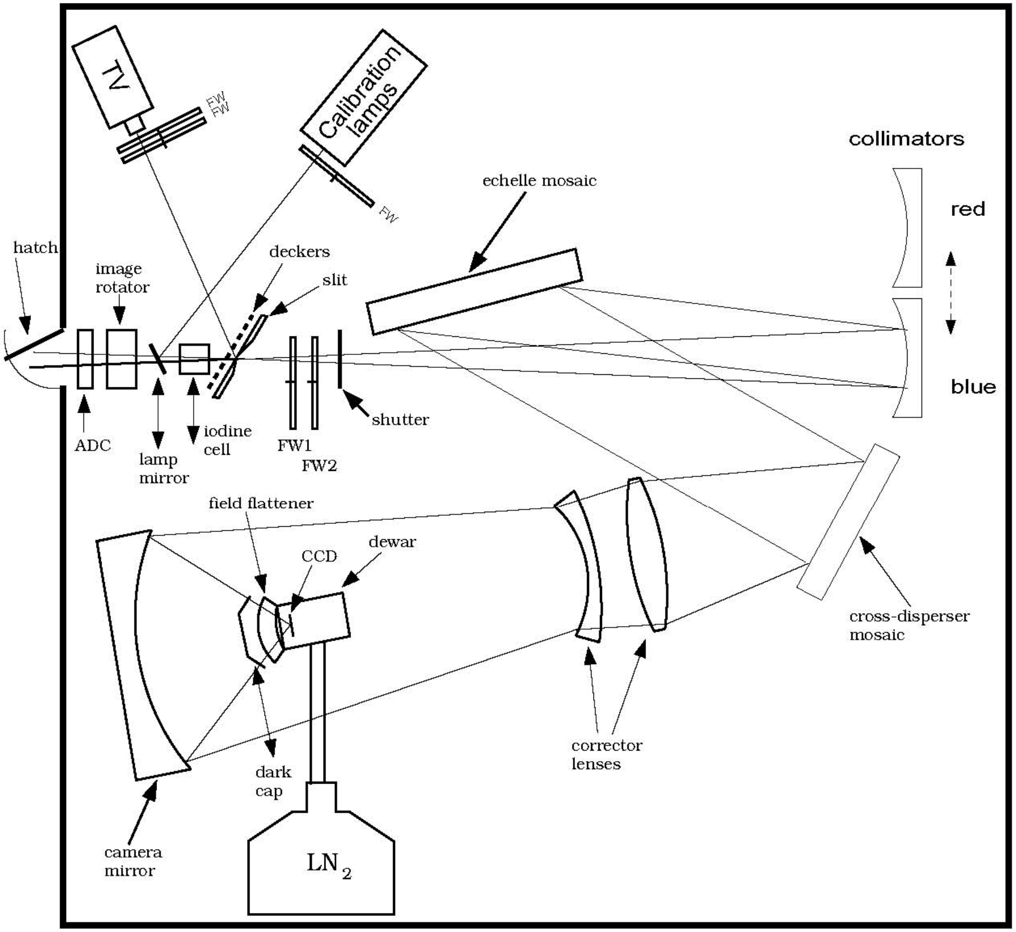
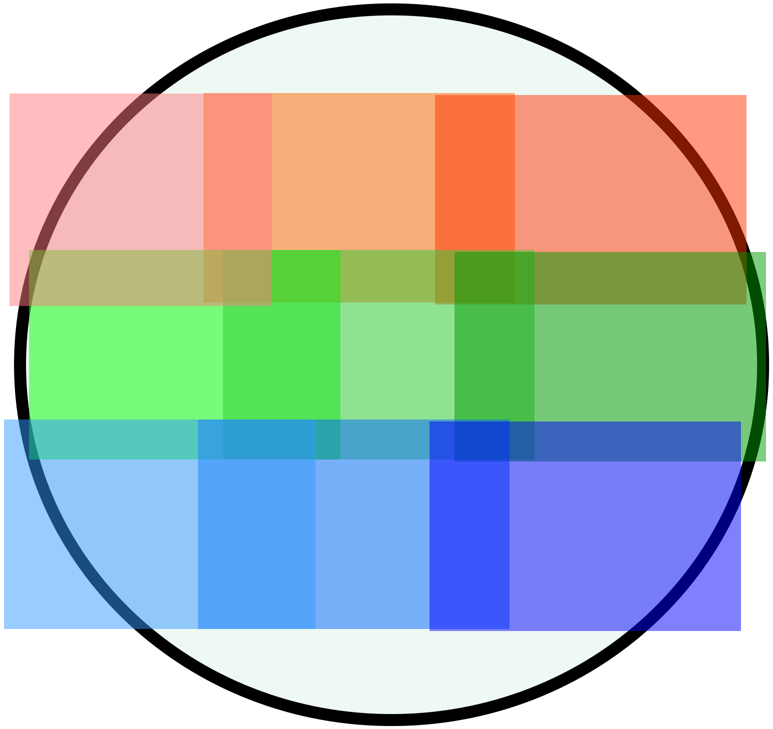
Optical Fibers in Spectrograph Design; A Technical Overview

- **Spectrographs for Precision Radial Velocities**
  - **Why fiber coupling is useful**
- **Properties of Fibers**
  - **Transmission**
  - **Modal behavior**
    - **Focal ratio degradation**
    - **Scrambling**
    - **Modal Noise**

Keck HIRES: a classic well designed cross dispersed echelle



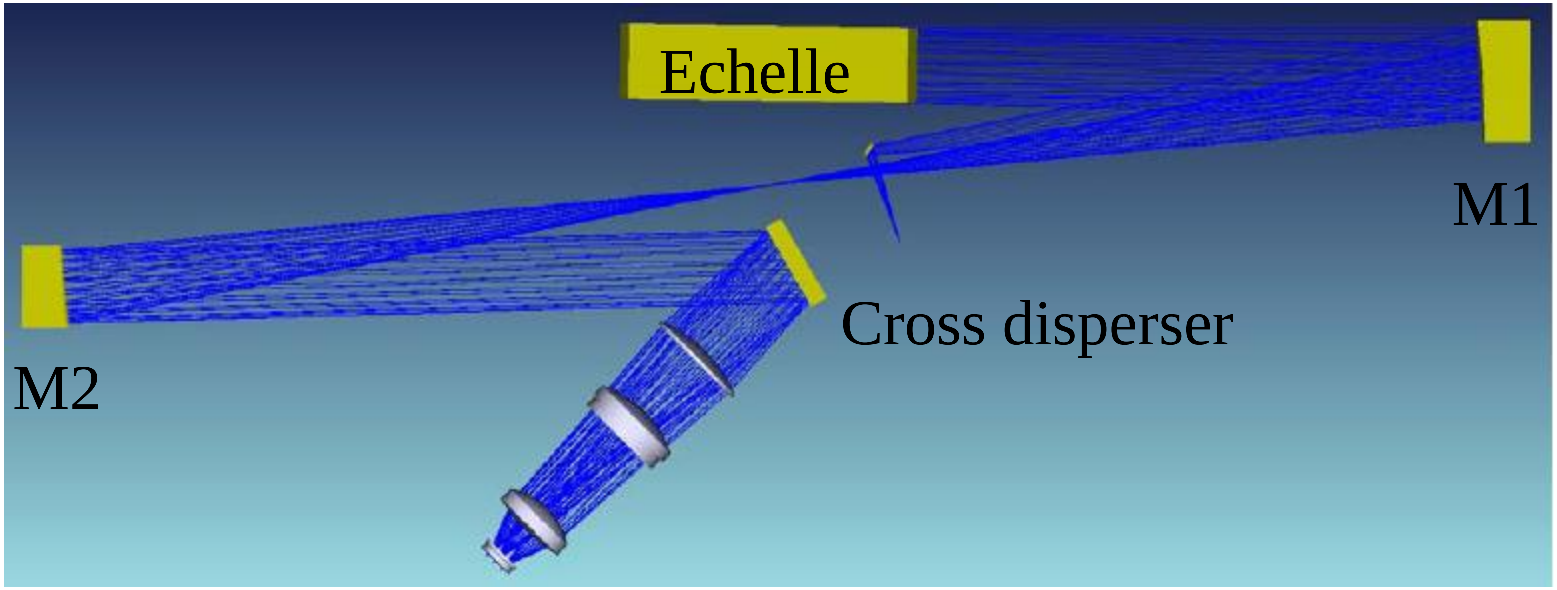
Camera Entrance Pupil must be larger than Grating(s)



Thus spectral regions take different paths through camera and undergo different field aberrations

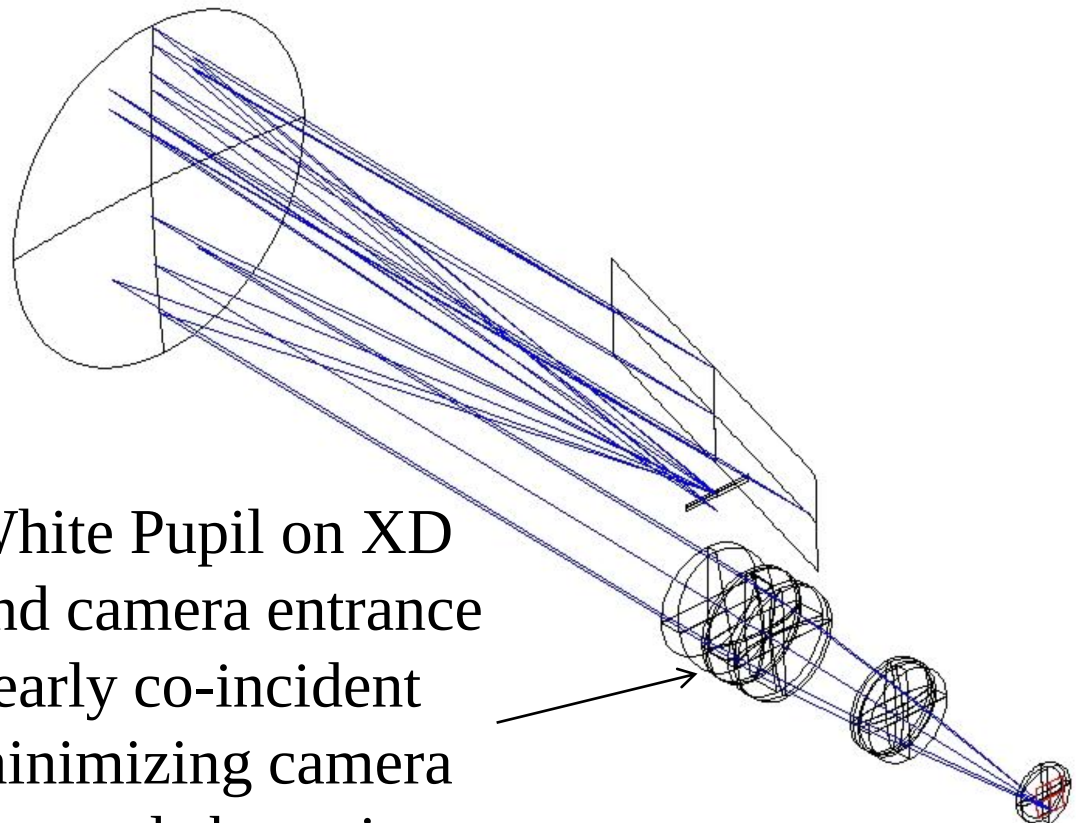
Hobby-Eberly telescope HRS

A "White" Pupil design based on UVES



Well defined pupil on Echelle AND on XD close the camera entrance.

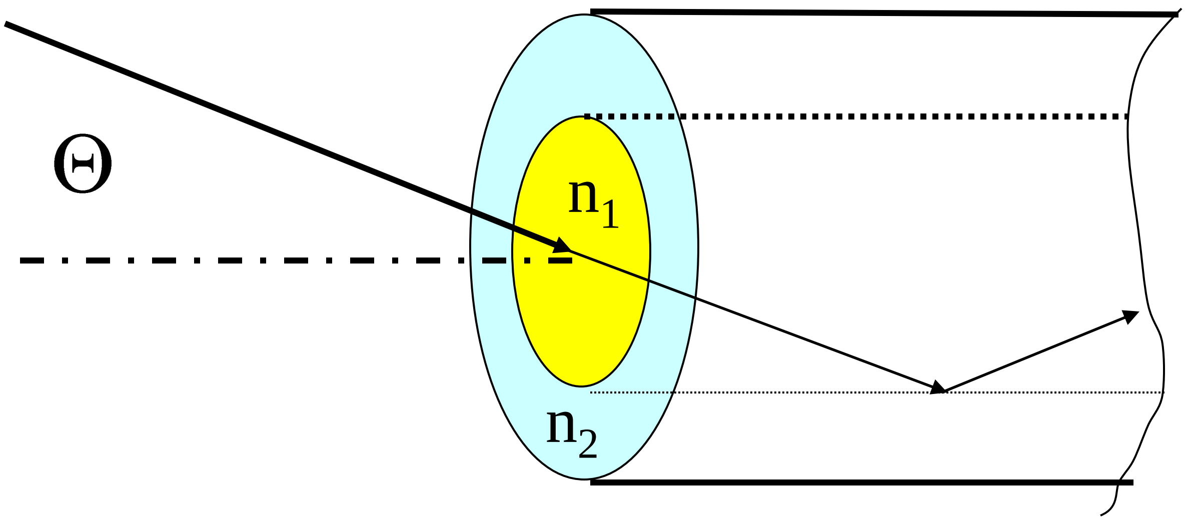
ESO HARPS



White Pupil on XD and camera entrance nearly co-incident minimizing camera size and aberrations.

