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Wavelength Dependence of Multimode Fiber Bandwidth
&
Dual Wavelength Channel Performance

P802.3cd Ethernet Task Force
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Outline

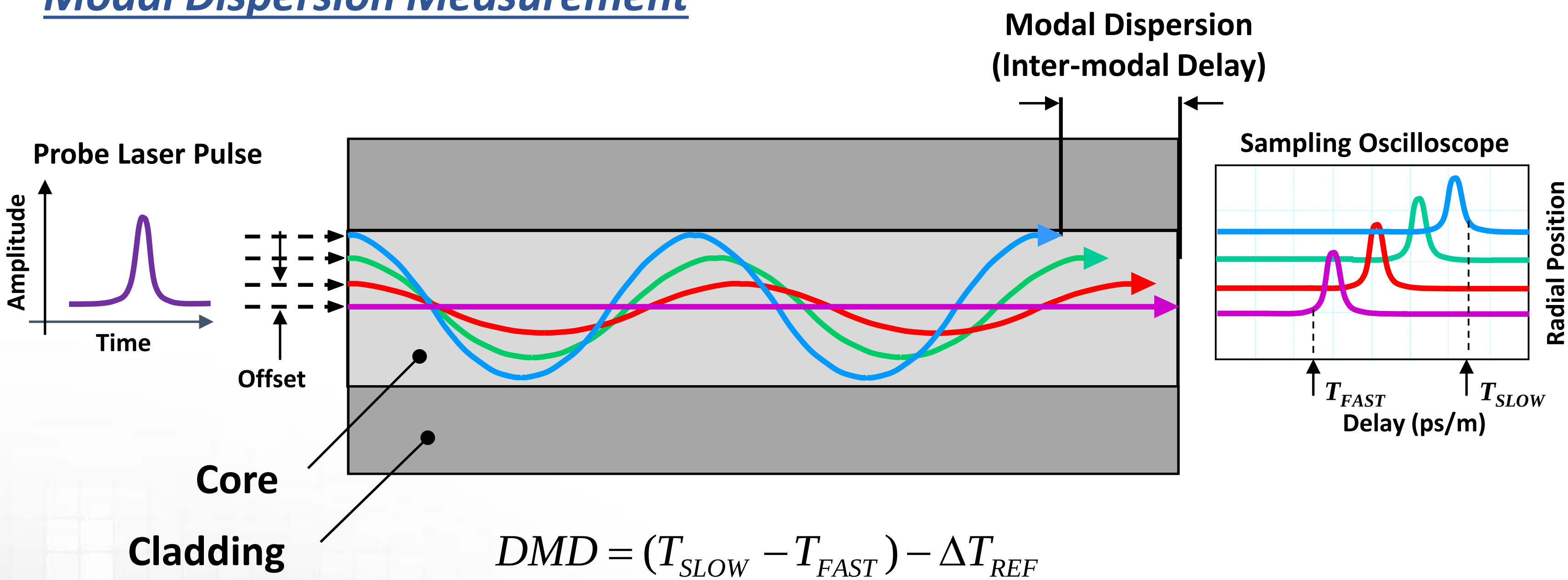
- Wavelength dependence of OM3/OM4 bandwidth
- Impact of two wavelengths on MPN
- Dual wavelength channel reach and BER performance
- Modal-Chromatic Interaction
- Measured channel performance
- Conclusions

Panduit's Ti:Sapphire DMD System

Differential Mode Delay (DMD) Measurement

DMD Test Bench - Tunable Titanium:Sapphire Laser

Modal Dispersion Measurement



$$DMD = (T_{SLOW} - T_{FAST}) - \Delta T_{REF}$$

$$\Delta T_{REF} = (\Delta T_{PULSE}^2 + \Delta T_{chrom}^2)^{1/2}$$

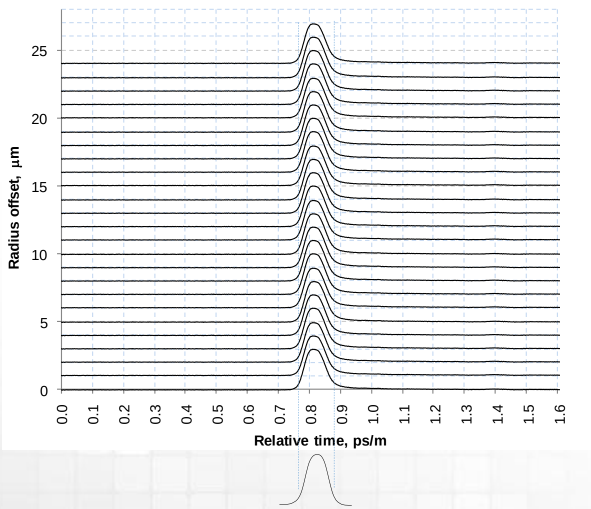
Used to calculate EMB

(Effective Modal Bandwidth)

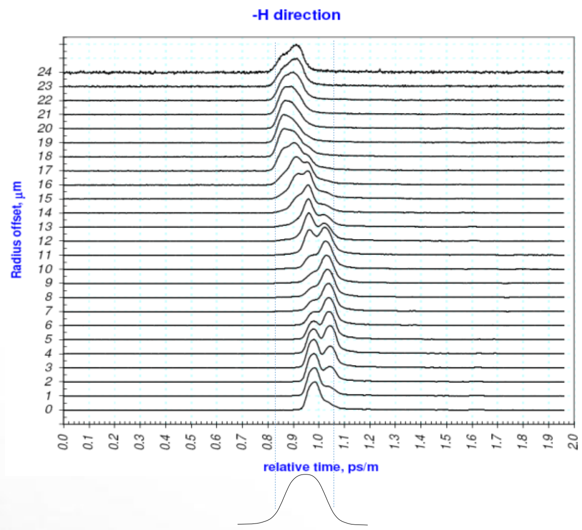
Two Examples of DMD

Due to process variation, each fiber has a unique DMD

As Designed

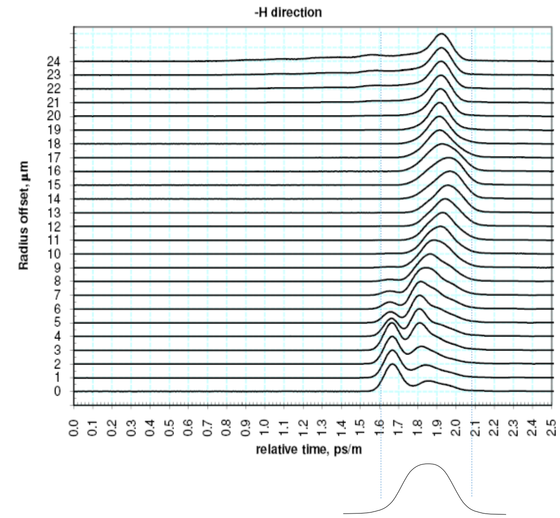


Fiber A



Left-Shifted

Fiber B



Right-Shifted

- ***Effectively No Fiber has an "As Designed" DMD Profile***

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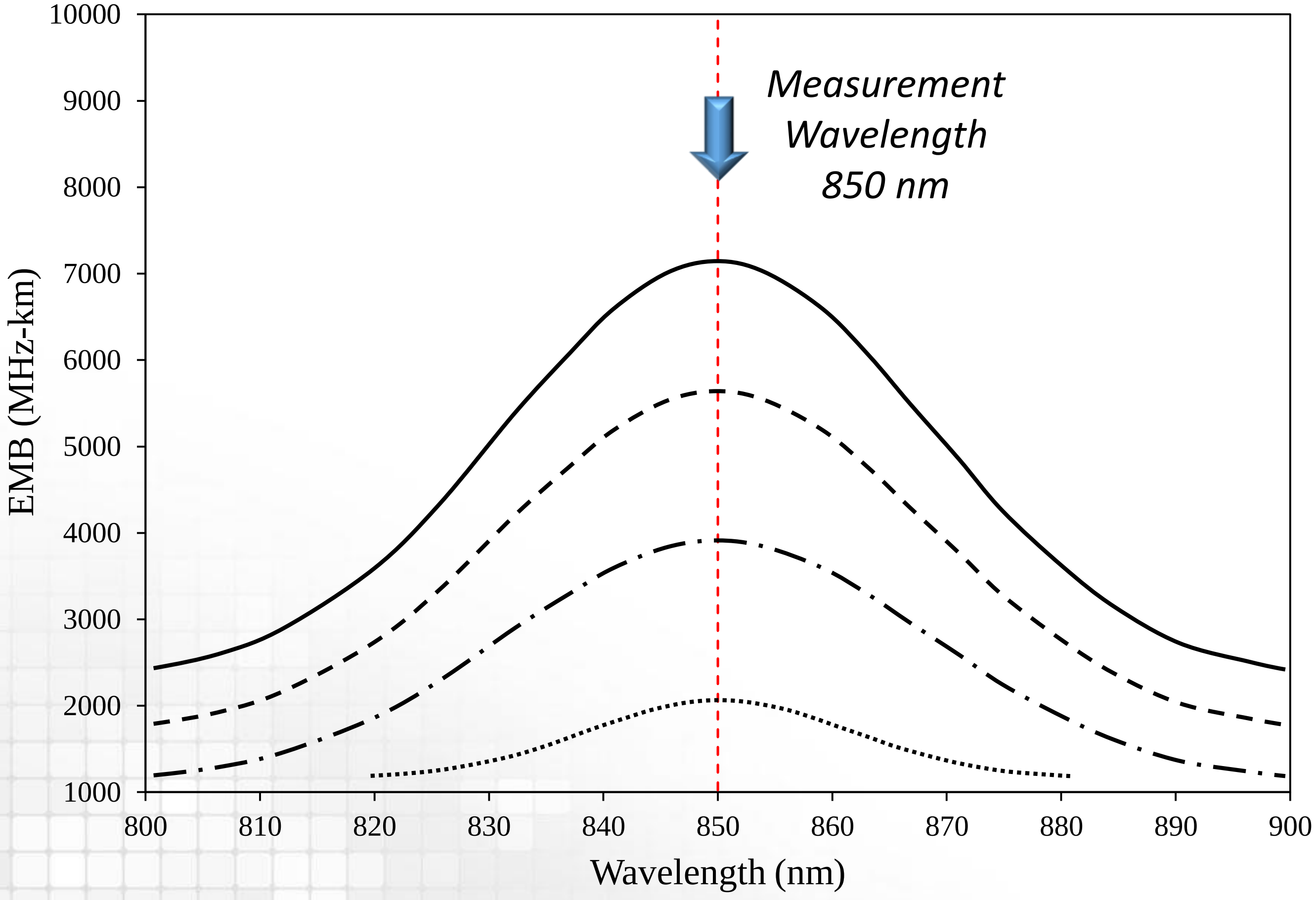
Widespread Belief – Wavelength Dependence of EMB Is Symmetric Around 850 nm



