Shaped Fiber Tips for Medical and Industrial Applications

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ABSTRACT

Shaped fiber tips are machined or sculpted fiber ends which are formed using the glass from the fiber with no additional glass material. The tips are fabricated through either mechanical or laser machining processes. The tips are very useful in medical and industrial applications which require high power laser delivery (material or tissue cutting), even light distribution over a broad area (tissue ablation or photodynamic therapy), modified beam divergence or spot size (materials processing and communications links), or optical power redirection from the axis of the fiber in areas with small space restrictions (tissue ablation or perforations inside the human body). Descriptions of various shaped tips are provided, with concentration on tapered tips. The tapered tip is the most commonly used. The primary objective of this study was to measure the optical loss of such tapers vs. taper length, input (launch) numerical aperture (NA), and fiber diameter. The tapers fabricated and analyzed were 2:1 tapers using 0.22 NA fibers with 200, 400, and 500 um cores. The optical loss at 633nm for fibers with a 0.22 NA was measured to be 5.9dB (25% transmission) for a fully filled input NA and 0.8 dB (83% transmission) for a 0.12 input NA. The taper loss was found to depend strongly on input NA, but be relatively independent of taper length and fiber diameter. An optical modeling ray trace program was used to analyze the taper performance and validate the actual measurements. The modeling analysis will be a useful tool in design of tapers as well as other shaped fiber tips.

Keywords: shaped fiber tips, laser power delivery, tapers, optical loss, 0.22 NA optical fibers

1. INTRODUCTION

Shaped fiber tips have been successfully used in medical and industrial applications for many years. A variety of tip shapes and sizes can be used to reshape the beam pattern of the light entering or exiting an optical fiber. The tips themselves are machined or sculpted on the fiber end using the glass material of the fiber itself. No additional glass material is added in the process. The process can be either mechanical or thermal in nature, the latter being primarily but not limited to laser machining.

The shapes are made from the glass of the fiber, resulting in no interface between the shape and the fiber itself. Thus there are no coupling losses between the shape and the fiber. Furthermore, having no interface there is no potential for contamination that might exist if the shape were bonded by fusion splicing to the fiber. This serves to reduce optical losses and dramatically increase the mechanical strength and durability of the device.

Many different shaped tips have been successfully fabricated. Figure 1[1] illustrates several types and provides brief descriptions of their functions. Some of the more useful tip shapes are described in more detail below:

Lenses: A variety of lenses can be fabricated such as concave, convex, and spherical (ball). These tips are useful for modifying beam divergence and spot size. The shaped lenses are used for improved coupling from laser diodes to fibers, reduction in Fresnel losses, reducing or increasing the depth of focus, increasing or decreasing output spot size and collimating or decollimating light. Applications are very broad, from low power communications links to high power industrial lasers. The lenses can be combined with other shaped tips as well, such as a convex lens on the end of a taper.

Diffusers: Diffusers are generally used on the distal end as a means of redirecting and scattering the optical power in an even 360° cylindrical output along the length of the tip. This is typically performed by machining grooves or threads into the glass of the fiber deep enough to extract and scatter light traveling through the fiber core. The scattered light bathes an area with the optical power, making it useful for applications such as photodynamic therapy or tissue ablation

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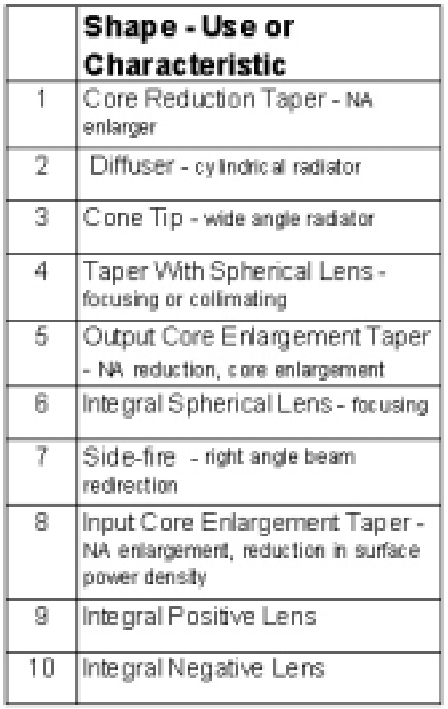
(e.g. prostate reduction and urology procedures). The diffuser tip, having the rather deep grooves, often has a silica cap placed over it for additional mechanical durability and protection from contamination.

Side-Fire: The side-fire consists typically of a 45° angle machined into the end of the fiber on the distal end. Optical power impinging on the angle is redirected 90 degrees from the fiber axis. This is particularly useful in invasive surgical procedures where the optical power needs to be redirected in a very confined space, such as tissue ablation, cutting and perforations (e.g. trans-myocardial revascularization (TMR)).

