

Initial considerations for 100G VCSEL-MMF reaches

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100 Gb/s Wavelength Short Reach PHYs Study Group
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(1) PANDUIT , (2) POLITECNICO DI TORINO , (3) LINKS

The logo for Panduit, featuring the word "PANDUIT" in a bold, black, sans-serif font.

POLITECNICO
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Introduction

- **MMF channels have important cost and resilience advantages**
 - Less expensive and more power efficient transceivers based on VCSEL sources
 - Less sensitive to contamination and misalignments
- **100G per lane using VCSEL presents significant challenges**
- **An evaluation of the feasibility of short reach channels at 100 Gbps per lane is needed**
 - Feasibility of 850 nm wavelength important for compatibility
- **This presentation addresses technical feasibility for 100G MMF channels**
 - It provides preliminary modeling and experimental data for potential reaches over MMF using a 850nm VCSELs operating at 50GBaud PAM-4
 - Lengths 30 m, 50m , 100m of worst-case OM3 and OM4 are investigated

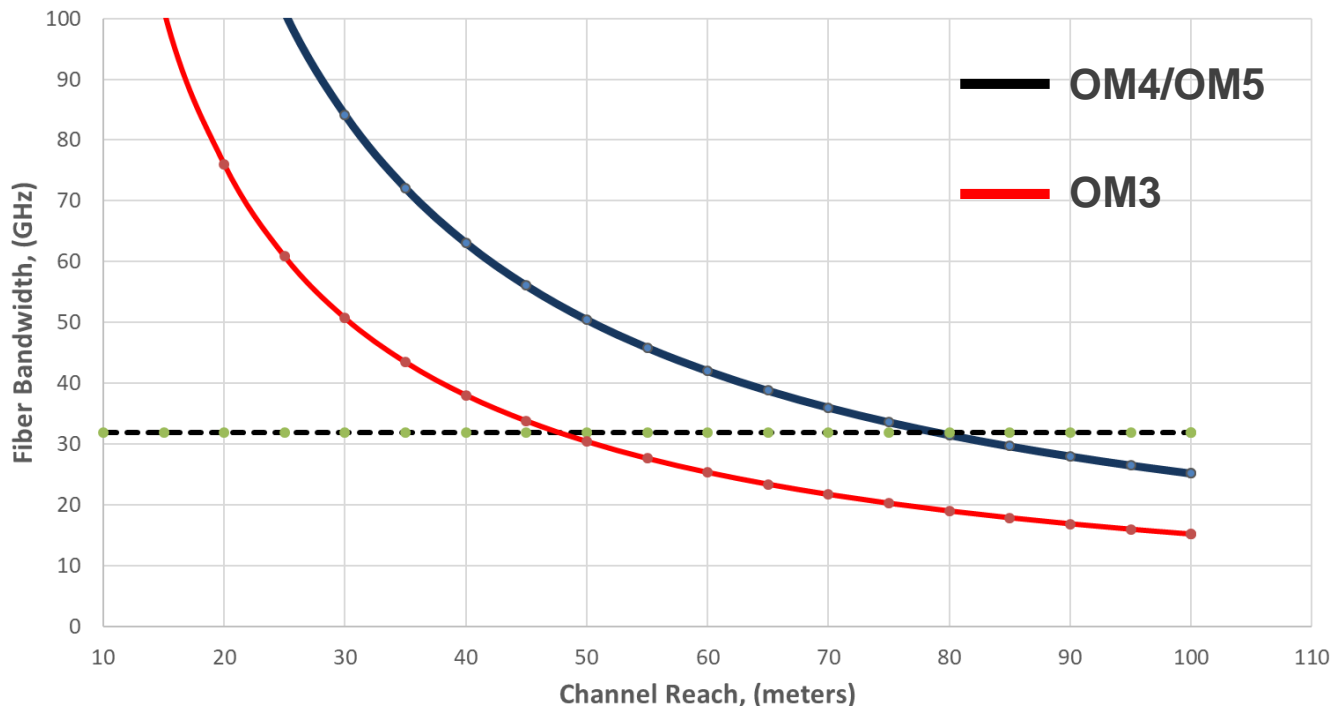
Fiber Bandwidth at 850 nm

The total bandwidth of the fiber is composed by modal and chromatic dispersion.

- **The chromatic dispersion depends on the chromatic parameters of the fiber (e.g. dispersion slope and zero dispersion wavelength), and the spectral-width of the laser source**
 - Assuming a VCSEL with worst case spectral width of 0.6 nm and dispersion parameter, ~ -101.2 ps/nm/km @ 844 nm, the chromatic bandwidth is ~ 41 GHz at 75 m and 31 GHz at 100 m
- **The modal bandwidth is caused by the multiple modes of the fiber (~ 380 modes at 850 nm)**
 - MMF are graded based on DMD measurements. At 850 nm the EMB for OM3 and OM4/OM5 is respectively 2 GHz-km and 4.7 GHz-km

Fiber Modal-Chromatic Bandwidth at 850 nm

- **The worst-case modal-chromatic bandwidth, is computed**
 - Here, for sake of simplicity we neglect the modal-chromatic dispersion interaction in the total bandwidth estimation
- **Depending on the receiver transfer function the optimum bandwidth is around 0.6 - 0.75 x Baud Rate**
- **Assuming initially a bandwidth of 0.6 x Baud Rate, the bandwidth required for 53.125 GBaud is ~32 GHz**
 - The bandwidth of the fiber alone need to be higher to accommodate for optical source and detector
 - Previous assumptions might be conservative in a highly equalized channel



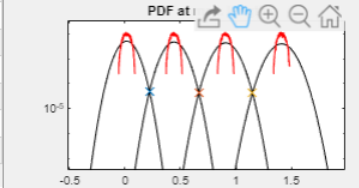
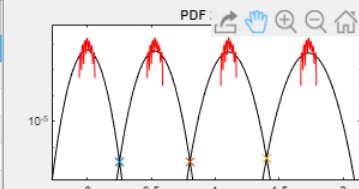
Optical Link Model

Optical Link Model

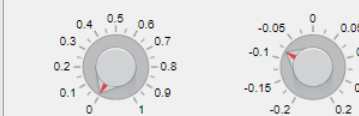
File Verification Tools Version

a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12	a13	a14	a15
Q=	3.4917	Ts(20-80)=	12 ps	Target reach=	0.0800 km	Attenuation=	3.5000 dB/km	Receiver						
Base Rate=	53125 MBd	Ts(10-90)=	18.2160 ps	L_start=	0.0100 km	att=	850 nm	NomSens OMA=	-7.9000 dBm					
Wavelength Uc=	850 nm	RIN(OMA)=	-136 dB/Hz	L_inc=	0.0050 km	C_att=	1	RefI Rx=	-12 dB					
RMS Width, Uw=	0.6000 nm	RIN at MinER=	-143.3200 dB/Hz	Power Budget P=	9.9000 dB	Attenuation=	3.5037 dB/km	Rec_BW=	28000 MHz					
Tx pwr OMA=	2 dBm	RIN_Coef=	0.7000	Connections=	1 dB	at	850 nm	c_rx=	480 ns.MHz					
Min. Ext Ratio=	2.9960 dB	DJ+ & TP4eye=	1.9000 ps inc. ...	Pwr.Bud.-Conn.Loss=	8.9000 dB	Disp. min. Uo=	1316 nm	T_rx(10-90)=	17.1429 ps					
"Worst"ave.TxPwr=	1.6800 dBm	DCD_DJ=	0 ps TP3	C1=	480 ns.MHz	Disp. So=	0.1027 ps/nm^...	TP4 Eye=	3.7647 ps					
Ext. ratio penalty=	3.6600 dBo	Effect. DJ=	0.1009 (UI) ex ...	Reflection Noise fact...	0 no units	Disp. D1=	-103.6208 ps/(nm...	Opening	(=Tx e...					
Tx mask=		MPN k(OMA)=	0.1000	Effective Rate=	5.3125e... MBd	Fraction Jitter TDE...	0.7500	RMS Baseline wande...	0.0120 fractio...					
X1=	0.3000 UI	Tx eye height=	#REF!	Tb_eff=	18.8235 ps	(not in use)	10	SECQ_rx=	0.9000 dB					
X2=	0.4000 UI	RefI Tx=	-12 dB	Effective Rec Eye=	0.2000 UI	Eff.BWm=	4400 MHz*km	P_BLW(no ISI)=	0.0047 dB					
Y1=	0.2500	ModalNoiseSTD_1...	0.0200 dB	Tx mask top=	0.2000 UI	DGD_max	0 ps/sqrt...	P_BLW=	0.0050 dB					

