resulting beams without phase drifts or perturbations. As a way of illustrating both the concerns about the usefulness of phased arrays, and the merits of the "power in the bucket" technique for characterizing laser beams, let us examine one particular example of a laser phased array using this technique.

The situation to be considered consists of 6 individual TEM_{00} gaussian beams arranged on a circle in a "bolt-hole" beam pattern with a near-field intensity profile as shown in Figure 4. This is not an unrealistic model; efficient high-power CO_2 lasers have been constructed in essentially this fashion, using 6 single-transverse-mode CO_2 waveguide lasers arranged in a fan array about a central axis. In the case considered here the axes of the 6 beams are separated by a spacing of πw_0 where w_0 is the waist spot size of each beam, so that there will be less than 1% overlap between any two beams. We then consider two extreme cases: the 6 lasers either oscillate entirely independently and incoherently (i.e., they oscillate at slightly different frequencies, with no phase coherence between the 6 gaussian beams); or the 6 lasers are locked together in frequency to form a completely coherent phased array.

Figure 5 shows the resulting far-field pattern for the incoherent case. The 6 gaussian beams spread or diverge independently so that their intensities add incoherently into a single gaussian beam in the far field, with exactly the same far-field spot size as any one of the beams independently. Figure 6 shows the same result for the fully coherent case. The 6 beams in this case add coherently to create a central lobe which is substantially narrower than the incoherent gaussian case, with a central intensity which is 6 times larger than the incoherent case for the same total power (although the plot is not properly scaled to show this). What is significant however is that in the M^2 description the coherent case, despite its apparently much better central lobe, is in fact almost no better than the totally incoherent case: the beam propagation factors are in fact $M^2 \approx 4.55$ for the incoherent case and $M^2 \approx 4.38$ for the fully coherent or phased-array case. Almost nothing has been gained by going to the complexities of the phased array over having just 6 incoherent lasers.

To understand this better, we can first look at the radial beam profiles (beam intensity versus radius along various radial trajectories) as shown in Figure 7. The coherent case indeed has an on-axis intensity 6 times larger than the totally incoherent case, as expected. What becomes apparent, however, is that the coherent case also has a series of outer secondary lobes, which are also apparent in Figure 6, and these outer lobes contain an unacceptably large fraction of the total power in the beam.

To see the effects of this even more clearly one can examine the power-in-the-bucket (PIB) curves for the two cases shown in Figure 8. These curves plot the integrated fractional power within a given radius (or, if you like, a given far-field angle) as a function of radius (or angular deviation) for the two beams at the same far-field distance. One sees that this curve builds up much faster at the center for the coherent case because of the strong central lob. It is also apparent, however, that the central lobe (which extends out to the first inflection point in the PIB curve) only contains about 45% of the total energy in the beam. Moreover if one goes out beyond the crossing point of the two curves, which occurs at about 75% of the total energy, the incoherent beam actually becomes better than the coherent beam—that is, beyond this point the incoherent beams will deliver more power into a given bucket than will the coherent array.

In any case, leaving aside the question of the merits of phased arrays, it is clear that even a few accurately measured experimental points located along and roughly defining the PIB curve for a given laser beam will give a much better picture of the nature of such a beam than a single M^2 number. Such a PIB curve can be obtained using circular buckets, as in the example here, or rectangular scans in x and y using a single knife edge and some appropriate mathematical manipulation. Plotting a PIB on a logarithmic horizontal scale will give an even more graphic indication of any pedestal effects in a laser beam by showing just how far out one must go to capture, for example, 90% or 95% of the total power in a given beam.

