Modeling, Simulation, and Experimental Study of a 50μm Multimode Fiber Serial 10 Gb Link

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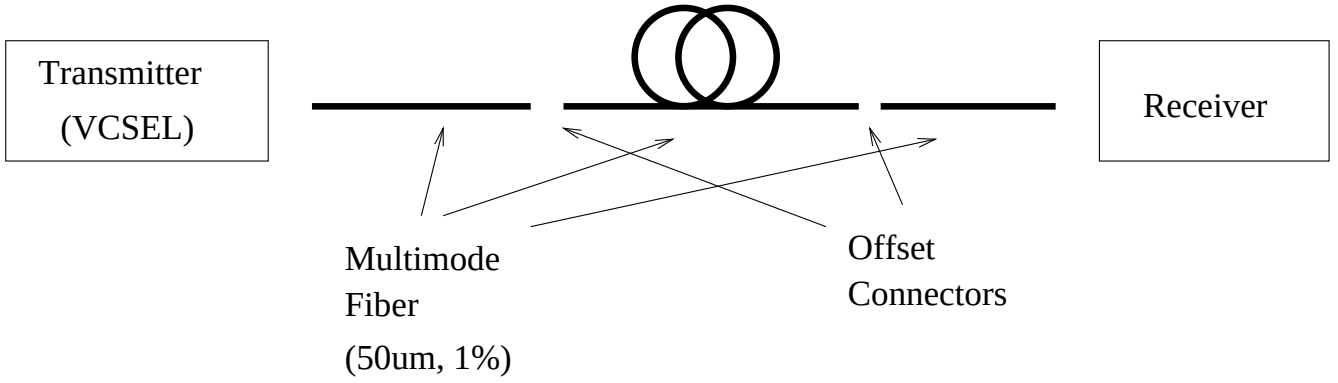
10 Gb Serial Link



- Experimental links proven very robust in stress tests
- Goals of modeling & simulation:
  - Demonstrate that system is robust to wide range of perturbations as long as transmitter and fiber meet specs
  - Probe more phase space than possible through experiments
  - Emphasis on interactions between transmitter, modal dispersion of fiber, and connection effects that influence 3dB optical BW

Proposed Specifications

The proposed source and fiber specifications are:

- Transmitters: encircled flux mask of $EF\left(R_{\text{source}}\right) > 85\%$
- Fiber: Differential Modal Delay (DMD) mask of temporal width ΔT_{DMD} for SMF launches at $r < R_{\text{DMD}}$

In above, R_{source}, ΔT_{DMD}, and R_{DMD} are chosen to guarantee desired BW (e.g. 2000 MHz km)

