FOCAL RATIO DEGRADATION IN OPTICAL FIBERS OF ASTRONOMICAL INTEREST

LAWRENCE W. RAMSEY
The Pennsylvania State University
525 Davey Laboratory, University Park, PA 16802

ABSTRACT Along with the spectral attenuation properties, the focal ratio degradation (FRD) properties of optical fibers are the most important properties for instrumental applications in astronomy. However, unlike spectral attenuation, the FRD properties are rarely addressed by fiber manufacturers. Accordingly many astronomers have undertaken the parameterization of FRD in terms of spectroscopy, the principal application of fiber optics in astronomy. This article discusses the sources and measurement of FRD properties of step index fused silica core fibers.

INTRODUCTION

It has been a little over a decade since the first paper proposing the use of modern fused silica core optical fibers in astronomy was published by Angel et al. (1977). To date the most important application of fiber optics in astronomy has been for multiple-object spectroscopy pioneered by Hill et al. (1980). This work and that of Gray (1983) has spawned many imitators and innovations. Fibers have also proved to be useful in removing instruments from the back of telescopes for precision measurements. This was first done by Hubbard et al. (1979) and Heacox (1980) using existing spectrographs and later by Ramsey et al. (1981) and Ramsey and Huenemoerder (1986) using spectrographs especially designed for fibers.

It became clear early on that a property of fibers equally important as their spectral transmission was the ability of a fiber to preserve the angular distribution of the beam defined by the telescope focal ratio. The fact that all fibers tend to change the incident f-ratio to smaller numbers is called focal ratio degradation (FRD). In most astronomical applications we are interested in step index, multi-mode, fused silica core fibers although there are some very interesting applications of single mode fibers in optical interferometry as the paper by Shacklin (1988) suggests. In this paper I will always be considering circular, step index, fused silica core, multimode fibers.

MODES AND FIBER LOSS MECHANISMS

The spectral attenuation or transmission characteristics of a fiber are, of course, critical to astronomical applications. In order to better appreciate how the FRD properties of fibers relate to this property, it is useful to consider fiber loss mechanisms from a "modal" point of view.

Formally a mode is defined in terms of the propagation vector of the electromagnetic wave in a circular dielectic waveguide (see Midwinter, 1979). Especially for visualizing some of the causes of FRD it is adequate to use a simplified geometrical model such as is illustrated in Figure 1. Here we consider different modes to be plane waves incident at different angles relative to the axis of the fiber. Those "modes" with $\theta < \theta_c$, where θ_c is the critical angle for total internal reflection (TIR), are clearly propagated where those with $\theta > \theta_c$ are termed "lossy" modes as they cannot be propagated by TIR. In reality an optical fiber is a waveguide and indeed some energy is carried in the cladding even for propagated modes. A given f-ratio has an associated modal distribution.

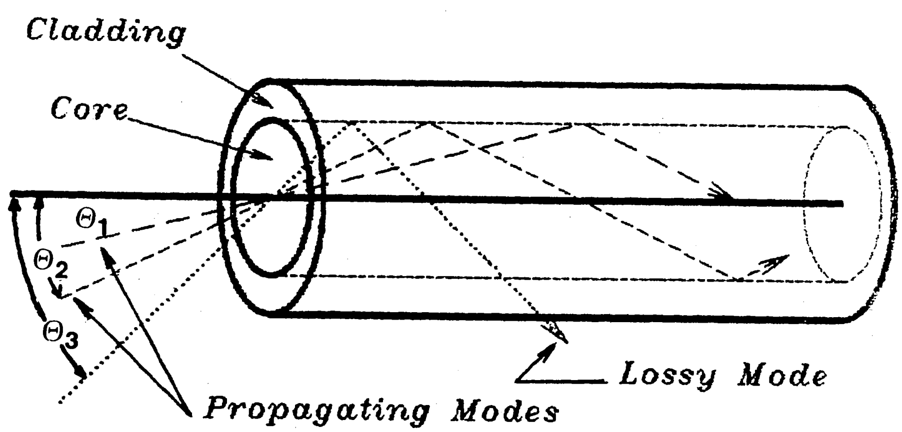

Fig. 1 A typical step index cylindrical fiber is shown with the axis indicated by the solid line. Modes are plane waves incident at a particular angle to the fiber axis. Several incident modes are shown with the dashed lines.

With this model of modes in mind we can now consider fiber loss mechanisms as two types; mode independent and mode dependent. Mode independent mechanisms are the material absorption and material scattering which have a spectral dependence. The material absorption in the visible and near Infrared (IR) is dominated by absorption bands of OH at 0.72, 0.95, 1.37 and 2.73 microns at the red end and by metal ion impurities at the blue end. Material scattering is due to density and composition fluctuations primarily in the fiber core. For fused silica core fibers it is the density fluctuations that dominate and lead to a Rayleigh scattering which sets the lower limit to fiber transmission. Avila and D'Odorico (1988) and Nelson (1988) both give examples of the effect of these mechanisms on various optical fibers. See Midwinter (1979) and Nelson (1988) for a more complete discussion of the spectral attenuation properties of fibers. These mode independent losses are reliably characterized by fiber manufacturers out to about 1.8 microns in most cases.