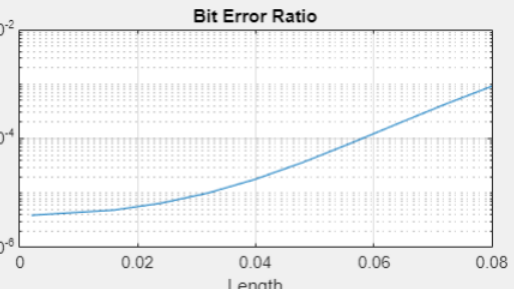
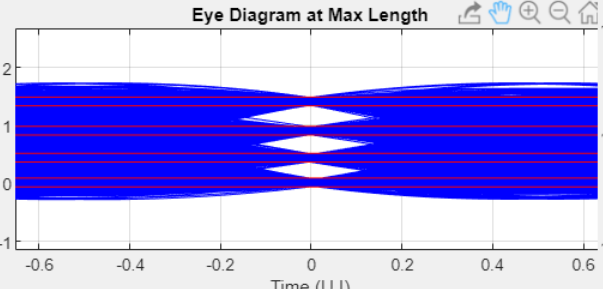
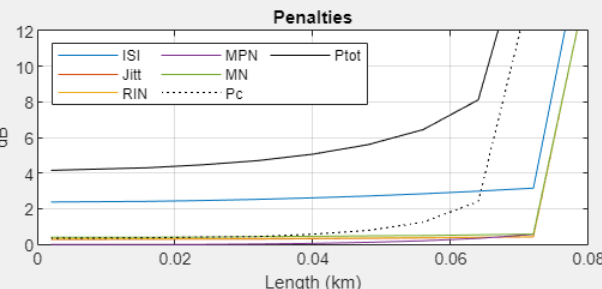
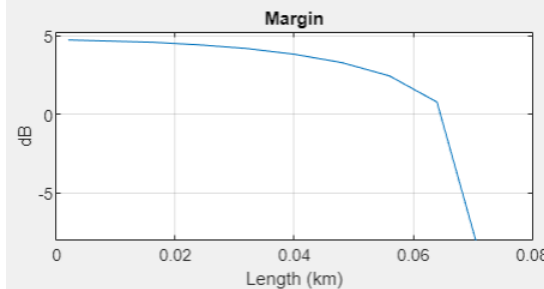
L (km)	Patt (dB)	ChIL	D.L (p...	BWcd (...	effBWm...	Te (ps)	Tc (ps)	Pisi-C...	Peye-...	P_DJ...	P_DC...	P_Re...	Beta	SDmpn	Pmpn...	Prin (dB)	P_MN (dB)	P_BLW	Pc
0.0020	0.0070	1.0070	0.2072	1503	1241	18.2200	25.0100	2.3793	0	0.2842	0	0	0.0207	0	0	0.3100	0.4000	0.4300	0.350
0.0160	0.0561	1.0561	1.6579	187	155	18.4700	25.2000	2.4160	0	0.2924	0	0	0.1659	0	0	0.3200	0.4000	0.4400	0.370
0.0240	0.0841	1.0841	2.4869	125	103	18.7900	25.4400	2.4627	0	0.3032	0	9.643...	0.2489	0	-0.0100	0.3300	0.4100	0.4600	0.420
0.0320	0.1121	1.1121	3.3159	93	77	19.2300	25.7600	2.5283	0	0.3032	0	1.928...	0.3319	0	0.0200	0.3400	0.4400	0.5100	0.440
0.0400	0.1401	1.1401	4.1448	75	62	19.7800	26.1800	2.6133	0	0.3201	0	1.446...	0.4148	0	0.0600	0.3500	0.4600	0.5500	0.570
0.0480	0.1682	1.1682	4.9738	62	51	20.4400	26.6700	2.7167	0	0.3420	0	4.821...	0.4978	0	0.1200	0.3700	0.4800	0.6100	0.790
0.0560	0.1962	1.1962	5.8028	53	44	21.1800	27.2500	2.8412	0	0.3668	0	9.643...	0.5808	0	0.2000	0.3900	0.5000	0.6900	1.250
0.0640	0.2242	1.2242	6.6317	46	38	22.0200	27.9000	2.9878	0	0.3955	0	0	0.6638	0	0.3400	0.4100	0.5400	0.8000	2.410



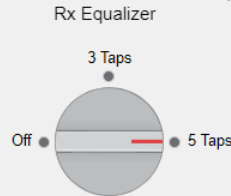
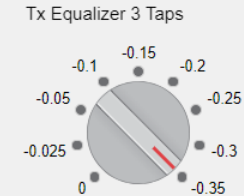
TDECQ 3.17



