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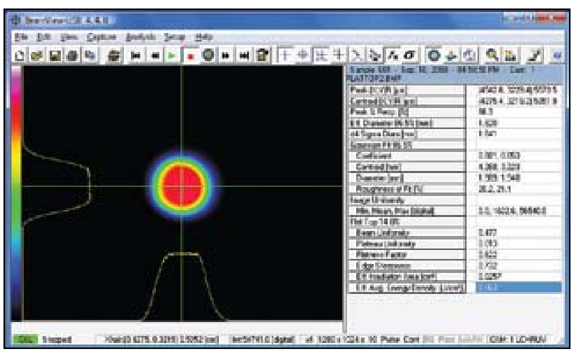
Understanding Laser Beam Parameters Leads to Better System Performance and Can Save Money

Lasers became the first choice of energy source for a steadily increasing number of applications in science, medicine and industry because they deliver light energy in an exceedingly useful form and set of features. A comprehensive analysis of lasers and laser systems goes far beyond the measurement of just output power and pulse energy. The most commonly measured laser beam parameters besides power or energy are beam diameter (or radius), spatial intensity distribution (or profile), divergence and the beam quality factor (or beam parameter product). In many applications, these parameters define success or failure and, therefore, their control and optimization seems to be crucial.

Beam Diameter (Radius, Width)

The beam diameter (generally defined as twice the beam radius, no matter what the particular definition of the beam radius is) is the most important propagation-related attribute of a laser beam. In case of a perfect top-hat (or flat-top) profile the beam diameter is clear but most laser beams have other transverse shapes or profiles (for example, Gaussian) in which case the definition and measurement of the beam diameter is not trivial.

The boundary of arbitrary optical beams is not clearly defined and, in theory at least, extends to infinity. Consequently, the dimensions of laser beams cannot be defined and measured as easily as the dimensions of hard physical objects. A good example would be the task of measuring the width of soft cotton balls using vernier callipers.
A commonly used definition of the beam diameter is the width at which the beam intensity has fallen to $1/e^2$ (13.5%) of its peak value. This is derived from the propagation of a Gaussian beam and is appropriate for lasers operating in the fundamental TEMoo mode or closely.



Screen shot of a flat-top beam image

Image of dialog box for flat-top calculations

Other common definitions of the beam diameter are the full width at half-maximum (FWHM) diameter or the diameter that includes 86% of the beam energy. A problem with these types of definition is that the result does not depend on how quickly the intensity decays in the wings of its intensity profile.

Many lasers exhibit a significant amount of beam structure, and applying these simple definitions leads to problems. Therefore, the ISO 11146 standard specifies the beam width as the $1/e^2$ point of the second moment of intensity, a value that is calculated from the raw intensity data and which, for a perfect Gaussian Beam, reduces to the common definition. Disadvantages of the second-moment method are that the beam radius or width calculation is complicated (usually requires numerical code) and that the result is easily compromised by some offset in the measured intensity distribution caused by ambient light or noise, especially in case of camera-based beam analyzers.

Spatial Intensity Distribution (Beam Profile)

The spatial intensity distribution of a laser beam incorporates all the mechanical, thermal and electromagnetic variables that created the beam. The way power is distributed across a laser beam depends on both the mode or combination of modes running in the laser cavity and on how those modes are distorted by the presence of apertures, refractive index gradients of optical elements used, imperfect optical surfaces and other perturbing influences. Intensity profiles can provide a useful window into these effects. Therefore, intensity profiles have emerged as a tool when tuning lasers, and an analytical tool when diagnosing laser problems. Spatial intensity distribution is one of the fundamental parameters which indicate how a laser beam will behave in an application.

In Depth: Dynamics of a Laser Resonator:
Diffraction effects in a laser resonator cause the beam mode to change as it propagates outside the laser. Therefore, it is very important where outside the laser cavity the beam is analyzed. There are three basic regions each with its own mode characteristics, the Near Field, the Rayleigh Range, and the Far Field.

