Multimode Fiber Communication System Simulation

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Introduction

- TIA standards development for laser optimized multimode fiber (TIA/EIA-492AAAC) required new modeling and simulation approaches. RSoft participated in TIA working group on modal dependence of multimode fiber bandwidth since 2001 and developed tools to address TIA needs
- These tools have been validated and are now used by industry
- RSoft Design Group is participating in IEEE 802.3aq 10GBASE-LRM Task Force to help Ethernet community with developing new standards and to better understand the current industry needs and requirements
- Our objective is to use our multimode fiber simulator to address Channel Modeling ad-hoc discussion topics such as fiber modeling, studying launch conditions, time-varying effects, reproducing of and comparison with Cambridge model and Monte-Carlo model results.
- Here we present some results of our initial studies
- This work has been supported by a Navy SBIR contract (through Gair Brown of the Naval Surface Warfare Center) and a NIST ATP contract (through the PCAD Consortium)

Requirements for Multimode Simulation

- Model and simulate spatial characteristics of multimode fiber
  - Modal and chromatic dispersion
  - Differential Mode Delay (DMD)
  - Mode coupling coefficients, mode power distribution (MPD)
  - Polarization
- Model modal fields of multimode components. Laser output beams can be modeled with different mode compositions to provide single-mode, restricted-mode, or overfilled launch with Gaussian, LG, HG, LP, donut spatial profiles, or any of their combinations
- Model a coupler/connector with 3D coupling into and out from fiber
  - x, y, z offsets, angular offsets, plus polarization
- Model and simulate encircled flux (EF)
- Model and simulate effective modal bandwidth (EMB)
- System simulation to also flexibly and accurately model other system components including lasers and receivers taking transient behavior, nonlinearities, and noise into account
- Take temporal and modal characteristics into account for total system simulation performance including signal to noise ratio, BER, signal waveforms, eye diagrams, power penalties, etc.

Multimode Fiber Model – Our Approach

- Fiber refractive index profile used to accurately calculate modes and delays
- Index profile can be defined analytically, by numerical file, by functional representation, or by power-law parameter
- Helmholtz equation solved numerically by simulator

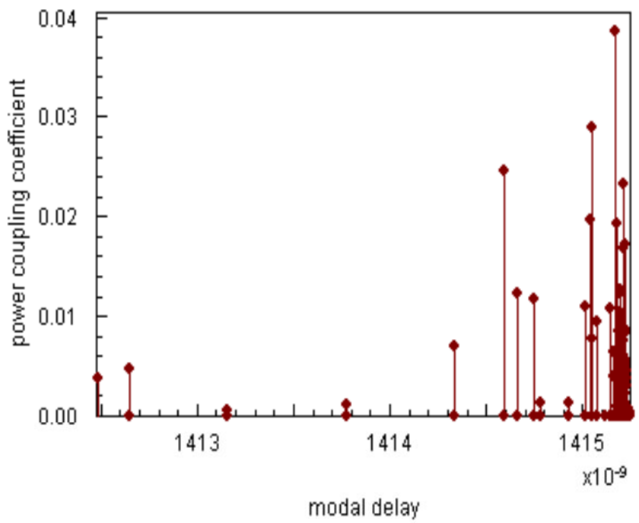
$$\frac{d^2E(r)}{dr^2} + \frac{1}{r}\frac{dE(r)}{dr} + \left[n^2(r)k_\circ^2 - \beta_{LM}^2 - \frac{L^2}{r^2} \right] E(r) = 0$$

$$E(r,\phi,z) = E(r) \cdot \exp(jL\phi) \cdot \exp(j\beta z)$$

- For a given azimuthal index *L*, the mode solver will generate solutions for each radial index *M*.
- Mode power distribution (MPD) calculated through overlap integration
- Outputs from fiber model include delay plots, coupling coefficients for each mode and for Degenerate Mode Groups

Multimode Fiber Model – Cont'd

Modal Delays

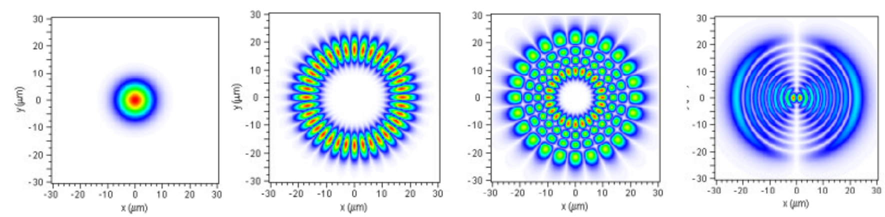


Coupling Coefficients

$$E_{input}(x,y) = \sum_{i=1}^{n} c_i \, E_i \,(x,y)$$

$$c_i = \iint E_{input}(x,y) E_i^*(x,y) dx dy$$

Representative Fiber Modes



- Both modal and chromatic dispersion are modeled. Chromatic dispersion can be either specified or calculated according to formula:

$$D(\lambda) = \frac{S_0}{4} \lambda \left[1 - \frac{\lambda_0^{\ 4}}{\lambda^4} \right]$$

