MMF Reach Extension for 10 Gbps by Spatially Resolved Equalization

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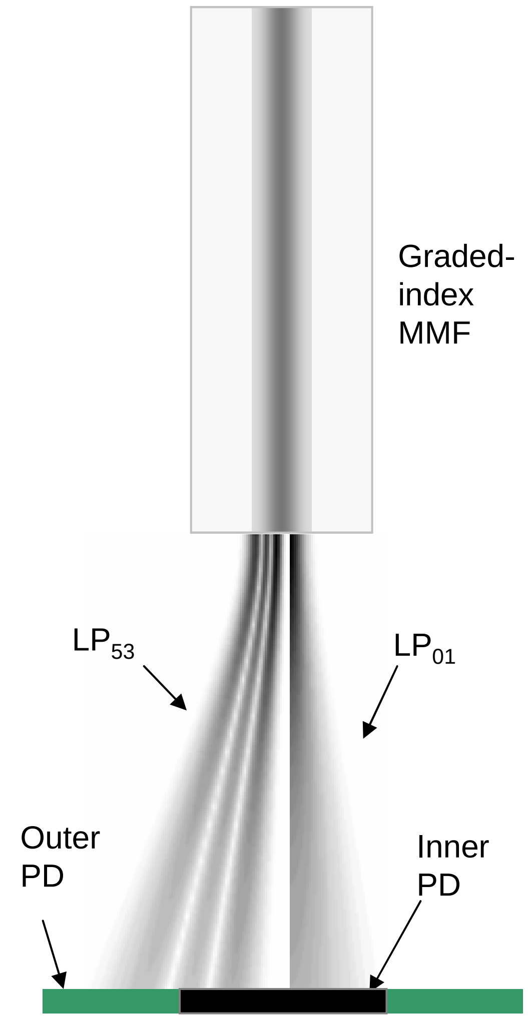
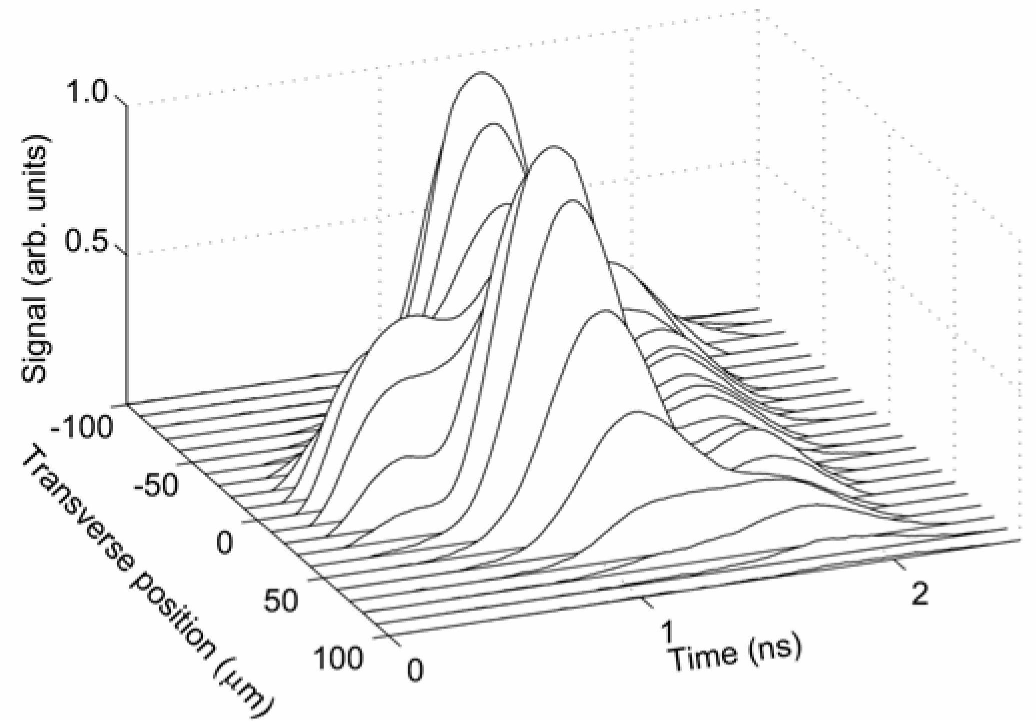
Spatially resolved equalization

- Multi-segmented photodetector (MSD) for spatially resolved equalization
  - Simple two-segment is effective and robust
- Exploits spatial diversity to retain "information" that is lost by conventional PD
  - Low-ordered modes (LOM) exclusive to inner PD
  - High-ordered modes (HOM) incident on inner and outer PD
- Electronically equalizes fiber response based on optical properties of mode in graded-index MMF
  - Variation in mode size allows partial mode separation
  - Subtraction of photocurrents reduces HOM energy
- Transmission format independent permitting additional electronic signal processing
  - SRE and FFE/DFE work synergistically
  - Mixed signal and other transmission formats allowed



