Characterizing Single Mode Lensed Fibers

THORLABS APPLICATION NOTE

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INTRODUCTION

Lensed single-mode optical fibers can be used to enhance coupling efficiency in certain specific optical systems, including photonic integrated circuits (PICs), solid-state quantum light sources, high-speed detectors, endomicroscopic imaging, and other sensing applications such as optical probes used for optical coherence tomography (OCT). In space-constrained systems, a common approach is to butt-couple a cleaved optical fiber directly to a component. However, when the component is smaller than the core of the optical fiber (typically ~9 µm), a core size mismatch can lead to significant signal loss. Additionally, if the component is not in direct contact with the fiber, coupling efficiency is further reduced due to the divergent nature of the light exiting the fiber and the longitudinal offset between the component and the fiber. Lensing the optical fiber addresses both issues by enabling focused spot sizes as small as 2 µm at a working distance laterally offset from the fiber tip. These smaller spot sizes and increased working distances (Figure 1) also greatly benefit high-speed detection where a smaller sensing area leads to faster response times.

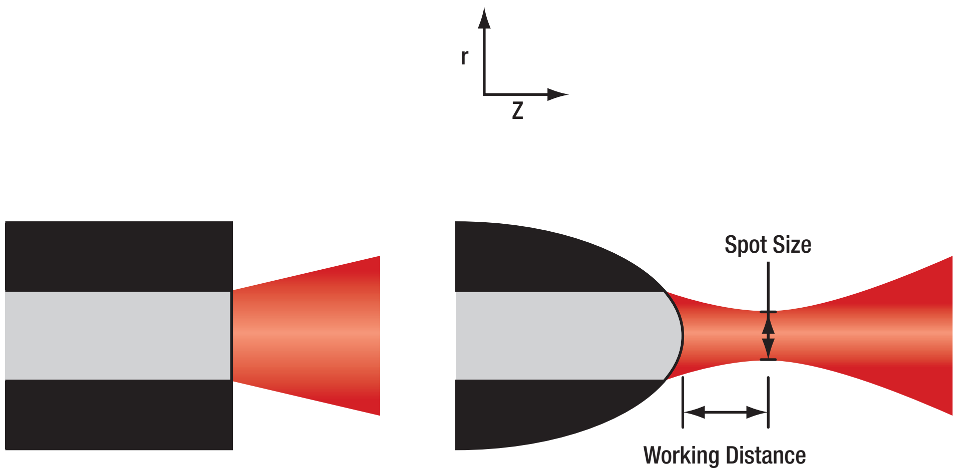


Figure 1: Schematic comparison of a flat-cleaved fiber tip, which emits a diverging beam, and a lensed fiber tip, which brings the emitted beam to a focused spot at a working distance from the tip. The following discussion will use the coordinate system shown here, in which r is the transverse distance and Z is the distance along the optic axis.

Several different approaches can be used to manufacture lensed fibers. These include polishing, micromachining, end capping with graded index fiber, or forming a rounded tip on the fiber using heat. It is also possible to make lensed fibers where the end is polished into a chisel point to obtain an elliptical light output. In this Application Note, we describe lensed fibers produced using heat which have a uniformly rounded radius of curvature and a circular light output.

Regardless of how the lens is formed, the key performance parameters for single mode lensed fibers are their focused spot size and working distance. These are constrained by the physics of diffraction; for instance, it is fundamentally not possible to realize spot sizes smaller than a micron in this geometry. Within these constraints, a range of focused spot sizes and working distances can be realized by altering the geometry of the lensed tip.

The spot size of a single mode beam exiting a fiber can be modeled using a Gaussian distribution. As shown in Figure 2, the width of this Gaussian can be defined by several equally valid metrics, e.g. FWHM and $1/e^2$. In the following discussion, we will define the profile edge of the beam as the point where the intensity falls to $1/e^2$ times the peak intensity.