Basic principle of total internal reflection

$$n_1 > n_2$$



Ray will reflect as long as sin θ < NA

$$\text{Sin } \Theta = NA = \{n_1^2 - n_2^2\}^{0.5}$$

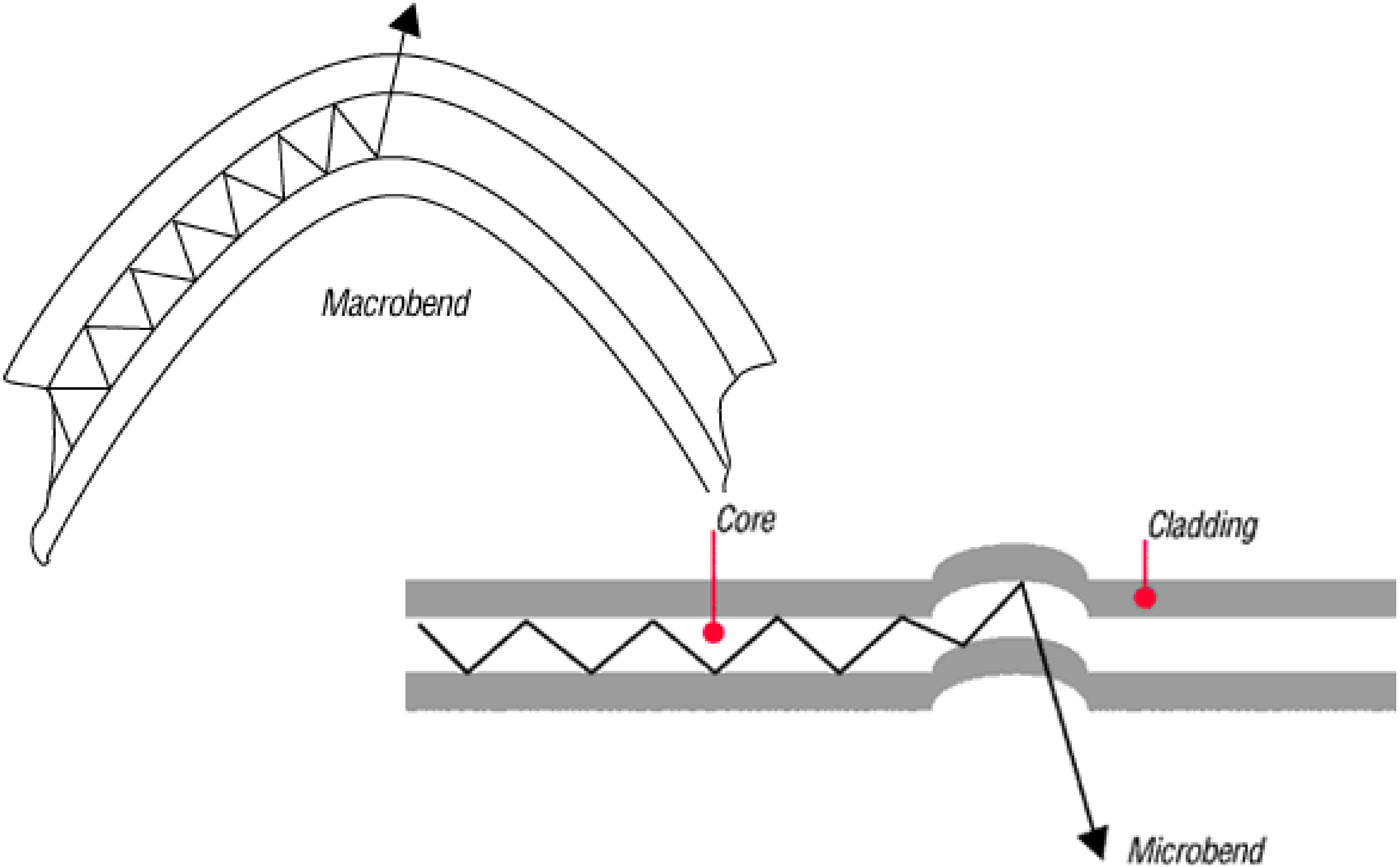
Some measurement terminology

- **Far Field**
  - Light distribution in diverging beam from fiber
  - Directly related to how spectrograph optical elements (collimator, gratings, camera) illuminated
- **Near Field**
  - Light distribution over face of fiber
  - Directly related to PSF imaged on detector

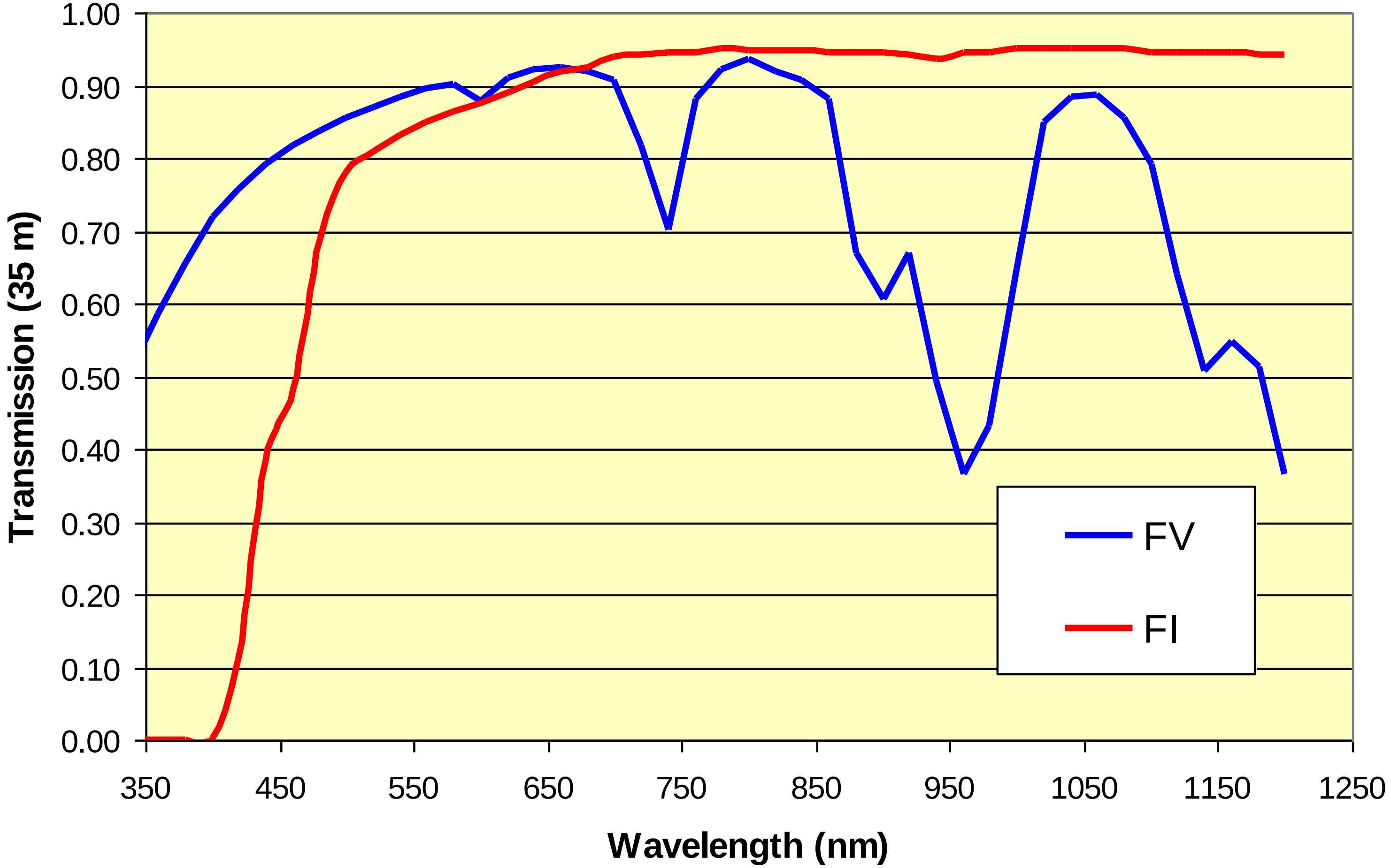
Fiber Loss Mechanisms

- Light transmission
  - $P(z) = P(0)\ 10^{-(\alpha z/10)}$
  - Loss (dB) = $-10 \log \{ P(z)/P(0)\} = \alpha z$
- Loss mechanisms
  - Basic limit due to scattering (goes a λ^{-4})
  - Metal impurities increase absorption in blue
  - OH absorption in red
  - Waveguide leakage