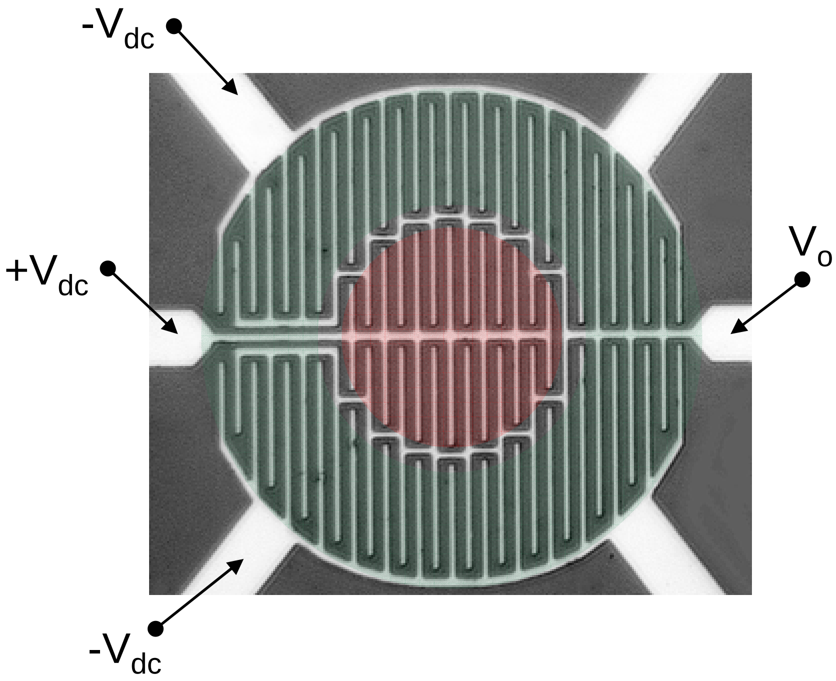
Diversity in output irradiance

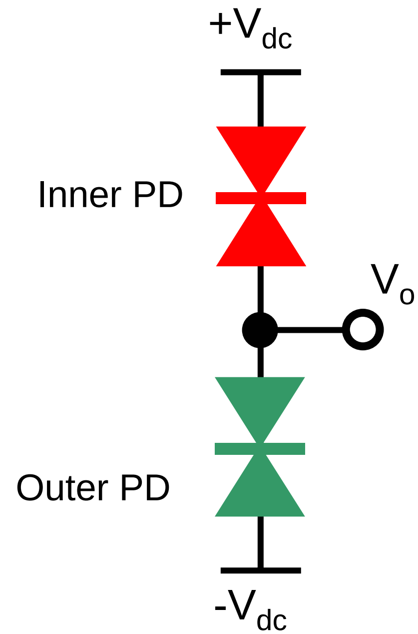
- Spatially resolved impulse response of irradiance
  - Measured of a 50-μm, 1.1-km MMF with 1550-nm optical pulse
    - Temporal response of irradiance scanned with 15-μm pinhole aperture at distance 400 μm from fiber output
  - HOM lags LOM in MMF at 1550-nm



Implementation of SRE

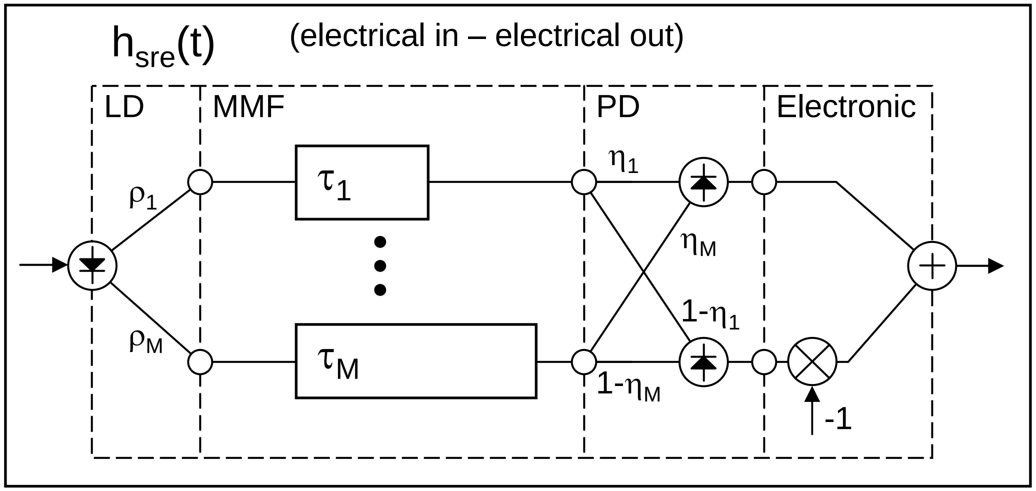
- Embodiment of simplified SRE
  - Subtraction of PD photocurrents by differential receiver
  - Inner PD radius specifies MSD size (outer PD assumed to be semi-infinite)
- SRE not limited to MSM-based detector
  - MSM-based photodetector used for ease-of-fabrication
  - SRE viable with p-i-n based detector





Linear, multipath fiber model

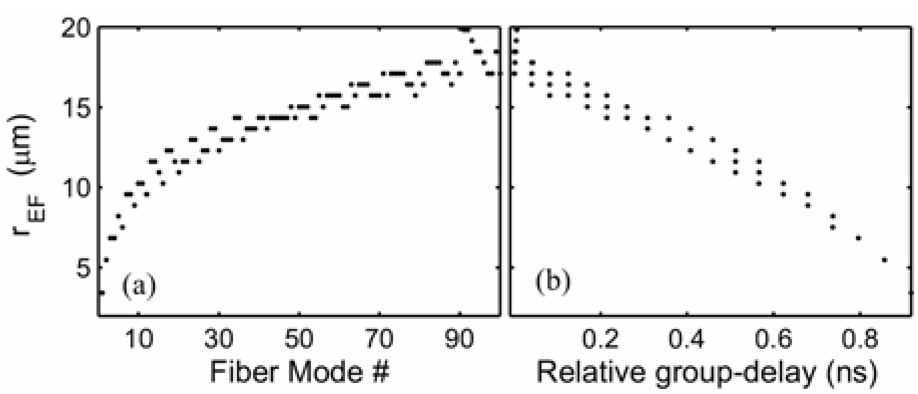
- DMD-limited graded-index MMF
  - Ideal α-profile MMF
    - no profile defect
  - Includes profile dispersion
- Fiber mode characteristics
  - Group delay (via WKB method[1]) only
    - No chromatic dispersion
    - No mode dependent attenuation
  - Mode-field profile
    - Scalar wave equation solver
- VCSEL emulation
  - 5 transverse mode source
    - Weakly guiding circular waveguide
    - Random rotational orientation
    - Equal power among modes
  - Asymmetrized about fiber axis
  - Meets EF launch criteria
- Multi-segmented photodetector
  - Ideal, uniform square-law detectors
  - Beam propagation out of fiber included
  - 100% photo-collection

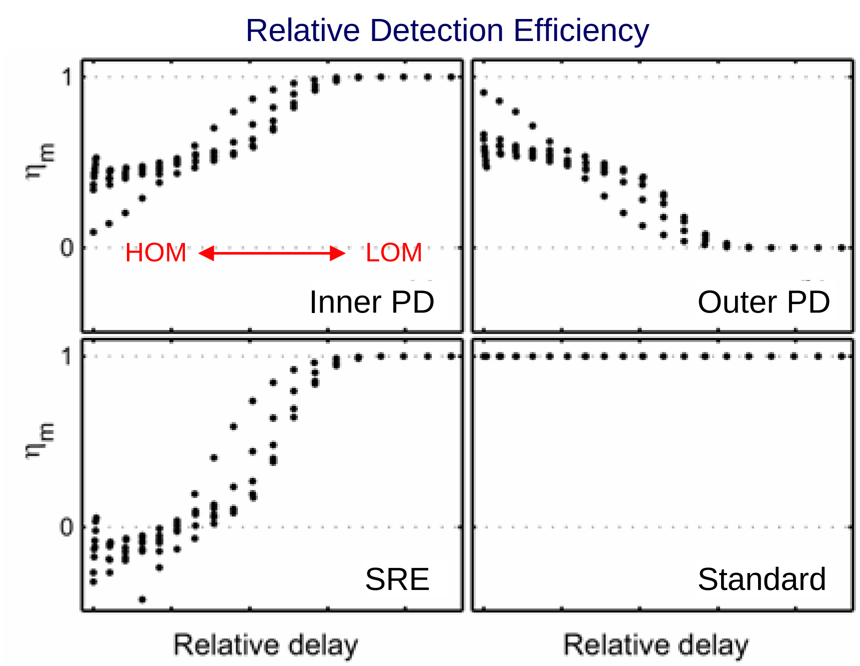


[1] R. Olshansky and D. B. Keck, “Pulse broadening in graded-index optical fibers,” *Appl. Opt.*, vol. 15, pp. 483-491, Feb 1976.

