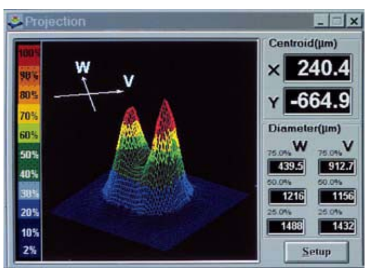
Understand Different Laser Beam Profiling Technologies Available and Learn How to Choose the Right System for Your Application

Spatial intensity distribution is one of the fundamental parameters that indicate how a laser beam will behave in an application. For example, in a materials processing situation, it is easily understandable why two beams of identical power and diameter leave different burn marks on a substrate if one beam features a Gaussian or near-Gaussian profile (maximum intensity in the beam center), while the other beam features a so-called donut profile (very little power in the beam center).

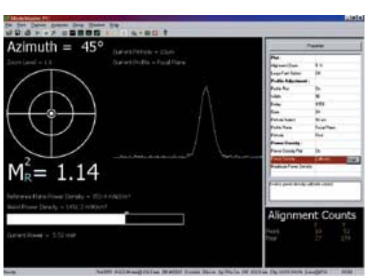
Theory can sometimes predict the behavior of a beam, but manufacturing tolerances in lenses and mirrors, as well as ambient conditions affecting the laser cavity, necessitate verification. Consequently, it is crucial for researchers, system designers, and laser manufacturers to be able to verify spatial intensity distribution (intensity profile).

Beam Profile vs. Beam Propagation

Beam profilers measure the spatial intensity distribution of a laser beam. However, no matter how accurately and diligently a profile is measured, this information does not predict the intensity distribution elsewhere along the beam path. If the propagation behavior, or the beam quality factor M^2 of a laser beam should be needed, a beam propagation analyzer or M^2 meter will be needed instead of a beam profiler.



BeamMaster 2D



M^2 Beam Propagation

Types of Beam-Profiling Instruments

There are four main types of spatial beam-profiling instrumentation; camera-based systems, pinhole scanners, knife-edge scanners, and slit scanners. Each has specific advantages and disadvantages and measurements that may result in slightly different results. In addition, each method has its own speed and accuracy characteristics that depend in different ways on various peculiarities: How the raw data is processed; sensitivity to the various noise sources; and, fundamental accuracy issues?

1. Camera-Based Systems

Cameras use a two-dimensional array of square or rectangular pixels as the imaging device. The intensity distribution of a laser or light source is recorded pixel by pixel and displayed as either a topographic or three-dimensional contour plot. The chief advantage of such profilers is that they can detect and display any structure that may exist on the profile, and they can be used with both continuous wave (CW) and pulsed lasers.

The chief disadvantage of these instruments is that their measurement resolution is limited by pixel size which limits their use in measuring extremely small beams. Pixel size varies by camera technology, as described in more detail further on, but typically the minimum beam size for these instruments will be on the order of 50 µm to 60 µm. Another disadvantage is their low saturation and damage threshold levels, which often requires considerable attenuation.

A very important aspect concerning camera-based analyzers is background noise monitoring and subtraction. The implementations of a powerful analytical method to address these issues are an essential feature of a useful beam diagnostic system. These functions are available in Coherent's BeamView™ software, which is used with all of its LaserCam™-HR camera-based beam diagnostics systems.

In Depth: CCD versus CMOS Cameras and CAPT™ Technology

The two most commonly used cameras in beam profiling utilize Charge-coupled devices (CCD) or Complementary metal–oxide–semiconductor (CMOS) sensors. Each has unique strengths and weaknesses giving advantages in different applications. Some special considerations should be made when choosing which type of technology to utilize in laser beam diagnostics.

Both types of imagers convert light into electric charge and process it into electronic signals. In a CCD sensor, every pixel's charge is transferred through a very limited number of output nodes (often just one) to be converted to voltage, buffered, and sent off-chip as an analog signal. In a CMOS sensor, each pixel has its own charge-to-voltage conversion, and the sensor often also includes amplifiers, noise-correction, and digitization circuits, so that the chip outputs digital bits.