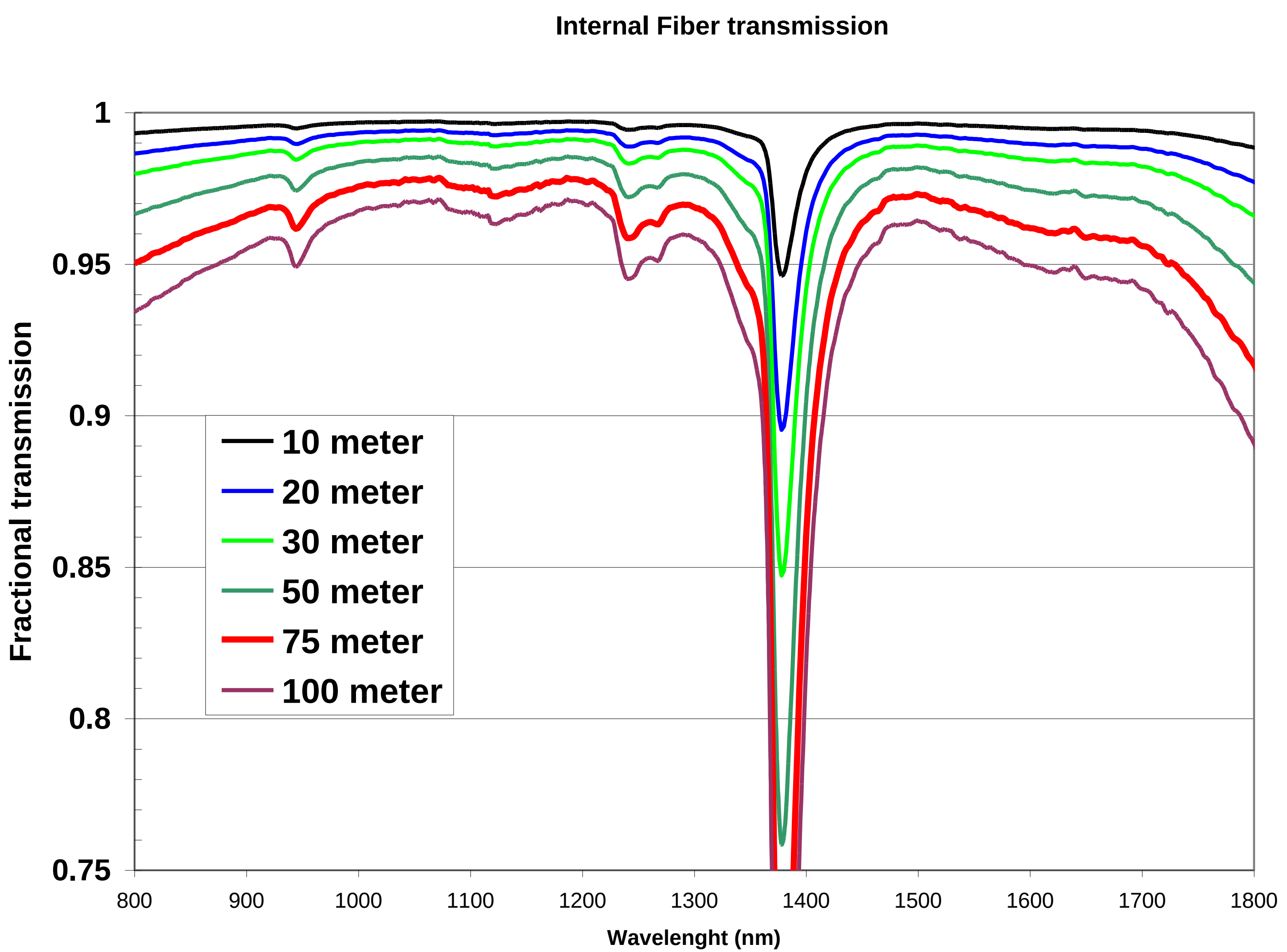
Bend losses



Fiber transmission



Transmission of Polymicro FIP fiber



Waveguide loss: Schotz et al. (ASPC152, 1998) plot

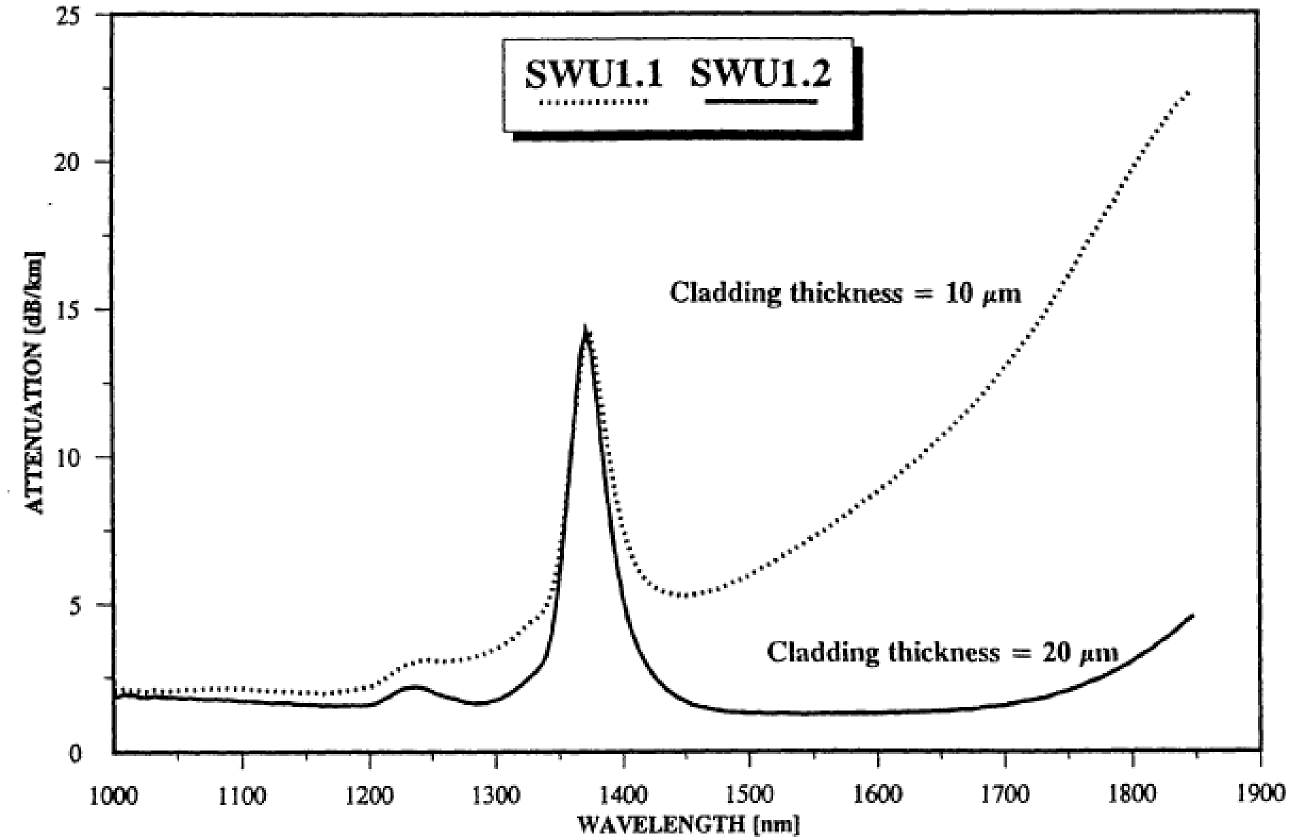
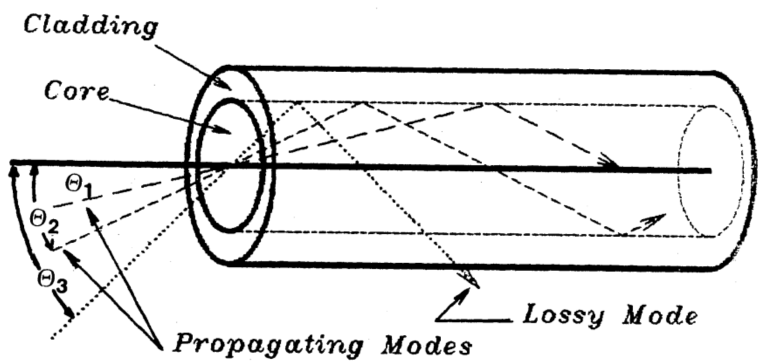


Figure 3. Transmission of fibers with different cladding thicknesses.

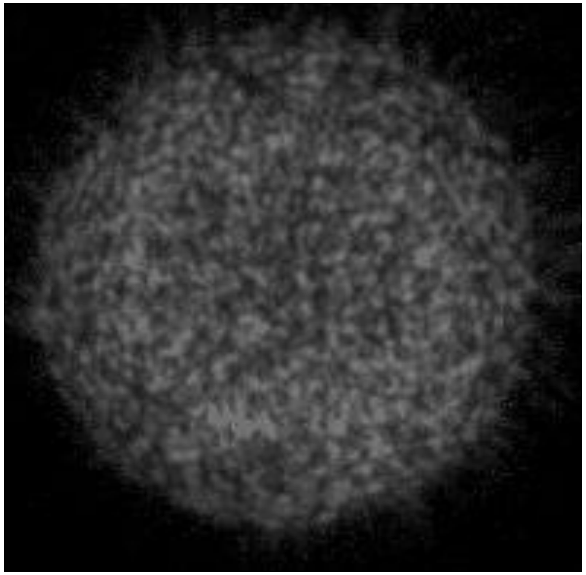
Fibers Modes

- **Simple view of modes is rays at different angles**
- **In reality fiber is a waveguide where modes can interfere at fiber ends.**



From Ramsey, ASPC 3, 1988

Familiar laser speckle



From Grupp, A&A 414, 2003

Fibers Modes

- **Number of modes $n = V^2/2$**

  Where $V = \pi d\, NA/\lambda$

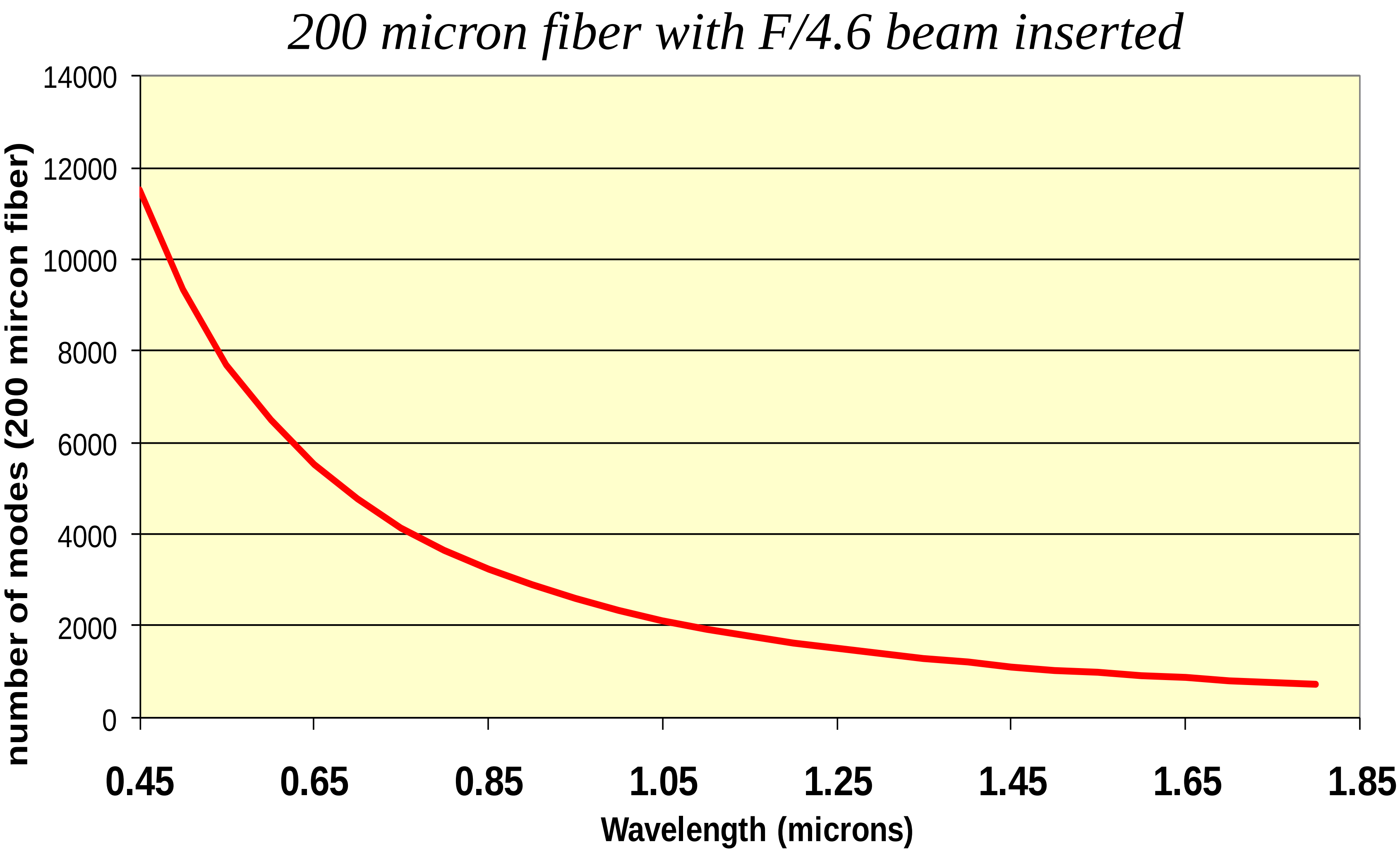
  d is diameter of fiber

  λ is wavelength in units of d

  NA is numerical aperture

- **Modal behavior responsible for**
  - **Focal Ratio Degradation**
  - **Scrambling**
  - **Modal Noise**

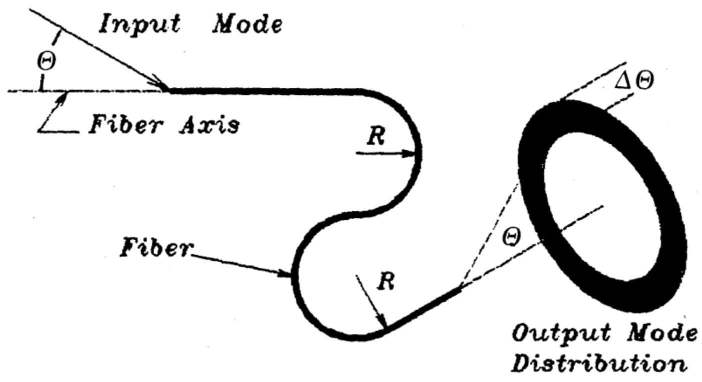
Modes decrease rapidly with wavelength

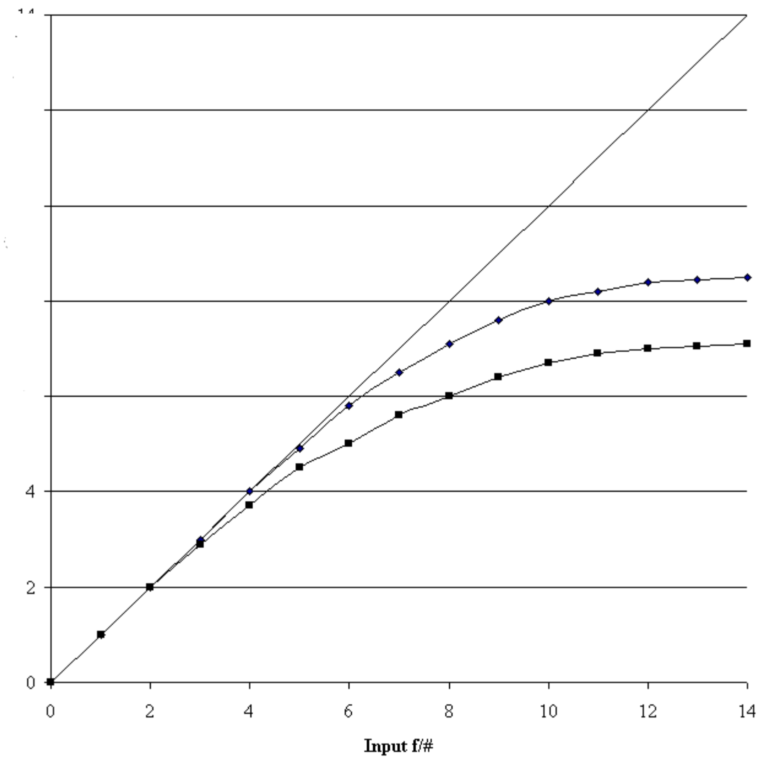


Focal Ratio Degradation (FRD)

- **Basically modal dispersion**
  - **Bending**
  - **Irregularities in core-cladding interface**
  - **Variations is fiber diameter**
  - **Small deformation at terminations**
- **FRD effects in spectrographs**
  - **Loss in throughput resolution product**

