Multi-gigabit Transmission over POF

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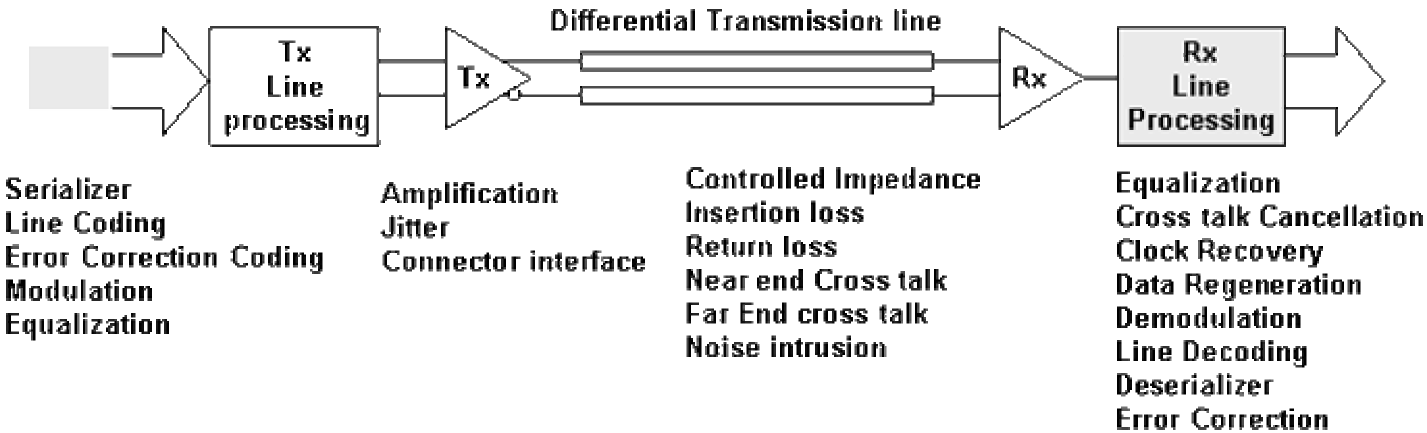
Generic Copper Based Gigabit Link



- Multigigabit performance is realized by:
  - Multi-tap equalizers
  - Decision feed back equalizers
  - Bandwidth efficient modulation
  - Link length for most standards is very limited

Copper Based Interconnect Standards

Standard	Media	Bit rate	Reach	Application
XAUI	PCB	3.125 G	0.5 m	Chip-Chip
CEI	PCB	6G, 11G	0.2-1.2 m	Chip-Chip, Backplanes
SRIO-SRIO-G Serial Rapid IO	PCB	1.25, 2.5, 3.125, 5, 6.25G	0.8-1 m	Backplane
SATA	Ribbon Cable	1.5 G, 3G, 6G	1-2 m	Bus Peripherals
Infiniband	Bidirectional Serial	2G, 4G, 8G		Bus-Peripherals
10GBASE-CX4 (IEEE 802.3ak)	8-Shielded Pairs ("Infiniband")	4x3.125 G	15m	LAN
1000BASE-T (IEEE 802.3ab)	CAT5 UTP	1 G	100m	LAN
10GBASE-T (IEEE 802.3ae)	CAT6, CAT7 UTP	10G	55 or 100m	LAN

Multi gigabit Multi-mode GlassFiber links

- Most use relatively small 50-62.5 μm core graded index fibers and 850 nm VCSELs
- Carefully controlled launch conditions are required for repeatable, standards-compliant performance
  – Offset launch
  – Restricted NA launch
  – Annular source emission patterns
- This is due to the low mode mixing in these fibers and residual fiber index imperfections

10 Gbps link standards using MMF Glass Fiber

	10GBASE-SW (OC192)	10GBASE-SR	10GBASE-SR	10GBASE-LX4
Wavelength	850 nm	850 nm	850 nm	1320 nm
Core Diameter	50 μm	50 μm	62.5 μm	50 μm
Fiber Grade	500 MHz•km	500 MHz•km	160 MHz•km	500 MHz•km
Baud per fiber	9.95328Gbps	10.3125Gbps	10.3125Gbps	3.125Gbps
Max Link Length	82 meters	82 meters	26 meters	300 meters
Lanes	1	1	1	4

Some Gbit/s POF Results

Bit rate (Gbps)	Distance	Bandwidth-Distance Product (Mbit/s-Km)	Fiber	Core Diameter (μm)	Source Wavelength	Emitter Type	Detector (Dia)
1	30m	30	PMMA-GI	550	670 nm	VCSEL	
1	100m	100	PF-GI	120	850 nm	VCSEL	Si-PIN 400 μm
2.2	10 m	22	PMMA-SI	1000	650 nm	LD	
2.2	11.9	26	PMMA-SI	1000	780 nm	LD	Si-PIN 800 μm
2.5	14.9	37	PMMA-SI	1000	780 nm	LD	Si-PIN 800 μm
2.5	100 m	250	PMMA-GI	420	647 nm	LD	
2.5	200 m	500	PMMA-GI	----	645 nm	LD	Si-APD
2.5	200 m	500	PF-GI	----	1310 nm	LD	
2.5	550m	1375	PF-GI	170	1310 nm	LD	InGaAs-APD 80 μm
2.5	550m	1375	PF-GI	170	840 nm	LD	Si-APD 230 μm
3.2	2m	6.4	PMMA-SI	500	850 nm	VCSEL	GaAs-PIN
3.2	5 m	16	SI-PMMA	980	850 nm	VCSEL	GaAs-PIN
7	80m	560	PF-GI	155	930 nm	VCSEL	InGaAs-PIN 16μmx16 μm
11	100m	1100	PF-GI	130	1300 nm	LD	InGaAs-PIN

GI means Graded Index, SI-Step Index, LD indicates a Fabry Perot type of semiconductor laser diode, VCSEL stands for Vertical Cavity Surface Emitting Laser.