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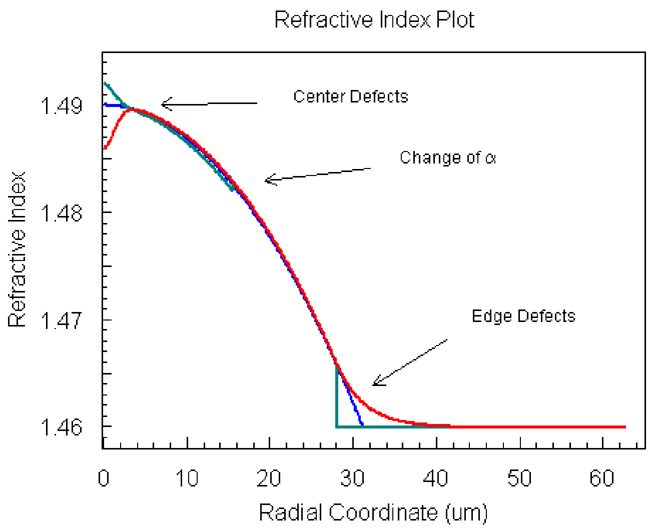
Refractive Index Perturbations

- We consider the index profile with perturbations as specified in Cambridge model

$$n(r) = \begin{cases} n_1 \cdot \left(1 - 2\Delta\left(\dfrac{r}{a}\right)^{\alpha}\right)^{1/2}, & \text{core}, \quad r \le a \\[2ex] n_1 \cdot (1 - 2\Delta)^{1/2} = n_2, & \text{cladding}, \; r > a \end{cases}$$



Four types of defects are included:

- Inner core α {1.89, 1.97, 2.05}
- Outer core α {1.89, 1.97, 2.05}
- Center defect – none, tip, dip
- Core/cladding defect – none, sudden, exponential

Total of 81 combinations

FDDI-grade fiber:

62.5/125 μm

n_1=1.49, Δ=0.02

- supports 253 modes

and 22 degenerate mode groups

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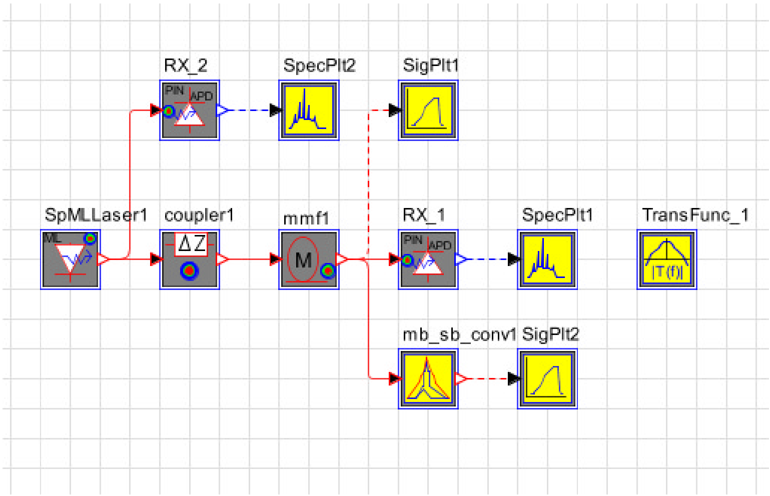
Impulse Responses and Modal Bandwidth

- A schematic to study impulse response and MB is shown on the right
- Launch signal is 50-ps Gaussian with 7 μm FWHM for RML or can use overfilled launch profile calculated by fiber model
- Operational wavelength 1300 nm



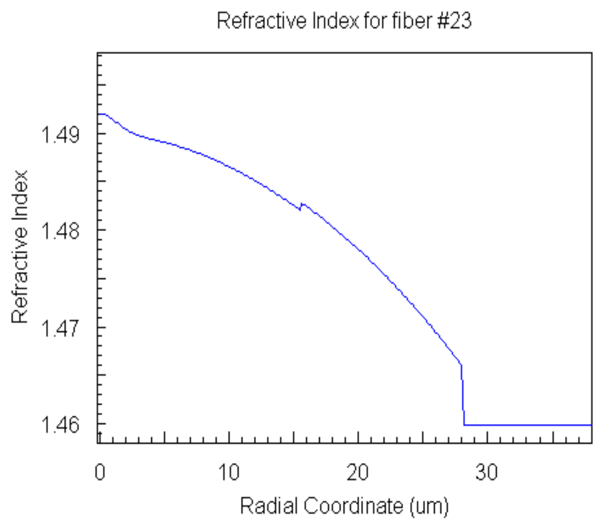
- Fiber is 300 m long with chromatic dispersion set to zero
- Coupler allows the radial and angular offset of the launch signal

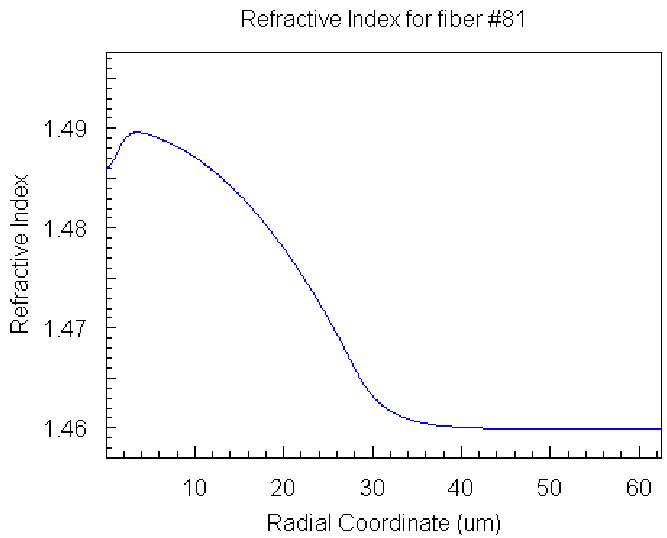
We generated a library of index profiles for 81-models for given fiber parameters (diameter, peak index, index step) and perturbation parameters. These index profiles (*index1.ipf, index2.ipf,..,index81.ipf*) are used as input files in simulator.