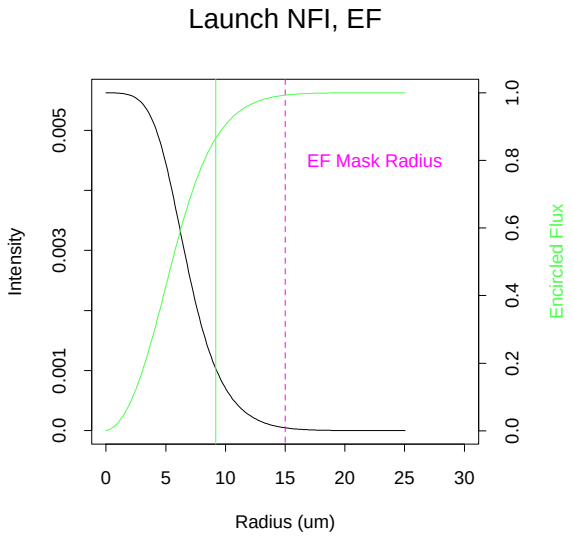
Transmitter Specification

- EF mask is applied to near field intensity (NFI) at end of test fiber

- Example: NFI of 6μm Gaussian beam offset by 5μm

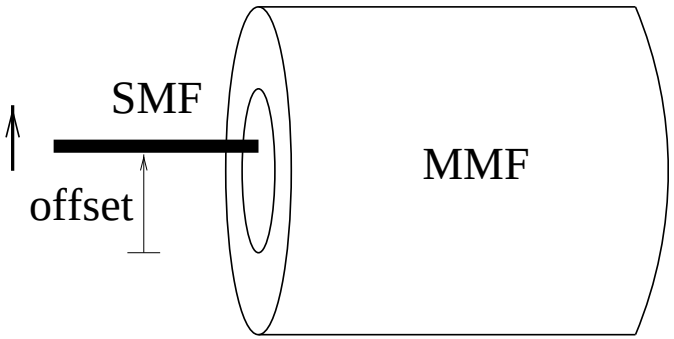
$$EF(r) = \frac{1}{P_{\text{total}}} \int_0^r 2\pi r' dr' I(r')$$

(Standard measurement: TIA/EIA-455-203)

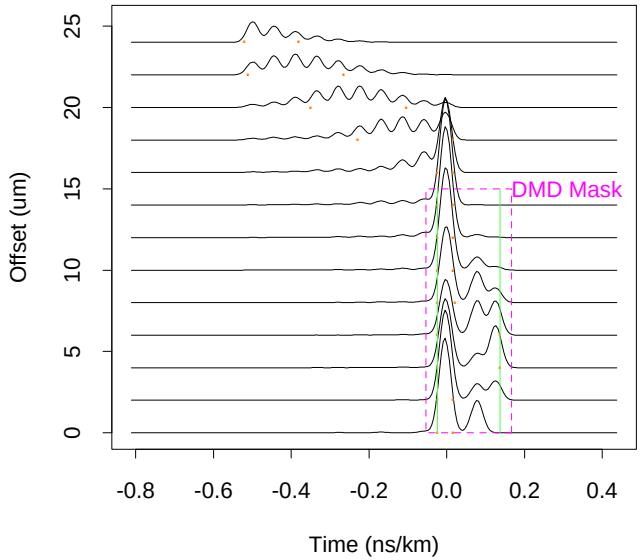


