Use of Statistical Moments for Evaluation of Far-Field Patterns

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Abstract

A common way to estimate the intermodal coupling coefficient for multimode fiber is to launch plane waves into a carefully prepared fiber endface, at different angles of incidence. After these initial conditions, the power distribution amongst the various modes will evolve along the multimode fiber. Gambling, et. al, proposed sweeping the angle of the plane waves, and observing the far-field pattern exiting a given length of fiber. As the angle of incidence of the plane waves is swept, the angle is noted where the far-field pattern changes from a circularly-symmetric, monotonically-decreasing shape to an annular ring. This angle of transition is judged by a trained eye, and is subsequently used to estimate the coupling coefficient.

In an attempt to make the measurement of the critical angle more quantitative, the far-field pattern is captured with a linear camera, and simple signal processing is performed on the intensity values. Once the data is correctly prepared, evaluation using a method analogous to a 4th-order statistical moment (kurtosis) is used to arrive at a numerical value of the "doughnut-ness" of the far-field pattern. In this paper the camera circuit and data acquisition will be described, as well as the algorithm which was performed in MatLab.

Mode Mixing Coeff. Experiment

- Launch plane waves into POF endface at normal angle $\theta = 0°$ noting the far field pattern (FFP)
- Vary the launch angle θ and observe the FFP
- Note the angle θ_c where FFP changes from monotonically-decreasing to an annular shape
- Record θ_c for a number of POF sample lengths
- Plot θ_c as a function of sample length on a log-log scale
- Coupling coefficient D inferred from Y-intercept

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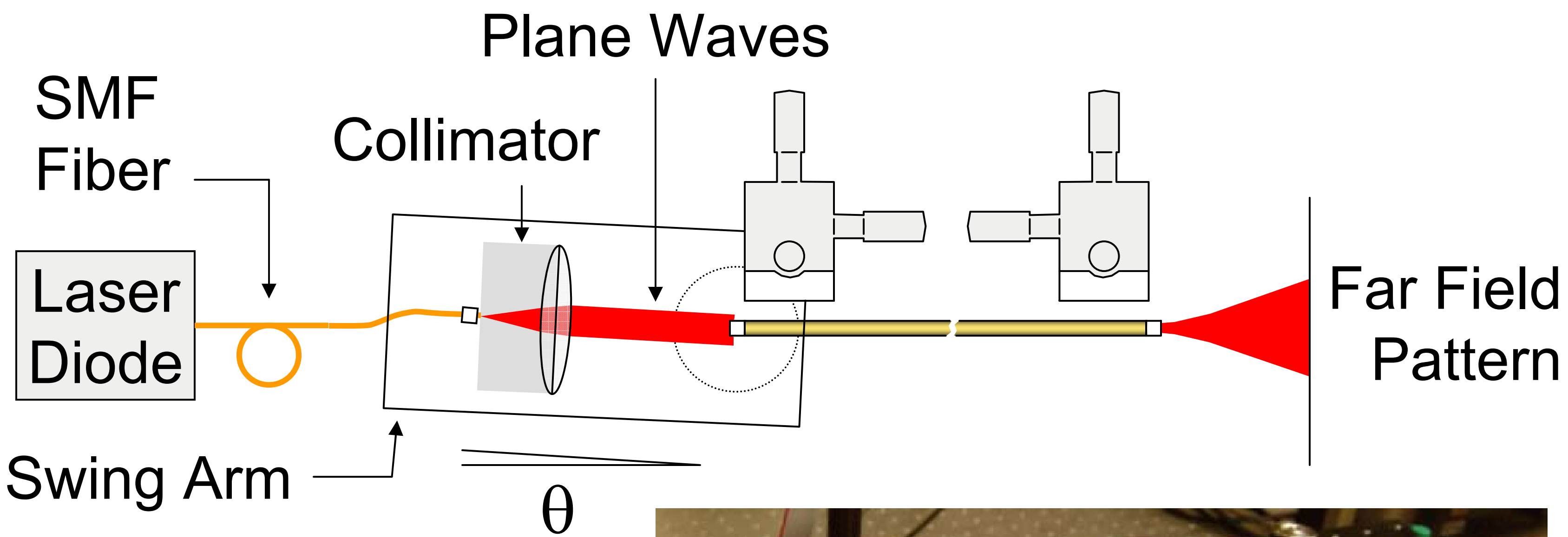
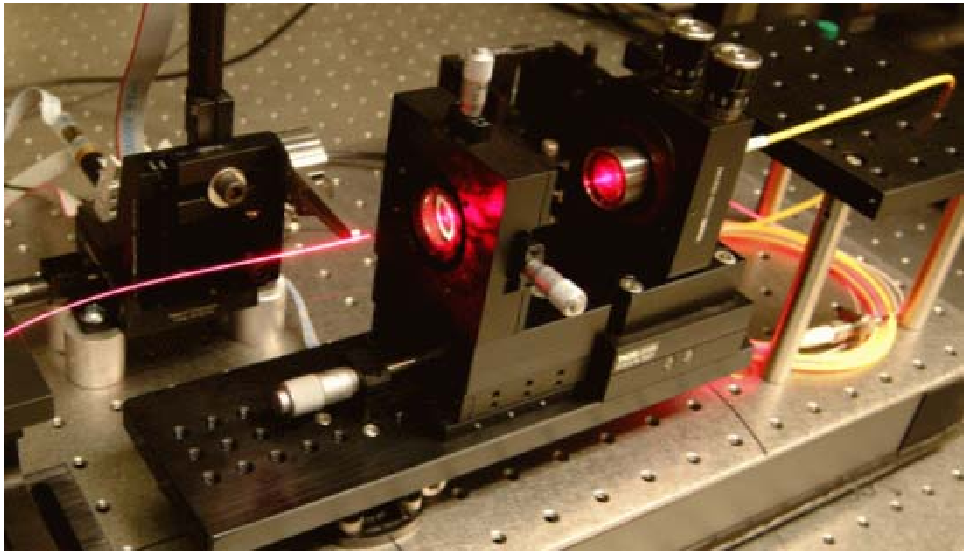
Reference [1]

Mode Mixing Experiment



Computer-controlled Rotary Stage underneath the Swing Arm



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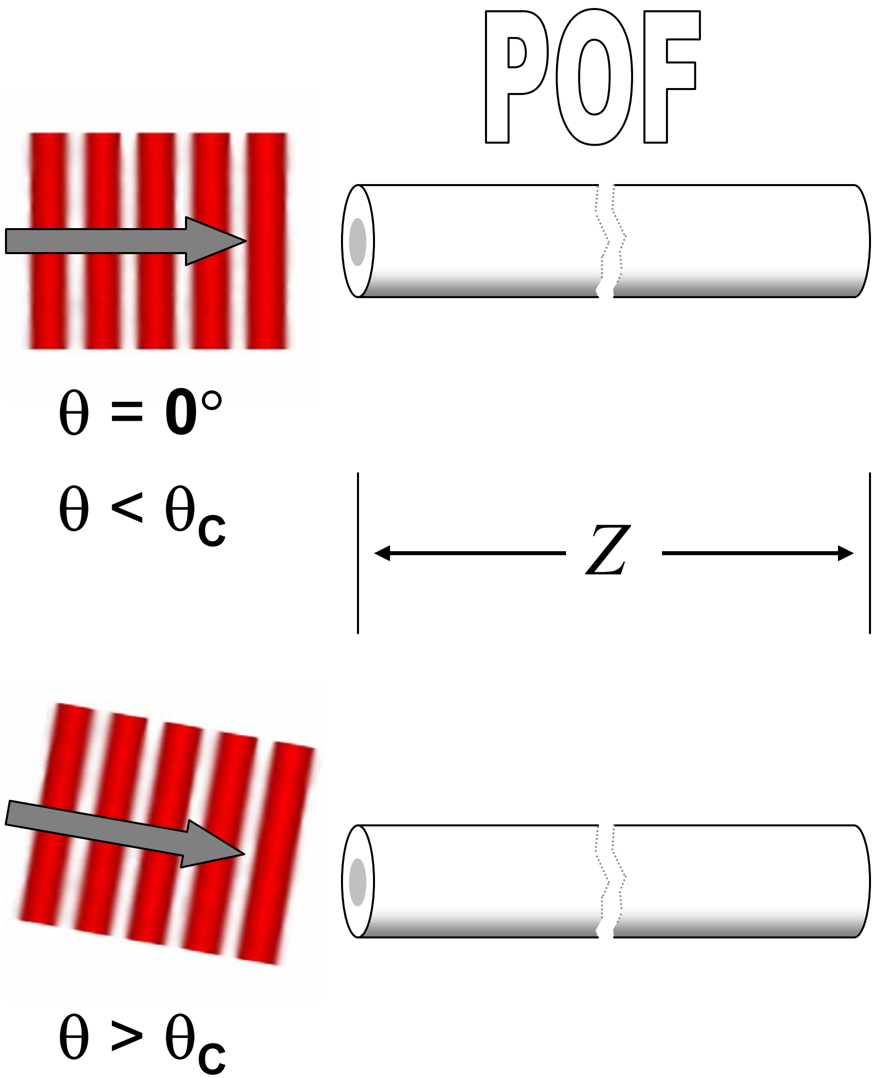

