Technical Memo – For Public Release

Fiber Imaging, Working Distance and Spot Size

(Can you place a spot of any size at any working distance with any fiber as the source? No.)

Background:

It is common when working with fiber optics that the output face of the fiber optic itself may need to be removed from the site where the energy is required. But it is just as common for one to assume the energy coming out of the fiber is a beam or narrow column, rather than as a diverging cone which is reality. Once that is understood the next question is usually if it is possible to create a collimated beam or to image the fiber face and hence focus the energy at a particular size and distance from the fiber face?

The answer to the collimated beam question is contained in another Technical Memo entitled: Optical Invariance And The Idea of "Best Collimation"

The answer to imaging or focusing question is the basis of this Technical Memo.

To image or focus the output of a fiber, an optic or optical system is attached to the fiber output. Descriptions of these systems usually include the words "focuser" or "imager", and key characteristics of these systems are the size of the image, usually called "spot size", and the distance from the end of the optical system where that spot or image is achieved, usually called "working distance".

The key thing to know is that simple systems are usually the most efficient from the standpoint of energy throughput - often THE key consideration. Yet, simple systems may require some flexibility in the design.

In other words, to answer the parenthetic question in the title: "No. You can't get any spot size you want at any working distance with any fiber, UNLESS you are willing to throw energy away."

This is really just a combination of simple relationships that all must hold together.

The Thin Lens Formula:

The "thin lens formula" describes the relationship of the lens' focal length to the object distance, the distance the fiber is from that lens and the image distance, the distance that the image or spot is from the lens. The simple algebraic relationship is:

$$1/f = 1/s + 1/s' \qquad (1)$$

where f is the lens focal length; s is the object distance and s' is the image distance.

There are two other relationships that are important in a system like this are:

Magnification: $M = s'/s$ (2)

where s is the object size (or distance) and s′ is the image size (or distance);

Clear Aperture: $D = 2[s(\mathrm{TAN}(\mathrm{ARCSIN}(NA))]+d$ (3)

where D is the diameter of the circle of energy that the fiber will cast upon the lens; d is the diameter of the fiber; NA is the Numerical Aperture of the fiber; and s is the object distance or the distance of the fiber face from the principal plane of the lense.

Magnification is merely the ratio of the image size to the object size but is also a relationship between distances which is intuitively clean. If you want to make something bigger it needs to happen at a greater distance.

Clear Aperture is the question of if the energy emerging from the fiber face will over fill the lens or be partially blocked or stopped. For efficiency you want a lens of sufficient diameter such that depending upon where the fiber is placed the emerging energy will not grow so large as to not pass through the lens.

Complex optical systems are analyzed by looking at one lens at a time and determining the object and image locations as well as the aperture throughputs or efficiencies (again the tech memo on Optical Invariance dovetails here). In this case, the second lens uses the image of the first lens as the object for that lens and a new image is calculated. And then you use the image from the second lens as the object for the third, and so on.

Note: The thin lens formula is limited to exactly that, lenses which are thin which enables a simplification of complexity. Here we are neglecting effects from aberrations which are beyond the scope of this tech memo making assumptions allowing the use of the thin lens relationship.

Example:

You have a 9um fiber with a 0.14 NA and you want to image it at a working distance of 19mm and an image size or spot size of 35um.

First… the magnification given by (2) above yields M=3.89. This means that the image distance (s′) must be 3.89 X the object distance (s).

Now, the working distance is desired to be 19mm (approximately) but there is some flexibility there. The working distance is usually taken to be the distance from the front surface of the part itself, not necessarily the lens. And to protect the lens, it is often recessed into the part. So, one of the things to do to practically achieve a particular working distance might be to recess the lens further back into the housing.

Also, you must be aware that the image distance is taken from what is known as the principal plane of the lens which is buried within the lens and is therefore difficult to measure. This is also the plane in the lens where the Effective Focal Length (EFL) is defined. This plane is often estimated to be midway through the lens. For example, if the Center Thickness (CT) of the lens is 3mm, then the EFL will be 1.5mm into the lens from each side. Now, conveniently, lens manufacturers know that the EFL is an approximation that many designers find hard to deal with exactly, so they also provide what is known as the Back Focal Length (BFL), which happens to be an exact measurement taken from a known and measurable surface on the lens. The point here is to define a measurable point from which to adjust for a desired working (or image) distance.

For this example, if the working distance (WD) is desired to be 19mm then the image distance should probably be about 23mm (or longer) to allow the lens to be recessed and protected.

Let’s then assume that a particular lens has already been provided for this example. It is a 6mm diameter X 6mm EFL lens. If the actual WD is to be 19mm, forcing the actual image distance (s’) to be 23mm, and we already know that the magnification we want is 3.89, that means that the object distance must be 5.91mm (all by #2 above).

Notice that this is within the EFL (6mm) of the lens! This means that the image that will be created is actually a “virtual image” or an image on the wrong side of the lens. This is a bit abstract and there is no need to really get into it here, because we all know that the light isn’t going backwards except in the math, but the thing to take away is that there is no image creation where you want it.

The result of this analysis demands that you choose another lens, OR, that you modify your WD and/or spot size requirements. If you choose another lens then just insert the s and s’ value into (1) and find what focal length you need. In this case, that formula will return a focal length of 4.7mm. And you could look for a lens like that, but another funny thing about lenses is that when their focal length and diameter get close then you end up with a sphere. And two things happen…. One is that that pesky thing called aberrations start to become a significant issue because the lens will be so highly curved. The second problem is that you are stuck with a small diameter and therefore the light may over fill the lens or at least you’ll need to run the numbers from (3) above.

How to Solve the Problem:

The example above is a perfect example of how you may not get everything you want from optical systems when you have the requirement of maximum throughput while you constrain yourself by other harsh realities like working distance and spot size.

This is also a perfect example of how to use simple single lens calculations to find a lens that will work. You must just not ask for everything you think you want. Instead, ask for what you really need.

If we need a 35um spot size from system and we need a working distance of AT LEAST 19mm, remember, you can always recess the lens into the housing to produce the exact working distance you want, then run the calculations on these needs. You will find that a 6mm EFL X 6mm Diameter lens will produce a 35um image of a 9um, 0.14NA fiber at about 29mm if the object distance is set at 7.4mm!!

This employs a standard OTS lens, gives the lens plenty of protection (by recessing it), and keeps the optic big enough so that we are only using the central portion and thus avoiding aberrations.

Conclusions:

These are all simple equations, but very interesting to work through and manipulate to achieve your desired results.