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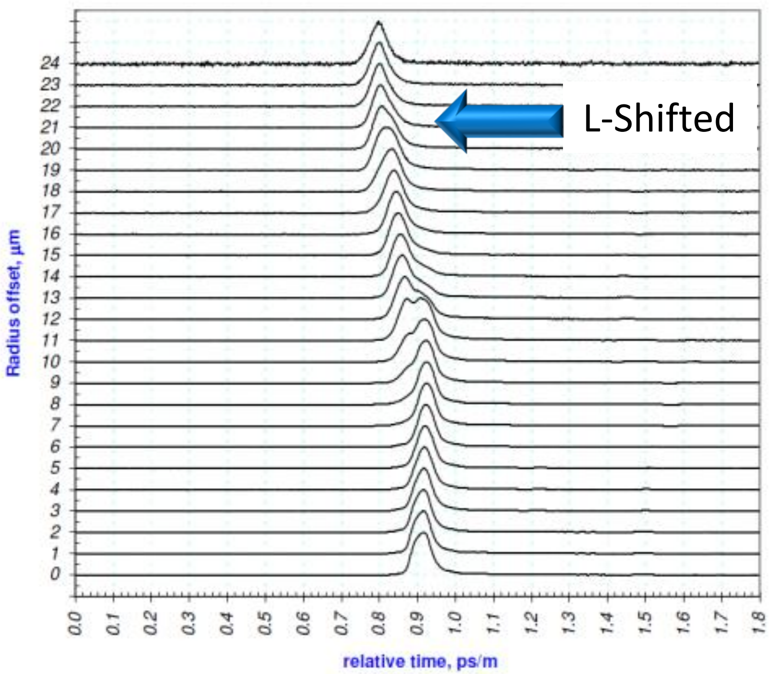
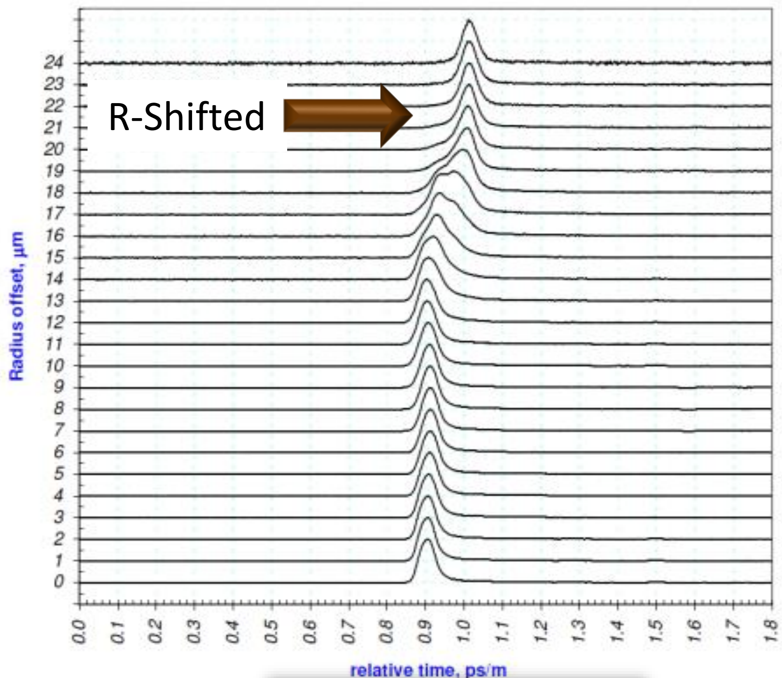
- *Two fibers from same cable with the same EMB (similar DMD profile)*
  - *L = 548 m*
  - *Ti:Sapphire Laser - DMD*

Fiber A



Blue Fiber
EMB = 4540 MHz·km
DMD_{inner} = 0.12 ps/m
DMD_{outer} = 0.15 ps/m
$DMD_{sliding}$ = 0.11 ps/m
DMD P-Shift = -0.098 ps/m

Fiber B



Brown Fiber
EMB = 4540 MHz·km
DMD_{inner} = 0.12 ps/m
DMD_{outer} = 0.13 ps/m
$DMD_{sliding}$ = 0.13 ps/m
DMD P-Shift = +0.096 ps/m

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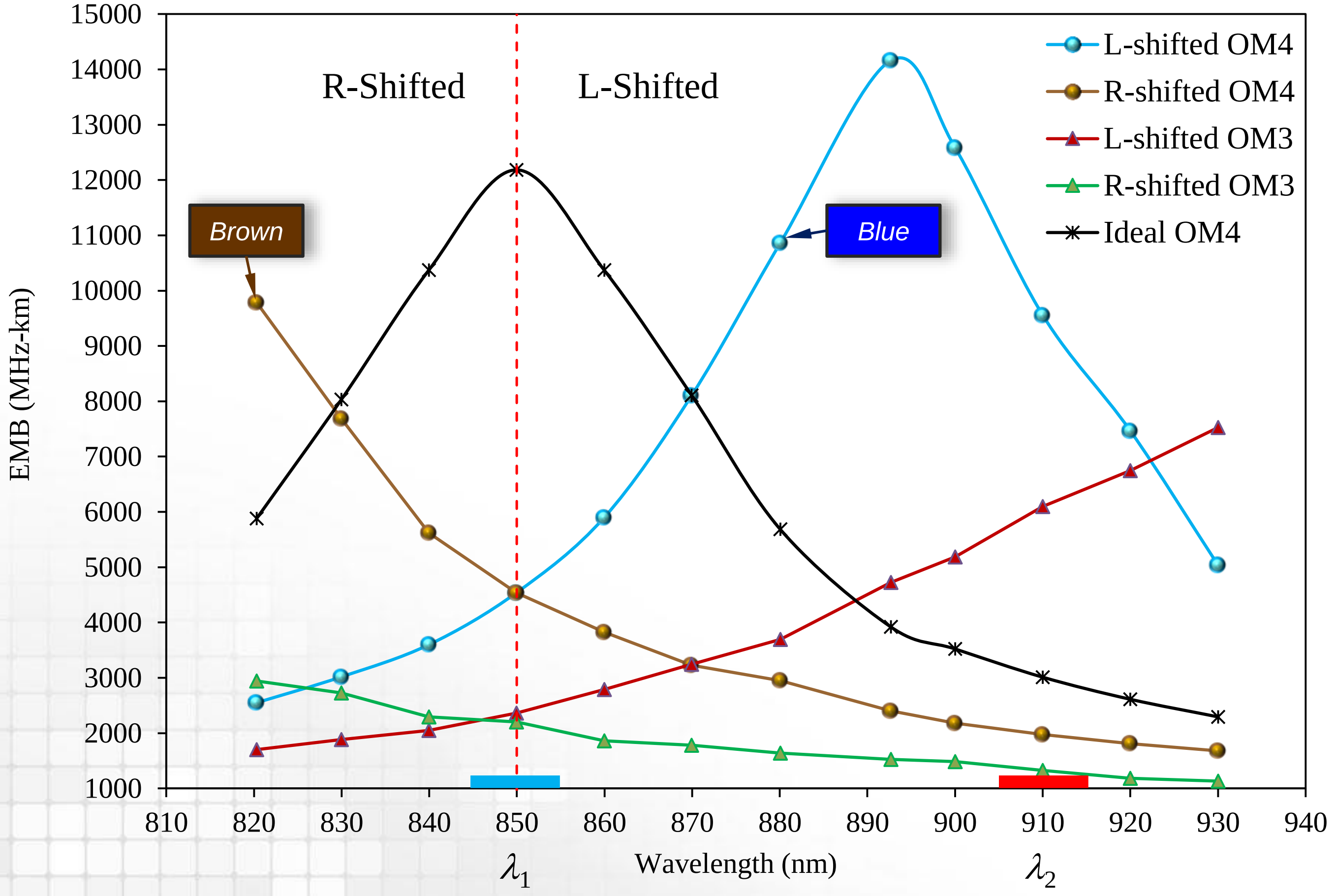
Measured EMB Wavelength Dependence
Panduit's DMD System Utilizes a Tunable Ti:Sa Laser



Fiber A (Left-shifted) Wavelength Dependence [1]