Tapers: Tapers can be used on either the proximal (input) or distal (output) ends, and can be either an enlargement or a reduction of the fiber core. The most common shaped tip used in medical and industrial applications is the enlarged core taper on the proximal fiber end. This type of taper allows a reduction in power density at the fiber endface and increases the size of the fiber core "target" for the incoming laser power. The tapers do not act as light "funnels", but actually change the NA of the light as it travels down the taper, losing light that exceeds the critical angle for total internal reflection in the optical fiber. [2] [3]

Proximal end tapers are the most common shaped fiber tips used in medical and industrial applications, where high power density yet small flexible fiber sizes are desirable. Several key questions and concerns were frequently asked regarding the optical loss in the tapers. In particular was the optical loss expected in a taper vs. the geometry of the taper (taper ratio, length of taper) and the geometry (diameter) of the fiber. It was often believed that the longer the taper length, the lower the loss experienced, leading to tapers a meter or greater in length! Tapers of this length are difficult and expensive to make and, as will be shown, typically not necessary. Another key question was the effect of input NA on optical loss.

Being the most common shaped tip, this type of taper is the main focus of this paper with additional description and test results presented below in Section 3. The key objectives of this study were to characterize and measure the optical loss in a fiber taper vs. fiber diameter, taper length, and input NA. An optical ray trace model was developed and compared to the actual measured results. The measured results and validation model will serve as a valuable tool in the design of tapers as well as other shaped tip types for a variety of application conditions.



	Shape - Use or Characteristic
1	Core Reduction Taper - NA enlarger
2	Diffuser - cylindrical radiator
3	Cone Tip - wide angle radiator
4	Taper With Spherical Lens - focusing or collimating
5	Output Core Enlargement Taper - NA reduction, core enlargement
6	Integral Spherical Lens - focusing
7	Side-fire - right angle beam redirection
8	Input Core Enlargement Taper - NA enlargement, reduction in surface power density
9	Integral Positive Lens
10	Integral Negative Lens

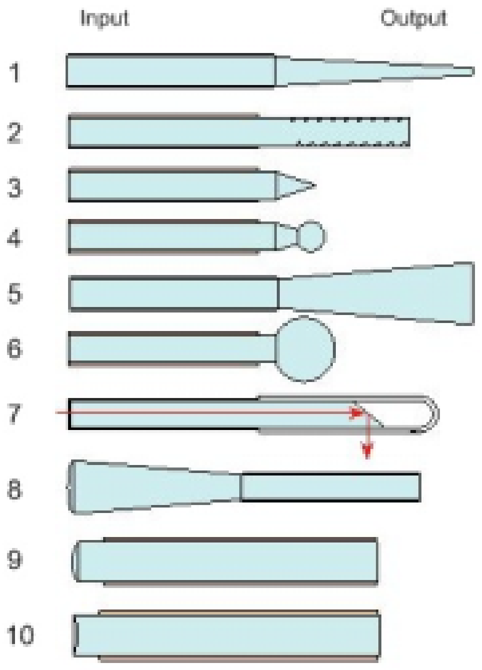


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Figure 1: Various Shaped Fiber Tip Diagrams

Figure 2: Picture of Shaped Fiber Tips

2. EXPERIMENTAL PROCEDURE

Figure 3 below shows the test setup for taper loss measurements. HeNe laser light (633nm) is launched into a large core fiber with a core size equal to the large end of the taper and with an NA similar to the fiber in the taper (in this case 0.22). This source fiber has a polished ferrule on the end for splicing to the test taper. The splice occurs in a silica sleeve, which aligns the source fiber to the large end of the taper. Index matching gel eliminates Fresnel reflections in the splice. The distal end of the taper is aligned to a power meter with a large area silicon detector. To determine the loss of the taper, the taper power is compared to a similar measurement through a non-tapered fiber pigtail with core diameter similar to the large end of the taper and the launch fiber. The difference between the two measurements is recorded in dB’s, which can easily be converted to percent throughput.

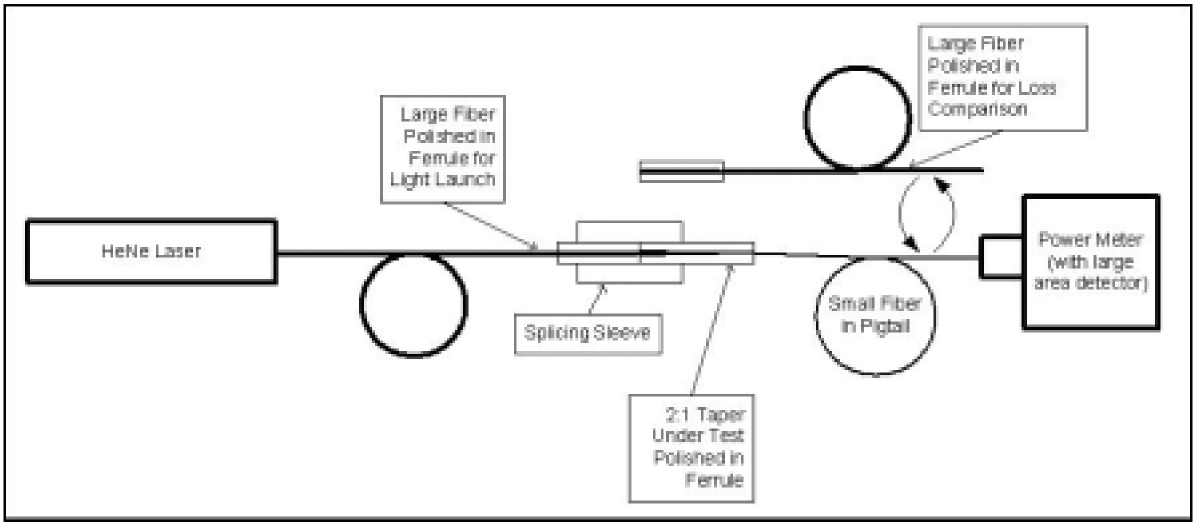

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Figure 3: Optical Loss Measurement Setup