Horiz. distortion Eye Compression

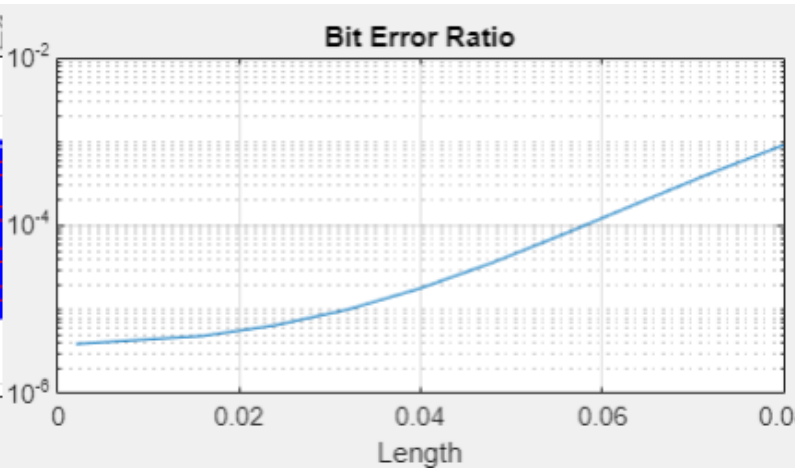
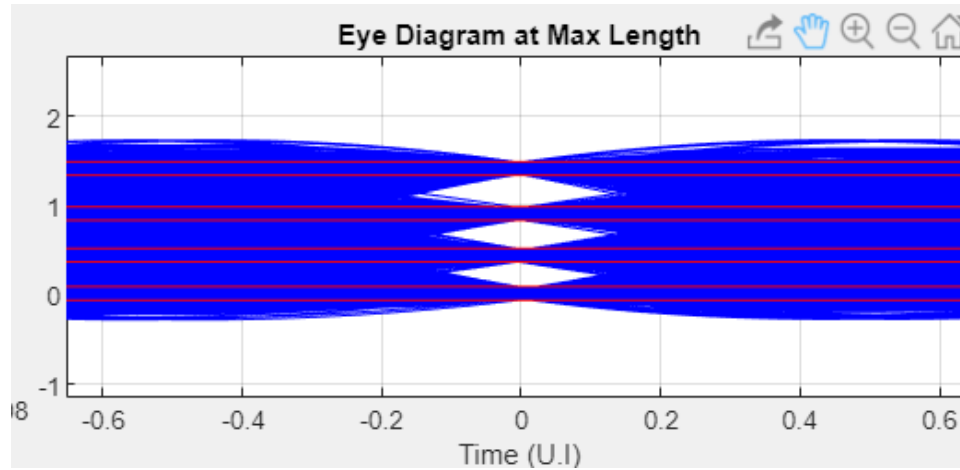
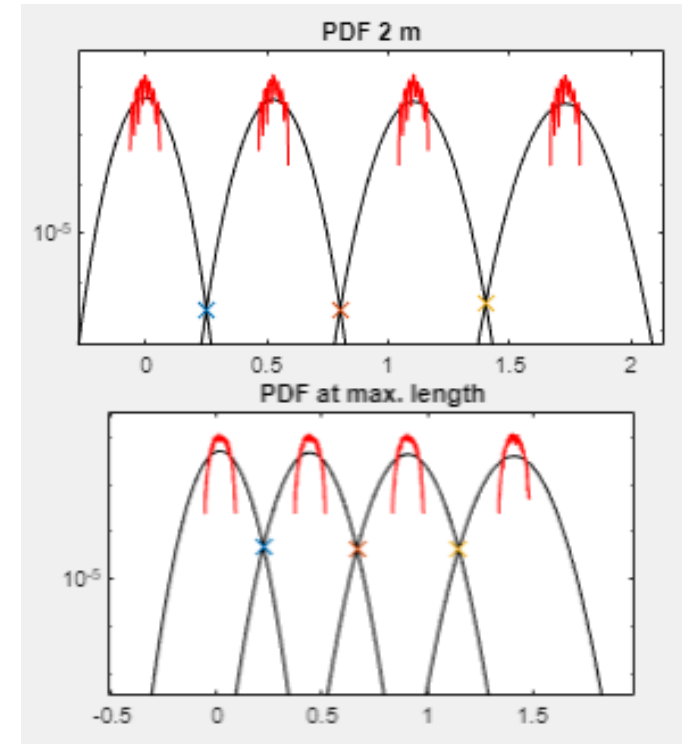
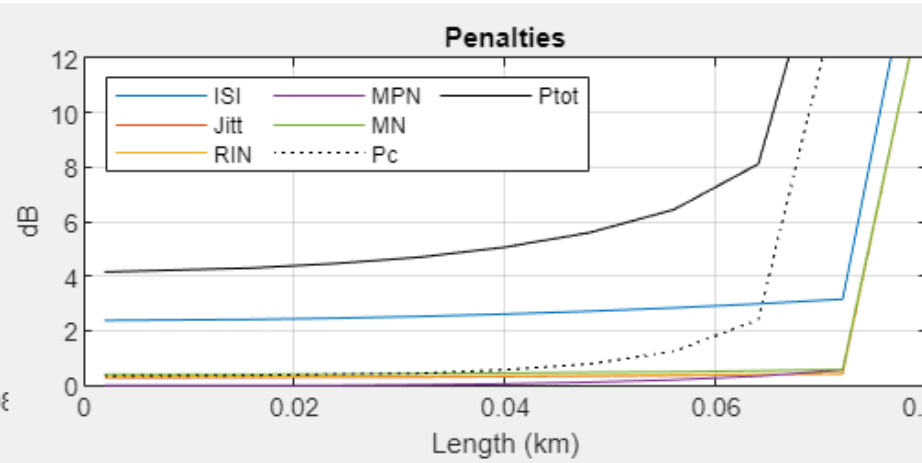
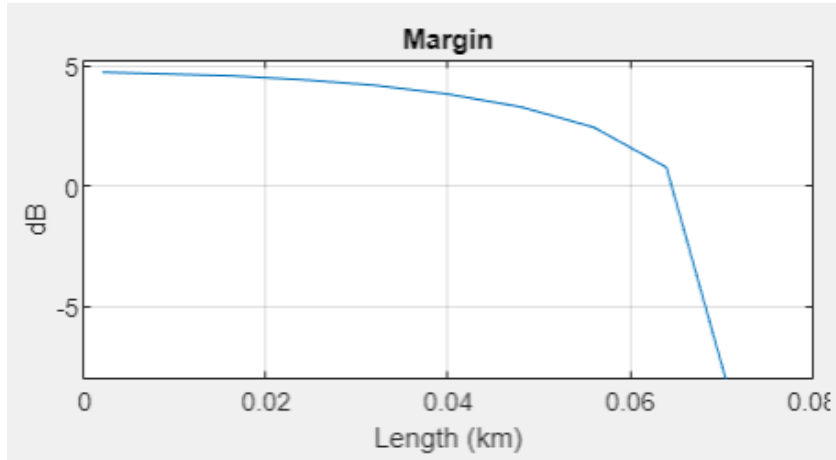