The mode dependent loss mechanisms are the causes of FRD and are rarely addressed by manufacturers. Mode dependent losses can be divided into two basic mechanisms. The first is waveguide scattering which causes transfer of energy into lossy modes by variations of the core diameter along the length of the fiber. The second is mechanical deformation.

Mechanical deformation is a change of the geometry of the fiber away from a straight cylinder. Large scale bending, or macrobending, is where the radius of curvature of the bend is very large in comparison to the core diameter. Microbends are deformations of the cylindrical core shape which are small compared to the fiber diameter (see Figure 3 in the paper by Nelson). These mechanisms all result in the transfer of energy from one mode to another. Over the length of the fiber these mechanisms lead to modal dispersion or what manifests itself in astronomical applications as FRD. Microbends are apparently the major cause of FRD. Studies by Engelsrath et al. (1986) show that macrobends are not a major loss mechansim. Powell's (1983) study, as well as our own experience, show that macrobends are not a major factor in FRD except in extreme cases. It should be pointed out that fiber cable bending or macrobends in some fibers appear to cause FRD. This is not so much due to the curvature of the fiber as the microbands introduced by the stress of the large scale bend.

Figure 2 depicts the net result modal dispersion. Here we imagine inserting a single mode, such as a vanishingly small diameter and divergence laser beam, at a given angle θ. As can be experimentally verified, the beam will emerge in an annulus of finite width $\Delta\theta$. As has been noted before by Angel et al. (1977) and Heacox (1986) the $\Delta\theta$ due to macrobending is approximately given by

$$\Delta\theta/\theta = d/R \qquad (1)$$

where d is the fiber core diameter and R is the bend radius.

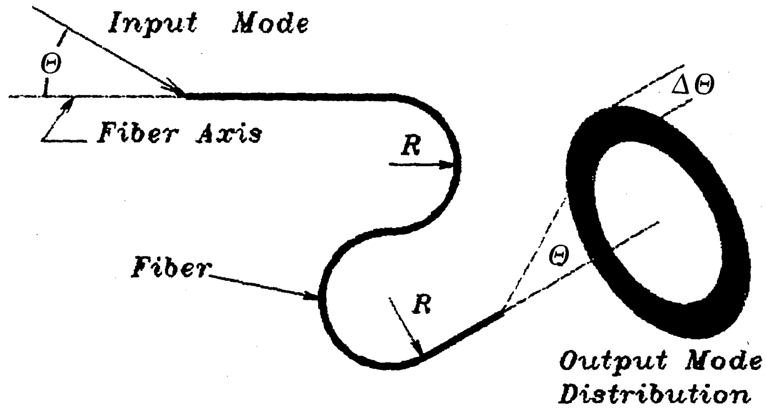

Fig. 2 We illustrate here the basic definition of FRD. As single "mode" is inserted into the fiber. It is azimuthally dispersed or "scrambled" and also dispersed to a lesser extent radially. This radial dispersion is the FRD.

It is important to realize that FRD is a LOSS in any astronomical spectroscopic application. Inspection of Figure 3 should make this point. The solid line is the relation of the input and output f-ratio for a circular aperture equal to the core diameter of a fiber. Obviously the slope is unity as any well designed spectrograph has a collimator f-ratio equal to that of the telescope. The dashed line represents the behavior of a generic fiber where FRD causes the output f-ratio to always be faster than the input number. It is clear that for a collimator designed to match the telescope we have a real light loss where the two curves begin to diverge as the light output from the fiber overfills the collimator. In principle one can recover this light by increasing the collimator diameter to keep the optical efficiency high. However, this increases the size of the grating and diameter of all optics with no attendant increase in resolution--certainly a financial loss. For large core fibers where one wants a high collimator-to-camera focal length ratio to match pixels on a detector, one rapidly finds oneself in the realm of very fast cameras.

The principal figure of merit for any spectrometer system is the throughput-resolution product (Meaburn, 1976) and is a constant for any given telescope spectrograph combination. The introduction of a fiber can only decrease this product. By operating with an input f-ratio where there is little FRD one can minimize the penalty in the throughput-resolution product that the fiber extracts. While some loss or design penalty due to FRD is unavoidable in an astronomical spectrograph, the benefits to be gained such as in object multiplexing (e.g. Hill et al., 1980) or in wavelength or intensity precision (Heacox, 1986, 1988; Ramsey and Huenemoerder, 1986) can more than justify such compromises.