A total of 30 tapers were tested using this procedure and setup. This included 3 each of 10 different fiber diameters and taper length combinations. Figure 4 below is a summary of sample configurations tested. The length of the pigtail on each tapered or non-tapered sample was not controlled or expected to affect results and was typically 1 to 3 meters. Two NA values were tested. For the first set of tests, the source fiber NA was overfilled by the HeNe laser, presenting a light beam to the taper that was equal to the 0.22NA of the fiber and equal in diameter to the large end of the taper. This provided a very uniform light distribution among the various fiber modes. The second set of tests used a lower (approximately 0.12) NA. For the 200/400µm tapers, the source used was a lower NA fiber which provided an excellent uniformly distributed 0.12NA. For the remaining taper sizes, a low NA fiber source was not available, and a lower NA was approximated by mechanically blocking the higher order modes at the HeNe laser interface. Unfortunately, this did not provide quite as uniform of a mode distribution and will be seen to impact the results somewhat.

Fiber Core Diameter	Taper Core Diameter	Taper Ratio	Source Fiber Diameter	Taper Length	Quantity
200µm	400µm	2:1	400µm	5mm	3
200µm	400µm	2:1	400µm	10mm	3
200µm	400µm	2:1	400µm	15mm	3
200µm	400µm	2:1	400µm	20mm	3
400µm	800µm	2:1	800µm	8mm	3
400µm	800µm	2:1	800µm	12mm	3
400µm	800µm	2:1	800µm	16mm	3
500µm	1000µm	2:1	1000µm	8mm	3
500µm	1000µm	2:1	1000µm	12mm	3
500µm	1000µm	2:1	1000µm	16mm	3

Figure 4: Summary of Sample Configurations Tested

3. RESULTS AND DISCUSSION

3.1 Shaped Tip Operational Parameters

The operational parameters first depend on whether the shaped tip will be used as an input or an output device. Obviously the launch conditions will be most critical when the tip is used on the proximal (input) end and output conditions more critical when used on the distal (output) end. The key operational parameters of concern are summarized on the table below:

Launch Conditions (proximal)	Output Conditions (distal)
Input NA	Input NA
Spot Size	Spot Size
Power Density	Power Density
Modal Distribution	Modal Distribution
Alignment	

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3.2 Taper Design and Performance

Taper shaped tips are the most commonly used. The key concerns regarding the use of such tapers are optical loss vs. taper and fiber geometry, input NA, and the transformation in NA over the length of the taper. Figure 5 below is a diagram showing some important taper parameters. The most significant of the physical parameters is the ratio of the diameter of the taper end to the diameter of the base fiber. Despite the funnel-like appearance of the taper, the well known optical concept of conservation of brightness prevents the taper from behaving as a magical light “funnel” to force light from a large fiber into a small fiber. There is a price to be paid in transmission through the taper, and this price is paid in numerical aperture. As light transmits through a sufficiently long taper, the following equation applies:

$$\frac{NA_{OUT}}{NA_{IN}} = \frac{d_{IN}}{d_{OUT}}$$

Therefore, if one applies an NA to the end of the taper that would be acceptable for the base fiber, the light throughput would be inversely proportional to the square of the taper ratio. For a 2:1 taper, the throughput would be 25%, exactly the same as butting a large fiber directly to the small fiber with no taper at all! However, if the source applied to the large end of the taper has an NA of ½ that of the base fiber, then perfect transmission can be expected through a perfect taper. Of course, the NA of the light in the fiber will now be twice the original source.

