Focal Ratio Degradation in Multi-Modal Optical Fibers

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Abstract

The Direct Fiber Positioning System consists of an array of carbon fiber masts with optical fibers running through them. The masts can be moved independently and simultaneously to select a celestial object, and direct its light into a spectrometer.

In fiber optics, a numerical aperture (NA) describes the angle at which light can enter the fiber tip and be totally internally reflected, equal to the sine of the half angle in radians. This is used to determine how much light a fiber can transmit in this cone and what amount of the light is focused. For our application, we are using a fiber with a lower numerical aperture to minimize the spreading of light in the back end of our spectrograph. To house thousands of fibers in a compact enclosure, the fiber cables must be coiled. Multimodal optical fibers experience a phenomenon described as focal ratio degradation, where a narrow input cone of light not filling the numerical aperture of a fiber can come out the other end of the fiber at a greater angle.

The primary objective of this study is to determine how two factors affect the focal ratio degradation experienced by a fiber held in a ferrule: the numerical aperture and the coiling of the fiber cable.

Method

Procedure

The contact injector holds the ferrule of the source fiber in place while shining a red LED under it at a high intensity. The light enters our apparatus from the injector, traveling through our source fiber out its ferrule on the other end into a plano-convex lens followed immediately by a neutral density filter, eliminating 99% of the light. This plano convex lens collimates the light into a beam and passes through an adjustable iris that is used to narrow the beam of light. The collimated beam is focused by a condenser lens onto the tip of our test ferrule, held in place by a micrometer stage. From there the light moves through the test fiber and out the other tip, projecting an image onto a CCD image sensor.

Our test stand consisted of two different optical fibers. The first is the “source” fiber that transmits light between a contact injector (OSI A2080) and the input ferrule of the test fiber. The second is a “test” fiber that receives the light from the source fiber and transports the light to an output ferrule, projecting it onto an image sensor. We used the same type of source fiber for each test (NA=0.22; core 200um), changing the test fiber out between trials.

