Technical Memo – For Public Release

Optical Invariance And The Idea of "Best Collimation"

Background:

A very common desire, when working with fiber optics, is to want to modify the output of the fiber and the most common desire among all the ways you might modify the output is to create a beam. Most people call devices that create beams from the fiber output, "collimators". And many collimators are sold without anyone ever explaining that the only source that can be collimated by a lens is a theoretical point source (which no one uses) with a low angular field (which is likewise rare).

So how does one take light emerging from a fiber and collimate it?

The Fundamentals:

Optical Invariance establishes that the product of the object size times its angular field must equal the product of the image size times its angular field.

Simply put, the size of the "source" (which may be the fiber size) multiplied by the amount the energy emitted from the fiber diverges, has to be equivalent to the size of the "beam" multiplied by it's divergence.

"Size" may be interchanged with aperture and fiber diameter or beam or spot diameter, and "NA" can be interchanged with angular field or divergence here. Reduced to symbols and you can see the relationship is trivial but you must accept that this is a fundamental physical limit:

$h \times n = h' \times n'$ where h and h' represents the fiber and the beam size respectively and n and n' represent the angular fields or NAs of the fiber and beam.

What this means is that if you take something of any size which has a large angular field and you want to reduce that angular field (collimated light theoretically has NO angle or at least a very small angle) then you must increase the size. Period.

This is the Law of Optical Invariance and it is a Law of Nature. It cannot be "gotten around" by using expensive ray tracing or optical design software, or "really good" lenses.

It is also important here to note that we are note concerned with imaging or image quality, what we are typically concerned with here is maximum energy through the system.

Example:

A) You have a 1mm bundle of fibers with a 0.22 NA and you want to collimate the output into a 10mm beam… what kind of lens would be needed and what will be the half angle of the "collimated" beam?

First… you must pick a lens with a focal length such that the energy emerging from the fiber will be captured by the lense. That is, the energy emitted by the bundle will pass through the clear aperture of the

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lense. This means that to create a 10mm beam you would need a lens with a focal length equal to the set back of the bundle necessary to create a 10mm illuminated circle at the principal plane of the lense you are going to select.

That is calculated using trigonometry where : $\tan(\sin^{-1}(NA_f)) = ((B/2) - r) / f$

But for small angles the left side of this equation can be reduced to and the equation can be rearranged to:

$f = ((B/2) - r) / NA_f$

Where f is the focal length of the lens; B is the desired Beam Diameter; r is the radius of the fiber; and NA_f is the Numerical Aperture of the fiber.

Once you know the focal length you can pick a diameter with a clear aperture larger than the desired beam.

In our example you need an f of about 19.9mm. So a 12mm diameter lens with a 20mm focal length should work OK.

But now, what is going to be the half angle of divergence of the resultant beam?

To do this we go back to optical invariance… $h \times n = h' \times n'$

where h and h′ represents the fiber and the beam size respectively and n and n′ represent the angular fields or NAs of the fiber and beam.

For our example, we'll solve for n′ (the beam NA) and since the beam diameter happens to be 10 times larger than the fiber bundle diameter, then the NA of the beam will be 10 times smaller than that of the fiber or…. 0.022 NA, and since…

$\sin^{-1}(NA)$ = Half Angle of the Beam in degrees, the beam has a half angle of divergence of 1.26 degrees.

Comment:

The example above is why terms like "Quasi-Collimated" or "Reduced Divergence" are used and we avoid the term collimation. We are trying not to mislead anyone into believing they are going to get a beam out of their fiber or bundle of fibers. There is always some divergence (even in laser beams)!

The thing to remember is that increasing the NA and/or the diameter of the fiber or fiber bundle, OR, decreasing the beam diameter ALL serve to increase the half angle of divergence (create a less collimated beam). The reverse is also true. If you want to drive down the half angle of divergence of a collimated beam from a fiber then you must decrease the NA and/or the diameter of the fiber or fiber bundle, OR, increase the beam diameter.

If you have more optical energy than you need, you can also "throw away" excess light as a way around a variety of optical "problems". Optical Invariance still holds of course, but you are simply "stopping" or filtering your way into selecting a portion of the energy available.

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