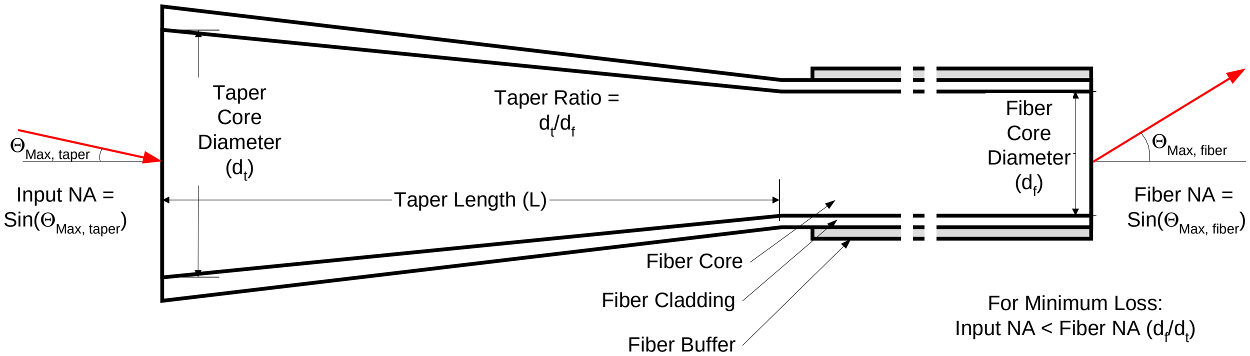

Figure 5: Diagram of Taper Parameters

3.3 Taper Loss vs. Input NA and Fiber Diameter

Loss tests were run on the 30 samples as described above to determine how well actual tapers perform compared to the theory of perfect tapers. The loss as a function of input NA is shown below in Figures 6-8 for the 3 fiber diameters tested.

It becomes immediately obvious that there is a large sensitivity to input NA. For the high input NA tests on the 200/400 and 400/800 tapers, the transmission is very nearly 25%, just as would be expected. For the case of the 500/1000 tapers, the transmission is 35%, noticeably more than expected. This was later discovered to be due to the 500µm fiber having an NA near the high end of the tolerance (0.233NA) and the 1000µm launch fiber having an NA near the low end of the tolerance (0.20NA). So, as expected, a slightly lower input NA relative to the allowed output NA gives better results.

The low NA tests, as expected, provide transmission much closer to 100%. For the 200/400 and the 400/800 tapers, the transmission with a 0.12NA input is typically 80% to 90%. Since this 0.12NA is very near to the 0.11NA that would be

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expected to give perfect transmission, it is not surprising the see transmission in this high range. The 500/1000 taper results were not quite as good (70% to 75%), likely due to difficulties in achieving a good uniform source profile with a 0.12NA.

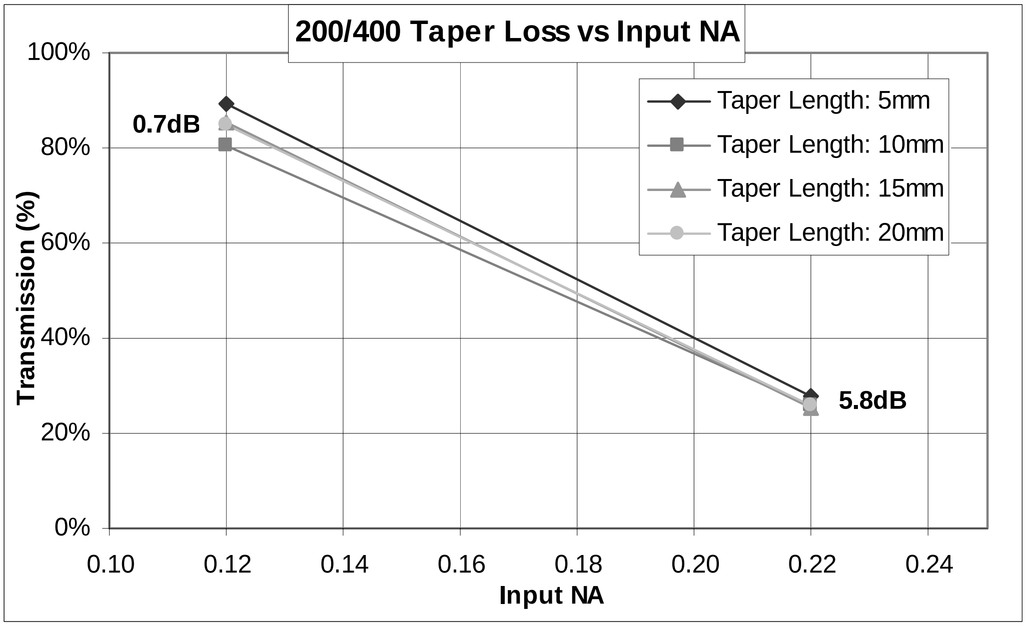

Figure 6: Loss vs Input NA for 200µm/400µm Tapers (Measured Data)