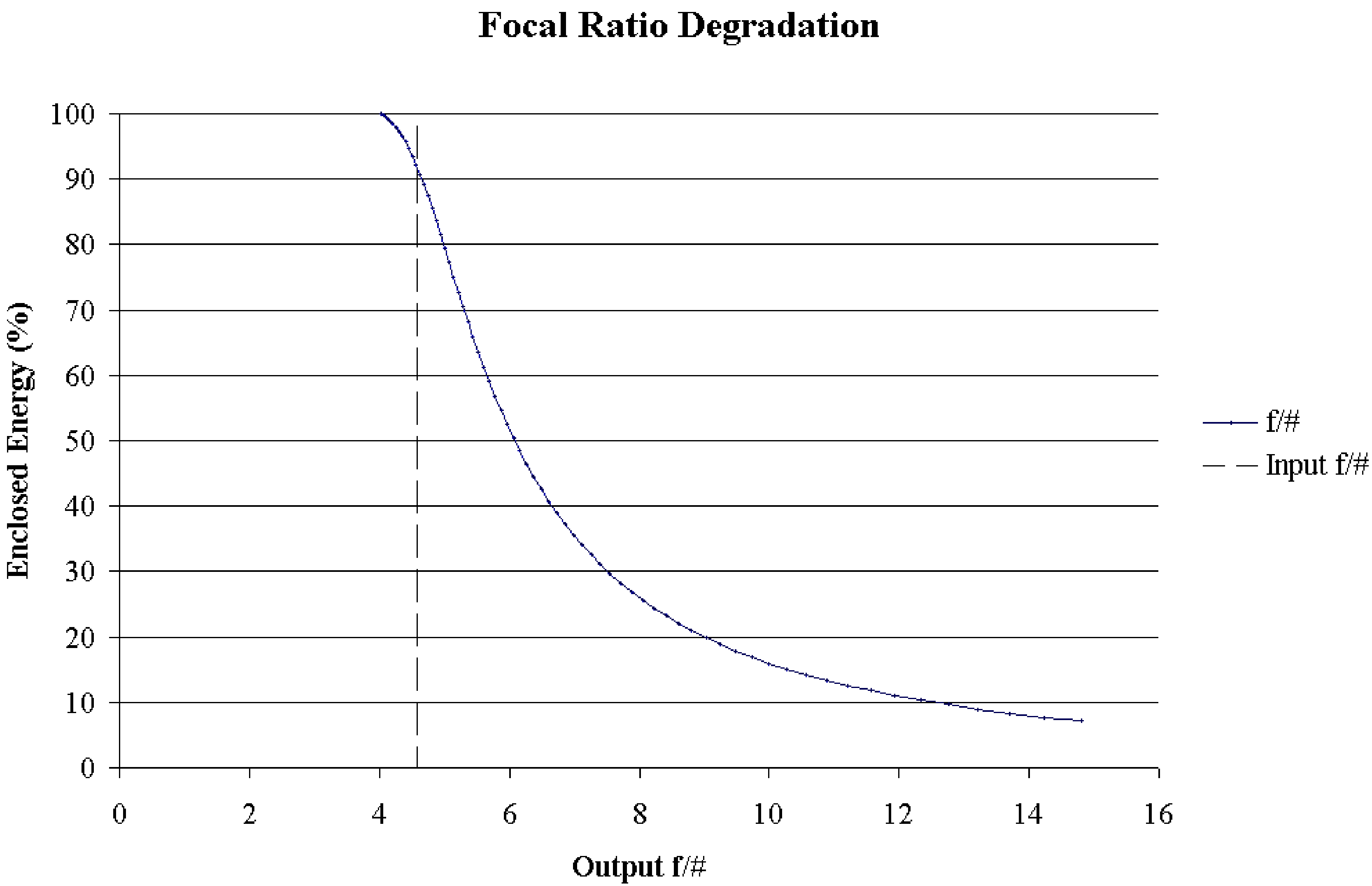
Focal Ratio Degradation





From Barden & Ramsey, PASP 1980

PENNSTATE 1855



Sessions & Ramsey unpublished; HET MRS fiber cable test

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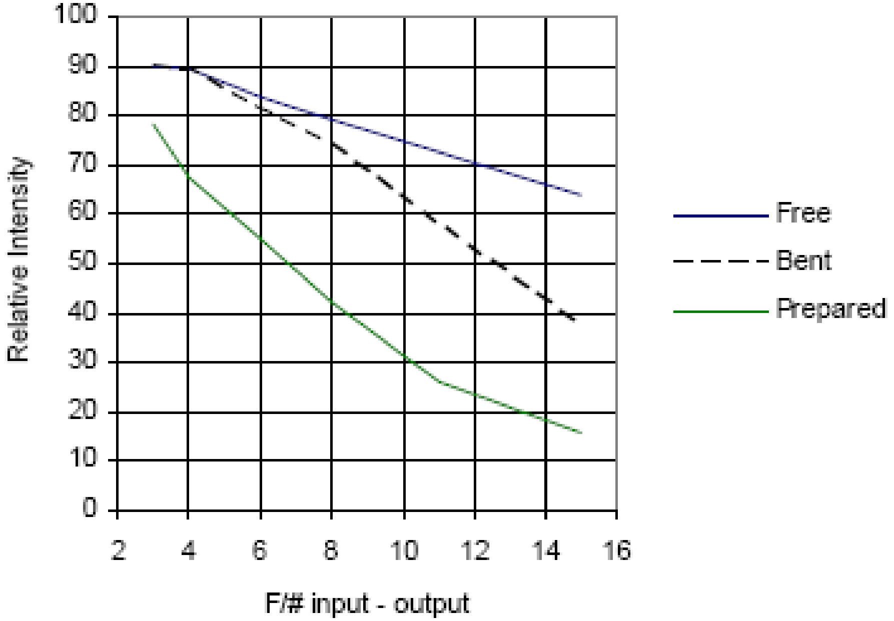
FRD depends on bending but weakly on length



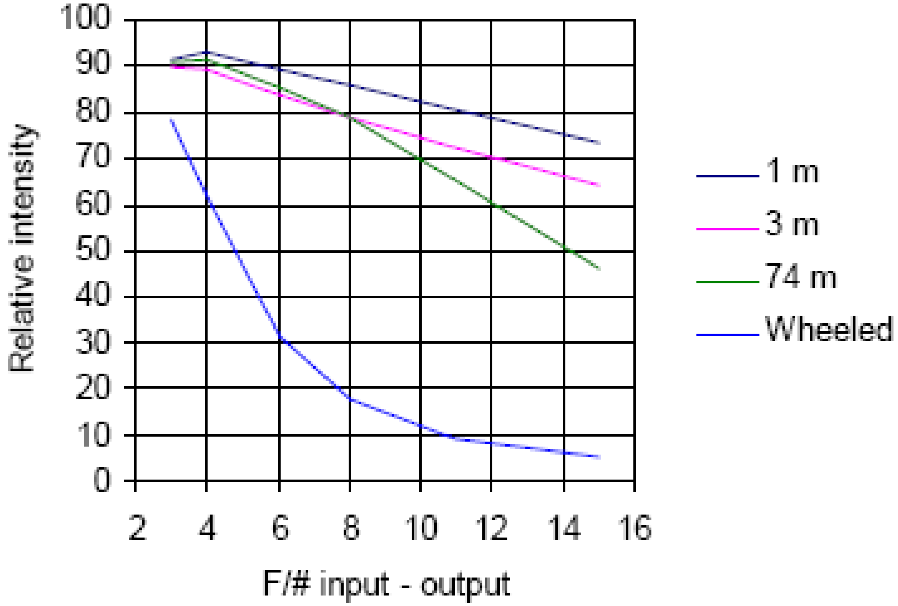


Figure 3. FRD of a 3m Polymicro 100 μm FBP fibre. In the first lower curve, the fibre is bent following a loop of 15 mm radius. The lowest curve is for a FBP fibre with connectors and protective cable

Figure 4. FRD for a 100 μm fibre for 3 lenghts: 1, 3 and 74 m. The influence of the transportation wheel on the 74 m is clearly shown

From Avila et al., SPIE 6269 2006

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FRD depends fiber core size & Photonic promise