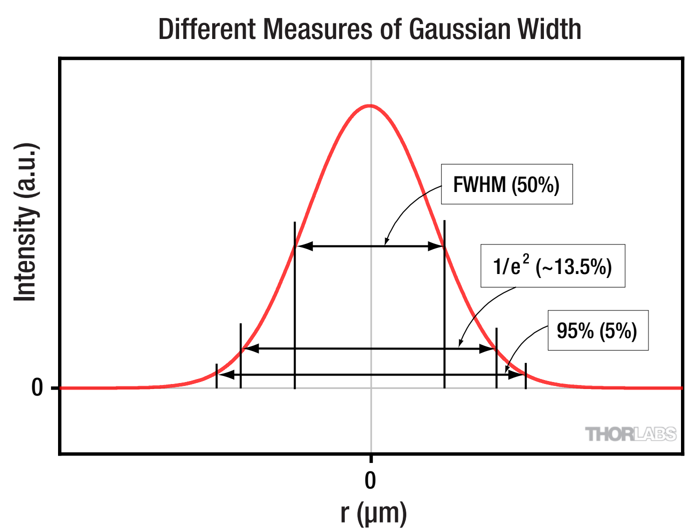


Figure 2: An ideal Gaussian spot profile, along with some common measures of its width.

Note that a beam does not become smaller when using the FWHM definition of beam width. There is just less of the total power encircled within the circumference bounded by the 50% peak intensity criteria than the $1/e^2$ (~13.5%) of peak intensity criteria. Table 1 shows conversion factors among some common definitions of beam width.

Beam characterization is a common requirement in all fields utilizing collimated or focused lasers, and a variety of approaches are used to measure spot size. These include scanning slits or scanning knife edges; power measurements through mechanical pinholes or on photodiodes of known area; and direct beam imaging using a camera.

	FWHM	$1/e^2$	95%	99%	99.9%
FWHM	1	1.699	2.079	2.578	3.157
$1/e^2$	0.589	1	1.224	1.518	1.859
95%	0.481	0.817	1	1.240	1.519
99%	0.388	0.659	0.807	1	1.225
99.9%	0.317	0.538	0.659	0.816	1

Table 1: Conversion factors for common width criteria for a Gaussian profile. Starting with a known width according to some criterion on the left, multiply it by the listed factor to arrive at the width according to the criterion on the top row.

As the spot size of light exiting an SM lensed fiber can be extremely small, often within an order of magnitude of the wavelength of the light itself, there are some additional measurement challenges (1). Though goniometric far field measurements can be made to estimate spot size, they require using the Petermann II integral to back calculate the spot size in the near field. The underlying assumptions of this approach may lead to inconsistency and ambiguity when characterizing the output from lensed fibers (2).

Although spot size and working distance are key performance parameters specified by lensed fiber manufacturers, there are often very few details about the actual measurement procedure and exactly how these parameters are determined. In this Application Note, we address this shortcoming by discussing in detail two measurement methods that are relatively straightforward and accessible to implement:

- A camera based measurement system
- A scanning knife edge

DIRECT BEAM IMAGING WITH A CAMERA

For larger width or lower intensity beams, a camera's bare sensor array can measure the beam profile directly without the need for any extra imaging optics. However, when beam widths become so small that they approach the pixel size of the camera, as is the case here, then additional optics are required to image the beam onto the camera with some magnification so that the spatial distribution of the beam can be resolved.

The imaging system used here is similar to that used in M^2 measurement systems. However, whereas those systems typically hold the light source at a fixed distance from the imaging lens and scan the camera along a length of the image space, this system holds both the imaging lens and camera stationary and scans the lensed fiber (i.e., the light source) backwards in object space (Figure 3). This allows successive cross sections of the propagating beam to be incident on the measurement plane in object space and imaged on the camera.