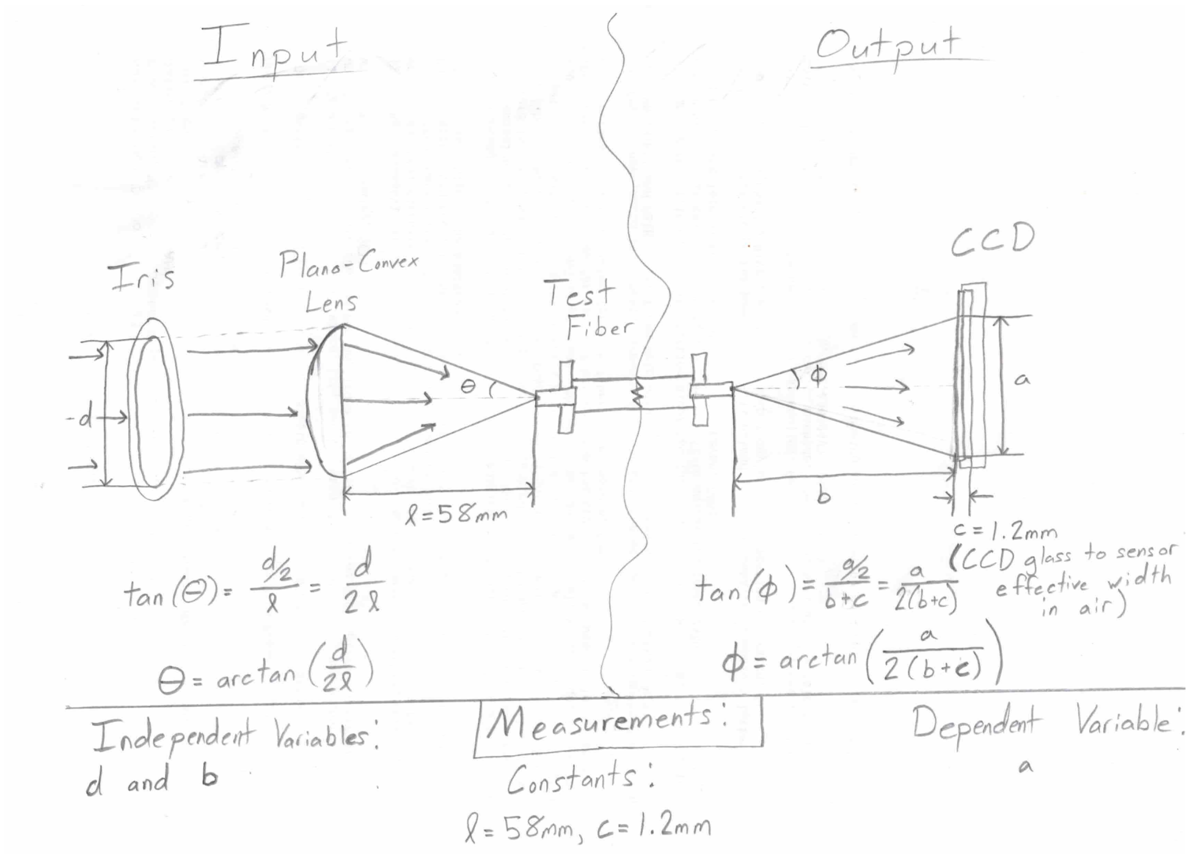


Figure 1: A drawing of our test stand

We first use a photodiode and a multimeter to measure the power emitted from the output ferrule of the fiber. The output ferrule of the test fiber is mounted in a small enclosure housing the photodiode, blocking out most outside light. We mount the input ferrule on a 3-axis micrometer stage and adjust the ferrule's position until we get the highest possible current through the photodiode.

From this projection we obtain an image of the output cone and use the BCAM program in the Long-Wire Data Acquisition System (LWDAQ) to calculate the length and width of the cone in pixels which we convert to microns using the specifications provided in the CCD's datasheet. By recording the distance between the tip of the fiber to the surface of the CCD, we can calculate the angle of each output cone. For convenience while considering numerical apertures, we present this data as the sine of the half angle.

