BEAM PROFILERS

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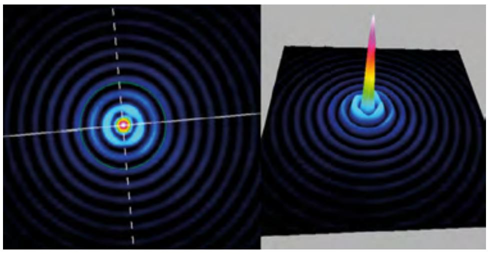

Since the first devices appeared in the 1960s, lasers have become deeply entrenched in many industries. Modern applications leverage a wide variety of lasers for increasingly complex processes. But how do we ensure that important beam characteristics are aligned with expectations?

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Beam profiling is a critical tool for understanding more about lasers and laser processes. In industries from biomedical to manufacturing and beyond, beam profiling can uncover critical information about beams, helping to develop more robust and effective processes and procedures.

CRITICAL DETAILS

Beam profilers are available for many wavelength regimes from UV to THz frequencies, but the exact wavelength of a laser dictates what type of sensors and detectors can be used. For example, simple CMOS sensors provide good performance for visible and NIR measurements while remaining relatively inexpensive. However, these sensors would provide nearly no useful results for IR beams. Choosing the correct type of profiler for your wavelength is important.

The diameter of the beam is also a critical consideration when choosing a profiler. A profiler which can accommodate very large diameters may not be a good choice for focused beams and vice versa. Maximum measurable beam diameter is generally dependent on the active measurement area size (for cameras) and the photodetector and slit size (for scanning slit profilers). Minimum measurable diameters in cameras are limited by the pixel size. Generally, for beam diameters less than 10 pixels wide at the 1/e2 clip level, the measurement error increases quite rapidly, so a minimum of 10 pixels wide at 1/e2 is a common minimum diameter specification [1]. Approximate wavelength and diameter regimes for a few common sensors and detectors are shown in Figure 1.

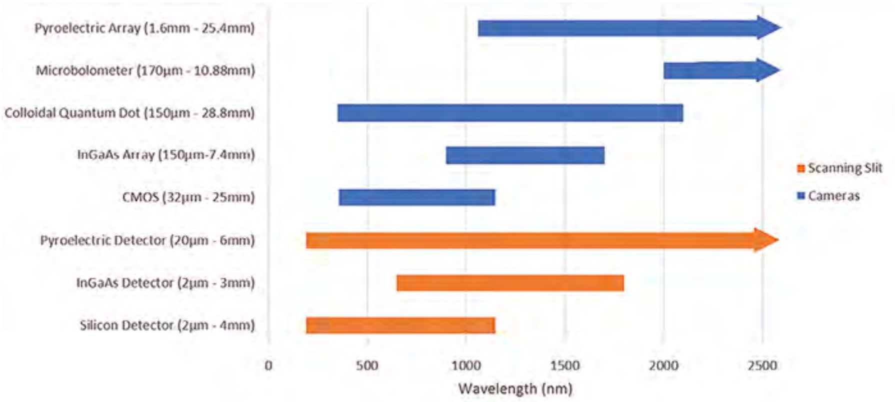

Figure 1: Approximate wavelength and diameter regimes for different sensors and detectors.

SCANNING SLITS AND CAMERAS

Beam profilers usually fall into two categories: camera-based or scanning-slit-based systems. Knowing when a camera or scanning-slit-based system is appropriate is critical

Figure 2: (left) A two-dimensional camera profile of a flat top beam.
(right) A one-dimensional integrated scanning slit profile of a flat top beam.

for accurate profiling measurements.

Scanning slit profilers use two slit-shaped apertures to profile beams. One slit is passed through the beam, allowing only a small fraction of the beam to pass through at a time. A photodetector on the opposite side of the slit measures the intensity of this light, generating a one-dimensional integrated beam profile. A second slit is passed across the beam in an orthogonal orientation to produce a second integrated profile. Because only two one-dimensional integrated profiles are measured, a true two-dimensional view of the beam is not possible with scanning slit profilers [2].

Camera profilers operate on different fundamental principles. Photons from the laser directly impact each pixel, generating a current that is read out from the imaging sensor. Each pixel is independent, resulting in a full two-dimensional beam profile. As a result, camera profilers can capture non-Gaussian and elliptical features that scanning slit profilers cannot [2]. For example, the uniformity of a flat top beam is easily observed with a camera profiler (Figure 2a), but the same one-dimensional integrated profiles produced by a scanning slit profiler do not accurately capture the plateau shape (Figure 2b).

