Technical Memo – For Public Release

Fiber Optic Tapers and Laser Damage Threshold

(Limitations of refractive waveguides for concentrating energy.)

Background:

We are often confronted with the challenge of trying to get a large diameter beams of light into a relatively small optical fiber or with trying to couple a high power laser into a relatively small core optical fiber. In the first case, the issue is completely controlled by the Law of Optical Invariance. In the second case, we have the added challenge of the laser damage threshold of the optical fiber itself.

One method frequently considered to handle these challenges is to use a fiber optic taper. Tapers fall into two basic categories - drawn and formed.

Drawn tapers are created in the fiber draw tower and are basically made by establishing either the large or small diameter and then speeding up or slowing down the draw speed so the fiber gets smaller or larger in a controlled fashion. This usually results in a taper that occurs over a length of several meters.

Formed tapers are made by taking a length of fiber, or preform waveguide, and heating it. As the fiber or waveguide starts to soften, and by moving the heating zone and /or the fiber or waveguide in a controlled fashion, you can create a taper shape. The heating can be done by a torch or a laser or resistance element. Formed tapers tend to be very short (on the order of 5-15mm).

For tapers described above the practical taper ratio limit is ~5:1. If larger taper ratios are required then either technique can be used in conjunction with fusing components together. Fusing does work but it does add the potential for losses at the fusion joints so it must be done very carefully for high power applications.

Once you have the taper, you now are faced with the actual use of that taper to act as a waveguide. As mentioned above, the first challenge is raised by the Law of Optical Invariance. Optical Invariance says that the product of the object (source) aperture times its angular field (NA) must equal the product of the image (output) aperture times its angular field (NA).

Reduced to a formula, you can see the relationship as follows:

$$h \times n = h' \times n'$$

where h and h' represents the object and the image size, respectively, and n and n' represent the angular fields of the object and image, respectively. For our purposes,

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you can replace the angular field with the effective NA of the taper input and the calculated NA of the fiber output, respectively.

This means that if you want to take a large diameter input and couple it effectively into a smaller core diameter output fiber through a taper (demagnification), then you MUST use a smaller input angular field (or NA).

Another way to look at this is based on the calculation of NA. NA can be determined in two ways. The first method is based on the refractive indices of the core and the cladding and is determined in the following formula:

$NA=\sqrt{[(R_{co})^2-(R_{cl})^2]}$; where Ri_{co} is the refractive index of the core, and R_{cl} is the refractive index of the cladding.

The second method is based on the acceptance angle of the fiber. The inverse sine of the half angle of the fiber is also the NA:

$NA=\sin^{-1}(ß)$; where ß is the acceptance half angle of the fiber.

While these two methods will give identical results in a normal optical fiber, you can quickly see how changing the angle of the core/clad interface (as occurs in a taper) will give completely different results. With the taper, the refractive indices of the core and cladding have not changed, but the angle at which the incoming light will intersect the core/clad interface has changed based on the taper angle which is related to the taper length and the ratio of input diameter to the output diameter.

Simply put, in a down taper going from a diameter of 3mm to a fiber diameter of 1mm is a 3:1 change. If the 1mm fiber has a 0.22NA +/-0.02, which means it could be as low as 0.18 NA, then you must inject light at 0.18/3, or an NA of 0.06. Likewise if you have a 0.22NA fiber with the NA filled and you put an up taper on it as described here, the taper will service to reduce the NA of the energy by a factor of 3.

Example:

A) You have a 1mm LED source with an f/1.00 output (0.45NA). Can you capture all of that light through a 5:1 taper into a single 200µm fiber with an NA of 0.22?

No!! You will lose all of the energy that enters the 1000µm taper input that is at an angle >2.522° (half angle). The Law of Optical Invariance says...

$1.0 * n = 0.2 * 0.22$ Solving for n yields n= 0.044 (the effective NA of the taper input). And 0.044NA is 2.522 degrees.

This should be intuitively obvious based on the geometry of the taper. The initial "bounce" of the light will be at a core/clad interface that is no longer parallel to the main axis of the fiber. Each successive "bounce" in the taper region will increase that angle. Very quickly, the angle will exceed the 12.7° half angle that is capable of being "bounced" in a 0.22NA fiber (the calculated NA based on the core and cladding refractive indices). In other words, any light with an input half angle >2.522° will be lost due to exceeding the critical angle while still in the taper region.

