40 Gbps Links using Plastic Optical Fiber

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Motivation and challenges

Plastic optical fiber

- Emerging medium for very short reach links
- Connectorization simplicity
- Low bending loss
- Attenuation
  - < 50dB/km, less than 30 demonstrated
- Bandwidth ??

Launch insensitive: Differential modal delay (DMD)
~2ps peak-to-peak for 200m

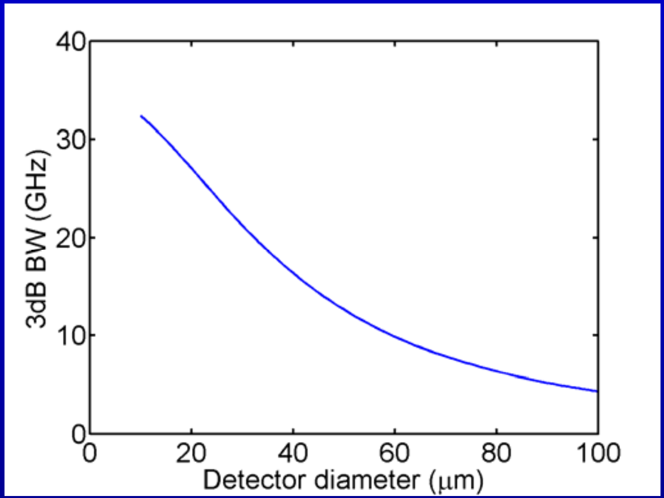
Large bandwidth: 40Gbps capability for >100m links

Some Available POF

	Chromis GigaPOF50SR	Chromis GigaPOF120SR	Lucina	Optimedia	Mitsubishi
Material	Perflourinated Graded Index (GI-PF)	Perflourinated Graded Index (GI-PF)	Perflourinated graded Index (GI-PF)	Polymethyl Methacrylate Graded Index (GI-PMMA)	PloyMethyl Methacrylate Step index (SI-PMMA)
Numerical Aperture (NA)	0.19 +/- 0.015	0.185 +/- 0.015	0.185 +/-0.01	0.23-0.3	0.5
Core/ Cladding Diameter (μm)	50/490 +/- 5	120/490 +/- 10/7	120/492 +/- 10/3	1000/2200 +/- 5%	980/1000 +/- 60
Attenuation (dB/km) @850nm	<50	<60	<40	<200	<200
@ 1300nm	<60	<60	---	<4000	<4000
Specified Bandwidth	>300MHz-km @850nm	>300MHz-km @850nm	>940MHz x200m @850nm	Dependent on NA	--

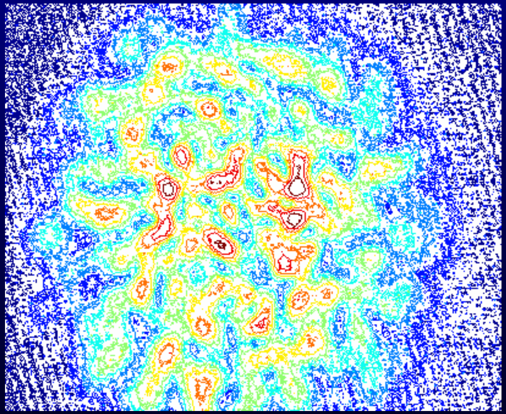
Detector limited by core size

- High-speed large core media are limited by the requirement to couple the large core fiber to a sufficiently small detector
- Trade-off
  - Tolerance of larger diameter POF
  - Coupling efficiency of POF to photodetector
  - Bandwidth of larger diameter detector
- 10 Gbps operation: core diam. < 150μm
- 40 Gbps operation: core diam. < 50μm



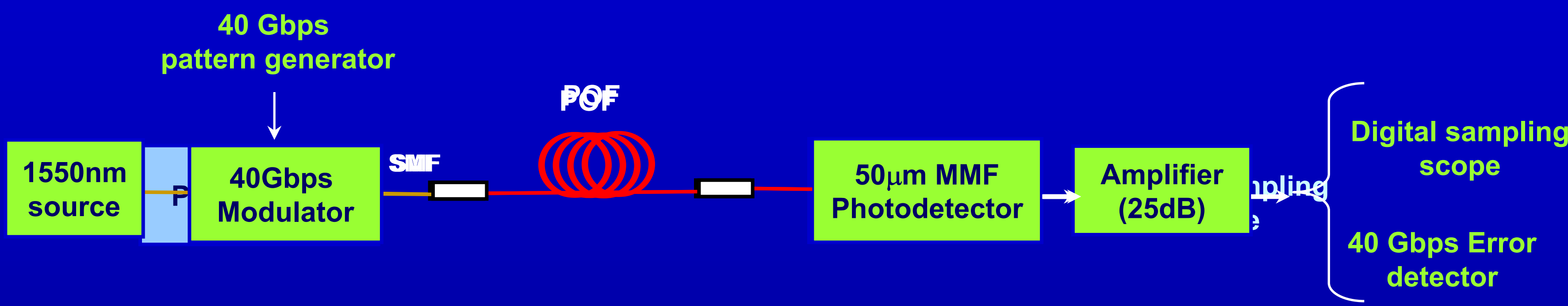
PIN Bandwidth vs. diameter

Transit time and RC



Speckle pattern after 200m

POF link set up



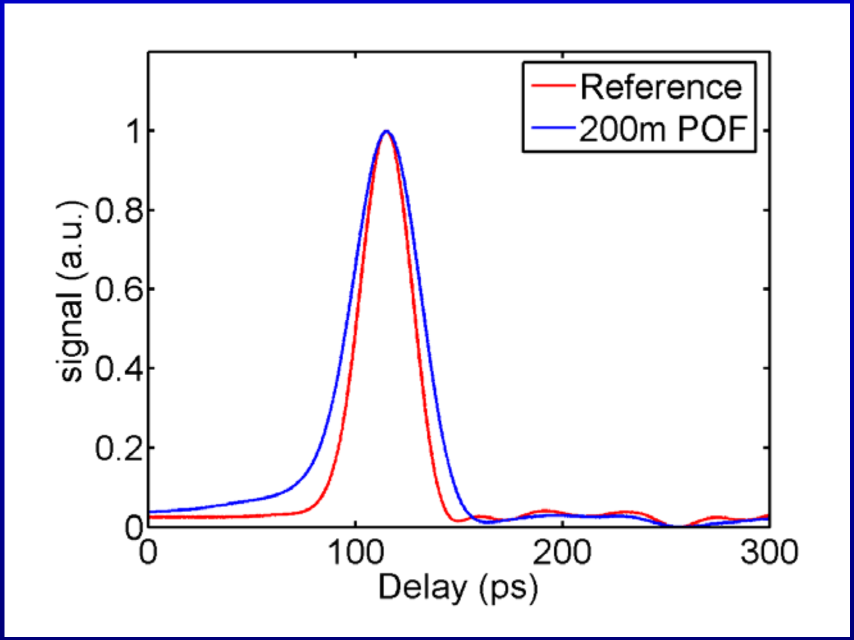
Impulse response measurement at 800nm and 1550nm

- Transmitter
  - 800nm, 16 ps: Ti-sapphire
  - 1550nm, 16 ps: mode-locked fiber laser
- Receiver
  - 800nm and 1550nm: commercial MMF PIN photodetector (Newfocus 1454) and digital sampling scope (Tektronix: TDS8200)

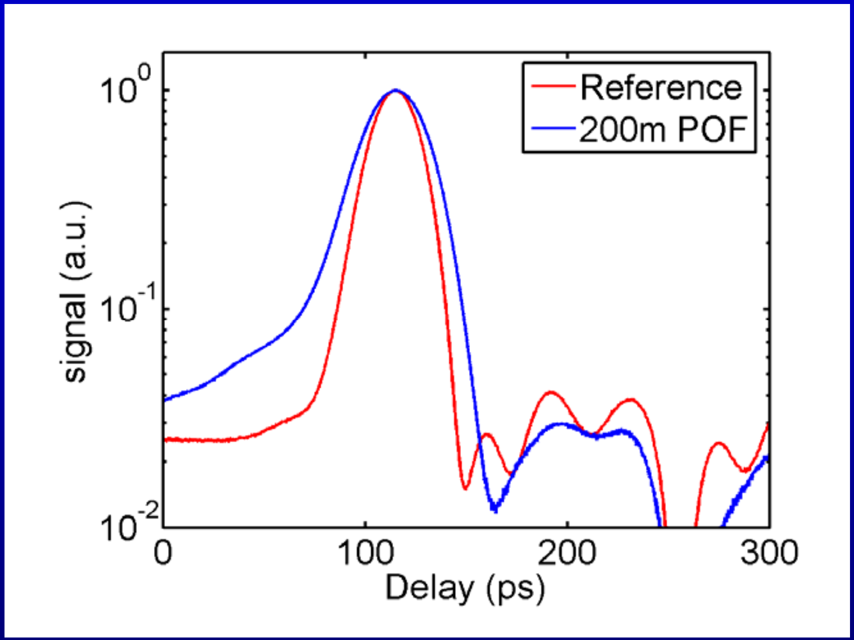
Link measurement at 1550nm

- Transmitter
  - 40Gbps PRBS data source
- Receiver
  - Commercial MMF PIN photodetector (Newfocus 1454) and 38GHz post-amp

