Optical fiber designs for beam shaping

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ABSTRACT

A large number of power delivery applications for optical fibers require beams with very specific output intensity profiles; in particular applications that require a focused high intensity beam typically image the near field (NF) intensity distribution at the exit surface of an optical fiber. In this work we discuss optical fiber designs that shape the output beam profile to more closely correspond to what is required in many real world industrial applications. Specifically we present results demonstrating the ability to transform Gaussian beams to shapes required for industrial applications and how that relates to system parameters such as beam product parameter (BPP) values. We report on the how different waveguide structures perform in the NF and show results on how to achieve flat-top with circular outputs.

Keywords: Fiber Laser, Flat-Top Fiber, Top-Hat Profile, Square Core Fiber, Shaped Core Fiber, Power Delivery Fiber, Beam Shaping, Mode Conversion, Laser Welding, Laser Scribing

1. INTRODUCTION

Recently, fiber lasers have increased in vast numbers, replacing more traditional solid state systems. Fiber lasers are used for marking, cutting and welding applications that range from tens of watts to multi KW power levels. The output of the lasers is typically Gaussian, which is suitable for many applications [1]. Gaussian beams are suitable for applications such as cutting where a central high intensity region is desired. However, certain applications such as welding, photolithography and processing of semiconductor wafers require a more uniform intensity profile. Flat-top, or top hat, profiles produce a more uniform intensity, which is desirable for these applications. Existing beam delivery fibers transmit the Gaussian beam from the source to the work piece without significantly altering its characteristics. A flat-top output can be achieved, post fiber beam delivery, through the use of lenses, optics and beam shapers, but these are all very sensitive to alignment and can be costly [2]. Due to the sensitivity and alignment issues that can incur with these options a more rugged solution is needed.

The ideal solution is to create an all-fiber system that delivers flat-top output without the use of additional optics or beam shaping devices. Previous work has been performed on multi-mode (MM) shaped core fibers, such as square and rectangular core fibers, in which a flat-top output has been achieved [3, 4]. However, the NF intensity profiles maintain the same shape as the core which has limited applications. Even more, no design rules on how to use these fibers in current laser systems have been reported.

Flat-top outputs have also been reported in the literature through modifications of standard single mode (SM) fibers. There have been a few papers discussing the use of long period gratings (LPG) that produce flat-top output with the use of commercially available fibers [5, 6]. Single mode fibers with abrupt tapers have also been reported to achieve flat-top outputs [7]. Both of these options can be wavelength dependent and have limited power handling due to small core diameters in fundamentally single mode fibers. Other areas of experimentation have included work on SM micro structured fibers and concave tip etched fibers [8] [9]. Both have the ability to produce flat-top output, but the output of the concave tip etched fibers is extremely sensitive to the etch depth and there is a reduced surface damage threshold due to

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the etching. The SM fiber solutions all would have additional losses associated with them when using inputs that are not low NA, such as 0.04.

Currently, there are some solutions for niche applications, such as SM lasers or shaped fibers to produce flat-top, but there is no fiber solution that transforms a Gaussian beam to a flat-top output, while maintaining a circular spot and meeting the BPP requirement of the system. This paper will discuss the work that has been done in understanding how certain fibers produce flat-top intensity profiles in the NF and will offer design rules to use them. Specifically, in the case of square core fibers, we report on how the input conditions affect the output and how these fibers can be used in current beam shaping applications where a specific BPP is required. Also, we report on the status of development of a beam delivery fiber that can provide a flat-top output with a circular spot. The ultimate goal of this work is to develop an all fiber solution that is able to achieve a circular flat-top output, with low losses, enabling multi kW power delivery economically. (double check these commas)