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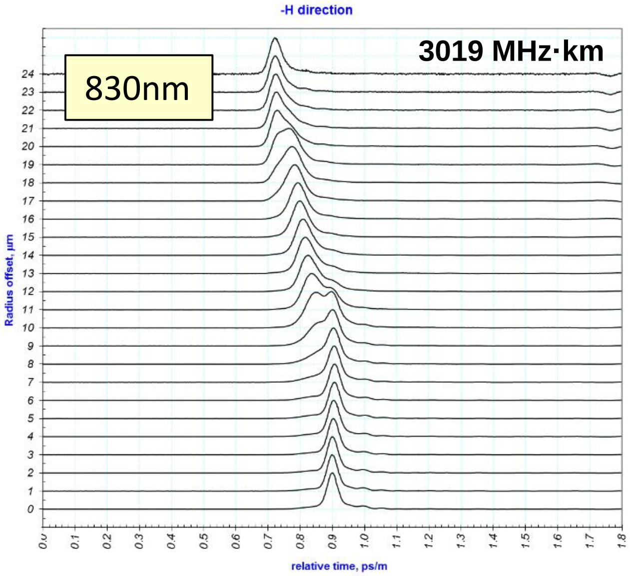
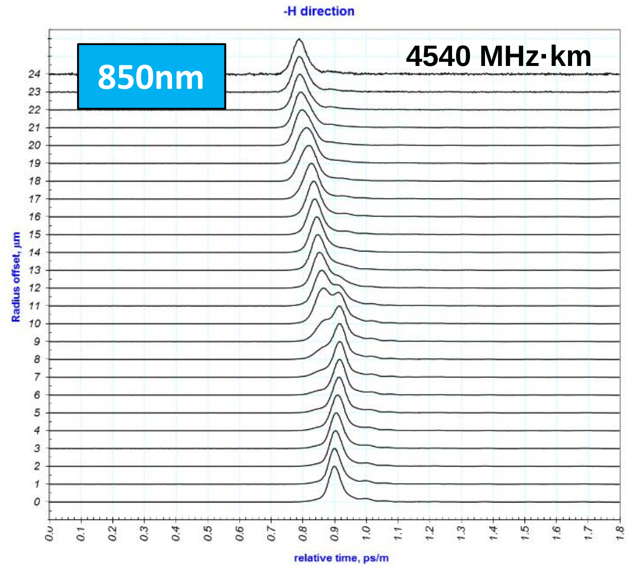
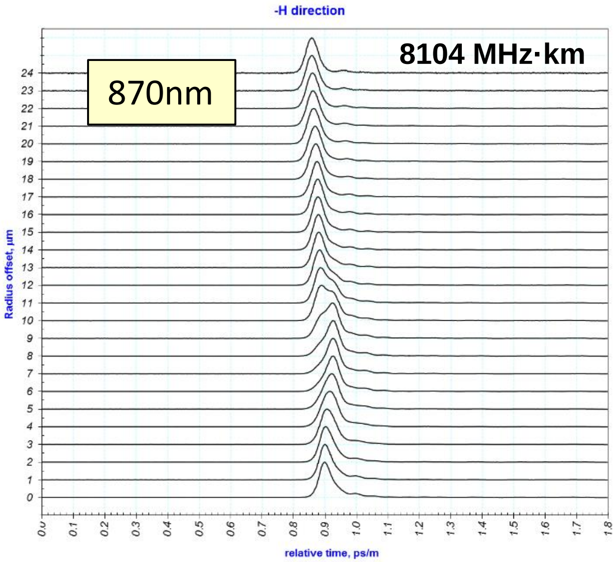
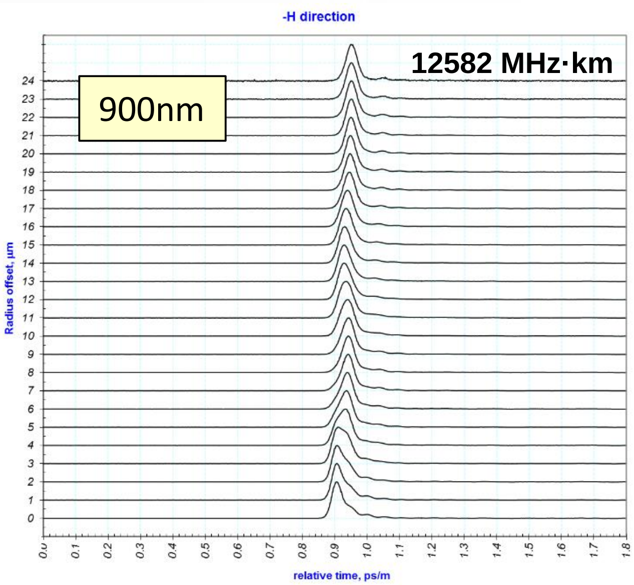
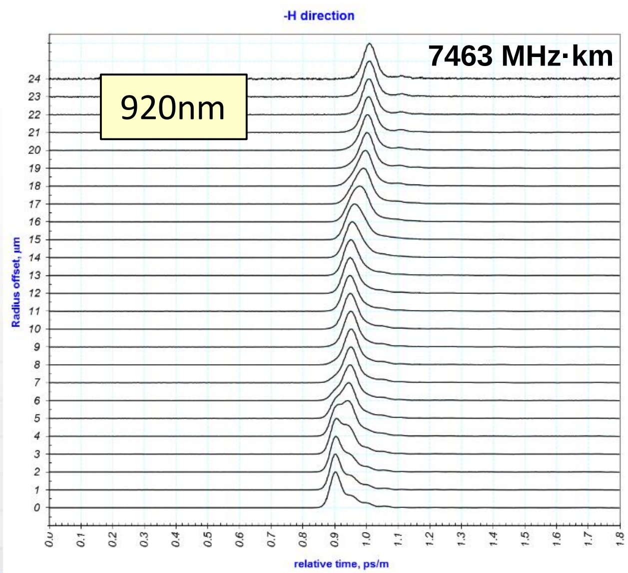
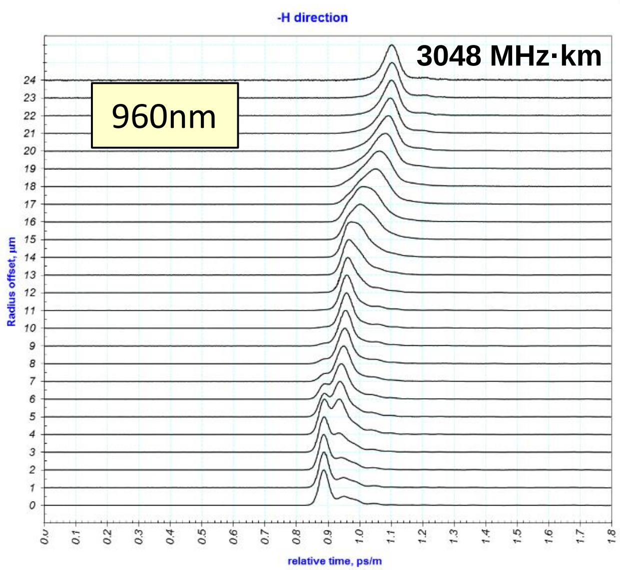




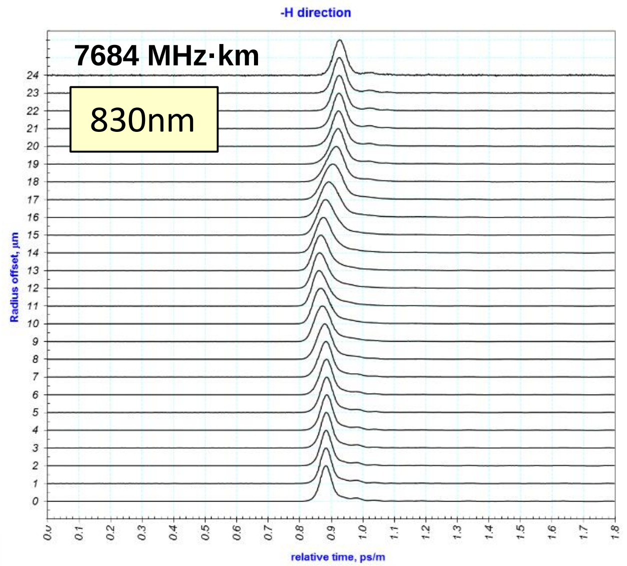


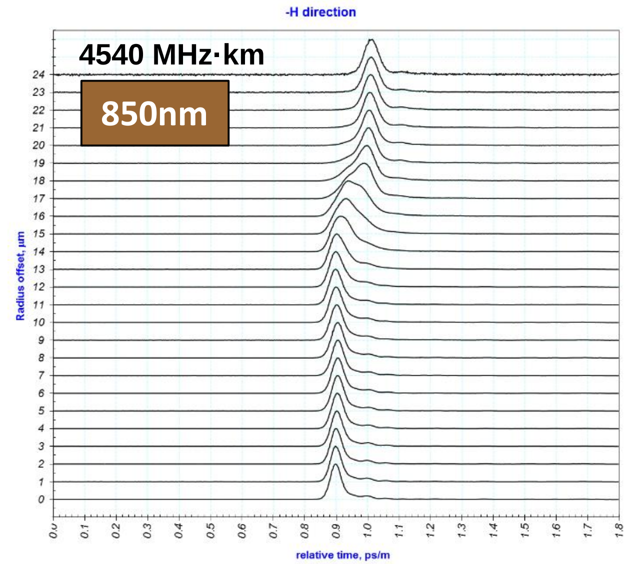


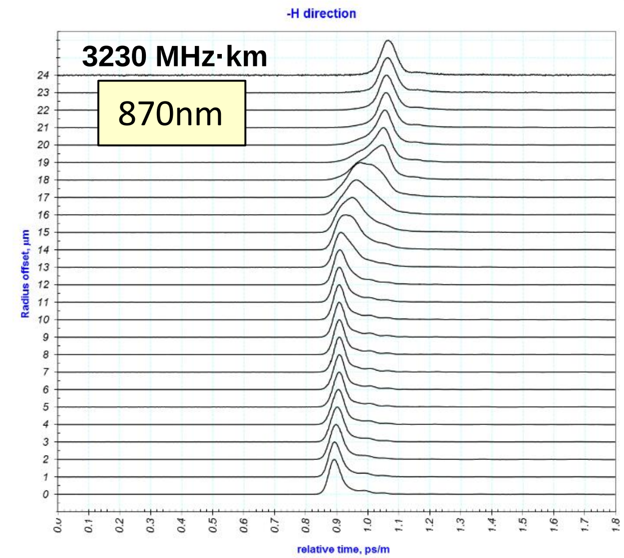


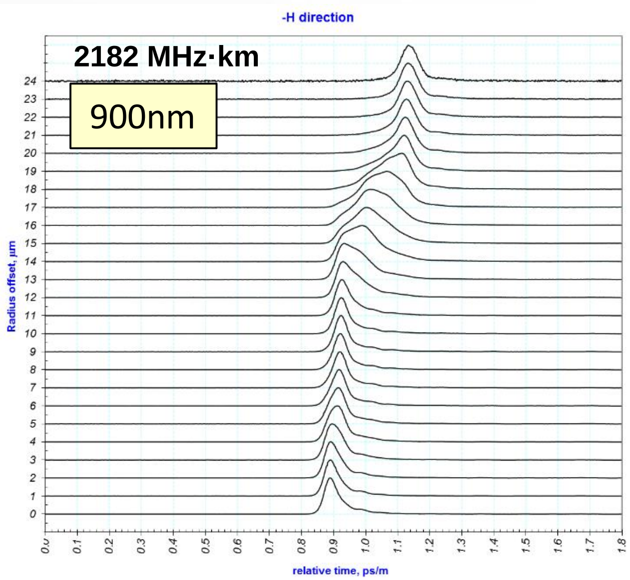


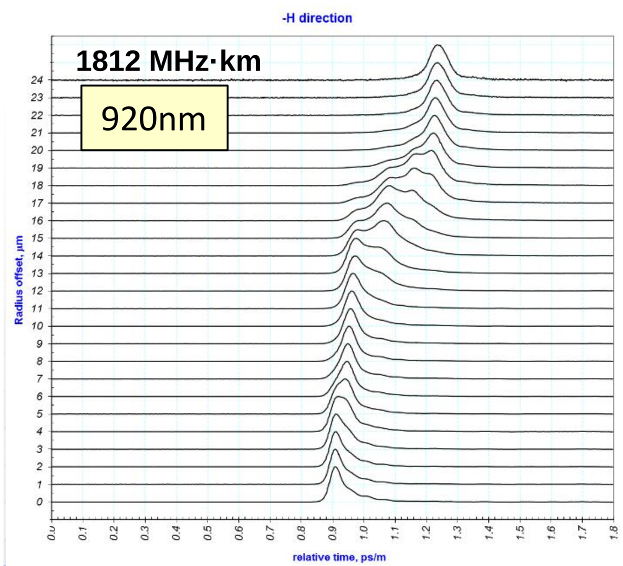
Fiber B (Right-shifted) Wavelength Dependence [1]