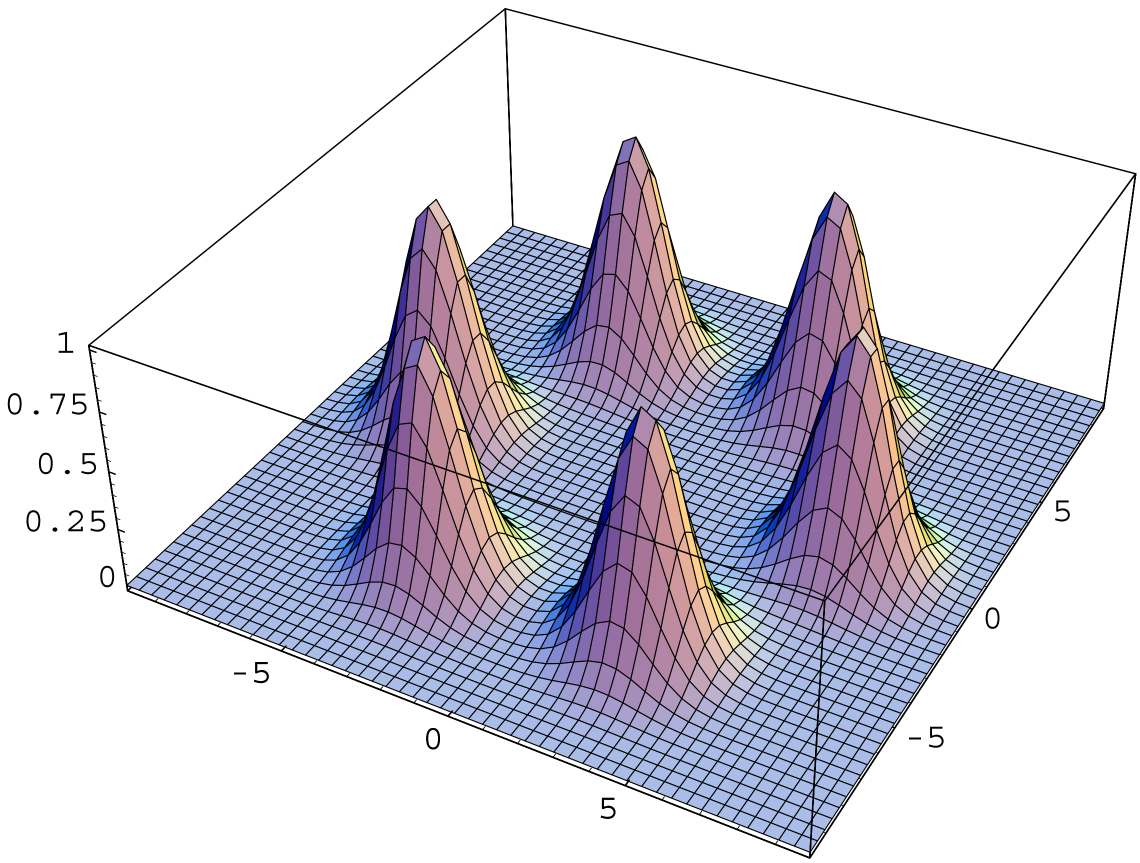

Figure 4. Six gaussian input beams arranged in a "bolt hole" beam pattern.

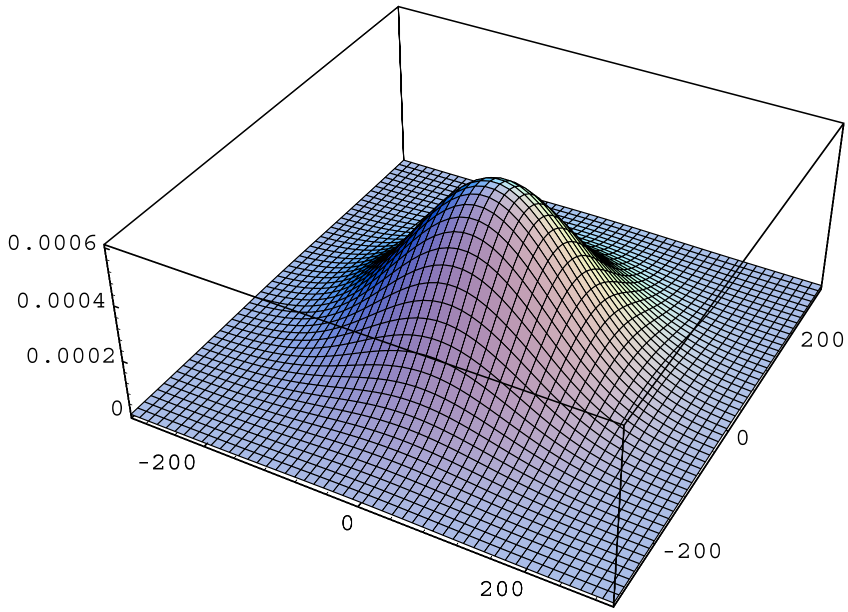

Figure 5. Far-field beam pattern for incoherent bolt-hole input beams.