Similarly, complex beam shapes can often be problematic with scanning slit profilers. For example, beams with orbital angular momentum (OAM) often produce ring-shaped profiles. With a camera, this ring shape is easily observed (Figure 3a). However, scanning slit profilers fail to show the dark center of the ring (Figure 3b).

Finally, when profiling elliptical beams, the orientation of the beam is fully captured with a camera. However, the orientation is entirely lost with a scanning slit profiler. While it is true that the source or profiler can be rotated to provide accurate results, this is not necessary with a camera profiler. Also note that scanning slit profilers do not correctly identify the major and minor axis of the diameter, only the diameter along the profiler's X and Y dimension.

TIGHTLY FOCUSED BEAMS

Due to current size limitations of imaging sensor pixels, scanning slit profilers can inherently measure smaller diameter beams compared to cameras. However, as previously discussed, scanning

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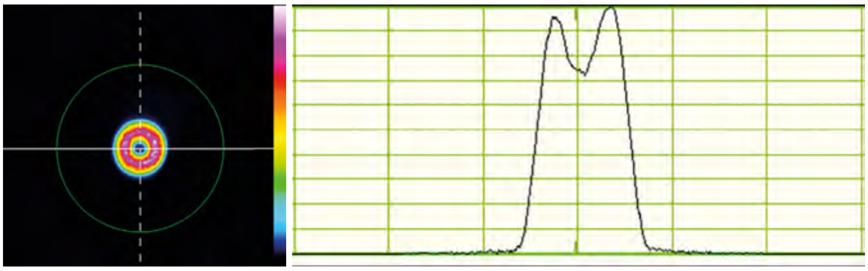
Figure 3: (left) A two-dimensional camera profile of an OAM beam.
(right) A one-dimensional integrated scanning slit profile of an OAM beam.



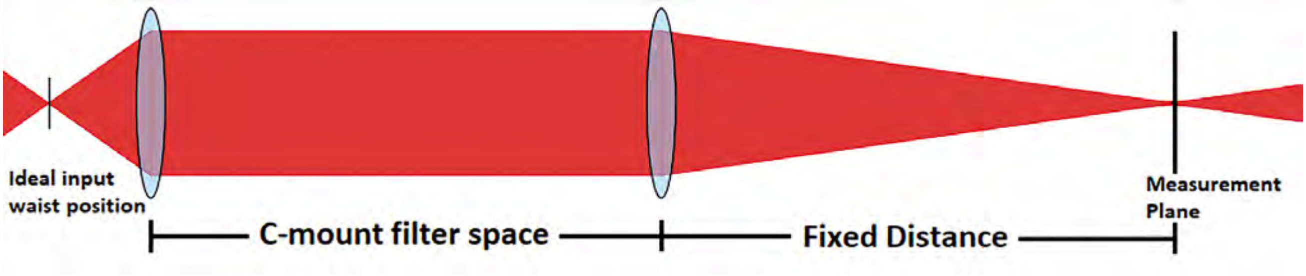


Figure 4: A typical two-lens magnification/reimaging system.

slit profilers are only capable of capturing one-dimensional integrated profiles, so tightly focused non-Gaussian beams may not be accurately represented by a scanning slit profiler. That's where magnification optics become useful.

Two-lens systems are capable of reimaging and magnifying beam waists. When paired with a camera profiler, we can generate full two-dimensional beam profiles of tightly focused beams without issue. The first lens is carefully chosen to collimate the light coming from the beam waist, while the second lens refocuses the beam onto a camera profiler. As with any two-lens system, the ratio of the lens focal length determines the magnification of the system. An added benefit of this method is that attenuation filters or beam samplers can be added between the lenses where beam irradiance is low. A typical magnification system is shown in Figure 4.

Choosing appropriate optics for these systems in critical. One important detail is the NA of the collimating lens. For accurate measurements, the tails of profiles need to be captured out to 1% of the maximum beam intensity. As a result, we must collimate the beam out to the 1% clip level for accurate measurements. While it can be tempting to simply choose a collimating lens with an NA to match our beam, this truncates the tail of the beam profile and can lead to artificially broadened profiles.