Modulation PAM-4

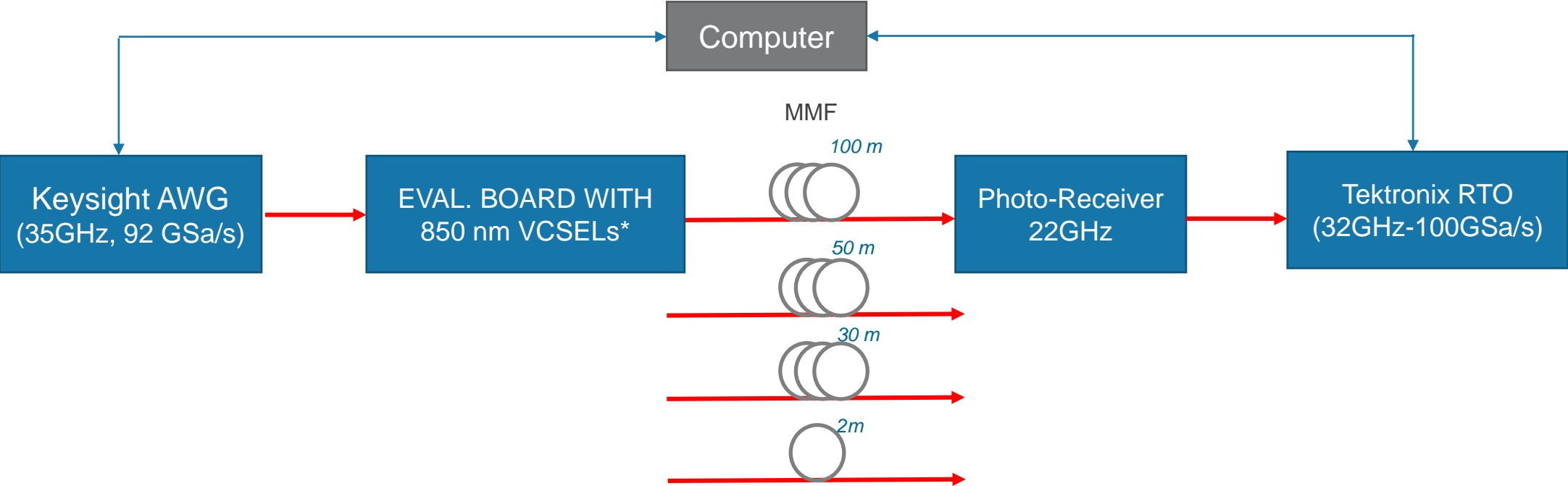


Gaussian Channel No-MCDI

Optical Link Model



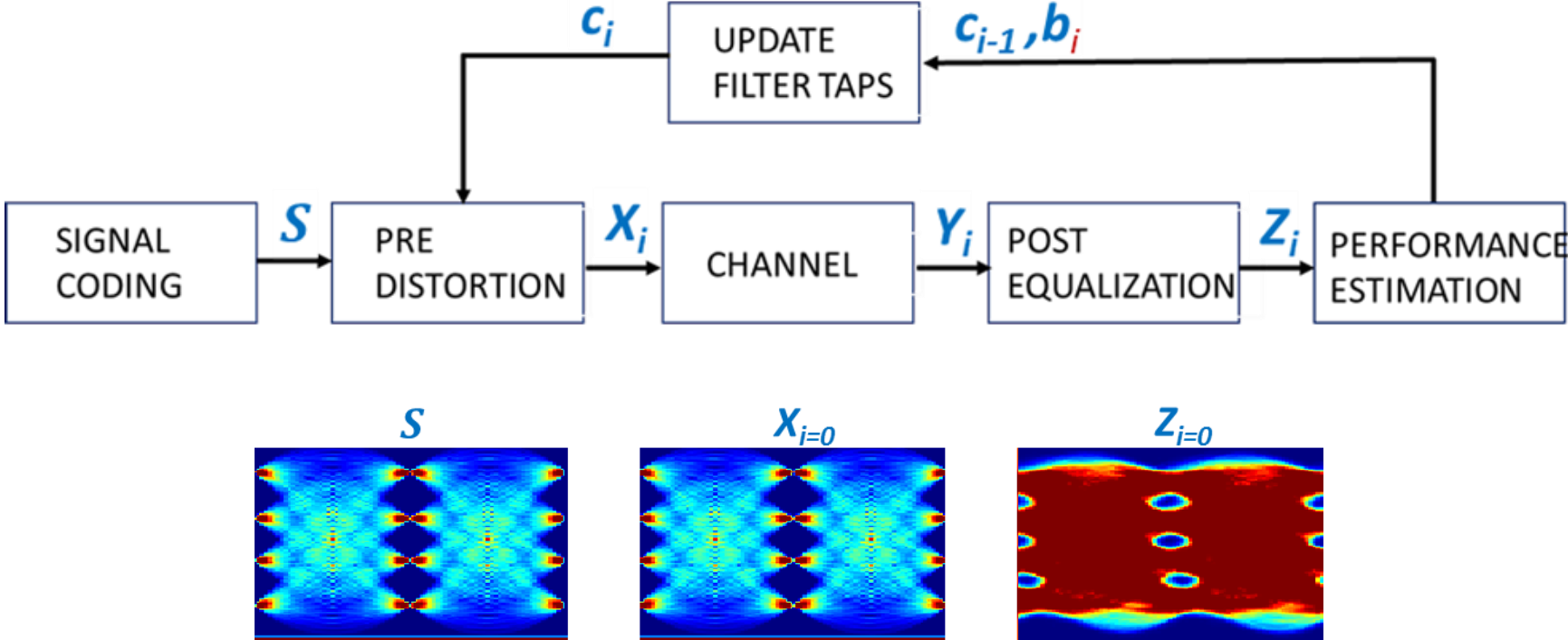
Experimental setup



MMF	EMB target (MHz-km)	Three links from the same fiber spool cut consecutively
(A) w-c OM3, EMB, 180 m	2000	(1) 30m, (2) 50m, (3) 100m
(B) w-c OM4, EMB, 180m	4700	(1) 30m, (2) 50m, (3) 100m

Methodology to open the eyes

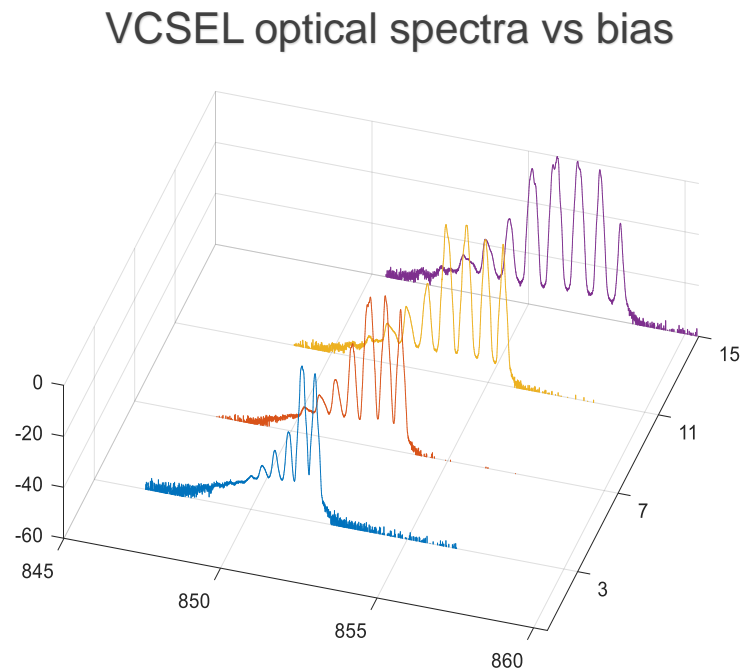
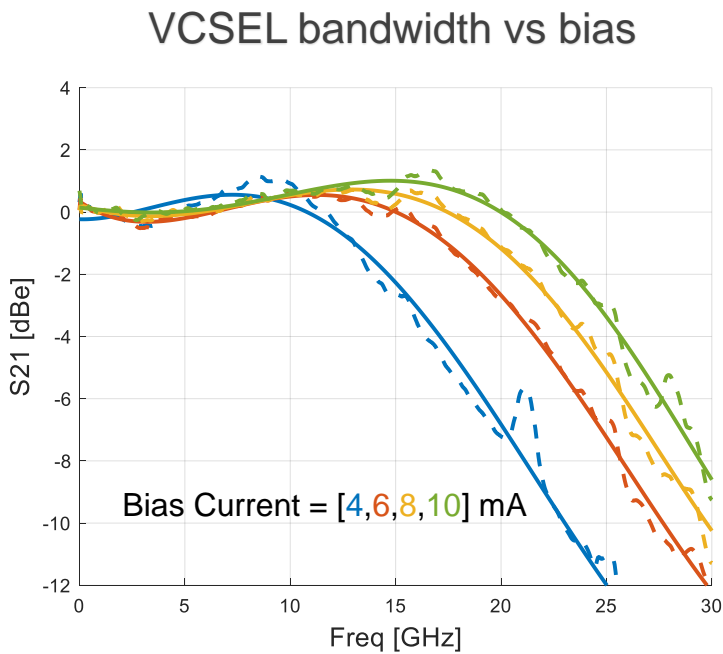
Based on previously developed for 66Gbps *



* "Eye Skew Modeling, Measurements and Mitigation Methods for VCSEL PAM-4 Channels at Data Rates over 66 Gb/s," Optical Fiber Conference 2017, W3G.3 DO - 10.1364/OFC.2017.W3G.3

VCSEL Bandwidth and Spectral Bias

For the data shown in the next slides the bias was 9.6 mA and spectral width ~ 0.6 nm, VCSEL BW ~ 24 GHz