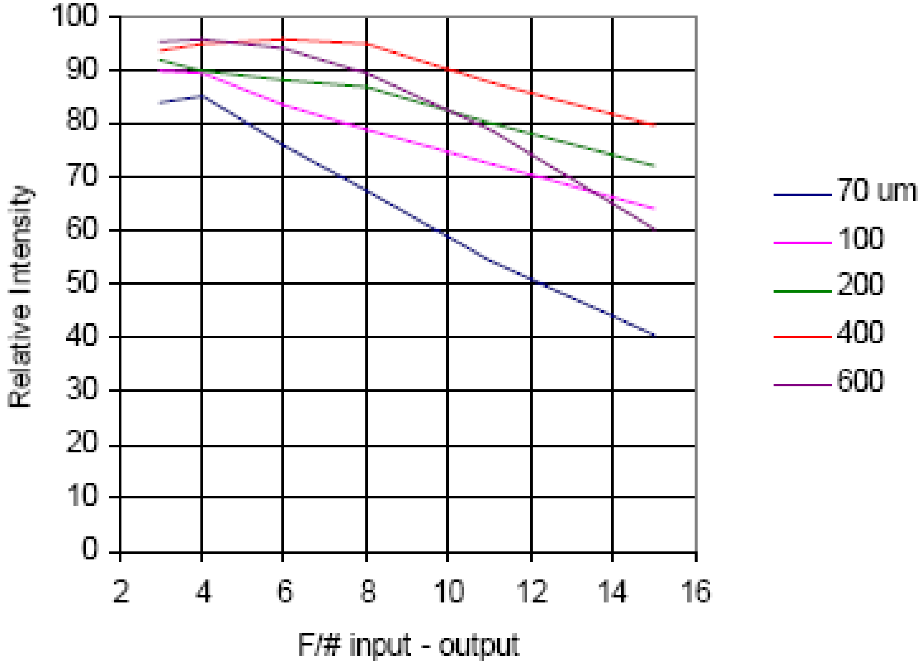


Figure 5. FRD for 3 m fibres as a function of the core diameter

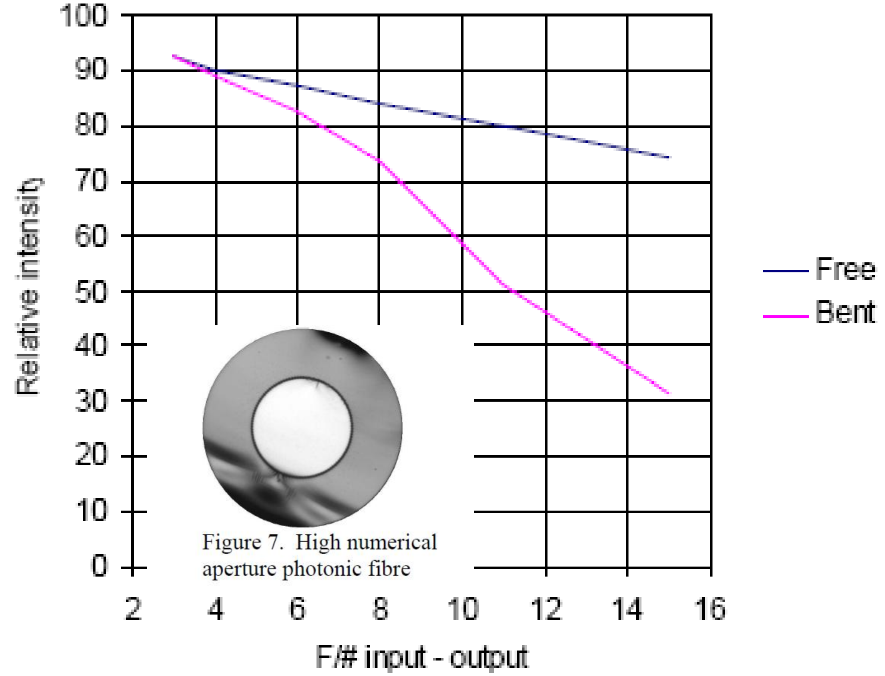


Figure 6. FRD by a photonic fibre. 110 μm core diameter and 20 m long

From Avila et al., SPIE 6269 2006

Early scrambling Characterization

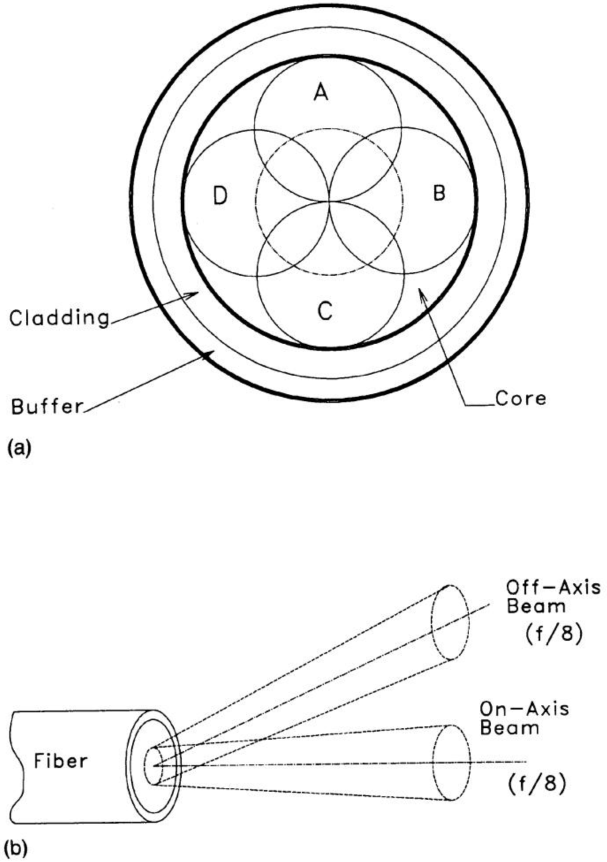
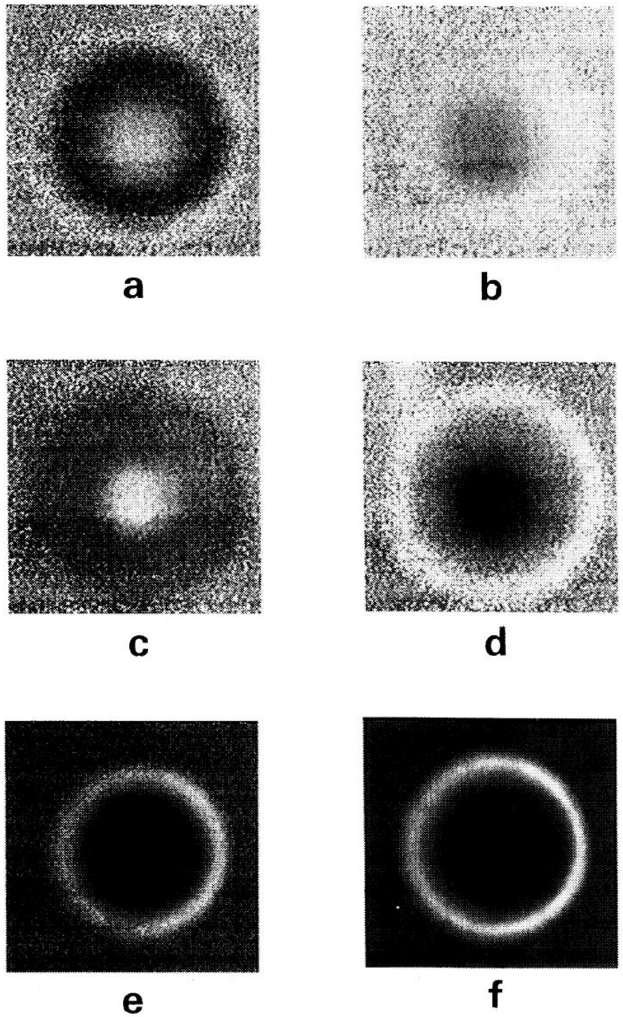
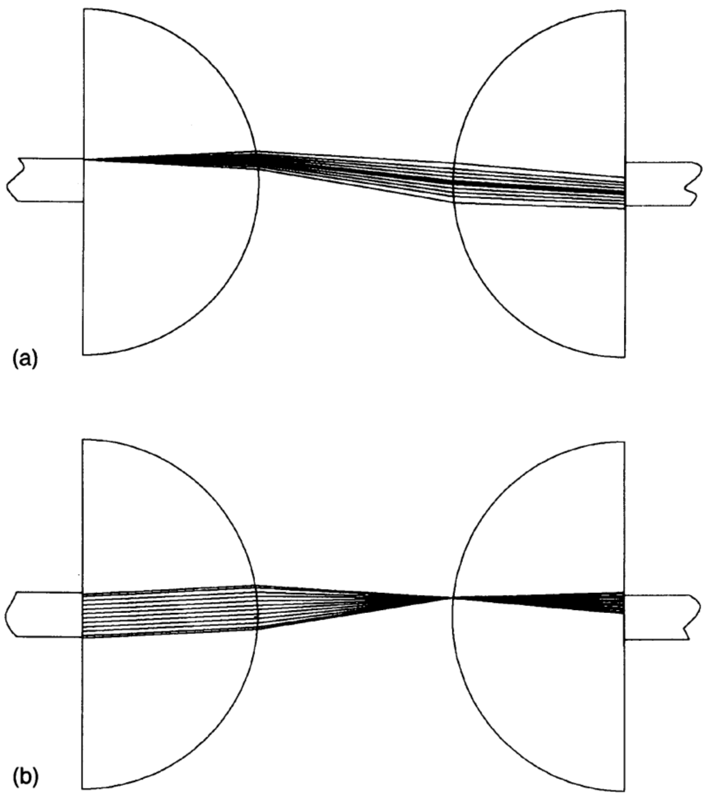


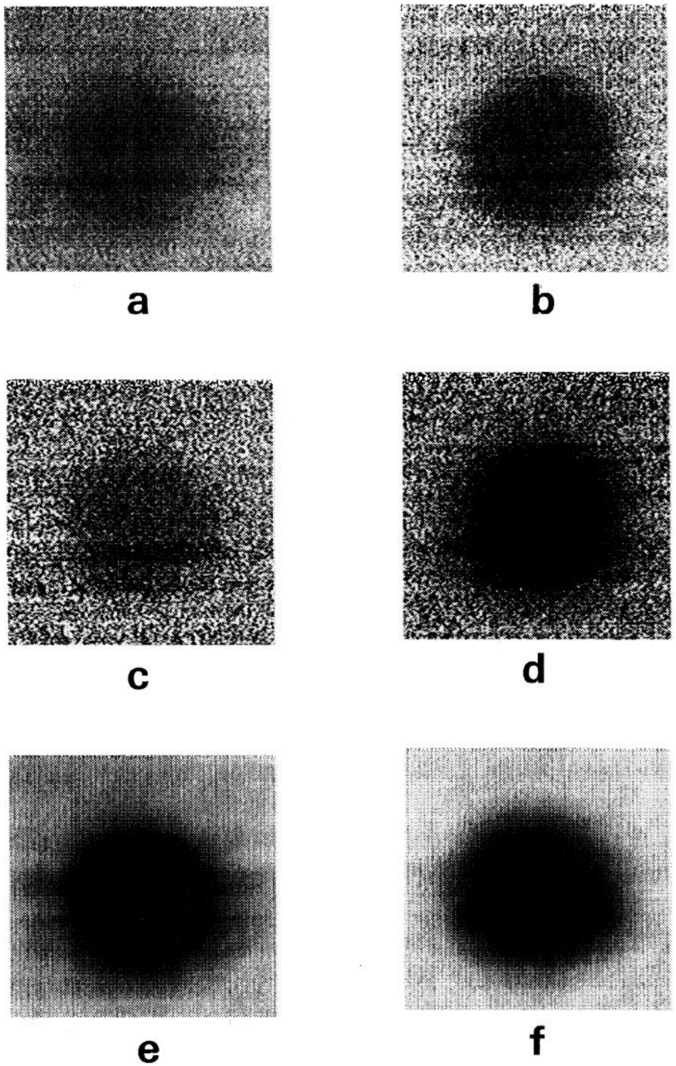
FIG. 3—The top panel (a) shows the positions of the 107 μm input spot from a $f/8$ beam on the core of a 200 μm diameter fiber. The dot–dashed line is the center position which is the reference position for measurements in this paper. The *top* position is labeled A with the *right, bottom* and *left* positions labeled B, C, and D, respectively, in the figure. The bottom panel (b) shows the off-axis illumination of the fiber keeping the $f/$ratio constant.



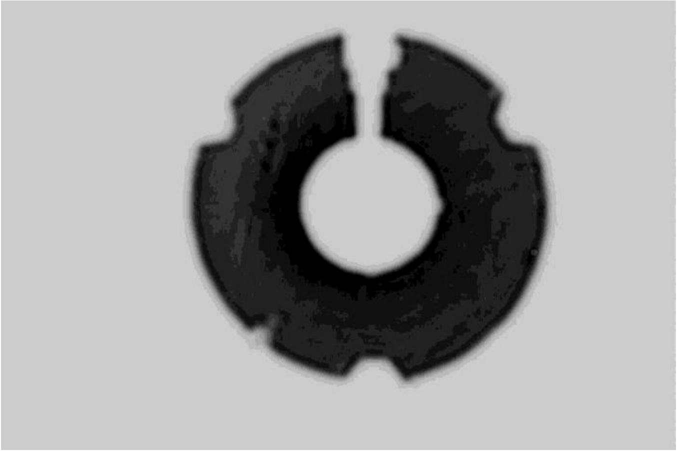
From Hunter & Ramsey, PASP 102 1992

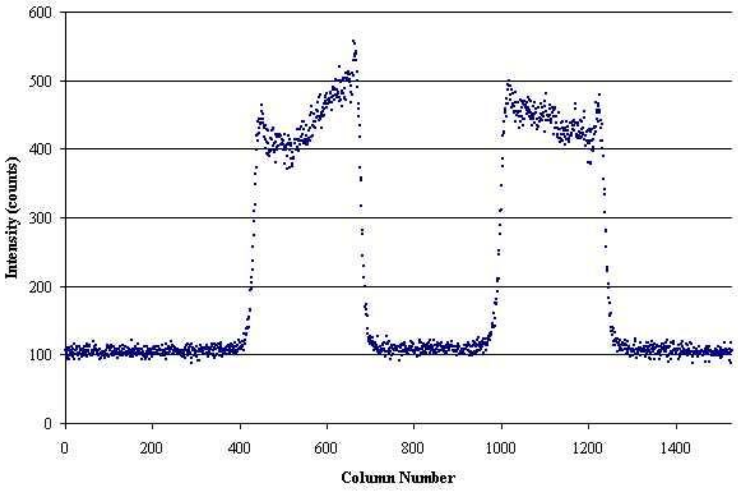
Early Double Scrambler

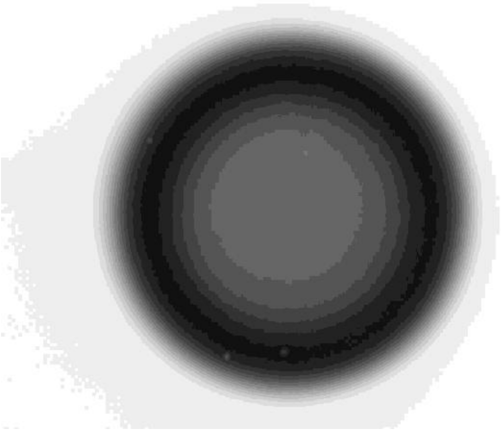


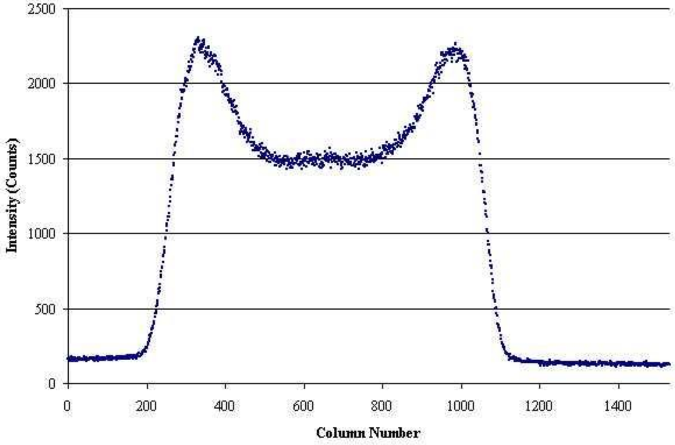


From Hunter & Ramsey, PASP 102 1992




600
500
400
300
200
100
0
Intensity (counts)
0
200
400
600
800
1000
1200
1400
Column Number




2500
2000
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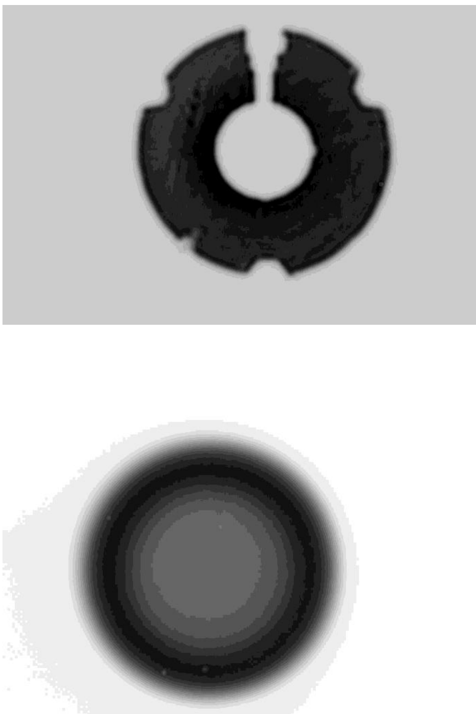
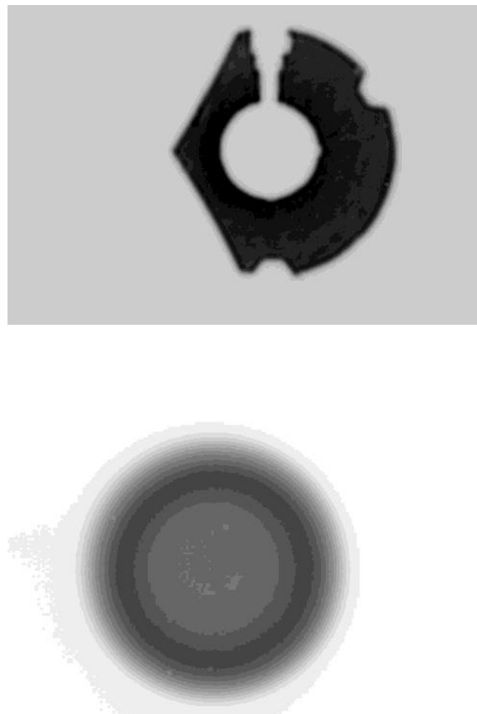
1000
500
0
Intensity (Counts)
0
200
400
600
800
1000
1200
1400
Column Number

