

Channel Performance – 2 vs 4 Wavelengths

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Panduit Labs, Panduit Corp.*

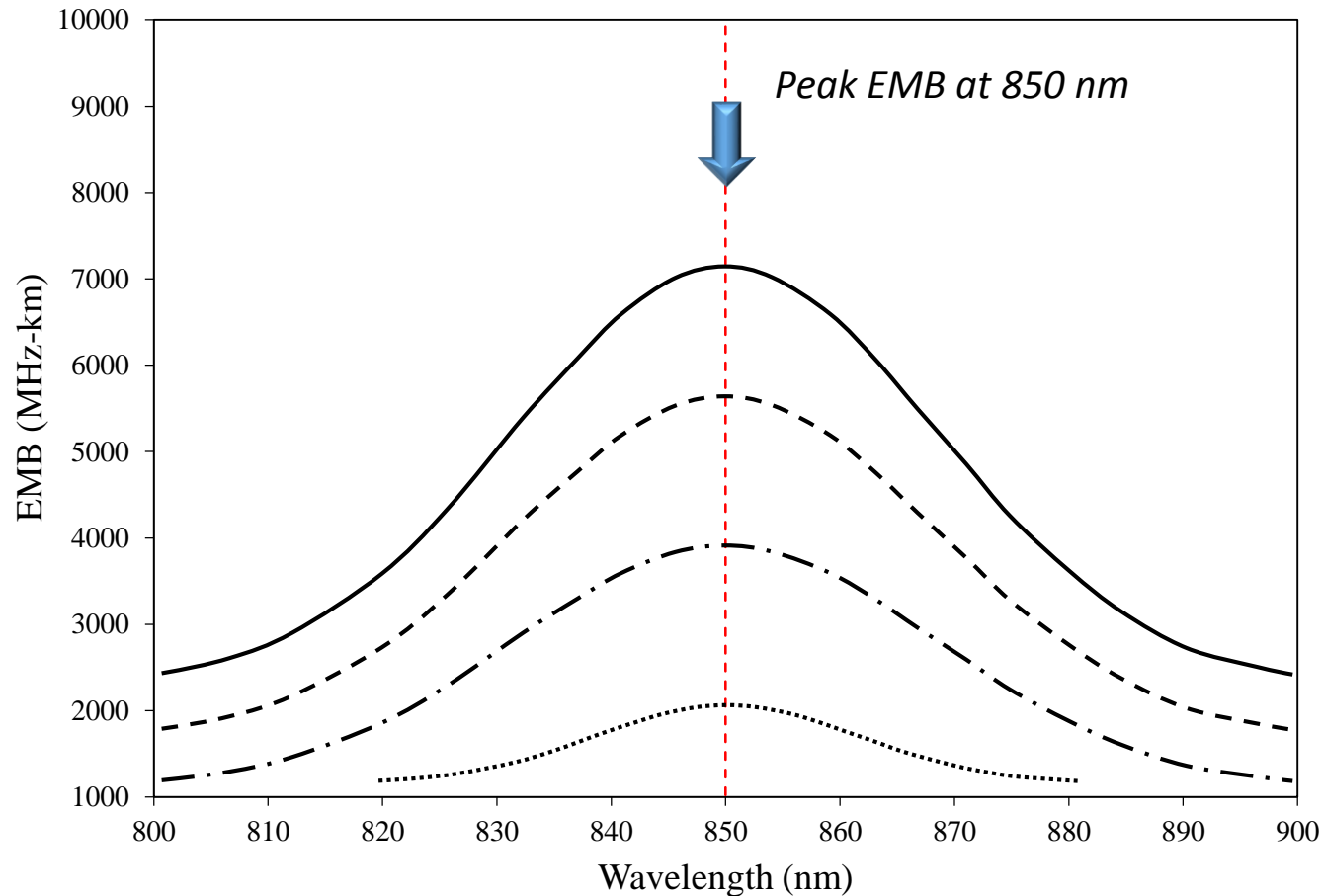
Supporters: Steve Swanson, John Abbott, Corning

NGMMF Study Group

Next-gen 200 & 400 Gb/s PHYs over Fewer MMF Pairs
Geneva, January 2018

Widespread Misunderstanding of Multimode Fiber Bandwidth

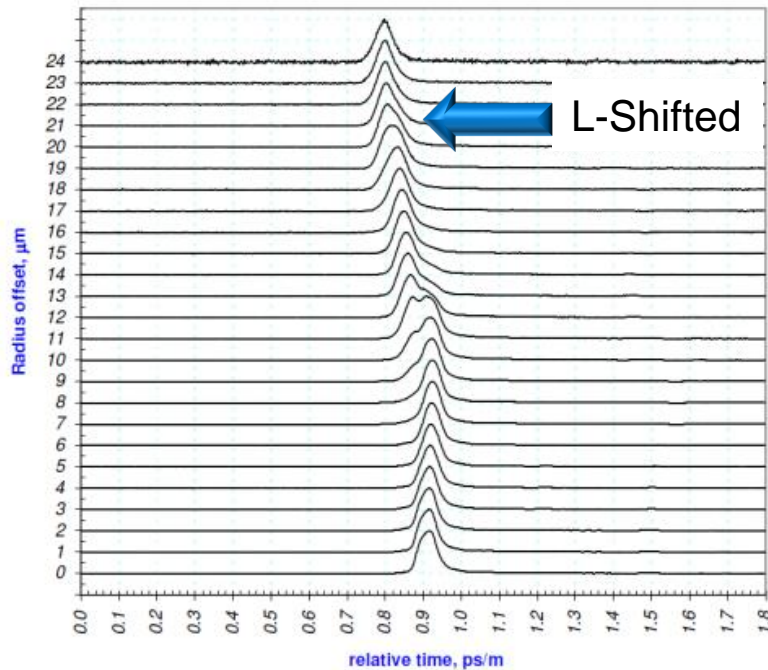
- *Peak EMB is at 850 nm and falls off symmetrically around 850 nm*
- *Reduction in EMB is due to refractive index profile defects*



DMD Plots for two fibers with same bandwidth @ 850 nm

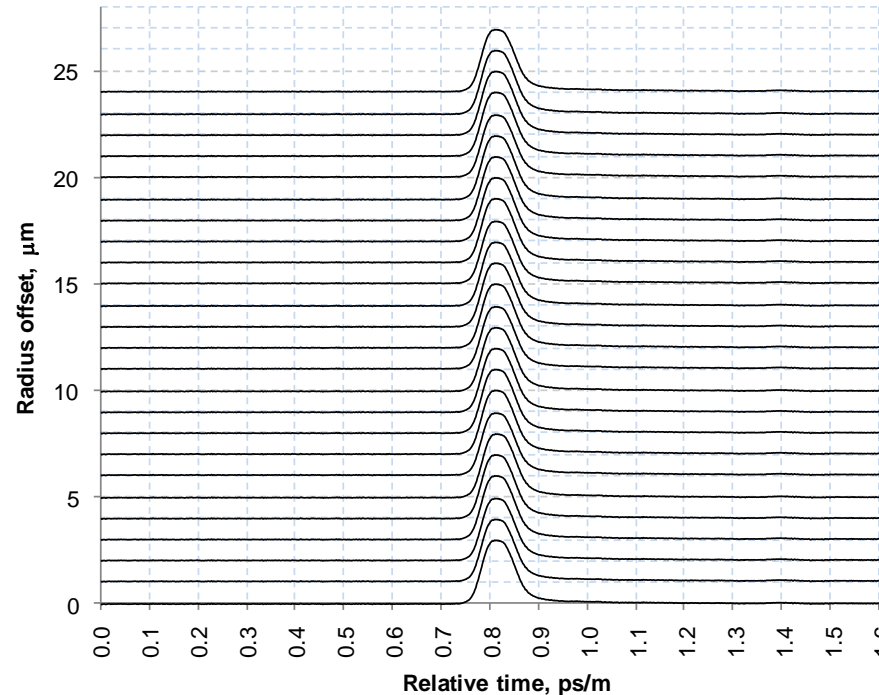
- Two fibers from same cable with the same EMB (similar DMD)
 - $L = 548 \text{ m}$
 - Ti:Sapphire Laser - DMD

C26_Blue

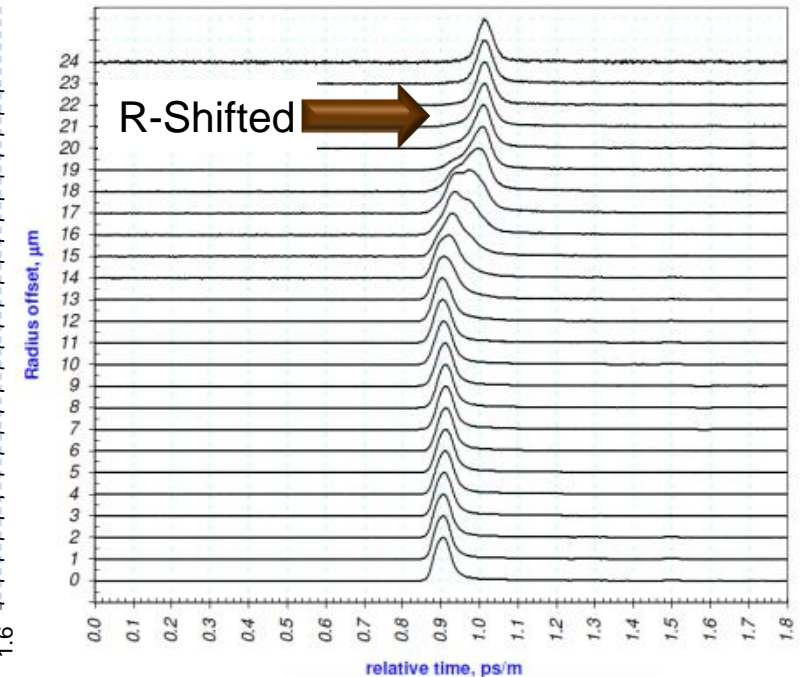


Blue Fiber
 EMB = 4540 MHz·km
 DMD_{inner} = 0.12 ps/m
 DMD_{outer} = 0.15 ps/m
 DMD_{sliding} = 0.11 ps/m
 DMD P-Shift = -0.098 ps/m