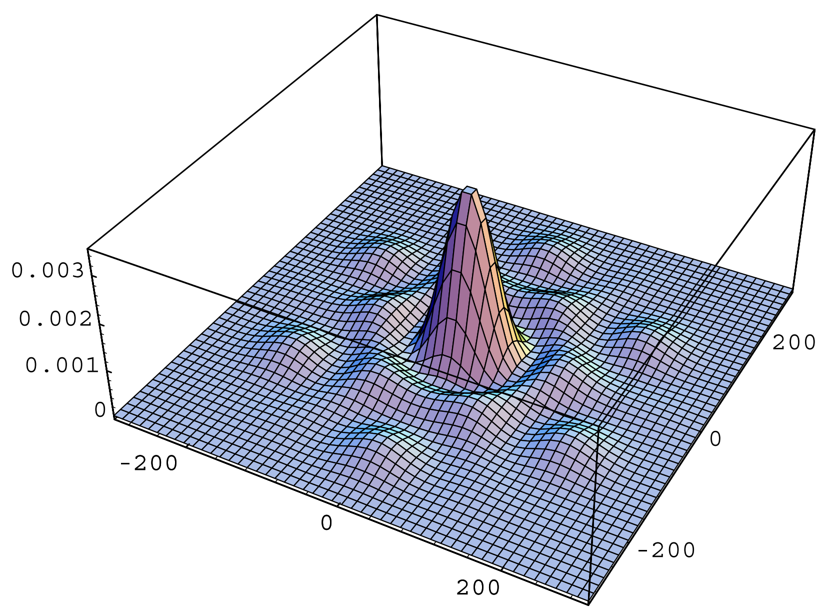

Figure 6. Far-field beam pattern for coherent bolt-hole input beams.
(Vertical scale is reduced by a factor of 6 compared to Figure 5.)

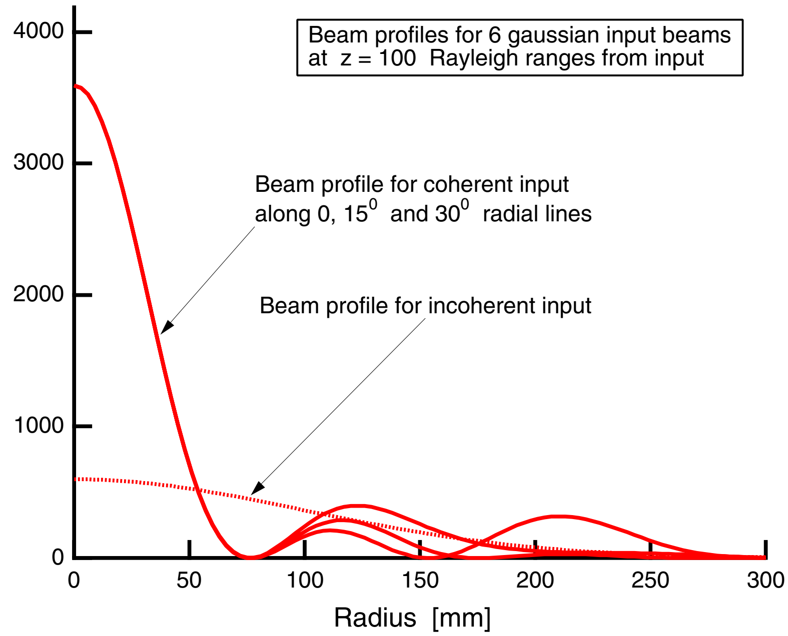

Figure 7. Far-field beam profiles for the coherent and incoherent bolt-hole cases.

