Measuring the Mode Field Diameter of Single Mode Fibers Using the Knife-Edge Technique

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I. Abstract

Single mode fiber is used extensively in both telecommunications and the scientific community. At the Laboratory for Laser Energetics (LLE), single mode fiber is used in the fiber amplifiers which seed the OMEGA and OMEGA EP amplifiers, among other applications. An important property of single mode fiber is the mode field diameter (MFD), which is traditionally determined as the $1/e^2$ width of the intensity inside the fiber. Knowing MFD is an important parameter for preventing loss when coupling or splicing fibers and predicting how light will behave when it exits a fiber. The knife-edge technique, unique for its simplicity, is a method of measuring MFD that uses a razor edge to incrementally cut off the amount of light that reaches a power meter. The MFD measured by a knife-edge setup was within vendor specifications for two types of single mode fiber, validating its accuracy. The MFD of the SM980 fiber, a fiber commonly used at LLE, was measured to be $6.0 \pm 0.1 \,\mu\text{m}$ at 1053 nm. This setup is a key step for improving LLE's technical knowledge of fibers, including polarization maintaining and other specialty fibers.

II. Introduction/Background

Knowing the mode field diameter (MFD) of a single mode fiber is useful because it allows for effective and efficient use of the fiber. Optical fibers are fibers made with a glass core that can guide light over long distances and in many directions without the light losing a significant portion of its strength. Single mode fiber is a specific type of optical fiber that is characterized by the fact that its core is so small that it can only support a single mode of light, whereas a multimode fiber has a larger core that allows for multiple modes of light to travel through the fiber. The light that travels through a single mode fiber maintains a Gaussian profile even as it exits the fiber and propagates into the air [1].

Fiber has many applications in the world and within the Laboratory for Laser Energetics (LLE). For instance, optical fiber has applications within cable TV and the internet, along with in medicine and dentistry, among other industries. In medicine, single mode fiber is used in procedures such as endoscopies to give medical professionals access to places in the human body that are otherwise difficult to see or access, such as the stomach or other parts of the gastrointestinal tract. Single mode fiber is also useful for data transmission because it can transport information better than the copper wires that are traditionally used. Single mode fibers can carry data over much longer distances and with reduced attenuation, or loss, compared to copper wires. Within LLE, fiber is used for various experiments as well as in the OMEGA and OMEGA EP lasers. Single mode fiber is used in the fiber amplifiers in the initial amplification stage of the two lasers.



Figure 1: Diagram of the inside of a single mode fiber. As light travels through the fiber, it doesn't stay within the core; instead, it extends into the cladding as well. The mode field diameter (MFD) is the diameter of the intensity curve of the light signal within the fiber at the $1/e^2$ level.



Figure 2: Diagram of spliced fibers with different MFDs. When two fibers with different MFDs are spliced or coupled, the smaller MFD cannot carry the same amount of light, so loss occurs.

MFD is an important property of single mode fibers, and it is usually defined as the width of the intensity curve at the $1/e^2$ level, as shown in Figure 1. As light travels through a single mode fiber, it propagates within the core and goes a little bit into the cladding, the material surrounding the core. MFD is the measure of the width of the area over which the light propagates [2]. It can be useful to know the MFD of different fibers at different wavelengths for experiments or setups that involve splicing or coupling different fibers or manipulating the light once it exits the fiber. If two fibers with different MFDs are coupled or spliced, loss will occur, as shown in Figure 2 [3]. Additionally, MFD is used to calculate other properties of the light once it exits the fiber and is manipulated in certain ways, such as with a collimator.

There are many different techniques for measuring the MFD of single mode fibers, but the knife-edge technique was chosen for this work. The knife-edge technique involves using a knife- or razor-edge to incrementally cut off the amount of light exiting a fiber that reaches a power meter. The amount of light that reaches the power meter is measured at each interval that the knife-edge is moved [4]. Compared to other methods of measuring MFD, the knife-edge technique is inexpensive since razor/knife-edges are cheaper than quality cameras or other equipment [5]. The knife-edge technique is also relatively easy to set up.



III. Experimental Setup/Data-taking Process

Figure 3: Diagram of the experimental setup. The test fiber is coupled to the laser source and is held on the z translation stage with a fiber clamp. The razor edge is positioned perpendicular to the test fiber on the x translation stage so that it can be moved to cut off the light emitted from the fiber. That light is focused by a lens into the power meter.



Figure 4: Photograph of the experimental setup.