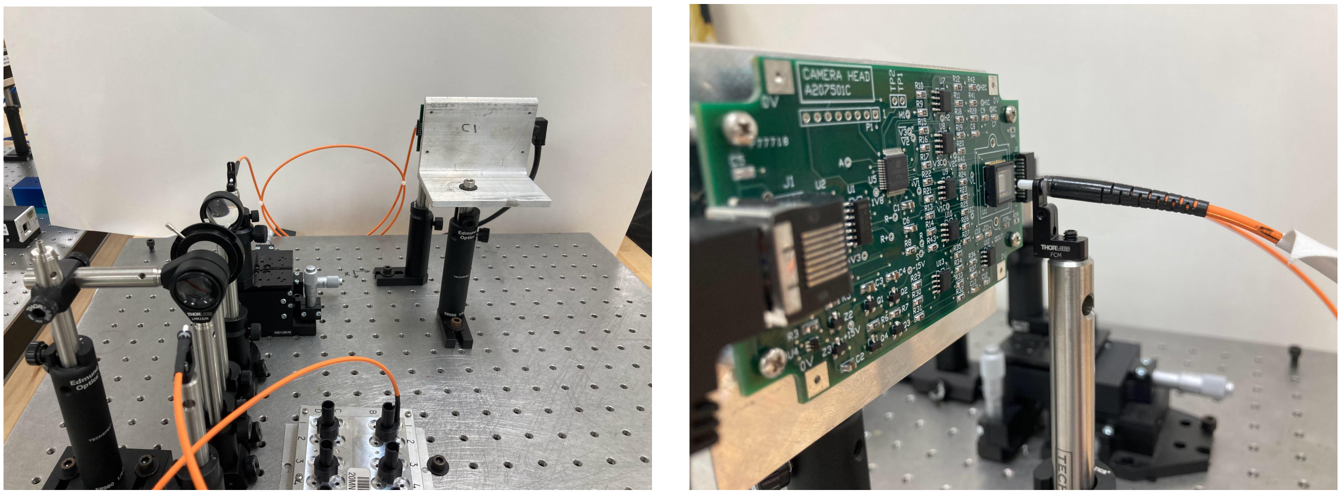


Figure 2: Pictures of our test stand

Materials

We experimented with several different types of optical fibers. For our test fibers, we used a fiber with a smaller core and a lower numerical aperture, as well as a fiber with a larger core and higher numerical aperture that would transmit more power. For both of these, a 200um core fiber is used as the source fiber to maximize output power. In house, we differentiate our fiber types by a lettering system. For this experiment, we studied two types, both of which were 1m cables. Fiber C is always used as the source fiber, and both C and H were measured test fibers.

	name	jacket	core (um)	clad (um)	coat (um)	NA	accepted angle (°)
C	Polymicro 1068000060	none	200	220	239	0.22	25.418
H	Optran UV	none	105	125	250	0.12	13.784