Two typical index distortions

- We studied just two different perturbed index profiles out of 81, one with a tip in the center, and the other one with a dip.

  - The first one is fiber #23 – has a tip, alpha change, and sudden edge defect
  - The second one is fiber #81 - has a dip and exponential edge defect

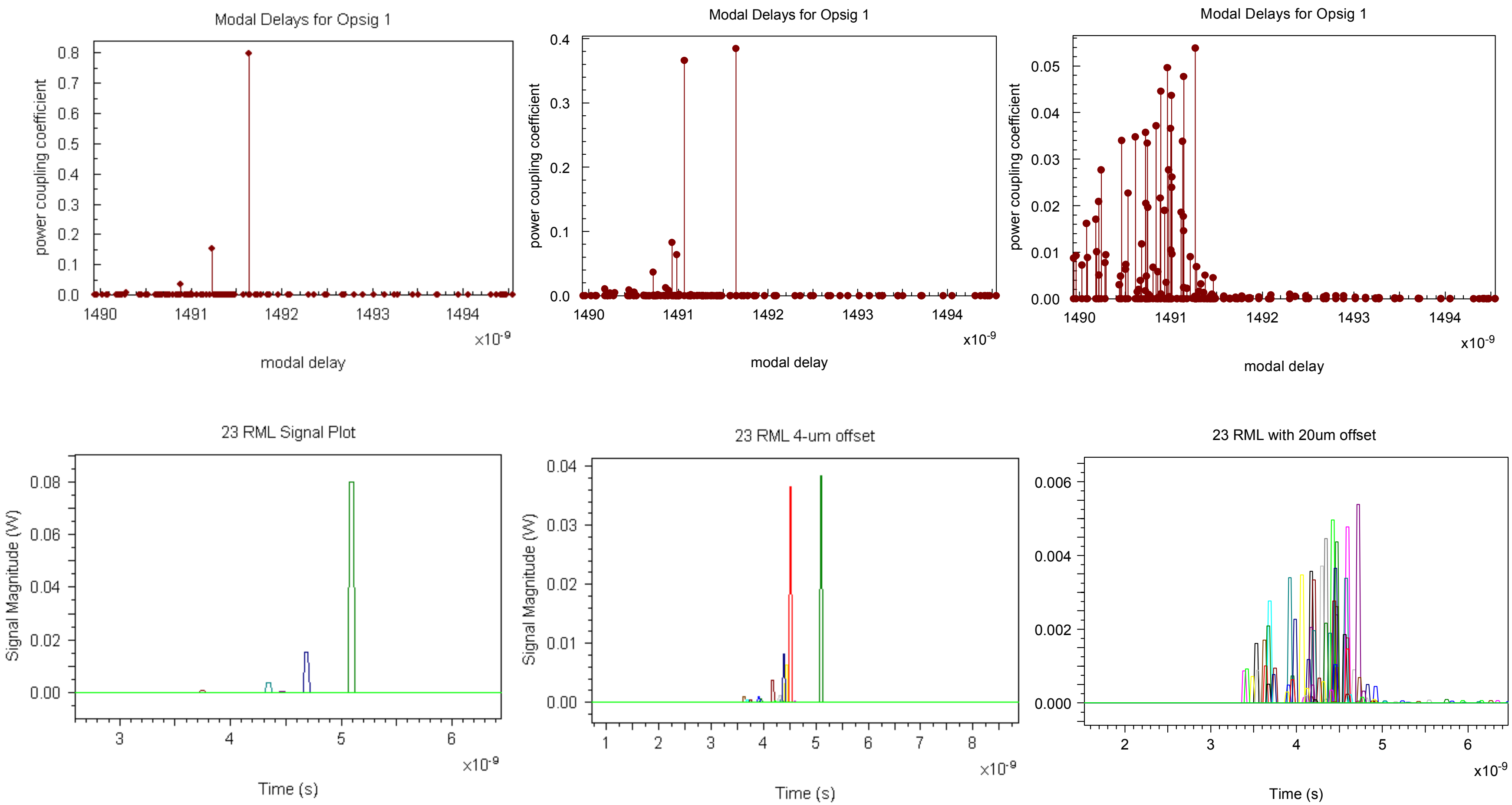




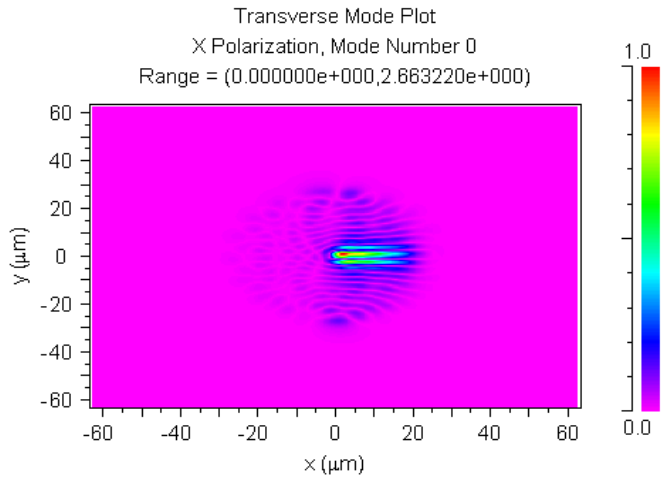
Note: Fiber model numerations here are different from those used in Cambridge model