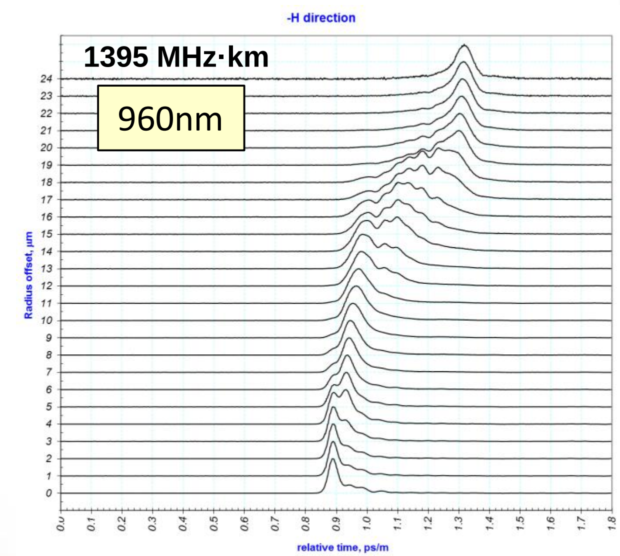












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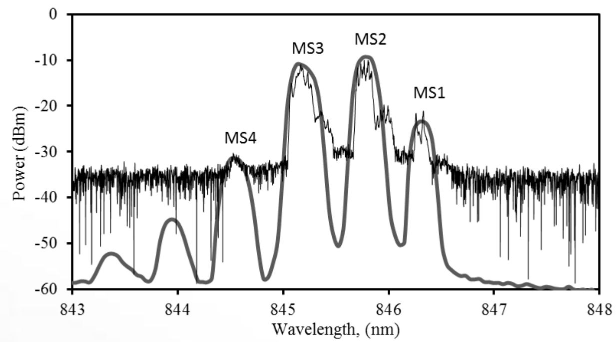
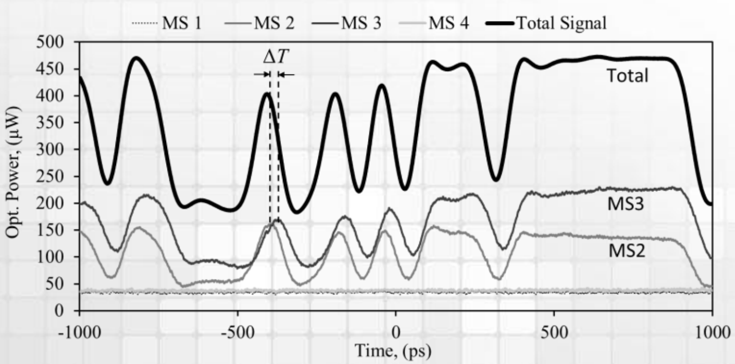
Impact of DMD profile on channel performance [2,3]

Bandwidth and Noise dependence on DMD tilt

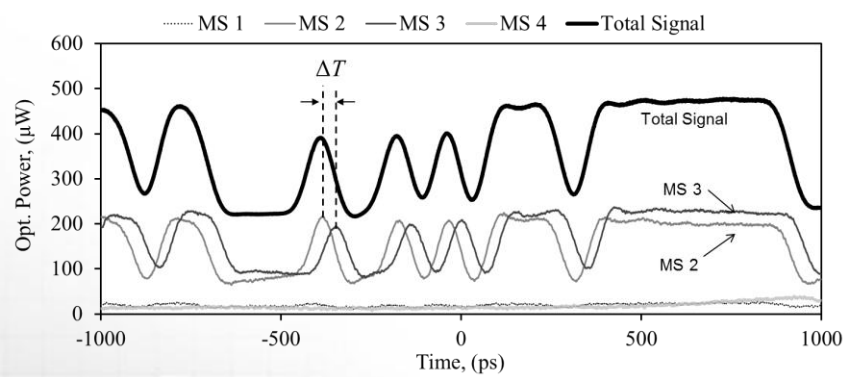
- For a similar EMB measured at 850nm, L-MMFs provide higher bandwidth at longer wavelengths than R-MMF.
- R-MMF produces higher levels of MPN due to longer separation of the modes in the MMF.
- Transceivers using equalization can partially compensate for channel bandwidth limitations. However, equalizers increase noise.



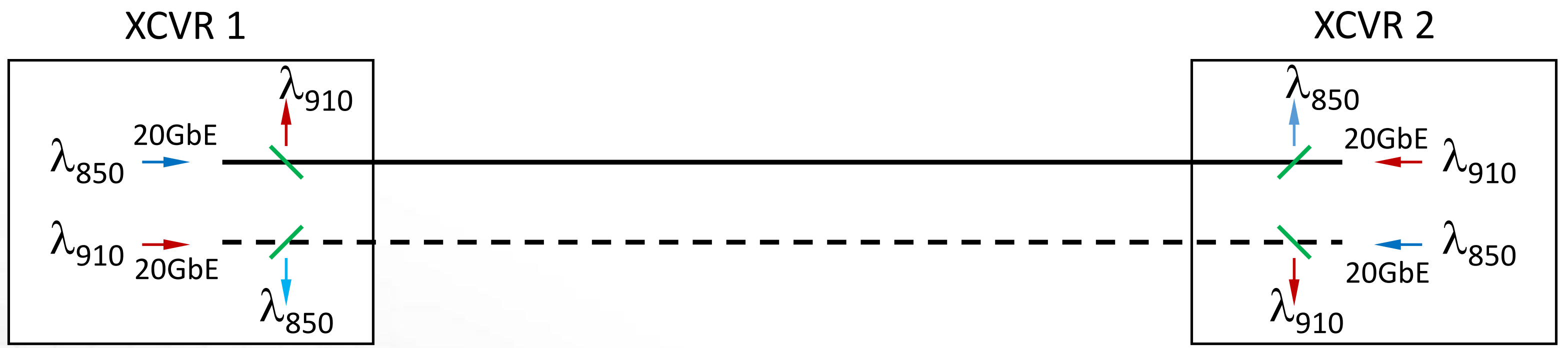
L-MMF



R-MMF



40GbE (2x20G) Bi-Directional, 2-λ's Measured Channel Performance



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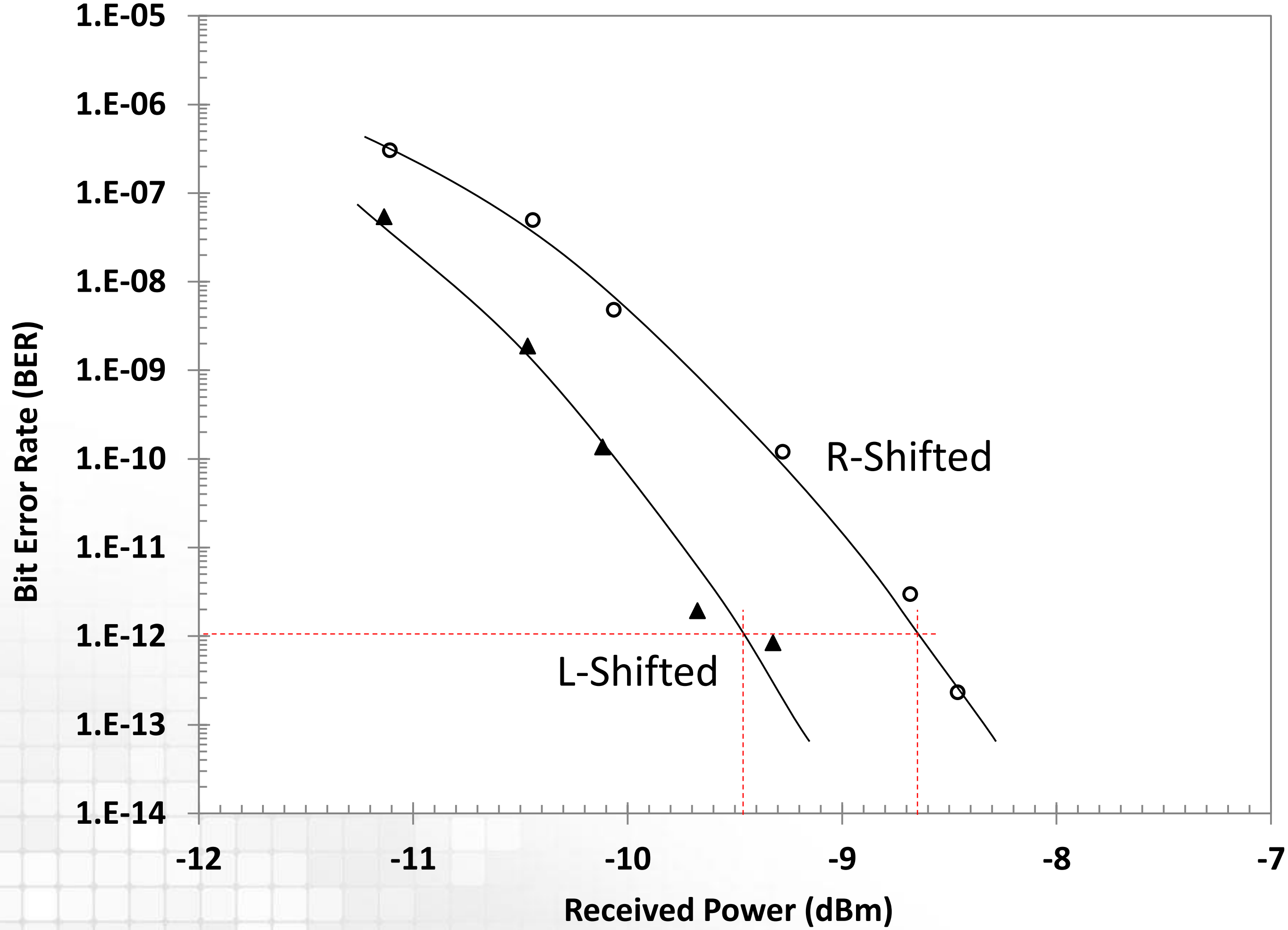
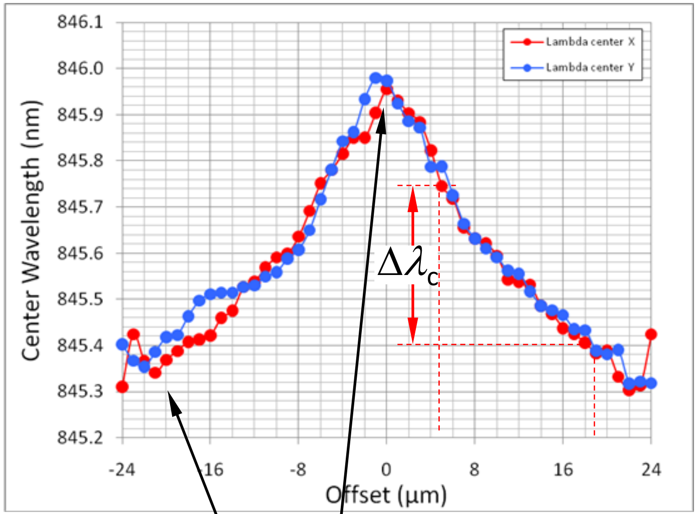
BER at 904 nm, 40Gbps, 150m
L- vs. R-Shifted DMD, EMB = 4540 MHz·km [4]