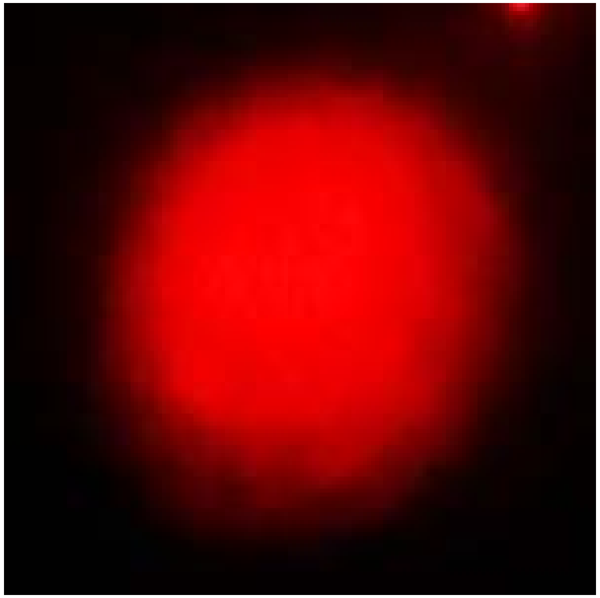

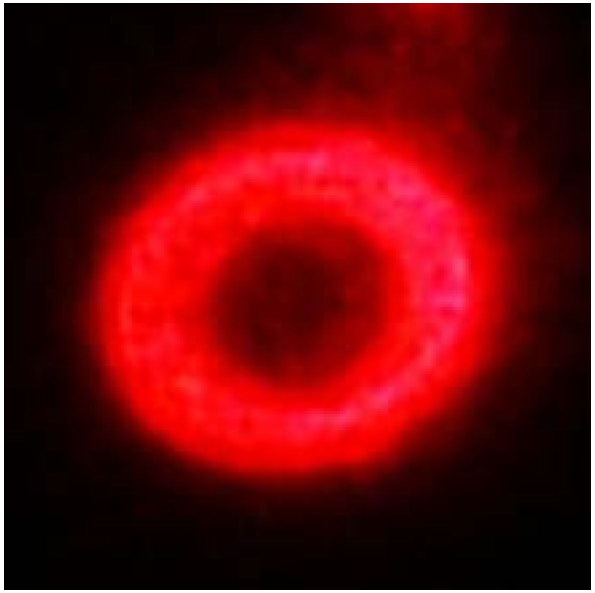

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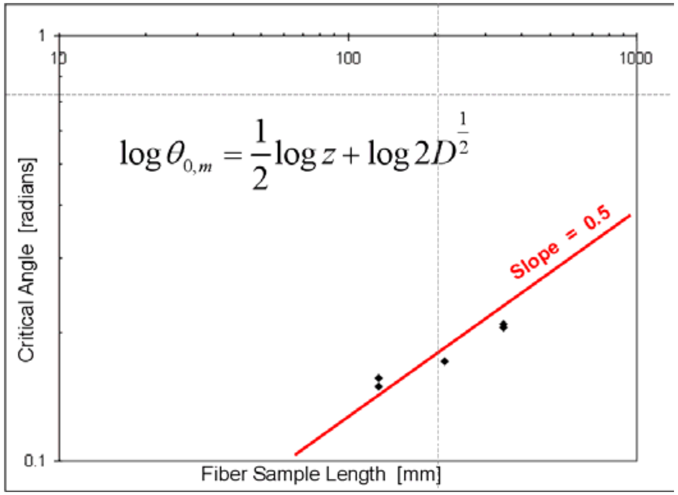
- Multimode wave guides will exhibit this property at sufficiently short length z
- Above a certain length no ring is observed
- To check results, the log-log plot should give a straight line with slope = 0.5

$$\log \theta_C = \frac{1}{2} \log z + \log 2\sqrt{D}$$

PROBLEM

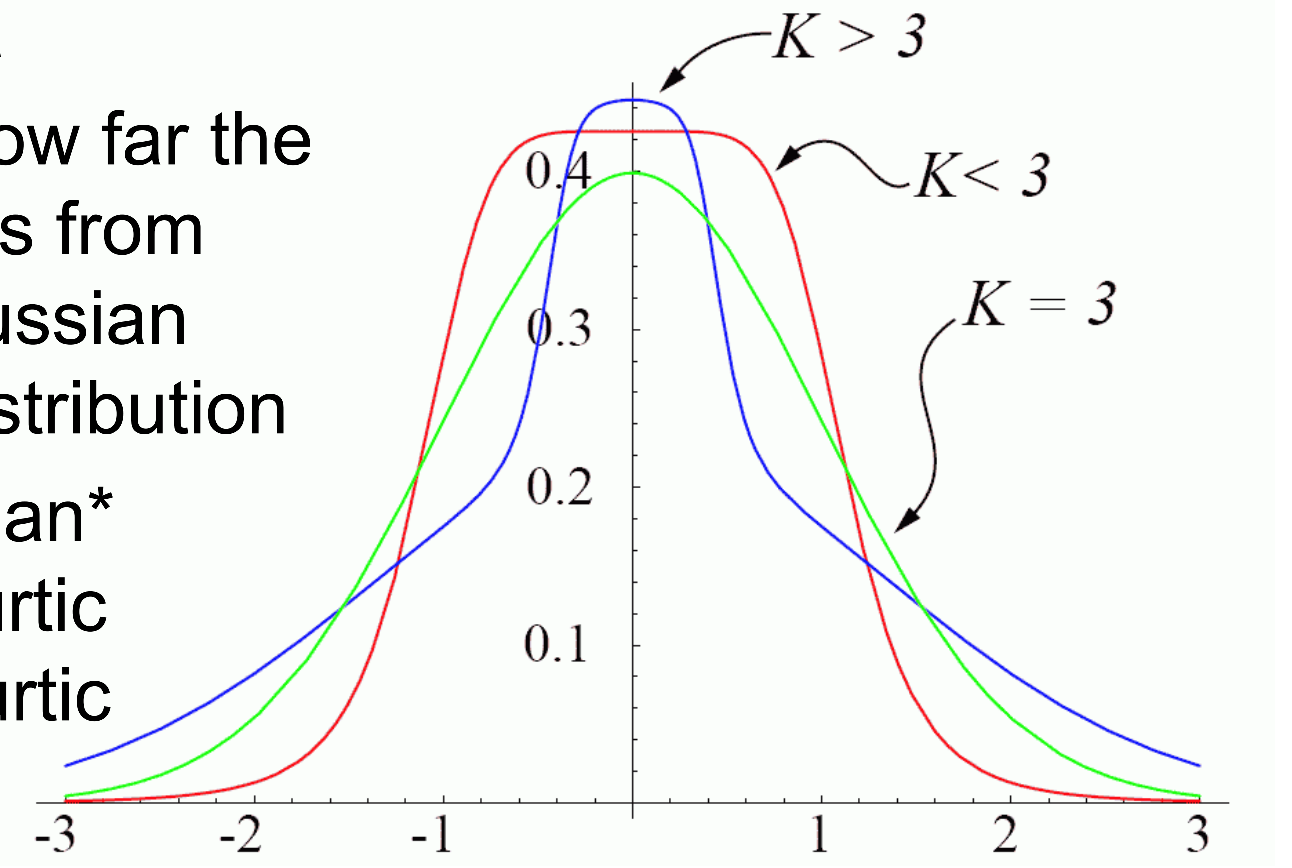
- Critical angle recorded by observing transition with naked eye