It is this simple geometric explanation that is often not considered when trying to use a taper as a "light funnel."

The bottom line is that if you want to shrink the size by a factor of 5 you must reduce the input NA by a factor of 5 as well. Unfortunately, if the input NA is larger than the reduced acceptance NA, then you will lose all the light in the larger angle rays.

How much do you lose? It depends on the modal energy distribution of the injected light. Typically, the loss can be estimated, by making assumptions about perfect energy distribution, by taking a ratio of the square of the Tangents of the angles. Expressed using NA of the fiber you would get:

$[\text{Tan}\ (\text{Sin-1}\ (NA_{\text{taper input}})]^2 / [\text{Tan}\ (\text{Sin-1}\ (NA_{\text{fiber output}})]^2$

For the example above, the coupling will only be ~4% assuming a uniform (Lambertian) energy distribution throughout all angles or modes, which can often NOT be assumed, but that is a topic for another Technical Memo. It is important to note that this transmission efficiency is about what could be expected if you had simply butted the 200µm fiber directly up to the LED. In other words, the addition of the taper effectively did nothing more than add a lot of cost to your assembly. Depending on the angular energy distribution, you might even get better coupling with the 200µm fiber butted directly up to the LED!

Laser Damage Threshold:

To further complicate the matter, in the situation where high power laser energy is involved, you have to account for the damage threshold of the optical fiber. The entire topic of laser damage threshold (LDT) is extremely hard to pin down. Not that this topic hasn't been researched at length but lasers rarely have nicely uniform, homogenous beam profiles. Thus, the total energy across a spot might be well within the theoretical LDT of the fiber but a spike or "hot spot" might result in localized energy densities far in excess of the allowable LDT.

As a general rule of thumb, an optical fiber can accept a pulsed laser input (within the wavelength region of 400nm-2000nm) with an energy density of ~1.5GW/cm^2. If the laser is a CW laser within that same wavelength region, the allowable energy density is more than 3 orders of magnitude less, or 0.15MW/cm^2.

The damage mechanism in both cases is slightly different. For the pulsed laser, the primary damage mechanism will be photonic shock. For the CW laser, the primary damage mechanism will either be plasma formation on flaws at the input surface or

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thermal management at the initial attachment point of the fiber in the assembly.

As with all "rules of thumb," exceptions can be made. In most cases, the exceptions will result in a lower LDT – rarely can you exceed these guidelines. And when it seems you may have exceeded these guidelines what you may have actually done is spread the energy out in time because of the increase in the optical path taken by the rays that have had significant interaction with the taper.

Where tapers can work in high power laser coupling is when they are used simply to reduce the energy density on the glass surface, so, as large format input or output devices, sometimes can beam expansion, but again, that is beyond the scope of the this memo.

Final Notes:

1. Let's assume that you have considered all of the points above and that you have one of the few applications where a taper is appropriate. The biggest question we get at that point is "Where do I place the focal point or beam waist in relation to the input surface?" In virtually every case, the most appropriate location for the focal point or beam waist is within the bulk of the fiber core. In other words, the input beam should still be converging at the surface. This is due to two factors. First, the bulk LDT of the fiber is far higher than the surface LDT (perhaps 5-10x). Second, the location of the beam waist within the bulk of the fiber will move the first "bounce" further into the taper region and will reduce the final angle of the higher order modes.
2. Another common question relates to spot size at the surface. The answer to this question is related to the degree of control you can exercise over the spot diameter and absolute location. In most cases, you would want a spot diameter of ~80% of the input core diameter. As the input core gets larger and your ability to control the size and position of the spot gets greater, you can increase the spot size relative to the input core. It is a rare application where you will want to have the spot diameter >90% of the input core diameter. In any event, the spot size at the surface is the dimension you will use to calculate the energy density for that surface.
3. Can a taper be used "backwards?" Yes. In that case, the taper will be acting as a Numerical Aperture Reducer and will perform the same function as a partial collimator. For example, if you start with a 200μm core and expand the beam through a 5:1 taper, the output will have a 1000μm exit beam diameter and an NA of 0.044 (44mRad divergence).
4. In all cases it is always a recommendation that the user perform a suitable patent search to ensure that infringement issues are no issue.