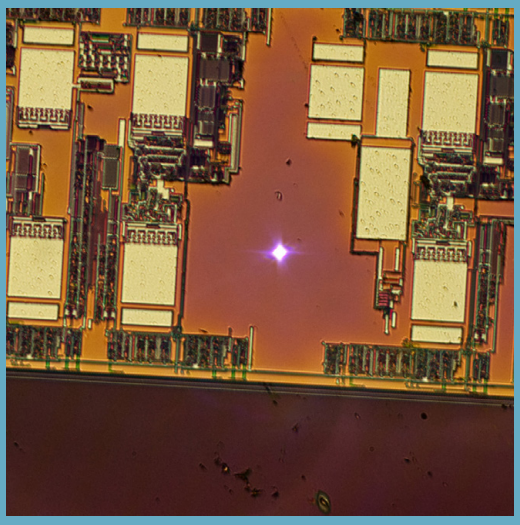
Application Note:
Microscopic spotlight generation



Microscopic spotlight generation

In some applications it is required to generate a very small (in the order of 10µm), brightly illuminated spot. One case may be that one wants to test a small optical component, like a photonic device or sensor. Another example is that one wants to use the light spot to trigger a chemical reaction in a very targeted way or to measure optoelectronic characteristics of a semiconductor junction.

What's common in these cases that you would like to concentrate as much light as possible to the small spot. The concept of étendue is useful to understand some physical limitations to that end, and to decide on a suitable setup.

Étendue -or throughput- is a measure of how spread-out the light in an optical system is. If on any given plane inside the optics the light has a large étendue, then this light in its entirety cannot be "squeezed" through an aperture (a lens, pin hole, fiber or else) that accepts only a small étendue. Moreover, in an ideal, loss-less system the étendue is preserved. This can be shown from the principles and there is no way around it[1]. Going from a large to a small étendue always means loss of light.

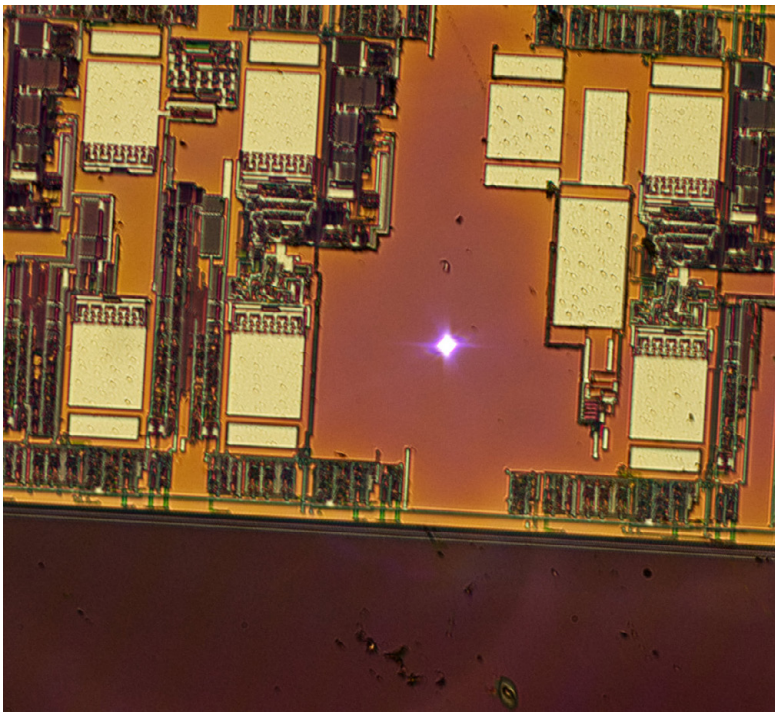
It also means that the smallest étendue in the optical system limits the throughput (you may know this concept from NA-matching in the construction of spectrometers, where as much light as possible needs to be "squeezed" through the entrance and exit slits). Therefore, the word *throughput* is quite intuitive, but not as unambiguous as *étendue*. We may use both as it is clear what we are talking about here.

For our purposes we simply may write the étendue *G* as the product of the area *S* of a surface of interest and the squared numerical aperture *NA* of the light beam that passes this surface.

$G = S * NA^2$

Thus, if the area S or the NA is increasing, the étendue is also increasing. Note that if the diameter of a circular area increases by a certain factor, the area S increases by the square of this factor. If in that case the NA would decrease by the same factor, both effects would cancel out in terms of G.

For our task it is helpful to change the viewpoint for a moment and consider the bright spot to be generated as the *source* of the light. The numerical aperture of the first lens following -the focusing lens- then defines the étendue together with the spot size.