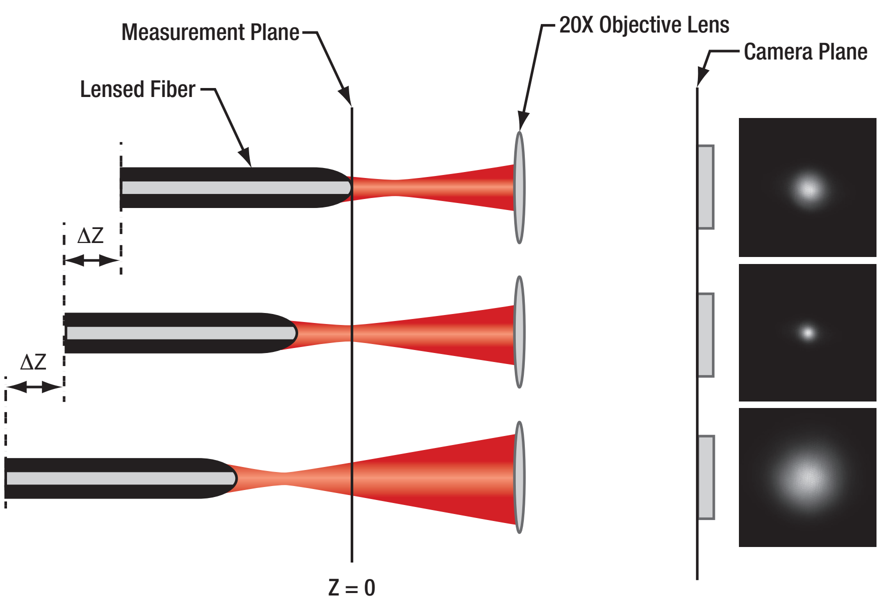


Figure 3: Camera based measurement system layout, showing how successive Z-slices of the focused beam are imaged onto the camera plane.

The magnification of the system is calculated, following (3), by placing a reference object of known size at the measurement plane, which is imaged onto the camera plane. Here, the reference object used is a flat cleaved end face of a fiber with 125 µm cladding diameter. Illumination is with the same wavelength light as used to characterize the light output from the lensed fiber (Figure 4).

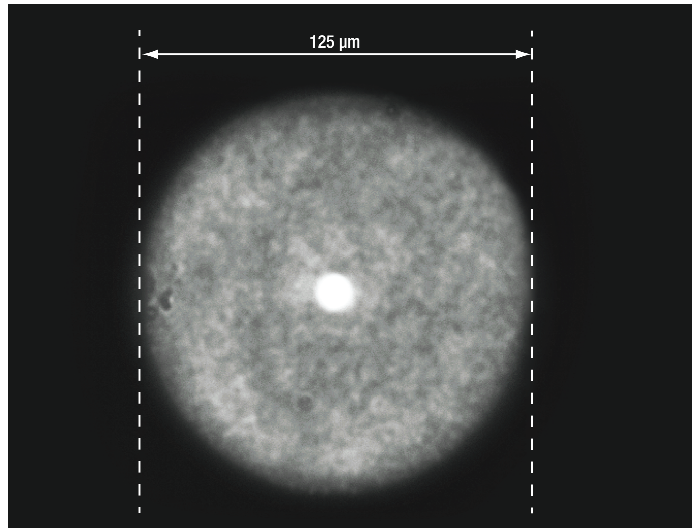


Figure 4: Image of a flat cleaved reference fiber in the camera measurement system. Illumination is with 1060 nm laser light, the same as subsequent measurements, in order to avoid chromatic aberration. This reference object is placed at the measurement plane and used to determine the magnification for objects placed there. The reference fiber has a known cladding diameter of 125 µm. The number of pixels across the image is determined, which can then be compared to the camera's pixel size to calculate the magnification.

Next, the reference object is replaced by a lensed fiber to be characterized. For this characterization, it is crucial that the Z-position of the lensed fiber tip is reliably registered with respect to the measurement plane as defined previously with the reference fiber. Here we take advantage of a feature of Thorlabs' Vytran® GPX3400 Glass Processor, which was used to fabricate these lensed fiber tips. The transfer inserts used in the GPX have a reference ball on the transfer clamp that enables precise and repeatable position registration of the insert, and therefore also the fiber tip (Figure 5).