[2]

Kurtosis

- Kurtosis is the 4^{th}-order statistical moment of a data set
- Describes how far the data deviates from an ideal Gaussian or normal distribution
- k = 3 Gaussian*
  k < 3 platykurtic
  k > 3 leptokurtic



*Some statistical packages define k = 0 as Gaussian

Data Acquisition

- Reticon is positioned in FFP with no lens
- Signal proportional to the 1D FFP profile is measured with TDS3054B oscilloscope
- Signal is time averaged to reduce noise
- The digitized data is spatially averaged in Excel
- Use Excel or MatLab to visualize data
- Data is further analyzed by MatLab to obtain the relevant statistical moments
- Swing arm is rotated to a new θ value

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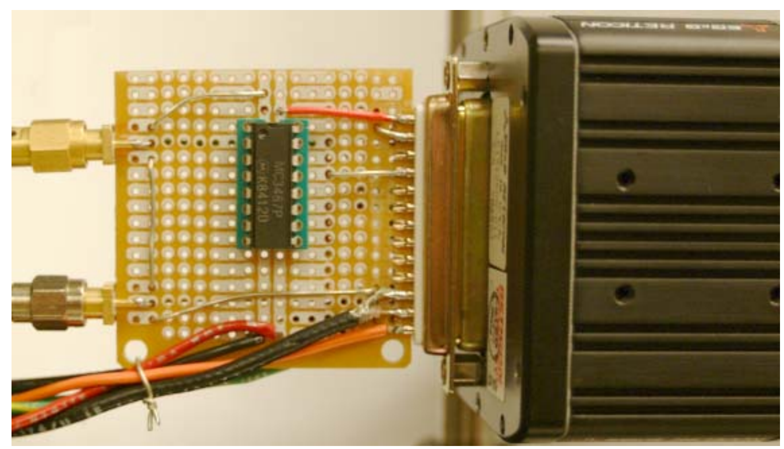
Reticon Linear Camera

- 2048 photodiode linear array camera
- Active area 26 µm x 26.6 mm
- Had to interface 75Ω video coax and correctly pad the impedance and perform the DC shift at the scope input.
- Had to add glue logic for clock and sync

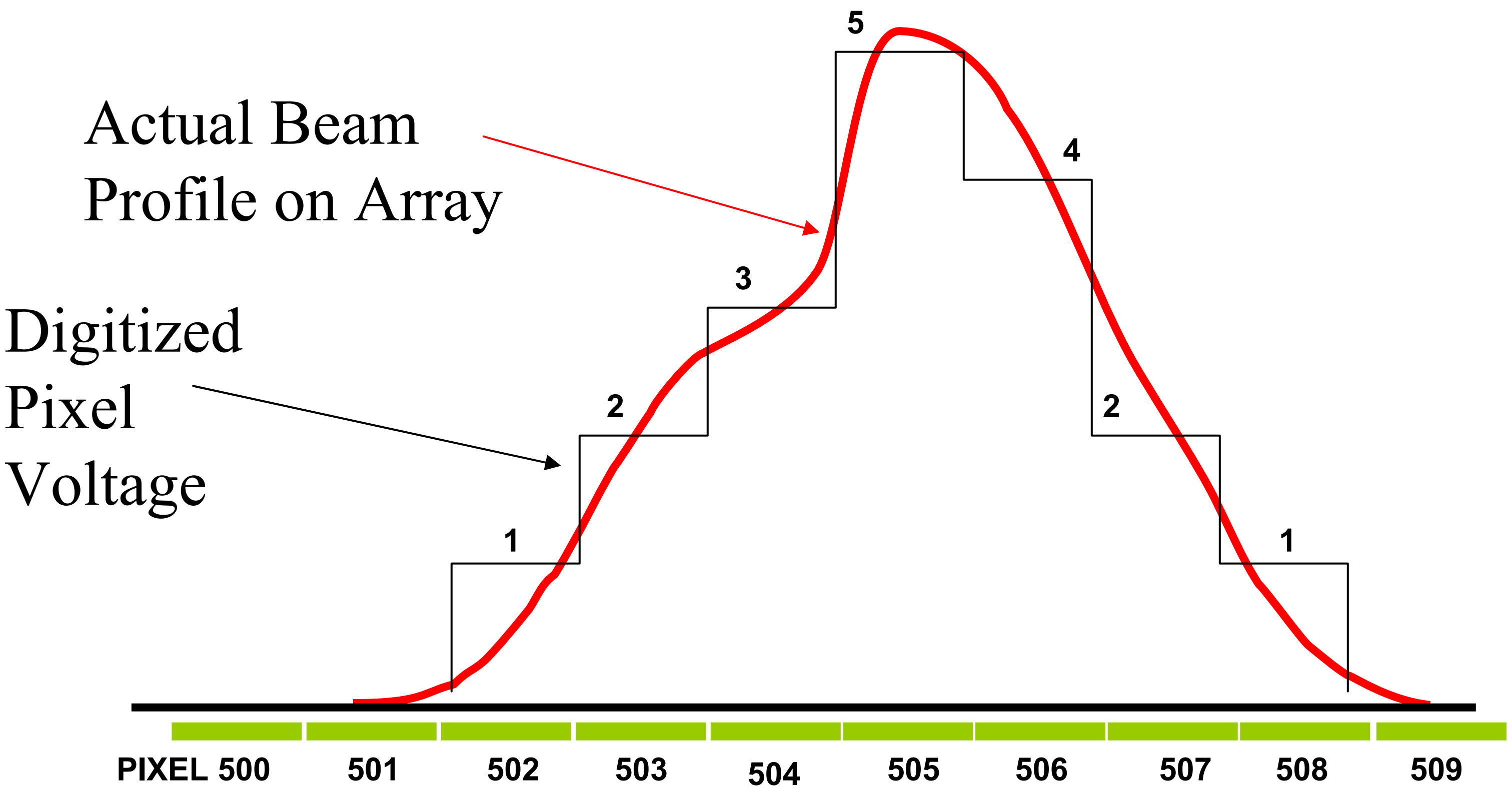
LC1912 Camera



Post Processing

- Pedestal removal and renormalization
- Large core MMF had a flatter than Gaussian FFP starting with $k = 2.8 \sim 2.9$
- The transition of the kurtosis k value below the nominal indicates further flattening of the profile before the ring (if any) is formed.
- MatLab assumes statistical data is a list of values, not a histogram. A novel algorithm was developed to convert the profile signal to an appropriately binned statistical ensemble