As Designed

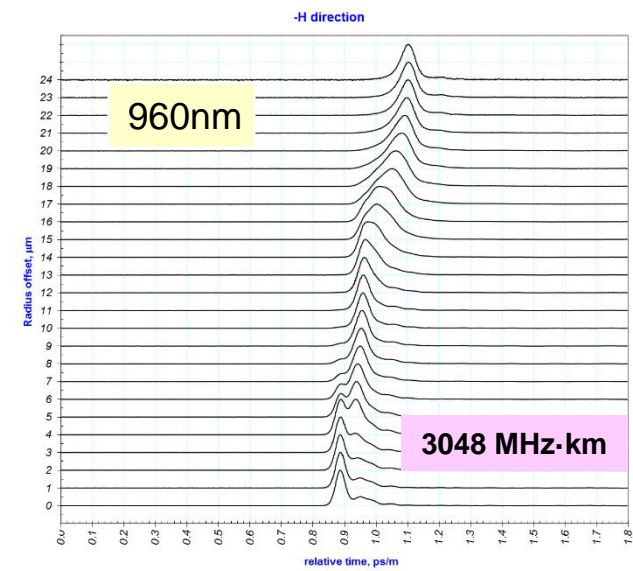
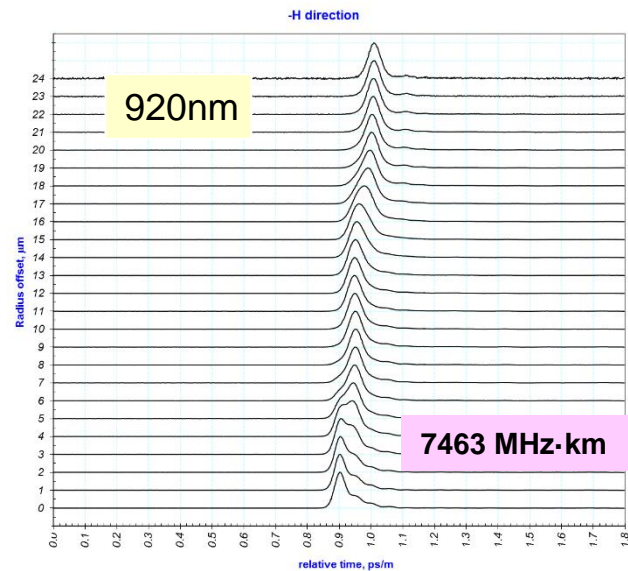
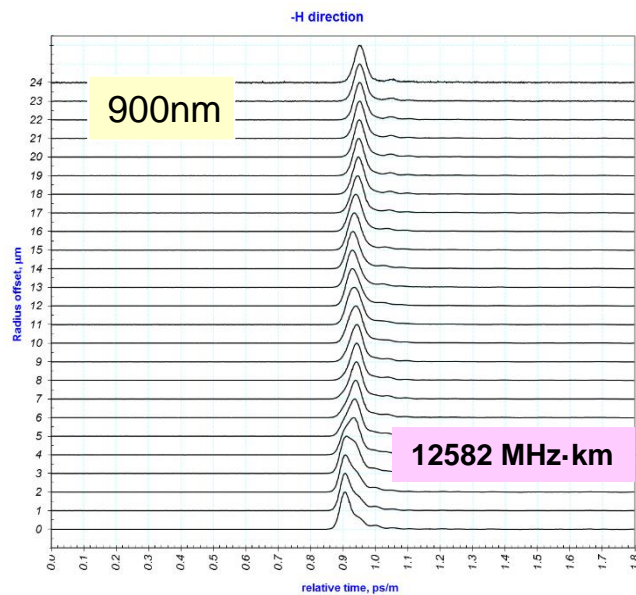
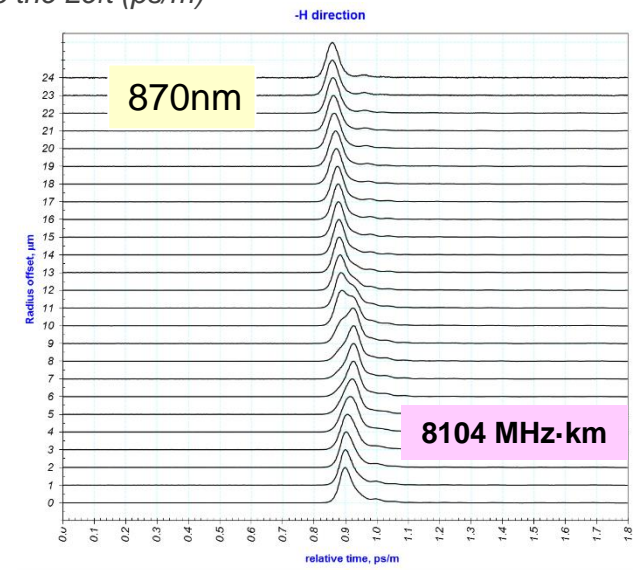
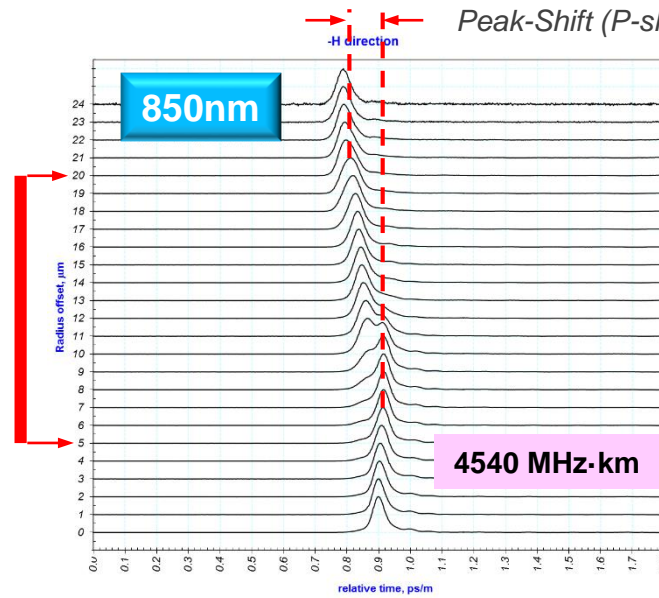
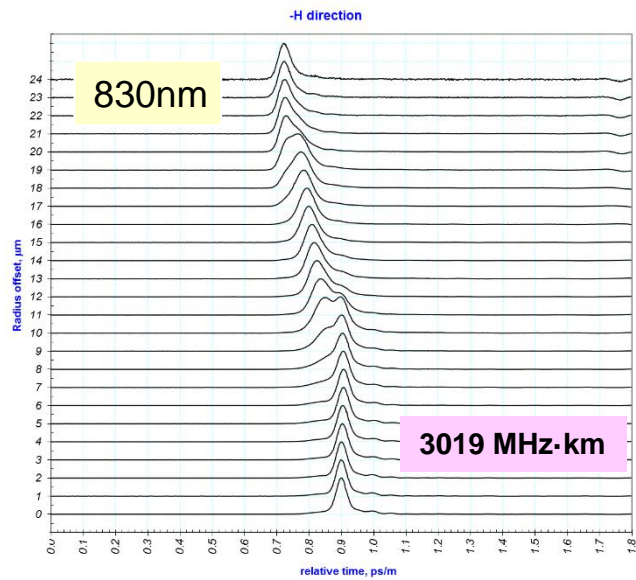


C26_Brown

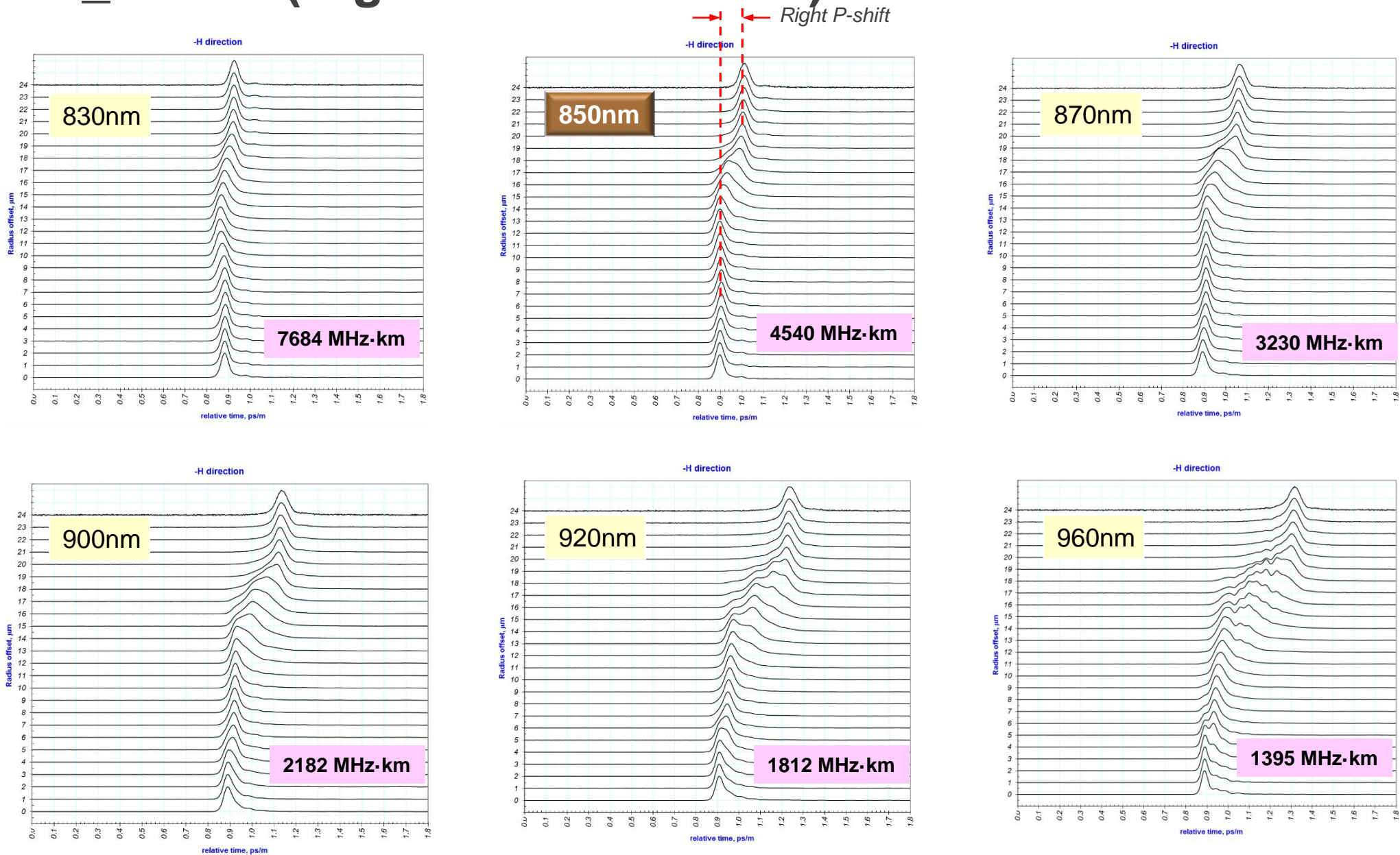


Brown Fiber
 EMB = 4540 MHz·km
 DMD_{inner} = 0.12 ps/m
 DMD_{outer} = 0.13 ps/m
 DMD_{sliding} = 0.13 ps/m
 DMD P-Shift = +0.096 ps/m

Fiber C26_Blue (OM3 Left-shifted at 850 nm)

