Lasers versus LEDs for Bioinstrumentation
Laser Advantage #1 - Spatial Brightness

A laser is a true point source that can be focused to a much brighter spot than a LED. This minimizes the real cost per watt of using a laser source, reduces optical complexity, maximizes signal to noise, and increases instrument speed.

Light Sources for Bioinstrumentation

In any instrument based on the detection of fluorescence and/or light scatter, the key to successful operation is the ability to maximize signal-to-noise ratio. This, in turn, is accomplished by delivering the necessary amount of useable excitation light (that is, light that actually excites the fluorescent probe) into the required illumination sample region, while minimizing the amount of wasted light that is of the wrong wavelength or in the wrong spatial location. There are several inherent characteristics of the laser that make it a much more efficient source for accomplishing this task than the LED, resulting in *lower instrument costs and superior performance (speed and sensitivity).* Here we examine the role of source brightness and its impact on optical etendue and, hence, focused spot intensity, optical efficiency, and optical complexity (i.e., system cost).

Laser – a True Point Source

In bioinstrumentation, the requisite spot size for optimum operation depends on the type of instrument and then the specifics of the particular model. It can range from tens of microns in diameter, to several millimeters in size.

Application	Focused Spot Size
Gene Sequencing/Medical Diagnostics	1 to 10 x 1 to 10 mm
Medical Diagnostics	100's x 100's μm
Cytometry	30 x 30 μm
Multi-Mode fiber	≤ 50 microns
Single-Mode fiber	≤ 3.5 microns

Probably the most significant inherent difference between lasers and LEDs is in their ability to efficiently collect and focus their outputs to attain these desired spot sizes. This is because the output of a typical laser is a well-behaved, narrow, low-divergence beam. Such a beam behaves like an ideal, true point source. This means that all the source output can be collected and focused into the precise spot size needed by the application, minus, of course, any small losses due to scattering or reflection by the system optics. The only true limit on the minimum focused spot size of such a source is diffraction, which prevents a laser from being concentrated to a spot diameter that is much smaller than the laser wavelength.
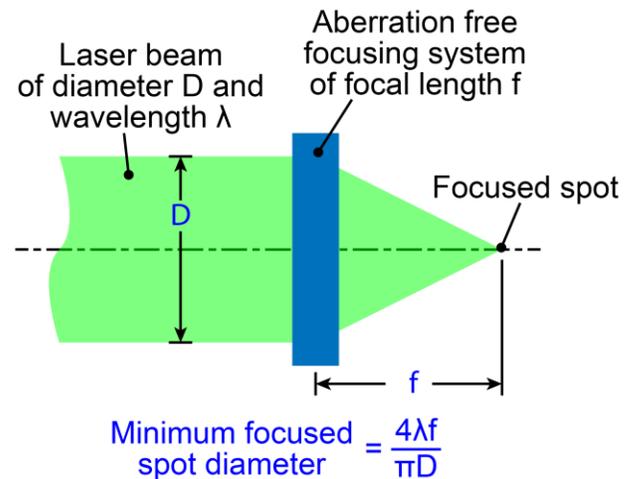

$$\text{Minimum focused spot diameter} = \frac{4\lambda f}{\pi D}$$

Figure 1. *The focused spot diameter of a high quality laser beam is limited only by diffraction.*

In many instruments, fiber coupling is needed to simplify the optical layout, to isolate the interaction zone or other reasons. So even in applications where the final spot size is relatively large, the ability to easily focus all the laser light into a very small area can be a critical enabling advantage. For example, for a single-mode polarization preserving fiber, the core diameter, and hence input facet diameter, scales with wavelength. At a wavelength of 405 nm for example, the diameter is 3.5 μm.

Simple Focusing – Lower Costs

The ability to easily focus a laser beam to a small spot delivers the advantages of high intensity and high optical efficiency (lower cost per watt). It also enables the use of lower cost focusing optics. As the focused spot size increases, the required numerical aperture (NA≡D/2f using the variables defined in the drawing) of the collecting and focusing lenses decreases. As shown in the table, most instruments need a spot size that is orders of magnitude larger than the diffraction limit and which can be readily achieved with relatively simple, low NA optical systems. This is a very important advantage for instrument builders, since the cost of lenses increases non-linearly with their NA, particularly if the lens needs to be aberration corrected so as to produce a diffraction limited spot size.