For diffraction-limited beams, the Rayleigh Range Z_R is determined by its waist radius R0 and laser wavelength λ ($Z_R = \pi \cdot (R_0)^2/\lambda$). For example, the Rayleigh Range of a Gaussian beam is the distance from the beam waist (in the propagation direction) where the beam radius is increased by a factor of √2 (which is equal to a doubling of the beam area).

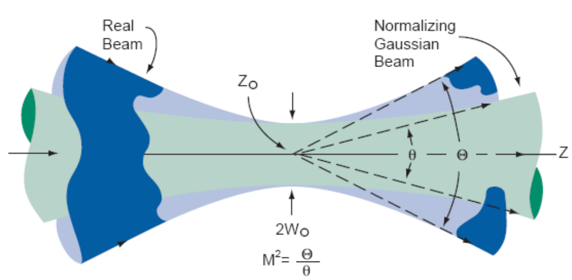
For beams with a non-perfect beam quality, the Rayleigh Range is decreased by a factor which is called the beam quality factor M^2 (or, $k=1/M^2$ which is also used occasionally). The mode in the Near Field often has a so-called "bullseye" pattern to it. In the Rayleigh Range, the mode can be controversial. The mode quality in the Far Field has mostly the best and most consistent characteristics.

Divergence
The beam divergence of a laser beam is a measure for how fast the beam expands as it propagates in space. There are different quantitative definitions in the literature. According to the most common definition, the beam divergence is the derivative of the beam radius with respect to the axial position in the Far Field. This definition yields a divergence half-angle, and further depends on the definition of the beam radius (or, diameter). Sometimes, full angles are used which results in twice as high angles. Therefore, some caution seems to be appropriate when it comes to a laser's divergence specification.

Beams with a very small divergence, i.e. with an almost constant beam diameter over a significant propagation distance are generally called "collimated beams".

To measure divergence correctly with a camera based beam analyzer (profiler), a lens or confocal mirror with known focal length must be introduced into the laser path. The sensor plane of the camera is then placed at the focal length of the lens or mirror to produce a Far Field image of the laser beam. Placing the camera sensor at any other location along the beam path will not produce the Far Field image and will give an incorrect measurement. Proper use of the background substraction feature must be used for accurate divergence measurement.

Beam Quality Factor M^2 (Beam Parameter Product):
The beam quality factor M^2 is derived from the uncertainty principle. The factor is shown to describe the propagation of an arbitrary beam. M^2 is a measureable quantity in order to characterize real mixed-mode beams. For example, the angular size of a non-Gaussian laser beam in the Far Field will be M^2 times larger than calculated for a perfect Gaussian beam. In other words, M^2 describes how close to "perfect-Gaussian" a laser beam is. For a perfect Gaussian beam, M^2 is 1. For a non-prefect Gaussian beam, M^2 is >1.



Θ = M² x 2λ / (πWo), FOR A BEAM WAIST DIAMETER 2Wo.

Laser Beam Quality

In a real world, perfect Gaussian (TEM_{00}) beams of $M^2=1$ are not possible; although some lasers come close. Effects that eat away at perfection for any real or realizable laser are: aperture-related effects inside the laser resonator, mode-perturbing influence of refractive index gradients, and imperfect and/or contaminated optical components.

> ***In Depth: Correlation of the Beam Quality Factor and Quantum Mechanics.***
> *The uncertainty principle of quantum mechanics comes in because M^2 is the product of a beam's minimum diameter and divergence angle. It is a measure of how well photons in the beam are localized in the transverse plane as they propagate. Acc. to the uncertainty principle, there is a minimum possible product of waist diameter times divergence, corresponding to a diffraction-limited beam. Beams with larger constants are described as "several times the diffraction-limit which is a constant equivalent to M^2. The quintessence of it is: The closer a real laser beam is to a diffraction-limited, the more tightly it can be focused, the greater the depth of field and, the smaller the diameter of beam handling optics needed.*