POF: Core Concerns and Recent Results

- How can POF based links take advantage of superior EMI, EMC, flexibility, weight and ease of termination cost effectively?
- Tradeoff between core diameter, coupling, cost and bandwidth
- We have investigated 3 areas:
  - Mode Mixing
  - Impulse response and DMD
  - Coupling

Mode Mixing Coeff. Experiment

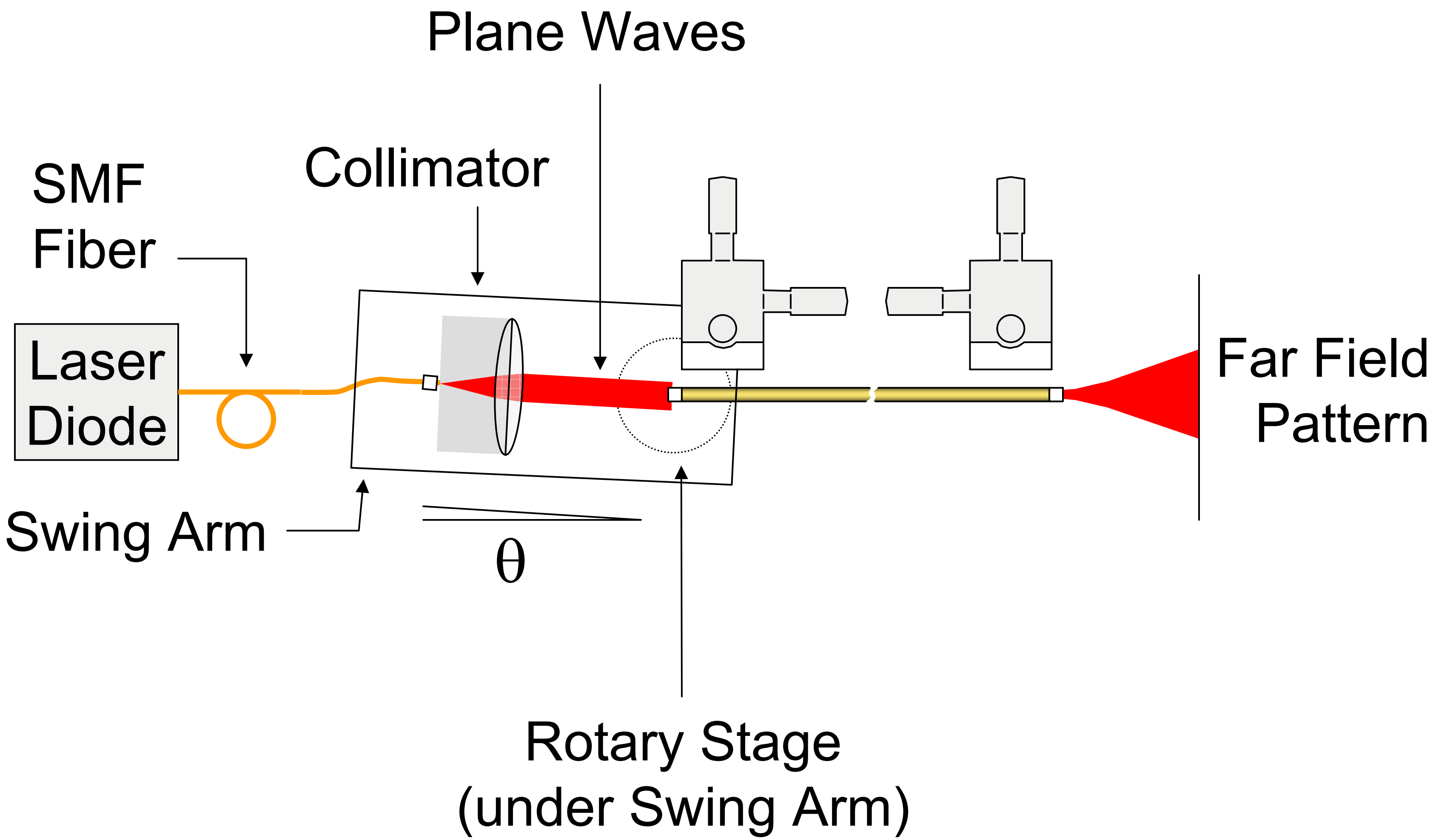
- Launch collimated beam into face of fiber and vary the launch angle
- Critical angle θ_o occurs where far field pattern changes from disk shape to annular shape
- The relationship between critical angle and length is given by

$$\log \theta_{0,m} = \frac{1}{2} \log z + \log 2D^{\frac{1}{2}}$$

- Critical angle is currently recorded by observing transition on a screen with an unaided eye
- Tentative results show mode mixing coefficient to be several orders of magnitude greater than for glass fiber with complete mode mixing within ~15 cm for a straight sample of fiber