Generating a microscopic spot of bright light for micro-spectroscopy, bandgap measurement, surface chemistry or sensor testing (shown: spotsize 10 µm on processed semiconductor wafer).

This gives the upper limit value G for the throughput. No matter how we do it, and however big the physical light source we would use is: we can only use *at maximum* a fraction of light that corresponds to that G value above.

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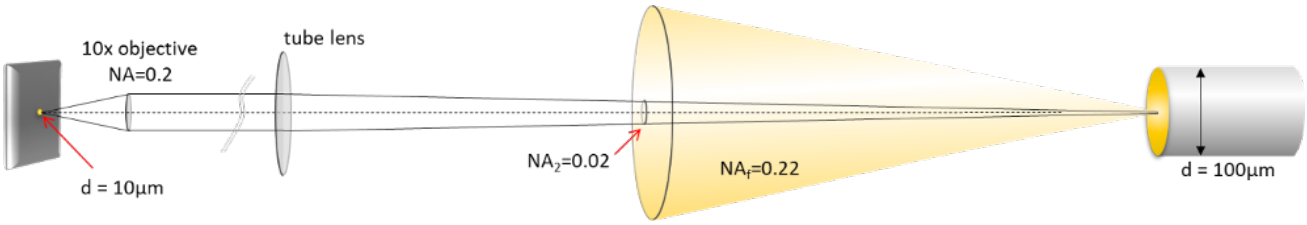
[1] Light recycling is possible, though, by passing some light through the source

A practical example

Imagine we wish to create a light spot of 10µm diameter on the sample. We could use a microscope to do so, by imaging the light source e.g., the end of an optical fiber, to the surface.

Let's say we would use a 10x objective with a numerical aperture of 0.2. The "10x" means that using the standard tube lens of that microscope make, the image of the 10µm spot on the sample would become 100µm wide. This image would be produced in the image plane of the microscope. For our purpose, we would place a 100µm wide light source exactly in that place, producing the small spot of light in the sample. This is the setup (distances & angles to scale, spot sizes exaggerated):



We could use the emission from an optical fiber with a diameter of 100µm as a point light source, with a typical numerical aperture of 0.22. The tube lens – having 10 times the focal length of the 10x objective- accepts a cone of light of a reduced aperture of 1/10 of the original aperture, thus NA2=0.02 only. In terms of étendue, the following equation holds:

$G = S_1 * NA^2 = (\pi * 5\mu m^2) * 0.2^2$
$= S_2 * NA_2^2 = (\pi * 50\mu m^2) * 0.02^2$

From all the light exiting the fiber we can only collect the small cone of light shown. How little would that be? Just take the ratio of the squared NAs:

F (fraction of light) ≈ $(NA_2/NA_f)^2 = (0.02/0.22)^2 \approx 0.8\%$

If we would use a small LED (or a large one covered with a pinhole of 100µm), the fraction would even be just $NA_f^2 = 0.02^2 = 0.04\%$ of the light emitted into the half sphere (Lambertian emitter). The excess light, more than 99%, is being absorbed inside the microscope.

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Consequences

The above illustrates how important *luminance*, i.e. emission per source area and solid angle, of a light source is for such type of application. As the étendue of the spot usually will be the limiting factor, one should also use a light source that emits its light with a small étendue. Only sources of extreme point brightness, like lasers, high pressure arc lamps, laser-driven plasma light sources or laser converter phosphors will provide brighter spots. These sources may be small in size and do not necessarily need high overall powers. Additionally, these sources may be coupled into optical fibers efficiently. The exit of the optical fiber then also forms a high brightness light source.

Sources of large geometrical extend, e.g. big high power LEDs, will not provide any advantage here.

Another finding is that -for a given spot size- the magnification of the objective does not directly play a role in the spot brightness. Only the numerical aperture is of importance. A larger magnification would reduce the illumination-side NA, which would then be balanced exactly by a larger source, i.e. fiber diameter.

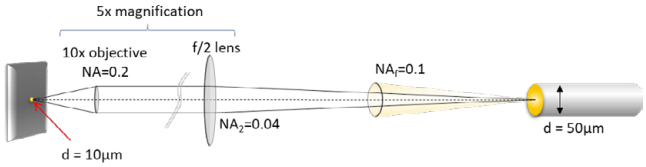
Finally, we find that it does not make sense to use high-NA fibers, because only a small cone of light will ever be used in this specific case.