Fiber Specification

DMD Measurement



Simulated DMD



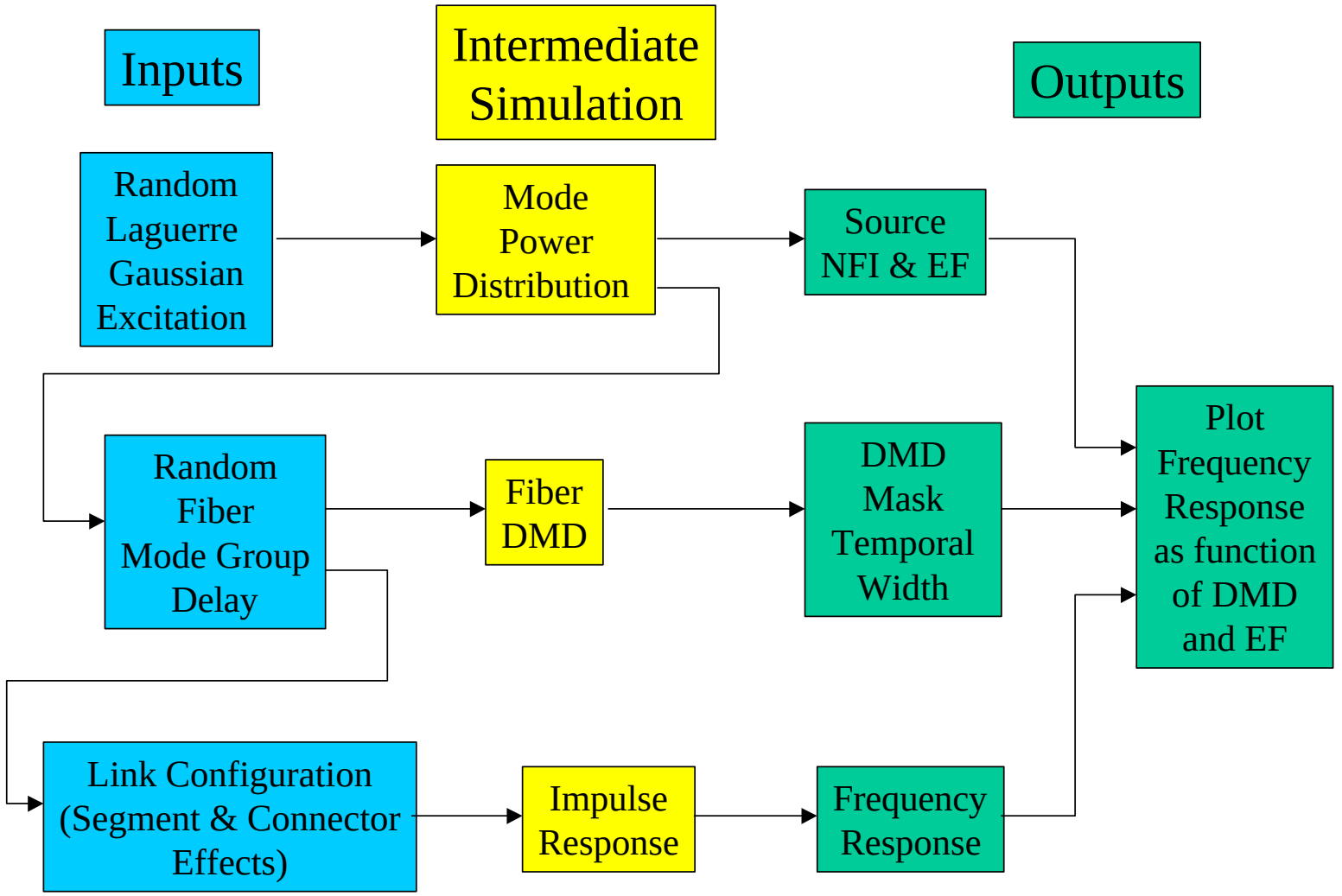
- The edges of a single impulse response are defined to be the earliest and latest times it crosses one half its maximum value
- A DMD is defined to meet the mask if the edges of the impulse responses of all launches at $r < R_{\mathrm{DMD}}$ lie within ΔT_{DMD}