2. BEAM SHAPING WITH STANDARD BEAM DELIVERY FIBERS

Standard round beam delivery fibers are ubiquitous for delivering high powers from the source to the work piece over tens of meter distances. The authors wanted to explore the feasibility of achieving flat-top outputs in existing fibers. Flat-top intensity can be achieved by exciting higher order modes in the fiber, which increases the divergence of the beam, and hence the BPP. Excitation of higher order modes can be achieved by misaligning the input into the fiber. The degree of radial and axial misalignment needed to achieve a flat-top intensity profile was evaluated to determine the feasibility of this approach. The setup for this experiment is shown in Figure 1. The1.06 µm light was launched into a 200 µm core standard beam delivery fiber. First, the light was focused on the end face of the fiber under test (FUT). Using a lens, the focal spot was incrementally moved in a radial direction (X-direction in Figure 2) from the center to the periphery of the fiber end face. Figure 2A shows the results of the test setup as the lens was misaligned radially from 0 to 45 µm. As the misalignment increased, there was little change in the NF intensity profiles indicating that a radial misalignment of even half the radial distance was not adequate to achieve flat-top intensity profile in a standard bema delivery fiber. Axial misalignment (Z-direction in Figure 2) was then examined by moving the focal spot both away from the end face of the fiber and into the fiber. Moving the focal spot to a position up to 500 µm outside the fiber end face had little change on the NF intensity profiles. Similarly, focusing the beam 500 µm inside the fiber in itself didn't flatten the NF intensity profile. Finally, radial misalignment with the spot focused in the fiber was evaluated. The results displayed in figure 2B show that the misalignment 500 µm inside the fiber along with radial misalignment can produce a flat-top output. A near flat-top intensity profile was achieved with the focal spot 500 µm inside the fiber and radial misalignment of 55 µm. Considering that this is a 200 µm diameter core fiber, the misalignment of over half the radial distance required to produce the flat-top output is quite significant. The alignment needs to be very precise and the large misalignment can cause a significant loss in power and is not recommended for practical applications. Since misalignment of the input beam into standard beam delivery fibers to achieve flat-top intensity profiles is not practical, the remainder of the work focused on creating a fiber solution by utilizing shaped and circular cores to achieve flat-top output.

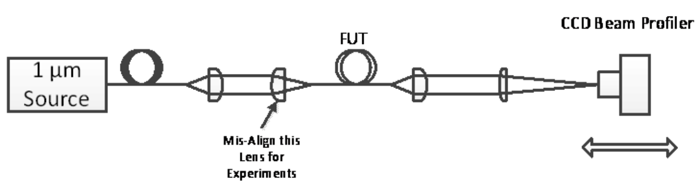


Figure 1 Schematic diagram of the experimental set-up for radial and axial misalignment of the input beam.

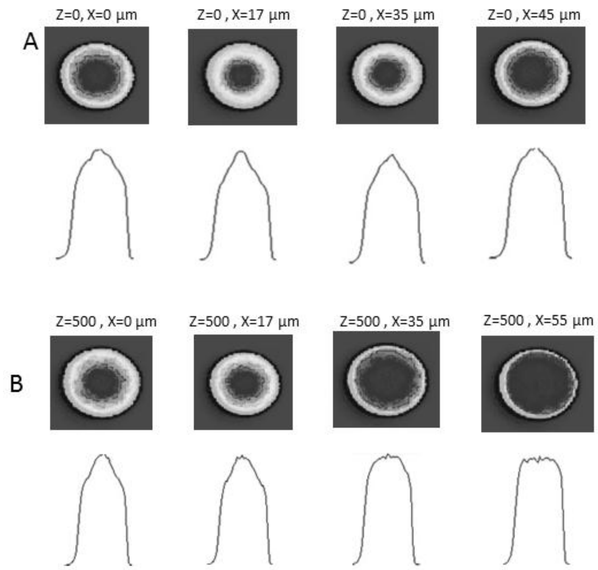
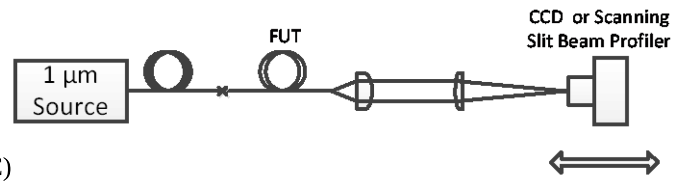


Figure 2 Near field images and intensity profiles for 200 micron core fiber misalignment experiment. (A) Misalignment in the radial direction (X-direction) only. (B) Misalignment in both the axial (Z-direction), and radial direction.