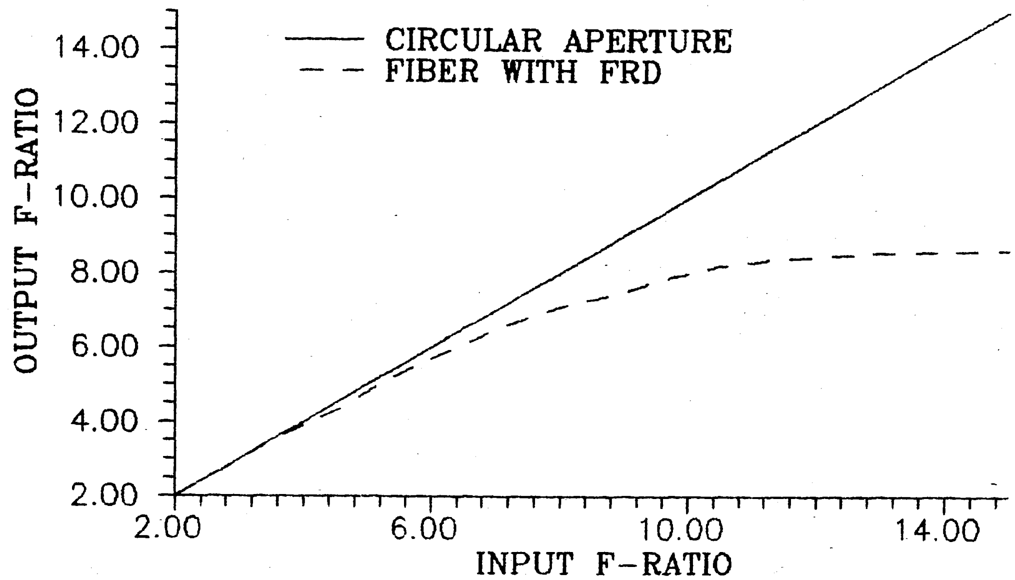

Fig. 3 The Focal Ration Degradation (FRD) of a typical fiber is compared to the throughput of a circular aperture of the same diameter as the core of the fiber.

MEASUREMENT OF FRD

As mentioned above, while manufacturers characterize their fibers rather well with regard to mode independent loss mechanisms, mode dependent properties are rarely discussed for multimode fibers. Astronomers recognized early on the need to perform those measurements relevant to FRD. The published literature is quite informative in this regard (Angel et al., 1979; Barden, Ramsey and Truax, 1980, 1981; Gray, 1983, 1986; Lund and Enard, 1983; Powell, 1983; Ramsey and Huenemoerder, 1986) and more measurements are given elsewhere in this volume (Avila and D'Odorico, 1988; Craig et al., 1988; Guerin and Felenbok, 1988; Kamper, 1988; and Latham, Andersen and Geary, 1988). We have also performed measurements of different lengths of over a dozen fibers at Penn State. In the interest of space I will only present here illustrative results and comment on them and their relevance to those of others.

Absolute Measurements

Measurement of the FRD is rather straightforward. The methods used by Powell (1983) and others (Lund and Enard, 1983; Guerin and Felenbok, 1988) are a clear improvement on the early technique employed by Angel at al. (1979) and Barden, Ramsey and Truax (1981). Most of the FRD measurements to date are relative in nature; that is, they assume all the light is transmitted at some lower limit of the output f-ratio. Powell's (1983) are an exception to this as they are absolute. While relative measurements are quite adequate for many purposes, they can be misleading when assessing the fibers performance at relatively fast f-ratios (f/# < 3.0) or looking at small core fibers. An apparatus that measures the amount of light output from the fiber relative to that input with a given mode distribution is depicted schematically in Figure 4. This scheme, originally designed by Barden while he was at Penn State, compares the light in the input beam to that emanating from the fiber by way of a simple 90 degree flip of two separate mirrors.

Our current implementation of this design uses a stabilized Quartz Tungsten-Halogen lamp (Newport Corp. Model 780) to illuminate a fiber, F1. This fiber is heavily mode scrambled to provide nearly uniform illumination over the pupil of the collimating lens L1. This lens can either be a zoom lens or a simple doublet. The collimated beam illuminates an imaging lens, L2, which has an internal iris, I1, to set the input f-ratio to the fiber. A beamsplitter, B1, is used to view the image of the output end of F1 focused onto the input end of the fiber under test, F2. The test fiber is in a 5 axis stage (Newport Corp. FP-2) which can be used to align the axis of the fiber with that of the input beam and set the spot position on the fiber. The output end is similarly mounted in a 5 axis stage. With the mirrors set as shown by the solid lines in Figure 4, the output of the test fiber illuminates the plane of the iris diaphram I2. A pair of lenses images the pupil defined by I2 onto a photodiode, D1, with 1 cm^2 area. An electrometer amplifier converts the photocurrent to a voltage which is read into a PC after analog to digital conversion.

If properly aligned, the areas on the mirrors which are illuminated in both the reference and fiber positions are the same to first order. All the measurements presented here use a variable iris (I2) to determine the output f-ratio being measured. For this to be accurate, the distance of the fiber output end and the focus of the input beam between the two flip mirrors must be equal. The errors introduced by this are in practice about 1%. We have calibrated both I1 and I2. The uncertainties in this calibration and the small nonuniformity of the L2 pupil illumination lead to estimated errors of about 5% on determined f-ratios. The repeatability is usually better than 1% as are the ratios of the input to output fluxes.