Input & Output (ff) Images

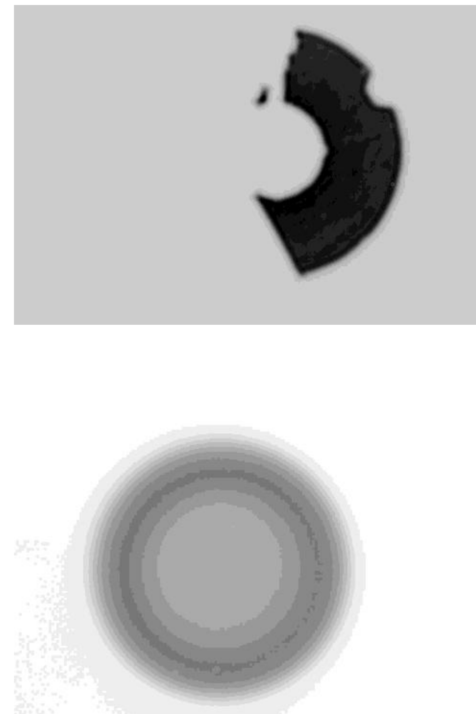
m0



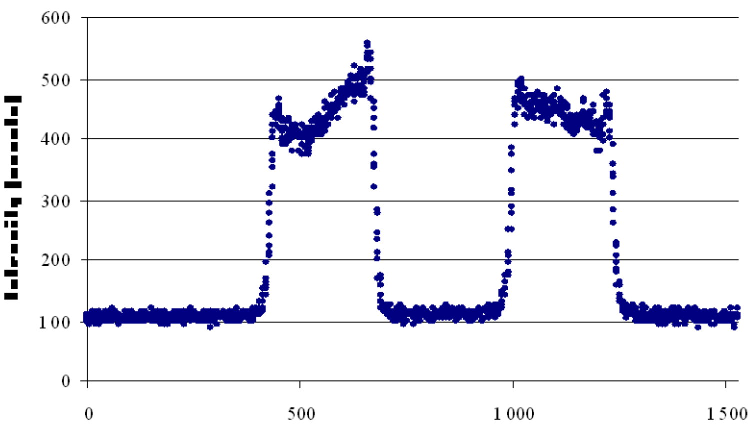
m3

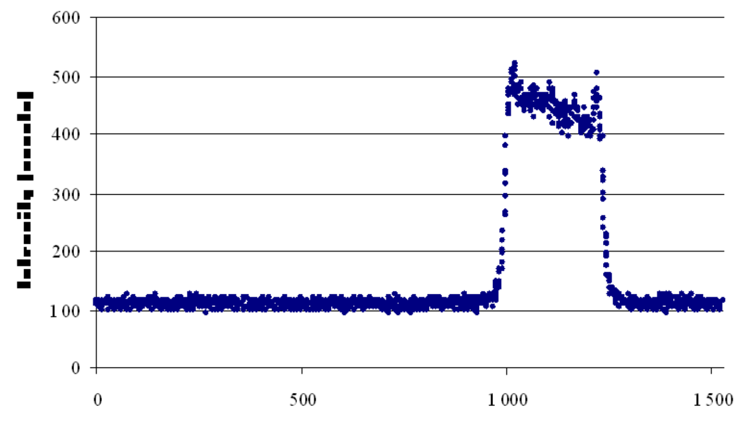


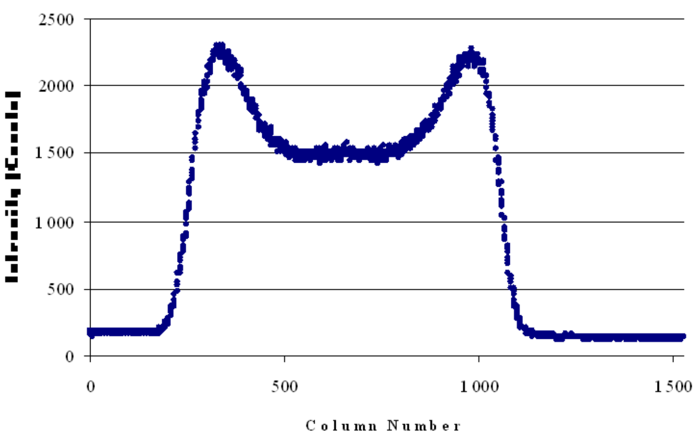
m6

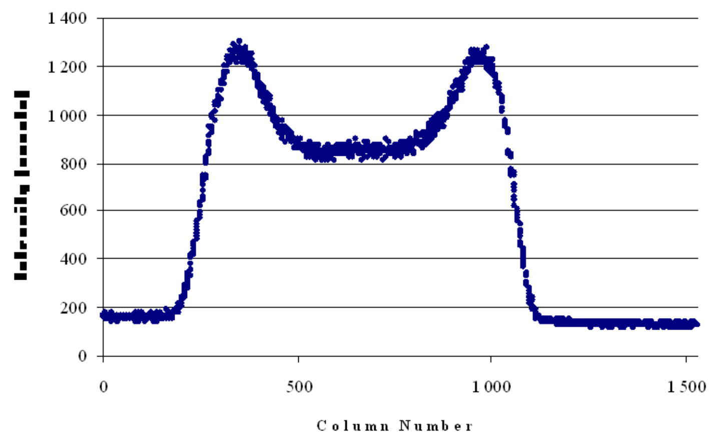


Cuts across image demonstrates scrambling

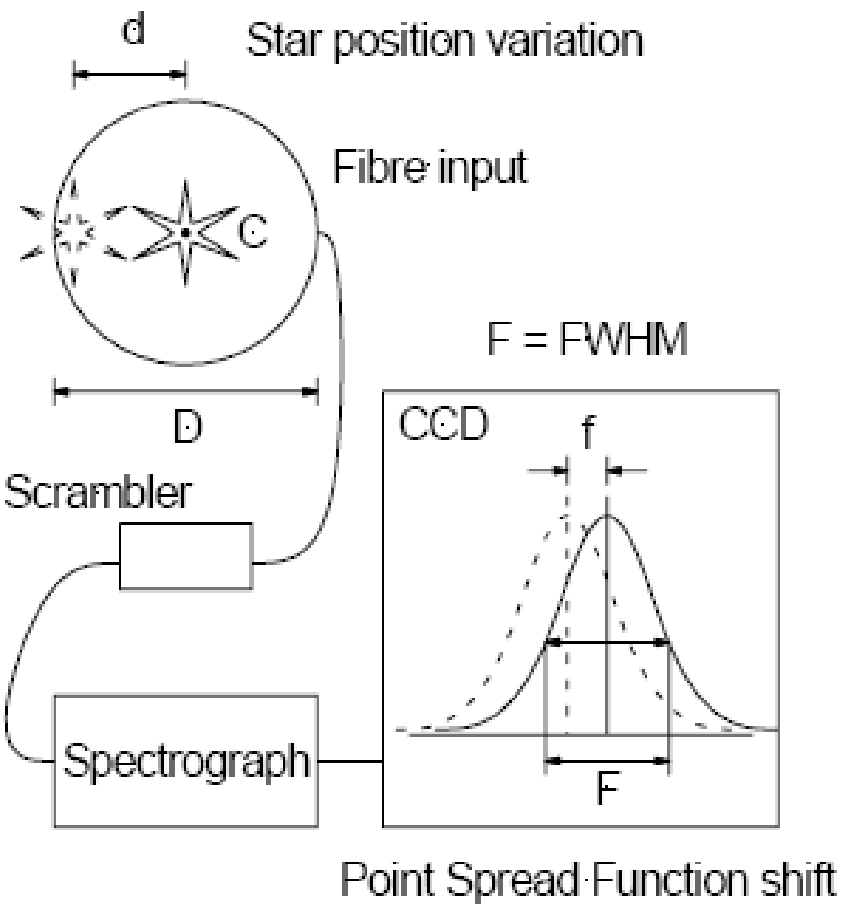








Scrambling Gain



$$G = d/D \times [f/F]^{-1}$$

From Avila & Singh, SPIE 7018 2008

ESO Scrambling Gain Measurements

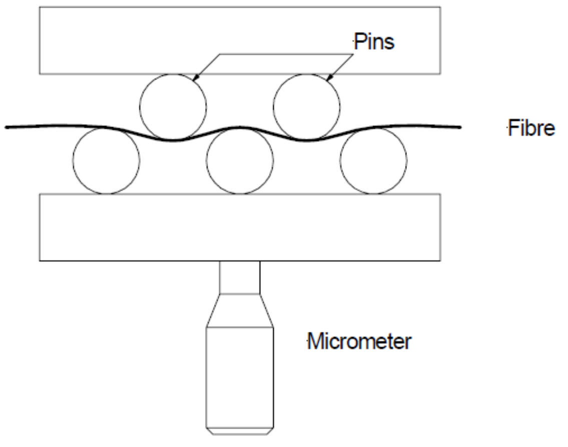


Figure 8. Fibre mode mixer

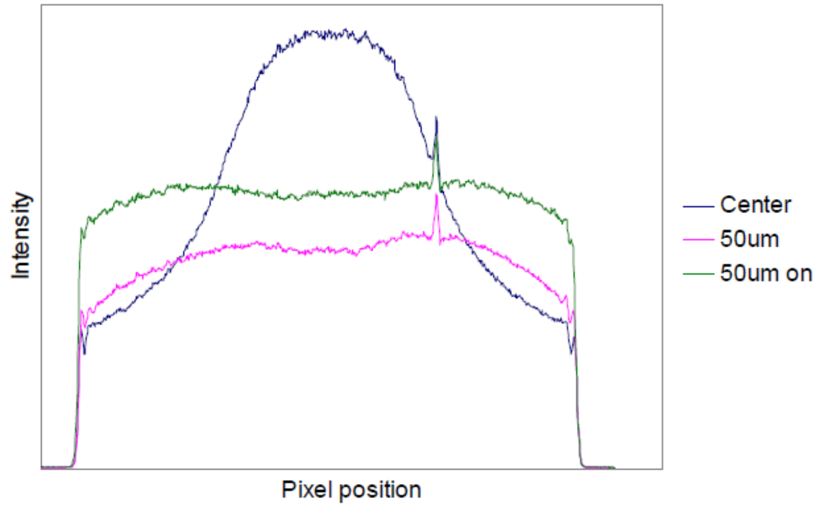


Figure 10. Intensity profile at the middle of the fibre

Star displacement	Free fibre	Mode mixer: weak	Mode mixer: strong	Vibrator ~ 40 Hz
- 0.5 Ø $_{fibre}$	104 / 112	642 / not available	1070 / 3350	803 / 112
+ 0.5 Ø $_{fibre}$	128 / 150	803 / not available	1280 / 5800	920 / 150
Δ FRD	100 % / 100 %	91 % / not available	83 % / 65 %	> 97 % / 100 %

From Avila et al., SPIE 6269 2006

Some conclusions on scrambling

(See Avila & Singh, SPIE 7018 2008)

- **Bare fiber has a scrambling gain ~100**
- **Vibration can increase to ~ 800 with no light loss**
- **Optical scrambler can give reasonable gains at some throughput loss; 20-40%**
- **Don't even think about pupil imaging**
- **Non-circular fibers in Chazelas talk?**