Mode size versus group delay

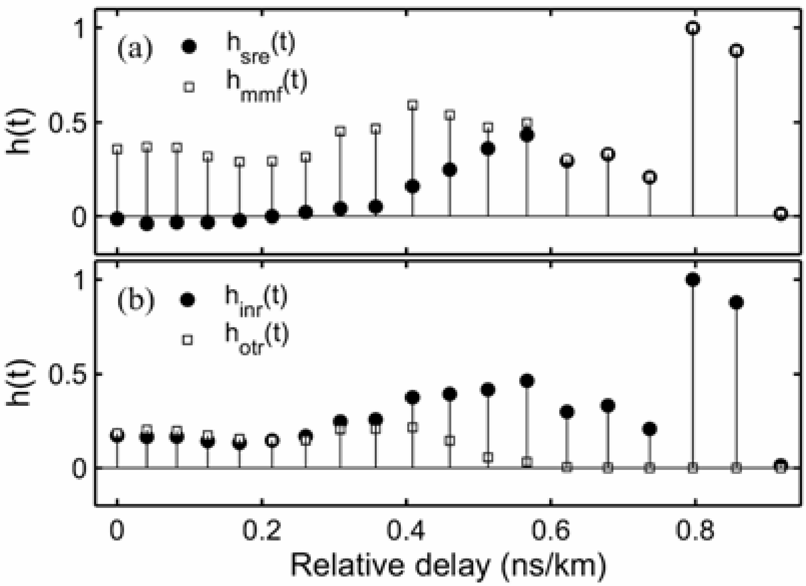
- Simulation of MMF link @ 850 nm
  - α = 2, Δ = 1%, y = +0.1
- Radius of 50% encircled-flux
- Near monotonic relationship allows simple subtraction of PD photocurrents for significant equalization





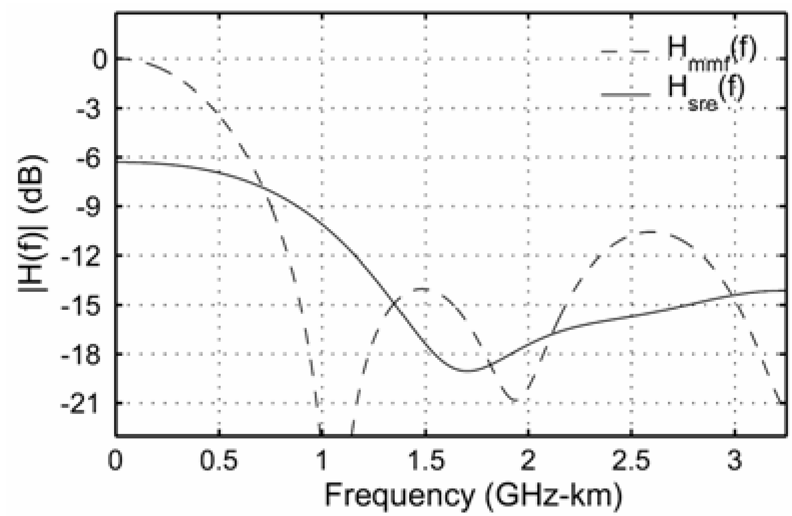
- Outer PD preferentially detects HOM
  - Slight bimodal response due to difference between azimuthal and meridional modes
- HOM-based ISI is subtracted from inner PD signal
  - SRE = Inner PD – Outer PD
  - Improvement on bandwidth
  - Alternative view: receive-side "enforcement" of EF launch condition

Simulated MMF link with SRE

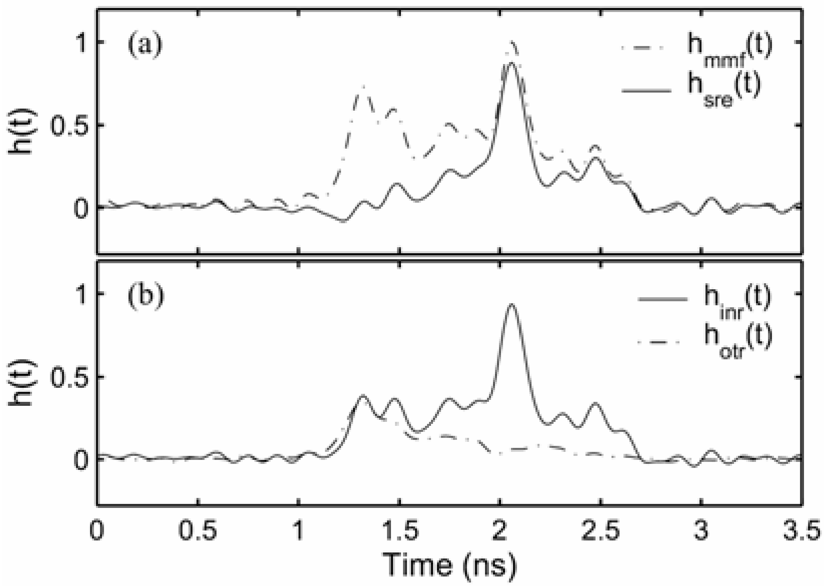


- 850-nm EF launch condition
  - Asymmetrized: 2-μm offset, 2° tilt
  - MSD size optimized specifically for 2x with launch condition
- Suppression of ISI energy
  - ISI in HOM which lead LOM at 850 nm
  - $h_{inr}(t)$ and $h_{otr}(t)$ are impulse response observed by each PD segment

- HOM leads to improvement in the frequency response
- 2x shift in 3-dB BW; shift in frequency nulls; reduction of null depth
  - 6-dB atten. at DC is equivalent to 3-dB optical power penalty
- MSD can be optimized for different launch condition or different bandwidth gain