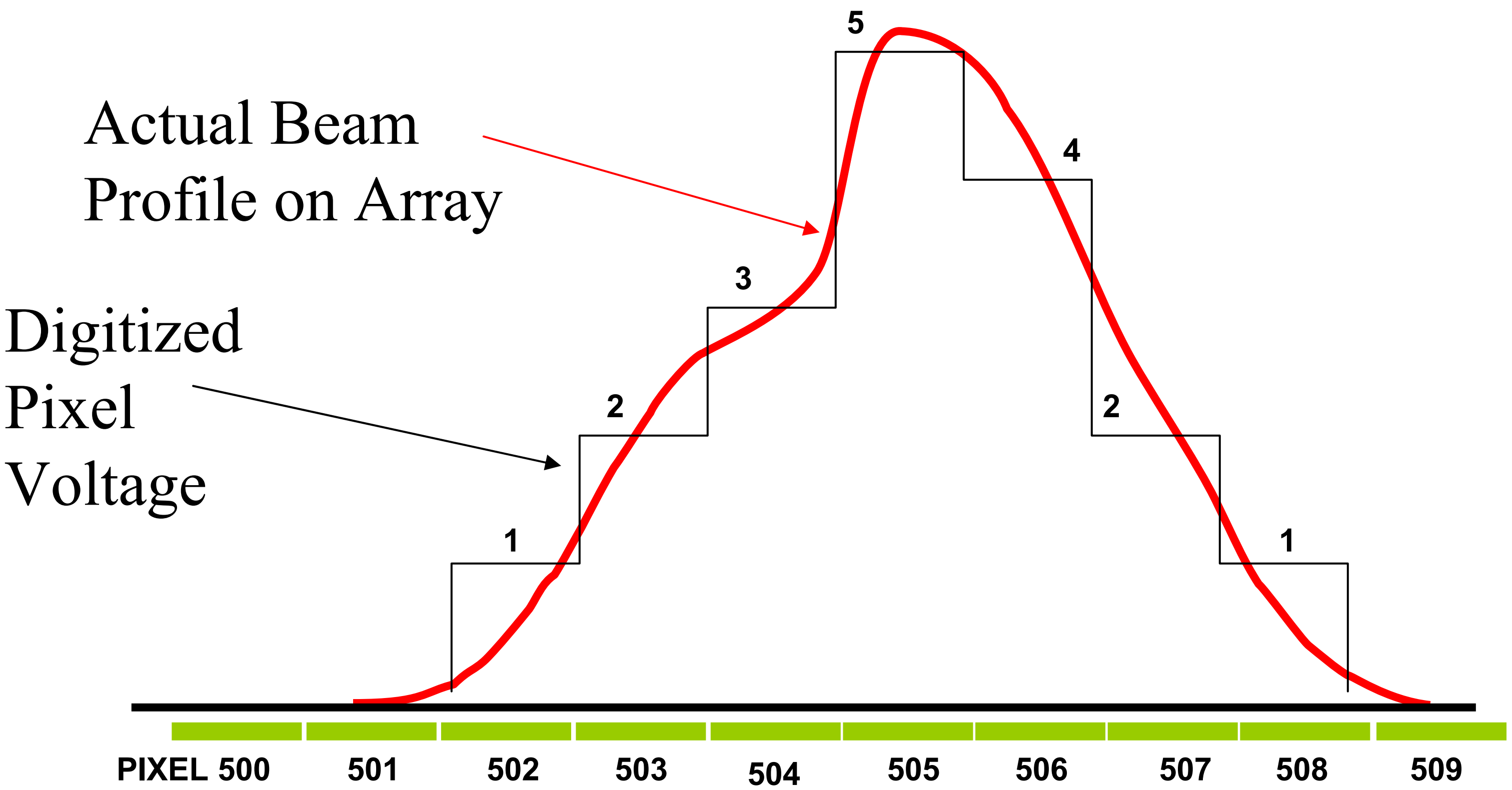
Algorithm (Normalized to 5)



Voltage array X = {0, 0, 0, 0, 0 .... 0, 0, 0, 0, 0, 1, 2, 3, 5, 4, 2, 1, 0, 0, 0, 0, 0, 0 .... 0, 0, 0, 0,0, 0 , 0} 2048 values

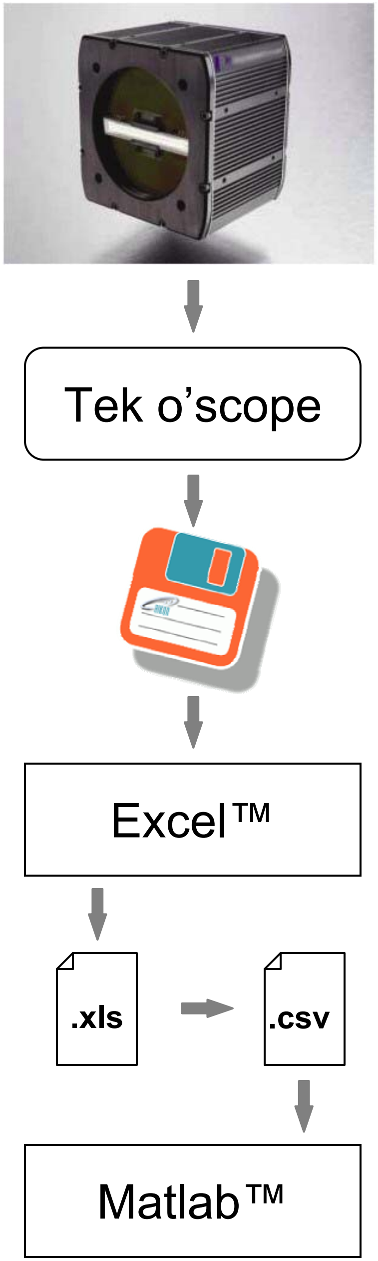
- MatLab will not give the results wanted

Need a Histogram of Pixels



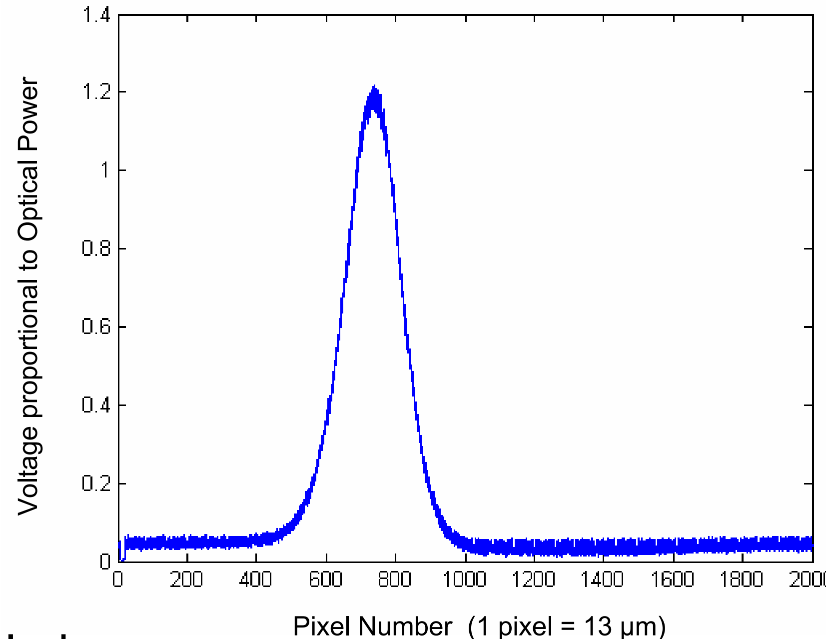
Converted to array X = {502, 503, 503, 504, 504, 504, 505, 505, 505, 505, 505, 506, 506, 506, 506, 507, 507, 508}

Note: 10,000 samples (2048 pixels) normalized to 100 takes about 600 seconds to compute array X