Link Model: Overview

We model interactions between transmitter, modal dispersion of fiber, and connection effects (ignore other effects for now)

- Transmitter: VCSEL modeled by low-order Gaussian beam modes (first four mode groups, various superpositions)
- Fiber: Modal delays chosen from a distribution representing typical manufacturing variations
- Connectors: Variety of plausible configurations considered. Offsets drawn from statistical distribution.
- Detector: Infinite detector BW assumed for fiber BW computations.

Simulation block diagram



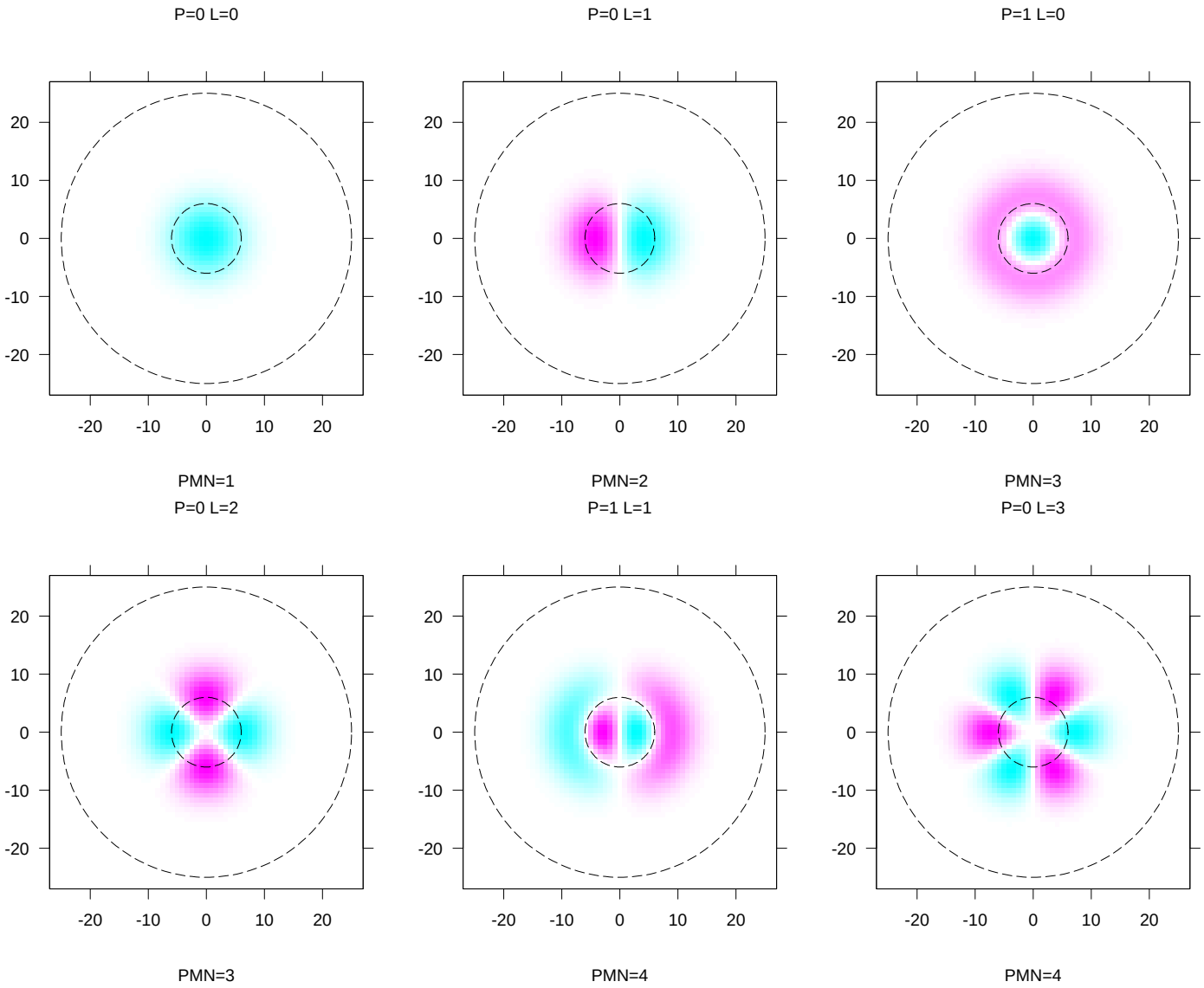
VCSEL model

- Modes of VCSEL cavity modeled as Gaussian beams

$$\psi_{p,\ell}(r,\phi,z=0) = \left(\sqrt{2}\frac{r}{w_0}\right)^{\ell} L_p^{\ell}\left(2\frac{r^2}{w_0^2}\right)\exp\left(-\frac{r^2}{w_0^2} - i\ell\phi\right)$$

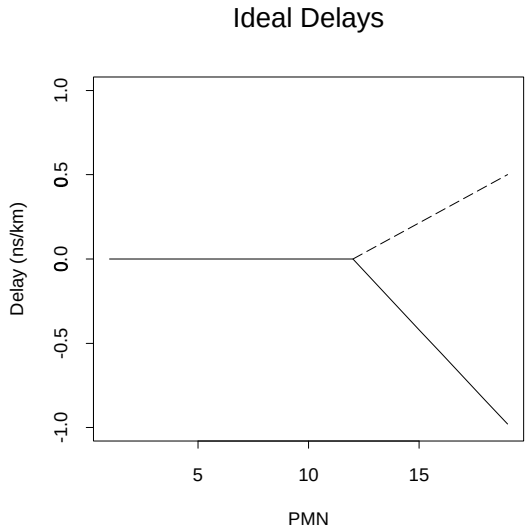
  (w_0 is spot size)
- Chromatic dispersion limits spectrum to a few modes;
  We include first four mode groups (6 modes & various superpositions)
- Gaussian beam spot sizes range from 1.5μm to 6μm (radius)
- Incident angles range from 0° to 2°
- Offsets range from 0μm to 5μm

Gaussian Beam Modes (at waist; w_0=6μm)