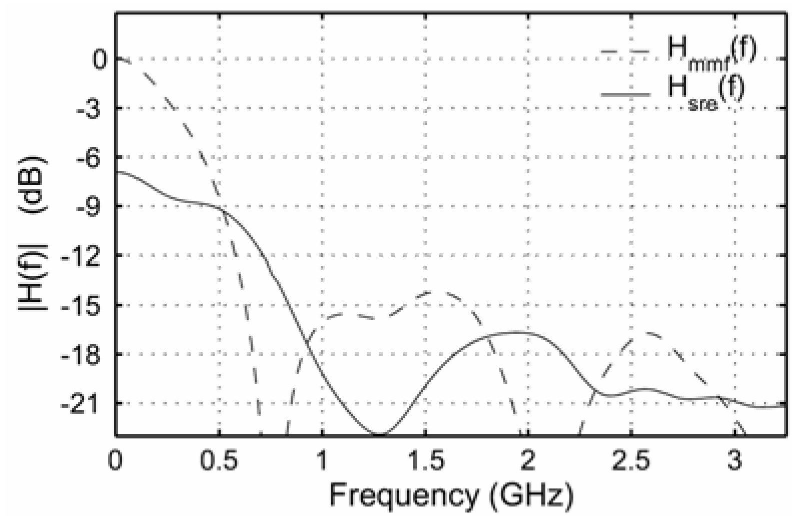


Measurement impulse response



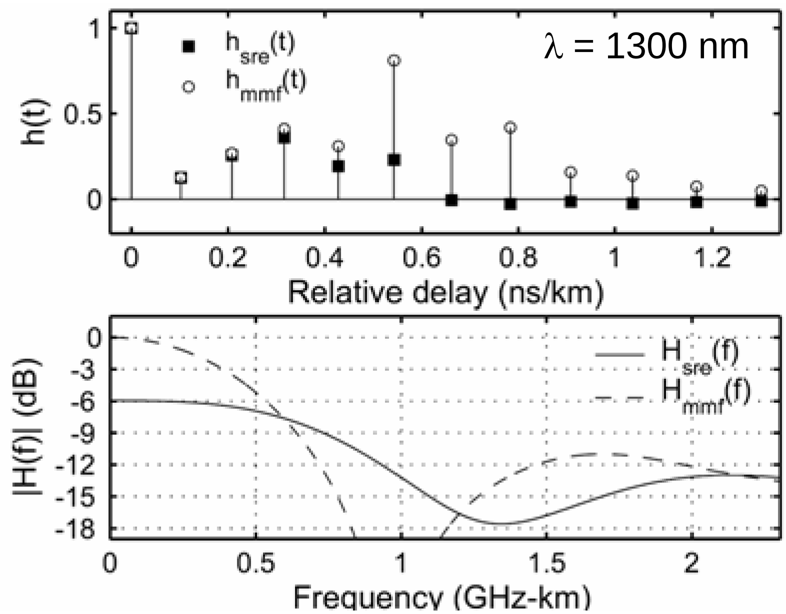
- Measurement with 810-nm impulse source in 1.1-km MMF
  - Multimode launch created with mode-scrambler (overfilled launch)
- All impulse responses measured with same MSD detector
  - Device configured with bias polarity
- MSD is 55-μm detector at 400 μm from fiber output
  - Optimized for given launch condition

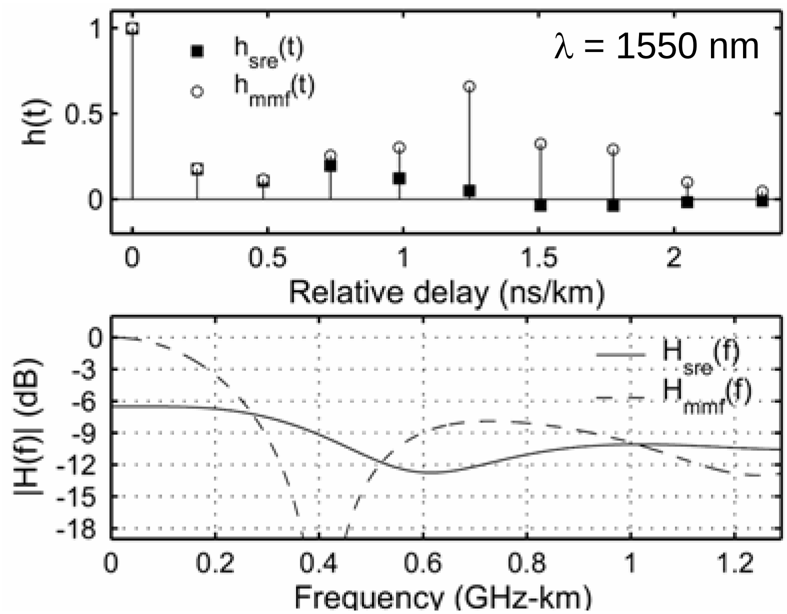
- HOM leads to improvement in the frequency response
- 2x shift in 3-dB BW, shift in frequency nulls, reduction of null depth
  - 6-dB atten. at DC is equivalent to 3-dB optical power penalty



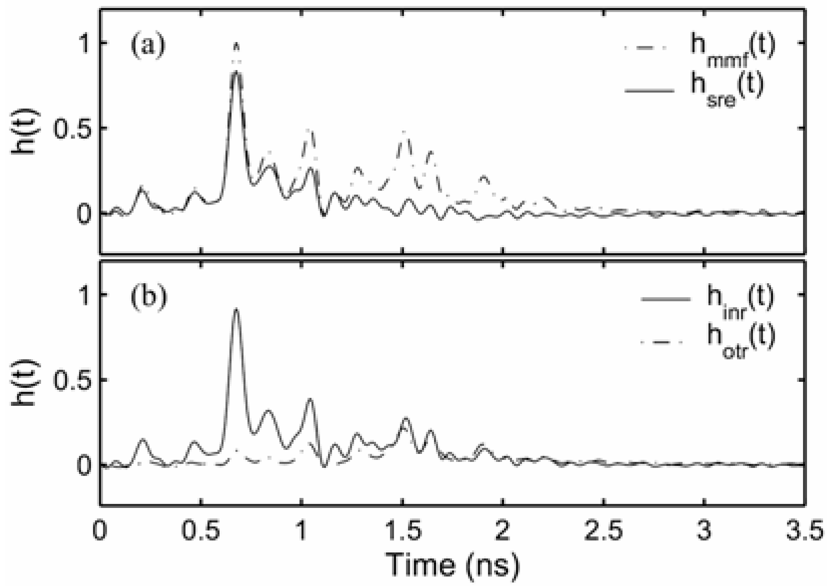
Simulation at longer wavelengths

- Using EFL launch condition for 1300 and 1550 nm
  - Anticipating use of multimode VCSEL at longer wavelengths
  - Same asymmetric fiber illumination
- Same MSD size used in simulation
  - MSD can be optimized for different launch condition (*e.g.* singlemode VCSEL)
- Desired bandwidth gain of 2x is achieved independent of wavelength
  - Regardless of HOM arrival time, HOM energy is suppressed