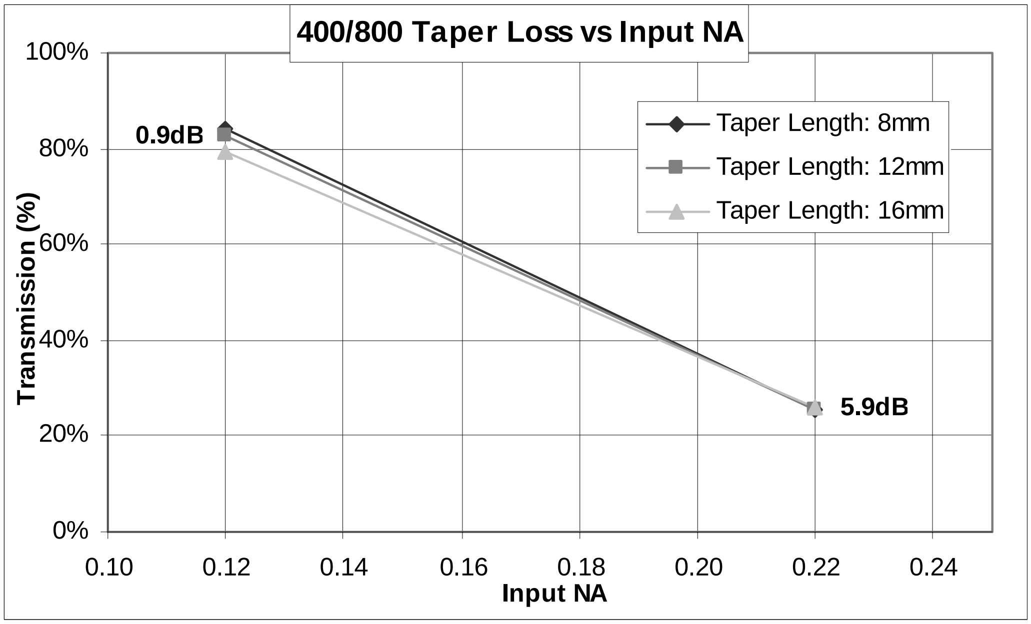

Figure 7: Loss vs Input NA for 400µm/800µm Tapers (Measured Data)

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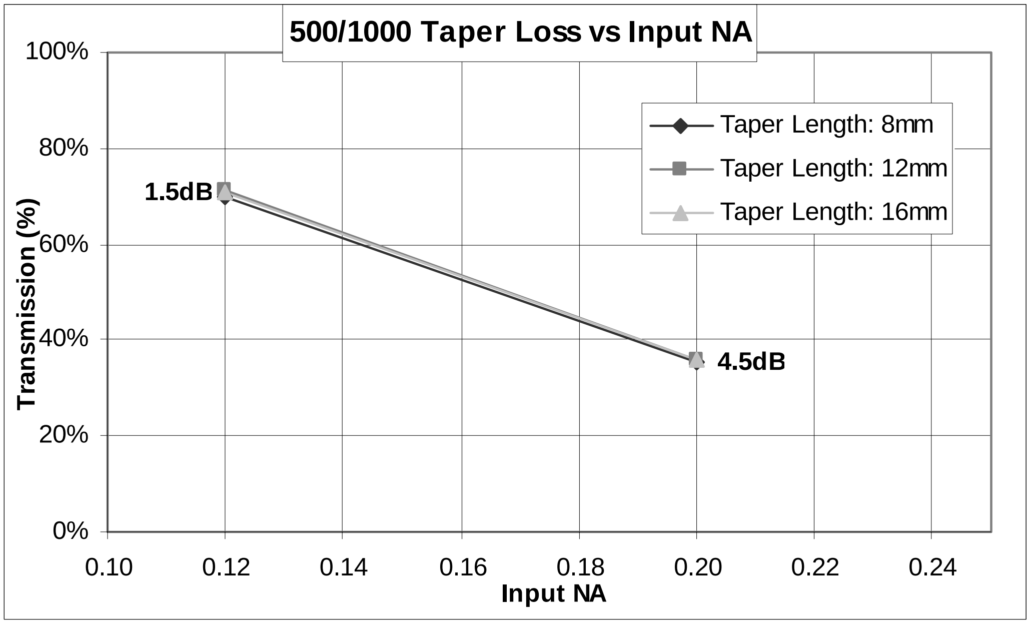

Figure 8: Loss vs Input NA for 500µm/1000µm Tapers (Measured Data)

3.4 Taper Loss vs. Taper Length and Fiber Diameter

Figures 9 and 10 show the same data as a function of taper length. There is no significant variation in loss through the taper as a function of taper length through our range of typically produced tapers. This lack of sensitivity is not surprising with the high NA source, since even a length of 0mm (a direct large to small fiber splice with no taper) would produce a 25% throughput. However, we can also see that good throughput is obtained with a low NA through a large range of lengths. Again, the 500/1000 taper results were not quite as good (70% to 75%), likely due to difficulties in achieving a good uniform source profile with a 0.12NA.