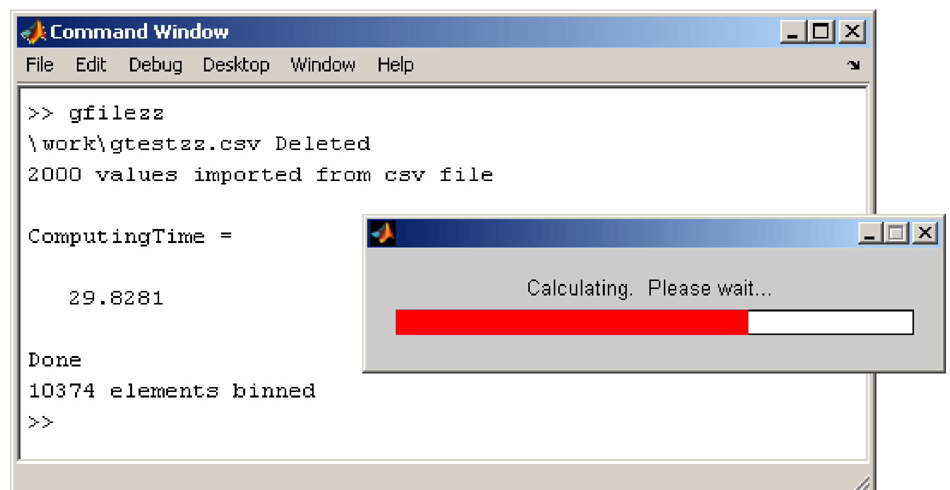


SMF

Example of Single-mode fiber FFP as represented by intensity vs. position

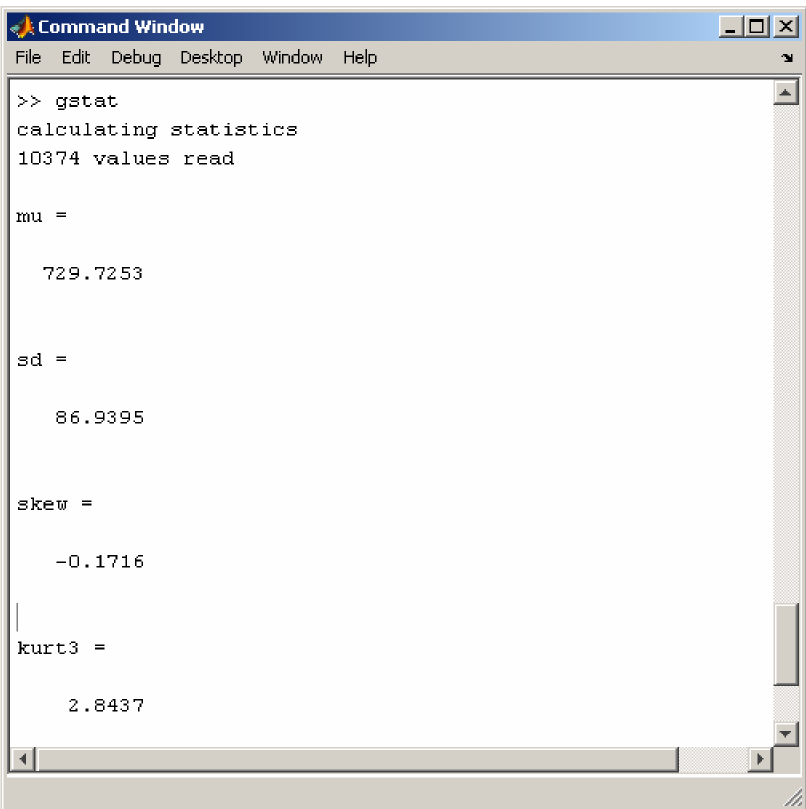


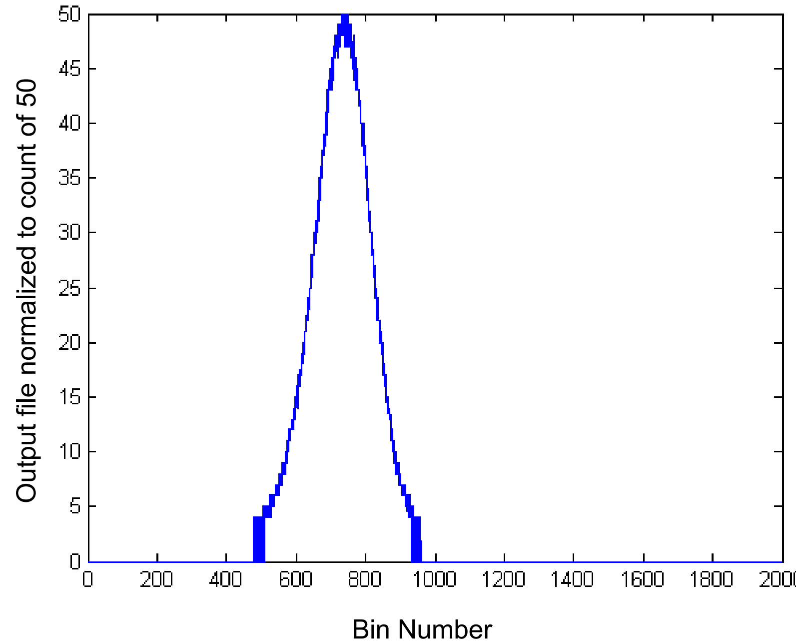
MatLab

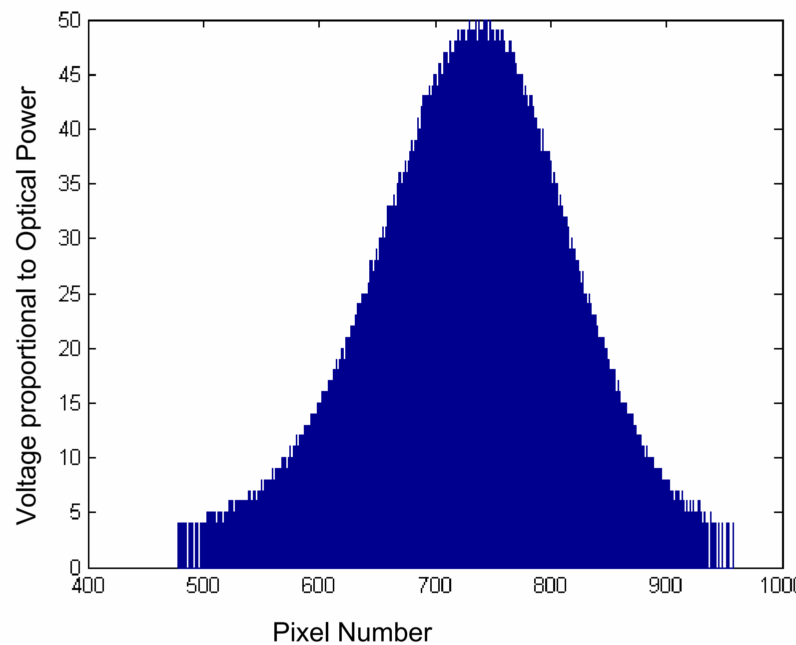


SMF

- reads in .csv file
- normalizes
- pedestal removal
- binning algorithm
- displays data
- computes statistical moments







Fiber Preparation Important

- Several causes for a large increase in apparent coupling - no observed ring
  - Any roughness or imperfection on the endface
  - Beveled or under-polished endface
  - “Hackle” or other damage from cleaving
  - Stress or bending leads to mode mixing
  - Artifacts from the collimator (flare, spots)
  - Endface contamination
- Developed reference-grade polishing process for POF endfaces

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Experience with Coupling Experiment

- Cladding modes can be present
- Aquadag™ suppresses cladding modes
- Blocking eliminates artifact from collimator
- Measure both + and – swing and average
    - Mitigates systematic error in zero fixture angle
- Flip fiber 180º and test again
    - Mitigates error due to non-perpendicular endface
- Cutback technique improves repeatability
- Coupling coefficient seems large
    - Extreme pains taken to keep fiber straight
    - Need short fiber samples to see any effect