Saturation and blooming are related phenomena that occur in all CCD image *sensors under conditions in which either the finite charge capacity of individual photodiodes, or the maximum charge transfer capacity of the CCD, is reached. Once saturation occurs at a charge collection site, accumulation of additional photo-generated charge results in overflow, or blooming, of the excess electrons into adjacent device structures. A number of potentially undesirable effects of blooming may be reflected in the sensor output, ranging from white image streaks and erroneous pixel signal values to complete breakdown at the output amplification stage, producing a dark image.*

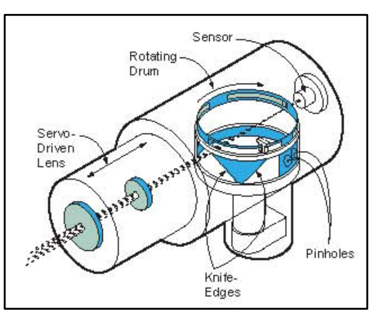
CMOS sensors have an amplifier for each pixel which means that every pixel can be read out individually. Consequently, there are no blooming effects (unlike a CCD). If a pixel gets saturated, neighboring pixels aren't affected. As mentioned above, since CMOS sensors can be susceptible to pixel-to-pixel offsets, non-linearities, non-uniformities, image enhancement and hot pixel processing features are needed in order to correct these issues and to provide extremely accurate images from which quantitative beam parameters can be derived. When these techniques are properly implemented the output from a CMOS sensor can be equal to or superior to that of a CCD device and eliminate the downside of CCD blooming issues which is very important when measuring lasers.

Coherent utilizes CMOS sensors in its digital camera-based beam profilers, and has developed a proprietary process called CAPT (Coherent Adaptive Pixel Technology) that addresses these CMOS pixel issues. CAPT utilizes an image enhancement and hot pixel processing feature that corrects these issues.

Scanning Based Systems: Knife-edge, Slit, and Pinhole Profilers

Knife-edge, slit, and pinhole scanners generate a profile by mechanically moving a knife-edge or an aperture (slit or pinhole) across the beam in a plane orthogonal to the optical axis. The light passing through is measured by a detector and correlated with the position of the aperture as it crosses the beam. Unlike camera-based profilers, scanners measure only one or two dimensions at a time. Consequently, three dimensional representations generated by these systems are calculated, not measured, and the accuracy or the reconstruction depends upon basic assumptions made about the beam characteristics and the algorithms used in the reconstruction. Typically these types of devices can only be used with CW lasers.

2. Pinhole Profilers



Pinhole profilers use a small pinhole as the aperture and plot the transmitted power versus position. The resolution of the profile is determined by the size of the aperture. The chief advantage of a pinhole profiler is its ability, within the resolution, to create an exact profile of a plane through a portion of the beam.

The disadvantages are:

- The transmitted power through the pinhole is very small
- Aligning the pinhole is difficult and time-consuming
- Multiple positional measurements are needed to generate a profile of the entire beam, which can take up a lot of time.

3. Slit Profilers

Slit profilers use a long, narrow aperture which encompasses the full width of the beam in a direction perpendicular to the travel of the slit. It then plots the transmitted power through the slit versus position. Unlike the pinhole scanners, the slit scans through the entire beam. However, unless the beam is circularly symmetric and near Gaussian, the profile may not be an exact representation of the intensity profile. Like pinhole scanners, the resolution of the scan is a function of the width of the slit, and the narrower the slit (higher resolution), the less light reaches the detector, decreasing the signal-to-noise-ratio.

4. Knife-edge Profilers

In this case, the "aperture" has one sharp, straight edge (knife-edge). As the knife-edge traverses the beam, the system measures the portion of the beam that is not blocked by the blade and plots the differential (rate of change in intensity) versus position of the power.

Several advantages compared to slit or pinhole scans apply: First of all, the beam intensity is not limited by the size of the pinhole or slit width. Secondly, the signal-to-noise ratio is very high. Thirdly, resolution is not limited by the size of the aperture allowing beams of a few microns in diameter to be measured with a resolution down to 0.1µm. And because, at some point in the scan the full beam strikes the detector, accurate power and noise measurement can be taken.

Like the slit scanner, the accuracy of a scan depends upon the geometry of the beam. For best results, the beam should be circularly symmetric and near Gaussian.

Within this category Coherent offers a knife-edge instrument called the BeamMaster™.