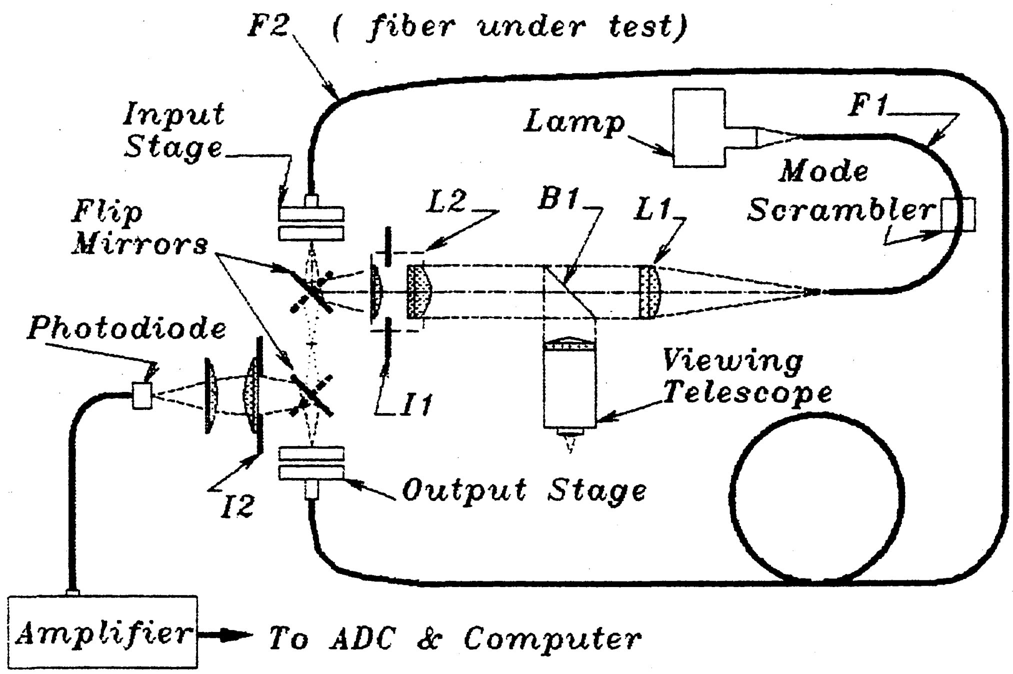

Fig. 4 The Penn State Fiber evaluation set up. See text for description.

Some Results

Figure 5 shows a typical set of measurements for an individual fiber taken on our system described above. The vertical axis is the output of the fiber into a circular aperture equivalent to the f-ratio given on the horizontal axis normalized by the total amount of light input into the fiber. We call this the absolute transmission. Each curve is for a separate input f-ratio. The legend on Figure 5 defines these. This set is for a Polymicro FHP series 320 micron core fiber taken with a 700 Angstrom FWHM interference filter centered at 6000 Angstroms. This data is unusual in that it represents the best FRD results we have been able to achieve to date. They are not quite as good, however, as those of Barden (1987) for the same type of fiber. What is interesting in this regard is that Barden's result was for a 32 meter fiber. The results in Figure 5 are for a 10 meter fiber. This and the previous work of Powell (1983) allows one to make the interesting statement that the FRD is not a strong function of the length of the fiber.

Figure 6 is another set of measurements for a small core fiber constructed similarly to that in Figure 5. It is a Polymicro FHP100/120/140. This fiber was prepared and mounted in much the same way as the 320 micron core fiber discussed