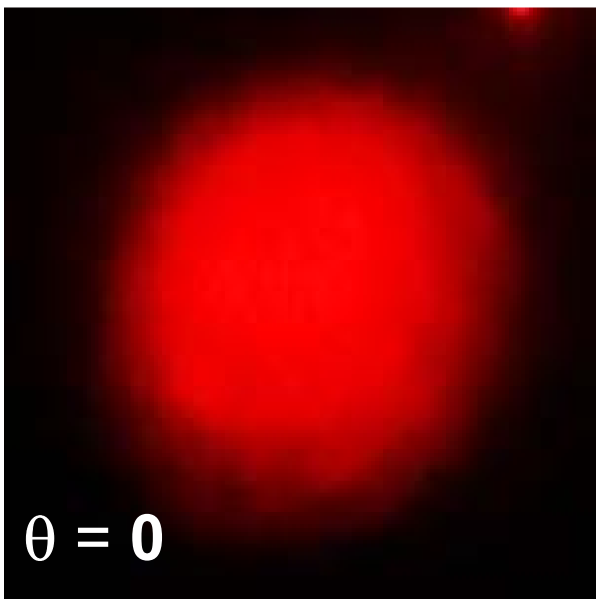
[Gambling, Payne, Matsumura, 1975]

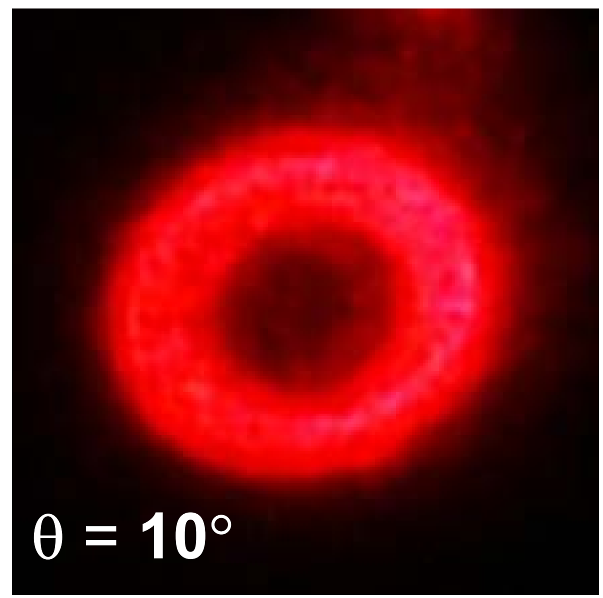
Mode Mixing Experiment



Example of far field pattern

- For short lengths of fiber, the far field pattern will change from monotonically decreasing structure to an annular shape at a critical launching angle θ_o





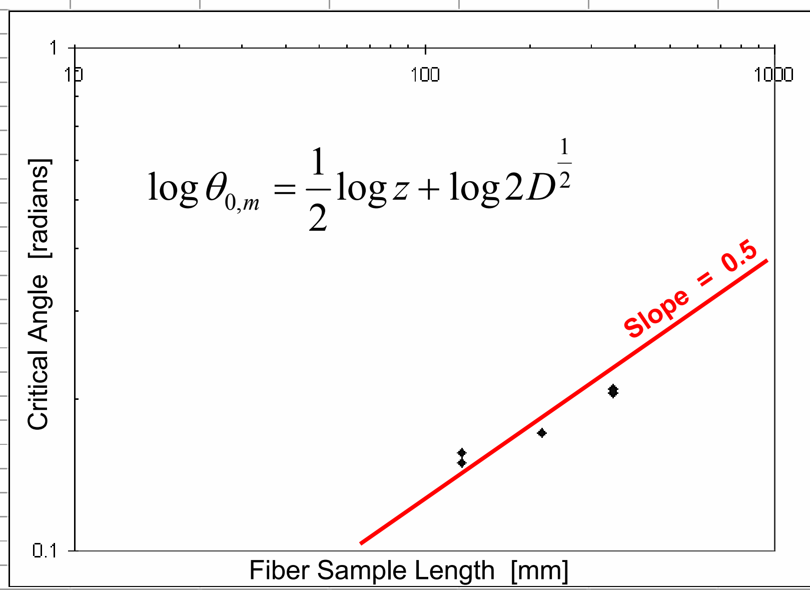
Fiber Preparation Important

- Several causes for a large increase in apparent coupling - no ring seen
  - Any imperfection on the surface
  - Beveled or otherwise under-polished endface
  - Stress or bending will cause mode mixing
  - Artifacts from the collimator (flare and spots)
- Cladding modes can be present in short lengths of fiber
  - Coated fiber with optical absorber (colloidal graphite)