> ***In Depth: The Beam Parameter Product (BPP).***
> *In some cases, people prefer the Beam Parameter Product (BPP) in order to specify beam quality (alternatively to the Beam Quality Factor M^2). The Beam Parameter Product of a laser beam is defined as the product of beam radius (measured at the beam waist) and the beam divergence half-angle (measured in the Far Field). The usual units are mm mrad (millimeter times miliradians). The smallest possible Beam Parameter Product is achieved with a diffraction-limited Gaussian beam; it is λ/π. For example, the minimum Beam Parameter Product of a 1064nm (Nd:YAG) beam is about 0,339 mm mrad.]*

The real-time measurement of the beam quality factor of a laser requires specially designed instrumentation which is more sophisticated than profilers and, thus, also more expensive.

It is possible, however, to measure the beam quality factor of a laser with a camera- or knife-edge-based profiler but it requires some experimental set-up and efforts. With a method called the "four-cuts method" it is possible to verify the beam quality factor M^2 with a minimum of just four beam diameter measurements at four defined locations along the beam path - three diameter measurements in order to find the beam waist (and location); a fourth measurement in order to measure the beam diameter at the waist. The four-cut method is pretty accurate (5% measurement error) and works with CW and pulsed lasers. *(Ref. Beam propagation (M^2) measurement made as easy as it gets: the four cuts method, Thomas F. Johnston, Jr. , Appl. Opt. Vol. 37, No. 21)*

A comprehensive measurement of laser beam parameters such as beam diameter, intensity distribution (profile), divergence, or the beam quality factor can have many benefits for people who develop, manufacture and use lasers: results get better and become more reproducible, products and features produced with lasers become more uniform, and processes become more manageable and predictable. Understanding laser beam parameters simply results in better performance and cost savings.

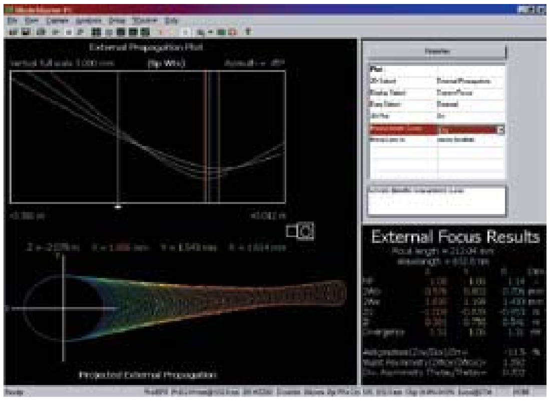
Examples:
In most laser applications, it is not just laser power that does the work, but power density or beam "brightness".

> ***In Depth: Laser Brightness***
> *Beam brightness is a commonly used descriptive, non-quantitative term used to describe laser output. In the context of laser technology, the brightness of a laser source (in a quantitative sense) is generally understood as being equivalent to its radiance, which is the total power divided by the product of the mode area in the focus and the solid angle in the far-field. For a given laser power, as the beam quality becomes higher, the beam brightness increases.*

The measurement and adjustment of the beam diameter does not affect the total power being delivered by a laser beam, but does effect how the total power is concentrated. Controlling the power density or brightness of a laser beam requires the control of both laser power and beam diameter.

The accurate verification of laser output power is generally done by means of a power meter while the accurate verification of the diameter requires a beam diagnostic system, which can be either a beam profiler or beam propagation analyzer (M^2 meter).

Many factors can affect laser performance. Misalignment is the most common source of substantially reduced brightness. The logical reverse is that proper alignment can result in substantially increased brightness. Often the optimization of a laser or laser system with regard to a higher power density or better brightness can be equivalent to the increase in output power achieved by turning up the operational current on the laser's control panel. Simply increasing the output power does not only cost money in terms of operational cost but it also stresses the laser unnecessarily since a better (and more beneficial) beam could be achieved through the control and optimization of other critical beam parameters (rather than just output power). So, comprehensive beam diagnostic can increase the lifetime of lasers and can help to save operational and maintenance costs.



As indicated before, the accurate verification of the diameter or contour of a laser beam results from the accurate verification of the beam's intensity distribution (or profile). In addition, the profile tells a user how the power is distributed across the beam area.