3. EXPERIMENTAL SETUP

Fibers that are used in laser systems have certain properties that need to be characterized. Geometrical tolerances and low loss spectral attenuations are important characteristics for many fibers. Measurements to characterize the beam quality for fibers used in beam delivery are vital. To properly perform this task, the applications of the fiber must be considered. Marking applications deliver a specific type of spot on the work piece which is governed by the fibers NF intensity profile, since the markings will be the same as the imaged NF profile. When considering unique beam shaping applications, such as flat-top, the way in which the fiber transforms the initial signal from the source needs to be quantified. Measuring the output divergence of the fiber shows how the initial light maintains the source NA or if the fiber induces an increase in the output NA (beam divergence) due to additional higher order mode excitation. An increase in the divergence from the source will excite more modes and make the profile flatter. Standard M^2 devices quantify how close a beam is to a perfect Gaussian output. These measurements are typically performed on SM lasers, but systems that are multimode still require characterization. Many end users specify the BPP on the output end of the system, which can be a Gaussian or flat-top beam. Measuring the divergence, near field intensity profiles and BPP is needed to completely characterize the beam delivery fiber for a laser system that requires a flat-top output.

The schematics for the 3 test setups are shown in Figure 3. The fiber under test (FUT) was spliced onto the 1.06 µm source, which was either a SM source (0.04 NA, 25 µm spot) or a multimode source (0.10 NA with either a 25 or 50 µm core). The 3 different launch conditions were selected to mimic a range of commercially available industrial laser sources. Best practices were utilized to ensure that all fibers had a cleave angle of <1°, and splice losses between the source and the FUT were minimized to <0.10 dB. Figure 3A shows the setup to obtain the NF image of a fiber. A focusing lens was used in order to image the NF onto the TaperCamD beam profiling system which was mounted onto a motorized stage. This captured both the NF image and the NF intensity profile.



C)

Figure 3 A. Schematic of near field image setup. B. Schematic of fiber divergence measurement setup. C. Setup for characterizing beam parameter product. (you used periods here, but in other figures, you used parenthesis

The fiber divergence setup is shown in Figure 3B. The measurement was performed by measuring the far-field diameter of the fiber at various axial positions using a TaperCamD beam profiling system and DataRay software. The divergence and output NA were then calculated by taking the slope of the change in position verses the change in diameter.

The measurement of the BPP is shown in Figure 3C. This test was performed using a TaperCamD beam profiling system and a second moment method (D4σ).

Both circular and square core fibers were tested as part of this investigation as shown in Table 1. There were 2 circular fibers tested. The first was a commercially available beam delivery pure silica core fiber of 50 µm, with a fluorine down-doped NA of 0.22 and a silica cladding extending to 360 µm. This was the baseline beam delivery fiber for this paper and is used regularly in industrial laser applications. The second fiber was fabricated via the modified chemical vapor deposition process (MCVD). The core refractive index profile (RIP) was modified from a step index profile in order to induce additional mode mixing and was drawn to a 40 µm core diameter.

Three different pure silica square core fibers were manufactured and characterized. These were drawn to have core diameters of 66, 80 & 100 µm in the flat to flat direction and had a fluorine down-doped annulus around the square core with a B/A of 1.4 to achieve an NA of 0.22. Different sizes were fabricated to see the effect of core diameter on the NF intensity profiles, the divergence and the BPP.

Table 1 List of Fibers Under Test

Fiber Core Diameter	Fiber NA	Waveguide Structure
50	0.22	Round
66	0.22	Square
80	0.22	Square
100	0.22	Square
40	0.15	Round

4. RESULTS AND DISCUSSION

4.1 Efficacy of square core fibers in achieving flat-top intensity profiles

The effectiveness of a fiber in achieving a flat-top output can be determined by observing the intensity profile in the NF. The NF intensity profile will show if the fiber has transformed the input beam from a Gaussian into a different output. The three square core fibers were tested and compared to the baseline round fiber using 2 different launch conditions over a fixed length of 10 meters for each of the fibers. Figure 4A displays the NF images and corresponding intensity profiles of the 4 fibers tested with a 0.04 NA launch. As expected, the baseline round fiber displays a Gaussian output in the NF. The square core fibers have a profile that is approaching more of a flat-top distribution. The NF images also show that the square cores produce better mode mixing than the baseline fiber. More is also learned through observing the NF images as the square core diameter increases from 66 to 100 µm. The images become more filled as the core size increases and the profiles themselves become flatter. The mechanism for this is not completely understood, and will be further investigated.