LED – Extended Source with Large Etendue

On the other hand, a LED is a conventional, extended light source, like a light bulb. It is an economical source that is useful in applications involving large area illumination – but in many bioinstrumentation applications the illumination area is very small as outlined in the above table. The ability to collect and focus light from an extended source into a finite target area is defined by the size of the emitting surface area and the solid angle into which it radiates in a property called etendue. The important thing about etendue is that, in the best case scenario, it is preserved across an optical system (and in a real world optical system, it always gets a bit worse). This means that for a LED, *there is always a trade-off between spot diameter and the amount of light that can be collected and focused into this spot.* You can collect more light, but only if you focus it into a larger spot; conversely, if you want a smaller spot you can only get this by collecting a smaller percentage of the LED output. Simply stated, the intensity of the source limits the intensity of the focused spot, which can be up to two orders of magnitude less than the focused intensity from a laser of the same optical output power. (In the case of the laser, the focused intensity is theoretically limited only by diffraction.)

How does this work in practice? For a LED, if we assume that it is a perfect "Lambertian" source:

Etendue = π x emitting area x $(NA)^2$

where the numerical aperture (NA) is the smaller of either the source's emission angle (i.e., source NA) or acceptance angle of the collecting optics (i.e., lens NA). Since real LEDs are never perfect Lambertian sources, this equation represents a theoretical best case.

To see the impact of etendue, let's consider the case of a 100 milliwatt LED that has an active area of 1 mm² and which emits into a hemisphere (a solid angle of 2π steradians corresponding to a NA=1). Let's say we wish to focus this output into a spot diameter of 100 µm. The etendue equation tells us:

Collecting etendue = Focusing etendue

π × 1 mm² × collecting NA² = π × (.1)² mm² × focusing NA²

collecting NA = .1 × focusing NA

The highest theoretically possible NA on the focusing side is a value of 1. Therefore, the *theoretical* maximum for this scenario is a collecting NA of 0.1. This means that only a mere 6% (6 milliwatts) of the LED output is focused into the desired 100 µm spot (using NA ≡ sin θ).

But, the NA=1 value for the focusing optics is not practically realizable. Even a value of NA=0.3 would represent a fairly sophisticated and costly optical system. Yet, even with such a high cost lens system, less than about 2% (2 milliwatts) of the LED output is contained in the 100 µm focused spot.

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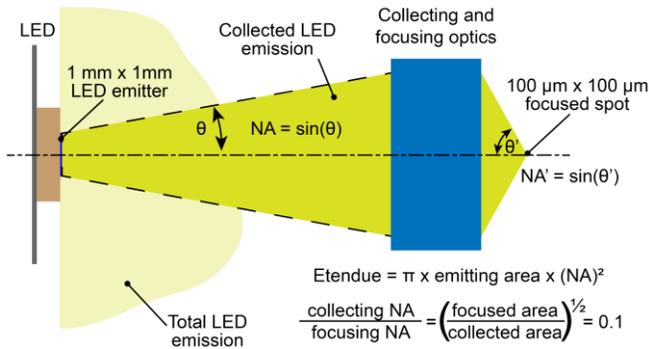
Figure 2. *Etendue dictates that if a source is imaged at a magnification of 0.1X, then the collection NA must be 0.1 times the focusing NA. Since the highest possible focusing NA is 1.0, this severely limits the ability to collect all the output from the source LED.*

High Cost Optics and Low Efficiency

Because of this phenomenon, it's usually not practical to concentrate even 1% of the output of a typical LED into the focused spot in an instrument! The etendue tradeoff for extended sources, such as LEDs, means that collecting more light means a bigger focused spot, or substantially more complex and costly focusing optics, or both.

This problem can't be avoided by combining multiple LEDs; that just increases source size even further, making the problem even worse. What would help is brighter LEDs; that is, LEDs which produce greater light output without an increase in emitter size. At present, typical LED brightness is increasing by only 10% per year in response to the marketplace. And since most LEDs go to into illumination or display applications that are many, many orders of magnitude bigger than the bioinstrumentation market, biotech has no leverage whatsoever to change this situation.

Summary

Laser. With a laser, all the light can be focused to a target area of any chosen size. As the spot size gets smaller, the focused intensity (light per unit area) increases. And even for applications needing a small (microns) spot size, this can often be accomplished using simple, economical lenses.

LED. With a LED, the light is emitted into a wide angle from an extended emitting area. Only a tiny fraction (typ. < 1%) of the LED output can be collected and refocused. The intensity is limited by a property of traditional light sources called etendue. For large area illumination (> several millimeters), this is not an insurmountable problem. But as the spot size decreases, the amount of usable light decreases so the intensity stays roughly the same, which is about two orders of magnitude less than laser. Even achieving this very limited performance requires expensive, high NA optics, significantly increasing system cost.

Result. Even with its higher component cost, a laser enables both lower overall instrument costs and much higher intensity for illumination areas less than a few millimeters. This intensity advantage translates into higher signal to noise and faster data.

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