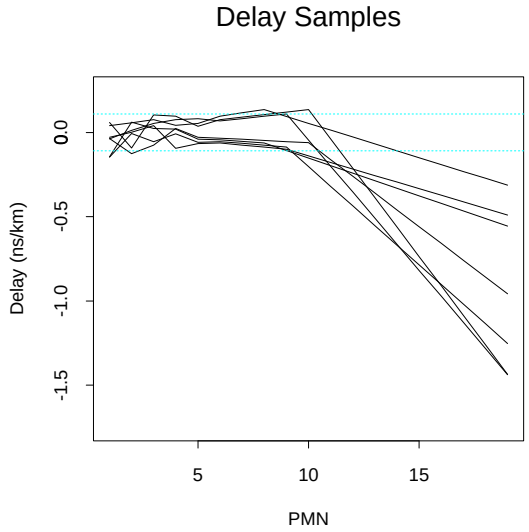


Distribution of Fiber Modal Delays

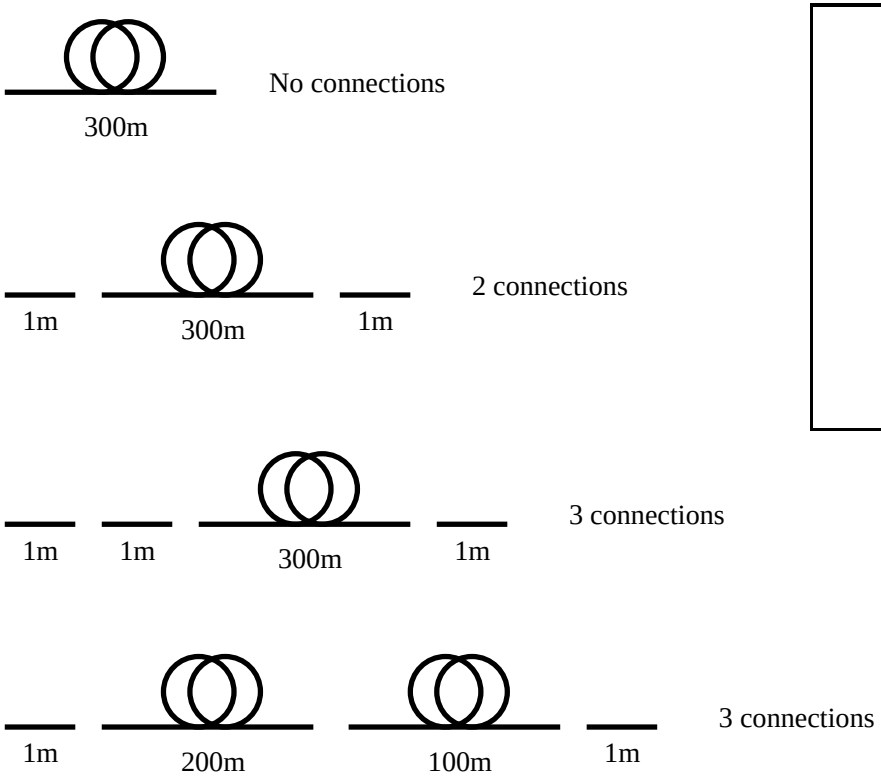
- Desired delay structure has flat low order DMD, but may have variation in high order modes



- Distribution of delay structures: simulated effects of
  - Center-line perturbations
  - α variation
  - Variations in r_α



Connection Configurations



- Mean connection loss chosen to be 0.3dB (std dev 0.2dB) = 4.8μm mean offset (std dev 1.9μm)
- Buckler model relates empirical loss to offset for 50μm fiber