There are limitations to reimaging and magnification systems. First, these types of systems are only appropriate for profiling at the beam waist. If measurements need to be made away from the beam waist, alternative methods should be considered. When the first lens is positioned one working distance away from the beam waist, a well-designed magnification system can refocus the beam directly onto a camera profiler (shown in Figure 4). However, as the optical system is moved further or closer from the beam waist, we are simply changing the real object location with respect to the lens, not profiling some arbitrary plane away from the beam waist.

ATTENUATION

Most beam profiling applications require external attenuation. For relatively low average powers, simple neutral density filters are often adequate (<~1W, in some cases lower). Various filter materials have been employed by beam profiling manufacturers, but generally they fall under three main categories, reflective, absorptive, or a combination of reflective and absorptive [3].

However, more powerful beams may heat up filters and cause thermal lensing or damage. This can dramatically impact profiling results. For those cases, beam samplers are generally a more effective means of attenuation. A small portion of the total beam power is reflected off an angled wedge or prism and the reflected beam is then profiled [4]. Depending on wavelength, certain wedge materials will perform better than others. For example, fused silica wedges can provide excellent results for UV, visible, and NIR beams, but tend to absorb energy at longer wavelengths.

It is also often a good idea to use two orthogonal wedges or attenuation. When light reflects off a surface, the fraction of the s and p-pol beam components which is reflected is not the same. However, by using two orthogonal wedges, the polarization of the original beam can be preserved. One such dual-wedges attenuator is shown in Figure 5.

Finally, in the examples above, most of the beam's power will pass directly through the wedge. This extra residual beam needs to be handled appropriately for safe operation. Passive beam traps are a good option for average powers up to 50W, but beyond that, actively cooled traps may be required.

SIMULTANEOUS PROFILING AND POWER MEASUREMENTS

For some applications, both beam profiles and absolute power measurement are important. An example could be an ablative process where a uniform irradiance over a controlled area is required. In that case, it may be required to both confirm the shape of a flat-top beam while quantifying the exact intensity of the flat-top region.

As discussed previously, beam samplers are well-suited for high power attenuation, but they can also be used for simultaneous profiling and power measurements. Because only a fraction of the beam is reflected off each wedge, we can capture the residual beam with a power meter instead of a beam trap. Since some of the beam's power is reflected off the wedge, the power meter reading needs to be corrected for these losses, but this is straightforward using the Fresnel equations. By correcting for the fractional power that is reflected off the front of the wedge, we can easily measure the total power using a residual from the beam sampler.

DIVERGENCE MEASUREMENTS

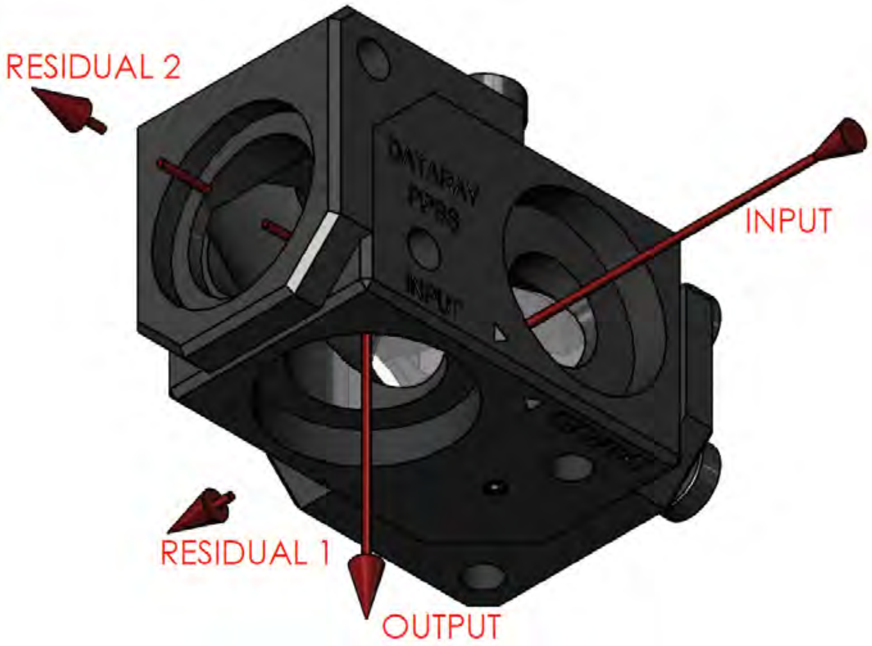
The divergence of beams is a common metric to determine how quickly a beam expands in the far-field. While there are many methods to measure divergence, the best choice is generally dependent on the scale of the expected divergence angle.