200m impulse response (800nm)



Linear scale

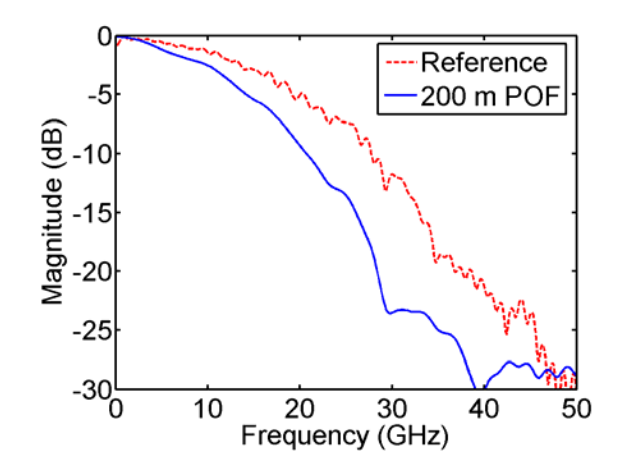


Log scale

- 200m 50μm core GI PF-POF
  - GIPOF50-SR from Chromis Fiberoptics
- Sufficient bandwidth for 40Gbps?

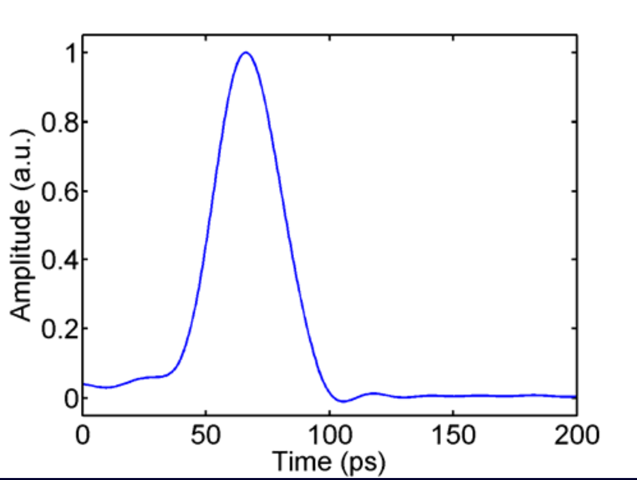
Frequency response

- Deconvolved response: ~29 ps FWHM
  - Primarily detector limited response
  - Channel insertion loss including connectorization: 8 dB



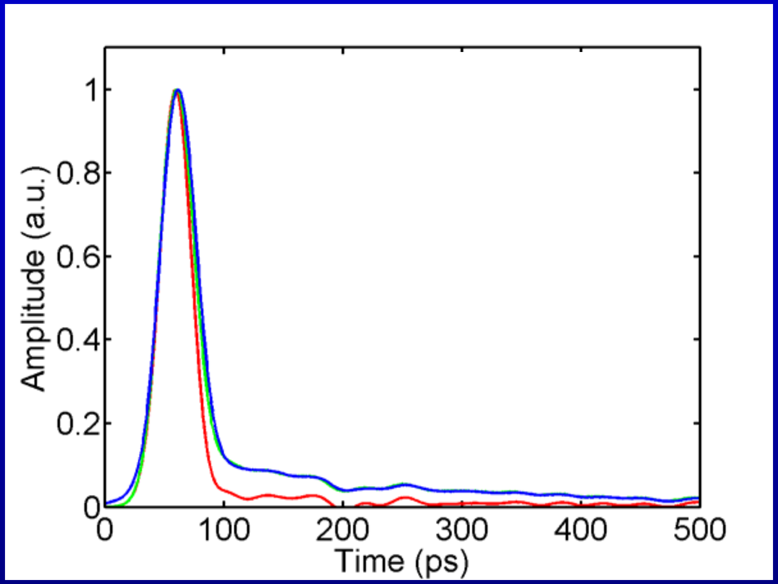
Frequency response

- 200m power penalty using the deconvolved response
  - 30 Gbps: 4 dB
  - 40 Gbps: 10 dB
- 100m power penalty
  - 40 Gbps: <4 dB