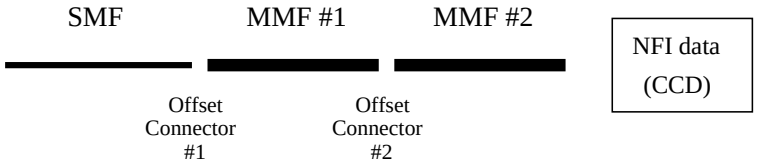
Coupling into a Multimode Fiber

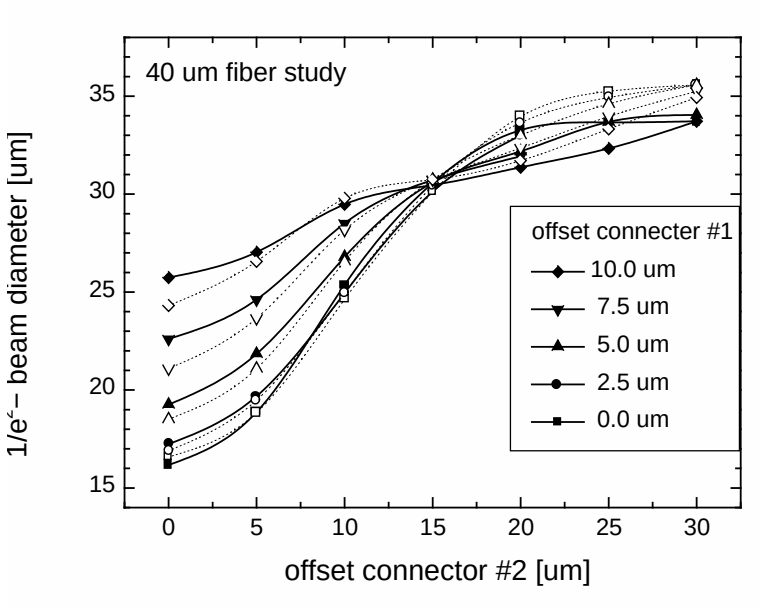
- Use modal EM theory to calculate coupling coefficients from laser modes to fiber modes, or fiber modes to fiber modes

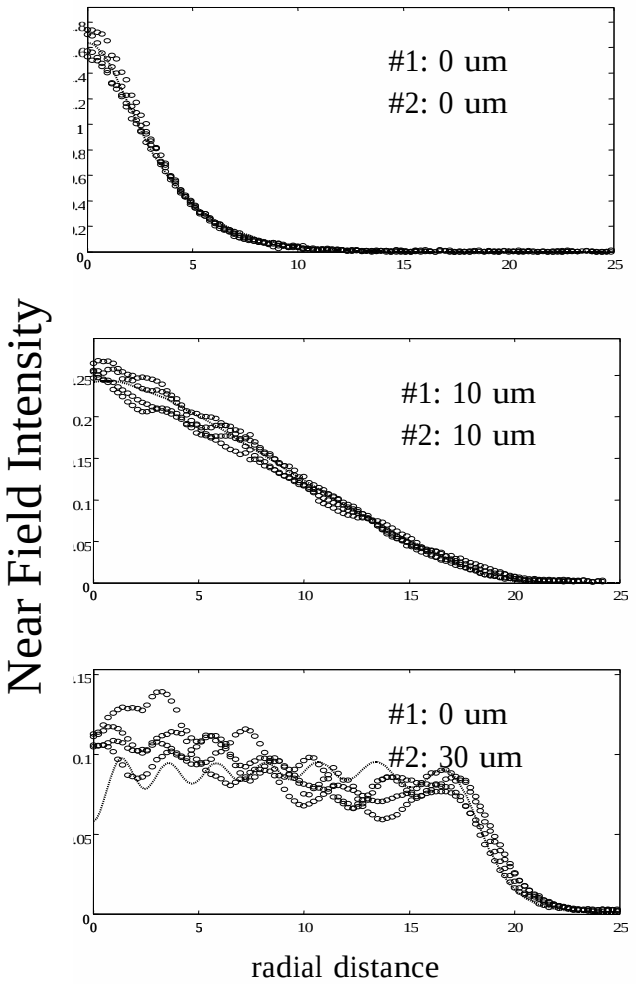
$$a_{\text{input}}^{(m,\ell)} = \int d^2\mathbf{x}\, E_{\text{input}}^{*}(\mathbf{x}) E_{\text{MMF}}^{(m,\ell)}(\mathbf{x})$$

- Accuracy of this method is suppored by a large literature (e.g. Miller, Mettler & White, “Optical Fiber Splices and Connectors”)
- Recent measurements also performed to verify accuracy