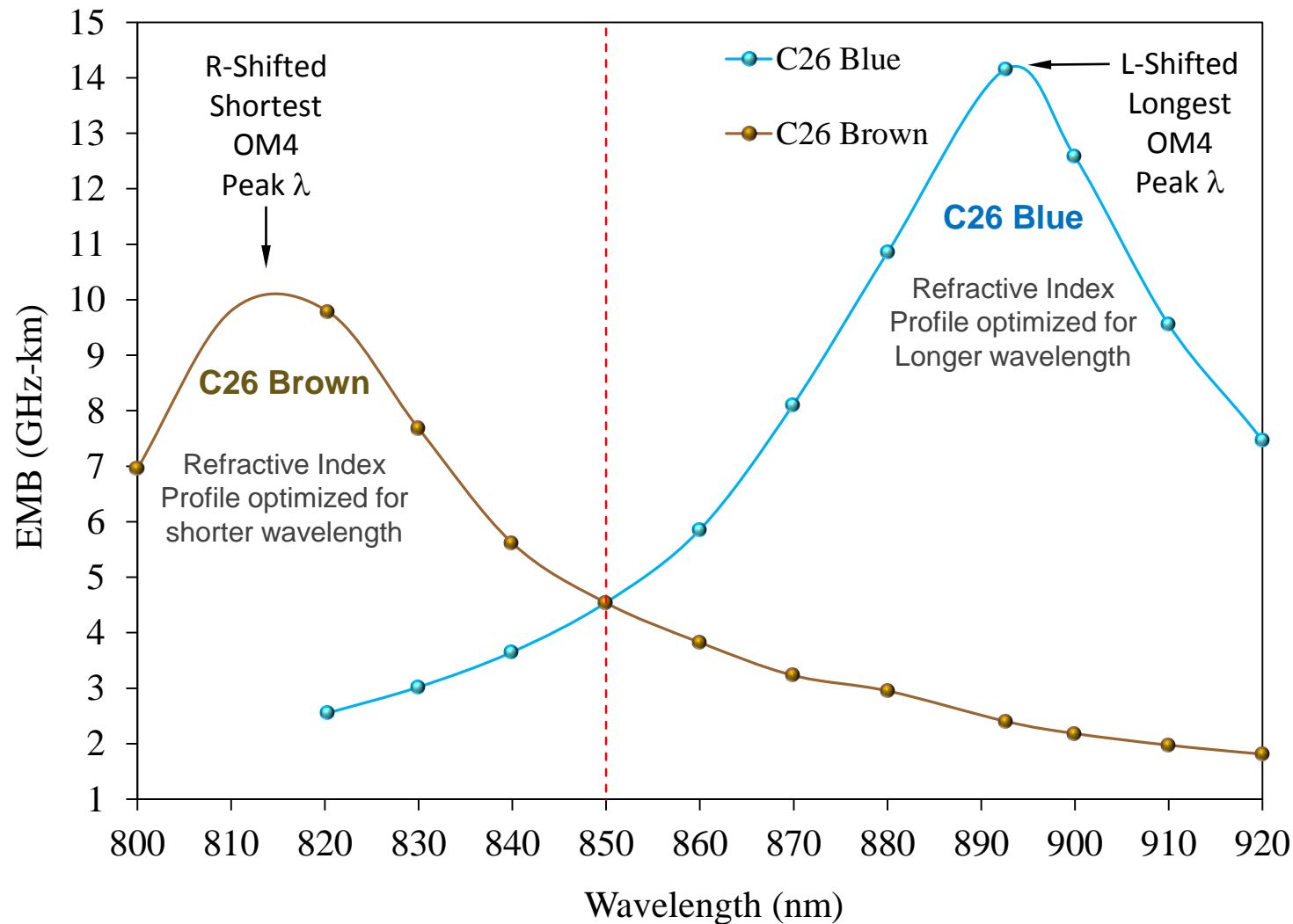


Fiber C26_Brown (Right-shifted 850 nm)



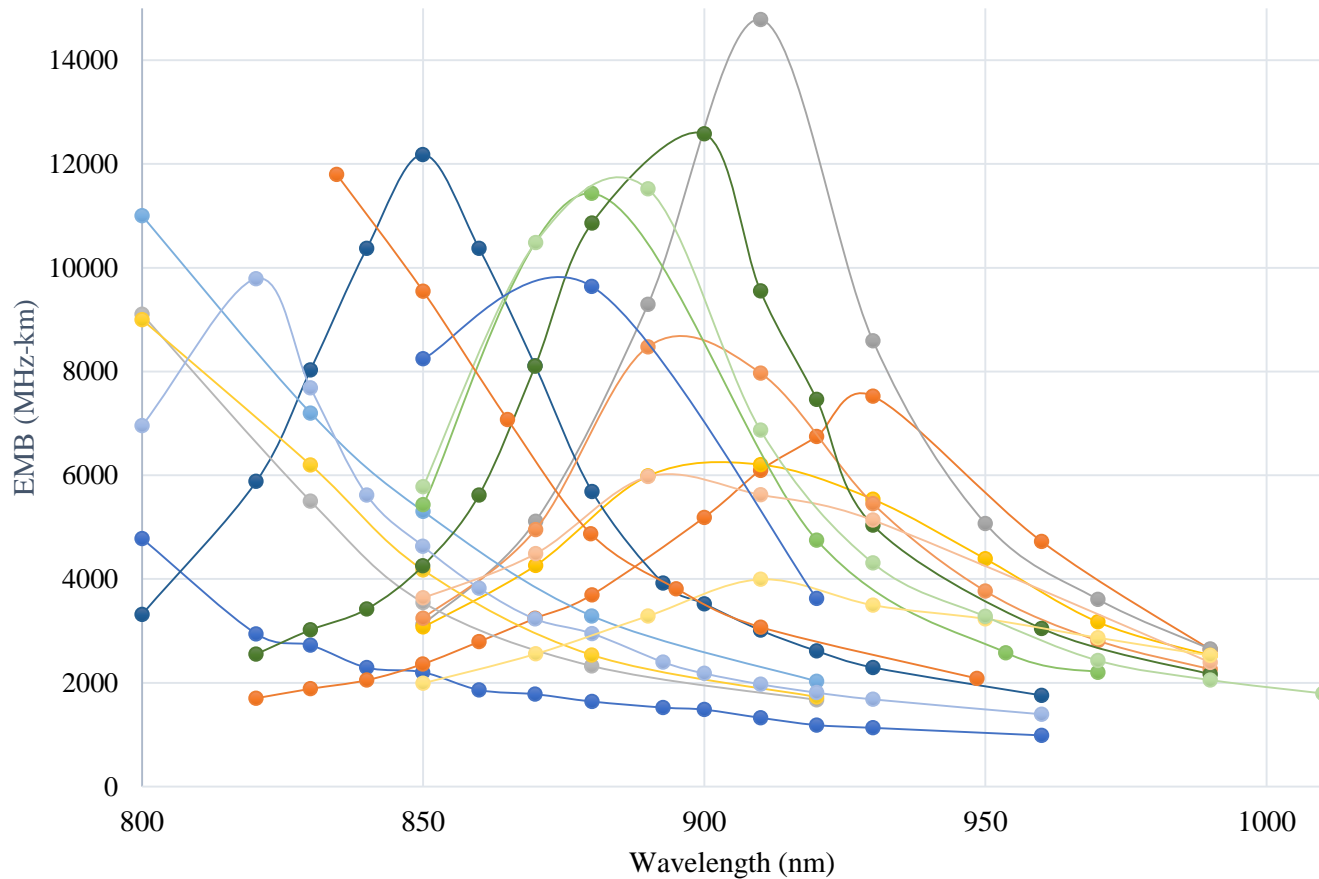
Range of EMB peak wavelengths for OM4 fibers

EMB wavelength dependence – Supplier C, same cable

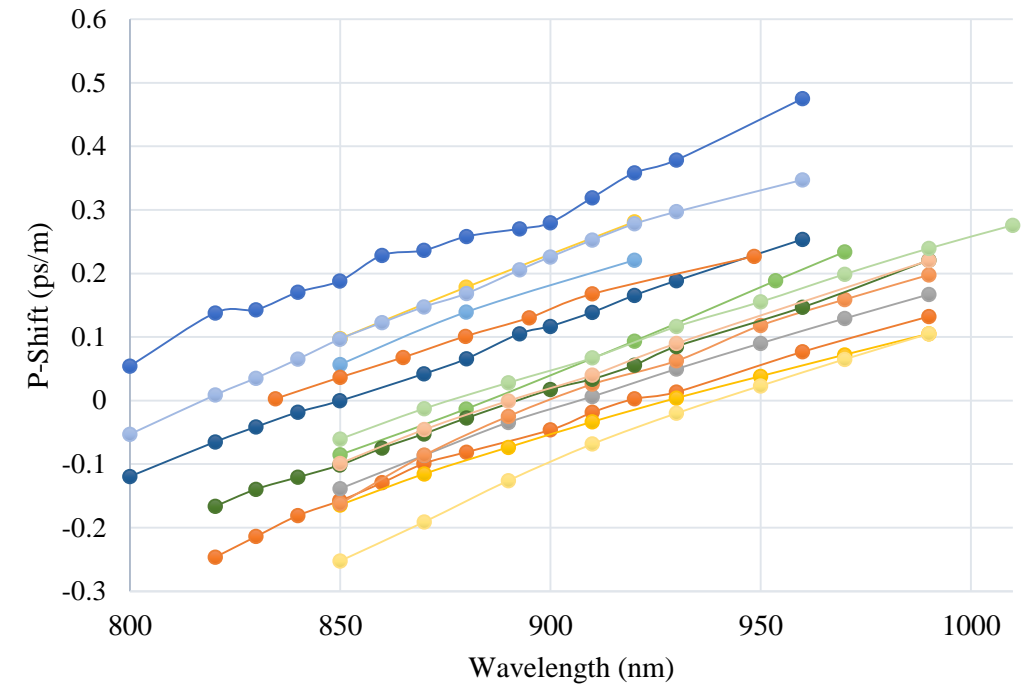


EMB Wavelength dependence & its relationship to P-shift [1]