Not all beam delivery fibers use single mode lasers sources with a 0.04 NA as an input, so higher NA launch conditions were explored. The 0.10 NA launch, typical of some industrial lasers, was also used and tested on the same 4 fibers as above, with the results shown in Figure 4B. The baseline fiber again has a Gaussian output and the NF image is more stable with excitation of higher order modes (HOM) due to the increased launch. The square core fibers also displayed a similar outcome with the NF images looking more filled and stable and the intensity profiles becoming more flat-top. For the same square core dimension, the higher NA launch has a greater effect on producing a flat-top output since more modes are excited at the launch and more coupling to higher order modes is achieved over a 10 meter length. Conversely, as the launch NA decreases, larger square core diameters are needed in order to obtain a more uniform flat-top output. These statements are valid when considering a fixed length of fiber. An increase in the length of the fiber may also promote further higher order mode coupling for a given square core dimension, and was therefore investigated.

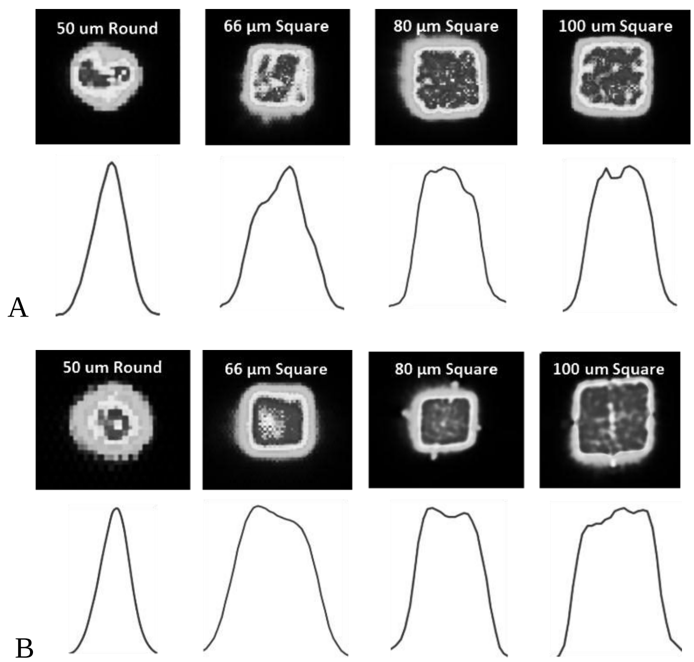


Figure 4 A) Near field image and intensity profiles for the 50 micron round core baseline fiber with the 66, 80 & 100 micron square core fibers for A) 0.04 NA launch. B) 0.10 NA launch. All samples were 10 meters in length. .

4.2 Effect of length on NF intensity & beam divergence

As discussed in section 4.1, small square core fibers are not effective in transforming low NA (0.04) Gaussian beams from single mode laser sources into flat-top profiles. However, depending on the specifics of the application, smaller core sizes may also be a requirement. In these situations the smaller square cores need to be able to produce a more stable and uniform output to be most useful. For the purposes of the initial experimentation, the length of fiber was chosen to be 10 meters since that is a reasonable length for beam delivery. The effect of using longer lengths to achieve a stable, flat-top output was investigated.

It has already been discussed that the 66 µm square core fiber with the 0.04 NA launch was least effective in producing a stable, uniform flat-top output. Therefore, this fiber was chosen to see if a longer length would improve the output. Figure 5 shows the NF images and intensity profiles for 10 & 40 meters of fiber. The 40 meter fiber appears to have provided additional mode mixing than the 10 meter sample resulting in a flatter NF intensity profile. The additional mode mixing should manifest itself in higher divergence. Divergence measurements for different lengths of fiber were therefore conducted to quantify the mode mixing.