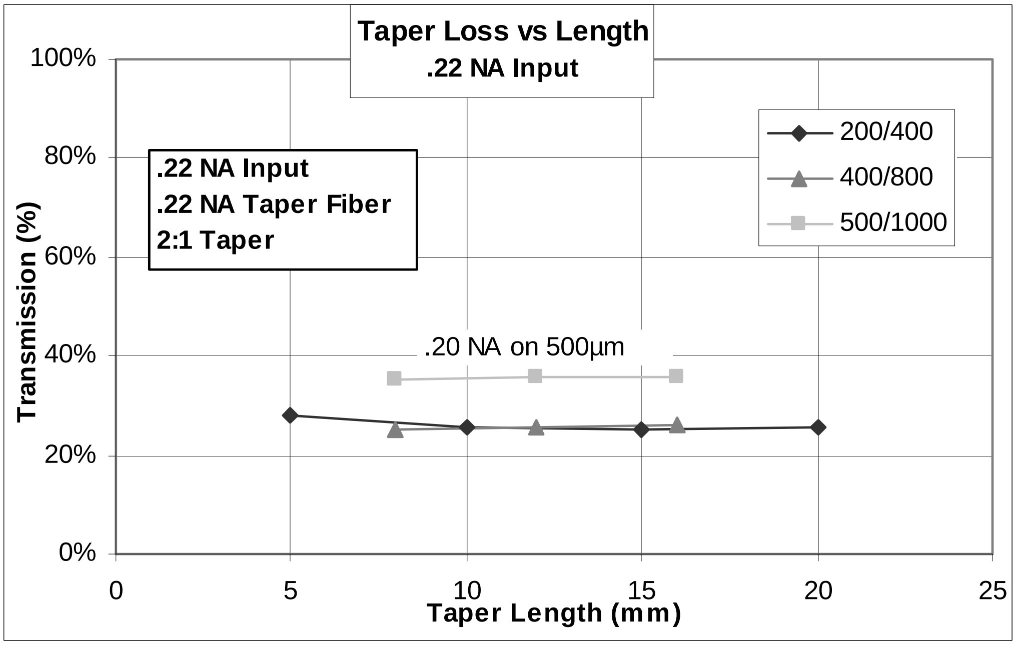

Figure 9: Loss vs Taper Length for .22NA Light Launch (Measured Data)

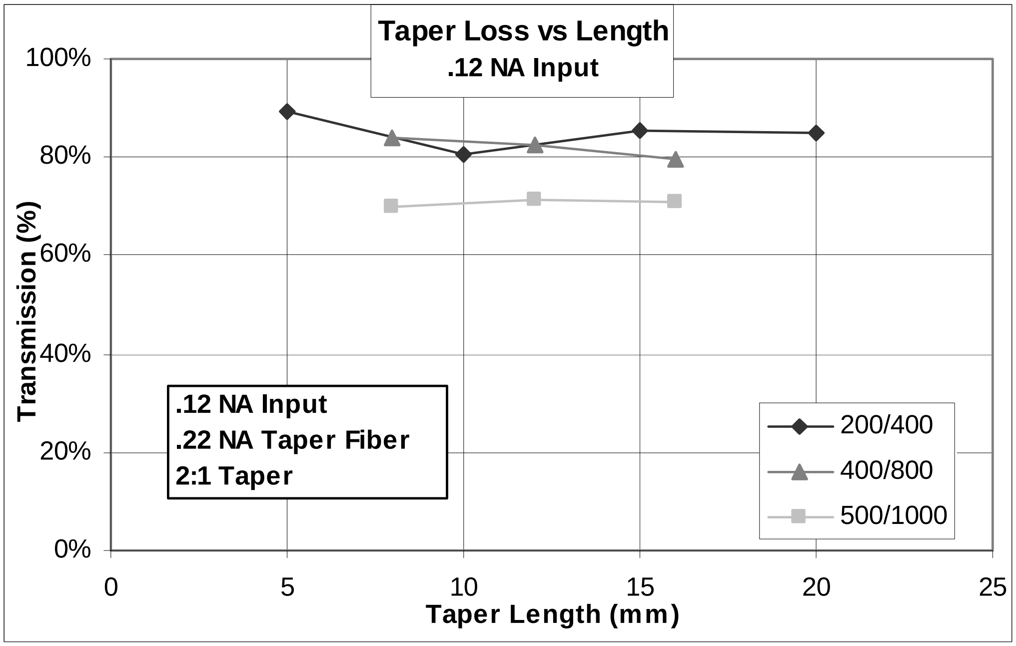

Figure 10: Loss vs Taper Length for .12NA Light Launch (Measured Data)

3.5 Optical Modeling of Taper

In order to perform a independent validation of the experimental results discussed above, ray trace models of representative tapers were constructed using Tracepro Opto-Mechanical Modeling software [4] from Lambda Research Corp. An added benefit of the optical model is that it can be adapted for use in evaluating many other shaped fiber tip configurations.

The models consisted of cylindrical silica core fibers surrounded by a cladding layer with a material optimized for a 0.22NA fiber. Around the cladding material was placed an absorbing buffer layer, which closely represents the polyimide buffer used in Polymicro Technologies optical fiber. In an effort to match the lab test set-up, an input fiber with a 400µm core diameter was coupled into a 200µm core fiber using varied lengths of linear tapers (10, 15, 20 and 1000 mm). For each of the taper lengths, the input NA of the source light was varied from 0.22NA (total fill) down to .10NA. The output loss was then calculated based on the number of rays traced which successfully propagated out of the 200µm fiber onto a reference plane 50 mm away. This analysis was repeated for the other fiber sizes as well.

3.6. Modeled Optical Loss vs. Input NA

The result of the modeled loss calculations was found to closely match those of the measured values. This is shown in Figure 11, where the 10, 15, 20, and 1000 mm taper results are plotted. In the figure, results from the measured tapers is plotted and show good agreement. One interesting result from the model was that the case of the extremely long taper, 1000 mm, did not show any detectable improvement in loss characteristics. This reinforces the conclusion that the loss is highly insensitive to taper length.