Fiber #23 – Impulse Responses and Mode Delays

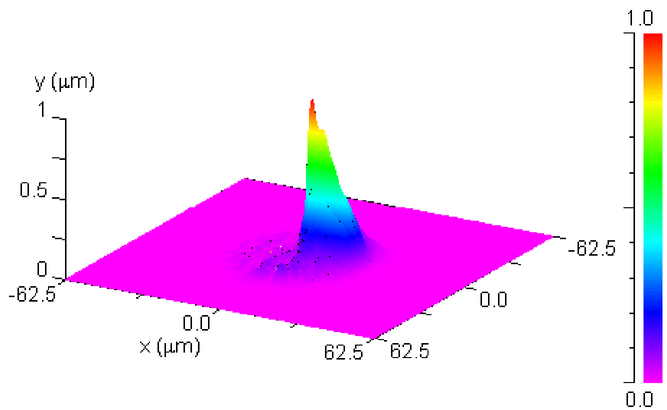
- Modal delays and impulse response at offset =0, 4, and 20 μm

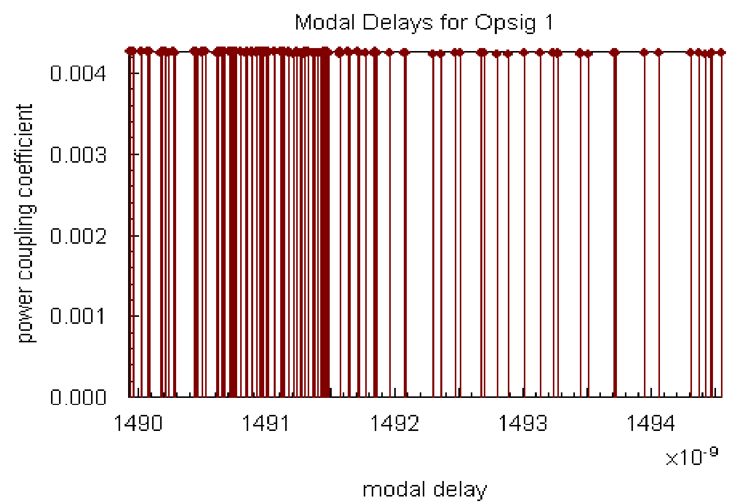


Fiber #23 – overfilled launch



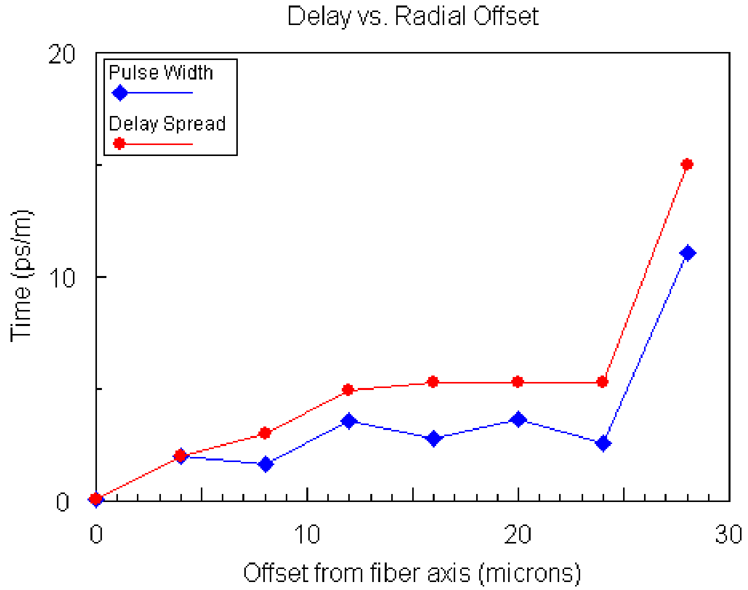
- On the left – mode field for overfilled launch (contour and 3D plots)
- On the bottom – mode delays for overfilled launch – all modes are equally excited