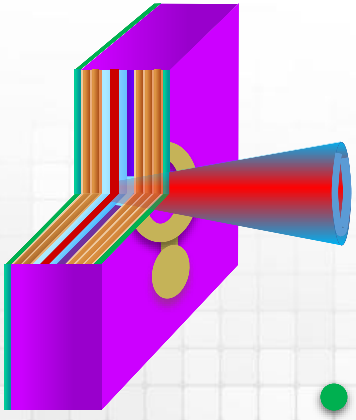


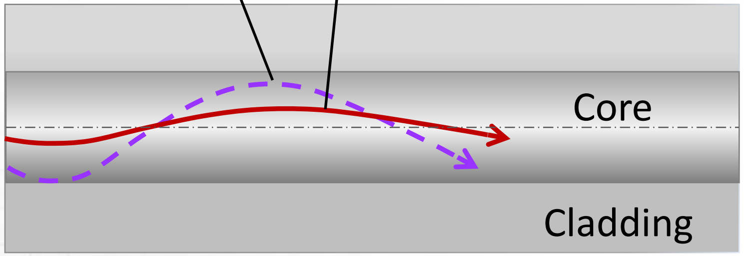
VCSEL spatial-spectral coupling into MMF

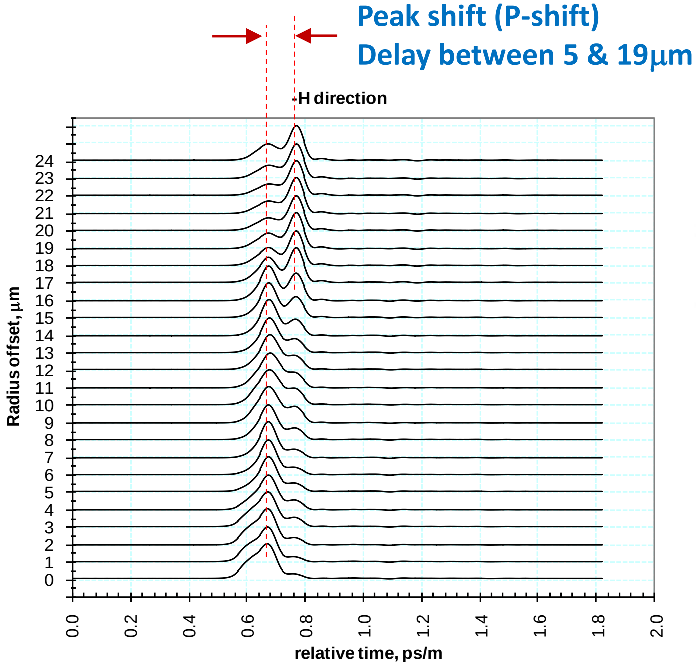


- *There is a significant fiber coupled spatial-spectral distribution*
  - *Shorter spectral components preferentially coupled to larger fiber radii*
- *Interaction of modal and chromatic dispersion*

Radial Spectral Dependency



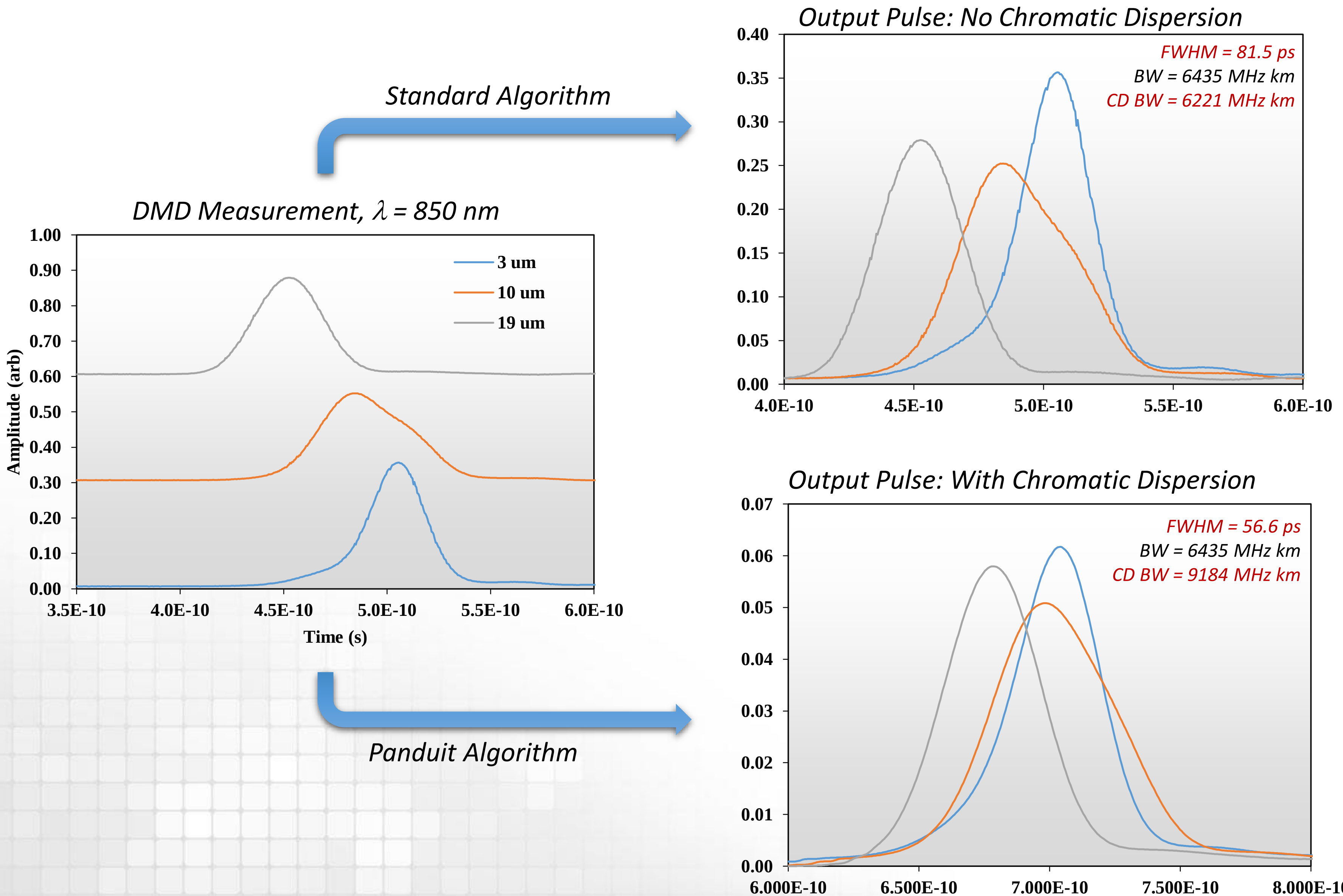




- Short wavelengths couple to high-order modes
- Long wavelengths couple to low-order modes

Resultant DMD due to Modal Chromatic Dispersion

Modal-Chromatic Dispersion Interaction [5]



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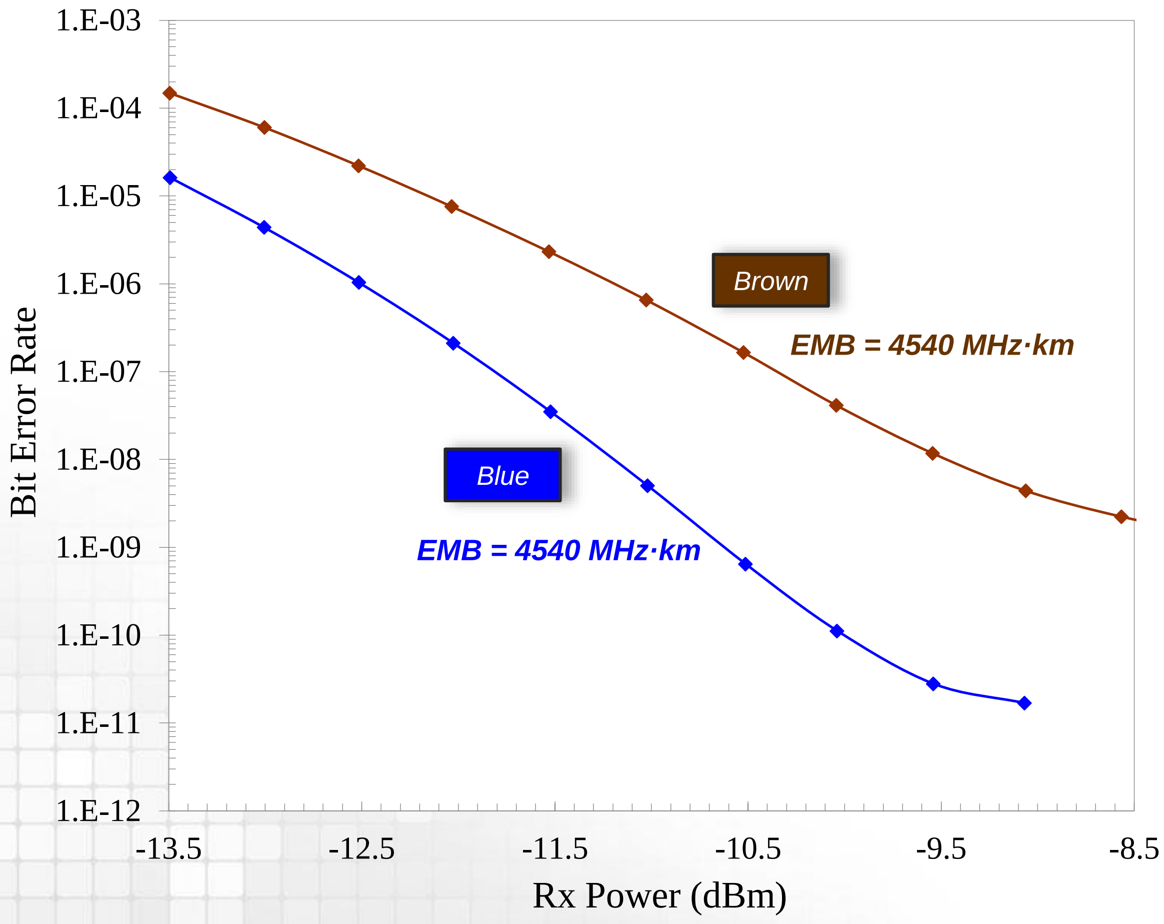
Channel Performance Difference – Same EMB

- *Two fibers in same cable with the same EMB*
  - *10GBASE-SR Transceiver*
  - *L = 548 m*