Example of 12 data points

Microsoft Excel - ChromisAsahiOM

	A	B	C	D	E	F	G	H	I
1	Fiber	Length	CW steps	CW Angle	CCW steps	CCW Angle	Angle (rad)	D estimate	Notes
2									
3	Optimedia	650	Too long to get ring						
4									
5	Optimedia	345	22000	13.5	-16000	10.08	0.20567	0.030652282	Sample 1 down
6	Optimedia	345	16000	9.83	-23000	14.16	0.209246111	0.031727489	Sample 1 up
7	Optimedia	216	16000	9.83	-16000	9.83	0.171478889	0.034033576	Sample 2 down
8	Optimedia	216	26000	15.83	-6000	3.83	0.171478889	0.034033576	Sample 2 up
9	Optimedia	128	14000	9.42	-14000	8.5	0.156302222	0.047715595	Sample 3 down
10	Optimedia	128	9000	5.67	-18000	11.5	0.149760556	0.043805125	Sample 3 up
14								0.036994607	AVG
15								0.007026034	SDV



$$\log \theta_{0,m} = \frac{1}{2}\log z + \log 2D^{\frac{1}{2}}$$

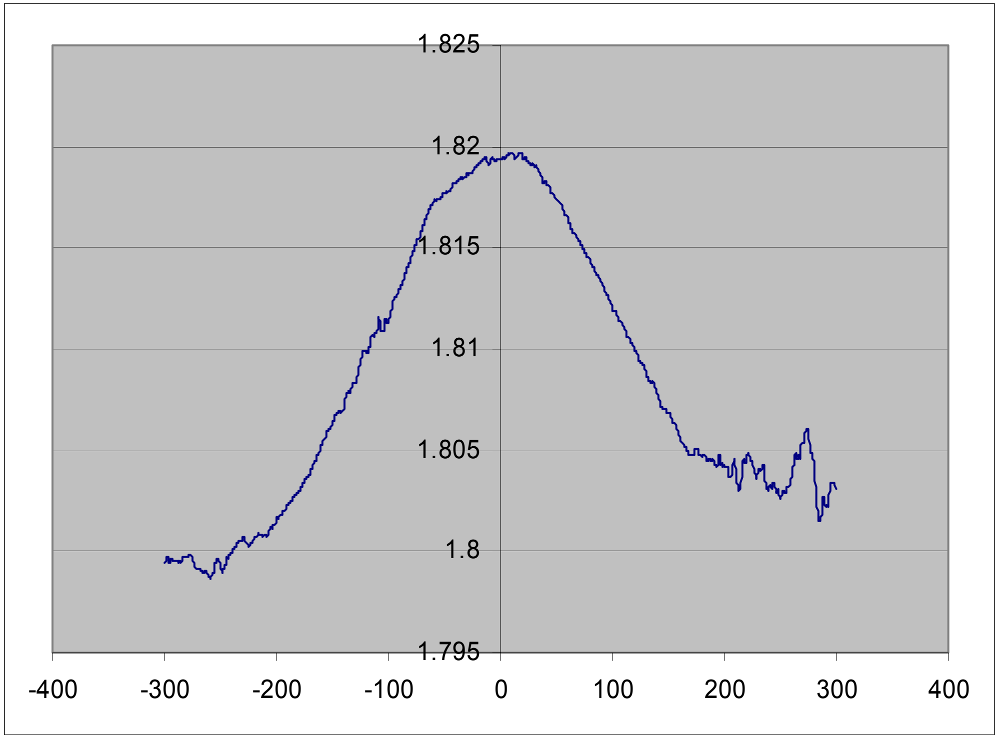
Chromis / Lucina / Eska / OMgiga

Ready

Need Short Fibers to See Rings

- Modal coupling coefficient much higher than initially thought
    - Higher inter-modal coupling coefficient
    - Core size variations and perturbations are larger than in 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