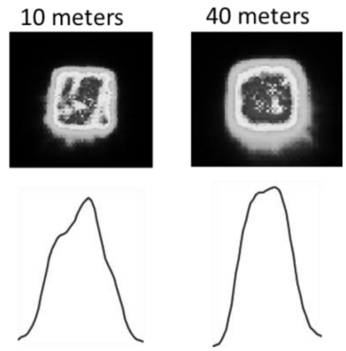
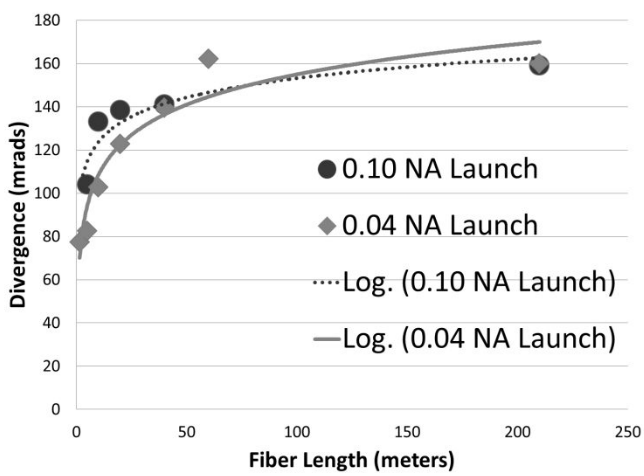


Figure 5 Near field image and intensity profiles for the 66 micron core square fiber at 10 & 40 meters in length, tested with a 0.04 NA launch.

Divergence measurements were made for various lengths of a 66 μm square core fiber with a 0.04 NA input as it was cutback from 210 meters to 1.3 meters and the results are presented in Figure 6. The divergence ranges from 78 mrad at 1.3 meters up to 160 mrad at 210 meters length. As the length increases, the fiber divergence also increases. The data shows that the 40 meters of fiber has a divergence of 140 mrad, which is 25% greater than that of the 10 meter fiber. Longer lengths of square core fiber increase the flatness of the profile. This study also showed that the divergence did level off at a certain length. For the 0.04 NA launch this occurred at about 60 meters, at which point there was no additional increase in divergence up to 210 meters. A similar study on the effect of fiber length on beam divergence was performed for the 0.10 NA launch. It can be observed from Figure 6 that higher divergence values are achieved at shorter lengths when a 0.1 NA launch is used instead of a 0.04 NA launch. It is also notable that while the maximum divergence is achieved at a shorter length of fiber, the value of the maximum divergence achievable is independent of the source NA. The result indicates that the maximum divergence achievable is solely dependent on the shape of the fiber. These results indicates that significantly longer lengths of beam delivery fiber are needed for single mode laser sources compared to multimode laser sources to achieve the maximum mode coupling and the flattest intensity profile.



[KT1]

Figure 6 The effect of fiber length on divergence for 66 um square core fiber with 0.04 NA launch and 0.10 NA launch.

4.3 Effect of launch conditions on divergence and BPP

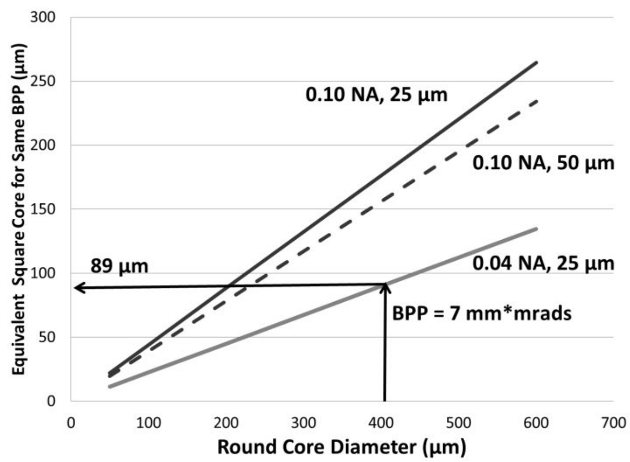
Understanding the output divergence and how the fiber behaves in the NF are very important parameters for beam shaping applications in industrial lasers, but does not necessarily tell the complete story. We earlier indicated that certain systems can require a specific BPP out of the beam delivery fiber based on the optics and working distances of the systems. The BPP is a product of the fiber core radius and the divergence. Since the divergence changes with input conditions it is of key importance to study these differences to better comprehend the impact on BPP to be able to utilize these fibers in systems.