Tomographic Scanning

Knife-edge scanners cannot generate truly accurate three-dimensional reconstructions of laser beam profiles. Reasonable approximations can be made by using tomographic techniques ("*Reconstructive Tomography*"). This same type of process is used by X-ray systems to create X-ray images in medicine (tumor diagnostics). The key to making these constructions is to scan the beam in as many different directions as possible. Scans from at least three different directions are needed. If scans could be made from more directions, the three-dimensional reconstruction would be even more accurate.

Of the four main types of spatial beam-profiling instrumentation, camera- and scanning knife-edge-based systems became the most widely established analyzers on the market place.

Which type of profiler works best for you (camera- or knife-edge-based)?

The primary factors which determine the type of beam profiler to use are wavelength, beam size, laser power (or energy) and operating mode (CW or pulsed).

Wavelength

The wavelength being measured largely determines the type of detector device needed. For the wavelength range from 190 nm to 1100 nm, CCD and CMOS cameras or Si-sensor based knife-edge detectors should be the choice technology. For the near infrared, from 800 nm to 1800 nm, InGaAs-based arrays or sensors are on-hand. However, for wavelengths from 800 nm to 1100 nm, CCD-, CMOS- and Si-based arrays and sensors should still be the first choice. Above 1100 nm, InGaAs-based arrays and sensors are needed, and they are more expensive than the other detector options.

Special attention should be paid to a camera or knife-edge system when used in the ultraviolet wavelength range from 190 nm to 355 nm. Commonly, knife-edge detectors use a UV-enhanced Si-based sensor in order to ensure good and stable (long life) performance over the whole wavelength range from 190 nm to 1100 nm including the UV range.

CCD and CMOS arrays in cameras are generally subject to on-going severe degradation by the ultraviolet light unless a special technology ensures their permanent protection. A useful solution to this problem, now available to the market, is in the form of a high quality UV resistant phosphor coating applied to the front surface of the CCD or CMOS array that prevents UV degradation. Coherent offers a product in this category called the LaserCam-HR-UV.

Beam Size

There are several questions related to beam size that will help determine the appropriate system for your application.

Question: ***Is your laser beam appropriately sized for the camera array or knife-edge sensor?***

Answer

If you are going to use the sensor for beam size measurement, a good rule of thumb in the case of round beams is that the beam diameter should be 15 to 20% smaller than the physical size of the array or sensor. In the case of beams that are not round, use the longest dimension for this comparison.

In Depth: Laser Beam Size

The boundaries of optical beams are not clearly defined and, in theory at least, extend to infinity. Consequently, the dimensions of laser beams cannot be defined 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 beam width 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. In reality, many lasers exhibit a significant amount of beam structure, and applying this simple definition 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/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 of the camera.

Question: ***How accurate of a beam diameter measurement do you need, and what is the specified spatial resolution of the beam analyzer? In other words, how accurately can your laser beam diameter get measured?***

Answer

Camera arrays are limited by the size of their pixels. In case of CCD or CMOS camera arrays, the typical pixel size is in the order of 4 µm to10 µm which means that a beam should be larger than 50 µm to 60 µm to ensure that enough pixels contribute to an accurate measurement. InGaAs arrays have considerably larger pixel sizes than CCD and CMOS arrays. Their typical pixel size is in the order of 30 µm what limits the minimum measurable beam size to around 250 µm.

In Depth: Transforming the Beam

If the beam size is greater than 15 to 20% of the array aperture, or the sensor is too small to get measured with reasonable accuracy due to pixel size, a transforming optic can be used in order to either expand or reduce beam size.

Whatever the optical method chosen for external beam attenuation, the most important factor is that it introduces virtually no beam distortion. To avoid or minimize beam distortion, any attenuation optics in the beam path must be manufactured to exacting specifications, i.e. they must be specially designed for beam diagnostic applications. The optics must be laser-grade substrates with proper flatness in order to avoid wavefront distortion and wedge angle in order to avoid etaloning and fringing. For this reason, good beam diagnostic accessories are sophisticated and expensive components and should not be considered as an unneeded purchase.

Knife-edge detectors have a resolution in the order of 0.1 µm, which is considerably better than camera-based arrays. Beam diameters down to approximately 3 µm can be measured directly and with good accuracy. The main benefit of these systems is that beam expansion is not required to accurately measure extremely small beams.