GI-POF Fiber RIP



120 um core sample typical data

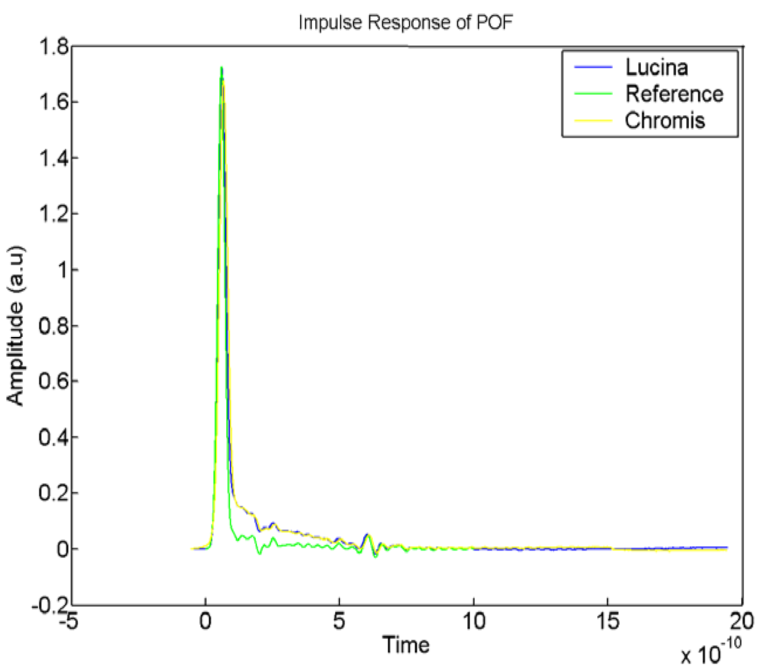
Data courtesy
PHOTON KINETICS

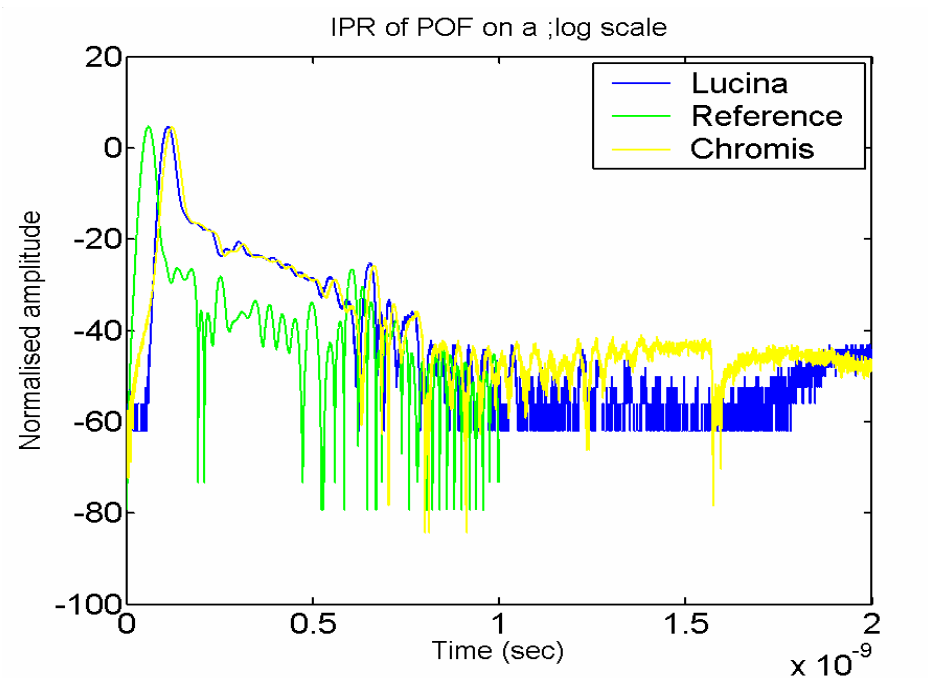
Impulse response Test

- A psec pulsed laser is scanned across the POF using a short length of SMF
- Carefully gather all of the modes exiting the fiber onto a photodetector

POF Impulse Response

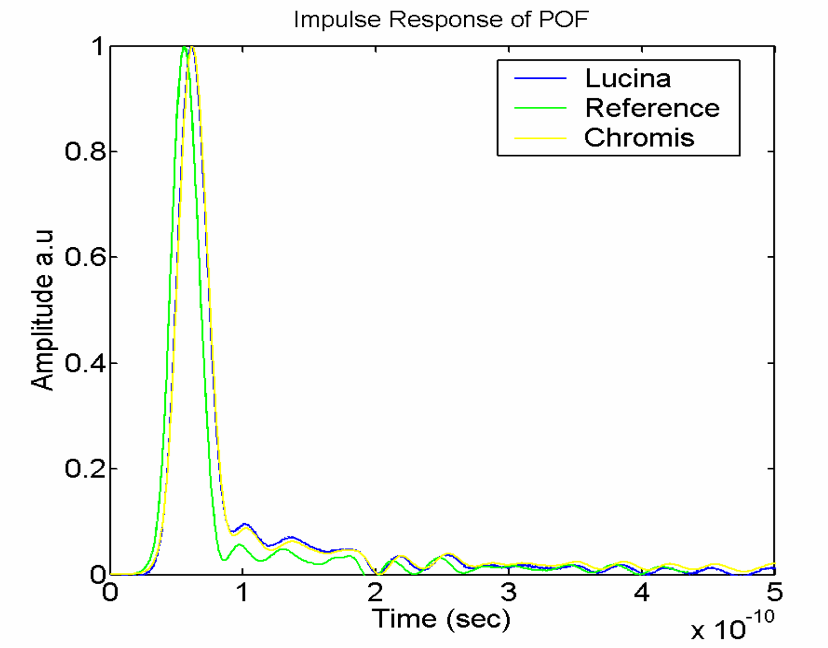
- 775 nm T:sapphire source: 20ps FWHM
- Launched via SMF into the POF
- The 120 micron core is butt coupled to the receiver
  - Net DMD is very small
  - Better temporal resolution may help; narrower pulse width and faster receiver