Three different launch conditions were explored: 0.04 NA with 25 µm cores, 0.10 NA with 25 µm cores & 0.10 NA with 50 µm cores. The output NA was measured for 10 meter lengths of the baseline fiber and the 3 square core fibers, with the results being shown in Table 2. The source NA was maintained for all 3 launch conditions for the baseline fiber, corresponding to no additional mode-mixing within the fiber for the fixed 10 meter length. The square core fibers were tested with the same launch conditions and the output NA increased from that of the source in each case. Interestingly, the output NA for each launch condition was very similar for each of the 3 core diameters. The data shows that the output NA is independent of the square core diameter and changes only with the launch condition.

Table 2 Effect of Launch Conditions on Output Fiber NA[KT2]

Source Properties		Output Fiber NA (10 meters)				AVG output NA
Launch NA	Spot Size	50 µm Round	66 µm Square	80 µm Square	100 µm Square	
0.04 NA	25 um	0.036	0.104	0.117	0.113	0.111
0.10 NA	25 um	0.091	0.131	0.135	0.125	0.130
0.10 NA	50 um	0.091	0.148	0.155	0.142	0.148

The fact that the fiber output NA is the same for all the square core diameters simplifies how these fibers can be utilized for beam shaping applications. A simple methodology may be followed to determine the square core fiber that can replace an existing round core fiber within an existing laser system while maintaining the BPP. It is tempting to replace a round fiber with a certain core diameter with a square core having the same diagonal length. Since the BPP is a product of the core size and the divergence, the increase in divergence achieved with a square fiber has to be compensated with a decrease in square core dimension to preserve the BPP. Figure 7 shows a plot of the equivalent square core dimension that can to be used for a given round core fiber diameter in order to maintain the same BPP while achieving a flat-top intensity profile. There are 3 lines, one for each of the specific launch conditions tested, ranging from 50 to 600 µm round core diameters as that covers the typical range for beam delivery fibers. Using the data in figure 7, the square core size required to achieve flat-top output while preserving the current BPP can be predicted. The example displayed in Figure 7 shows that a laser system with a 400 µm core output and a 0.04 NA input would have a BPP of 7 mm*mrad. The square core diameter needed to have the same BPP would be 89 um flat-flat. This large decrease in core size is required to offset the increase in divergence from 36 mrad in the round fiber to 111 mrad in the square core fiber. A similar approach can be used for determining the equivalent square core fiber size for 0.1 NA launch. Since the divergence changes with length for a given square fiber, a fairly precise BPP may be achieved by tailoring the length of the beam delivery fiber. These results show that square core fibers can be used in place of standard beam delivery fibers for transforming Gaussian beams to flat-top outputs, while adhering to BPP requirements of the system by following simple design rules. The only limitation of using square core fibers is that the near field image, and hence the spot on the work piece, is square shaped. While a square shaped spot is desirable in some applications, the need for round shaped spots is more widespread. Hence, creating a fiber that produces a circular spot and flat-top output is still the requirement for the majority of applications.



[KT3]

Figure 7 Plot of the equivalent square core diameter required to replace a round core diameter (for 10 meters) to achieve a flat top intensity profile while maintaining the same BPP. The core diameter for the square cores is a measurement from the flat-flat section of the square. The BPP is calculated based on the diagonal length of the square core as it's the longest length. The three lines displayed are based on the 3 different launch conditions explored.

4.4 Fiber designs to achieve flat-top outputs while maintaining a circular spot

Non-circular shaped cores aid mode coupling to higher order modes and help in transforming Gaussian beams to flat-top profiles. If a circular spot is needed, this approach cannot be utilized. Higher order mode coupling can also be achieved by modifying the index profile from a pure step index profile used in standard beam delivery fibers. We investigated refractive index profiles that would promote coupling of lower order modes to higher order modes. Figure 8 shows the RIP of a typical 50 µm step index fiber. The figure also shows a 40 µm core fiber with a modified RIP for comparison. The modifications to the RIP were designed with the intention of forcing the power from the central region of the Gaussian beam to the outer edges of the core to achieve a flatter intensity profile. Since the modified index profile attempts to couple power to higher order modes, and hence increase the divergence, a 40 µm core size was chosen to maintain the BPP of the baseline 50 µm round fiber.