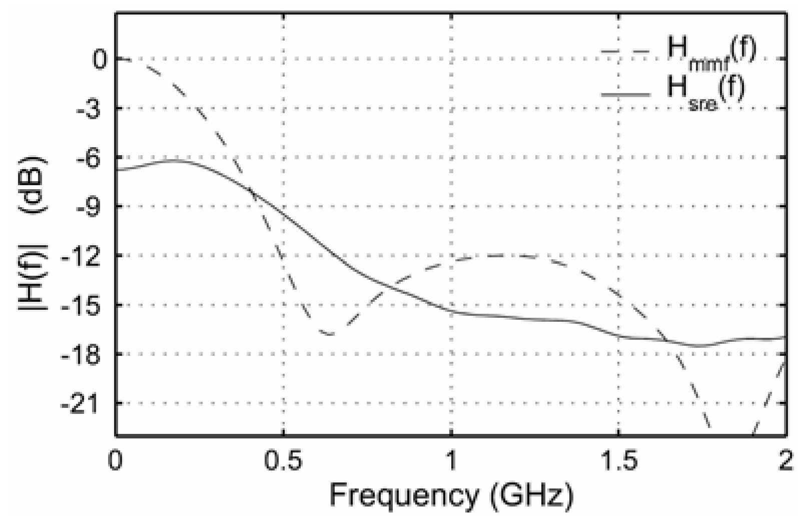


Measurement at long wavelength



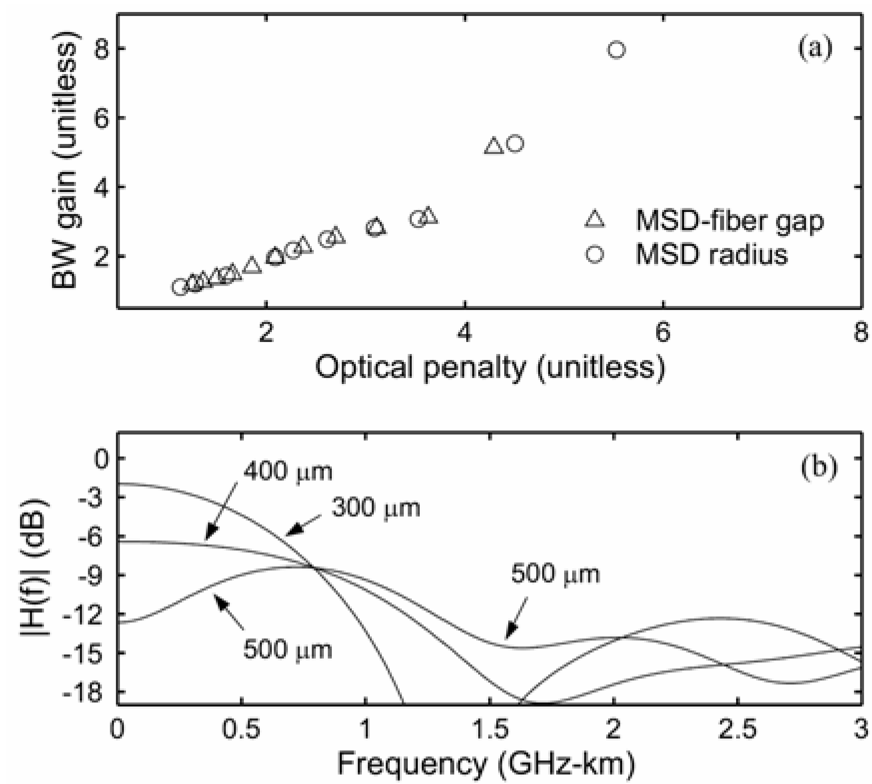
- Measurement with 1550-nm impulse source in 1.1-km MMF
  - Multimode launch created with mode-scrambler (overfilled launch)
- No change in MSD
  - 55-μm detector at 400 μm from fiber output
  - Diffraction of beam highly dependent on numerical aperture of fiber

- Equalization independent of wavelength
- Equalization independent of magnitude or “direction” of DMD



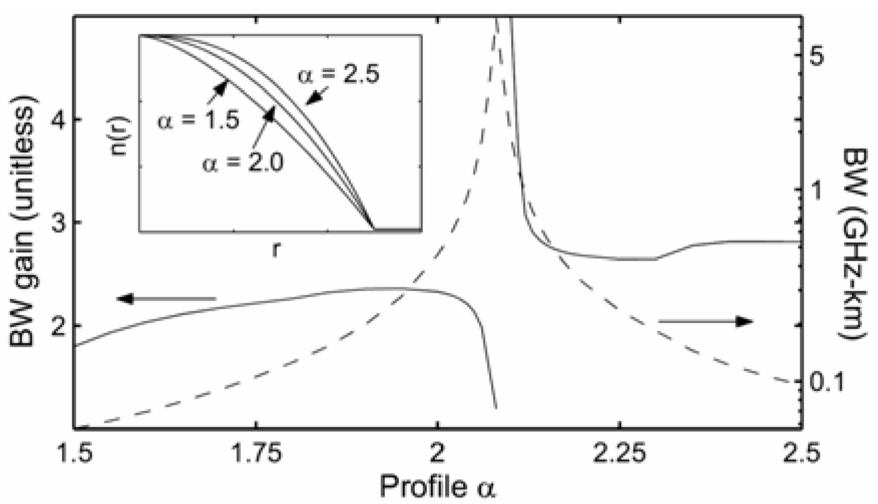
Optimization of MSD

- Bandwidth gain by SRE not limited to 2x
  - 2x bandwidth chosen as trade-off between ISI mitigation and optical penalty
- Trade-off controlled by MSD-fiber gap or MSD radius
  - Sweep of inner PD radius: 5 to 100 μm
  - Sweep of MSD-fiber gap: 0 to 500 μm



Robustness to fiber design

- Intended BW gain is achieved over range of α
  - MSD optimized specifically for 2x bandwidth gain at α = 2
  - Bandwidth enhancement is not sensitive to variation in index profile design
    - *i.e.* fiber optimized for 850 or 1300 nm
  - Only near optimal bandwidth is BW enhancement by SRE limited
    - Monotonic relationship between group delay and mode size fails
    - Second-ordered effect of group delay to mode number dominates
- Sweep α over extreme range
  - *y* = 0.1 assumed (@ 850 nm) [1]
  - Chromatic dispersion NOT included

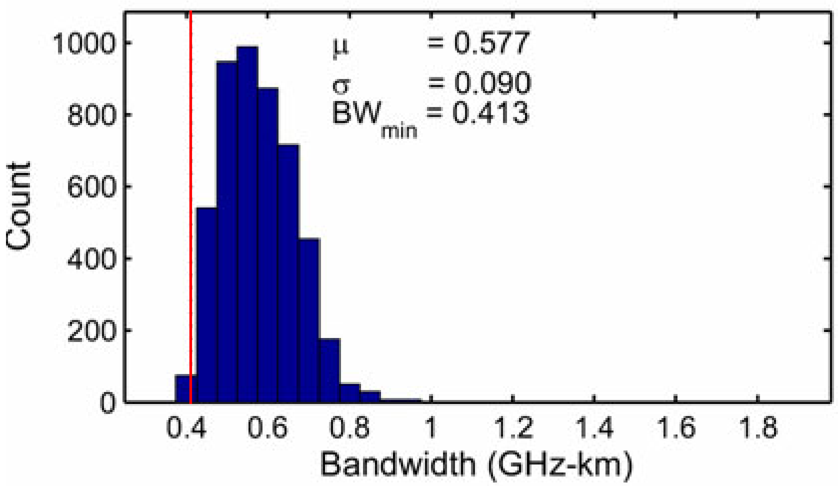


[1] R. Olshansky and D. B. Keck, "Pulse broadening in graded-index optical fibers," *Appl. Opt.*, vol. 15, pp. 483-491, Feb 1976.