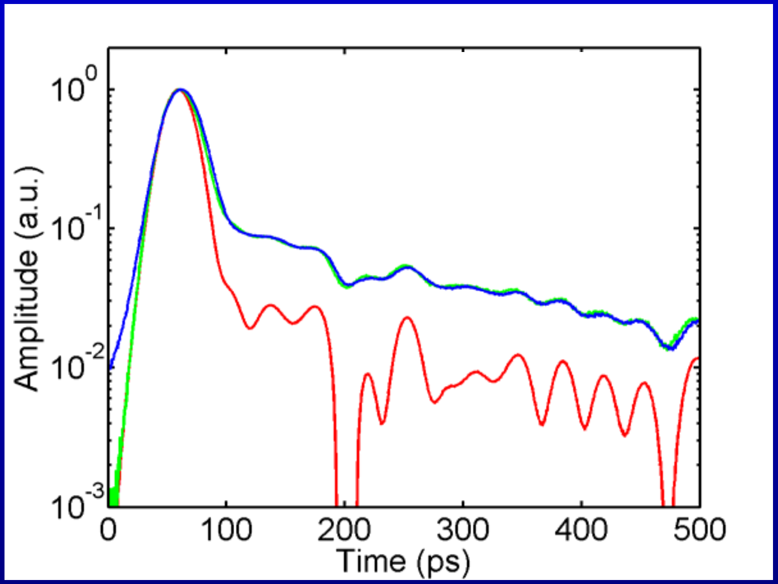


Deconvolved impulse response

120μm core POF



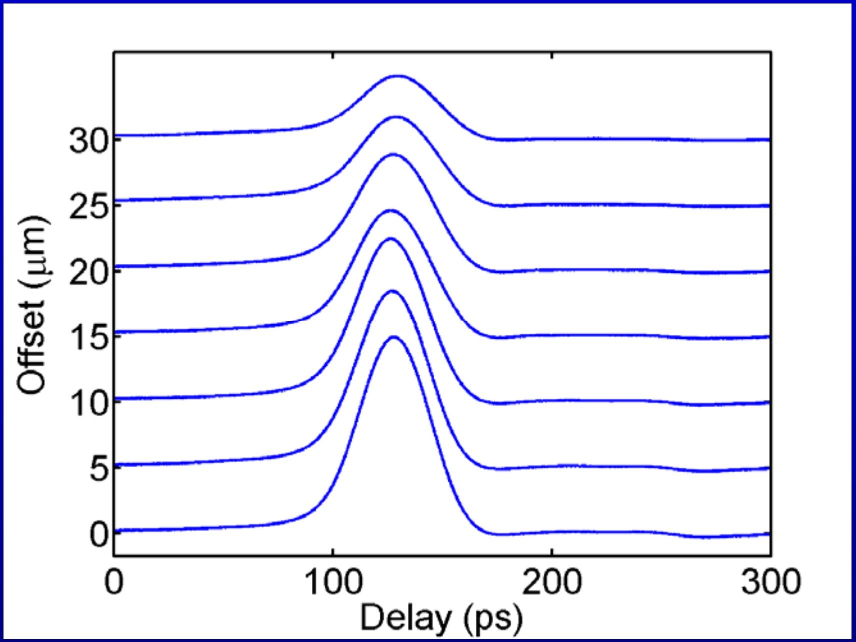
Linear scale



Log scale

- 20m 120μm core GI PF-POF
  - Detector bandwidth limited response

Launch insensitivity

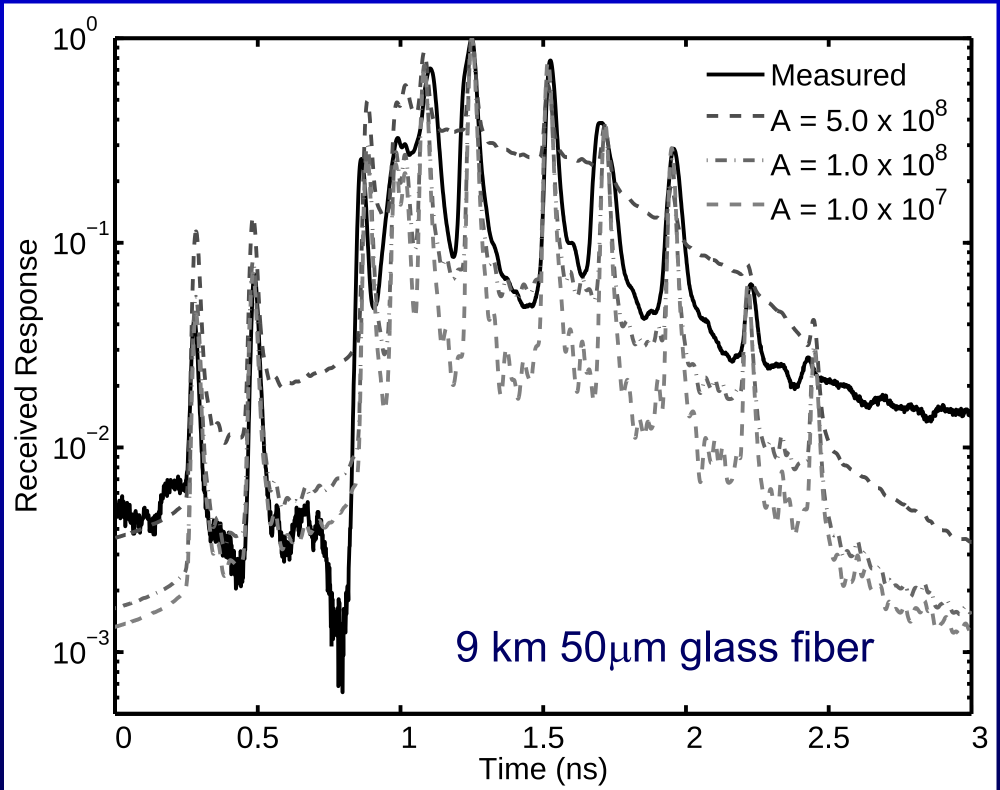


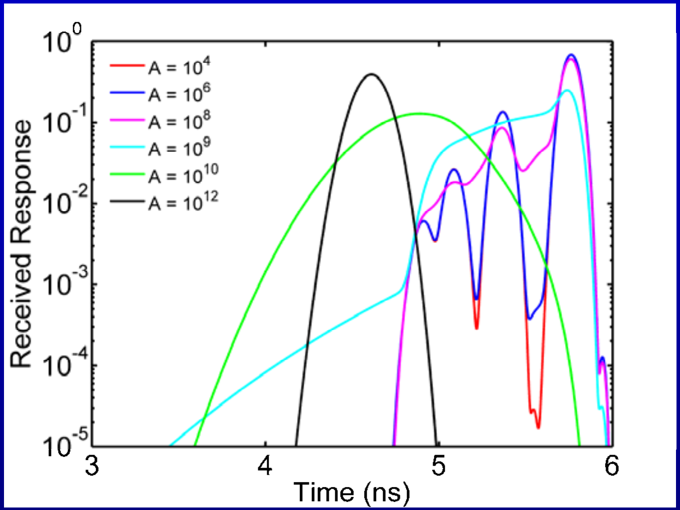
- Differential modal delay: 2 ps peak-to-peak
- Attenuation at larger offsets
  - Coupling to leaky modes
- Bandwidth is independent of launched mode power distribution
  - High offset tolerance
  - Tolerant of multimode sources

- High Bandwidth
- Launch insensitive
- Gaussian-like response

MODE COUPLING

Mode coupling in glass fiber



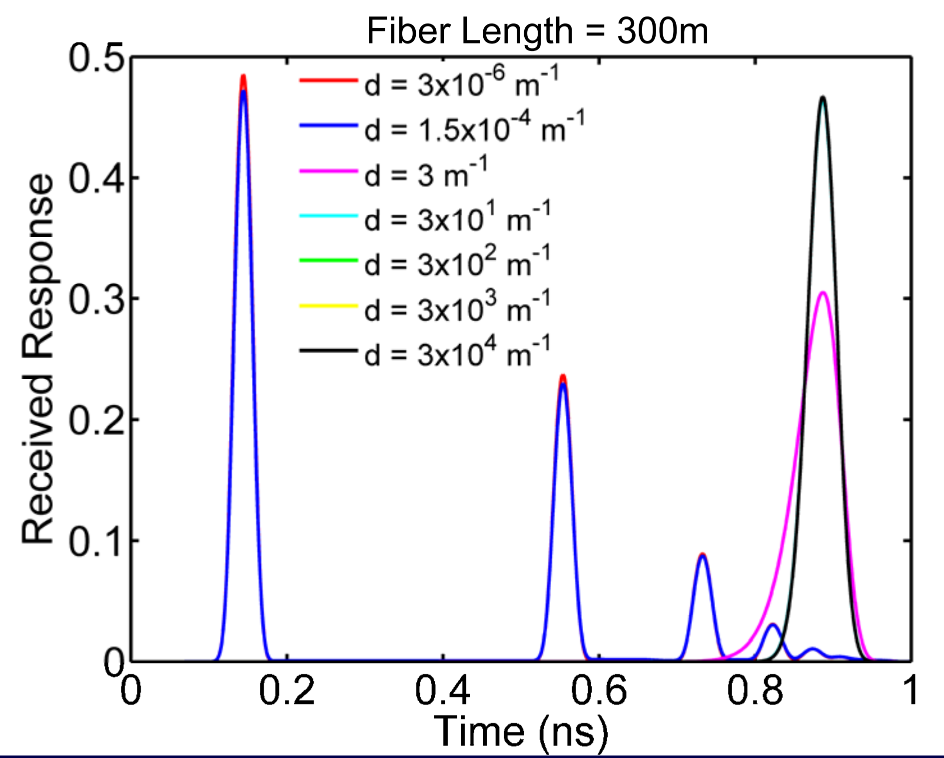


- Impulse response with high temporal resolution and high dynamic range
- Low coupling in glass fiber allows the direct time domain assessment

Mode coupling

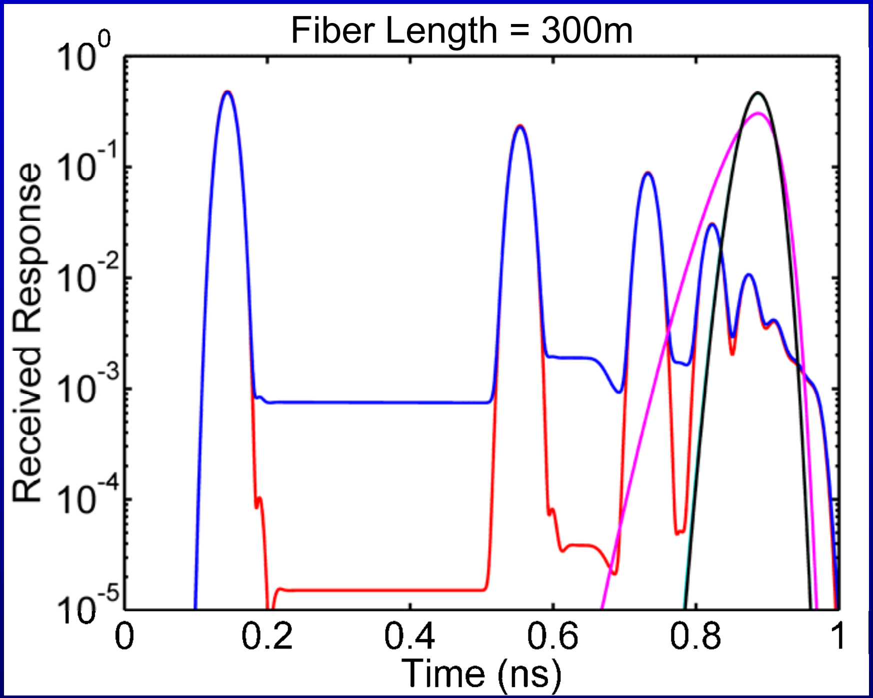
Strong modal coupling insures all photons behave equally
i.e. group delay is uniform