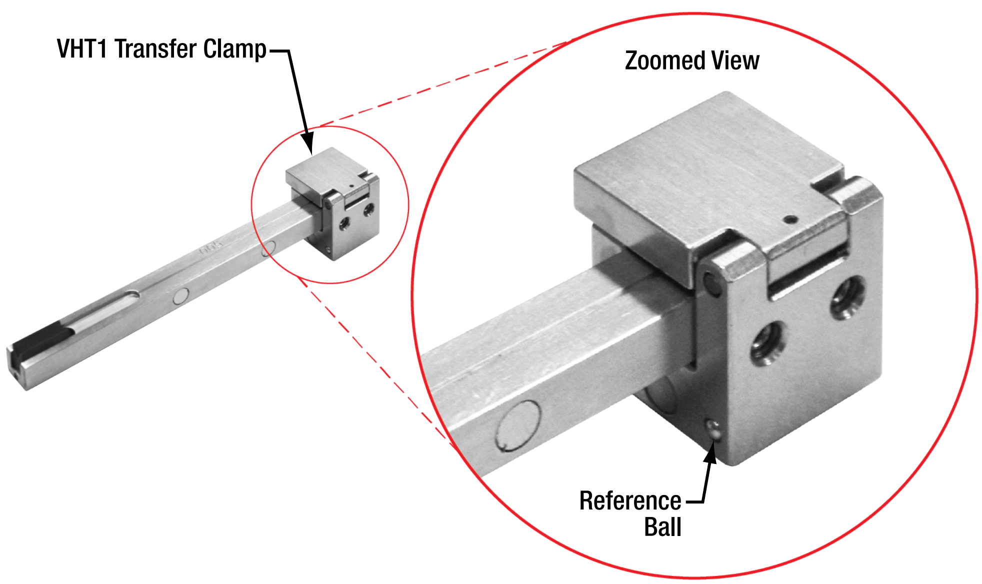


Figure 5: The fiber transfer inserts used with Vytran® Glass Processors, e.g. GPX3400, use a VHT1 clamp. This clamp has a reference ball for precise position registration, which is crucial for calibrating the imaging system with a reference object.

By displacing the lensed fiber backwards in the Z direction from the imaging lens, the evolution of the beam profile propagating out of the lensed fiber can be mapped out. At each new Z-position of the fiber, a new cross section of the propagating beam intersects the stationary measurement plane and its 2D beam profile is captured by the camera. Care is taken that the image brightness (i.e. intensity) is not saturated. A 1D slice through the centroid of the beam image, $I(r)$, is extracted and fitted to a Gaussian (see Figure 6):

$$I(r) = I_0 \exp\left(-\frac{2r^2}{\omega^2}\right)$$

where r is the radial position, and I_0 and ω are the peak intensity and $1/e^2$ radius, respectively, of the Gaussian profile of the current Z-slice.

By repeating this procedure at successive increments in Z, the evolution of the beam's spot size is mapped out. The working distance of the lensed fiber can then be determined as the Z-position of the minimum measured spot size diameter, and the far field divergence angle can also be evaluated. Figure 7 compares this data for two fabricated lensed tips of different spot sizes and working distances.