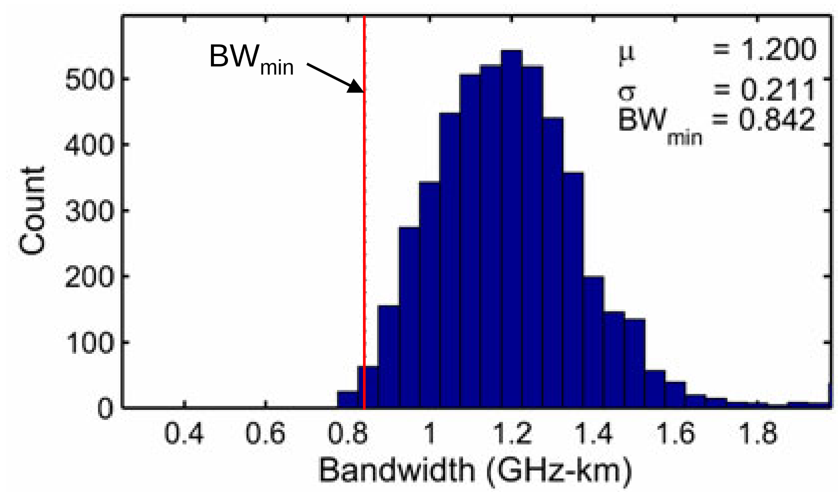
Monte Carlo simulation

- Monte Carlo simulation varying symmetry on EF launch condition
  - VCSEL offset: σ = 5μm
  - VCSEL tilt: σ = 2°
  - Relative modal power: σ = 10%
  - 5000 trial
  - No change to fiber or MSD
- Mean BW improves 2x
  - MSD optimized specifically to achieved this result given simulated launch condition
- Minimum BW improves 2x
  - Worst case bandwidth of 99% of trials

Standard MMF link

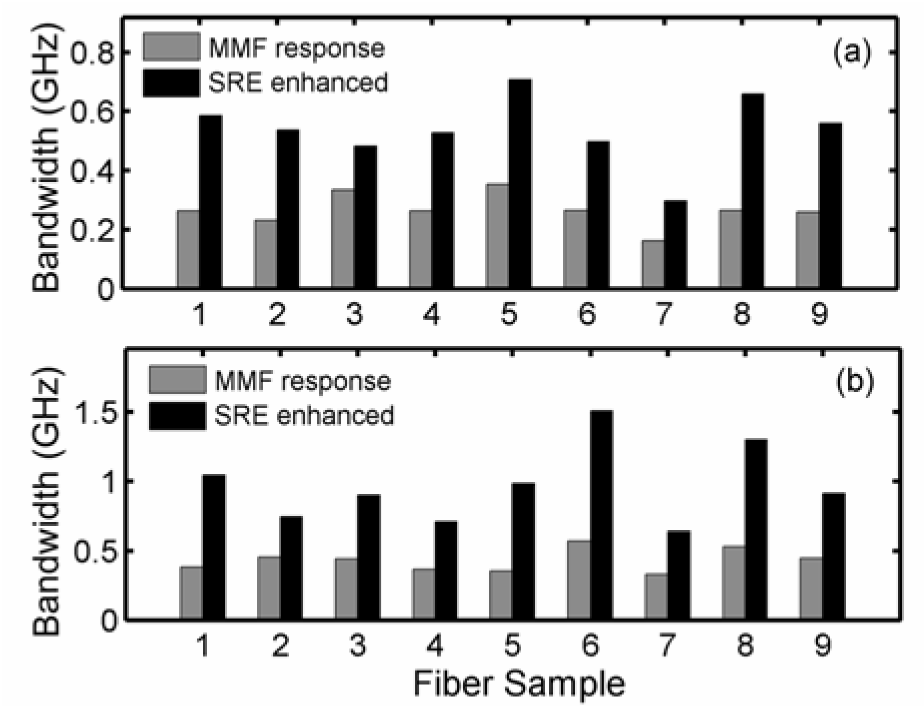


SRE enhanced MMF link



Measurement over fiber samples

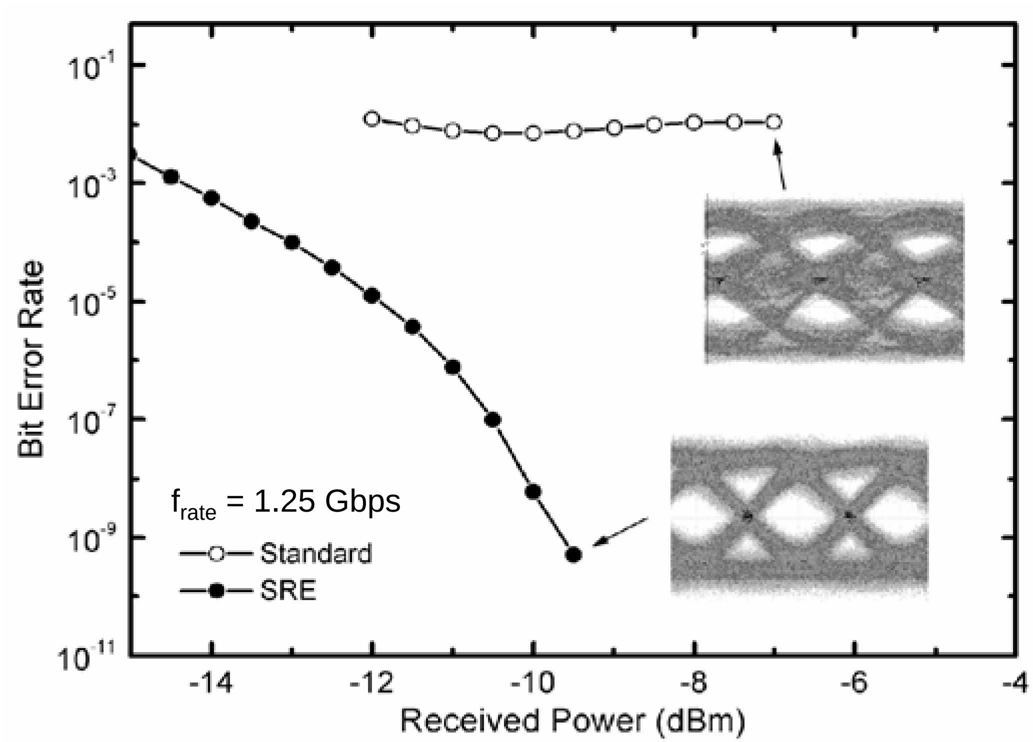
- Impulse response measurements made on sample of 1.1-km MMF
  - Measurements at 1550-nm
  - Multimode launch created with mode-scrambler
  - No optimization on fiber-to-fiber basis
- Consistent bandwidth improvement demonstrates robustness and potential cost-effectiveness of SRE