Measured EMBs for OM3 and OM4 Fibers



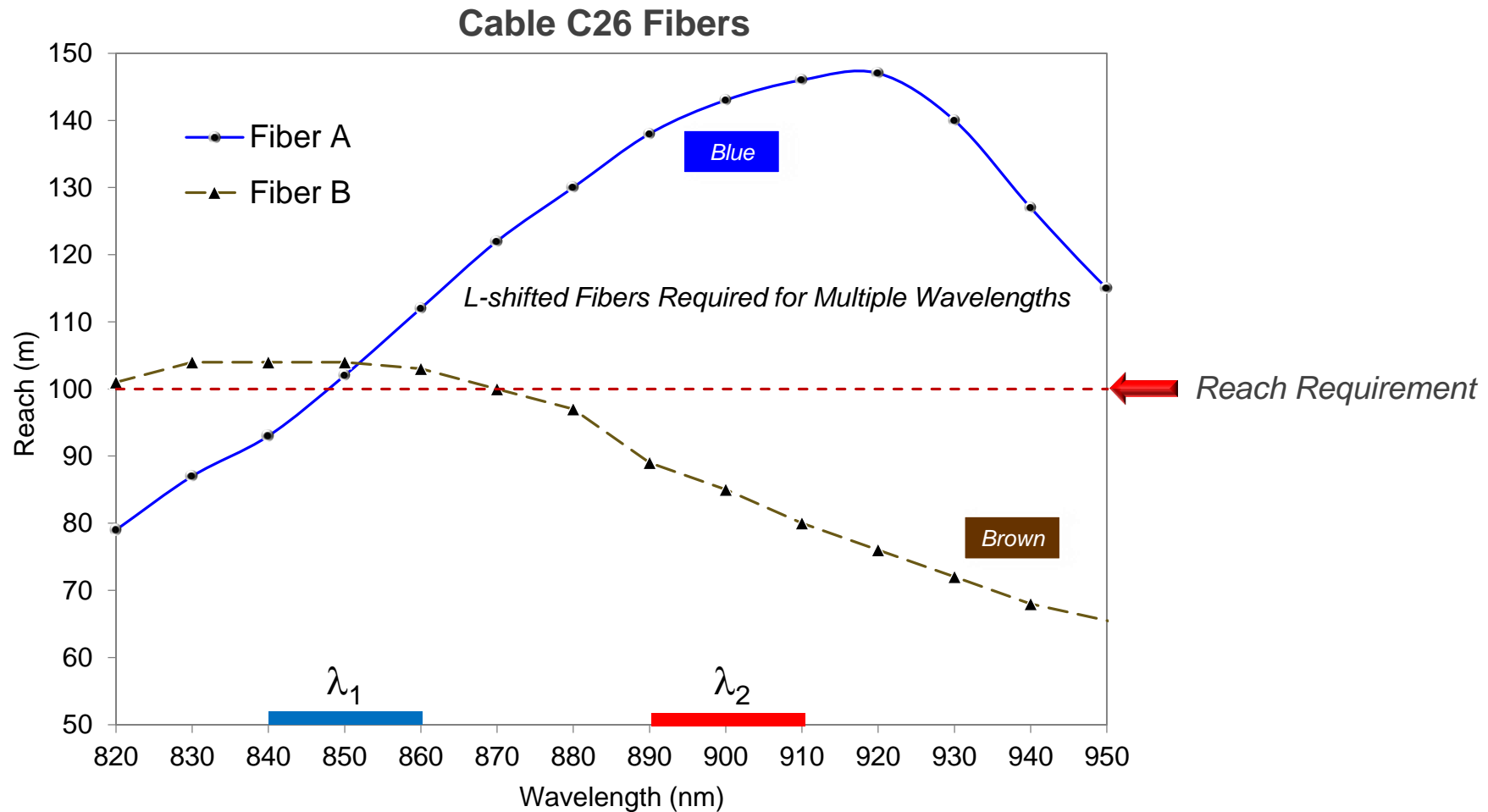
Measured P-Shifts for OM3 and OM4 Fibers



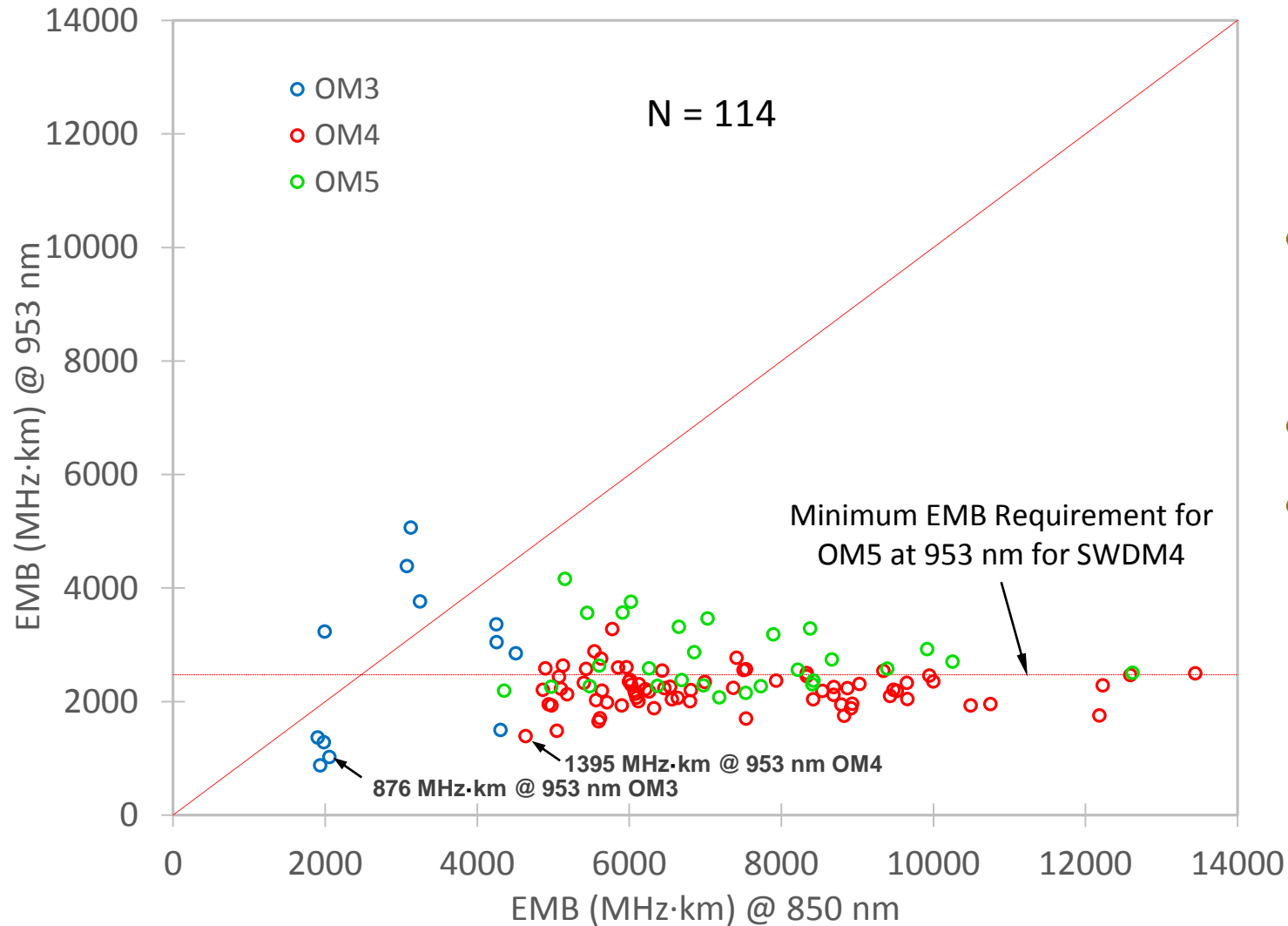
P-Shift varies linearly with wavelength

1. "Characterizing Differential Mode Delay Tilt and its Relationship to the Effective Modal Bandwidth of multimode Fibers as a Function of Wavelength," Asher Novick, Bulent Kose, Jose M. Castro, Rick Pimpinella, Paul (Yu) Huang, Alexander Berian, and Brett Lane, Proceedings of the 66th IWCS 2017

IEEE Link Model Calculated Channel Reach For Cisco's 40G BiDi Using Measured EMB Wavelength Dependence



Measured EMB at 850 nm & 953 nm for 114 OM3, OM4, & OM5 Fibers from 4 Major Manufacturers



- Minimum measured EMB @ 953 nm
 - 1395 MHz·km for OM4
 - 876 MHz·km for OM3
- Theoretically verified
- To be published, OFC March 2018

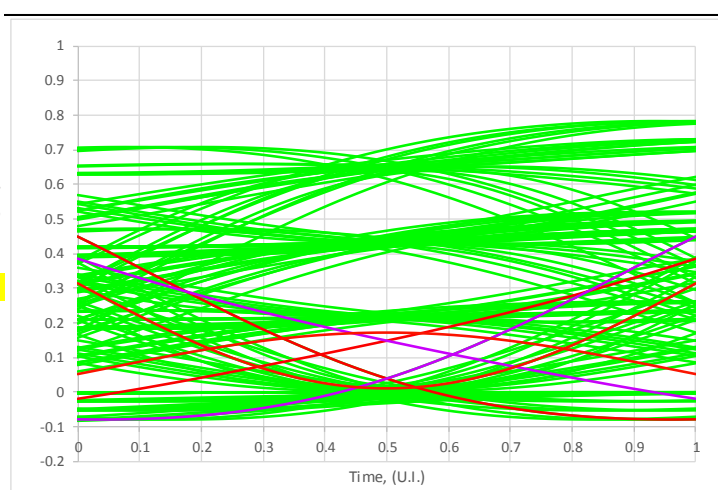
Worst-case modal bandwidths for OM3 and OM4 at 953 nm

- Panduit's model predicts 1% worst-case bandwidth to be 975 MHz·km for OM3 and 1500 MHz·km for OM4
- Corning's model predicts 1033 MHz·km worst case bandwidth for OM3 and 1459 MHz·km for OM4
 - Differences: 5.6% and 2.8% for OM3 and OM4 respectively
- Recommendation is to select worst-case EMB from both models, closer to measured data
 - 975 for MHz·km OM3
 - 1460 for MHz·km OM4