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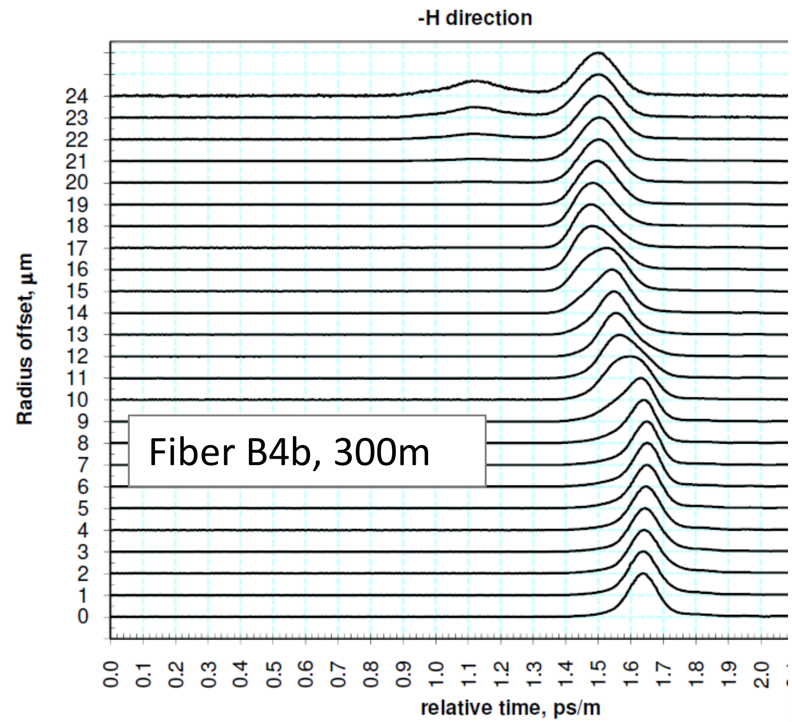
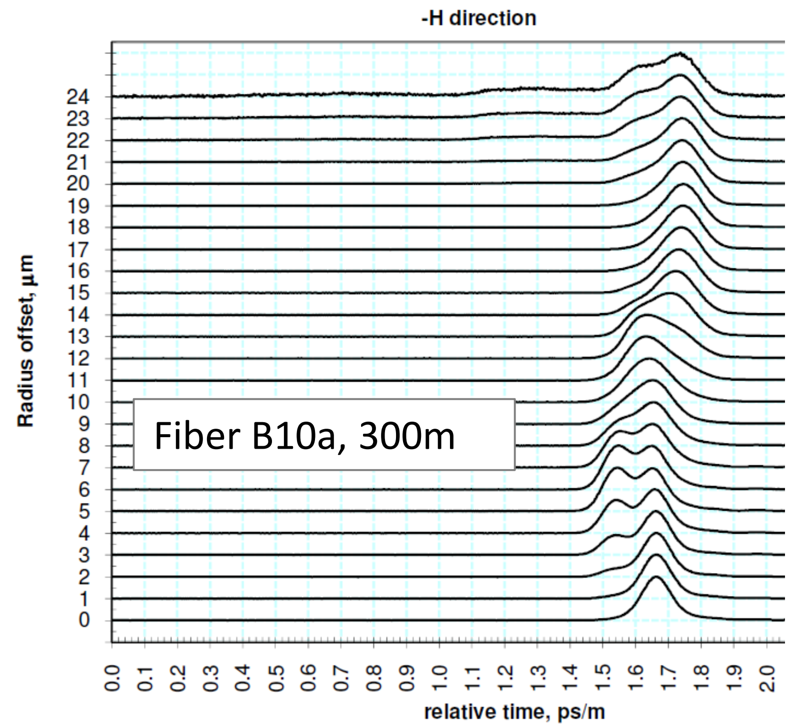
Spectral Performance Comparison, B4 and B10
*(Same manufacturer & same EMB, ~2400MHz*km)*



Numerical results	B4a DMD & EMB test			FOTP220	Gaussian
	DMDouter	DMDinner	DMDsliding	EMB	EMB
-H	0.213	0.202	0.181	2364	2454
+H	0.196	0.196	0.174	2428	2504
-V	0.197	0.196	0.186	2408	2494
+V	0.222	0.208	0.181	2295	2381
mean:	0.207	0.201	0.181	2374	2458
SD:	0.013	0.006	0.005	59	56



Numerical results	B10a DMD & EMB test			FOTP220	Gaussian
	DMDouter	DMDinner	DMDsliding	EMB	EMB
-H	0.240	0.240	0.216	2380	2482
+H	0.238	0.236	0.212	2390	2442
-V	0.257	0.249	0.216	2230	2234
+V	0.247	0.238	0.190	2426	2545
mean:	0.245	0.240	0.209	2357	2426
SD:	0.009	0.006	0.013	86	135

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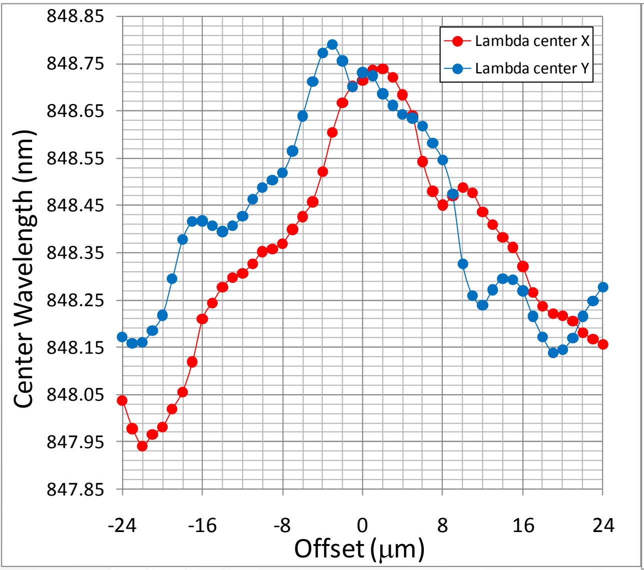
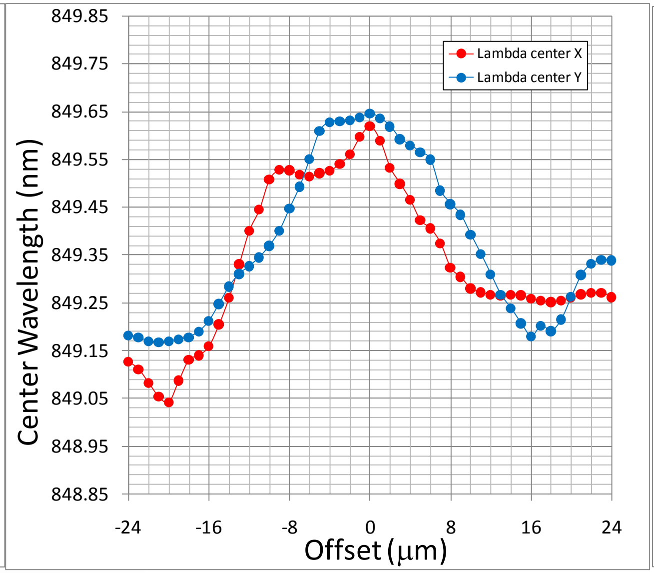
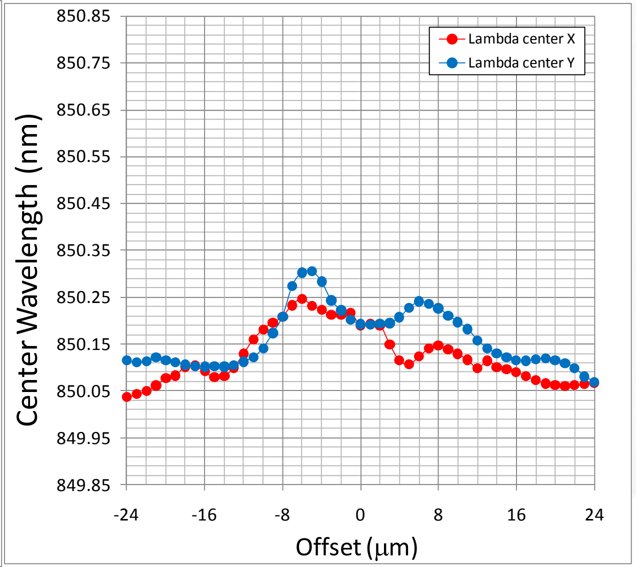
Three Transmitter spectral radial dependencies







	BERT	***XFP JDSU032***	***SFP+ 2M***
$\Delta\lambda_c$ (nm)	0.72	0.53	0.22
$\Delta\lambda$ (nm)	0.45	0.34	0.23

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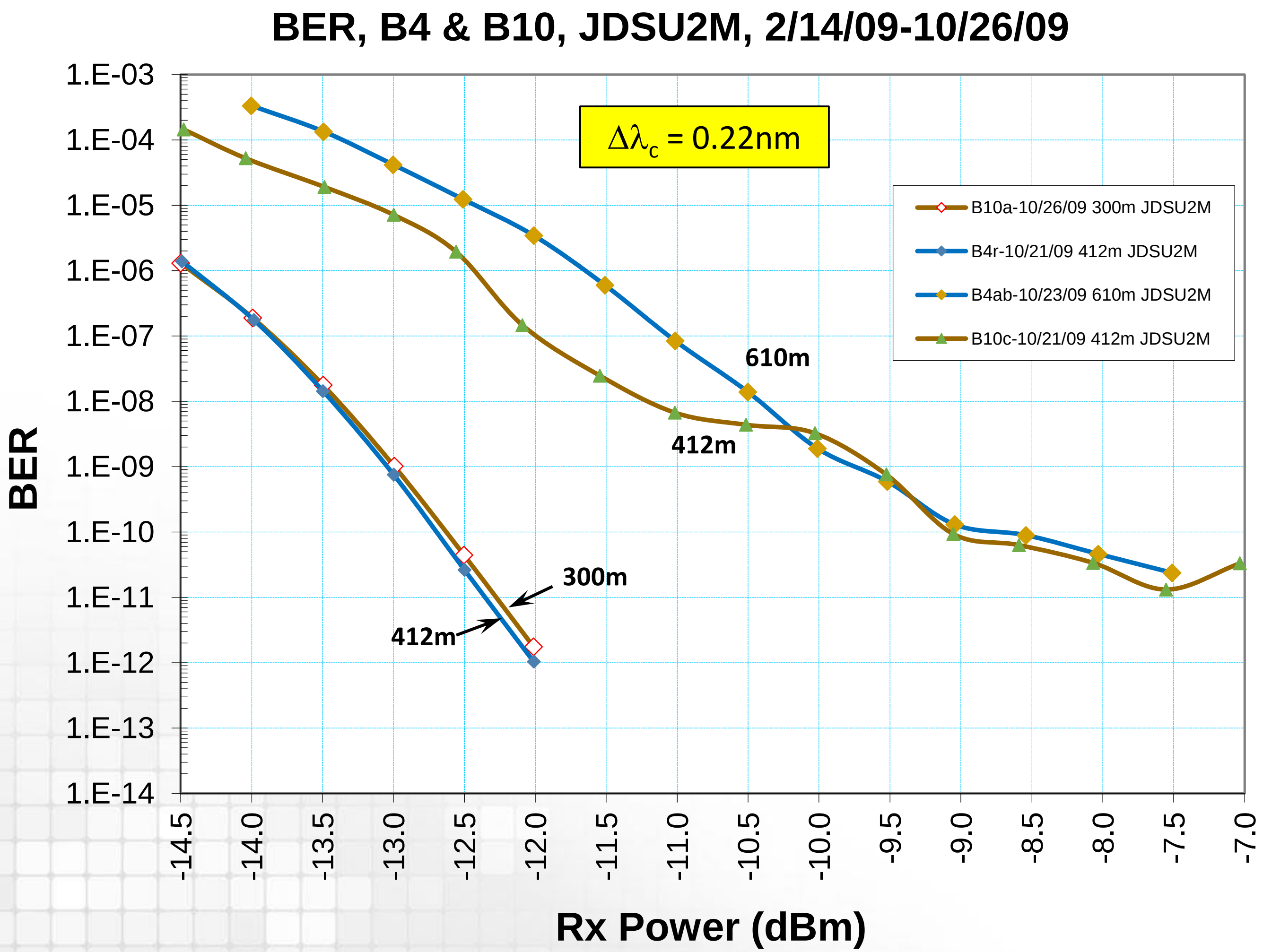
JDSU-2M Transceiver R v. L-Shifted