For many applications, simply mounting a profiler onto a stage and profiling at many distances from the source is an appropriate method. Since many beam profiles are taken along the axis of propagation, it is generally easy to find the far-field (identified by a constant divergence angle), and a simple linear regression fit will provide the divergence angle [5]. However, if the divergence of a beam is low, the above method can yield a flat regression line. Naturally, no beam is ever perfectly collimated, so if a high accuracy divergence measurement is needed, other methods should be employed.

For low-divergence Gaussian beams (full-angle divergence of a few mrad and below), we can use an ancillary lens and a profiler. A profiler is positioned such that the image plane is located precisely at the focal length of a lens. A simplified diagram of one of these systems in shown in Figure 6. The beam is simply aimed at the lens, and the resulting divergence is equal to 2W/F, where 2W is the second moment diameter, and F is the focal length of the lens. Care must be taken when selecting a lens for these applications. These systems are particularly sensitive to the exact position of the image plane with respect to the lens, so usually long focal length lenses are required to ensure low measurement error (f = 500-1000mm is not uncommon).

On the other hand, if the divergence of a beam is high (full-angle divergence of several hundreds of mrad or more), the beam may expand too quickly to use a simple stage and profiler. In these ●●●

Figure 5: A dual wedged polarization preserving beam sampler. The wedges are positioned orthogonally with respect to one another, preserving the polarization of the input beam.



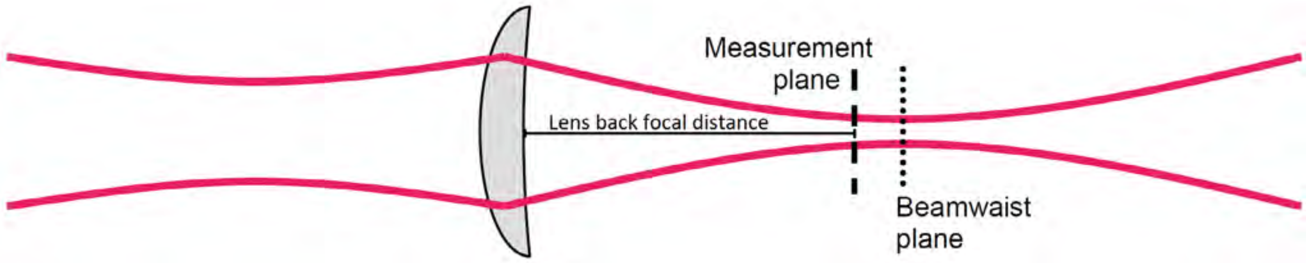


Figure 6: Divergence measurement system using an ancillary lens.

cases, sometimes a single-plane divergence measurement suffices. If the precise location of the beam's focal plane is known, a single diameter measurement can be made in the far-field, then a point-source approximation can be used to determine divergence.

M^2 MEASUREMENTS

M^2, sometimes referred to as beam quality, measures how closely a given beam is to a perfectly ideal Gaussian. The minimum value of 1 indicates a theoretically perfect Gaussian beam, while higher values indicate a greater and greater deviation from Gaussian behavior. The lower the M^2 value is, the smaller a beam can generally be focused by a given lens. For example, if a 250mm focal length lens is used to focus a 5mm diameter (at $1/e^2$), 1064nm beam, we expect the resulting focal spot to vary depending on M^2 (from ~34 – 68um for M^2 of 1 to 2, respectively). Alternatively, for a given beam spot size, higher M^2 beams diverge faster.

Measuring M^2 involves profiling a beam in the near-field and far-field. This can be done by manually moving a profiler along the laser's axis of propagation, but it is often faster and less cumbersome to use an automated stage for these measurements. Since near-field and far-field measurements are needed, collimated beams are generally first focused by a lens for M^2 measurements. If they are not focused by a lens, stages often need to be unrealistically long to accommodate the long Rayleigh lengths [6].

The exact calculations required to measure M^2 are included in ISO11146 [6]. While these equations are beyond the scope of this article, an ISO compliant M^2 measurement generally involves measuring several profiles in the near and far field and using the second moment of these profiles to calculate M^2.

While it may be tempting to use M^2 for non-Gaussian beams, it may not provide useful results. Since M^2 only measures how close a beam is to a Gaussian, high M^2 values simply imply that a Gaussian does not accurately represent the beam. For beams where the anticipated M^2 is high, other metrics can often provide more fruitful results. ●

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