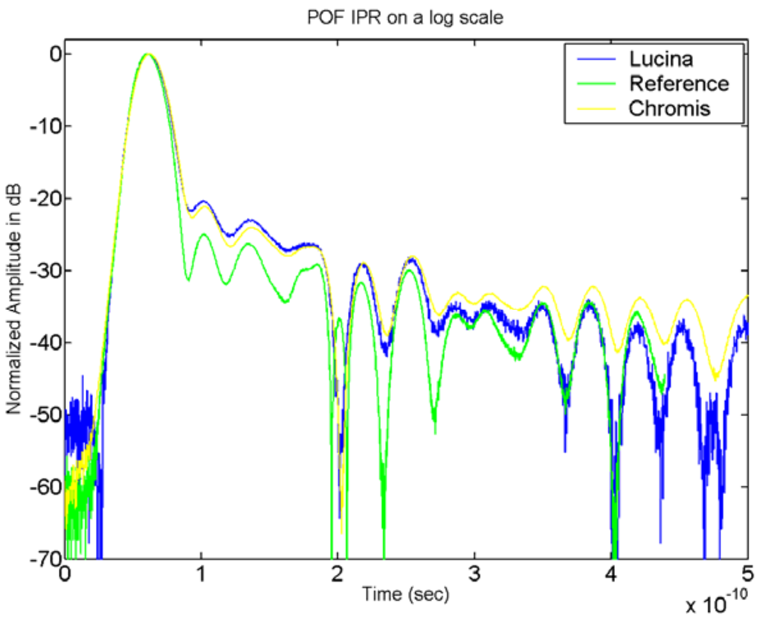




POF Impulse Response

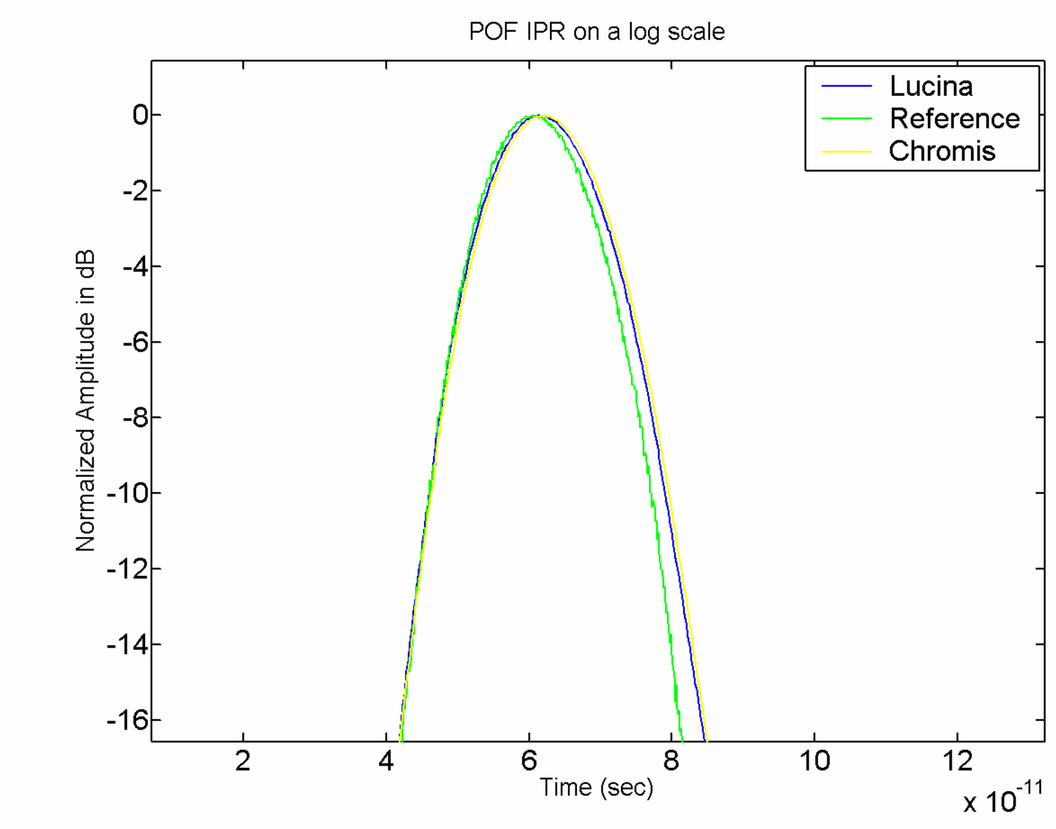
- 1550nm fiber laser: 2 ps pulse width
- Very close to reference (no fiber)