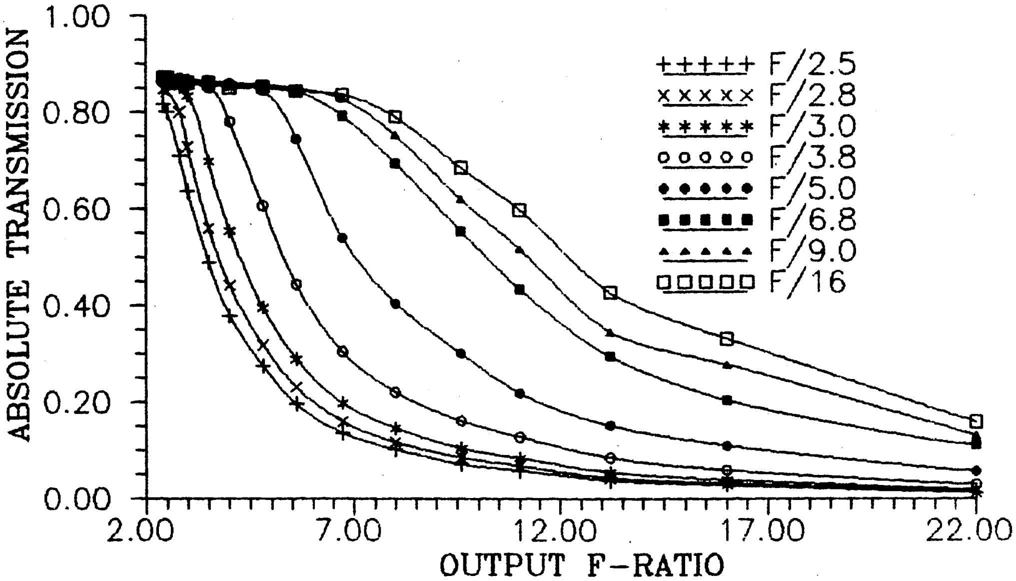

Fig. 5 Test results for a Polymicro FHP 320/385/415 fiber obtained using the facility depicted in Figure 4. The vertical axis is the total transmission of the light output from the fiber into a circular aperture equivalent to the f-ratio on the horizontal axis.

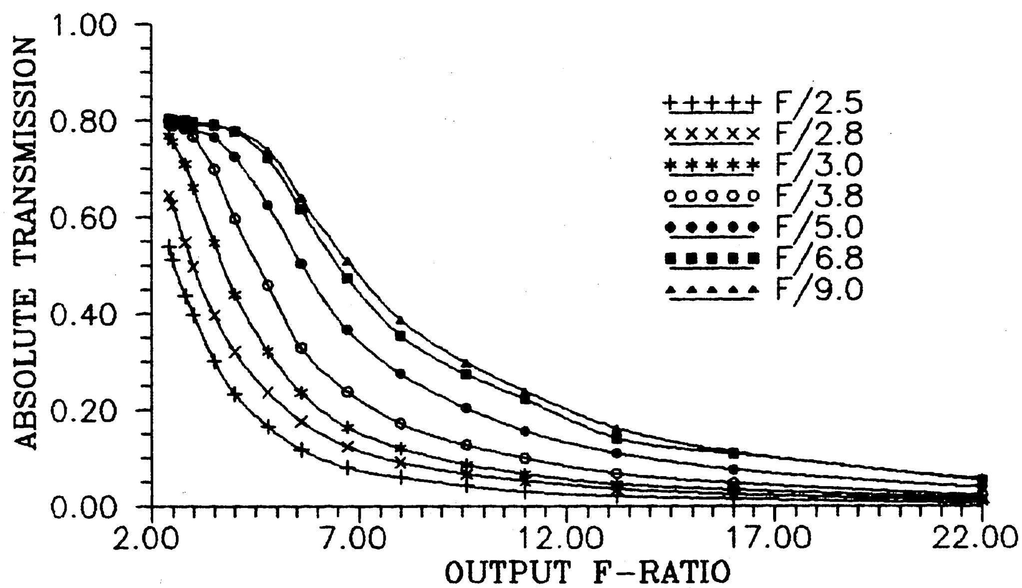

Fig. 6 Test results for a Polymicro FHP100/140/170. Otherwise similar to Figure 5.

above. Clearly the FRD properties are significantly worse. Our tests on other manufacturer's fibers show the same trend; that is larger core fibers tend to have better FRD properties. The control of the fiber diameter is about the same for both the large core and small core fibers but the relative change is greater for the smaller fiber and waveguide scattering may play a larger role in the small core fibers. Our experiments, however, provide some evidence that microbends may still dominate. Table 1 shows the comparison of the absolute transmission of the fiber in Figure 6 to a fiber identical with the exception that it has a thick soft silicon buffer (FHS100/140/500). We conjecture that the polyimide buffer in the FHP series may cause more stress on the fiber introducing more microbends. We have found the FHS fiber also much less sensitive to the type of epoxy used (see discussion below).

TABLE I Comparison of FHP and FHS Fibers with Identical f/7 Inputs

Fiber	% Output into f/7 (Absolute)
FHP100/120	47
FHS100/140 #1	63
FHS100/140 #2	68

If we use the results in Figures 5 and 6 and plot the absolute amount of light output into a f-ratio equal to that input we obtain the results given in Figure 7. For f-ratios much faster than f/3 the absolute throughput decreases. This is much more so for the smaller fibers. What is likely happening here is that fast beams have more modes propagating near the critical angle and microbends cause an increasing fraction of them to become lossy. This Figure also makes it clear that f/3 - f/4 is the best f-ratio to insert into a fiber. The large core fiber has a broader peak extending to numerically larger f-ratios. Again other manufacturer's fibers follow this general trend. In this respect our results disagree with those of Powell (1983) where he finds little dependence on fiber size.