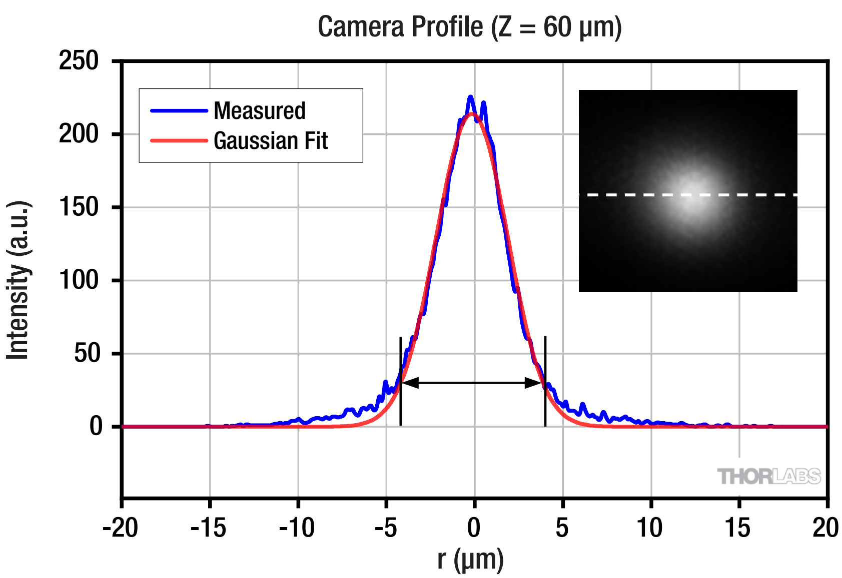


Figure 6: Gaussian fit to a 1D radial slice of the 2D intensity profile (inset). The $1/e^2$ beam width of the fitted Gaussian is marked.

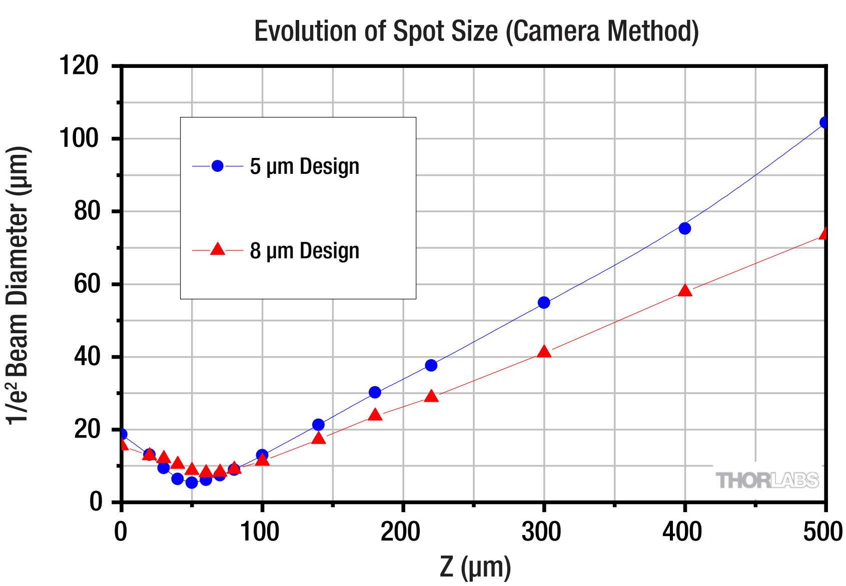
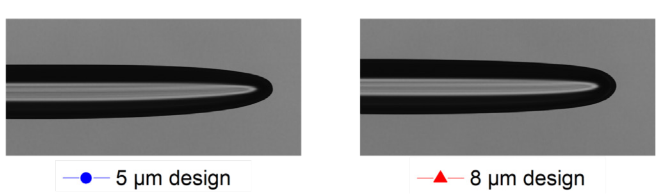


Figure 7: By determining beam width for successive Z-slices, the evolution of the beam can be mapped out. In this way, the spot size and the working distance at which the beam is most tightly focused can both be determined. Here we show data for two fabricated lensed tips, one designed for a targeted spot size of 5 µm, and one for 8 µm.



One disadvantage of a camera-based measurement system is that it is limited to a wavelength range detectable by silicon based camera detectors. Outside of the visible and near infrared, imaging optics and cameras can become very expensive. An alternative method which mitigates these issues is a traditional knife edge measurement.