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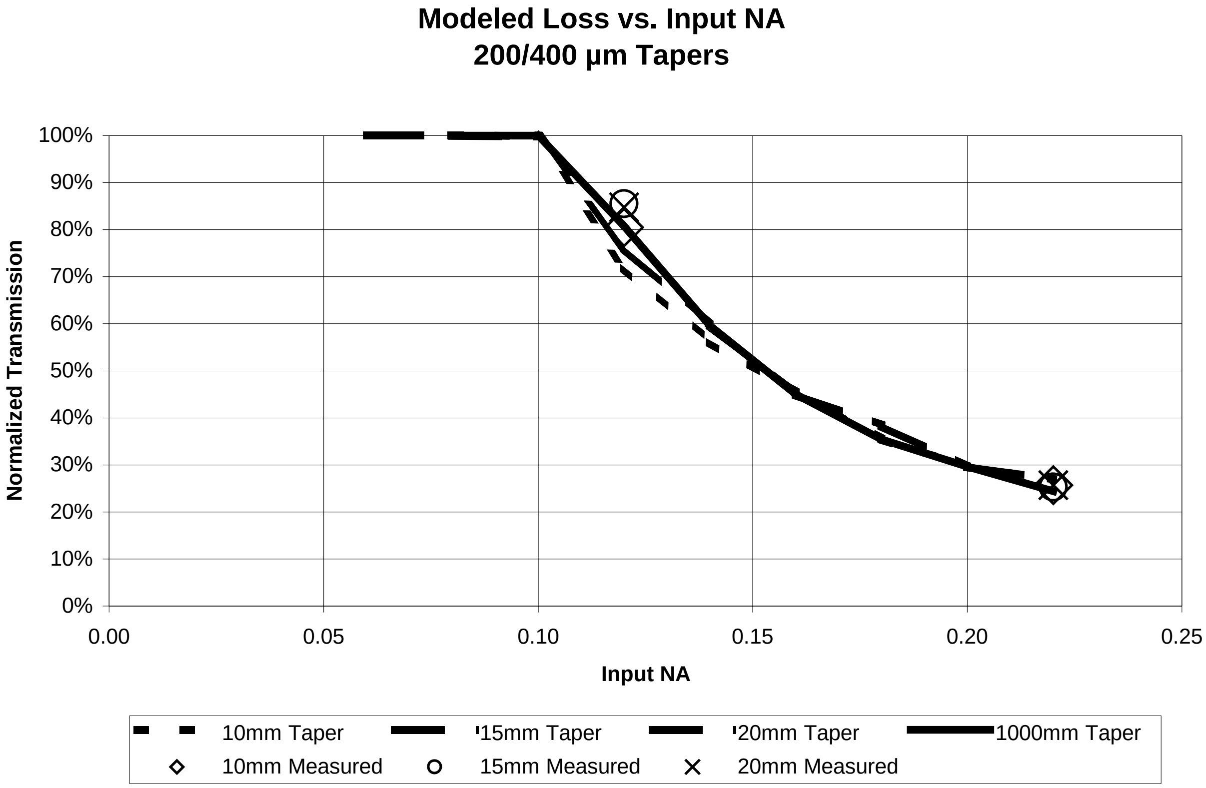

Figure 11: Loss vs Input NA for Different Taper Lengths in The Optical Model (With Measured Data Overlaid)

3.7. Model Far Field Output

The loss calculations were performed by comparing the initial number of rays traced from the source (4681) to the number of rays which successfully propagated through the taper and smaller optical fiber, eventually passing through a reference plane on the output. The analysis software outputs a radiance map based on the output rays incident on the reference plane. This map includes a listing of the incident rays. An example of the radiance map is shown in Figure 12. The ringing evident in the plot is a function of the finite point source used in the model, along with the non-infinite number of rays traced. With a longer taper length, the ringing is much less pronounced, as shown in Figure 13, which shows the radiance profile with a 1000 mm taper and .22 NA source input. This demonstrates that the longer taper will likely have a more uniform output pattern, even if the effective loss characteristics are relatively unchanged. While in the case of a reasonably uniform input beam the ringing should not be an issue in actual use. Ringing may need to be considered in the case of a significantly non-uniform input beam, where a longer input taper may be of interest.