Another result that we and others have found is that, in general, glass clad fused silica core fibers have better FRD properties that plastic clad silica (PCS) fibers. PCS fiber may be better for very fast f-ratios since they can be made with larger Numerical Apertures (see Nelson, 1988). Our experiments have also shown that the FRD of most fibers are rather insensitive to coiling. Measurements of the FHP320 and FHP100 fibers in Figures 5 and 6 with a very gentle

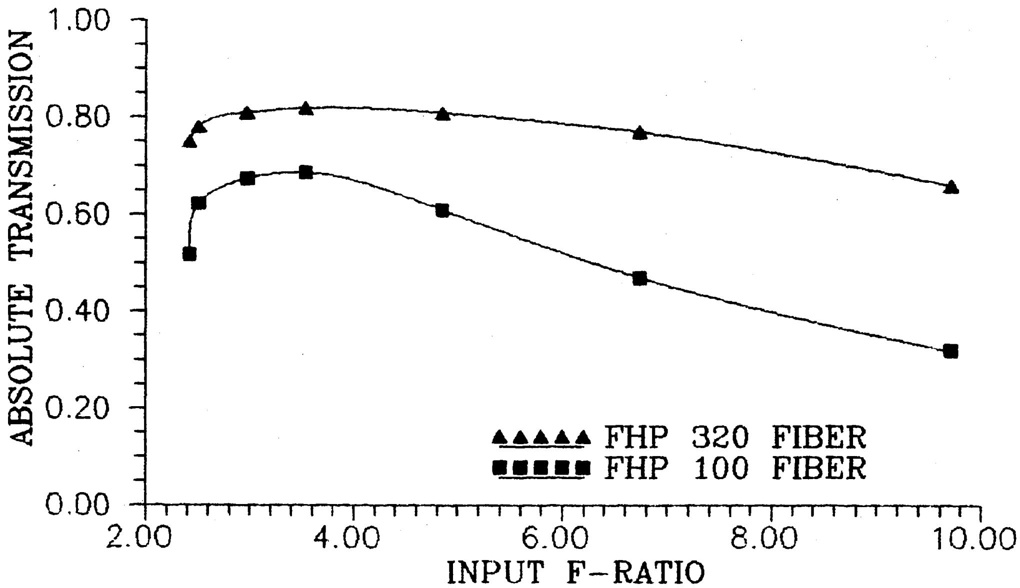

Fig. 7 The vertical axis is the absolute transmission into a aperture equivalent to the input f-ratio given on the horizontal axis. Both the FHP320 and FHP100 fibers are shown.

(several meters) curvature needed for the test apparatus and coiled with a radius of about 20 cm showed no detectable difference. The improved performance of the FSH100 fiber noted in Table 1 was wound on a tabbaco can with a radius of 6 cm! While we have not explicitly tested it, it seems reasonable that fibers with hard buffers, such as the polymicro FHP series, might be more sensitive to small radius (R < 10 cm) bending than soft buffered fibers such as the FSH series. This is expected not so much from the curvature itself as to the microbending it introduces.

Effects of Epoxy and Mounting

The measurements of the 10 meter FHP320 sample discussed above were redone several times, each time changing the mounting scheme until finally the measurements in Figure 5 were done with the fiber only lightly held by masking tape in a similar way to that described by Barden (1987). For this last measurement, the fiber was polished tacked in the ferrule with Nordlund 68 UV curing epoxy which was dissolved away with acetone for the measurements. It is clear that the epoxy can play a major role in FRD.

Obviously low shrinkage epoxy is a must to minimize induced microbends. Even when low shrinkage epoxy is used the best results are not guaranteed. In collaboration with Dan Fabricant at CFA we tested a short Polymicro FHP200/240/270 fiber with a very low shrinkage, slow curing epoxy (HYSOL EA9313). Table 2 shows the percentage of an f/8 input beam output into f/8. Clearly as the epoxy cured the FRD properties changed in a systematic way. We used a Minitool stainless steel furrule 1.5 mm in diameter which had a hole drilled in it slightly larger than the buffer, 300 microns in this case. The ends were "funneled" and held the epoxy well and kept the fiber centered with the side loads encountered during polishing. In this case the epoxy surrounds the fiber and is constrained by the funnel to the outside. Thus as it cures and shrinks it must constrict the fiber and introduce microbands near the end of the fiber.

TABLE II Time Dependence of FRD in a FHP200/240/270 Fiber Mounted with HYSOL EA9313 Epoxy

Date	% of f/8 input beam in f/8 output
10-13-88	81
10-14-87	73
10-21-87	64

During the course of our experiments we have noticed that fibers, especially hard buffered and PCS, are especially sensitive to the microbends introduced by the bonding epoxy. It is quite likely that the difference noted by different investigators are due to this. For example Avila and D'Odorico (1988) show that about 78% of the light output by a 2.6 meter length of Polymicro FHP320/385 falls within an F/8 beam. Barden (1987) obtains over 90% for a 30 meter length of the same fiber. We have noted over a factor of two difference in the same fiber with different epoxies or mounting schemes.

Our experience indicates better results when the fiber is tacked to the mount away from the end. Our current preferred mounting scheme is to tack the fiber in a triangular groove as described by Barden (1987). Figure 9 shows a complete mounting scheme for a single fiber in the focal plane of a telescope. The end of the fiber protrudes from the end of the ferrule. It was polished tacked with Nordlund 68 which is dissolved before use.