KNIFE EDGE METHOD

The operating principle of knife edge measurements is well defined in various industry standards (4, 5). An obstruction with a straight edge is scanned laterally across the beam while the total power allowed past the obstruction is measured (Figure 8). Maximum power is measured when the knife edge does not impinge on the beam at all, and minimum power is measured when it fully blocks the beam. The measured power is fitted to the following function, expected for an ideal Gaussian beam profile, and the $1/e^2$ beam width can be extracted as a fit parameter[6]:

$$P = P_{\text{offset}} + A \cdot \text{erfc}\left[\frac{r - r_0}{\omega/\sqrt{2}}\right]$$

where r is the position of the scanning knife edge, r_0 and ω are the center position and $1/e^2$ radius of the Gaussian beam, respectively, and the term P_{offset} accounts for the background power even when the detector is fully covered.

This formula holds only when the knife edge is narrow in the Z-dimension, as compared to the Rayleigh range of the focused beam (here, only a few tens of μm). In order to achieve a sufficiently narrow knife edge, a structure of submicron thickness is lithographically fabricated on a microscope slide. When the knife edge impinges upon a coherent beam, it will produce a diffraction pattern after it, so a sufficiently large area detector is chosen such that all the transmitted light is still captured.

The lens fiber is held in a transfer insert on a motorized translation stage. The system is initially aligned so that the fiber tip is placed in front of the microscope slide and the beam is unobstructed. Under motorized control, the fiber is then stepped laterally across the knife edge so that gradually more and more of the beam is blocked. Once the scan to minimum power has been completed, the motorized stage is then returned to the same lateral starting position, but also moved backwards in Z. The lateral scan process across the knife edge is then repeated at this new Z position.