Eska 980 µm core fiber

L = 204 mm θ = 0º

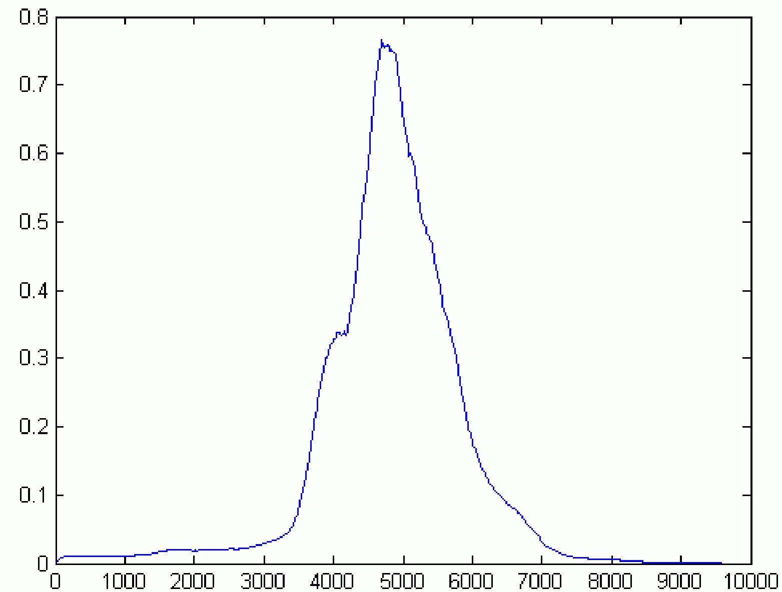
μ = 4926

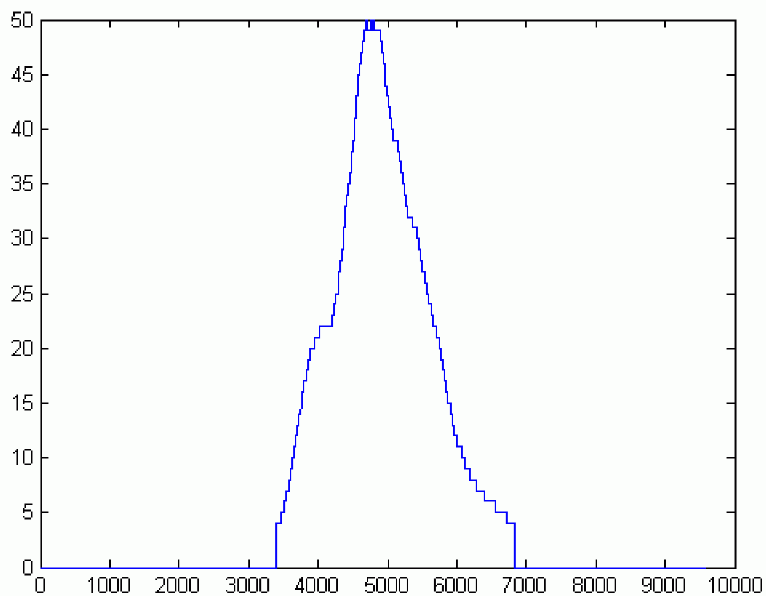
σ = 691

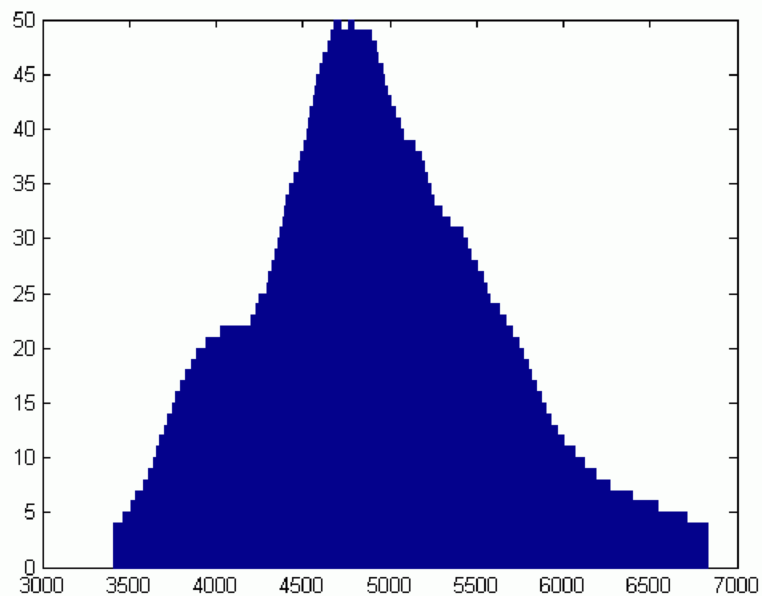
Skew = +0.29

Kurtosis = 2.77

(3.00 is Gaussian)