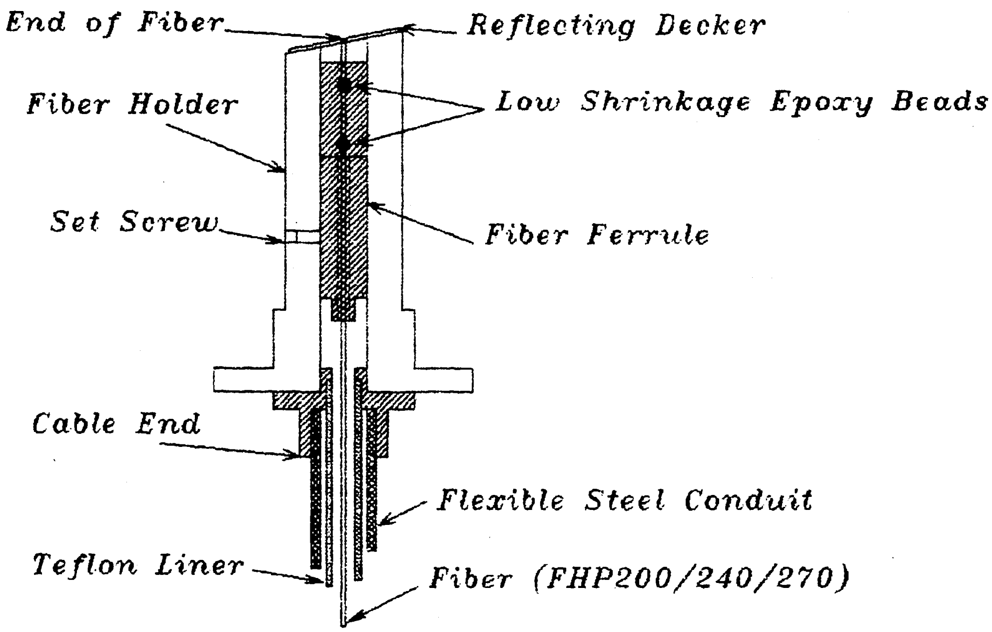

Fig. 8 This illustration shows how we currently mount single fibers located at a cassegrain focus. The tilted decker allows the use of conventional guiding hardware.

FRD VERSUS SCRAMBLING

As intimated by Figure 2, fibers are quite effective scramblers of azimuthal information. Heacox (1987) points out that substantial radial structure is preserved by a perfect cylindrical step index fiber. Experiments in our lab with even 20 meter fibers show that movement of a small spot across the input end at a constant f-ratio changes the radial output distribution. Indeed, fibers with better FRD properties such as the large core polymicro FHP320 show more apparent changes than the smaller core FHP100. As Heacox points out, while incomplete, the radial scrambling is substantial. However, for demanding applications such as stellar seismology where short term variations of about 1 meter/sec or less are sought even a small radial "memory" can be a serious source of error.

In a recent experiment using the Fiber Optic Echelle (Ramsey and Huenemoerder, 1986) at KPNO, Brown et al. (1988) found that the rms fluctuations in velocity from sky light were at a level consistent with that expected from the photon noise and system resolution and coverage. However observations of Procyon with the 2.1 meter telescope yielded velocity fluctuations somewhat less than expected given the photon noise. This is thought to be due to the fact that the solar sky light, since it uniformly illuminated the input end of the fiber, provide a stable radial and azimuthal output distribution. The stellar observations, subject to seeing and guiding fluctuation on the input of the fiber, caused some radial variation in the fiber output. This caused the illumination of the spectrograph pupil to vary in a small way which is important at the meter/sec level. This experience and the theoretical arguments of Heacox (1987) lead one to conclude that fibers with the best FRD properties are not the best scramblers for precision observations.

Only relatively short lengths of fiber will preserve a significant "memory" of the central obstruction in most telescopes. The output of fibers tends to be centrally peaked. The radial scrambling that does exist is sufficient for one to question using spectrograph optics with central obstructions. All refracting camera designs are more efficient for fiber spectrographs in general.

CONCLUSIONS

While much good work has been done in quantifying FRD in fibers, it is clear that improvements can be made in the testing techniques. There is still inconsistency in the measurements of different experimentors. At this time, it is not clear if this is so much due to experimental technique as to differences in fiber preparation procedures. It is important that we better define what and how we are measuring so we can provide better input to manufactures for improved fibers.

Some tentative generalizations do seem possible. FRD does not appear to be sensitive to the large scale bending of the fiber. Nevertheless, care must be taken to assure that this bending does not induce stress which causes microbends. Secondly, larger core fibers do appear to have better FRD characteristics than smaller core fibers with identical construction. Similarly, soft buffered fibers have better FRD than hard buffered fibers. The best f-ratios to feed typical glass clad fibers appears to be from about f/3.0 to about f/7.0 depending on the fiber diameter. Faster or slower ratios are more lossy. Lastly, it appears that good FRD characteristics are not compatible with the good radial image scrambling needed for high precision radial velocity observations.