- 50-μm MMF
  - Nominal 500 MHz-km MMF @ 850 nm
- 62.5-μm MMF
  - FDDI grade

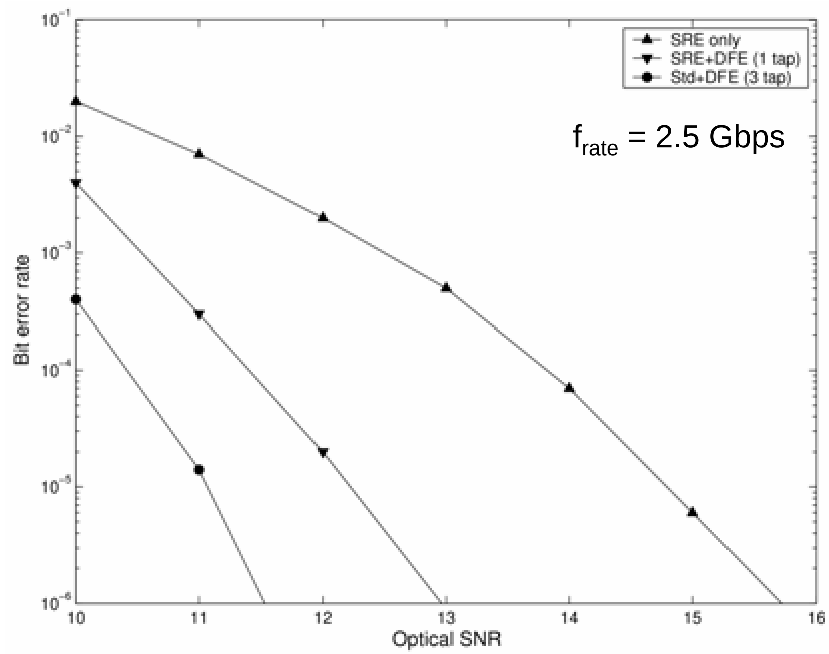
Measured bit error rate

- 1.25-Gbps data link in 1.1-km, 50-μm MMF
  - Externally modulate FP at 1.25 Gbps, launched via mode-scrambler
- MMF link completely dominated by ISI
  - ~8 dB SNR penalty due to non-optimal MSM
- SRE improved deterministic jitter and vertical eye opening
- Modal noise not apparent in measurement
  - Modal noise can be issue with spatial filtering by SRE
- Modal noise managed by low-coherence FP source
  - *i.e.* source coherence time less than DMD



Synergy of DFE and SRE

- Numerical simulation of DFE on MMF fiber link to increase capacity up to 2.5 Gbps
  - Simulate data link at with DFE enhancement but with measured impulse response of fiber used in BER experiment to model link
    - with and without SRE
- 2.5 Gbps possible with SRE alone
- SRE with DFE improves on ISI penalty compared to SRE alone
  - ISI penalty reduced by 3 dB with DFE
- DFE with SRE permits simplified DFE structure
  - Reduced from 3 backwards tap without SRE to 1 backward tap with SRE



Conclusion

- Segmented photodetector works to equalize MMF link
  - Equalization exploits optical information lost by conventional photodetection
- Simplified two-segment with photocurrent subtraction shown to be effective
  - Maintains simplicity and cost-effectiveness characteristic of MMF
- SRE is independent of temporal behavior of modes
  - Effect of high-ordered modes are suppressed regardless of magnitude or direction of DMD
    - Independent of wavelength
    - Independent of fiber length
  - Independent of transmission format
  - Independent of data rate
- SRE can be optimized for launch condition
  - SRE can be implemented with EF launch or other launch conditions
- SRE works with DFE for further enhancement than by either alone

SRE related publications

K. M. Patel and S. E.Ralph, "Improved multimode link bandwidth using spatial diversity in signal reception," *CLEO Technical Digest*, p. 416, May 2001.

K. M. Patel and S. E. Ralph, " Spatially resolved detection for enhancement of multimode-fiber-link performance," *Proc. LEOS. Annual Meeting*, vol. 2, pp. 483–484, Nov 2001.

K. M. Patel and S. E. Ralph, "Enhanced multimode fiber link performance using a spatially resolved receiver," *IEEE Photon. Technol. Lett*., vol. 14, pp. 393-395, March 2002.

K. M. Patel and S. E. Ralph, "Multimode fiber link equalization by mode filtering via a multisegment photodetector," *IEEE Microwave Symposium Digest*, vol. 2, pp. 1343-1346, June 2003.

K. M. Patel, A. Polley, and S. E. Ralph, Modal dispersion compensation by simultaneous use of spatially resolved equalization and restricted mode launch," in *Proc. LEOS. Annual Meeting*, vol 2, pp 973-974, 2003.

S. E. Ralph, K. M. Patel, C. Argon, A. Polley, and S. W. McLaughlin "Intelligent receivers for multimode fiber: optical and electronic equalization of differential modal delay," in *Proc. LEOS. Annual Meeting*, vol. 1, pp.295–296, Nov 2002.

R. Khosla, K. Kumar, K. M. Patel, C. Pelard, and S. E. Ralph, "Equalization of 10GbE multimode fiber links," in *Proc. LEOS. Annual Meeting*, vol 1, pp 169-170, Oct. 2003.

C. Argon, K. M. Patel, S. W. McLaughlin, and S. E. Ralph, "Spatially resolved equalization and decision feedback equalization for multimode fiber links," in *Proc. LEOS Summer Topical*, pp. 19-20, July 2002.

C. Argon, K. M. Patel, S. W. McLaughlin, and S. E. Ralph, "Spatially resolved equalization and forward error correction for multimode fiber links," in *Proc. of ICC*, vol. 3 , pp 1726-1730, May 2002.

C. Argon, K. M. Patel, S. W. McLaughlin, and S. E. Ralph, "Exploiting diversity in multimode fiber communications links via multisegment detectors and equalization," *IEEE Comm. Lett*., vol. 7, pp. 400-402, August 2003.