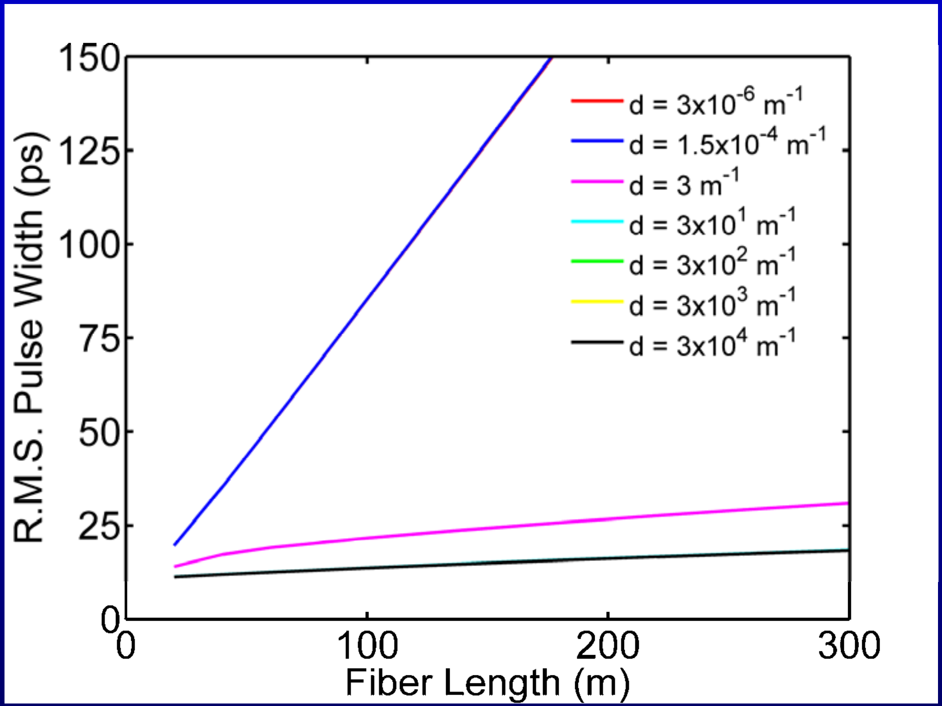
- Mode coupling coefficient
  - Glass MMF: 0.15 km^{-1}
  - GI-POF: 5 m^{-1}
    - 4-5 orders larger
- Effects
  - Reaches complete mode coupling regime i.e. steady-state mode power distribution
  - Large bandwidth
  - Low DMD
  - Bandwidth $\propto 1/\sqrt{\text{Fiber length}}$



Ref: K. Balemarthy, A. Polley, and S. E. Ralph, "Electronic Equalization of Multi-km 10Gb/s Multi-Mode Fiber Links: Mode Coupling Effects," *J. Lightwave Tech* Dec. 2006.

Pulse Width

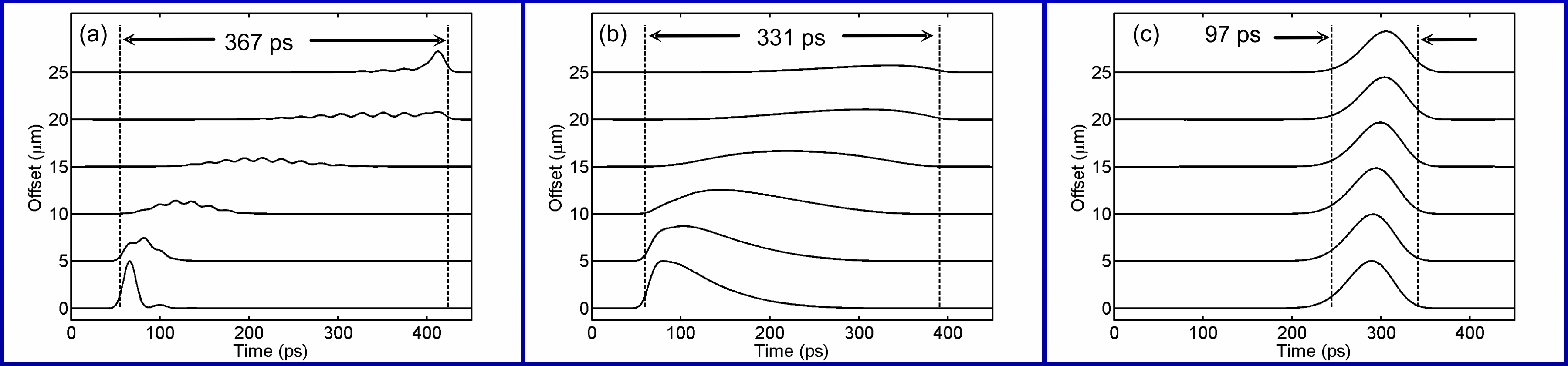




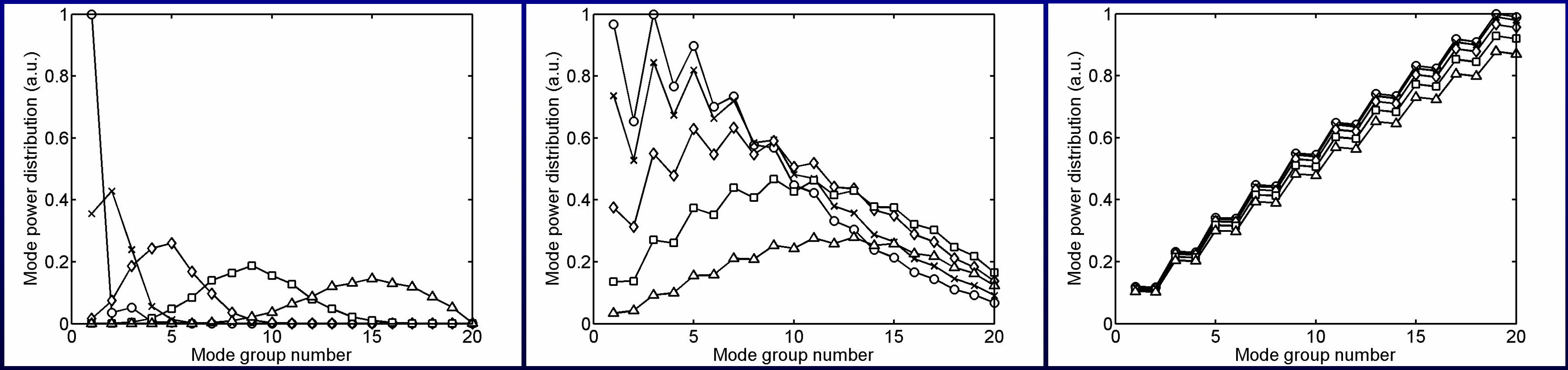
- POF is strongly coupled
  - Anticipate near Gaussian response for short fibers
- What is the MPD as the length increases?