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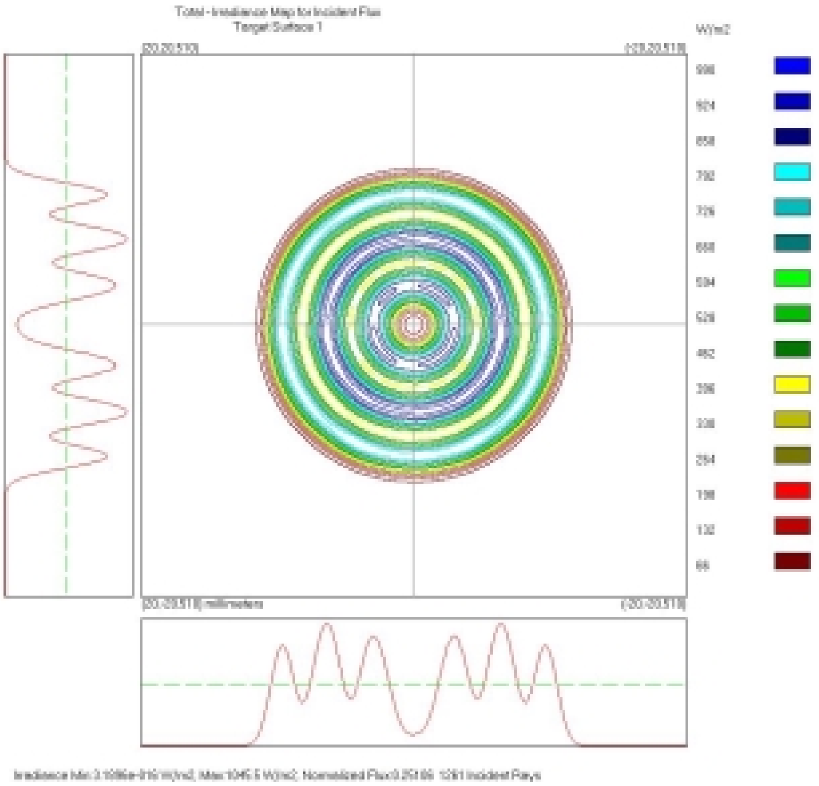

Figure 12: Example Far Field Radiance Map at Output Reference Plane (Short 10mm taper with .22 NA Input)

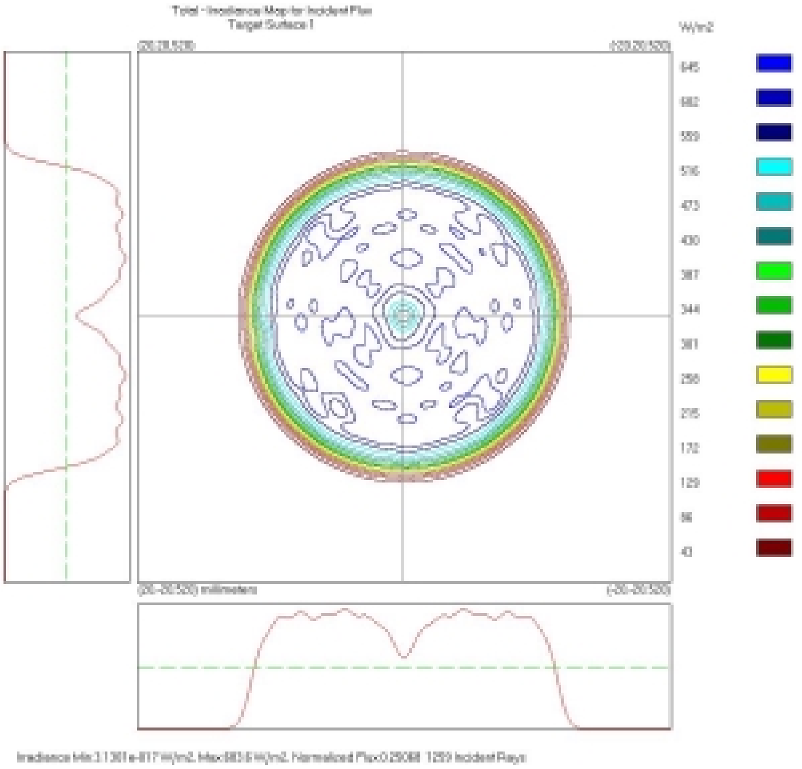

Figure 13: Example Far Field Radiance Map at Output Reference Plane (Long 1000mm taper with .22 NA Input)

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4. CONCLUSIONS

Shaped fiber tips are useful devices for medical and industrial applications which require high power laser delivery (material or tissue cutting), even light distribution over a broad area (tissue ablation or photodynamic therapy), modified beam divergence or spot size (materials processing and communications links), or optical power redirection from the axis of the fiber in area with small space restrictions (tissue ablation or perforations inside the human body).

The most commonly used shaped fiber tip is the taper. Tapers allow a reduction in power density at the fiber endface and increase the size of the fiber core “target” for the incoming laser power. The tapers do not act as light “funnels”, but actually change the NA of the light as it travels down the taper, losing light that exceeds the critical angle for total internal reflection in the optical fiber.

Actual optical loss in a taper fiber tip was measured vs. input NA, taper length, and fiber diameter. The tapers fabricated and analyzed were 2:1 tapers using 0.22 NA fibers with 200, 400, and 500 um cores. The optical loss at 633nm for fibers were measured to be 5.9dB (25% transmission) for a fully filled (0.22) input NA and 0.8 dB (83% transmission) for a 0.12 input NA. The taper loss was found to depend strongly on input NA, but be relatively independent of taper length and fiber diameter.

An optical modeling ray trace program was used to analyze the taper performance and validated the actual measurements. The model agreed with the general trends of loss being strongly dependent on input NA and relatively independent of fiber diameter and taper length, even for very long length (>1m) tapers. For launch conditions which utilize significantly non-uniform beam profiles, the model does predict that a longer taper will help to smooth the beam profile of the output power.

The modeling analysis will be a useful tool in design of tapers as well as other shaped fiber tips.

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