50G PAM4 Channel Reach for OM4 at 916 nm = 86 m

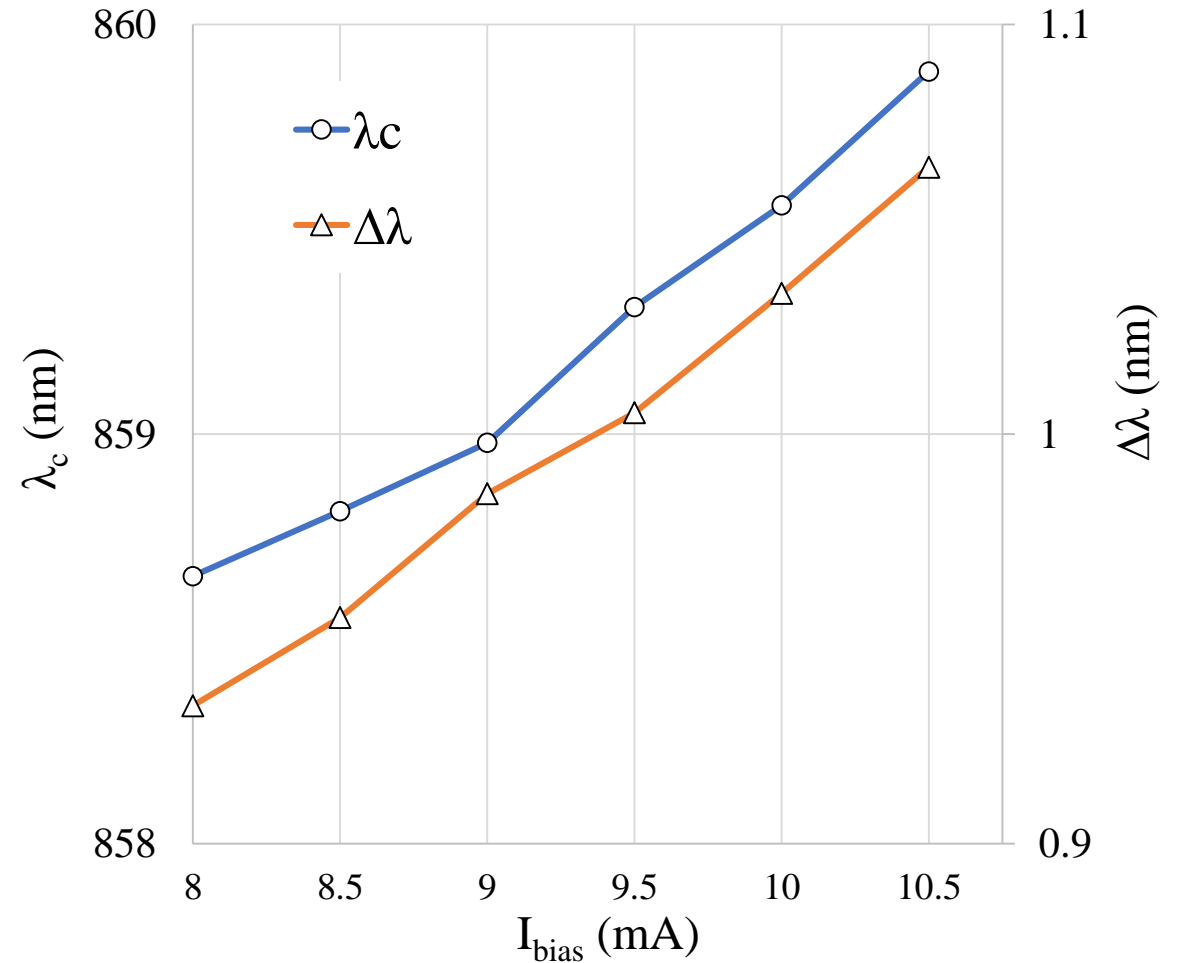
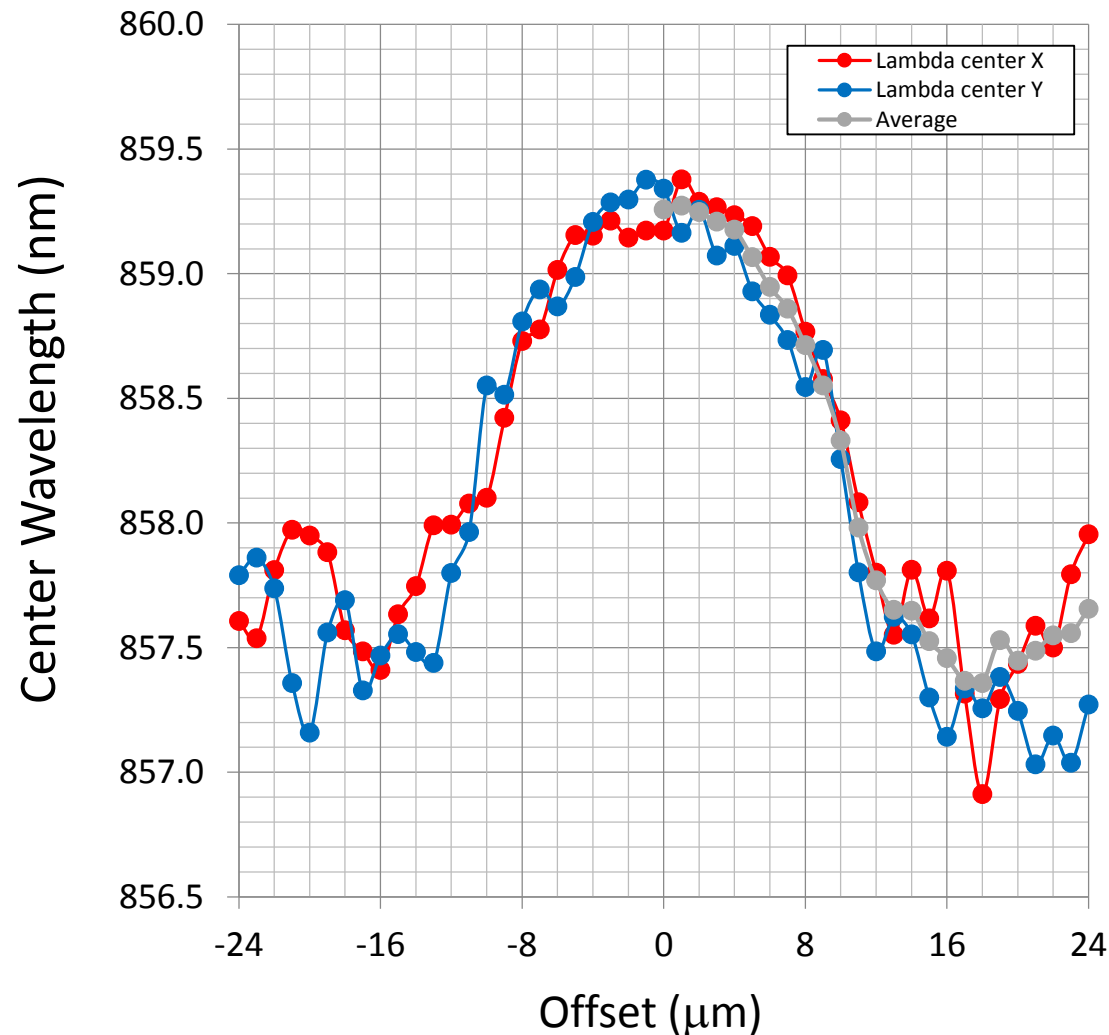
Spreadsheet by Del Hanson, David Cunningham, Piers Dawe, Modified for PAM4 by Panduit															Rev.	This file		10GEPBud3_1_16a.xls		of		17-Oct-01												
Basics															Attenuation=	3.5		dB/km		Model/format rev 3.1.16a		of		31-Oct-01										
Transmitter															Fiber	at		850 nm		NomSens OMA		-10.80		dBm		Margin		0.00		dB at				
Receiver															Refl Rx	-12		dB		Rec_BW=		18,800		MHz		Test Rx BW		21,038		MHz				
Disp. min. Uo=															1316		nm		T_rx(10-90)		17.5		ps		Test Source ER=		6.5		dB					
Disp. So=															0.1028		ps/nm ² *km		TP4 Eye		7		ps		TestERpen		1.98		dB					
Disp. D1=															-76.71		ps/(nm.km)		Opening		RMS Baseline wander SD		0.012		fraction		of 1/2 eye		V.E.C.P. #####		dBo			
Reflection Noise factor															0		no units		(not in use)		BWm=		2100		MHz*km		P_BLW(no ISI)		0.01		dB			
Effective Rate															29526		MBd		Tb_eff=		34		ps		P_BLW		0.01		dB		Stressed			
Effective Rec Eye															0.21		UI		Eff. BWm=		2.1E+03		MHz*km		P_BLW		0.01		dB		Rx sens			
Pisi P Eye P_DJ P_DJ															central		corner		central		corner		central		corner		central		corner		central		corner	
Preflection															central		Beta		SDmpn		Pmpn		Prin		Pcross		Ptotal		<Ptotal		LP Pen		Margin	
Ptotal															central		corner		central		corner		central		corner		central		corner		central		corner	
LP Pen															central		corner		central		corner		central		corner		central		corner		central		corner	
Margin															central		corner		central		corner		central		corner		central		corner		central		corner	
OMA															central		corner		central		corner		central		corner		central		corner		central		corner	
0.002	0.006	1.0057	-0.15	9E-05	2031344	1E+06	30.364	35.046	1.83	0.9	1.295	0.41	0	-0.009	2E-05	0	0.342317	0.0340217	3.568	3.98	3.56185	3.23	-4.429											
0.066	0.189	1.1894	-5.06	0.003	61555.9	31818	34.787	38.941	2.78	0.8	1.67	0.42	0	-0.282	0.0162	0.01	0.46655	0.0700601	5.246	5.67	5.05617	1.55	-4.766											
0.068	0.195	1.1951	-5.22	0.003	59745.4	30882	35.041	39.168	2.84	0.7	1.695	0.42	0	-0.29	0.0171	0.01	0.481097	0.0740667	5.362	5.79	5.16733	1.44	-4.789											
0.07	0.201	1.2009	-5.37	0.003	58038.4	30000	35.301	39.4	2.91	0.7	1.722	0.42	0	-0.299	0.0181	0.01	0.4972	0.0785389	5.486	5.91	5.28469	1.31	-4.815											
0.072	0.207	1.2066	-5.52	0.003	56426.2	29167	35.566	39.638	2.98	0.7	1.749	0.43	0	-0.307	0.0191	0.01	0.515046	0.083546	5.615	6.04	5.40869	1.18	-4.842											
0.074	0.212	1.2123	-5.68	0.003	54901.2	28378	35.837	39.881	3.06	0.7	1.778	0.43	0	-0.316	0.0201	0.02	0.534856	0.0891716	5.752	6.18	5.53979	1.05	-4.872											
0.076	0.218	1.2181	-5.83	0.003	53456.4	27632	36.113	40.129	3.14	0.7	1.809	0.43	0	-0.324	0.0212	0.02	0.556887	0.0955164	5.897	6.32	5.67854	0.9	-4.905											
0.078	0.224	1.2238	-5.98	0.003	52085.7	26923	36.394	40.383	3.22	0.6	1.84	0.43	0	-0.333	0.0222	0.02	0.581442	0.1027037	6.049	6.48	5.82556	0.75	-4.94											
0.08	0.23	1.2295	-6.14	0.003	50783.6	26250	36.68	40.641	3.3	0.6	1.873	0.43	0	-0.341	0.0233	0.02	0.60888	0.1108847	6.211	6.64	5.98156	0.59	-4.98											
0.082	0.235	1.2353	-6.29	0.004	49545	25610	36.971	40.904	3.39	0.6	1.907	0.43	0	-0.35	0.0244	0.02	0.639632	0.120248	6.383	6.81	6.14739	0.42	-5.023											
0.084	0.241	1.241	-6.44	0.004	48365.3	25000	37.267	41.172	3.49	0.6	1.943	0.43	0	-0.358	0.0256	0.03	0.674214	0.1310305	6.565	7	6.32405	0.23	-5.071											
0.086	0.247	1.2468	-6.6	0.004	47240.6	24419	37.568	41.444	3.58	0.5	1.98	0.43	0	-0.367	0.0267	0.03	0.713256	0.1435342	6.759	7.19	6.51272	0.04	-5.124											
0.088	0.252	1.2525	-6.75	0.004	46166.9	23864	37.874	41.721	3.68	0.5	2.019	0.44	0	-0.376	0.0279	0.03	0.757526	0.1581496	6.967	7.4	6.71484	-0.17	-5.184											
0.09	0.258	1.2582	-6.9	0.004	45141	23333	38.184	42.003	3.79	0.5	2.06	0.44	0	-0.384	0.0291	0.03	0.80798	0.1753904	7.19	7.63	6.93219	-0.39	-5.252											
0.092	0.264	1.264	-7.06	0.004	44159.7	22826	38.498	42.289	3.9	0.4	2.103	0.44	0	-0.393	0.0303	0.04	0.865817	0.1959446	7.431	7.87	7.16698	-0.63	-5.329											
0.094	0.27	1.2697	-7.21	0.004	43220.1	22340	38.816	42.579	4.02	0.4	2.147	0.44	0	-0.401	0.0315	0.04	0.932558	0.2207555	7.692	8.13	7.42202	-0.89	-5.416											
0.096	0.275	1.2755	-7.36	0.004	42319.7	21875	39.139	42.873	4.14	0.4	2.194	0.44	0	-0.41	0.0328	0.04	1.010174	0.2511502	7.976	8.42	7.701	-1.18	-5.518											
0.098	0.281	1.2812	-7.52	0.004	41456	21429	39.466	43.172	4.27	0.3	2.242	0.45	0	-0.418	0.034	0.05	1.101259	0.2890554	8.29	8.74	8.00886	-1.49	-5.637											
0.1	0.287	1.2869	-7.67	0.004	40626.9	21000	39.797	43.474	4.4	0.3	2.293	0.45	0	-0.427	0.0353	0.05	1.209307	0.3373775	8.639	9.09	8.35245	-1.84	-5.779											
0.104	0.30	1.30	-8.0	0.00	39,064	#####	40	44	4.42	###	2.30	0.45	0	-0.44	0.04	0.06	1.23	0.35	8.7	9.2	8.4	-1.9	-5.8											