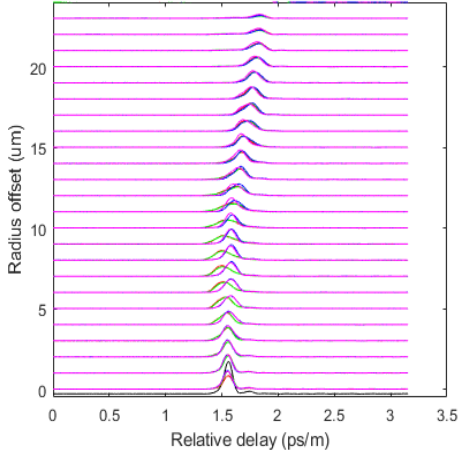


Current	4 mA	7 mA	11 mA	15 mA
Spectral Width ($\Delta\lambda_{\text{RMS}}$)	0.24 nm	0.33 nm	0.60 nm	0.63 nm

MMF utilized for the experiment

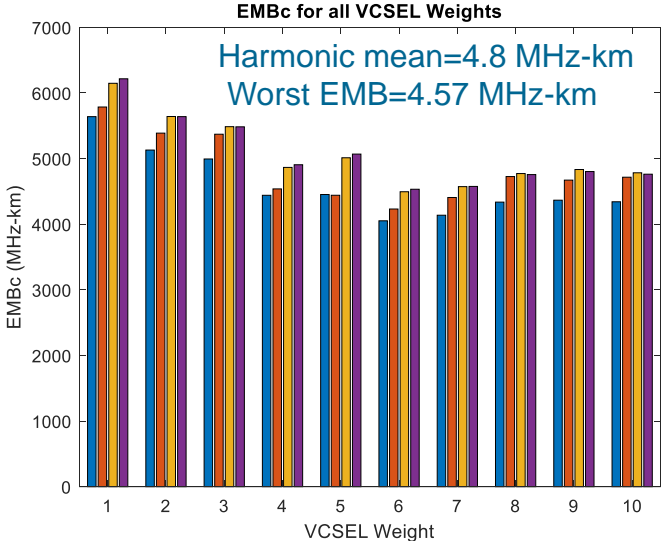
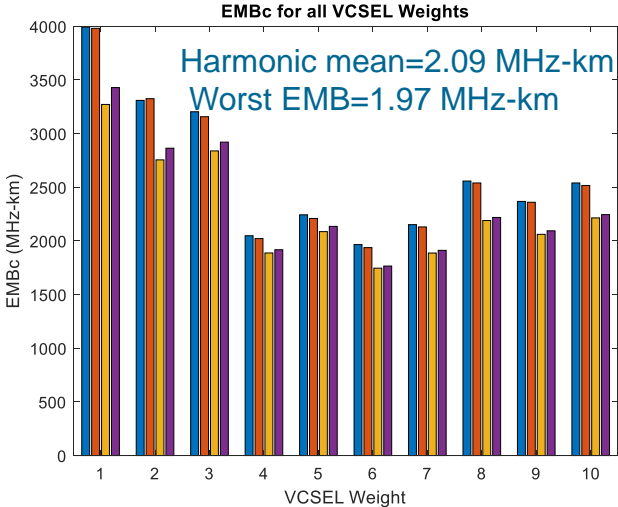
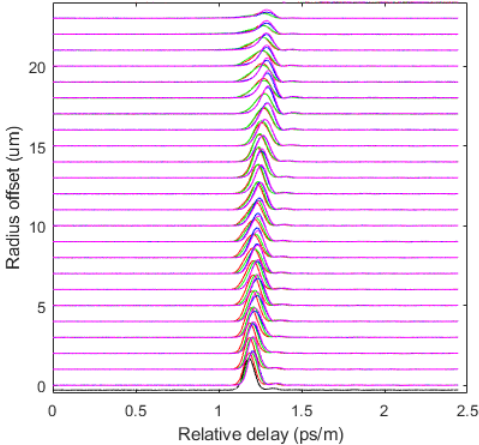
Worst-case OM3

4 Quadrant Plot. Black is initial (0,0). #1(red), #2(green), #3(blue), and #4(magenta).



Worst-case OM4

4 Quadrant Plot. Black is initial (0,0). #1(red), #2(green), #3(blue), and #4(magenta).

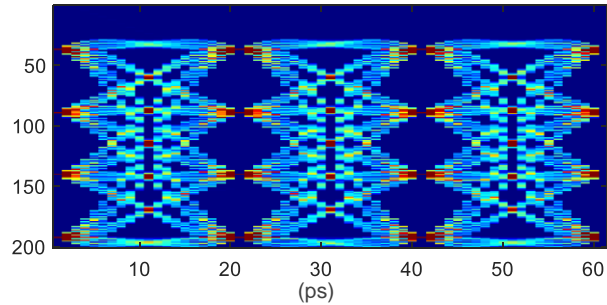


Experimental Procedure and Result

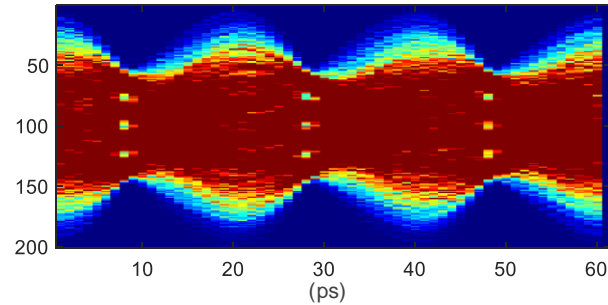
- **The Eye Diagrams shown in the next slides are used to study the effect of the fiber on the channel performance degradation as a function of length for worst-case OM3 and OM4**
 - SSPRQ utilized, equalization using FFE, tap range : 7 to 21
 - Symbol Error Rate (SER) computed from Eye Diagrams after Gaussian fitting
- **Since the current evaluation board showed a relatively high degree of electrical noise, our experiments are performed in two steps:**
 - Initial tests shown here use averaged waveforms to focus the study on the dispersion components of the channel, primarily the fiber effect
 - In a second step, the non-averaged waveforms are used. Therefore all noise components are used (more data in appendices)

100Gbps PAM-4 B2B with pre-distortion, *averaged waveform*

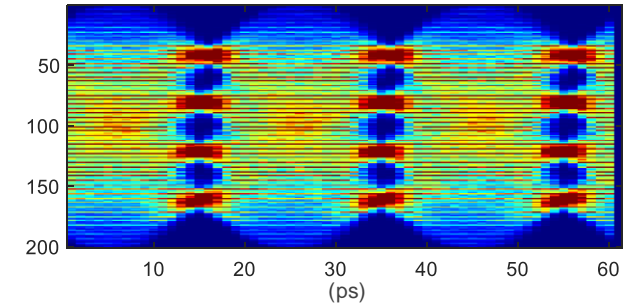
Mathematical Signal (R.C)