Offset Connector cw Measurements

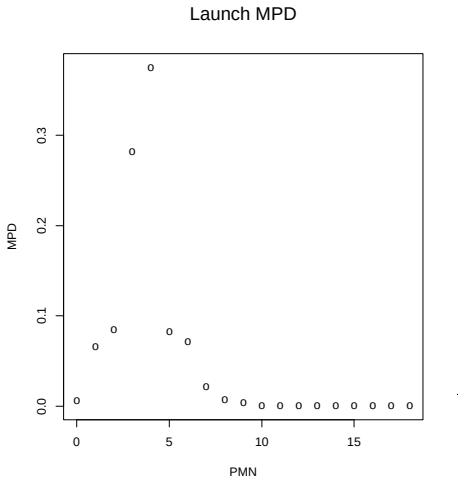


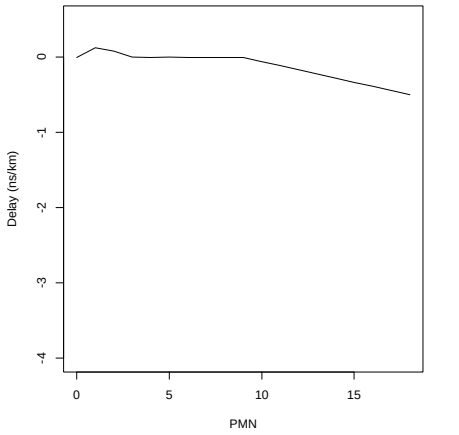




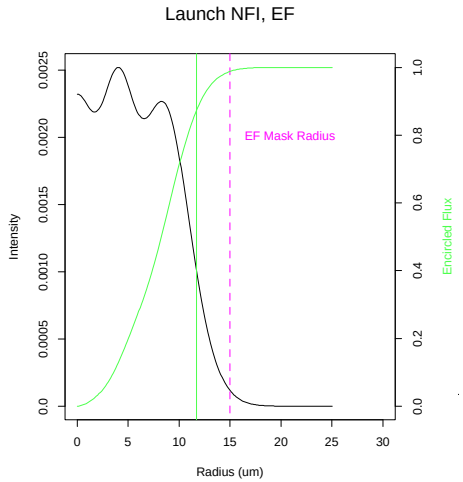
Example: Simulation of Single Source/Fiber