Ultrafast Optical Communications Lab

- FOTP-220 compliant DMD measurement of MMF in the time domain
- High-resolution impulse response characterization of optical and opto-electronic component
  - 8-ps resolution at 850 nm and 1550-nm
  - 100-ps resolution at 1300 nm
- Frequency response characterization of optical and optoelectronic components
  - up to 20 GHz
- Optical source characterization (800 thru 1600 nm)
  - Spectral content (0.01-nm resolution)
  - Temporal content (8-ps resolution)
  - Jitter (800 fs jitter)
  - Speckle contrast
- Numerical modeling
  - Fiber/waveguides
  - Links
  - Electronic dispersion compensation

Georgia Electronic Design Center

- "Equalize This!"
  - Georgia Tech testbed: Design and implement testing and benchmarks for high-speed backplane and serial interconnect markets.
- UXPi testbed
  - Standardized backplane testing methodology
  - Silicon testing methodology
- Capabilities
  - Frequency/Time Domain Analysis
    - Cross talk (NEXT, FEXT)
    - Forward Transmission
  - Eye diagrams
  - Bit Error Ratio (BER)
  - Jitter Analysis
    - Random Jitter (RJ) – results from accumulation of random process
    - Deterministic Jitter (DJ) – results from systematic effects
  - EMI Analysis

Simple SRE variants

- Consideration of other SRE variations using measured impulse response
  - Compute SRE response from measured impulse response by individual PD segments
  - Overfilled launch condition

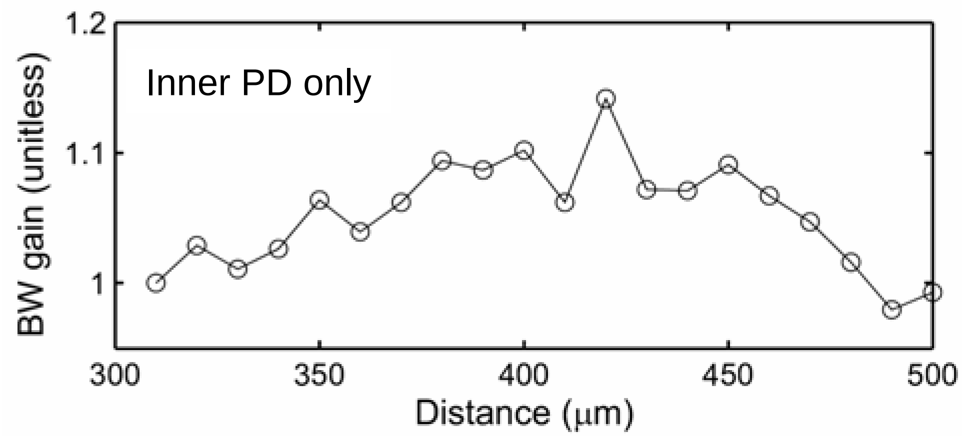
- Single segment spatial filtering

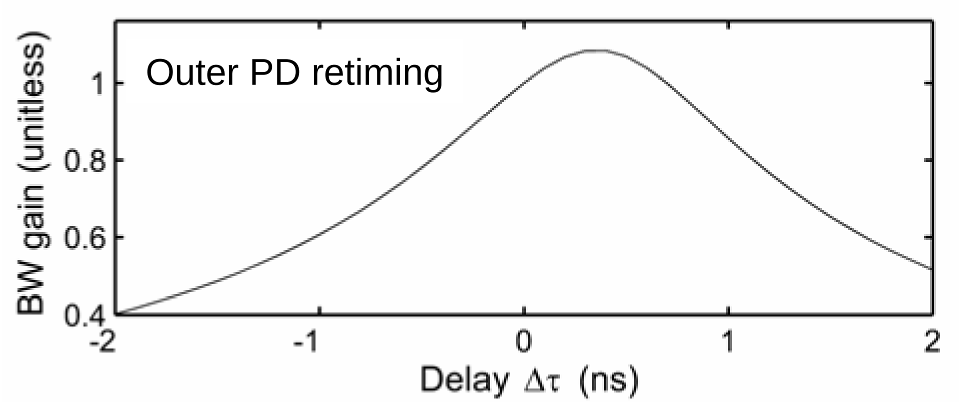
$$h_{sre}(t) = h_{inr}(t)$$

- Recombination with timing adjustment

$$h_{sre}(t) = h_{inr}(t) + h_{otr}(t + \Delta\tau)$$

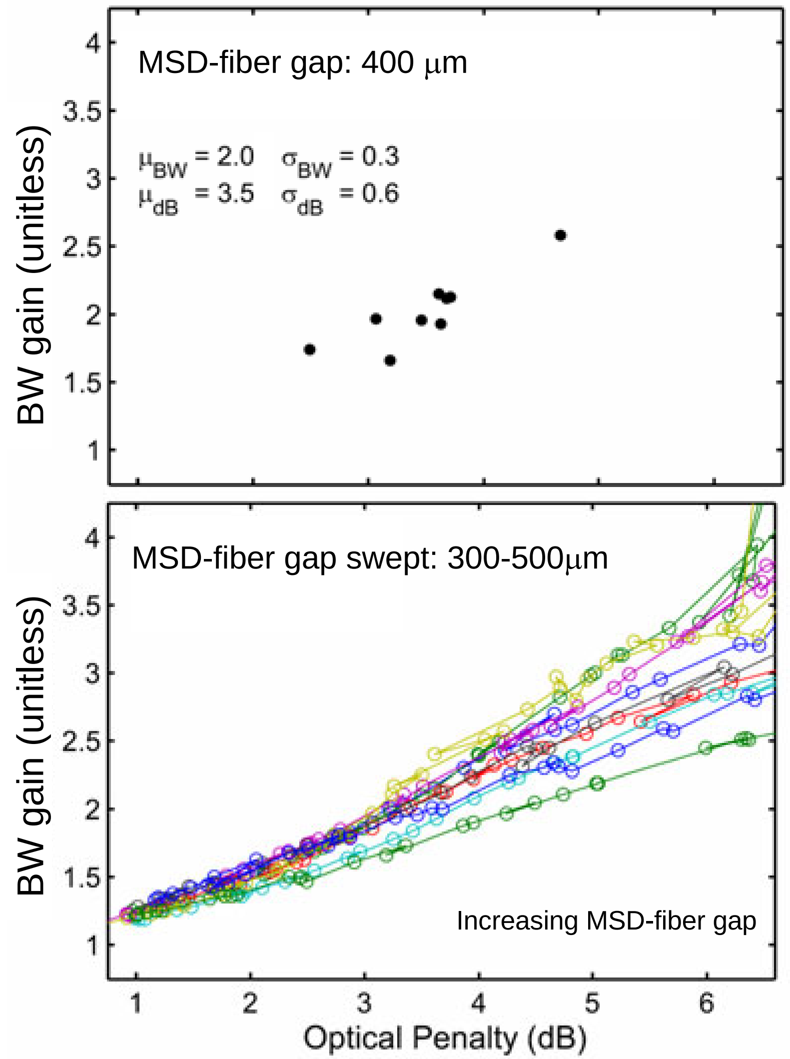
- Conclusion: Photocurrent subtraction is useful given limited modes separation by MSD





Bandwidth gain trade-off

- Variation in BW gain versus discarded optical power
  - 9 samples of 1.1-km, 50-μm MMF
  - Fixed configuration: source, launch, and MSD size
- Similar trade-off as demonstrated with simulation
  - Variation in slope results from unique fiber characteristics



Monte Carlo simulation (cont.)

- Mean bandwidth gain of 2.1x
- Low lying BWG are for EFL which result in high link bandwidth
- MSD can be optimized for launch conditions the results in consistently higher bandwidth
  - *i.e.* lower HOM energy