Table 1: A table providing specifications of each fiber

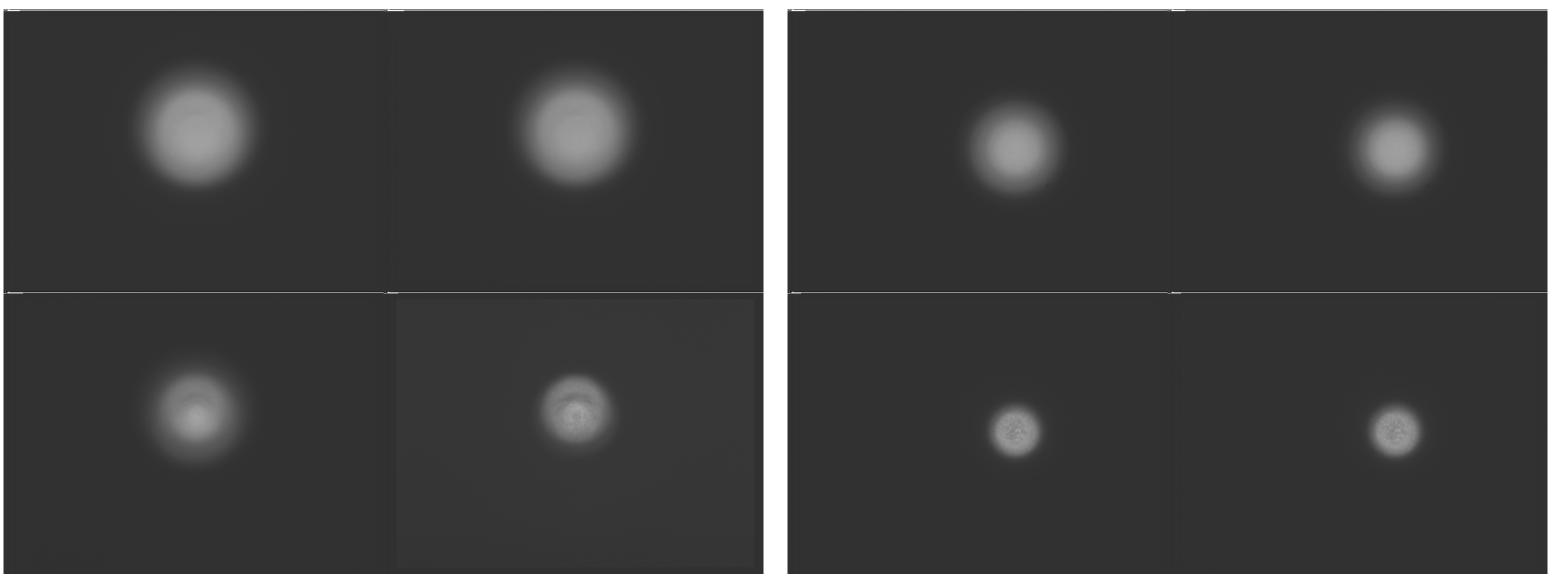
Measurements

For each test fiber, we take measurements as we stop down the iris at four different diameters in millimeters: 24, 12, 6, and 1. Once the iris is positioned, we take an image of the output cone and obtain its width and height. With this procedure we are able to control the diameter of our collimated beam and the angle of the input cone. Our threshold is set to define the cone as the width for which the intensity is greater than 20% from minimum to maximum. For each set of data we also coil the fibers to 3” and 6” to study the interaction between coiling and the appearance of the cone of light.

Results

	iris diameter (mm)	% open	W (pixels)	H (pixels)	avg. W/H (pixels)	avg. w/h (mm)	distance tip from glass (mm)	distance to image sensor (mm)
Fiber 17	24.5	100%	164	165	164.5	1.2173	3.5	4.7
H - 1m	11	45%	150	151	150.5	1.1137	3.5	4.7
NA=0.12	3.2	13%	114	113	113.5	0.8399	3.5	4.7
	1.5	6%	99	99	99	0.7326	3.5	4.7
Fiber 17 3" coil	24.5	100%	165	168	166.5	1.2321	3.5	4.7
H - 1m	11.12	45%	149	153	151	1.1174	3.5	4.7
NA=0.12	6.13	25%	136	136	136	1.0064	3.5	4.7
	1.8	7%	110	110	110	0.814	3.5	4.7
Fiber 17 6" coil	24.5	100%	164	165	164.5	1.2173	3.5	4.7
H - 1m	11.44	47%	155	157	156	1.1544	3.5	4.7
NA=0.12	5.64	23%	137	142	139.5	1.0323	3.5	4.7
	1.5	6%	104	104	104	0.7696	3.5	4.7
Fiber 29	24.55	100%	204	205	204.5	1.5133	3.5	4.7
C - 1m	12.88	52%	200	203	201.5	1.4911	3.5	4.7
NA=0.22	6.66	27%	157	158	157.5	1.1655	3.5	4.7
	1.14	5%	132	127	129.5	0.9583	3.5	4.7
Fiber 29 3" coil	24.71	100%	123	122	122.5	0.9065	2	3.2
C - 1m	12.94	52%	122	122	122	0.9028	2	3.2
NA=0.22	6.55	27%	108	110	109	0.8066	2	3.2
	1.47	6%	86	89	87.5	0.6475	2	3.2
Fiber 29 6" coil	24.25	100%	158	160	159	1.1766	3	4.2
C - 1m	12.1	50%	157	159	158	1.1692	3	4.2
NA=0.22	6.23	26%	147	148	147.5	1.0915	3	4.2
	1.88	8%	127	125	126	0.9324	3	4.2

Table 2



Figures 3-4: Images of cones as iris diameter decreases from 24, 12, 6, to 1 (±3mm)
(L: NA=0.22, R: NA=0.12, 1m Uncoiled Fibers)