Power (or Energy) of the Beam

The power or energy of the beam is another important point that can influence the choice of beam profiling technology. In general, beam analyzers are too sensitive to view laser beams directly, which is particularly true for camera-based analyzers, where saturation levels are on the order of low µW/cm² or mJ/cm². Some form of attenuation will almost always be needed with camera-based systems. Most manufacturers will offer attenuators as part of their camera-based product line.

A special feature of camera-based analyzers is variable camera exposure time, which allows "quasi-attenuation" via an electronic shutter. This allows the user to decrease or increase the signal intensity levels using exposure time instead of external attenuation. Nevertheless, additional external attenuation is still typically required in most applications.

Knife-edge systems, on the other hand, have much higher saturation and damage threshold levels often higher than camera-based systems by many orders of magnitude. Therefore, with knife-edge systems the use of attenuation optics is often not required for many beams.

Question: *How fast can beam image information and data get captured? How do continuous-wave (CW) lasers differ from pulsed lasers?*

Answer

Continuous-wave versus pulsed lasers:

A key parameter that will help define the appropriate beam profiling technology is whether the beam is CW or pulsed. Camera-based systems can be used with both CW and pulsed lasers, whereas knife-edge profilers can only be used with CW lasers, unless special techniques are used in addition which are complicated and expensive.

Image Capture Rates

The speed of beam image capture will depend on the computer being used, type of analyzer (camera- or knife-edge based analyzer, type of camera), data capture resolution, number and type of calculations being done, and whether calculations are being done after each image capture or after all specified images have been captured.

Computer

The update rate of a particular computer will be influenced by a variety of factors: CPU Speed, Computer RAM, Video Card, Video RAM, Screen Resolution, Screen Color Depth and Operating System being used. In short: a fast and powerful computer will process and provide data fast.

Knife-edge Profiler versus Camera-based Profiler:

As far as knife-edge profiler is concerned, the motor speed or rotation frequency of the drum containing the knife-edges limits the maximum update rate. It is typically in the order of several Hz. Things are much more complex in case of camera-based profilers because of their pulse measurement capabilities and type of camera array.

Triggering

Capturing desired images is important in measurement instrumentation. To capture images from a pulsed laser source, a trigger signal is often used. This signal serves to tell other devices to either generate or capture data at a specific time. The triggering method used is especially important in pulsed applications where these signals are used to fire and/or detect the output of a laser. BeamView systems from Coherent have the ability to either receive or generate these signals, and provide a number of features and options to control the timing of a sample capture for both CW and pulsed laser application. No trigger signal is required in CW operation.

In Depth: Image Capture and Triggering

Most camera types have a small period of vulnerability, between one image and the next, where the incident light on the camera sensor is not being recorded or is otherwise invalid (analogous to a camera shutter being closed). For CW laser sources this period is not important, but for pulsed laser systems the laser pulse must either not be generated during the period of vulnerability, or the image generated during the vulnerability period must be disregarded.

Generally, there are two types of capture mode in a pulsed laser measurement situation, Asynchronous Triggering and Auto Triggering.

Asynchronous Triggering

Asynchronous mode allows the laser to run at its own rate. In this mode, the laser is fired asynchronously relative to (independently of) the Video Frame rate of the camera. A TRIGGER-IN signal from the laser source must be provided to capture pulsed image data. The signal normally comes from the laser electronics external synch output.

Auto Triggering

Another triggering mode is auto triggering which is similar to the trigger used in oscilloscopes. Image capture occurs when the intensity level on any pixel in the video image is greater than a user-selected level.

There is a maximum pulse trigger in rate for capturing images from a pulsed laser source without averaging adjacent pulses. It generally depends of camera type and model.

Summary

Whatever the application is, there are certain defined beam parameters of a laser source beyond just power or energy that need to be measured, optimized, or specially monitored. Beam profilers are important tools used for laser beam characterization.

The two main beam profiler technologies most commonly used are knife edge scanners and camera-based systems. Each technology has its benefits and disadvantages and is most appropriate for different types of lasers.

Knife-edge scanners are most useful with very small beams, CW lasers, and high power lasers. Camera-based systems work with larger beams, and either pulsed or CW lasers.

When choosing a camera-based system, the sensor technology must be considered. For example, CCD cameras are susceptible to blooming effects, whereas CMOS sensors are not. Attenuation will likely be needed when use camera-based systems with higher power lasers, and careful attention must be made to the quality of the optics used.