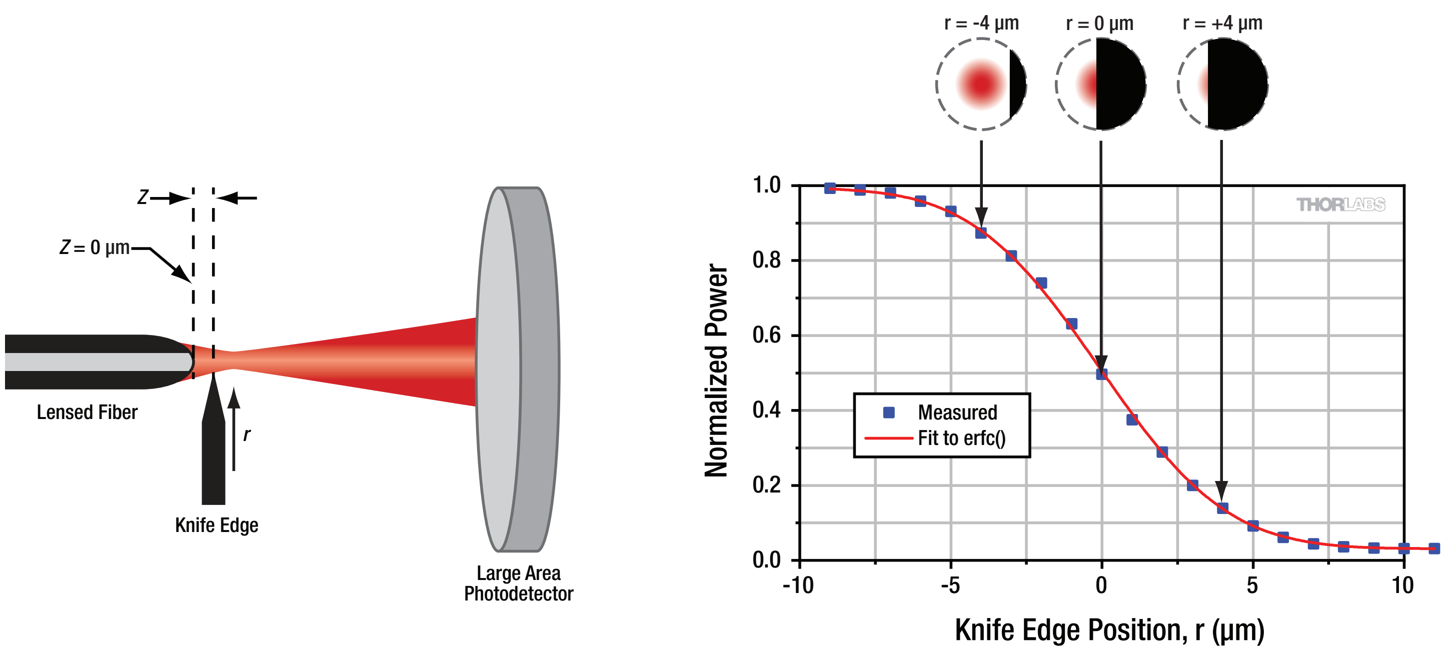


Figure 8: Left: schematic of the knife edge measurement setup. Right: a typical scan obtained from this setup. The measured scan data is well fitted by an erfc function, as expected for a nearly Gaussian beam profile.

By repeating this sequence of steps in Z and lateral scans (Figure 9), the knife edge profile at various Z positions is acquired. This enables the evolution of the beam exiting the lensed fiber to be mapped out in Z, thereby allowing the focused spot size and working distance to be determined.

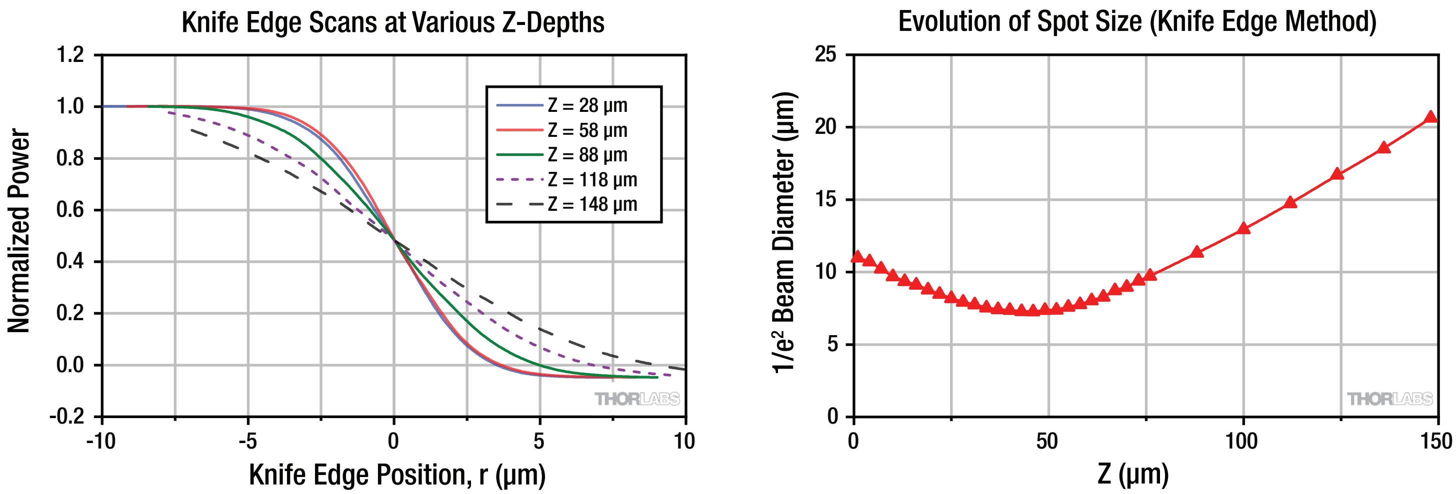


Figure 9: By repeating the lateral scan of the knife edge at various Z-positions (left), the diameter of the spot size emerging from the lensed fiber is mapped out (right). Note that the s-shaped scan curves become steeper at Z-positions close to the focused spot. Results shown here are for a lensed fiber fabricated with a designed spot size of 8 µm.

COMPARING METHODS

In order to directly compare the two measurement methods, characterization of the same lensed fibers was carried out using each measurement system in turn. The measurements were carried out blind, in order to avoid confirmation bias. Lensed fibers were fabricated from 1060XP fiber using a GPX3400 Glass Processor. In total, two sets of 10 lensed fibers were produced, one set targeting an 8 µm spot diameter and the other set targeting 5 µm. Spot sizes were measured with 1060 nm light launched into the distal end of each sample. The two methods were found to agree to within ±0.5 µm on average.