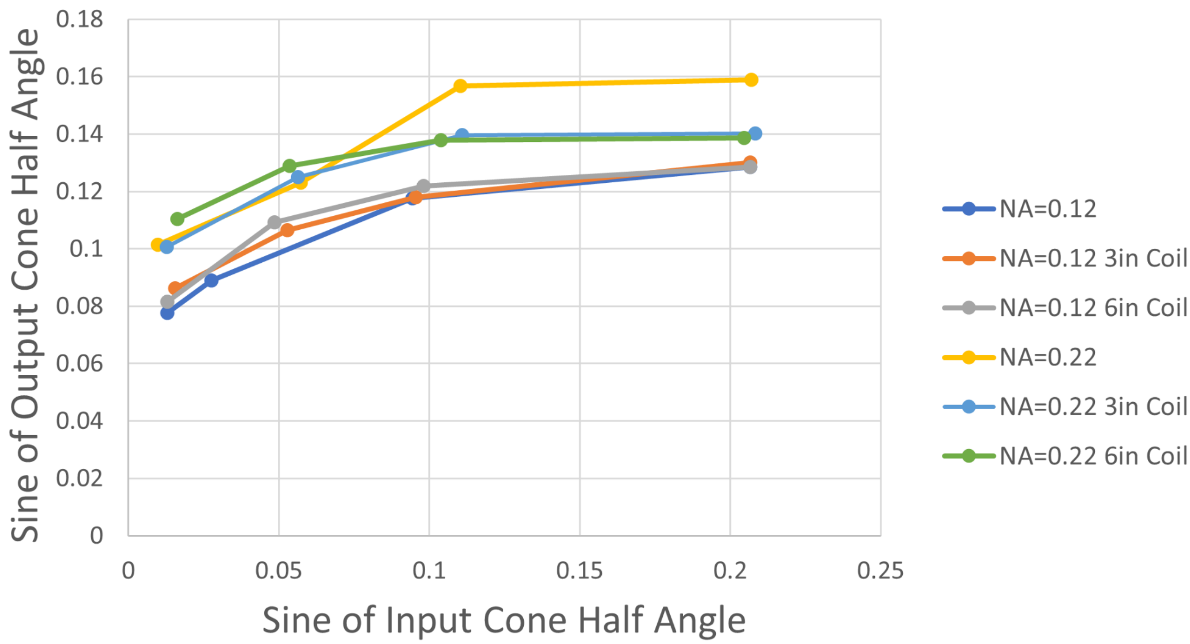


Figure 5: Output cone vs. Input cone measurement expressed in sine of half angle to assist while considering numerical aperture.

Discussion

The sine of the output cone did not significantly interact with the coiling of the fiber. The output cone increased at a similar rate with respect to the input cone, regardless of coiling. The output cone angle of Fiber 17 (NA=0.12) never exceeded 13.8°, while Fiber 29 (NA=0.22) was never measured having an output cone of more than 16-18°; in contrast, we expect a 0.22 NA fiber to allow for an output cone of 25.4°. We suspect that this does not match with what we observed due to the analysis software setting the bounds of the circle where intensity is greater than 20% from minimum to maximum. Where the 0.12 NA fiber concentrates the light toward the center of the image sensor, the 0.22 NA fiber allows for the light to spread out much more radially. With more area to cover on the CCD, the intensity of light on the outer rim of the cone is much less than that of the outer rim of the 0.12 NA fiber, causing the output cone from the 0.22 NA fiber to appear more narrow than it is.

References

CerumOptec, *Optran UV*, Manual https://www.ceramoptec.com/products/fibers/optran-uv-/-wf.html

Hashemi, K. *DFPS Development Log*, https://www.opensourceinstruments.com/DFPS/, 2023

Hashemi, K. *Contact Injector (A2080) Manual*, http://www.bndhep.net/Electronics/A2080/M2080.html , 2018

Hashemil, K. *Camera Head (A2075) Manual*, http://www.bndhep.net/Electronics/A2075/M2075.html 2018.

Hashemi, K. *LWDAQ User Manual*, http://www.bndhep.net/Electronics/LWDAQ/Manual.html, 2023

Molex, *1068000060*, Manual, https://www.literature.molex.com/SQLImages/kelmscott/Molex/PDF_Images/987650-8934.pdf

Sony, *Diagonal 6mm (Type 1/3) Progressive Scan CCD Solid-state Image Sensor with Square Pixel for B/W Cameras.* ICX424AL Datasheet, https://www.opensourceinstruments.com/Electronics/Data/ICX424AL.pdf