Eska 980 μm core fiber

L = 204 mm   θ = +2º

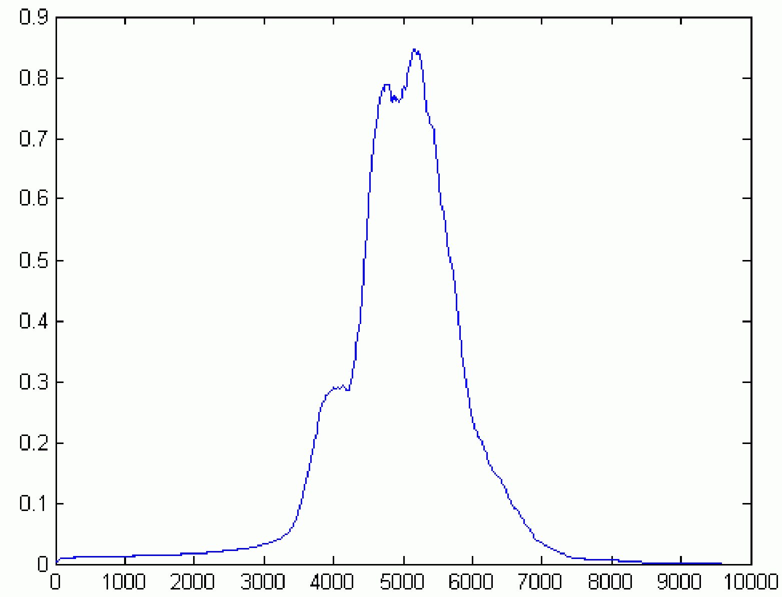
μ = 5034

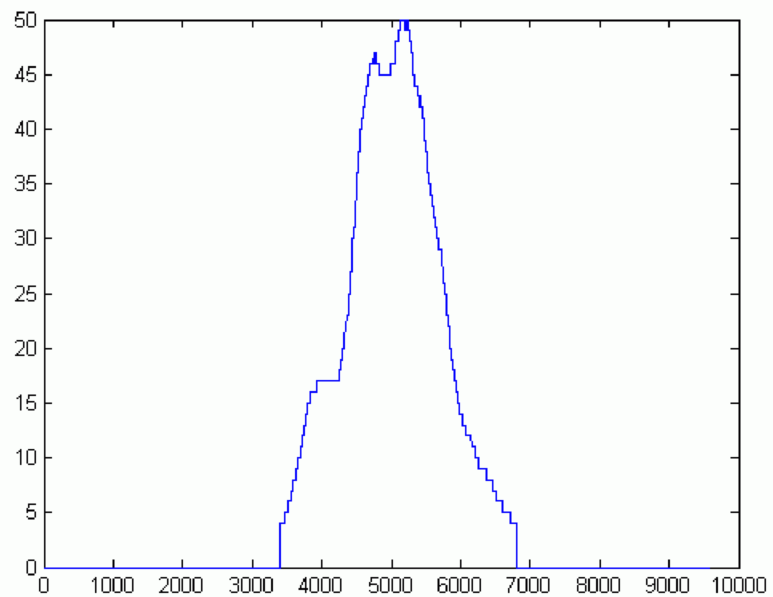
σ = 679

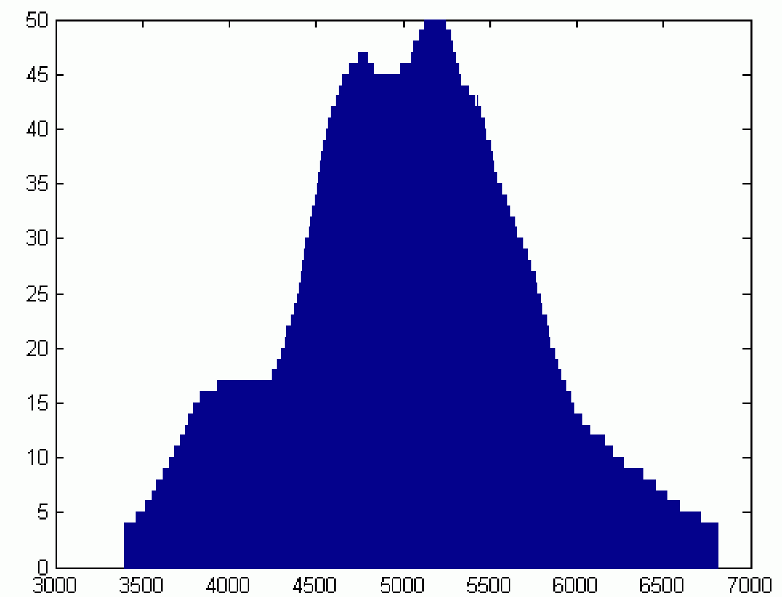
Skew = +0.04

Kurtosis = 2.74

(central dip noted)







Eska 980 μm core fiber

L = 204 mm $\theta = +6^{\circ}$

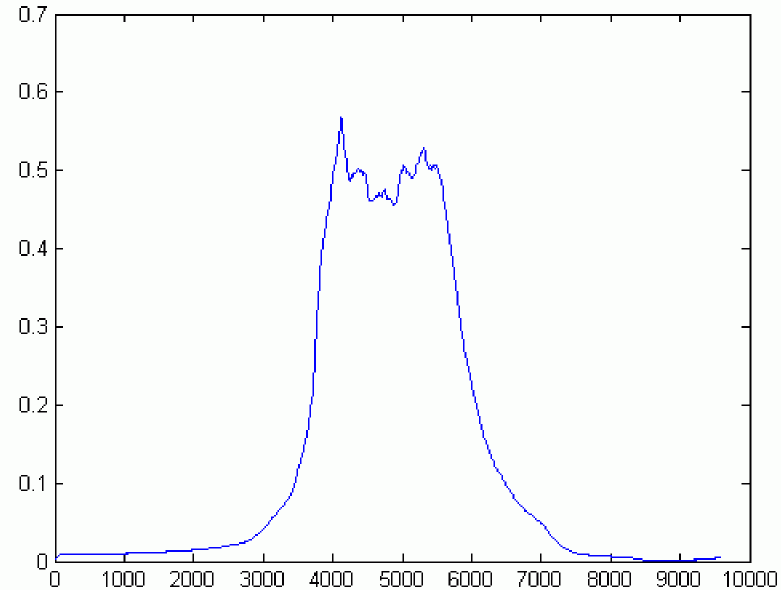
$\mu = 4895$

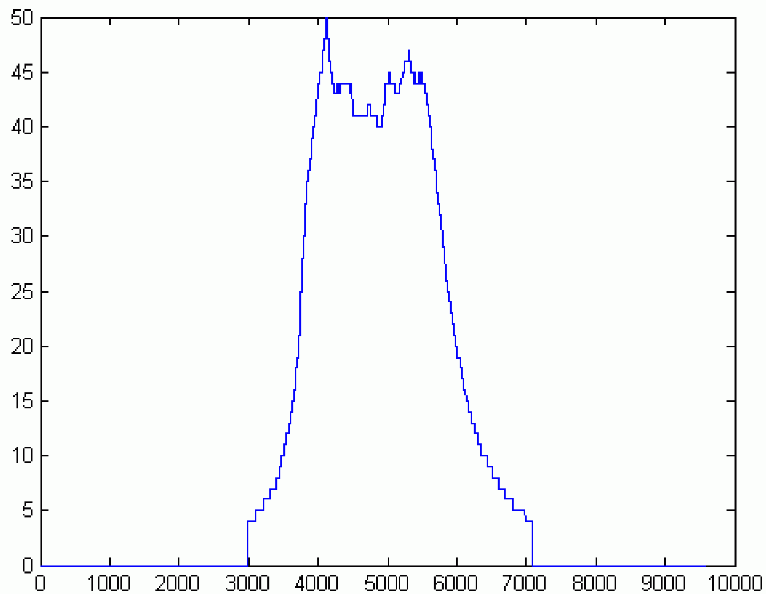
$\sigma = 818$

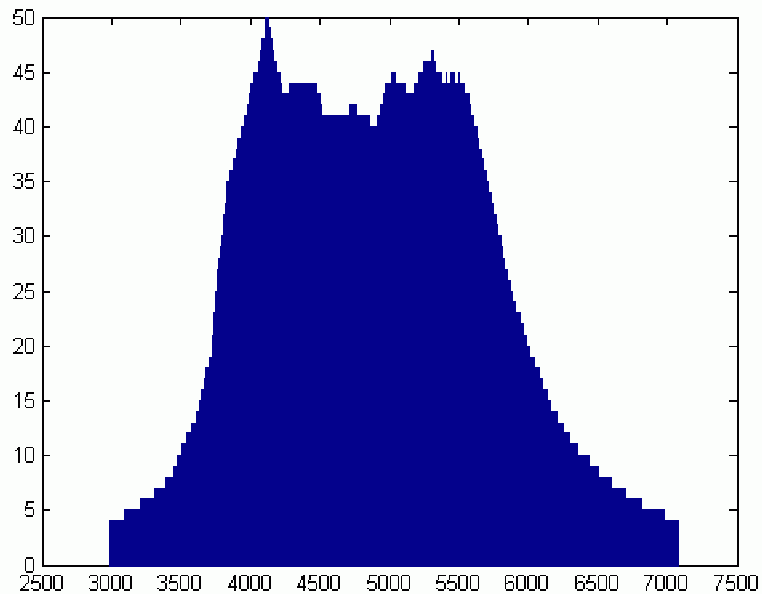
Skew = +0.20

Kurtosis = 2.48

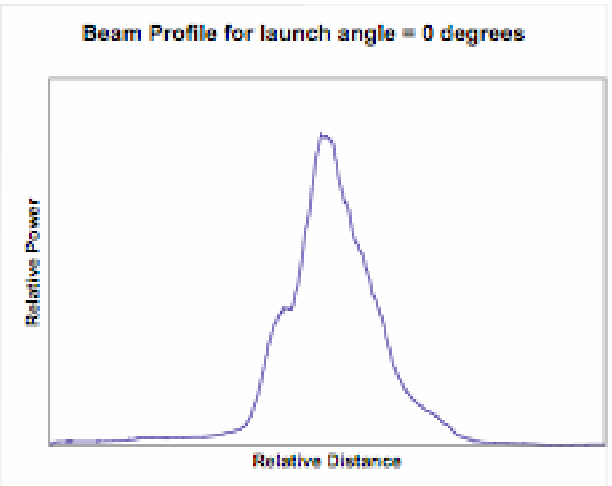
(platykurtic)