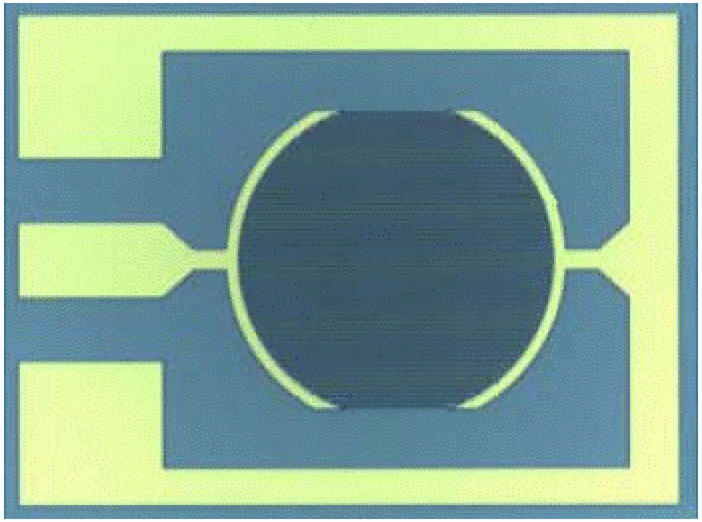


Detail of Impulse response

- 1550nm fiber laser: 2 ps pulse width
- DMD just observable

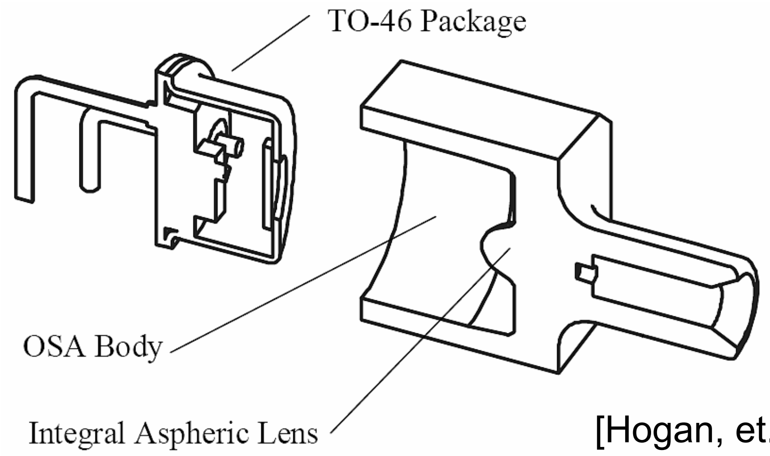


Approaches to Concentration

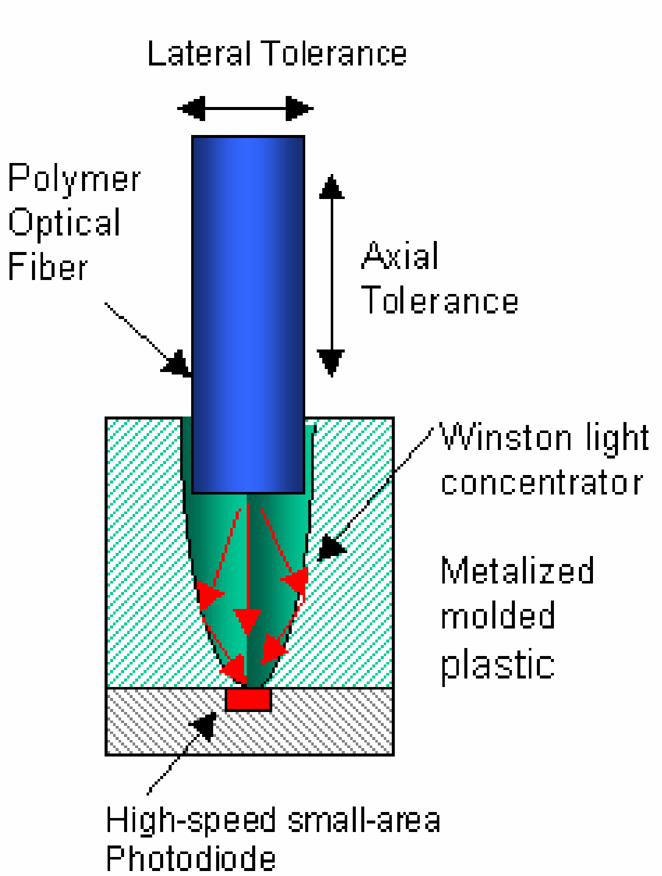


250 μm
Ø MSM

MSM image courtesy ASTRI used with permission



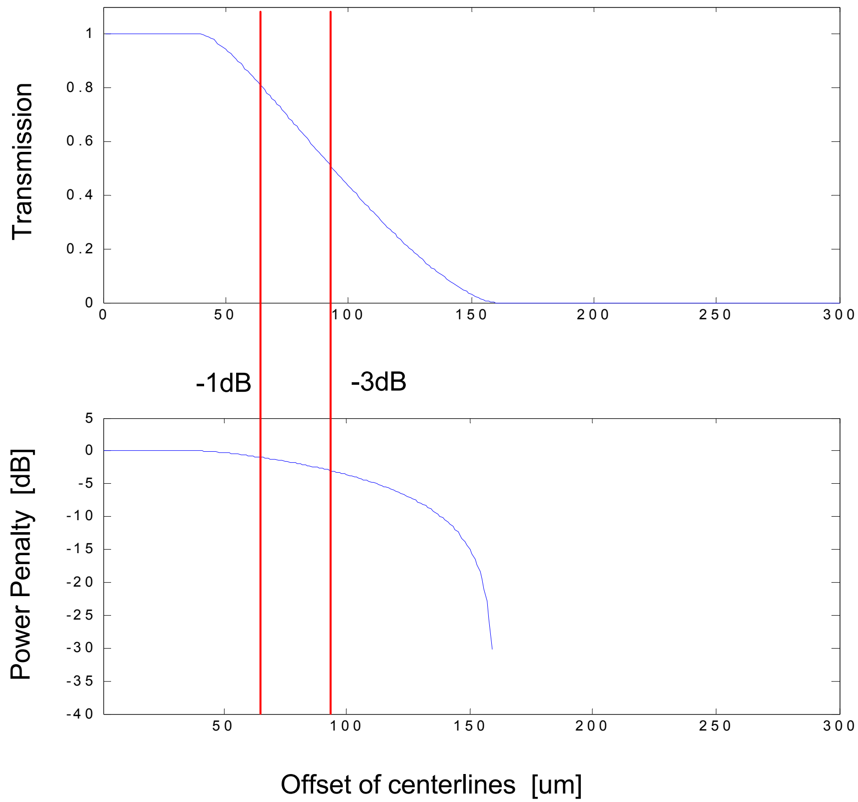
[Hogan, et. Al, 2000]