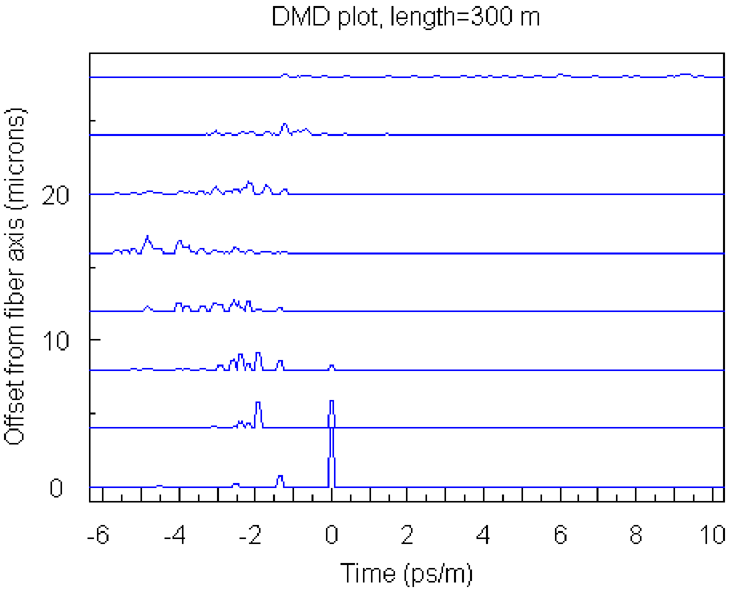




Fiber #23 - DMD

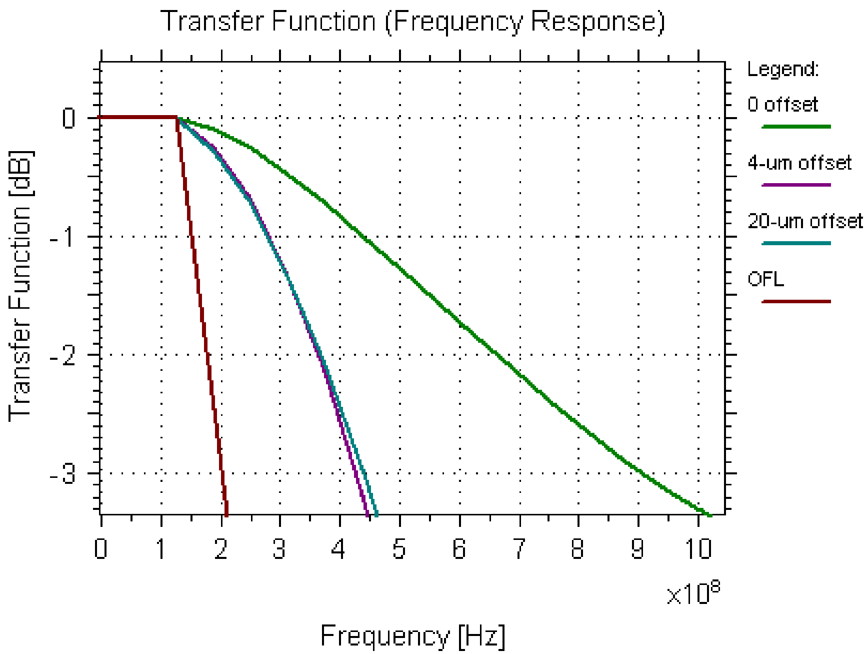
- DMD is calculated according to TIA/EIA-455-220 definition





Fiber #23 – Modal Bandwidth

- Frequency response (transfer function) for 0-, 4-, 20-μm offset RML, and OFL launches after 300 m



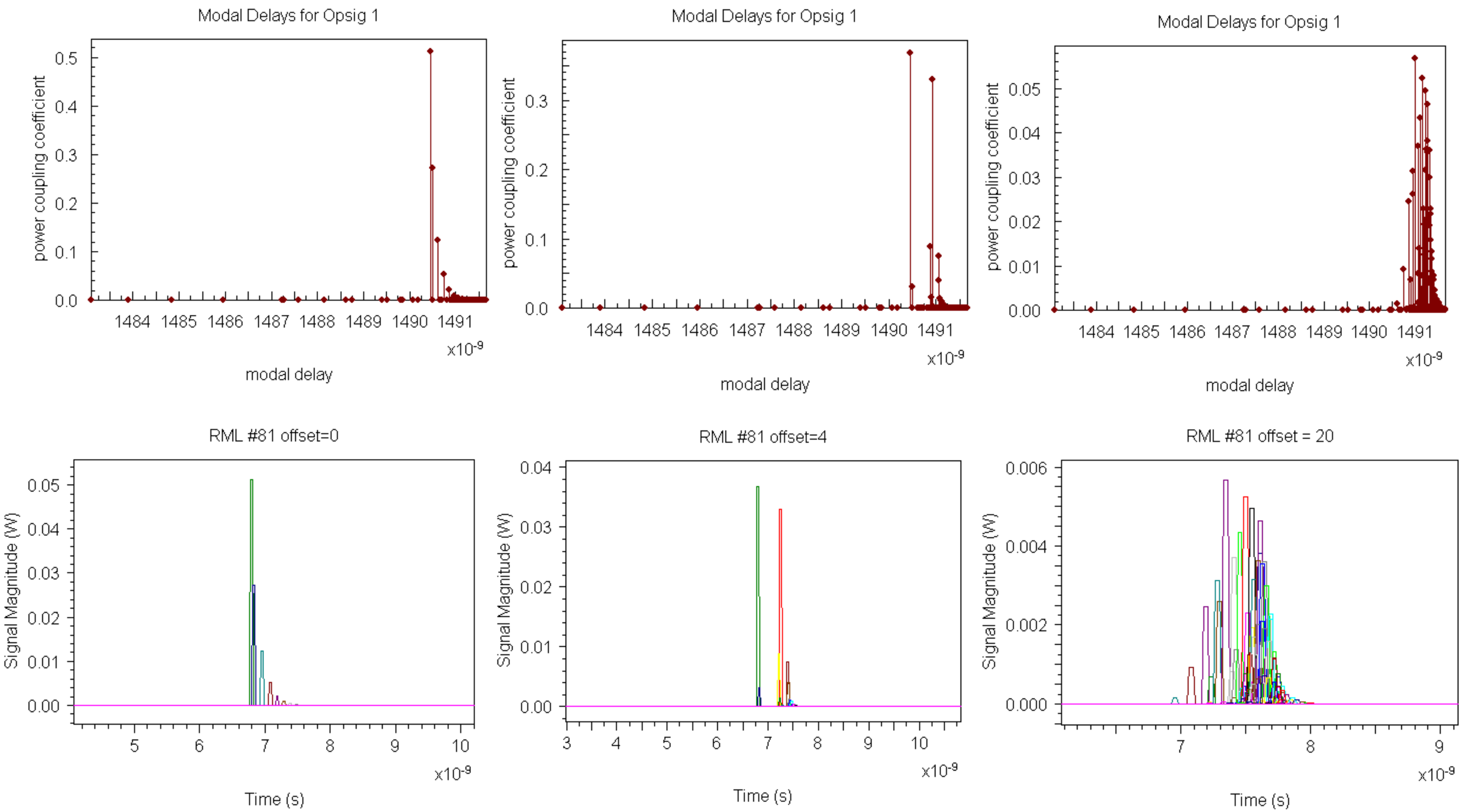
Modal Bandwidths:

- RML 0-offset – 270 MHz•km
- RML 4-um offset – 130 MHz•km
- RML 20-um offset – 135 MHz•km
- OFL – 60 MHz•km

Note: We did not apply here DMD scaling to 2 ps/m as in Cambridge model

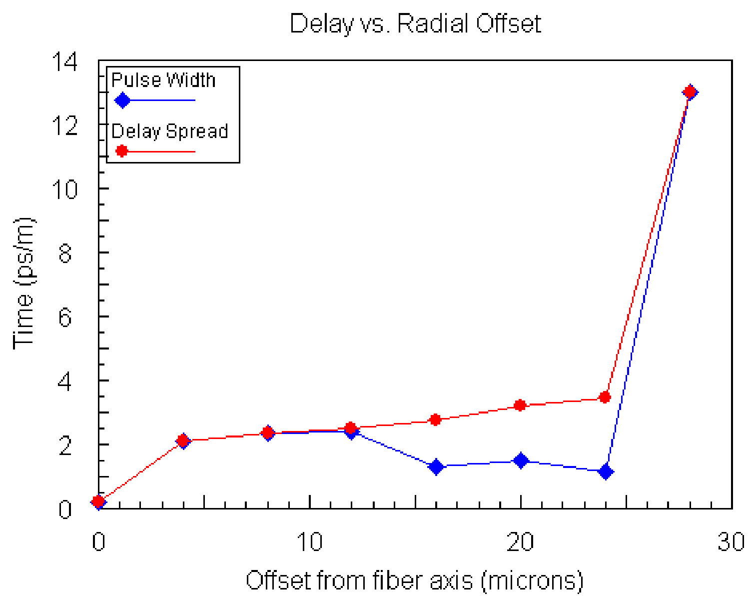
Fiber #81 – Impulse Responses and Mode Delays

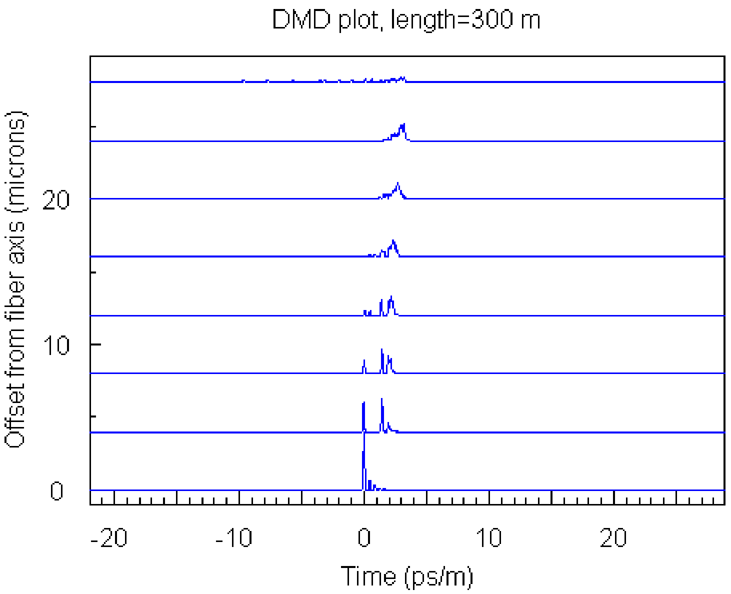
- Modal delays and impulse response at offset = 0, 4, and 20 μm