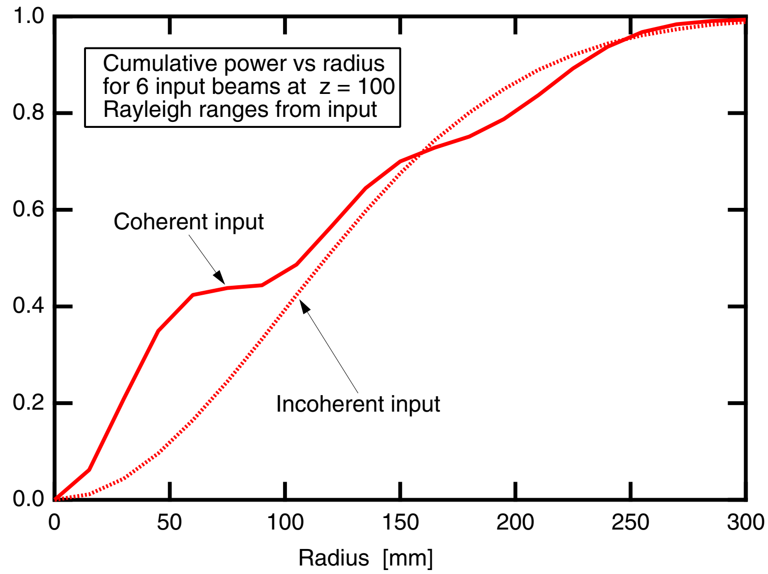

Figure 8. Power-in-the-bucket curves for coherent and incoherent bolt-hole beams.

7. Conclusions and Prejudices

The bottom line conclusions from this tutorial are:

- Second-moment based M^2 values are very useful, e.g., for comparing different lasers or laser beams, for designing optical beam trains, or for studying laser physics, but are by no means the whole story so far as "beam quality" is concerned.
- No other equally useful and general single-parameter beam width or beam quality measure has been found (and none may exist).
- The M^2 value for any given beam should nonetheless be referred to as the "beam propagation factor", and not the "beam quality" for that beam.
- In reporting measurements on an optical beam, one should not refer to a measured result as an M^2 value unless it is really second-moment based, or the reader is warned that the beam width measurements were made in some other fashion and converted (necessarily approximately) to second moment equivalents.
- If one wants to convey more information about some real laser beam than just its M^2 value, a near-field intensity profile combined with the corresponding far-field power-in-the-bucket curve (on a horizontal log scale) is probably the best next step upward.
- Phased arrays are a doubtful solution for obtaining good optical beam quality.

Finally, the term "beam quality" at this point remains a handy buzz word, but it is not yet a solidly defined technical term—and very likely never will be.

8. Selected Commercial Instruments

A partial list of vendors who can supply commercially available instruments for making beam profile or beam quality measurements includes:

- Blue Sky Research, 35 EncinaStreet, Santa Cruz, CA 95060,tel (408) 459-6605, fax (408) 459-6698, www.blueskyresearch.com.
- Coherent, Inc., Instruments Div., 12789 Earhart Ave., Auburn, CA 95602-9595, tel (916) 888-5107, (800) 240-4740, fax (916) 885-6039, www.cohr.com.
- Dataray, 605 Stapp Road, Boulder Creek, CA 95006, tel (408) 338-9055, fax (408) 338-9098.
- Gentec Electro-Optics, 2625 Dalton St., Sainte-Foy, Quebec, Canada, G1P 3S9 , tel (418) 651-8003, fax (418) 651-6695, www.gentec.ca.
- Merchantek, Inc. 6150A Yarrow Dr., Carlsbad CA 92009, tel (619) 930-9191, fax (619) 930-9192, www.merchantek.com.
- Melles Griot, Electrical-Optics Instr., 4601 Nautilus Ct. S, Boulder, CO 80301-5303, tel (303) 581-0337, fax (303) 581-0960 www.mellesgriot.com.
- SensorPhysics, 105 Kelleys Trail, Oldsmar, FL 34677, tel (813) 781-4240, fax (813) 781-7942, www.sensorphysics.com.

- Spiricon Inc., 2600 N. Main, Logan, UT 84341, tel (801) 753-3729, fax(801) 753-5231, www.spiricon.com.
- WaveFront Sciences, 15100 Central Ave SE, Suite C, Albuquerque, NM 87123, tel (505) 275-4747, fax (505) 275-4749, www.wavefrontsciences.com.

9. Selected References

A limited and selected list of references on beam quality and beam propagation measurements might include:

- D. R. Hall and P. E. Jackson, eds. *The Physics and Technology of Laser Resonators* (Adam Hilger, 1989).
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A more extensive list of 300+ references related to beam quality and beam propagation can be found at http://www-ee.stanford.edu/ siegman/laser_beam_quality_refs.html.