Modal Noise

Modal noise is proportional to $S/n^{1/2}$

Ignoring dark current we have S/N for a CCD:

$$S/N = S\,[S + R^2]^{-1/2}$$

With Modal Noise:

$$S/N = S\,[S + R^2 + S^2/n]^{-1/2}$$

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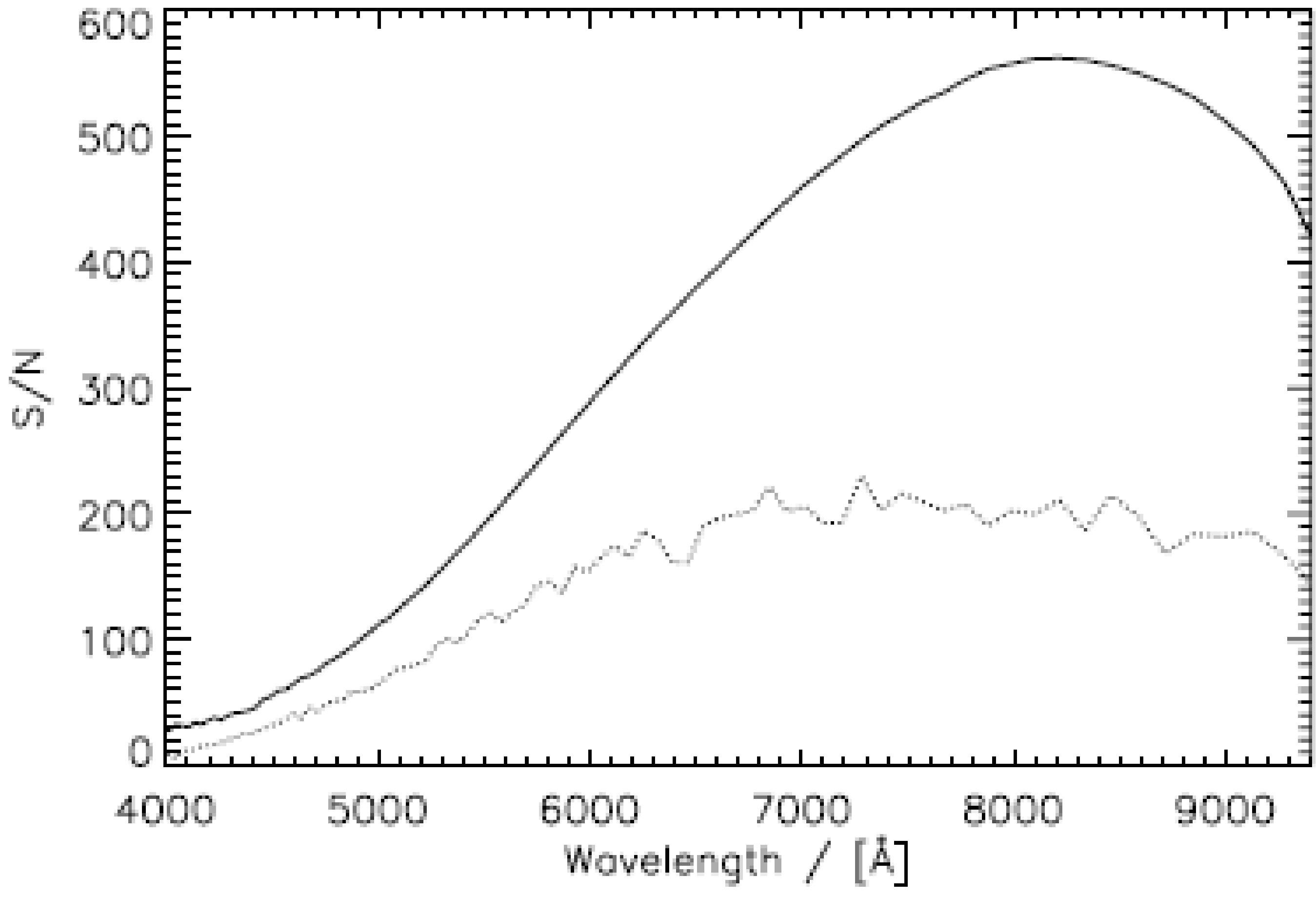

Fig. 1. Measured and predicted signal to noise. Upper full curve: expected photon noise; lower dotted curve: measured noise.

From Grupp, A&A 414, 2003

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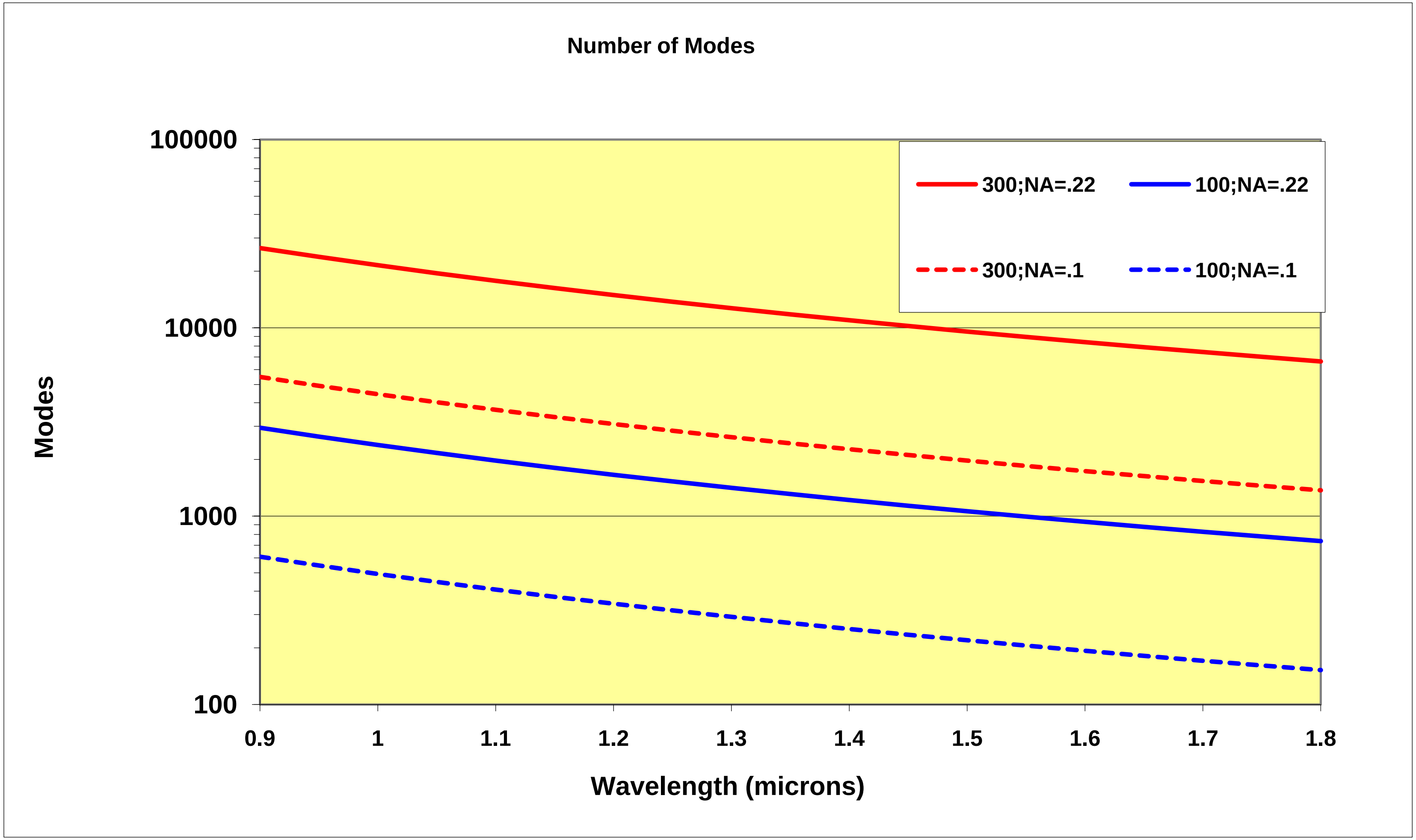
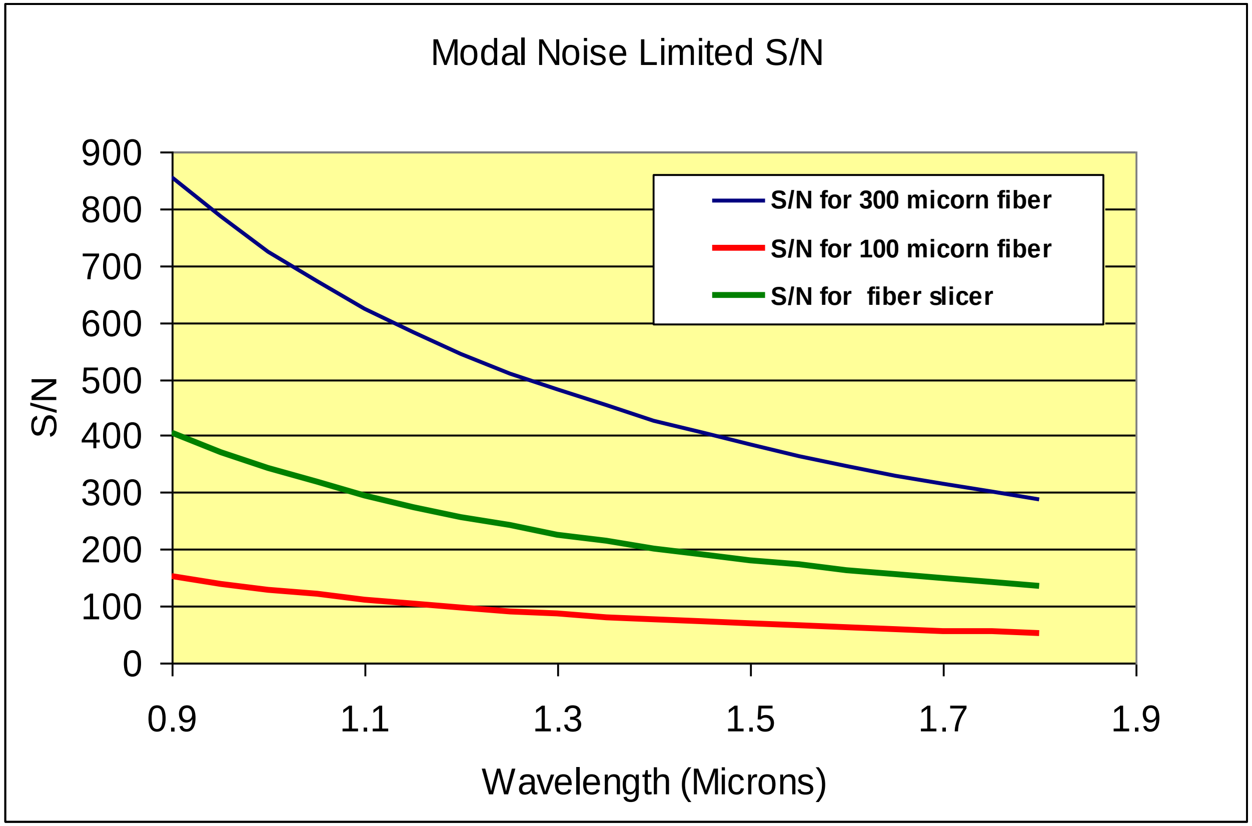
Modes in Near IR



Modal Noise Prediction

Baudrand and Walker (PASP 113, 851, 2001)

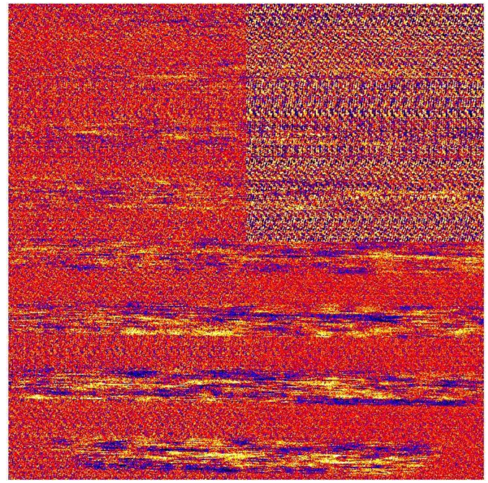
$$(S/N)_{limit} = (N_\lambda)^{0.784}$$



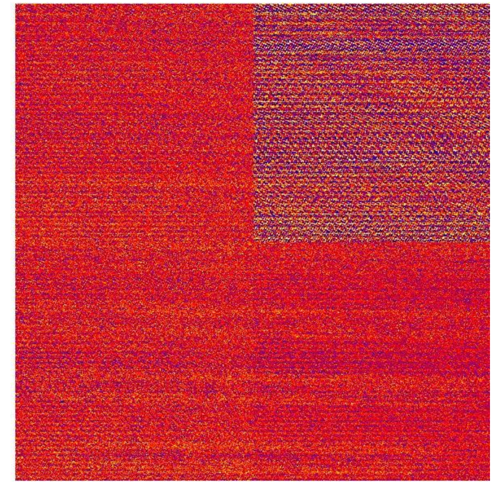
Will need vibrational modal noise elimination to work in H