Conclusion

- A variety of solutions exist for low multigigabit rates
- 850 nm VCSELs and PF-GI POF present the most attractive solution for 5-10 Gbps
- EMD distance is very short on POFs tested
- Strong mode mixing can lead to relaxed tolerances for coupling into POF with controlled link bandwidth-length products
- Complicated equalizers are not needed for high bandwidth POF in the 1-10 Gb/s range for very short reach links
- Relaxed tolerance coupling into small high bandwidth detectors is needed for cost effective "snap together" detector coupling

Power Penalty – Radial Misalign



- Matlab model of power penalty for simple obscuration of missing aperture
  - Simple overlap or round detector
  - Working on Z power penalty for butt-coupling
  - Working on Gaussian beam, square detector

200 µm diameter detector and
120 µm diameter uniform beam

Data On Fiber Samples

- Four samples per fiber length
- 3 to 5 different lengths per fiber vendor
- Estimate of coefficient [radians^2/m]

Glass Fiber	D	σ	Χορε		
Eska	0.0075	(long sample)	980	SI	0.5
Chromis	0.066	0.027	120	GI	0.185
Asahi	0.054	0.0147	120	GI	0.185
Optimedia	0.037	0.0070 *	900	GI	0.3

* Much better data when cutback used

Microsoft Excel - ChromisAsahiOM

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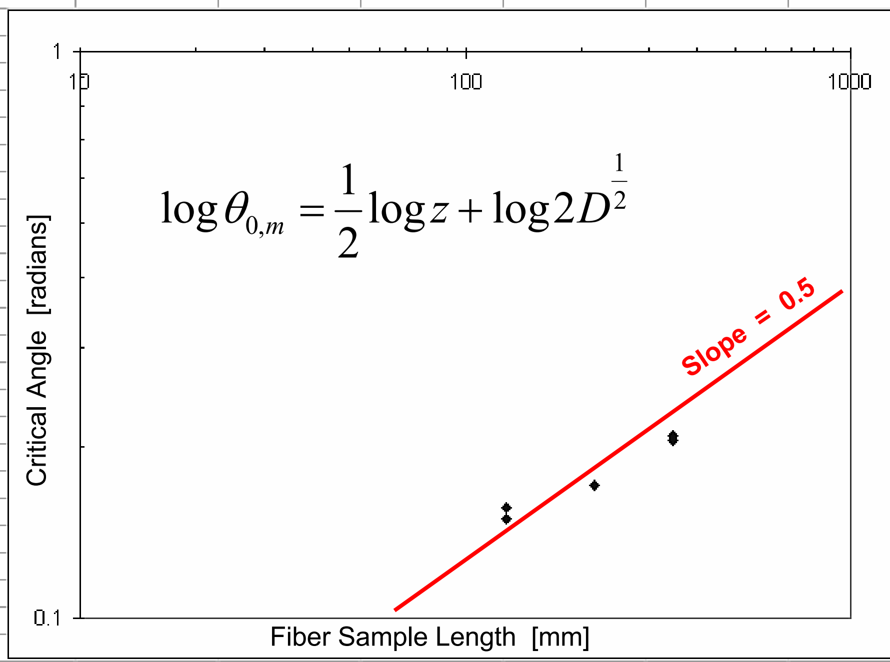

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Ready

Proposed Topics for "Alignment tolerant Highbandwidth POF Links"

- Demonstrator link based on Picolight VCSEL, Hamamatsu PD, Chromis 120 μm fiber.
  - Proof of concept, base line design
  - Correlation of experimental results with modeling effort
  - Test bed for evaluation of new components and approaches
  - Demonstrate equalization-alignment tolerance tradeoff

- Critical circuit blocks
  - TIA, equalizer, low-power low-jitter serial-to-parallel/ parallel-to-serial conversion
  - Laser Driver, CDR, have? needed?
  - CMOS vs. BiCMOS, technology choice trade-offs

- Other Research Questions:
  - Quantify equalization penalty
  - Measure modal noise due to under fill, MSM contact shadowing
  - Quantify power penalty and estimate costs for link and coupling options
    - Tradeoff between equalization and alignment tolerance
    - Physical Interface-ball lens, butt coupling, lens, concentrators
    - Tradeoff between fiber core size, input coupling, output coupling, equalization
  - Assessment of manufacturability

- Possible work division
  - IIT- equalizer, equalizer/TIA
  - Georgia Tech, modeling, equalizer investigations, numerical link optimizations, modal noise
  - UCSC, hardware demonstrator, serializer/deserializer, modal noise, connector design, assessment of manufacturability