Equalizer	1	(0) No Equalizer, (1) FFE 3 Taps, (2) FFE 5 Taps
M	4	
B1=	2.563	no units
D2	0.0432	ps/(nm.km)
Geo mean R	0.0631	linear units
Spec extinction ratio	1.99	linear units
Spec ext. ratio penalty	3.01	linear units
Test Source ER pen.	1.98	dB
Net Ext R pen Per	2.81	dB
Min. Tx power OMA=	501	uW
Worst ave launch pwr	755.1	uW
ERF arg=	1.75	
ERF=	0.99	
ISL_TP4_Rx	0.95	
Vrin(2m test)	#####	
Vmn	1.6E-03	
T_test_rx(10-90)	15.6	
Test Tc	34.2	
Test erf arg 1b	1.02	
Test erf arg 2b	0.78	
Test closed eye	0.58	

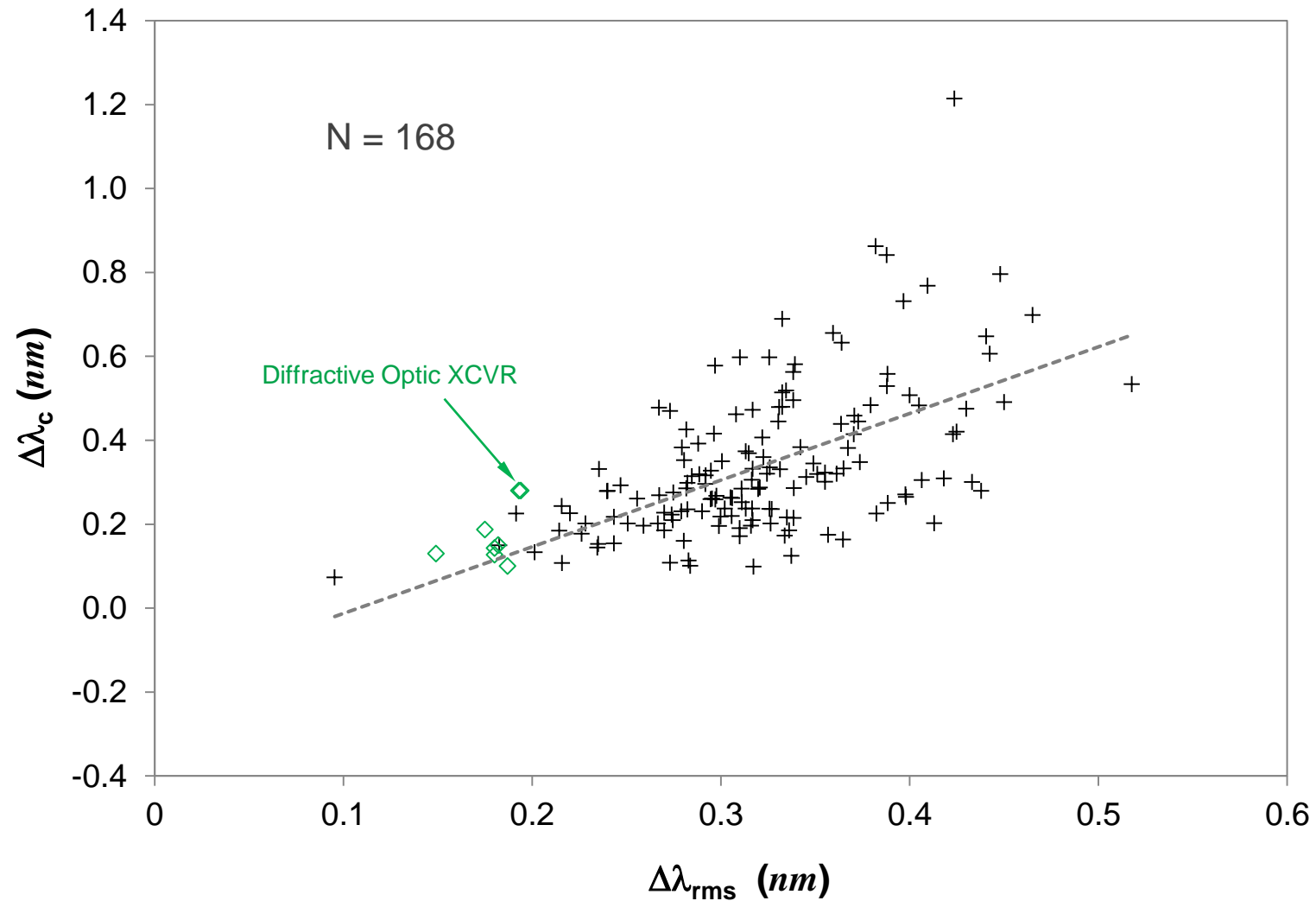


Spatial Spectral Output Distribution of a 22 GHz VCSEL

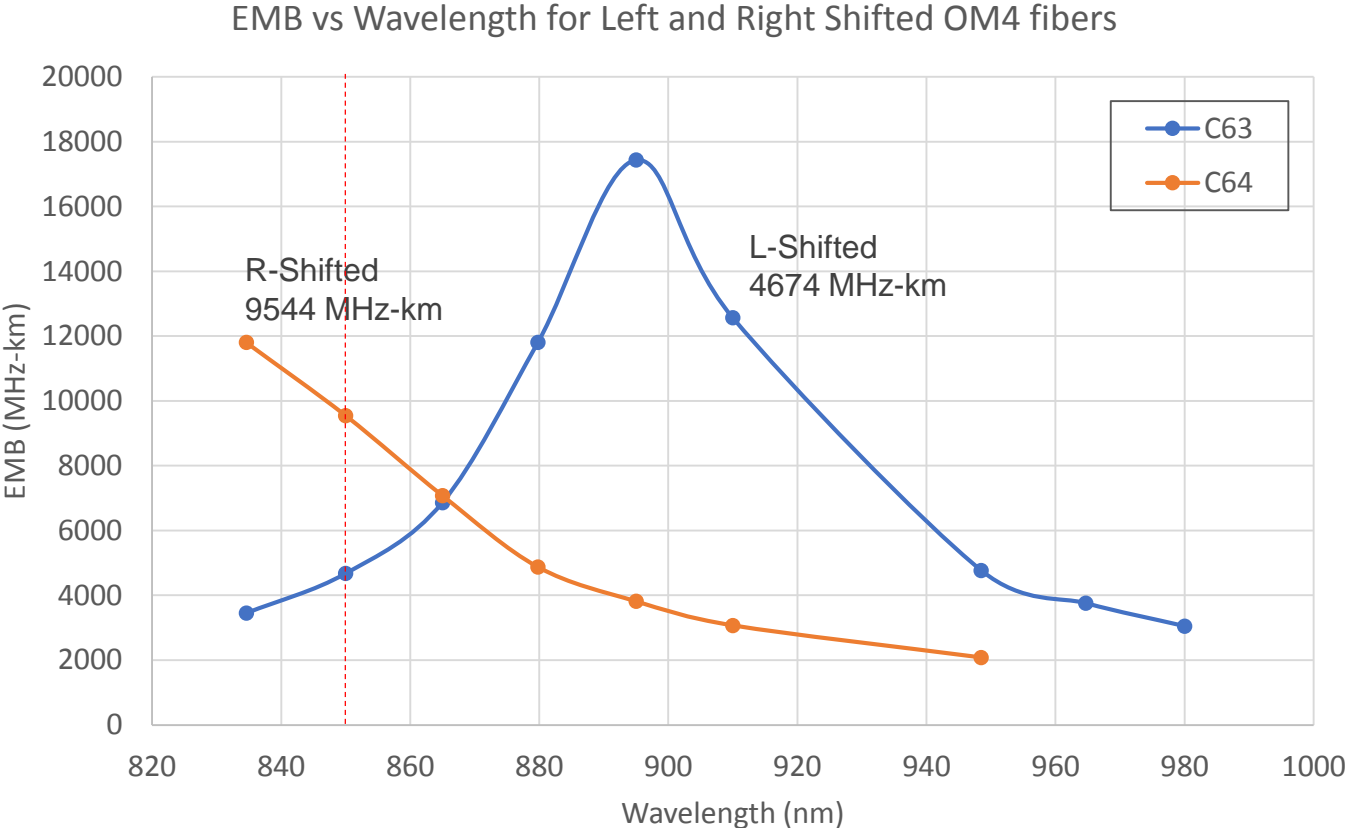
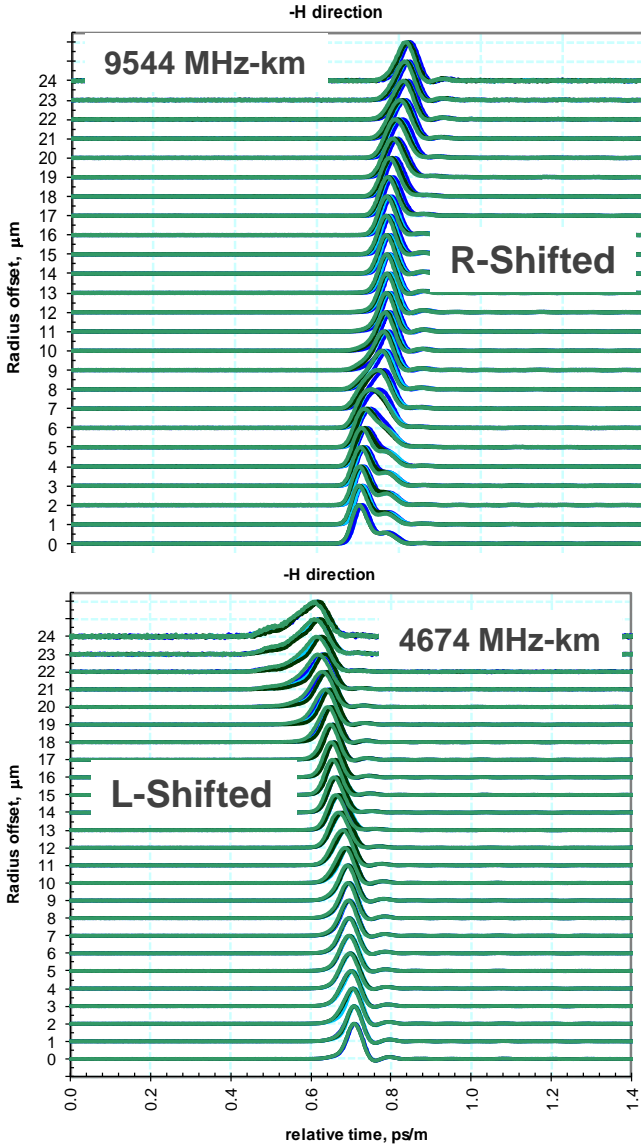
- Reach calculations do not include the modal-chromatic interaction