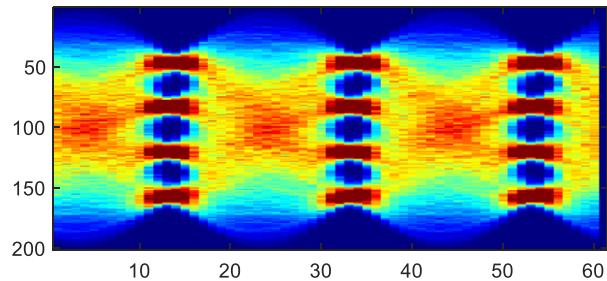
Pre-distorted



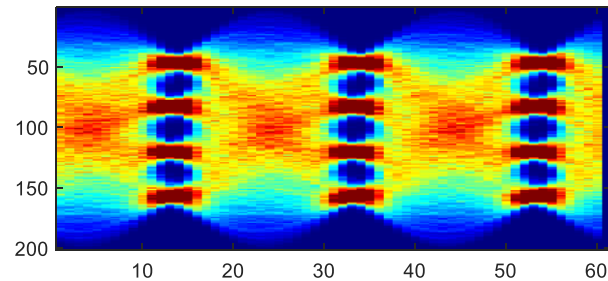
Received by the Scope



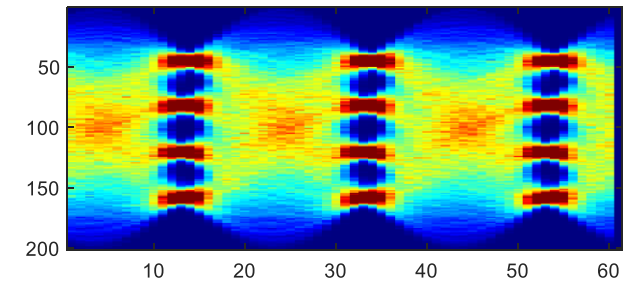
Equalized, FFE with 13 taps



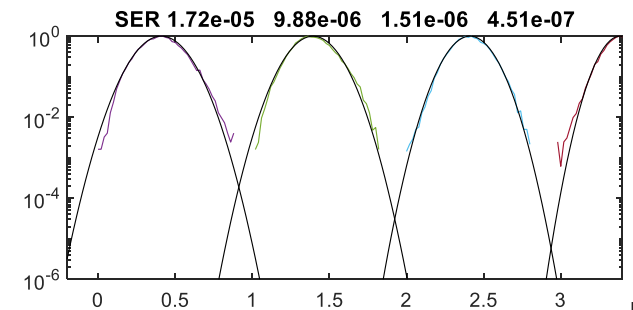
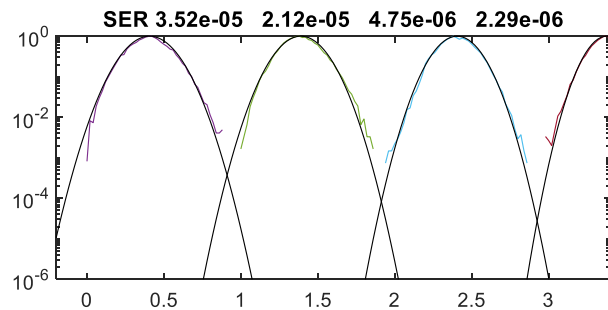
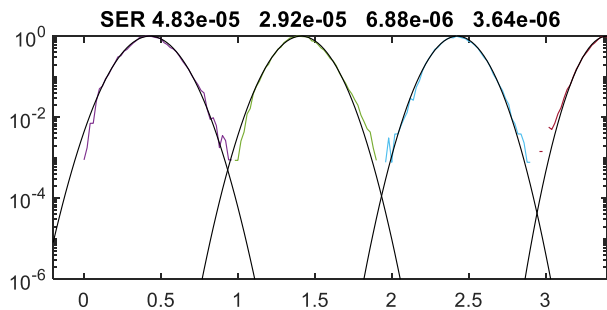
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps

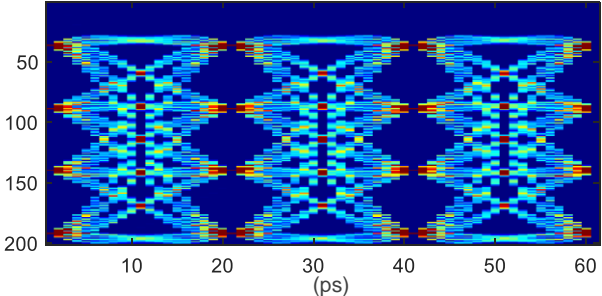


Histograms, and Symbol Error Rate

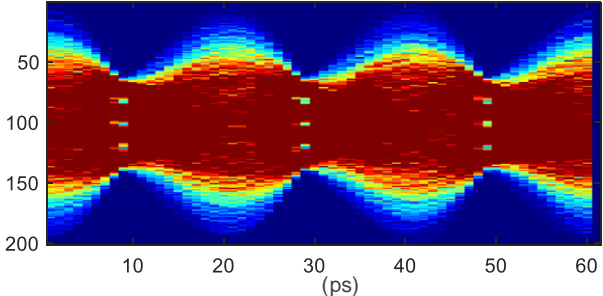


100Gbps OM4 100m with pre-distortion, *averaged waveform*

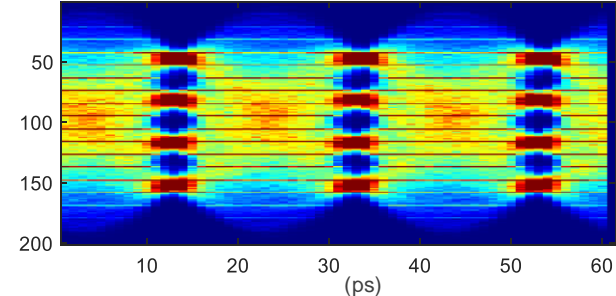
Mathematical Signal (R.C)



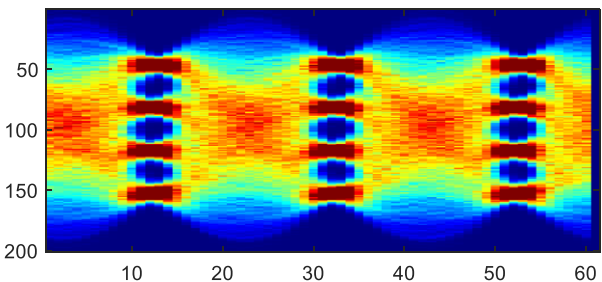
Pre-distorted



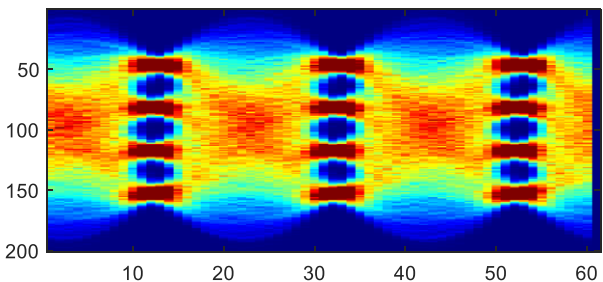
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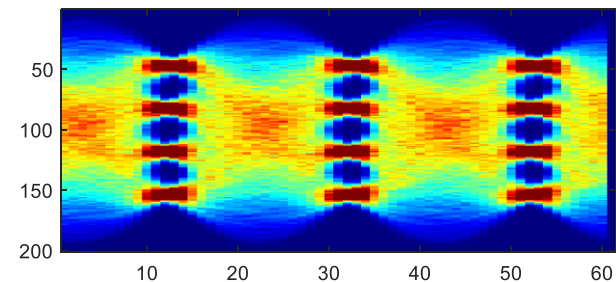
Equalized, FFE with 13 taps