Here is a table listing some representative spot diameters and objectives (these numbers do not take in account any absorption or reflection inside the optics) and a comparison of spot brightness.

Spot size (µm)	Objective (M/NA)	Étendue G (µm²)	Fiber size (µm)	Typical fiber NA	Rel. spot power²	Rel. spot brightness
10	10x/0.2	3.14	100	0.22	100%	100%
10	20x/0.4	12.57	200	0.22	400%	400%
8	50x/0.5	12.57	400	0.22	400%	625%
5	10x/0.2	0.79	50	0.1	25%	100%
5	20x/0.4	3.14	100	0.22	100%	400%
4	50x/0.5	3.14	200	0.22	100%	625%
4	50x/0.9	10.18	200	0.22	324%	2025%
4	100x/0.8	8.04	400	0.22	256%	1600%

Improvements

If the tube lens with focal length f can be swapped with a lens of half focal length f/2, setup size can be decreased. The overall magnification then also reduces by half to become 5x, while the illumination-side NA increases by a factor of 2 to become 0.04. Because of the reduced magnification, also the fiber (or light source) size needs to be reduced to 50µm to give the 10µm spot sought. Note that the typical NA of 0.1 for a 50µm fiber still is more than enough to fill the used NA of 0.04.



In terms of étendue, nothing has changed compared to the first setup:

$G = (\pi * 50\mu m^2) * 0.2^2 = (\pi * 25\mu m^2) * 0.04$ [2]

Thus, the spot will have the same brightness.

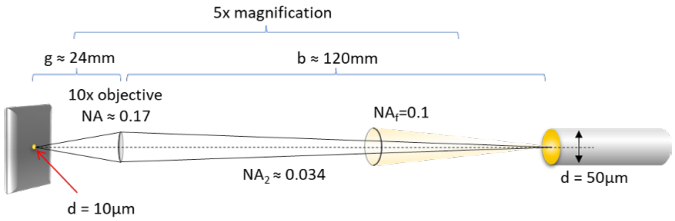
Instead of using the microscope-type setups above, finite imaging with the objective alone may be an easier solution. Although most objectives today are designed for infinite imaging and work with tube lenses, for our purpose of illumination finite imaging without a tube lens will work well.

Simply shifting the objective a bit further away from the sample would create an image of the spot in a finite distance. The other way around, this image plane would be the place to put the fiber end to create the spot. In this setup, the usable NA of the objective, and thus the étendue, is slightly decreased due to the longer working distance.

For a certain magnification M aimed at, the distances g and b are roughly given by:

$$g = \left(1 + \frac{1}{M}\right) * f \qquad b = (1 + M) * f$$

where f is the focal length of the objective.



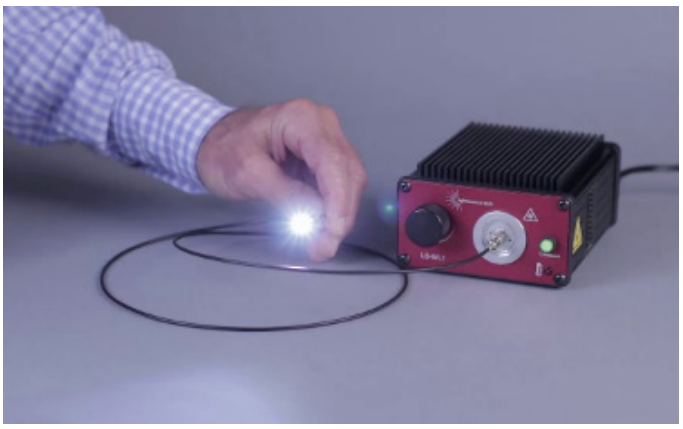
The focal length of the objective, if not known, may be easily calculated from its nominal magnification and the tube length standard t of the objective manufacturer:

$$t/f = M_{nom} \qquad f = t/M_{nom}$$

With t = 200, 180, 165 mm for Leica/Nikon, Olympus, Zeiss, a 10x objective of those manufacturers would thus have a focal length of f = 20, 18, 16.5 mm, resp.

A light source particularly useful for microscopic spot illumination is our LS-WL1. This compact fiber-coupled source provides extremely high luminance from small core optical fibers. The luminance of this special source, based on conversion of a laser spot into non-coherent "white" light, is orders of magnitude higher than with LEDs.

lightsource.tech will be happy to discuss your micro-spotlight project with you.



1 The LS-WL1, an ultra-bright fiber-coupled light source

[2] Based on constant fiber luminance regardless of diameter.
This is often the case if the primary light source coupled into the fiber is larger than the fiber diameter.

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