Fiber #81 - DMD

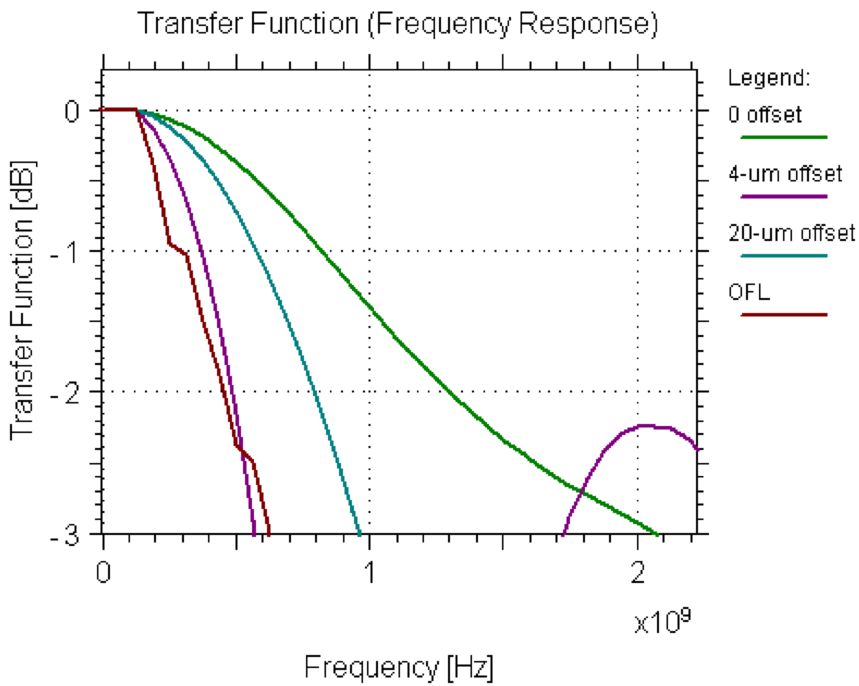
- DMD is calculated according to TIA/EIA-455-220 definition





Fiber #81 – Modal Bandwidth

- Frequency response (transfer function) for 0-, 4-, 20-µm offset RML, and OFL launches after 300 m



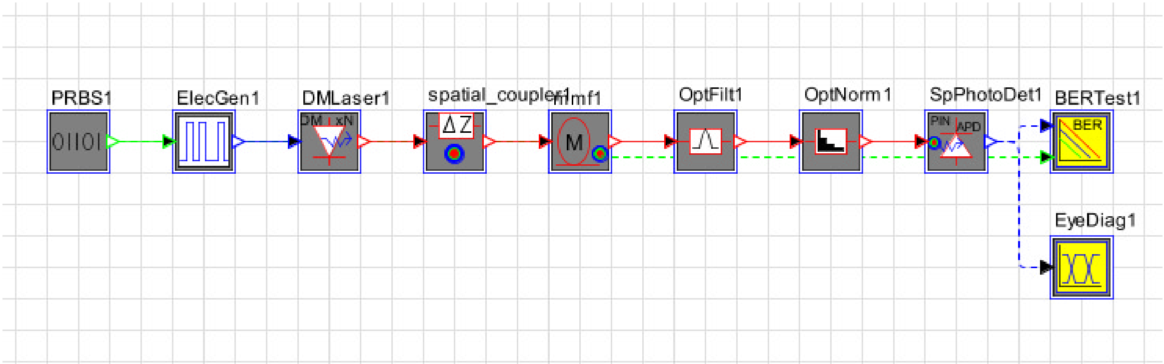
Modal Bandwidths:

- RML 0 offset – 600 MHz•km
- RML 4-µm offset – 170 MHz•km
- RML 20-µm offset – 290 MHz•km
- OFL – 190 MHz•km

Note: We did not apply here DMD scaling to 2 ps/m as in Cambridge model

Eye Diagrams

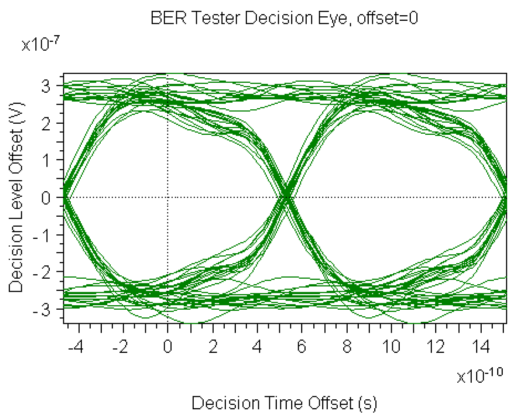
- MB and DMD only provide part of the information necessary to determine whether link failures are likely to occur.
- In order to assess system performance metrics such as BER and eye opening, one has to simulate fiber response to modulated signals.

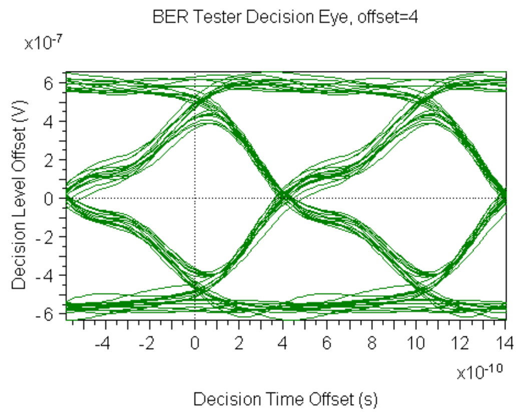


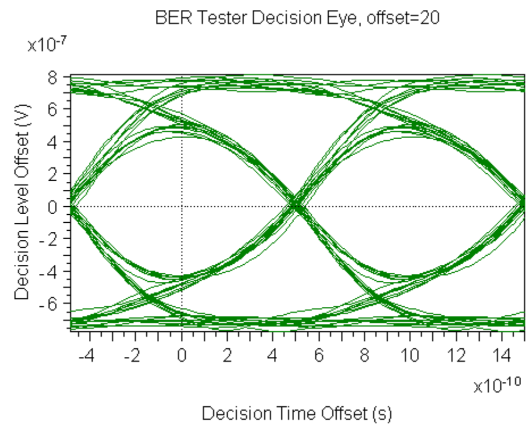
Schematic used to study case of 1 Gb/s NRZ-modulated signal