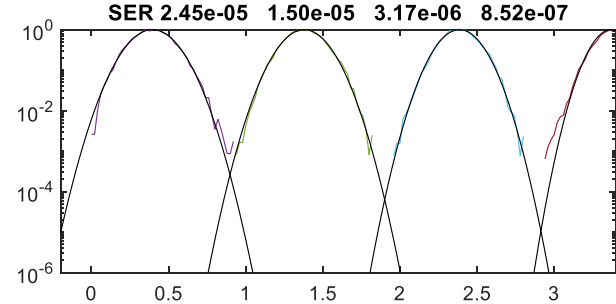
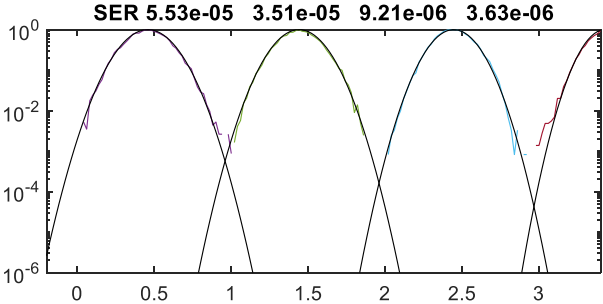
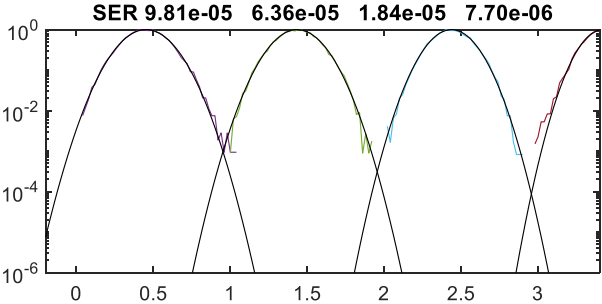
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps



Histograms, and Symbol Error Rate



Symbol Error Ratio results

- SER used in the table is the worst observed in the four levels using a FFE with 15 taps using averaged waveforms.
 - Using Gray coding, and assuming that errors occur among adjacent symbol levels, the bit error ratio can be estimated using $BER = SER/2$

	B2B		OM3		OM4	
	Without Pre-distortion	With pre-distortion	Without Pre-distortion	With pre-distortion	Without Pre-distortion	With pre-distortion
2m	3.4e-4	3.5e-5				
30m			4e-4	8.3e-5	3e-4	3.4e-5
50m			3e-4	3e-5	2.5e-4	2.2e-5
100m			4.7e-4	7e-4	2.9e-4	5.6e-5

- The SER degraded significantly when waveforms were not averaged. For example, the SER for 100m OM4 was $\sim 6e-4$.

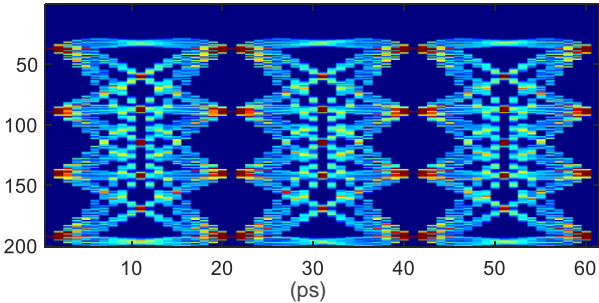
Summary and preliminary conclusions

- **Preliminary experimental work evaluated the impact of modal-chromatic bandwidth on reaches**
 - SER and reaches limited by bandwidth of VCSEL and photo-receiver (24 GHz and 22 GHz respectively) and noise
 - SER better than $6e-5$ for 100m worst-case OM4 achieved with averaged waveforms (electrical noise removed)
 - SER better than $7e-4$ for 100m worst-case OM4 achieved with non-averaged waveforms (all noises included)
- **Investigation indicates that for OM4 max. reaches in the range of 75m should be considered**
 - Although experiments were performed at 50 GBaud (100m OM4), they indicate the potential for 53.125 GBaud 75m with higher bandwidth components
 - Faster VCSELs and photo-receivers, e.g., 28 GHz components, can reduce the complexity of implementation
 - Reaches in the range of 75m can support a very significant percentage of MMF links used in data center
 - Cost and complexity vs reach need to be considered

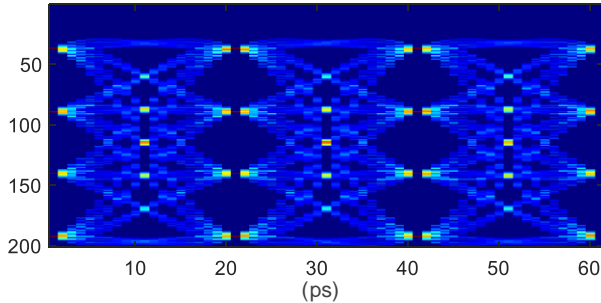
Appendices: Eye Diagrams

100Gbps PAM-4 B2B without pre-distortion, *averaged eye*

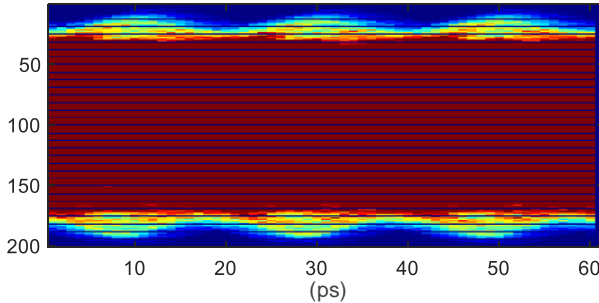
Mathematical Signal (R.C)