VCSEL Transceiver Spectral Spatial Outputs

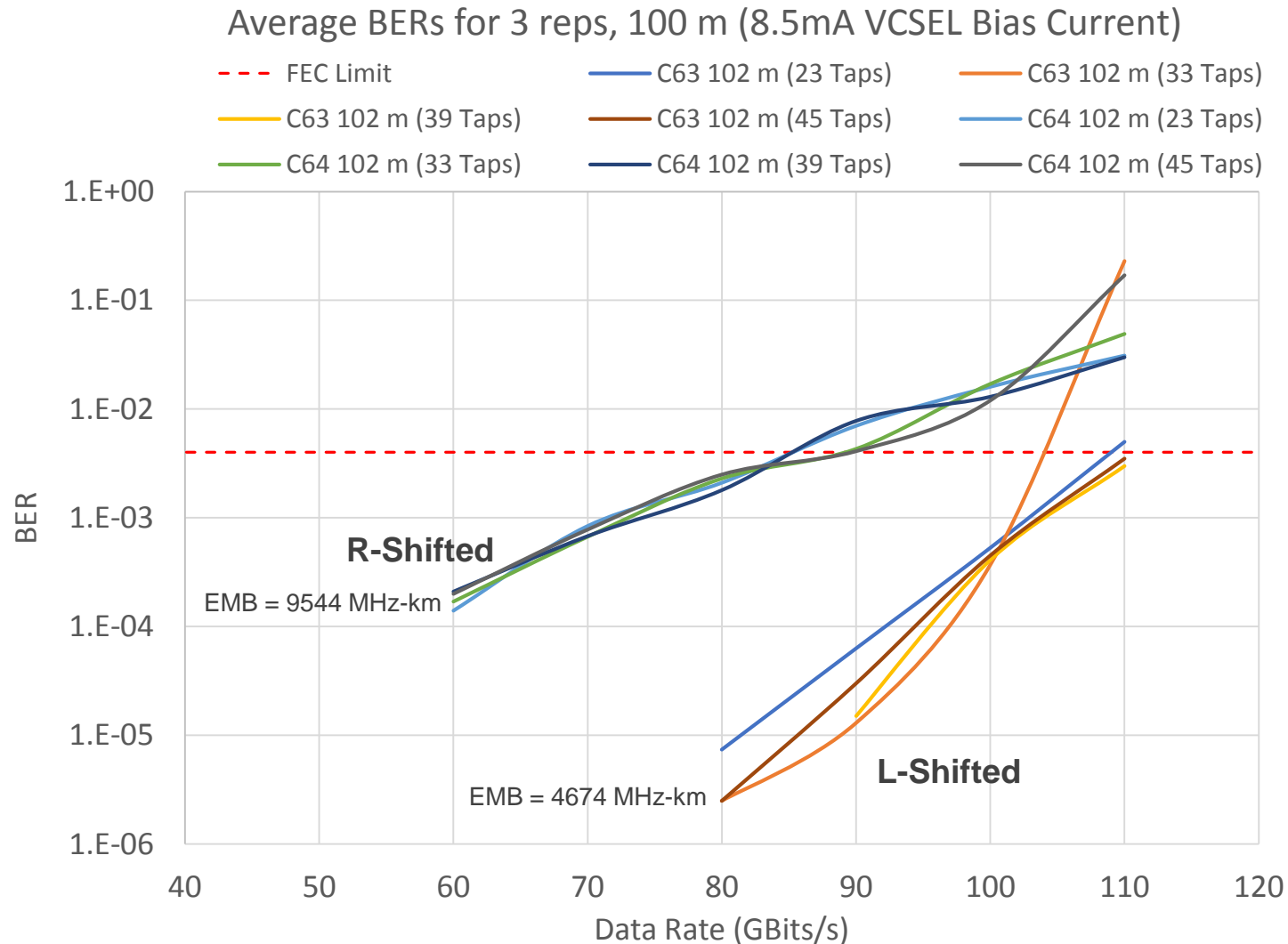


Fiber Samples: C63 L-Shifted and C64 R-Shifted



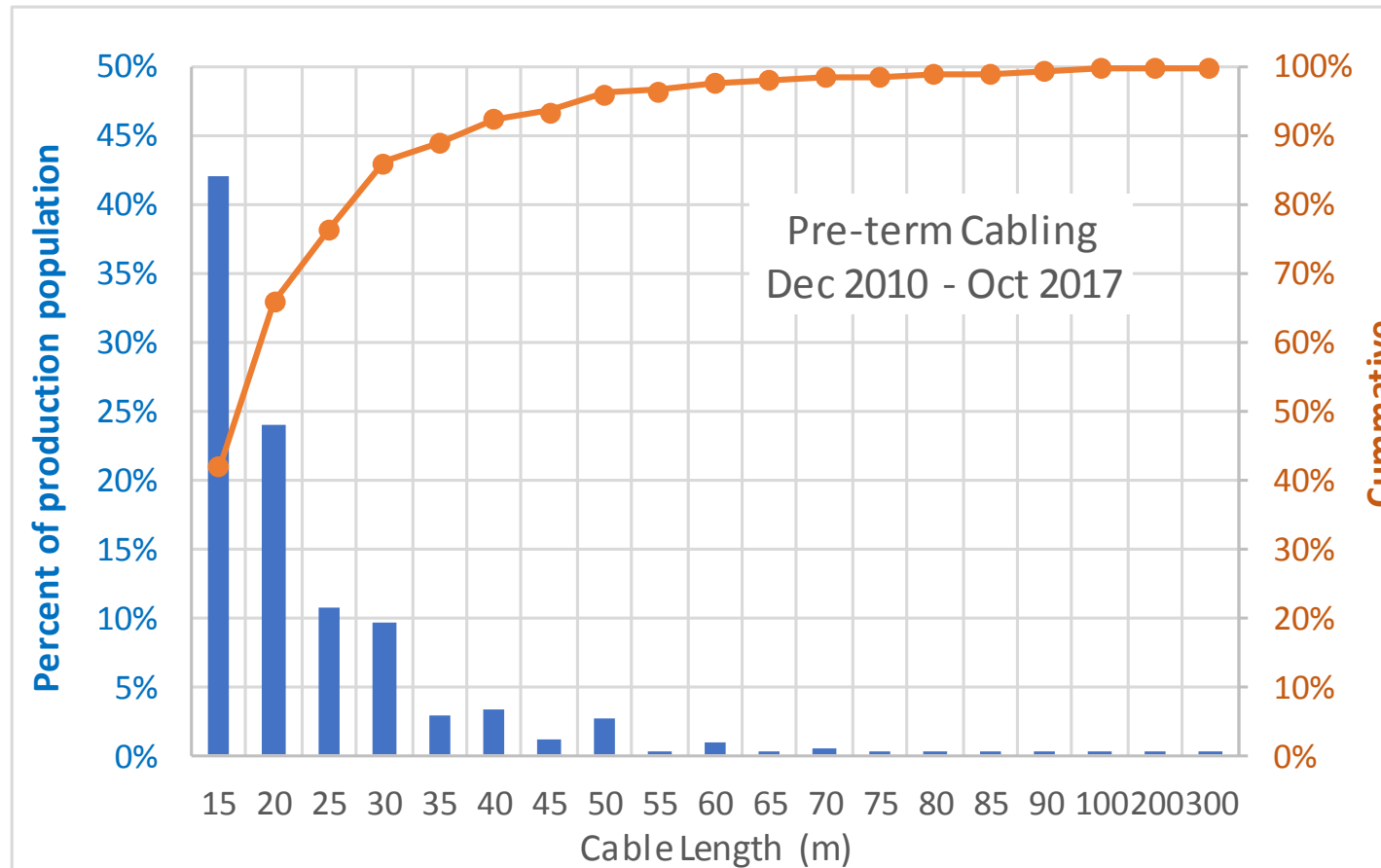
Measured BER for PAM-4 over 100 m MMF

- To be published in OFC March 2018



Data Center Structured Cabling Link Lengths

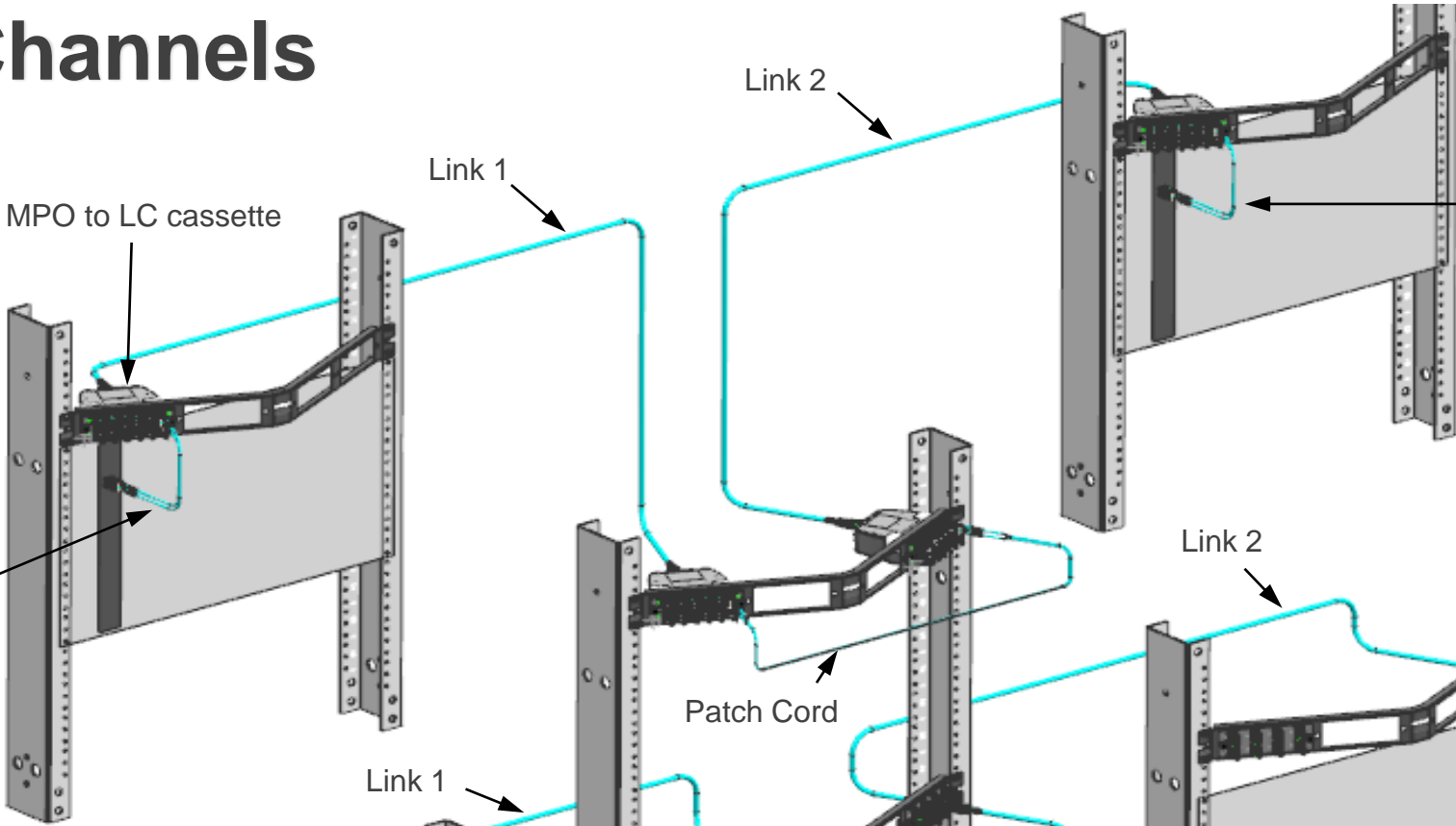
- Cable lengths shipped from Dec 2010 to Oct 2017



Double Link Channels

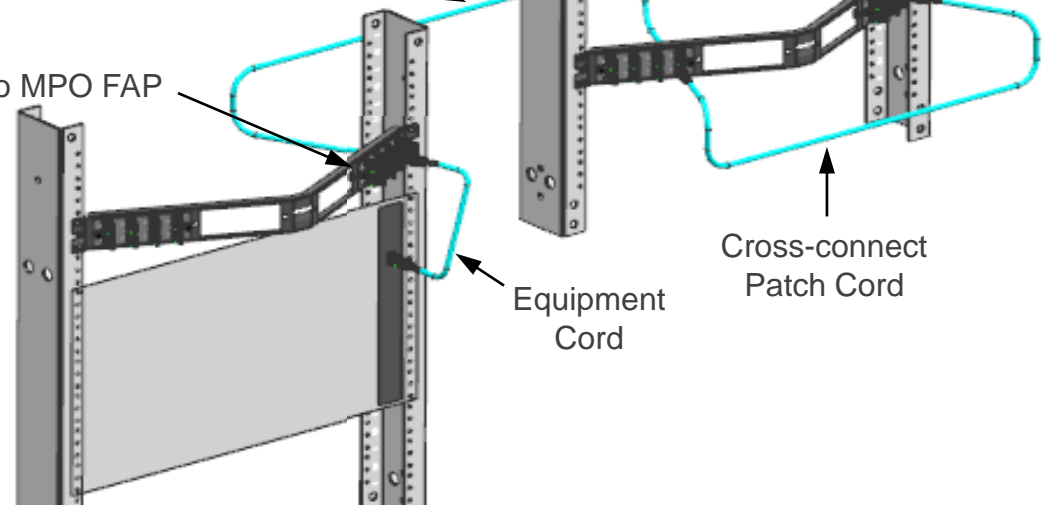
SWDM4 LC Transceivers

MPO to LC cassette
Equipment Cord



SR4 MPO Transceivers

MPO to MPO FAP
Equipment Cord



Patch Cord

Cross-connect Patch Cord

Link 2

Equipment Cord

Equipment Cord

Link 2

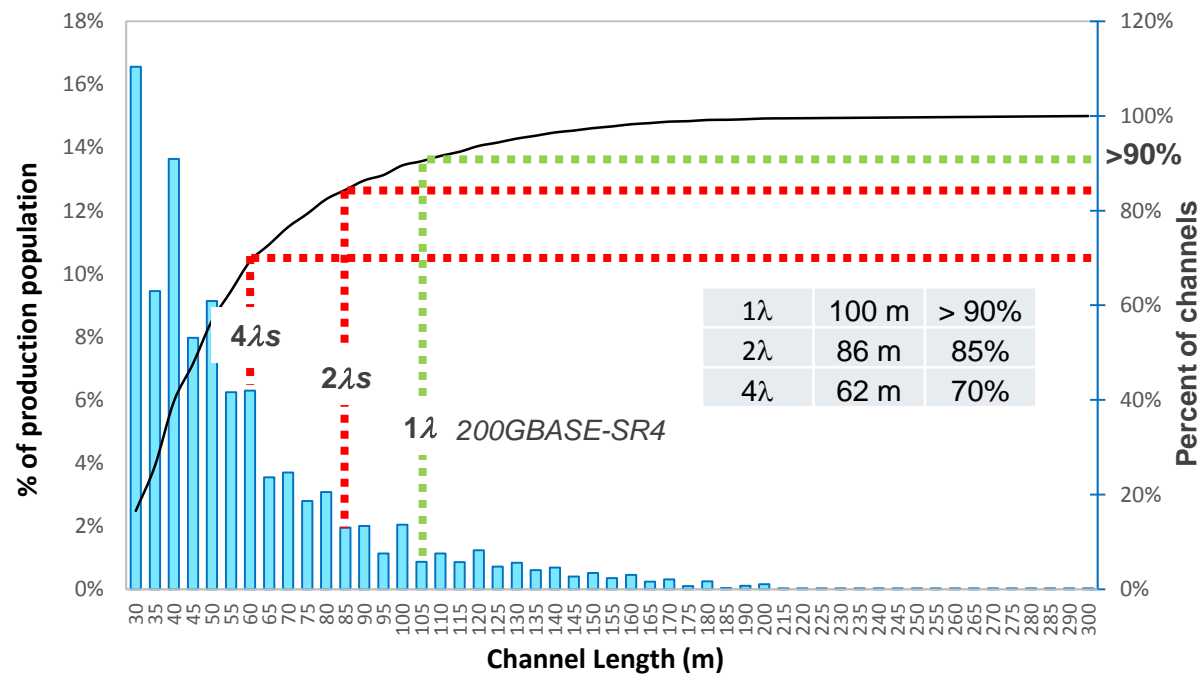
Link 1

Impact of 2λ vs 4λ on Double and Triple Link Channel Reach

- convoluted production lengths

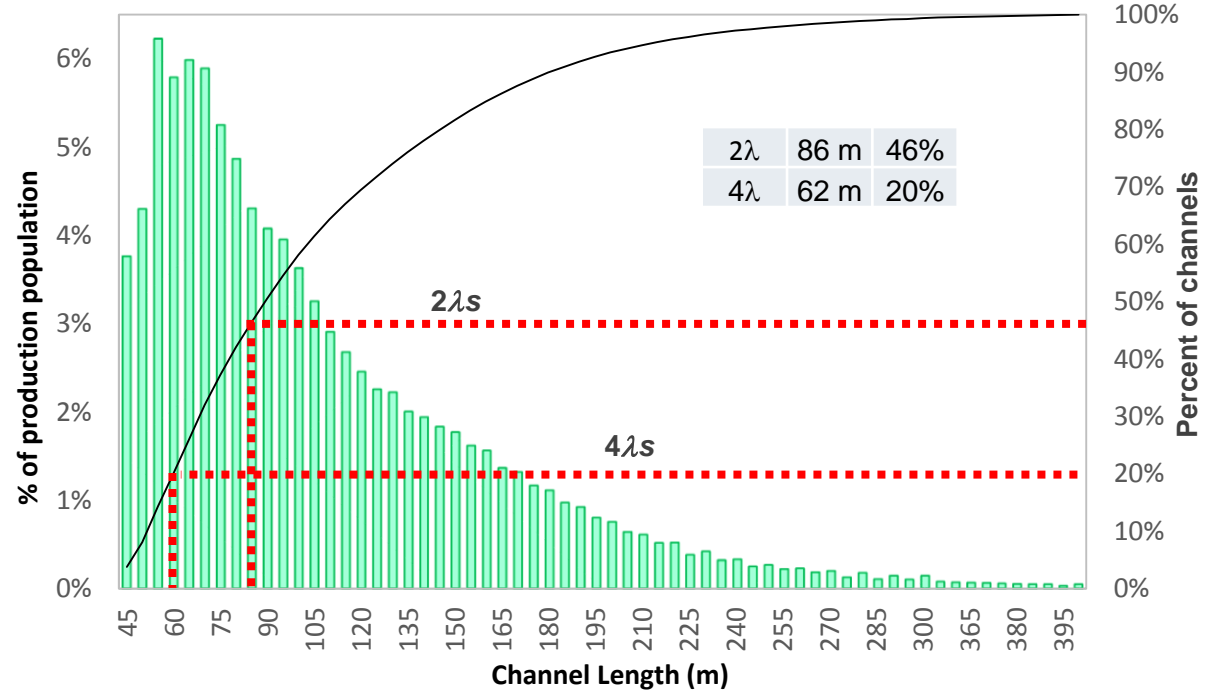
- reach calculations do not include modal-chromatic interaction

2λ s Supports 13% More Channels than 4λ s



Double Link OM4 Channels

2λ s Supports 20% More Channels than 4λ s



Triple Link OM4 Channels

Conclusions

- Performance:
 - 200GBASE-SR1.4 has no performance advantage over 200GBASE-SR4
 - Given the same 850 nm VSCEL performance, parallel optics will have longer reach
 - 200GBASE-SR1.4 will introduce uncertainty in channel reach over legacy OM3 & OM4 fibers
 - No standards for OM3 and OM4 bandwidth at longer wavelengths
 - Need to address the spatial spectral coupling of VCSEL modes into fiber modes (modal-chromatic interaction)

- Customer issues:
 - A 2nd 200G PMDs will cause customers confusion regarding upgrade paths and compatibility
 - Reach limitations at 953 nm will force customers to upgrade to more expensive OM5
 - Requiring more expensive cabling might limit broad market potential

- Recommendation:
 - The Study Group should only define objectives for a 400GBASE-SR4.2 solution
 - Specifying 2 wavelengths will provide
 - 39% greater reach than 4 wavelengths over a double link OM4 channel
 - 130% greater reach than 4 wavelengths over a triple link OM4 channel
 - 2 wavelengths more likely to maintain the current 70/100 m reach requirements over OM3/OM4