Modal Noise Experiment: J band

Ratio of consecutive Flats with no fiber disturbance

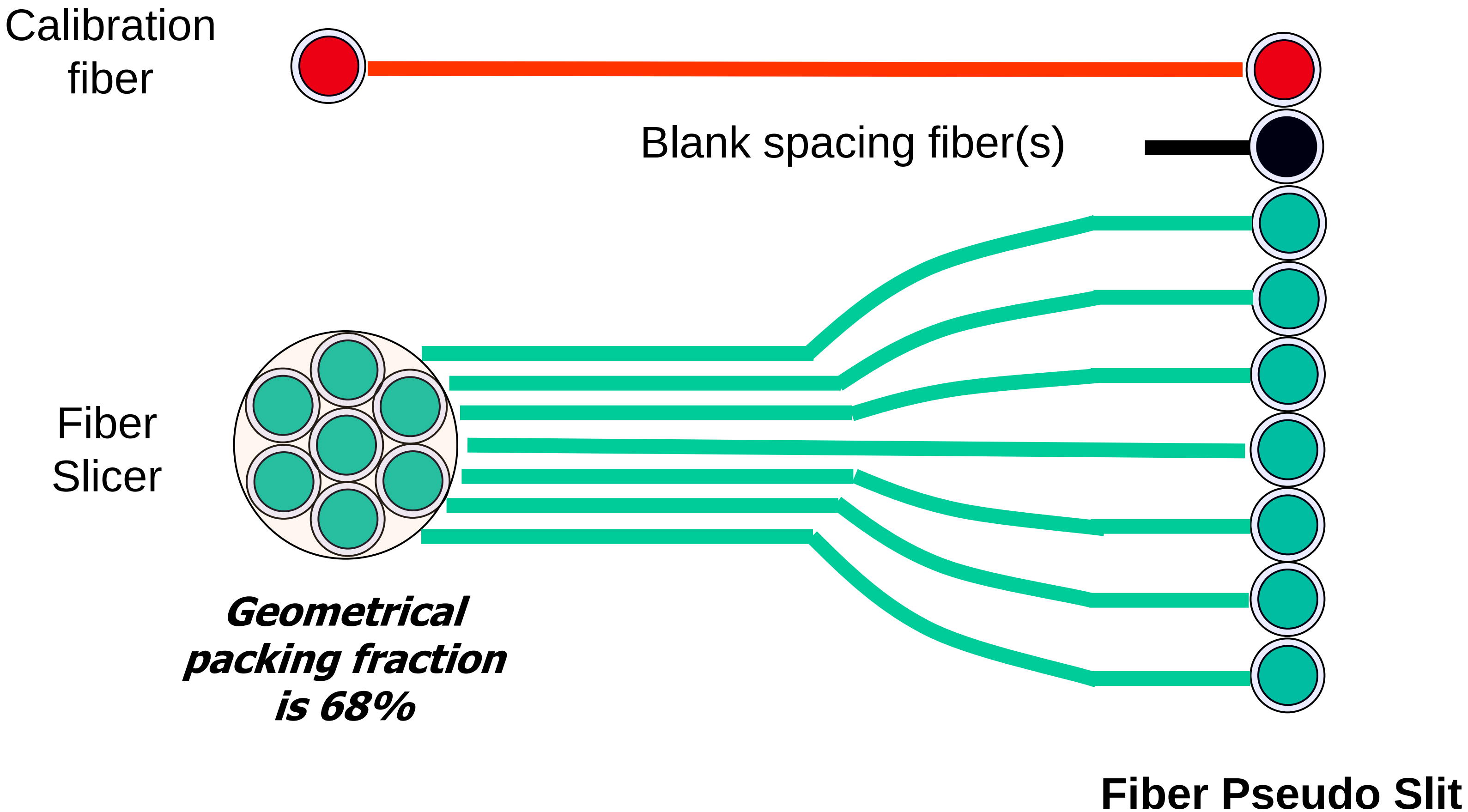


Ratio of consecutive Flats with fiber disturbance



Ratio of consecutive Flats with fiber disturbance and vibration

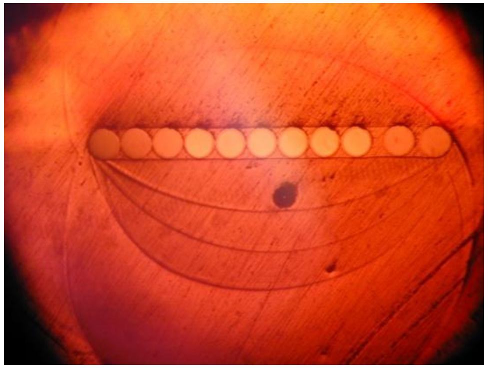
PRVS Fiber Slicer Concept



Note: Effective width of a circular fiber is ~80% diameter of the fiber

Fiber Slicer construction

- **Use 1.1 core/cladding ratio fibers**
  - **Minimize geometric packing fraction loss**
  - **Risk of waveguide loss**
- **Keep length at 2 meters or less**



Waveguide loss: Schotz et al. plot

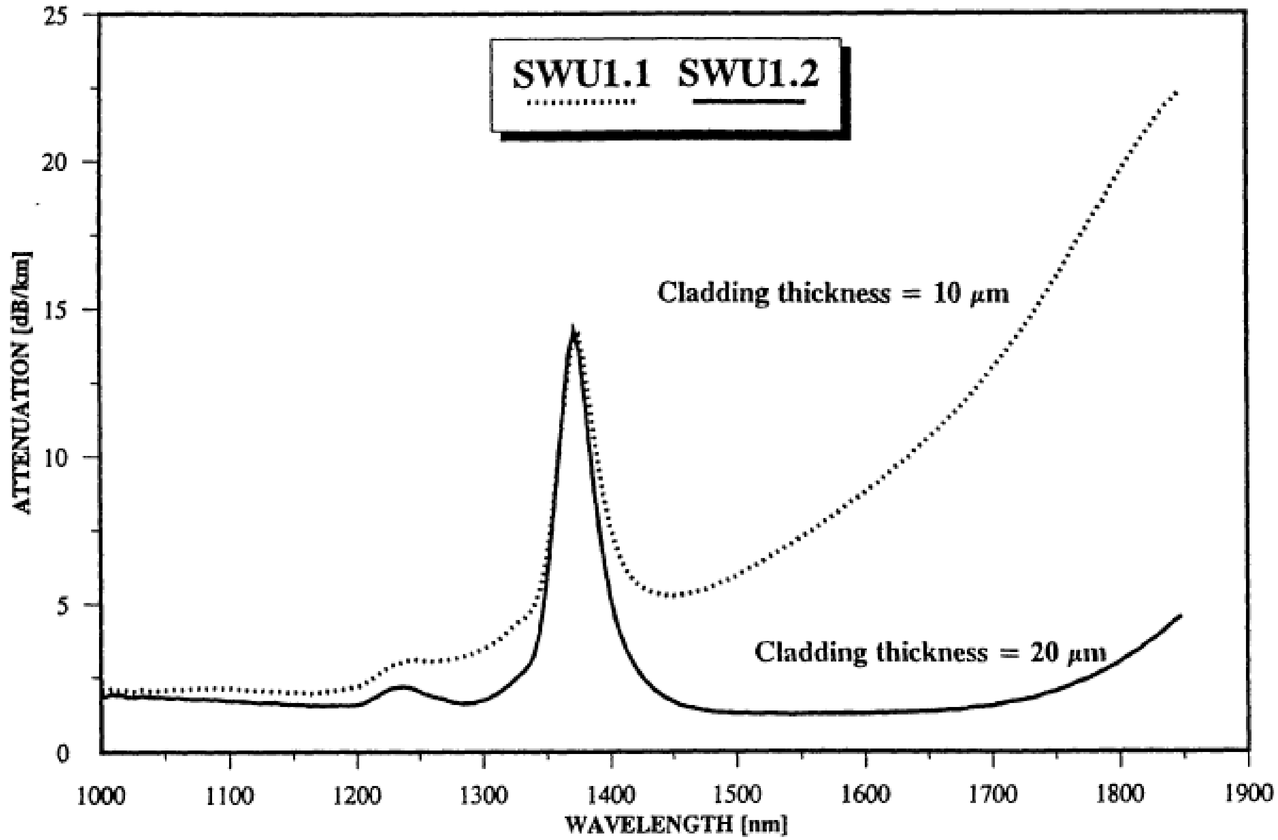
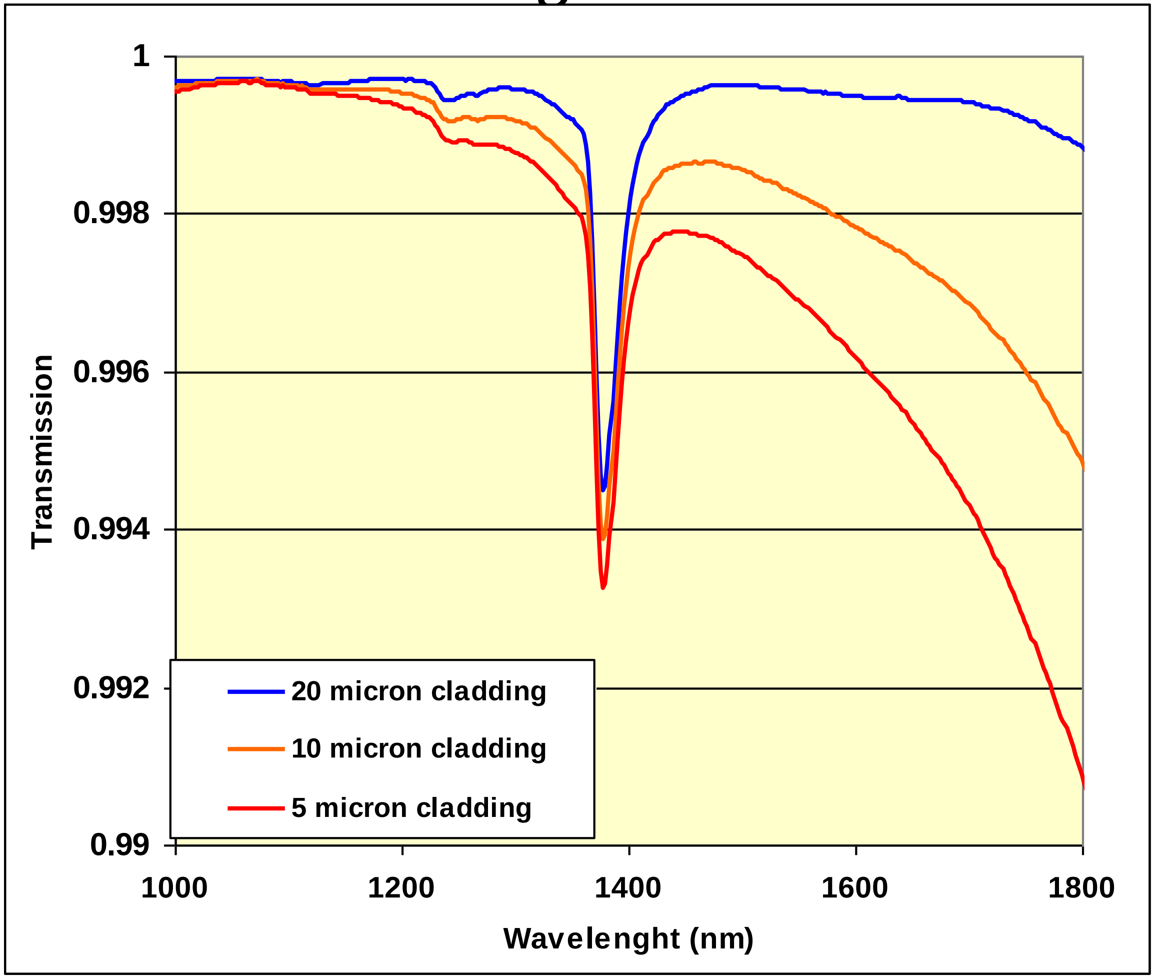


Figure 3. Transmission of fibers with different cladding thicknesses.

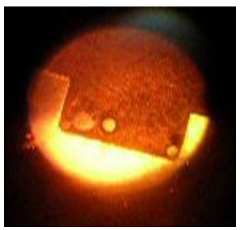
Estimated Waveguide losses in slicer



Preliminary Experimental results with ~5% errors are consistent with above

Preliminary Tests

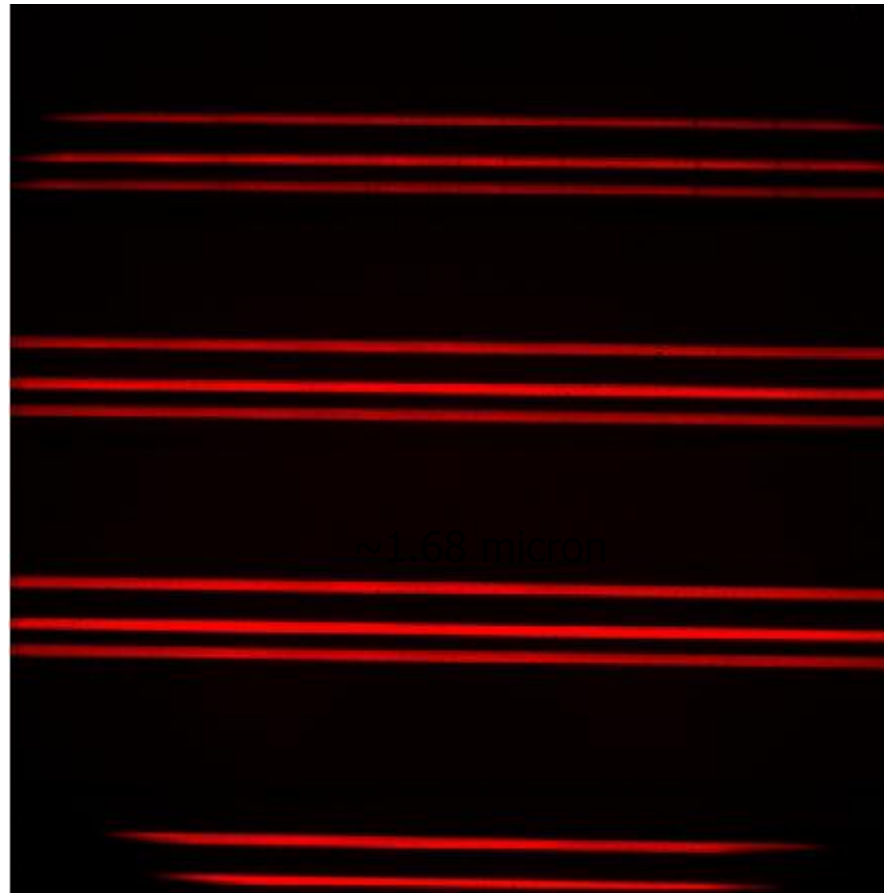
Build 4 meter long cable with three sample 100 micron core fibers to test <u>transmission</u> and <u>modal noise</u>



FIP100120140 ; 5db/km @800 nm

FIA100140250 ; 3db/km @800 nm

FIP100110125; 6db/km @800 nm



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H-band frame