Some of the variation in each data set for the 5 µm and 8 µm spot sizes is due to manufacturing repeatability. However it is interesting and important to note that each of the spot size measurement methods track these manufacturing variations independently. This provides compelling evidence supporting the validity of these two different measurement approaches.

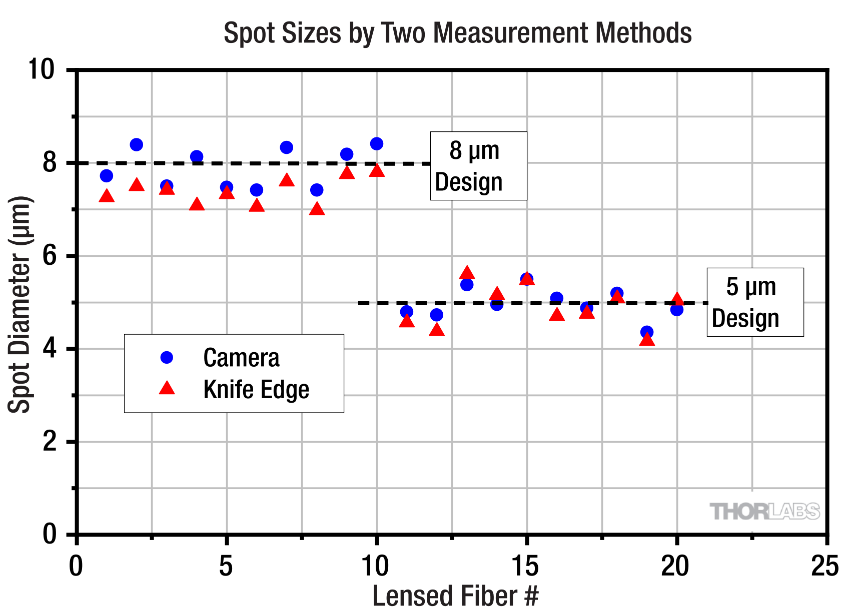


Figure 10: Measured spot sizes for two batches of lensed fibers. Each batch comprises ten lensed fibers, fabricated with identical design parameters. The two measurement techniques are in reasonably good agreement, and some indication is visible of the manufacturing variation within each batch.

SUMMARY

In recent years there has been an increasing demand for lensed fibers with small spot sizes. While some lensed fibers are available from a number of manufacturers, there are very few details about how the dimensions of the focused spot size are determined. In this paper we have discussed two different measurement approaches to characterize the light output from a lensed fiber. Both methods are relatively low cost and simple to set up. The minimum focused spot sizes are in good agreement with one another, differing on average by less than 0.5 µm.

We hope that this demonstration of accessible measurement methods contributes to a greater transparency among both suppliers and individual researchers about characterizing these performance-critical parameters of lensed fibers.

REFERENCES

1) "Measuring Small-Beam MFD: Overcoming the Challenges," D. Peterman photonics.com

2) "Mode-Field Diameter and 'Spot Size' Measurements of Lensed and Tapered Specialty Fibers," J. L. Guttman, 2012 techbriefs.com

3) "Gaussian Beam Optics", CVI Melles Griot 2009 Technical Guide vol. 2, issue 1 Equation 2.15 (2009)

4) ISO 11146-1 "Test Methods for Laser Beam Widths, Divergence Angles and Beam Propagation Ratios — Part 1: Stigmatic and Simple Astigmatic Beams", 2021 iso.org

5) FOTP-174 "Mode Field Diameter of Single-Mode Optical Fiber by Knife-Edge Scanning in the Field", 1988

6) Measurements of Laser Beam Using Knife Edge Technique", M. M. M. R. Mohamed, Equation 2.5 (2019) Politecnico Milano