The experimental setup consisted of the fiber under test, a fiber coupled laser source, two translation stages with micrometers, a razor edge, a fiber clamp, a lens, and a power meter (Ophir PD300R-IR), as shown in Figures 3-5. The fiber under test was mounted in the fiber clamp and

aligned such that the lens (f = 25.4 mm) focused all of the light exiting the fiber onto the power meter. The alignment and position of the lens and power meter were checked with an IR card. The razor was mounted in a filter clamp which was secured to the x translation stage that moved perpendicular to the fiber. The z position of the razor edge must satisfy the inequality

$$z > 30w_0^2 / \lambda \tag{1}$$

where z is the distance from the fiber tip to the razor edge, w_0 is the mode field radius, and λ is the wavelength [4]. This ensures that the razor edge is sufficiently far from the fiber so that the beam will have a Gaussian shape where data is being taken. The x position of the razor edge was such that, depending on the position of the x translation stage, it could either block all of the light exiting the fiber from reaching the power meter or allow all of it to reach the power meter. The fiber under test was a sample at least 45 cm long of either SM980 or XP1060 spliced to a single mode pigtail. The pigtailed end was butt coupled to one of three fiber coupled laser sources. Three laser sources were used, Innovative Photonic Solutions 1064 nm laser source, a New Focus TLB-6700 tunable laser source, and a 976 nm pump diode. The other end of the fiber under test was a slittle fiber sticking out from the fiber clamp as possible, approximately 1-2 cm, and the fiber clamp was secured to the z translation stage.



Figure 5: Camera view of the setup. The camera was used to help measure the z distance. From left to right are the fiber clamp, razor, lens, and power meter. The ruler is behind the setup.

The distance from the tip of the fiber to the razor edge (z) is necessary for calculating MFD, and it must be measured before taking data. A camera (Manta G-145) with a 16 mm TV lens was positioned perpendicular to the test fiber so that the fiber was in focus. An index card and ruler were placed directly behind the fiber. The ruler was used to mark the fiber position and the index card provided a background so that the position of the fiber tip could easily be seen on

the camera. First, the razor edge was moved using the x translation stage to a location in front of the fiber tip; the razor edge was moved to the same micrometer position for each measurement of z to decrease possible error that could have resulted from the razor being slanted in the mount. Next, the fiber was replaced with a "dummy fiber" which was a thin piece of wire, approximately 0.5 mm in diameter, that did not bend without significant force. The advantage of a dummy fiber is that it ensures that the flat cleave of the fiber under test is not compromised. The wire was placed in the fiber clamp and the z micrometer was used to move the wire up until it touched the razor edge. The reading on the z micrometer was recorded and the wire was moved away from the razor edge by the desired z distance, usually 10 mm. The camera was used to find the position of the wire tip. The camera and TV lens were adjusted so that the wire was in focus. The wire was replaced with the test fiber and the position of the fiber on the ruler was recorded. Since the fiber is extremely thin, an extra light source, such a desk lamp, was sometimes necessary to see the fiber in the camera. Since it was extremely difficult to place the fiber in the same location as the dummy fiber, the tip of the fiber was repositioned with the z micrometer, using the ruler as a guide.

Prior to taking data, the laser source was turned on and left to warm up for approximately 15 minutes. If the z value being used was significantly different from previous data runs, an IR card was used to check the alignment of the lens and power meter. Initially, the data-taking process started with moving the razor so that it blocked all of the light exiting the fiber. This method, as opposed to starting out with the razor blocking none of the light exiting the fiber, allowed the experimenter to see at which x-value the data set should end. By removing an increasing number of data points from both ends of a data set until a significant change in MFD occurred, it was determined that there should be at least 5 data points of a constant power at either end of the data set. Since the razor is placed in a way that guarantees 5 points of constant low power, starting at low power allows for the last data point to be determined by the experimenter. After the range of x-values that should be used for data taking were determined, the data-taking process was started with the razor moved out of the way so that it wasn't blocking any light.

Once the razor edge was in place for the first data point, the average power over 20 seconds was recorded. The x micrometer was then moved 0.50 mm in the direction in which the data was being taken and the process was repeated. In order to block the same amount of room light during each 20 sec interval to reduce error, the person doing the experiment stood at approximately the same location while waiting during the data taking process for each data point. After all data was collected, assuming there was not another run of data collected, the laser was turned off.

IV. Calculations and Results



Figure 6: Graph of data points (open circles) fitted with an error function (fitted curve) and an upper and lower bound (data1 and data2).



Figure 7: Intensity vs translation stage position at the location of the razor blade.



Figure 8: Intensity vs angular spread θ at the location of the razor blade.