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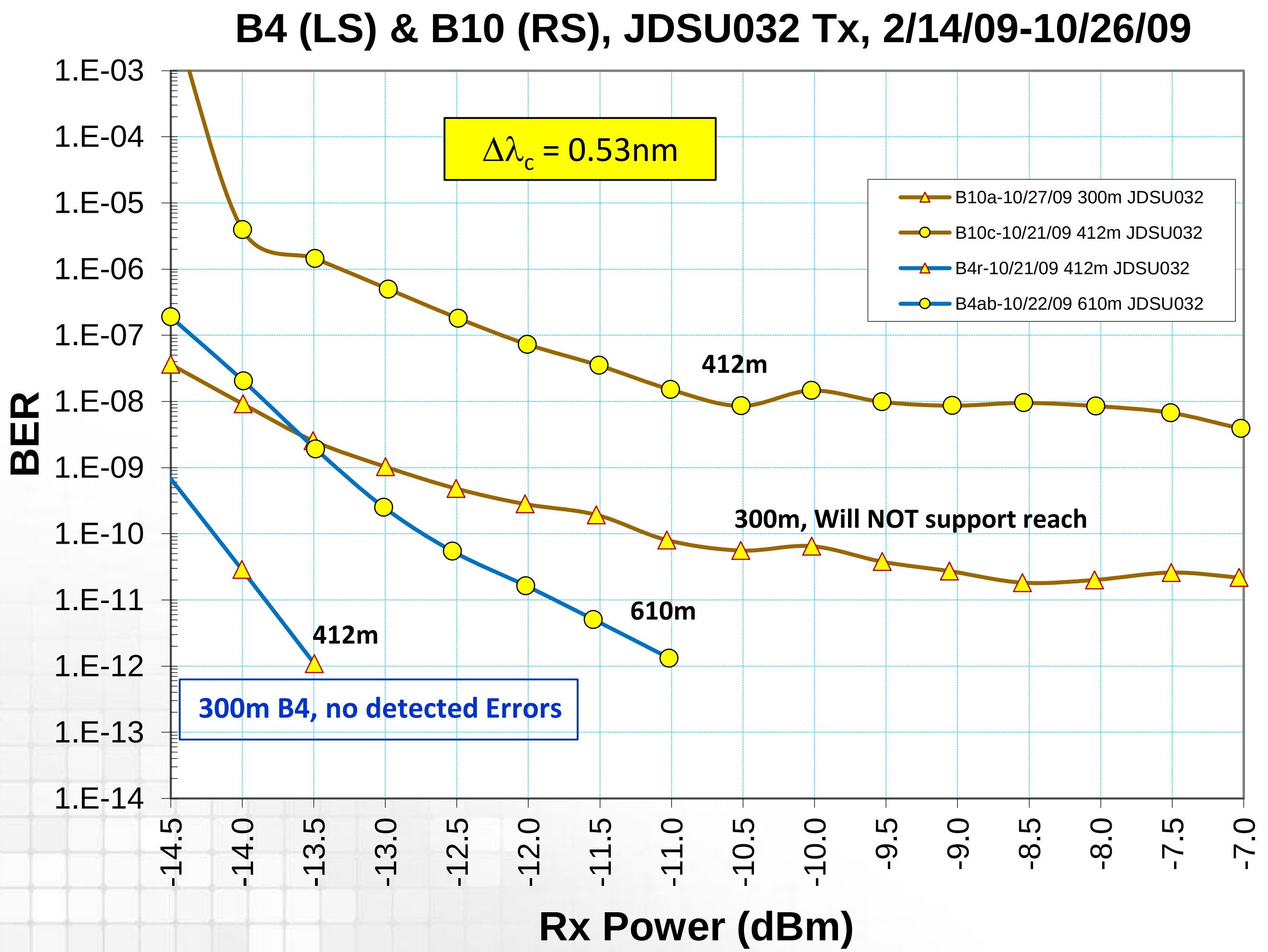
JDSU-032 Transceiver

Spectral Shift well matched to B4 Fiber



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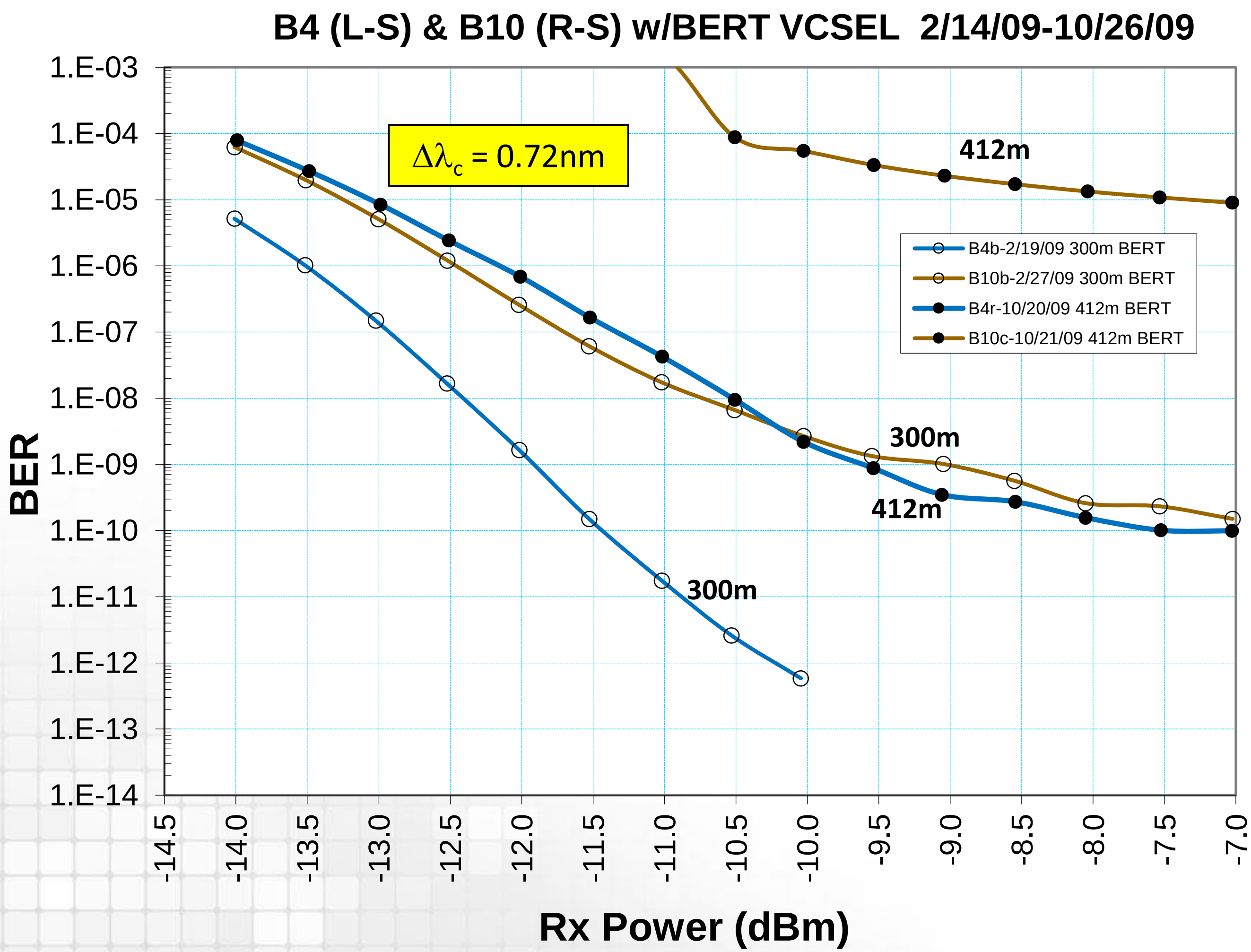
BERT Transmitter (spectral width 0.45nm)