Temporal and Mode Distribution

DMD



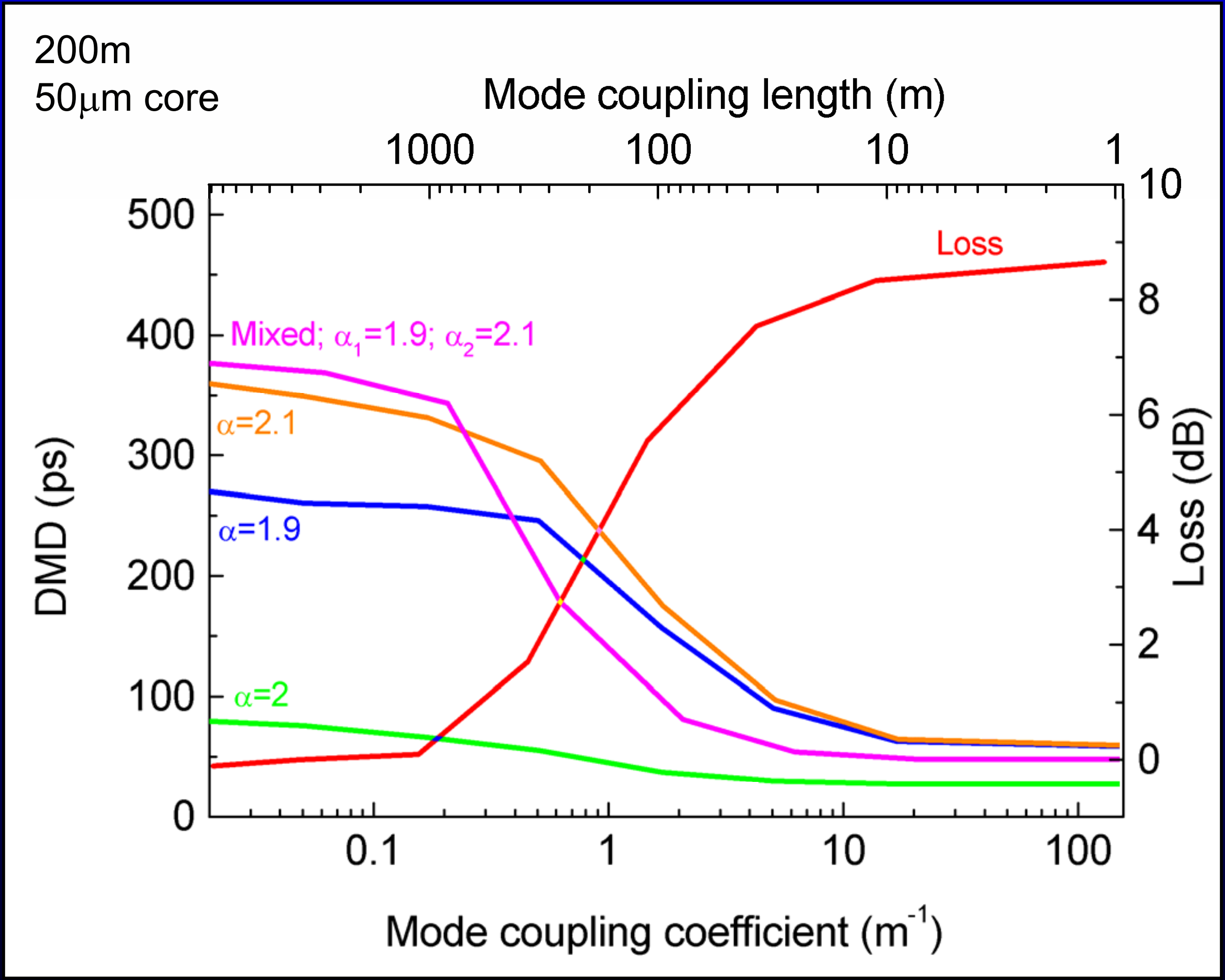
Mode Power Distribution



1.7×10^{-5} Increasing Coupling 0.17 $5 m^{-1}$

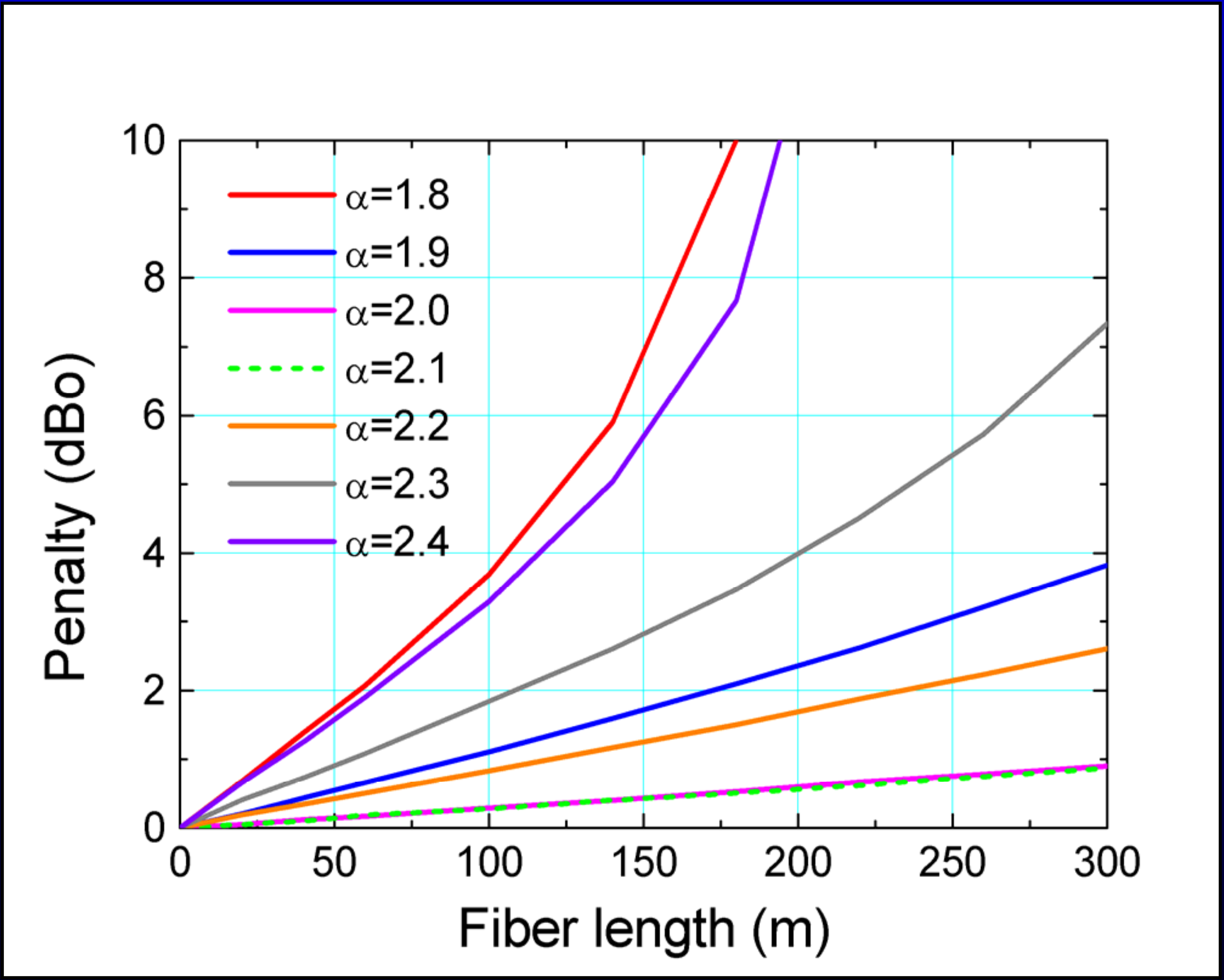
DMD and Mode Coupling

- Dependence of DMD on mode coupling coefficient
- Reported mode coupling length ~ 10-100 m
- Without coupling a tolerance is much tighter than ±0.1
- With strong coupling tolerance is increased by order of magnitude