For example, in a material processing situation, it is easily understandable why two beams of identical power and diameter (or contour) leave different burn marks on a substrate if one beam features a Gaussian profile (maximum intensity in the beam center) while the other beam features a so-called donut profile (very little to no power in the beam center). In fact, there are many material-processing related applications such as cutting, welding, drilling, marking, cladding and ablating which require a certain intensity profile and beam contour for the process to work properly beyond just the laser power or power density.

In many applications, it is required to focus the laser beam in order to create very small spot sizes and, hence, to increase power density or brightness. For a given output power, the power density can be increased by reducing the beam diameter or cross-section. From an application standpoint, beam efficiency is often directly related to the beam's ability to be focused. The intensity distribution or profile of a laser beam may not be sufficient to predict its ability to be focused, in which case the use of a beam propagation analyzer (M^2 meter) is needed. In fact, the performance and reliability of beam delivery systems is strongly affected by both alignment and focus.

The same considerations and conclusions are true for many non-material-processing applications such as laser pumping (pumping one laser with another laser), particle counting or sorting, or spectroscopy. For example, Fourier transformation IR spectroscopy is a laser application used to identify substances or microorganisms. In-situ molecular spectroscopy is another laser application that traces chemical reactions in a chemical or bio-reactor. In all of these cases, a “clean” beam reduces unwanted stray light effects and noise, and leads to better results.

Researchers dealing with ultrafast applications where non-linear processes are relevant will appreciate the help from a beam diagnostic system because the conversion efficiency of a non-linear crystal in an amplifier stage depends strongly on the uniformity and excitation intensity of the pumping beam from the pump laser. One of the most important considerations of these systems is: How well can the pumping beam get focussed on the crystal? A meaningful answer is possible only after a comprehensive analysis of the laser beam is performed by means of an appropriate beam diagnostic system. The benefit from a user perspective is better laser performance that leads to better results.

Fiber-coupling is a laser delivery method that is becoming more and more important in many industrial applications. Fiber-coupled microscopes are one of many known examples. No matter what the exact application is, there's one common requirement in all cases: a good coupling efficiency is a function of beam quality (i.e. “clean” profile and small focus). A bad beam will not only lead to a dissatisfying system performance, but will also accelerate fiber degradation and the need for replacement, thus increasing system down-time and maintenance costs.

Conclusion

Nobody knows better than laser designers that lasers have many features beyond output power which need to be regularly measured, optimized, and controlled during a laser development project. The challenging requirements of a fast moving market and the competitive environment force laser designers to make sure that every effort is taken in order to create lasers that can be sold successfully to the market place. The chance of entrepreneurial success will increase with the overall performance and quality of the products. One common goal that all laser designers share is to develop superior lasers which deliver good and clean beams consistently over a long period of time (i.e. long lifetime), which requires more than just the regular verification of laser output power during a development project.

Besides electronic measurement techniques there are alternative non-electronic techniques or tools available such as burn papers, films, wooden tongues, acrylic blocks, fluorescing plates or cards, etc. These simple methods of laser beam evaluation have clear disadvantages: Poor resolution; the spot size is highly dependent on exposure time; since the results are not quantitative, they are subject to subjective judgements; potentially toxic vapors can be produced from burned materials; results do not reveal short-term fluctuations. Last but not least, the human eye features a logarithmic sensitivity; it can only see a limited number of shades; and it has difficulty to distinguish enough structure in burn spots.

Beam analyzers for a comprehensive characterization of laser beams are not inexpensive. Beam propagation analyzers (M^2 meters) are generally more expensive than beam profilers due to their higher degree of instrument sophistication. With respect to the costs of purchase, it is often overlooked by users the disadvantages in the technical, financial and also individual domain can evolve without a powerful beam diagnostic system. In many cases, the benefits of beam diagnostic analysis achieve a positive return on investment even after a short time. Therefore, instrumentation for laser beam characterization is a valuable addition to any laboratory or manufacturing facility.