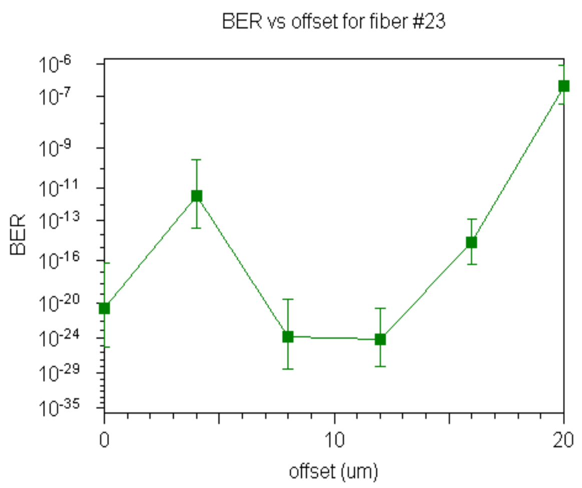
- Input signal is Gaussian fundamental mode with 7 μm FWHM
- BER and eye diagrams for fibers #23 and #81 were studied at different launch offsets

Eye Diagrams and BER for fiber #23



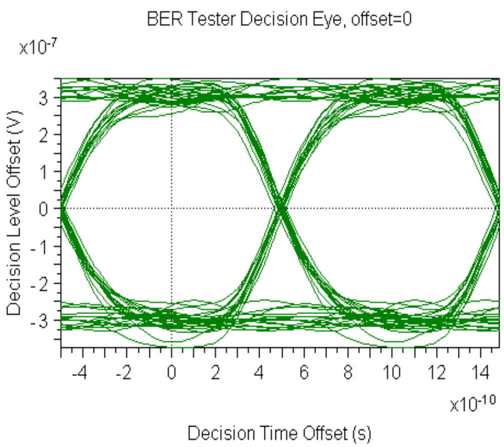


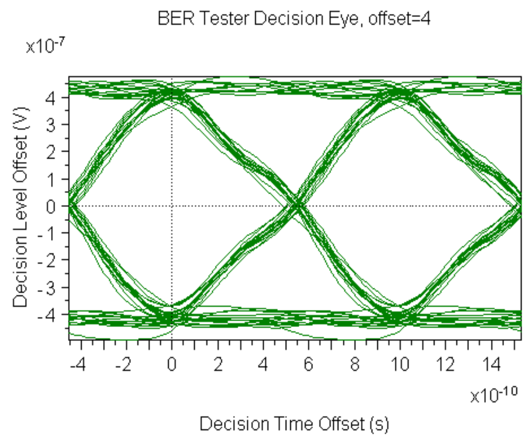


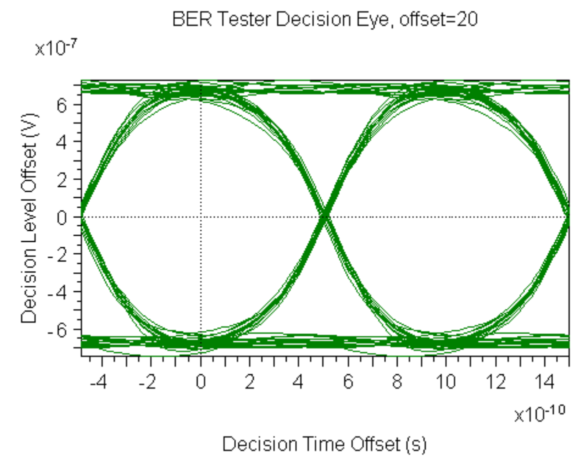


- Top 3 plots give eye diagram for fiber #23 at different radial offsets - 0, 4, and 20 microns.
- Plot on the left shows simulated BER vs. radial offset

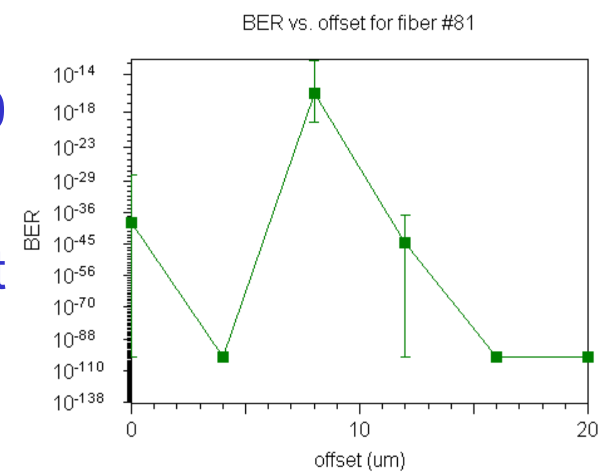
Eye Diagrams and BER for fiber #81







- Top 3 plots give eye diagram for fiber #81 at different radial offsets - 0, 4, and 20 microns.
- Plot on the right shows BER vs. radial offset



Summary

We demonstrated simulation results based on index profiles corresponding to the Cambridge model

- Simulations can take into account time-varying channel responses
- Further simulation studies can be performed by varying system and component parameters to study their impact on performance:
    - Chromatic dispersion
    - Fiber length
    - Radial/angular offset launch conditions, launched modal field, beam width, etc.
    - Launched temporal waveform / pulse shape
    - Variations/perturbations on fiber index profiles

Selected References

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Most available at http://www.rsoftdesign.com/products/system_simulation/ModeSYS/publications.cfm