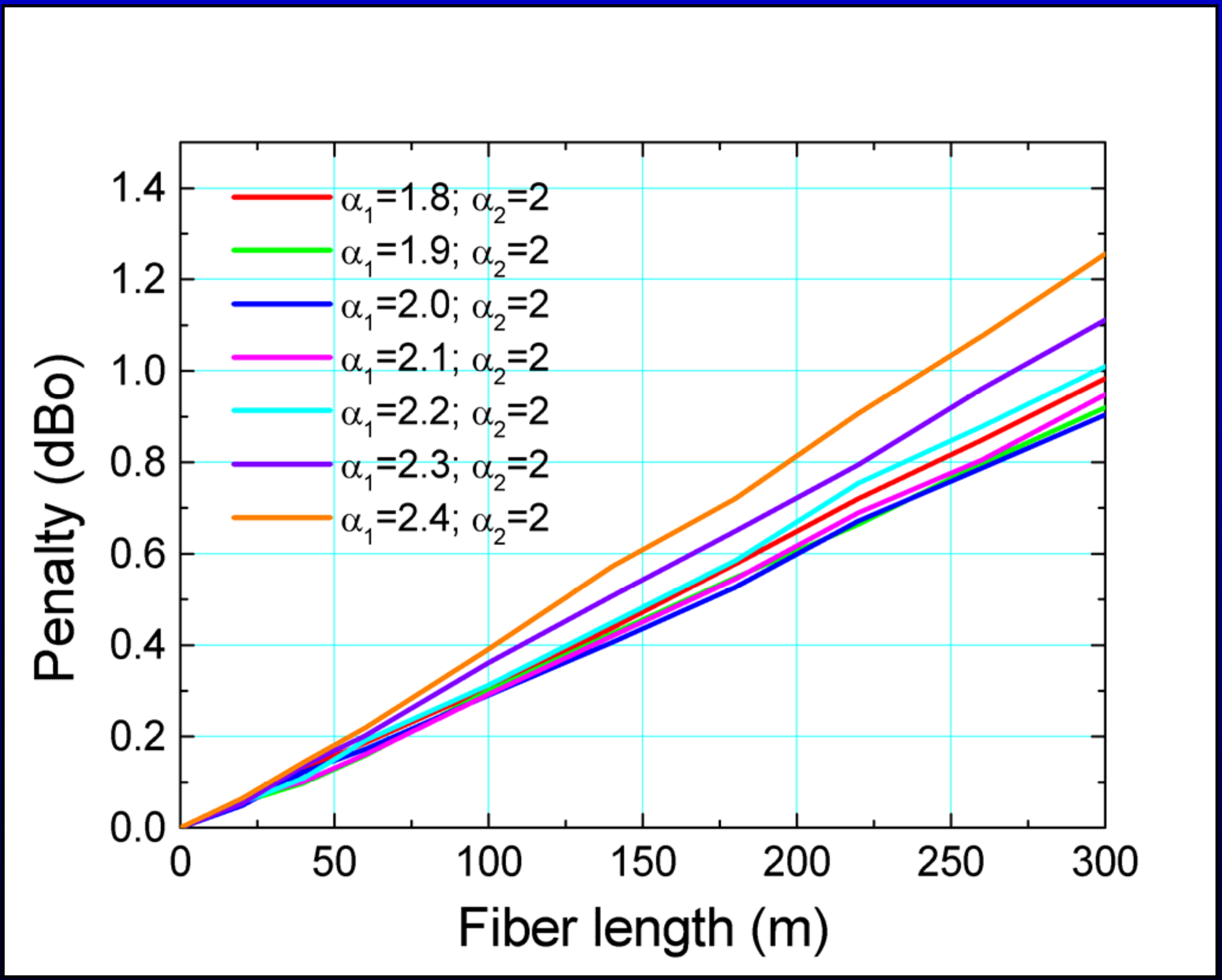
10 Gbps Index Tolerance

- Sensitivity of the power penalty on refractive index profile
- Strong coupling allows relatively large index profile tolerance
  - 300m tolerates α=2.0 ±0.12
  - 100m tolerates α=2.0 ±0.3



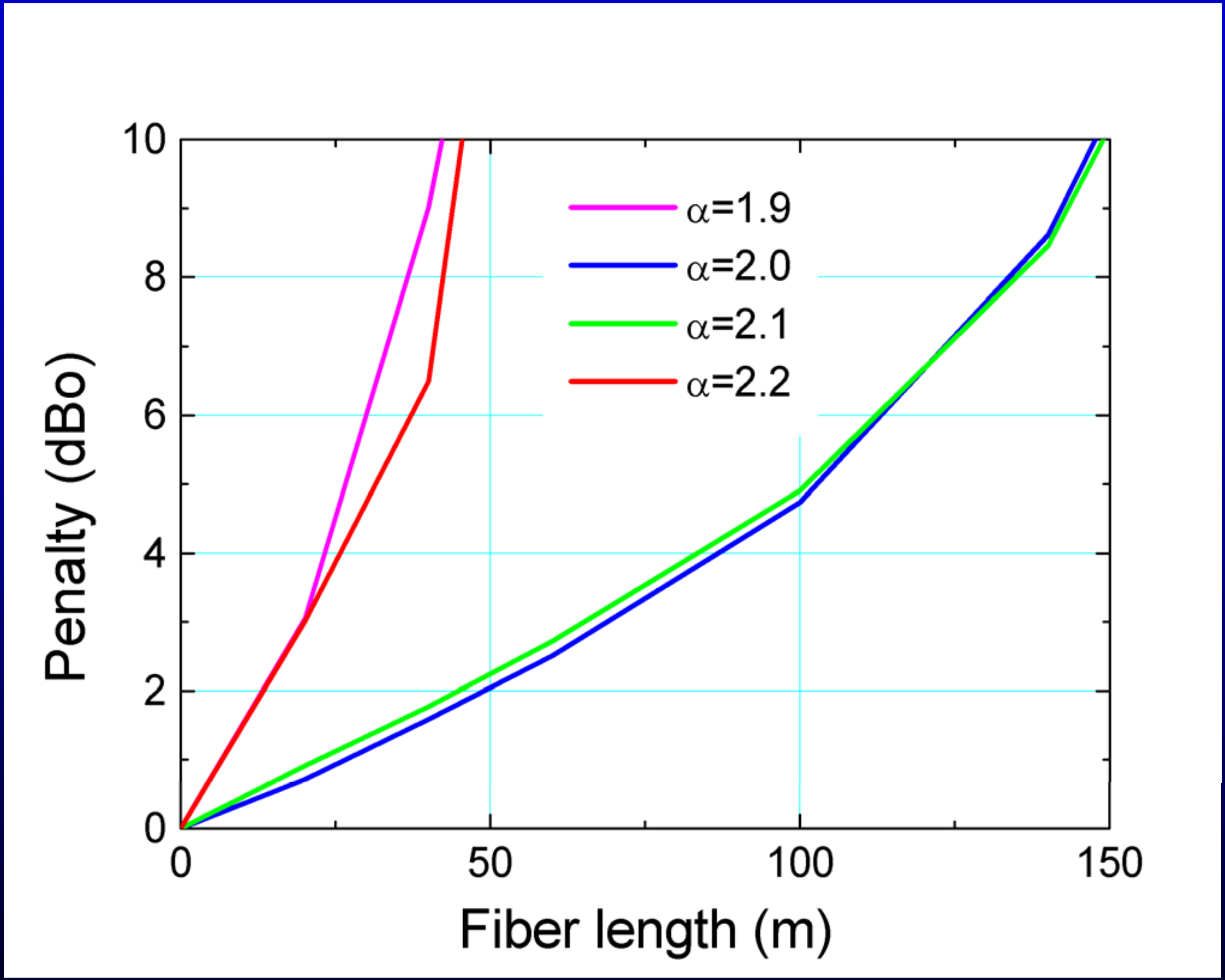
10Gbps Tolerance to Mixed α

- Penalty is more sensitive to α_2
  - Modal delays of higher order modes are more strongly dependent on α_2
  - Mode degeneracy is larger for higher order modes