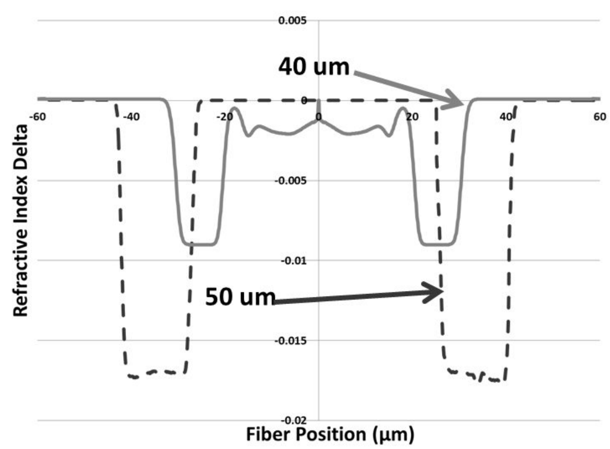


Figure 8 Comparison of the refractive index profiles of a standard 50 micron round beam delivery fiber to a 40 micron core fiber with a modified index profile designed to induce a flat-top output.

The fibers with step index and modified index profiles were tested with both 0.04 NA and 0.10 NA sources. The SM 0.04 NA launch for each of these fibers produced similar BPPs and NF intensity profiles, which were Gaussian in shape, indicating that the index profile modification was not adequate to transform a SM beam to a flat-top output. As the launch NA increased to 0.10, the baseline fiber with a step index profile maintained a Gaussian output. However, the 40 μm fiber with the modified RIP produced an output that exhibited some ability to produce more flat-top behavior, as shown in Figure 9. The NF intensity image retained its circular shape and excited additional modes over the baseline fiber. As the fiber length increased from 10 to 230 meters in length, the NF image and intensity profile displayed a modest improvement in the uniform flat-top intensity profile as shown in Figure 9. The result indicates the feasibility of using modified index profiles for beam shaping applications while retaining circular spots on the work piece. Further investigations into optimal index profiles that will yield flat-top intensity profiles at practical lengths are underway and will be reported in the future.

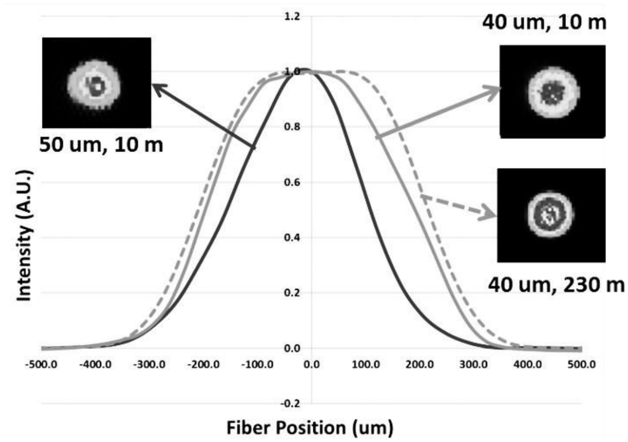


Figure 9 The near field intensity profiles & images for 50 micron beam delivery fiber and the 40 micron core fiber with modified RIP

5. CONCLUSION

The development of beam shaping fibers is a significant area of interest for industrial laser applications. End users have tried to use current beam delivery fibers as a way to obtain flat-top profiles. This is very difficult and has not been shown to occur with SM and MM NA launches under 0.10. Axial and radial misalignment can produce flat-top in standard beam delivery fibers; however, this is not a practical solution. A more rugged and robust option is to have a passive fiber solution. We have reported on the characterization of all glass square core optical fibers. The square core fibers are effective in achieving flat-top output. The change in the divergence is dependent on the input conditions, specifically the source NA and spot size, and the length of fiber that is deployed. The data also shows the output divergence is not a function of the square core fiber diameter. A simple design rule is provided to determine the square core fiber needed to achieve a flat-top output while preserving the BPP. These options serve a small percentage of applications due to the square shaped spots on the work piece. The feasibility of using modified refractive index profiles to achieve flat-top output while retaining circular shaped spots is demonstrated. Further work is needed to optimize the refractive index profiles for efficient beam shaping for operational deployment.

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