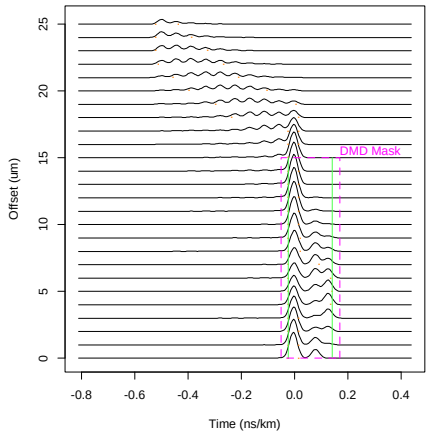
Simulation Inputs



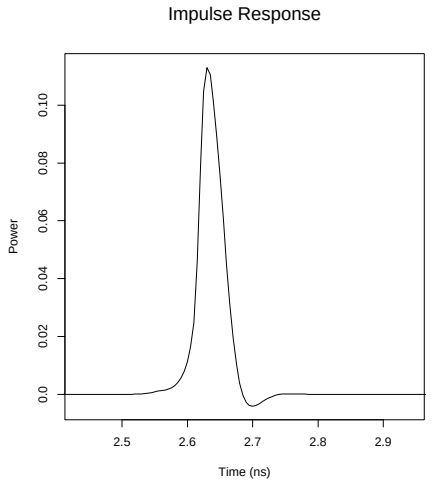


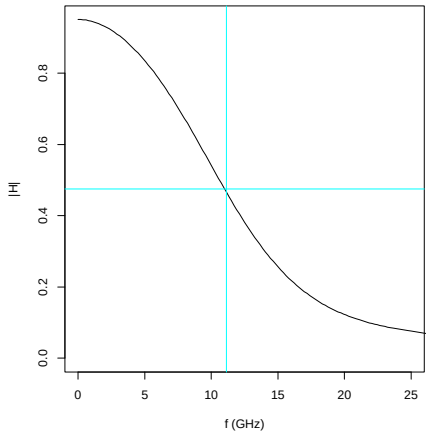
Source, Fiber Screens

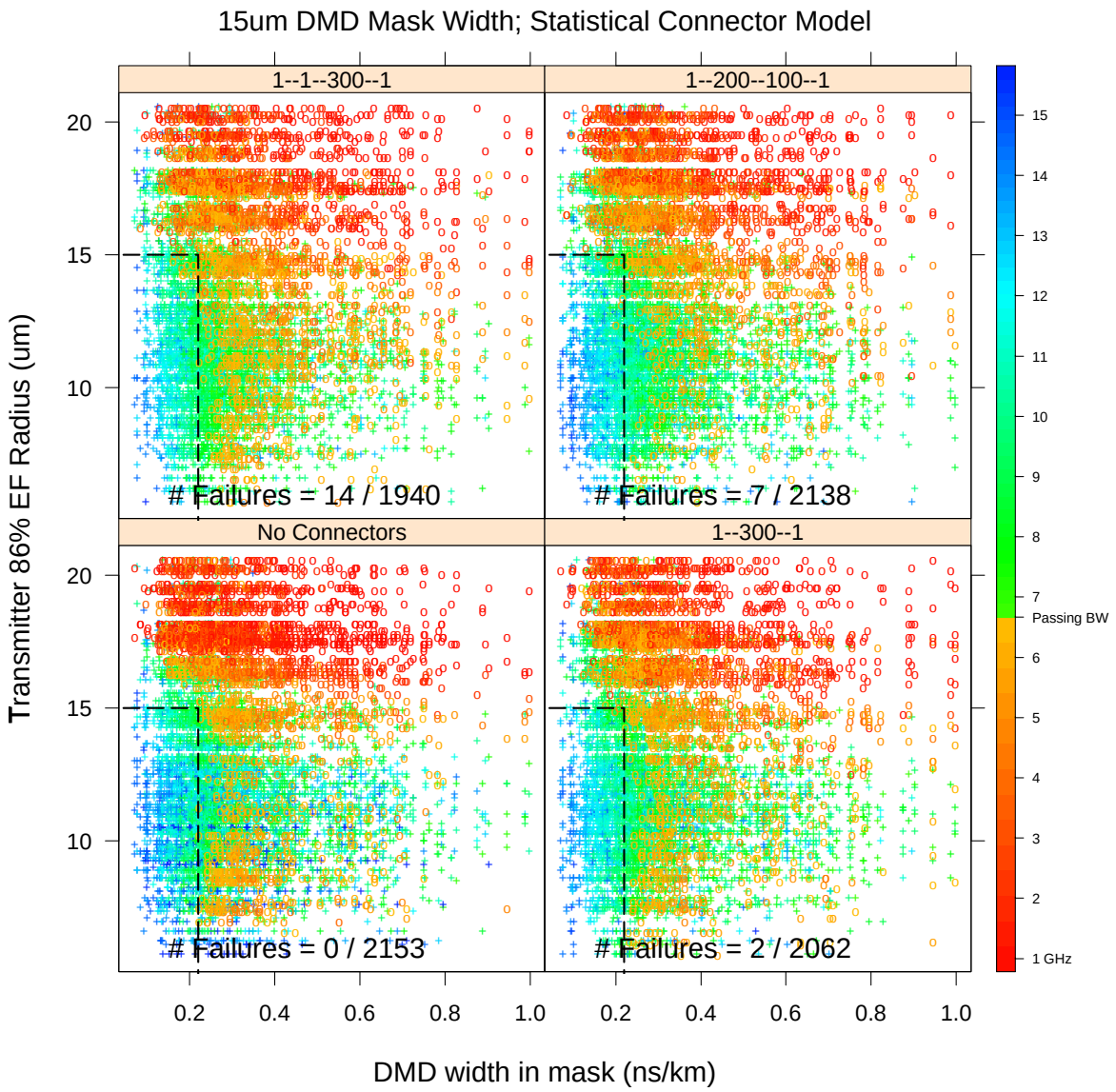




Simulation Outputs






15um DMD Mask Width; Statistical Connector Model
1--1--300--1
1--200--100--1
No Connectors
1--300--1
Failures = 14 / 1940
Failures = 7 / 2138
Failures = 0 / 2153
Failures = 2 / 2062
Transmitter 86% EF Radius (um)
DMD width in mask (ns/km)
Passing BW
1 GHz