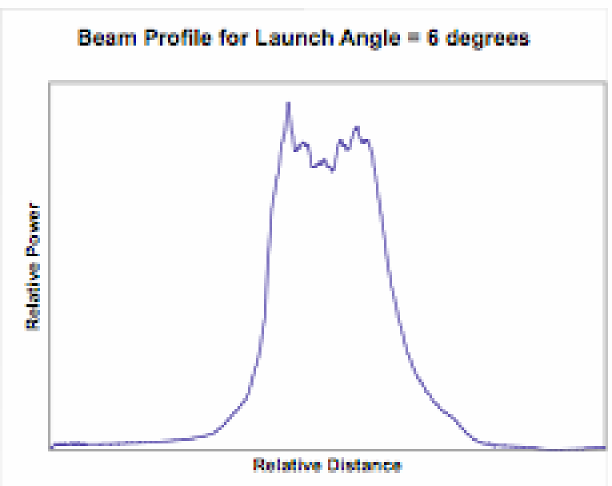


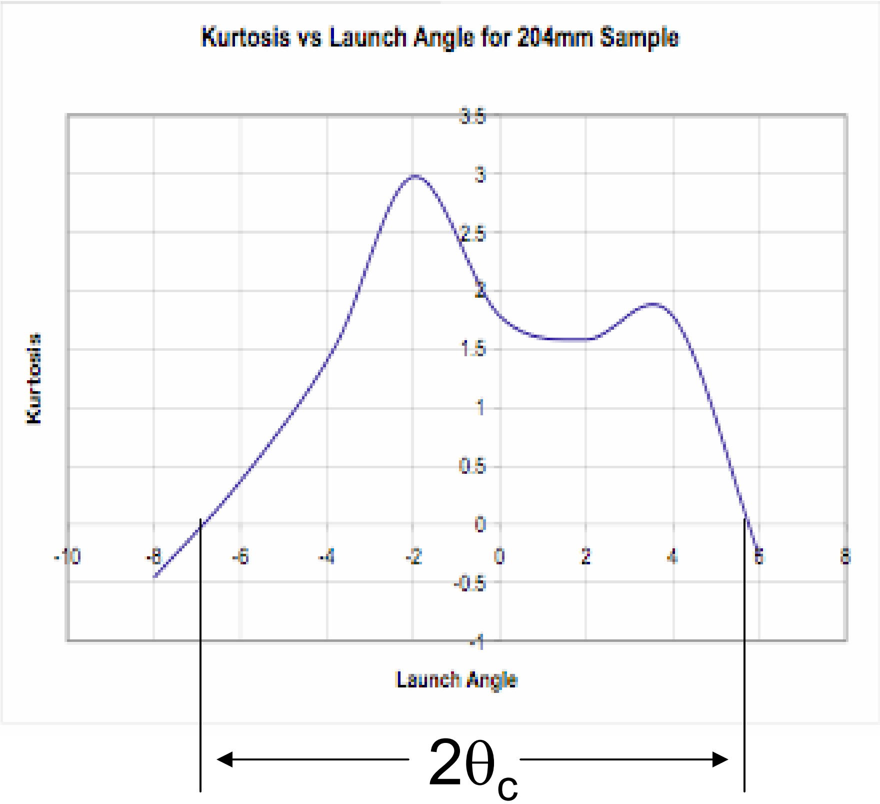




Eska 980 μm Core Diameter





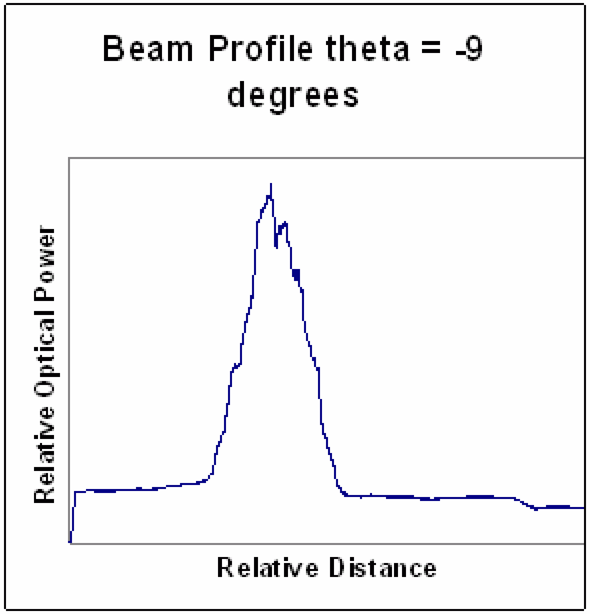


D = 0.014 rad^2/m

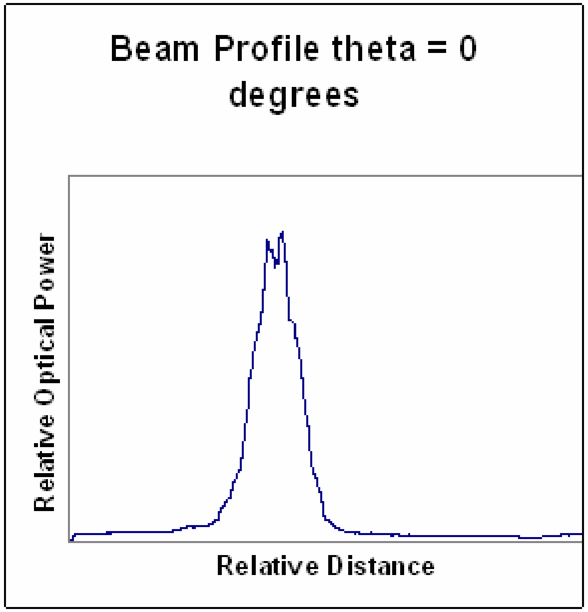
Chromis 50 μm Core Diameter

- Figures are all normalized, hence the increasing pedestal relative to the (darker) max
- Small change in k value over all θ suggests near complete mode mixing for this short length

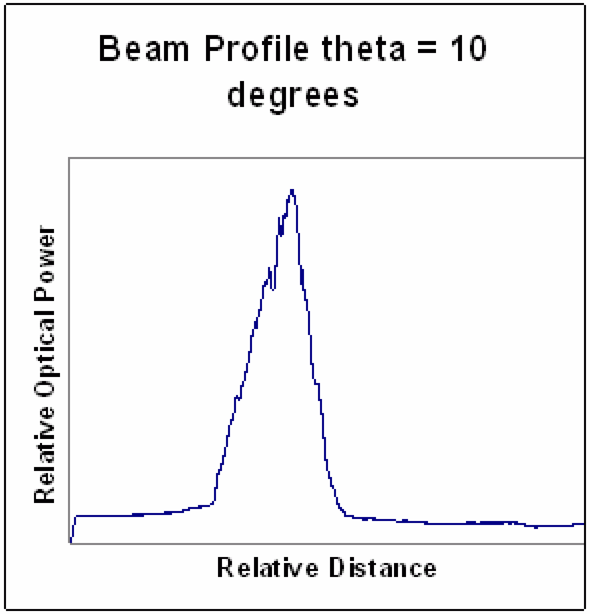
Kurtosis = 2.3710



Kurtosis = 2.3058



Kurtosis = 2.3861



Need Short Fibers to See Rings

- Non-ideal initial launch conditions
- Illumination of full cross-section of surface
- Core size variations are larger than in glass fiber
- Geometric perturbations larger than glass fiber
- Frozen-in fluctuations in polymer density, orientation, and dopant density
- Much more “curl” than glass optical fiber
- Impurities in the core region
- Diffusion tails make core edge less crisp
- Imperfect refractive index profile in POF

Conclusions and Future Work

- A novel, kurtosis-like approach is useful to remove subjectivity of FFP observation near θ_c
- Simple in theory, the details are critical
- POF fiber required in some cases very short (30mm) length samples to see rings
- Would like to integrate experiment and analysis
- Need to resolve discrepancy with coupling coefficients measured with the impulse response method [3] (possibly related to launch spot size)
- Possibly re-evaluate theory and suitability for graded index POF media

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REFERENCES

[1] W. Gambling, et. al. Applied Optics V14, N7, P1538-1542.
[2] K. Pedrotti, et. al. POF World West 2006
[3] S. Ralph, Symposium on Optical Fiber Measurements 2006