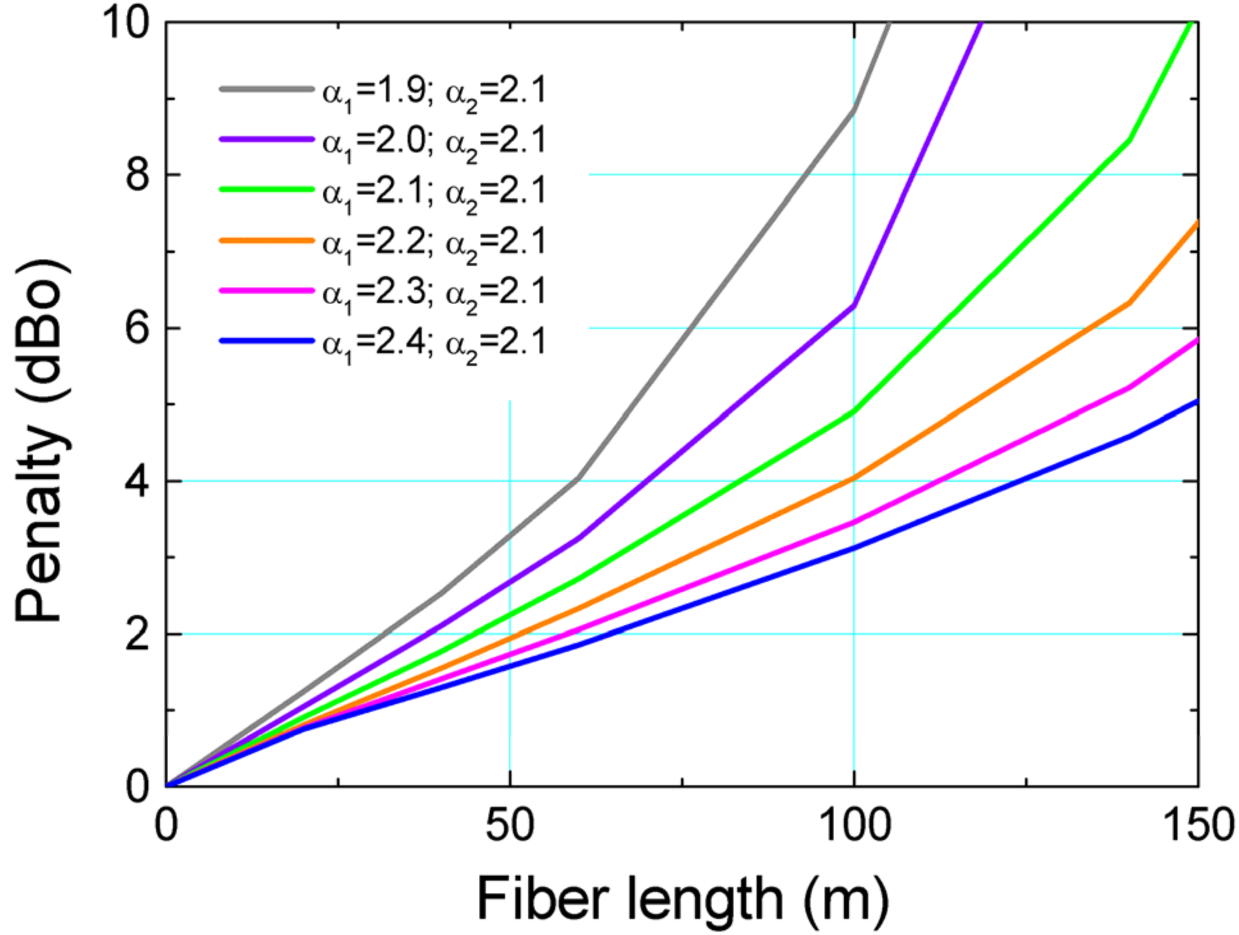
40Gbps Index Tolerance

- Manageable tolerance is required for 40 Gbps links

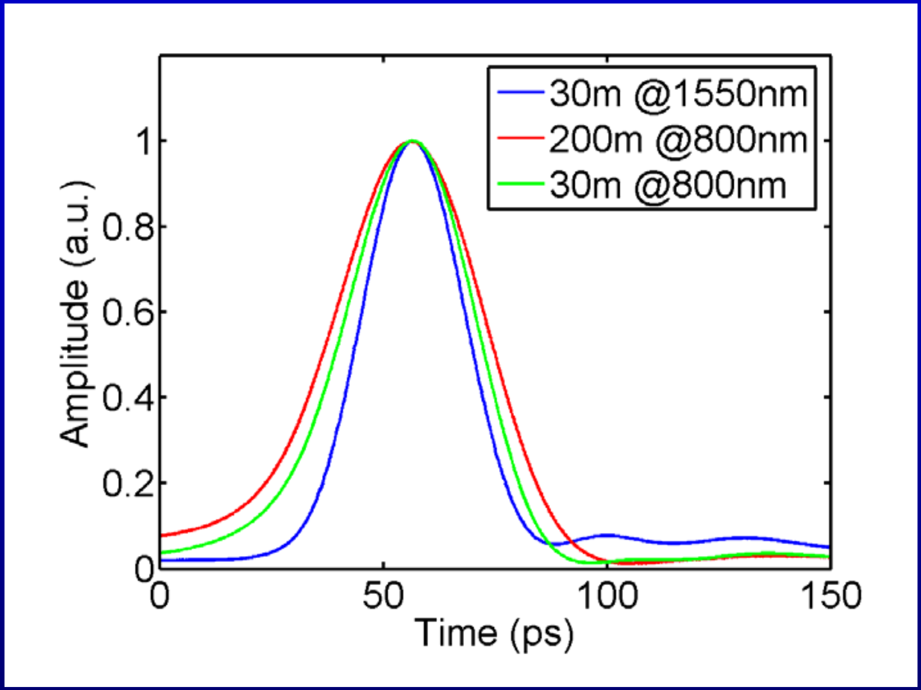


40 Gbps Mixed α

- Similar sensitivity on α_2



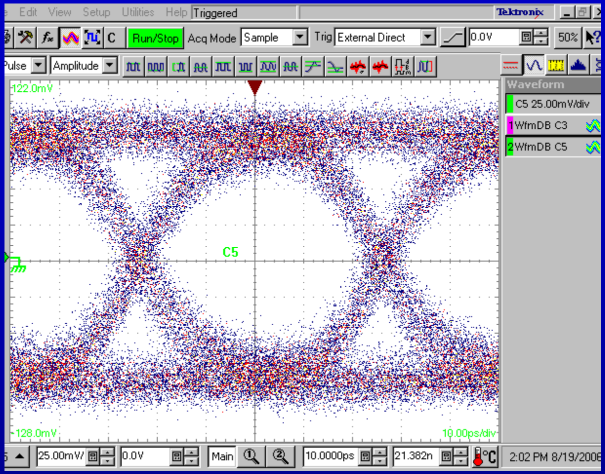
POF links at 1550nm



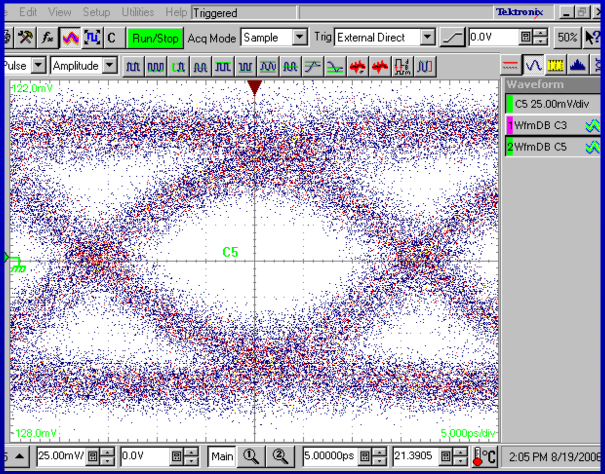
Impulse responses

- Optimum operating window: 850 and 1300 nm
- Channel bandwidth is λ independent

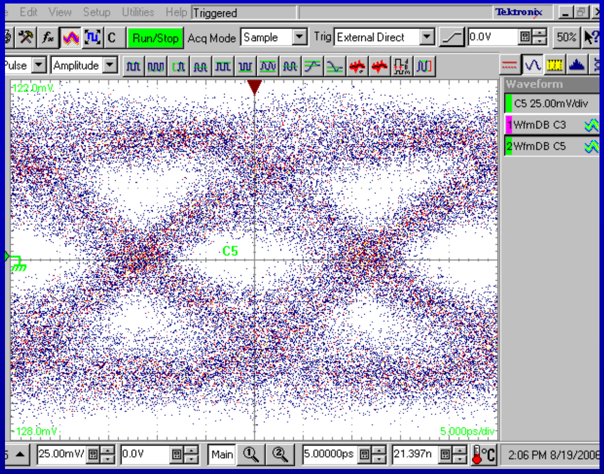
30m links: 1550nm



20 Gbps



30 Gbps

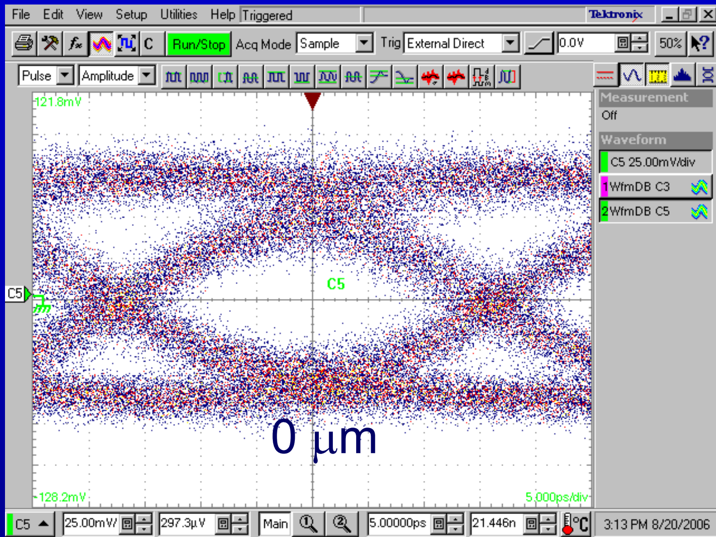


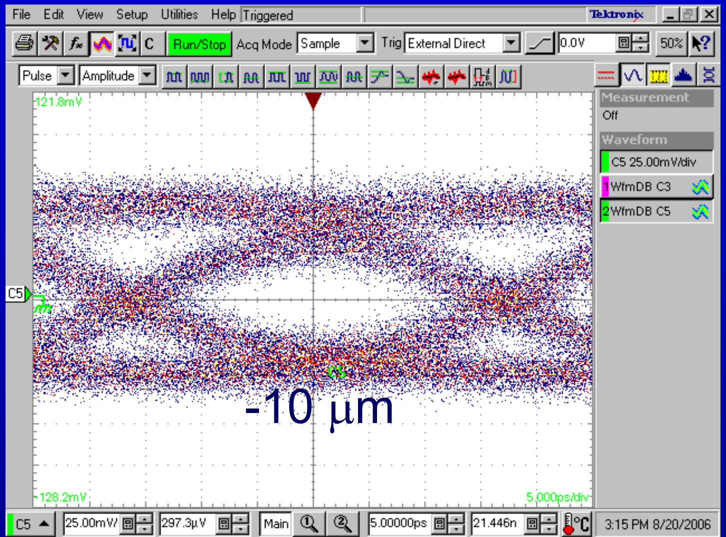
40 Gbps

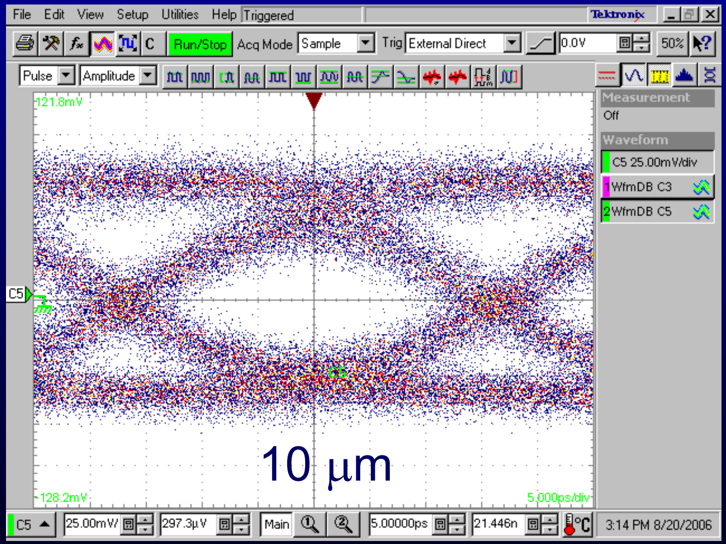
- Completely open eye for 20 Gbps and 30 Gbps
- Eye at 40 Gbps: receiver bandwidth limited

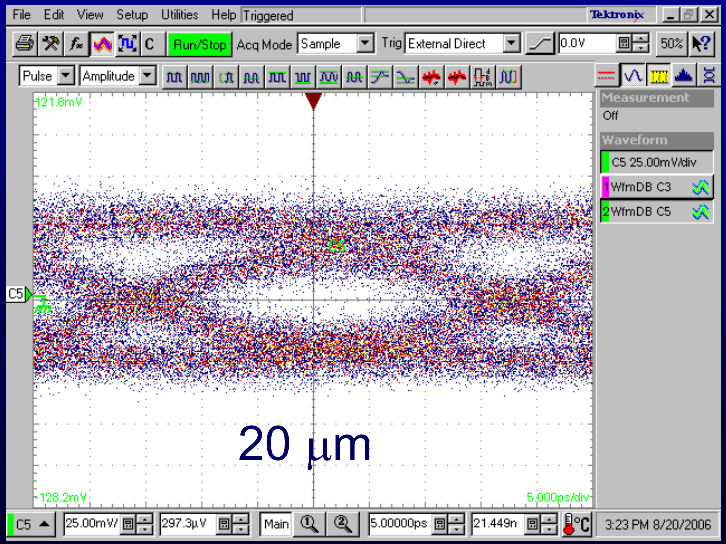
