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 $\theta = 0^\circ$ noting the far field pattern (FFP)
- Vary the launch angle $\theta$ and observe the FFP
- Note the angle $\theta_c$ where FFP changes from monotonically-decreasing to an annular shape
- Record $\theta_c$ for a number of POF sample lengths
- Plot $\theta_c$ as a function of sample length on a log-log scale
- Coupling coefficient $D$ inferred from Y-intercept

Reference [1]
Mode Mixing Experiment

- Laser Diode
- SMF Fiber
- Plane Waves
- Collimator
- Far Field Pattern
- Swing Arm

Computer-controlled Rotary Stage underneath the Swing Arm
\[ \theta = 0^\circ \]

\[ \theta < \theta_c \]

\[ \theta > \theta_c \]
• 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
Kurtosis

- Kurtosis is the 4\textsuperscript{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 $\theta$ value
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
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  \[ X = \{0, 0, 0, 0, 0 \ldots 0, 0, 0, 0, 0, 1, 2, 3, 5, 4, 2, 1, 0, 0, 0, 0, 0, 0 \ldots 0, 0, 0, 0, 0, 0, 0\} \]  \(2048\) values

- MatLab will not give the results wanted
Need a Histogram of Pixels

Actual Beam Profile on Array

Digitized Pixel Voltage

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

Voltage proportional to Optical Power

Pixel Number (1 pixel = 13 µm)

MatLab

Excel™

Tek o’scope

.xls

.csv

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

```matlab
>> getstat
calculating statistics
10174 values read

mu =
    728.7253

sd =
    86.9185

skew =
    -0.1716

kurt3 =
    2.8437
```
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
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 180° 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
$L = 204 \text{ mm}$   $\theta = 0^\circ$

$\mu = 4926$
$\sigma = 691$
Skew = $+0.29$
Kurtosis = $2.77$

*(3.00 is Gaussian)*
Eska 980 µm core fiber
L = 204 mm \[ \theta = +2^\circ \]
\[ \mu = 5034 \]
\[ \sigma = 679 \]
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
\textit{(platykurtic)}
Eska 980 µm Core Diameter

$D = 0.014 \text{ rad}^2/\text{m}$
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 $\theta_c$
• 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