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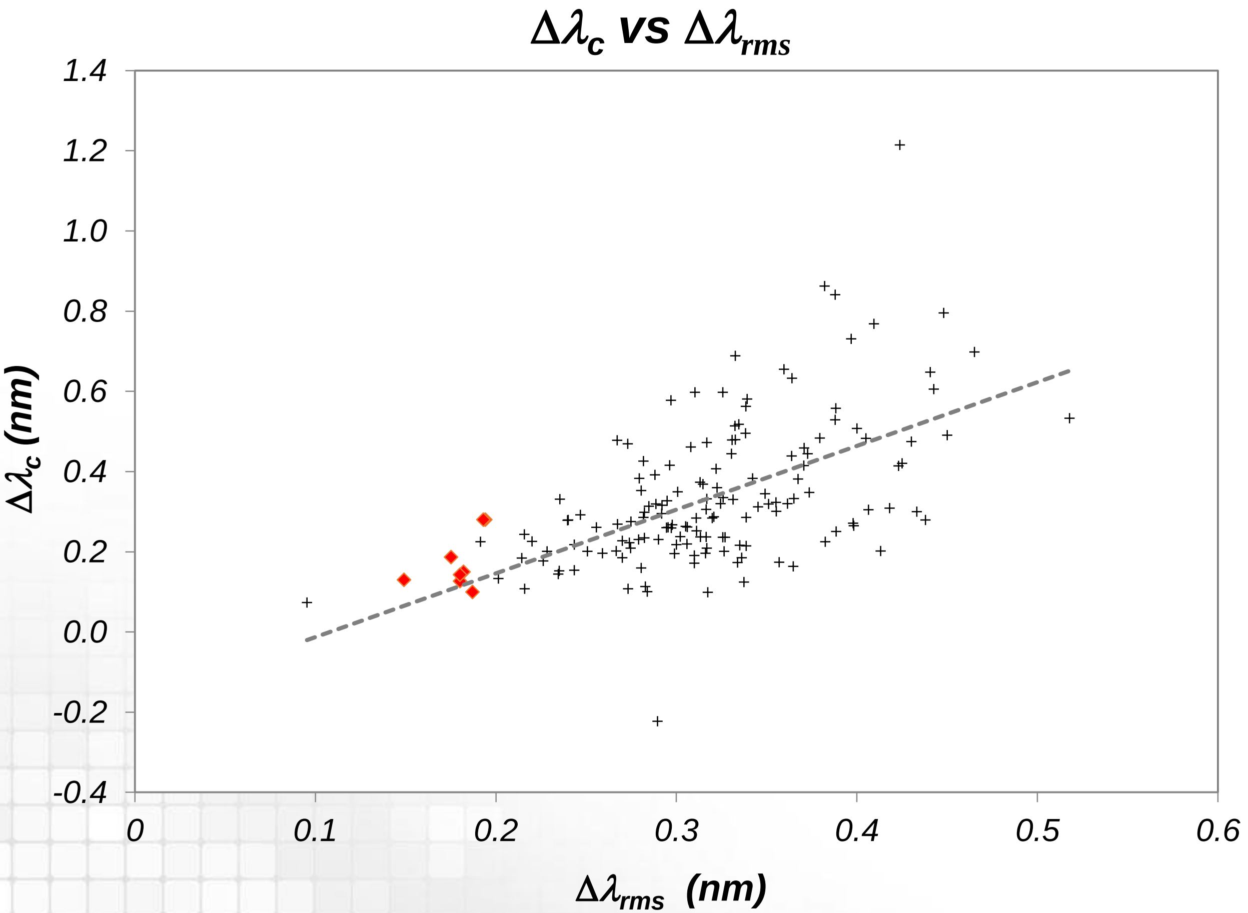
Correlation Between $\Delta\lambda_c$ and $\Delta\lambda$ 136 Transceivers (+2 eSR4s)



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Conclusions

- Process variation in the fabrication of MMF refractive index profiles result in MMFs with optimized bandwidth at different wavelengths.

- Current OM3/OM4 standard test methods do not estimate EMB for wavelengths longer than 850nm.

- OM3/OM4 reaches for wavelength longer than 860 nm need to consider worst-case standard compliant fiber.
  - OM3/OM4 fibers can be L-MMF or R-MMF which has significant impact on performance. [4]
  - R-MMF has reduced bandwidth and produce higher levels of noise in equalized channels
- Current channel link models do not include the modal-chromatic interaction
  - Results in lower bandwidth and larger MPN penalty

- Channel Reach for a multi-wavelength PMD requires further study and must be based on worst-case variation in refractive index profile.

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References

1. R. Pimpinella, B. Kose, and J. Castro, "Wavelength Dependence of Effective Modal Bandwidth in OM3 and OM4 Fiber and Optimizing Multimode Fiber for Multi-Wavelength Transmission," Proceedings of the 63rd IWCS, 2014.
2. J. Castro, R . Pimpinella, B. Kose, and B. Lane ,"Mode Partition Noise and Modal-Chromatic Dispersion Interaction Effects on Random Jitter," J. Lightw. Technol., vol.31, no. 15, August 2013
3. J. Castro, R . Pimpinella, B. Kose, and B. Lane ,"Advances in characterization of the VCSEL mode partition noise penalty in optical fiber channels," OFC 2014, Th2A.13.pdf
4. J. Castro, R. Pimpinella, B. Kose, B. Lane, "Investigation of the Interaction of Modal and Chromatic Dispersion in VCSEL-MMF Channels," J. Lightw. Technol., vol. 30, no. 15, August 2012
5. R. Pimpinella, J. Castro, B. Kose, and B. Lane, "Dispersion compensating Multimode Fiber," Proceedings 60th IWCS, 2011.

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BACKUP

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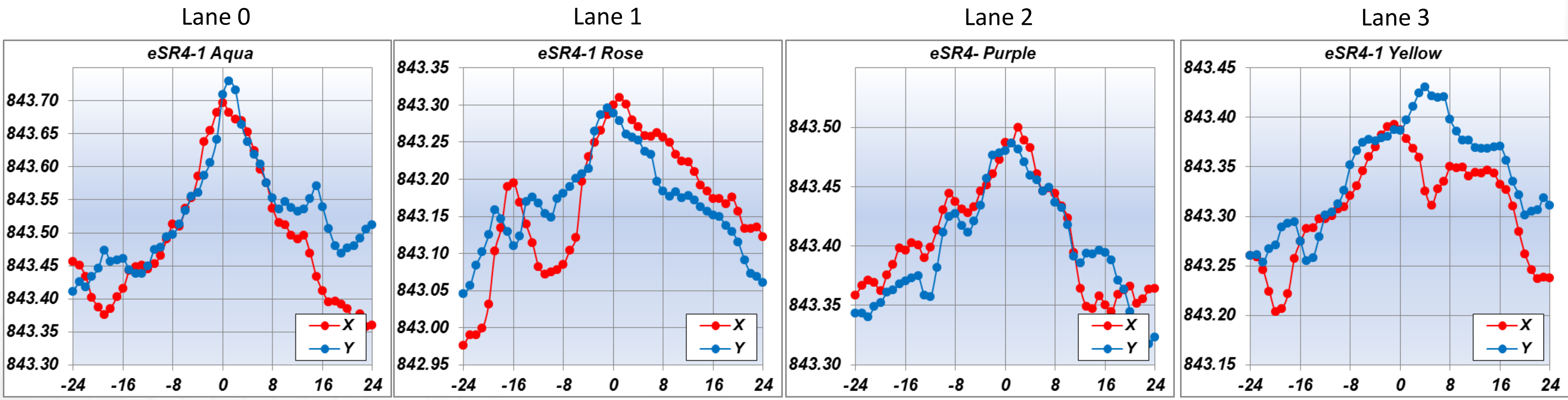
eSR4 VCSEL Mode Coupling, $\Delta\lambda_c$

(T = 23 ^{0}C)

Diffractive Optics

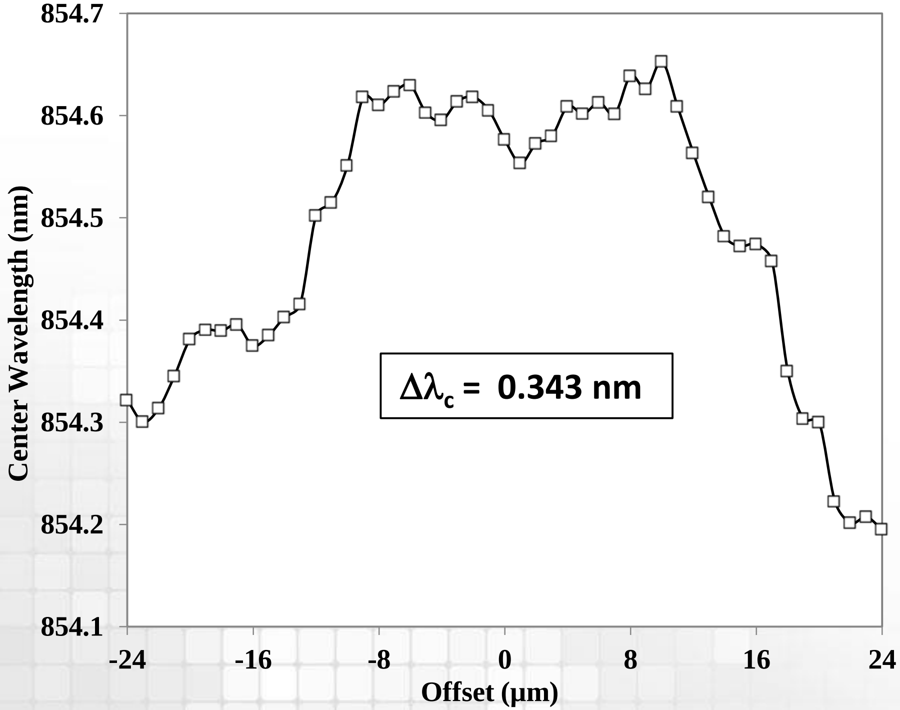


Dual Wavelength 40Gbps BiDi Transceiver

20Gbps per Wavelength

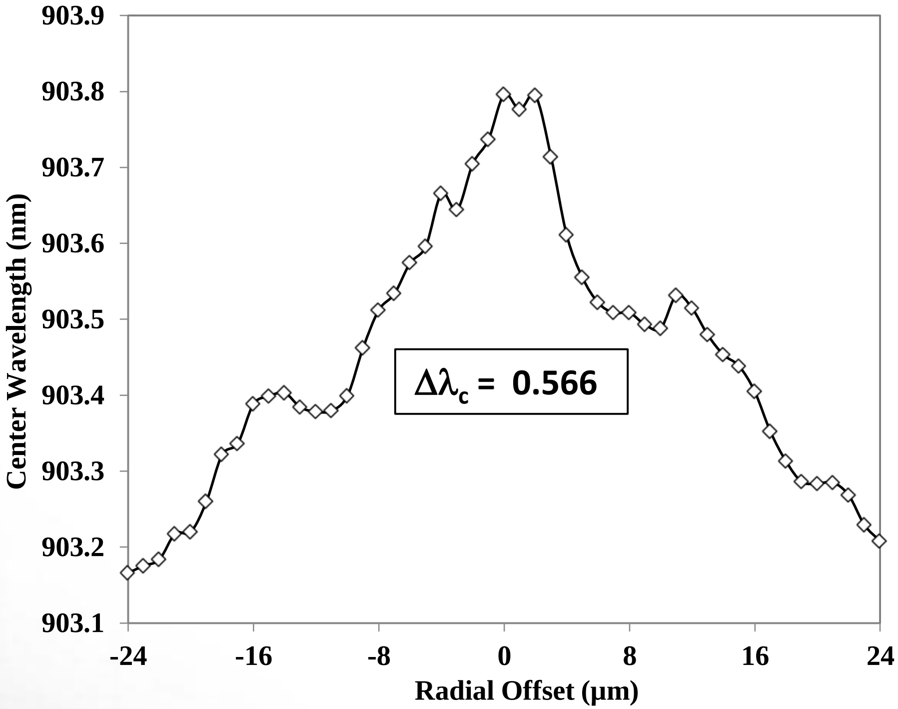
Short Wavelength 855 nm Spectral Bias

Mean Δλ = 0.42 nm



Long Wavelength 904 nm Spectral Bias

Mean Δλ = 0.43 nm



Panduit's Channel Simulation

Models Peak EMB & Reach for Multi-wavelength Channels