Thanks to SHF for use of 50G BERT

Eye at different offsets for 30 Gbps

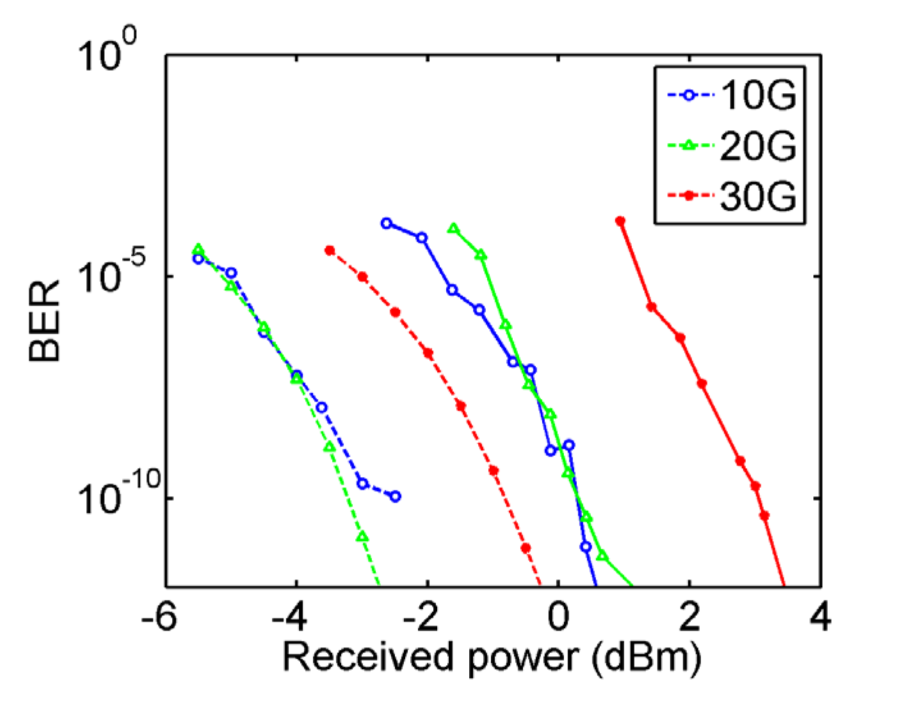






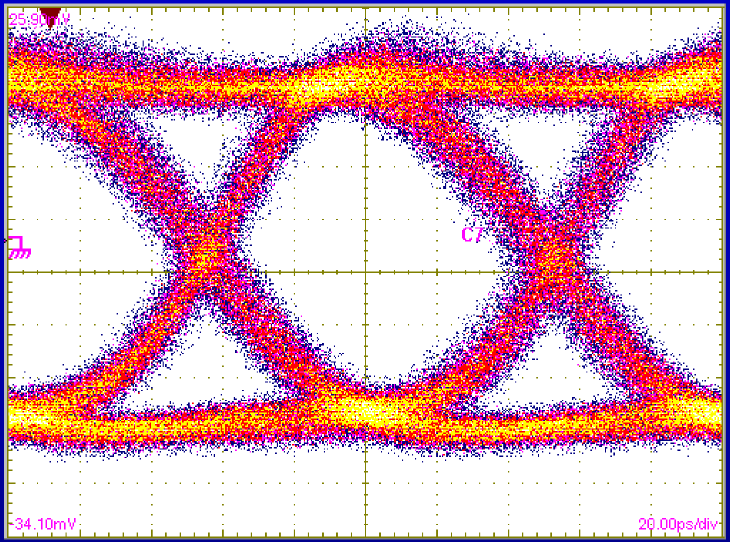


BER

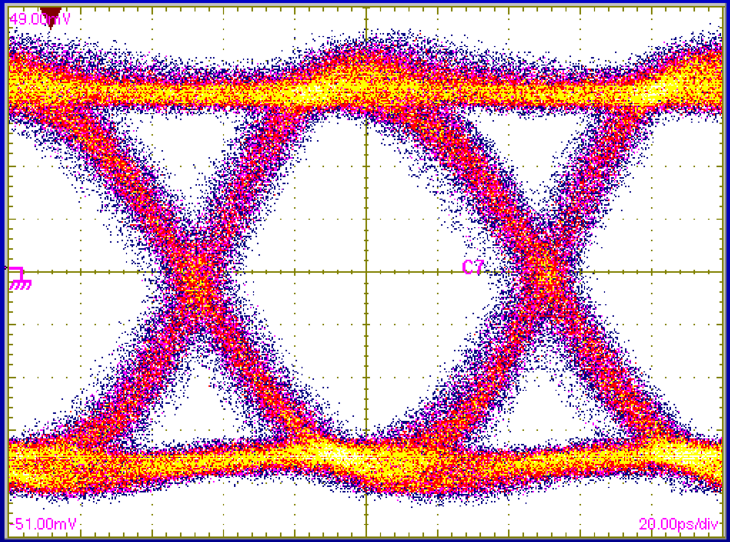


- ISI power penalty at BER of 10^{-9}
  - 10 Gbps: 0.6 dB
  - 20 Gbps: 0.6 dB
  - 30 Gbps: 1.5 dB
- ISI penalty = Measured power penalty - Coupling loss
  - Coupling loss from 50µm POF to detector = 2.5 dB

VCSEL and 120μm core POF



Chromis



Lucina

- Transmitter: 10 Gbps VCSEL
- 20m 120μm core GI PF-POF

Conclusion

- Quantitatively explained large bandwidth in POF
- Demonstration of launch insensitivity
- First demonstration of 40 Gbps capability in POF links
- First demonstration of 30 Gbps error free transmission in POF links