In order to find MFD from the data, a series of calculations were done. The power vs position data is first fitted with an error function,

$$I = a + b \operatorname{erf}(d^*x + f)$$
(2)

where a, b, d, and f are fitting parameters (Figure 6). The upper and lower bounds of the fitted function are calculated to account for any fluctuation in the laser's power. This data is inherently integrated over position so in order to get intensity vs. position, the numeric derivative over x was found, which results in a Gaussian beam shape (Figure 7).

$$I2 = dI/dx \tag{3}$$

Next, the z measurement was used to calculate the θ , the angular spread, using the following expression

$$\theta = \tan(\mathbf{x}/\mathbf{z}) \tag{4}$$

where x=0 at peak intensity. Note that x is defined from the location of the peak of the intensity curve, I2. Figure 8 shows the result of this change of variable, $I(\theta)$. Now that the $I(\theta)$ has been calculated, MFD is calculated using the Petermann II definition of MFD [2].

$$MFD = \left(\frac{\lambda}{\pi}\right) \left(\frac{2\int\limits_{0}^{\pi/2} I(\theta)sin(\theta)cos(\theta)d\theta}{\int\limits_{0}^{\pi/2} I(\theta)sin^{3}(\theta)cos(\theta)d\theta}\right)^{1/2}$$
(5)

where $I(\theta)$ is the intensity profile shown in Figure 8. The upper and lower bounds of the error function are put through the same analysis to get upper and lower bounds on the MFD.

In order to address potential sources of error in the experimental setup and procedure, the influence of several aspects of the experiment on data was tested. In order to get a baseline of error between trials, MFD was measured from a succession of trials for which nothing about the setup was changed. Next, MFD was measured for a series of trials for which the z was remeasured but kept constant for each trial. This was the dominant source of error and measurements from these trials are reported in Table 1. Then, measurements were performed at different values of z to determine if the z measurement had an impact on MFD. It was found that the value of z didn't have any larger impact on MFD than the error introduced by remeasuring z. This makes sense given that the measurements were made in the far field according to the inequality $z > 30w_0^2/\lambda$. Another potential source of error was if the fiber had an angled cleave. To test this MFD was measured four times with everything kept the same except for rotating the fiber 90° clockwise each trial. Since the MFD wasn't significantly different for each trial, it is suspected that this is not a dominant source of error. Finally, the impact of the length of the test fiber on the calculated MFD was tested to determine if light was coupling into the cladding. Test fibers with lengths 46 cm - 130 cm were tested and it was determined that the fiber length didn't have a significant impact on the calculated MFD.

Fiber Type	Wavelength (nm)	MFD (µm)	Vendor MFD Specification (µm)
1060 XP	1064	6.7 ± 0.1	5.7-6.7 (1060 nm)
SM980	976	5.6 ± 0.2	5.3-6.4 (980 nm)
SM980	1053	6.0 ± 0.1	N/A

Table 1: Table of final MFD measurements for each fiber-wavelength combination compared to the vendor specifications, if available.

To determine the final MFD of a fiber at each wavelength, 5-7 data runs were performed and the average and standard deviation for each set of runs was found. For comparison, the error due to power fluctuations between runs was 0.05 μ m. As shown in Table 1, the calculated MFD for the 1060 XP fiber at 1064 nm closely agreed with the vendor specification for MFD of that fiber at 1060 nm. The calculated MFD for the SM980 fiber at 976 nm was matched to the vendor specification for that fiber at 980 nm. This demonstrates the accuracy of the setup, data-taking process, and calculations. The MFD of the SM980 fiber, which is a fiber commonly used at LLE, at 1053 nm, was measured to be $6.0 \pm 0.1 \mu$ m.

V. Conclusion

The purpose of this project was to create a simple setup that could be used to measure the MFD of any single mode fiber at a variety of wavelengths. The setup built and tested here was qualified with two different types of single mode fiber, SM980 and 1060XP. In both cases the MFD was measured to be within vendor specifications.

The next phase for this work would be to create another setup for measuring MFD, such as one using the near-field technique. The near field technique involves focusing the light from a test fiber into a specific camera which takes a detailed picture of the fiber tip in the near field so that MFD can then be measured from this picture. This technique would be more difficult to set up but have an easier data-taking process and offer a 2-dimensional image of the intensity profile, rather than a 1-dimensional image, making it more useful for more exotic fibers that are not rotationally symmetric, like polarization-maintaining fibers. The knife-edge work done here will be critical to validate and test a near-field setup.

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VII. References

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