ACKNOWLEDGEMENTS

I would like to especially thank Sam Barden, Bill Heacox and John Hill who have shared their thoughts and data on fibers for nearly a decade. In addition useful and stimulating discussions with Roger Angel, Dan Fabricant, Paul Felenbok, Peter Gray, are acknowledged. Kristin Clouser aided in much of the recent fiber preparation and data acquisition at Penn State.

This work has been supported by the NSF through Grants AST 8512894 and AST 8618167, and by The Pennsylvania State University. This support is gratefully acknowledged.

REFERENCES

Angel, J.R.P., Adams, M.T., Boroson, T.A. and Moore, R.L. 1977, Ap.J. 218, 776.

Avila, G. and D'Odorico, S. 1988, These proceedings.

Barden, S.C., Ramsey, L.W., and Truax, R.J. 1981, P.A.S.P., 93, 154.

Barden, S.C., Ramsey, L.W., and Truax, R.J. 1980, BAAS, 12, 460.

Barden, S.C. 1987, in "Instrumentation for Ground Based Optical Astronomy" ed. L.B. Robinson (Springer Verlag, New York), p. 250.

Brown, T. Gilliland, R., Noyes, R. and Ramsey, L.W. 1988, Unpublished Research.

Craig, W.W., Brodie, J.P., Hailey, C.J. and Stewart, R.E. 1988, These Proceedings.

Engelsrath, A., Danielson, B.L. and Franzen, D.L. 1986, NBSIR 86-3052.

Gray, P.M. 1983, Proc. S.P.I.E., 445, 57.

Guerin, J. and Felenbok, P. 1988, These Proceedings.

Heacox, W. 1980, "Optical and Infrared Telescopes of the 1990's", ed. A. Hewitt (Tucson:KPNO), p. 702.

Heacox, W.D. 1986, A.J. 92, 219.

Heacox, W.D. 1987, J. Optical Soc. Amer. A, 4, 488.

Hill, J.M., Angel, J.R.P., Scott, J.S., Lindley, D., and Hintzen, P. 1980, Ap.J. Lett. 242, L69.

Hubbard, E.N., Angel, J.R.P., and Gresham, M.S. 1979, Ap.J., 229, 1074.

Kamper, K.W. 1988, These Proceedings.

Latham, D.W., Anderson, J., and Geary, J.G. 1988, These Proceedings.

Lund, G. and Enard, D. 1983, Proc. S.P.I.E. 445, 65.

Meaburn, J. 1976. "Detection and Spectrometry of Faint Light" Reidel, Dordrecht, Netherlands.

Midwinter, J.E. 1979. "Optical Fibers for Transmission" John Wiley & Sons, New York.

Nelson, G.W. 1988, These Proceedings.

Powell, J.R. 1983, Proc. S.P.I.E., 445, 77.

Ramsey, L.W., Barden, S.C., Nations, H.L., and Truax, R.J. 1981, BAAS, 12, 836.

Ramsey, L.W. and Huenemoerder, D.L. 1986, Proc. S.P.I.E. 627, 282.

Shacklin, S. 1988, These Proceedings.

DISCUSSION

Question: For a slow f/ratio input (f/20 to f/30), what is the loss if you accept a fast (f/4 to f/8) output cone?
Answer: The output into a fast beam, such as f/4, should be limited only by end reflection losses and internal absorption. For a fused silica fiber, such as the Polymicro, I would expect roughly 87% of the f/20 input beam to come out within f/4.

Question: Gloge's modal diffusion theory for optical fibers predicts that the extent of focal ratio degradation (FRD) is proportional to the square root of the fiber length. Is this consistent with your observations?
Answer: Given the likely systematic errors, I would say no.

Question: The polyimide hard buffer enables the fiber to be glued (epoxied) directly to glass without a ferrule and without removing the buffer. This squeezes the fiber less. Do you think this will also reduce the effects of FRD?
Answer: Unless the epoxy shrinks a lot, it might well induce less FRD.

Comment by S. Barden regarding light scrambling: If you put a small spot of light on the input of a fiber and inspect the distribution of light on the output face of the fiber, you notice a central peak when the spot is centered on the fiber. As you move the spot away from the fiber axis, the output central peak turns into a ring. This suggests that the Azimuthal scrambling of fibers is essentially perfect while the radial scrambling is not complete. This non-perfect radial scrambling may introduce some zonal errors in the spectrograph especially if the fiber end is reimaged onto a slit.

Question to G. Nelson from L. Ramsey: There is often a spiral structure seen in the output beam of a fiber. Is this related to the inherent concentric variations you get when the fiber preform is created with a CVD process?
Answer: It very well could be a possibility. If you look at a preform before it is drawn into a fiber, especially in the graded-index preforms, it looks like tree rings. I don't see that same property in the pure silica preforms we deal with, but I haven't examined them that closely to see if there are any variations from layer to layer. It may be a contributing factor though.