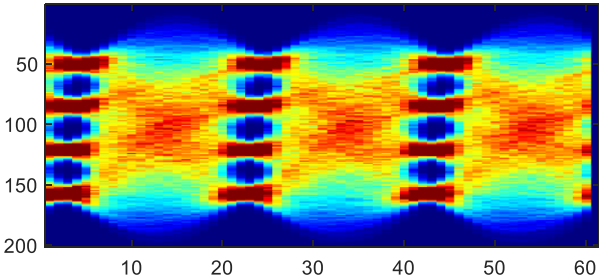
Pre-distorted



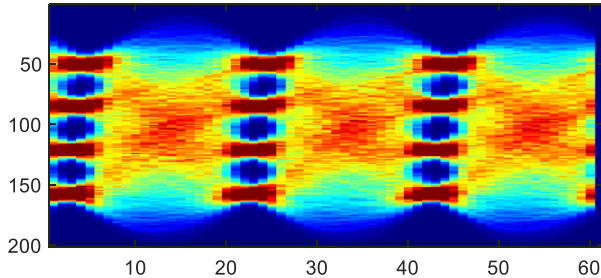
Received by the Scope



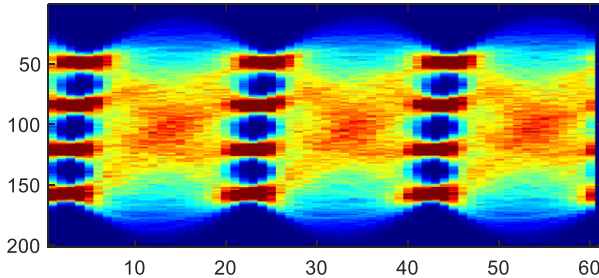
Equalized, FFE with 13 taps



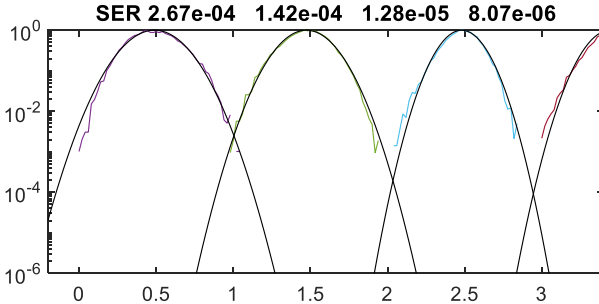
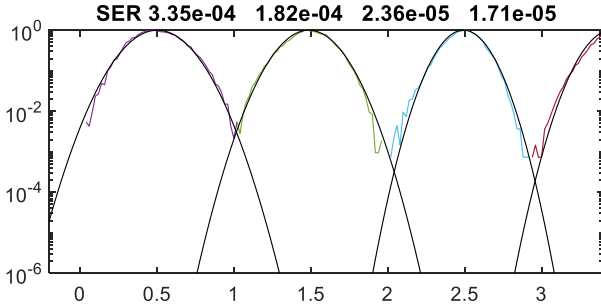
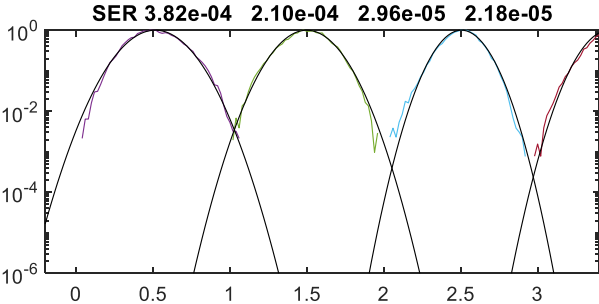
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps

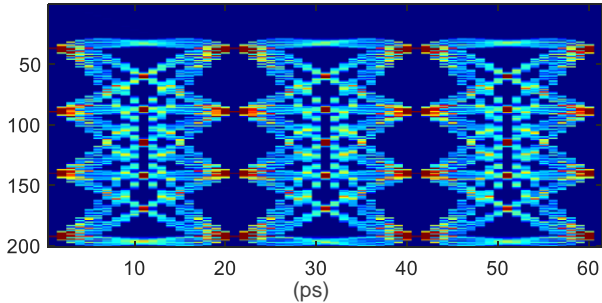


Histograms, and Symbol Error Rate

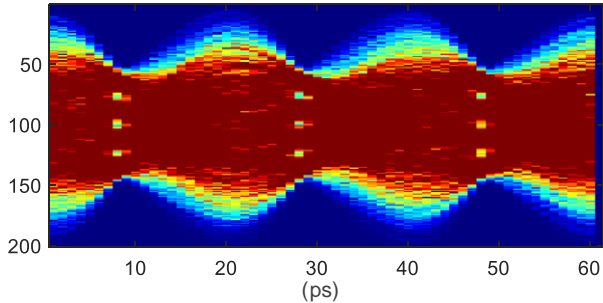


100Gbps PAM-4 B2B with pre-distortion, *averaged eye*

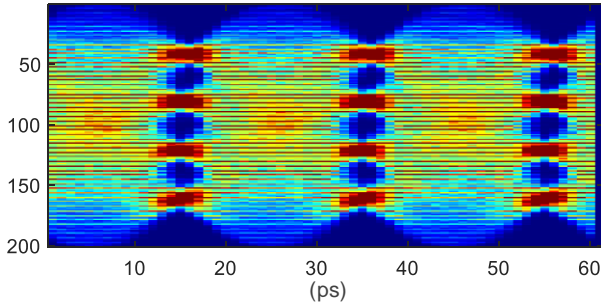
Mathematical Signal (R.C)



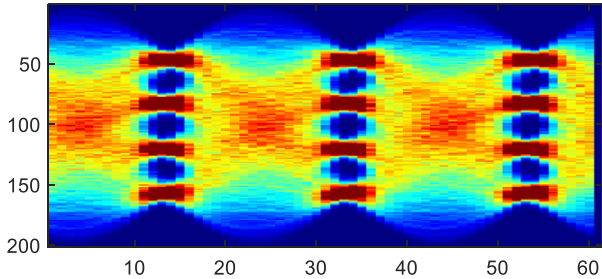
Pre-distorted



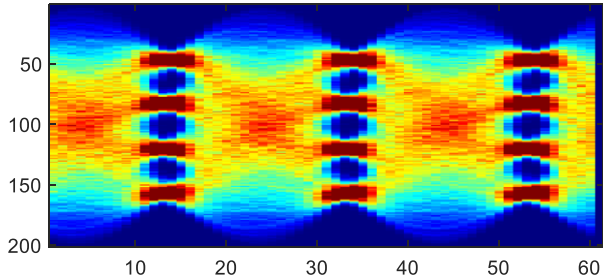
Received by the Scope



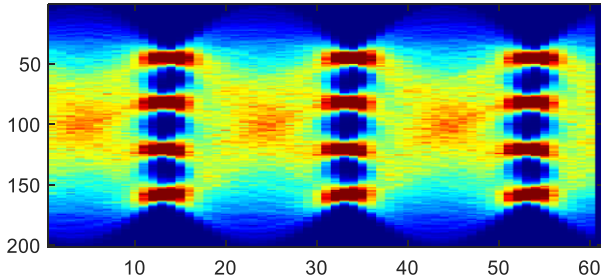
Equalized, FFE with 13 taps



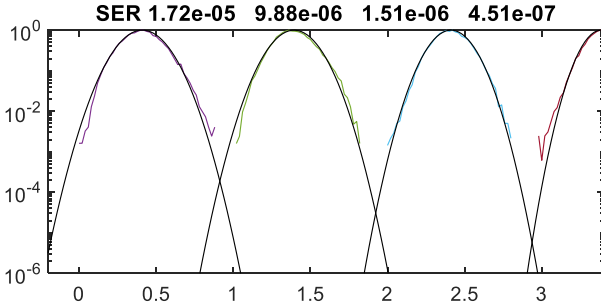
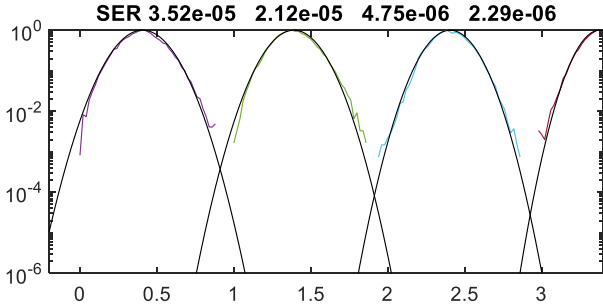
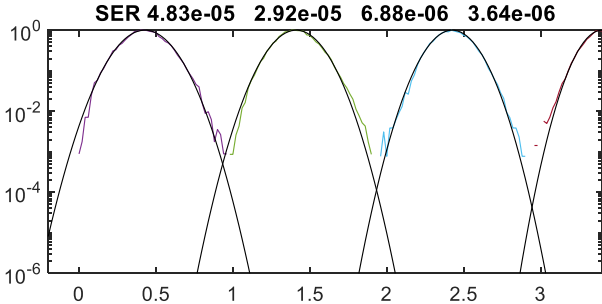
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps



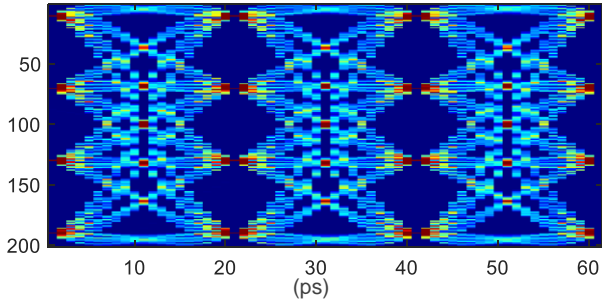
Histograms, and Symbol Error Rate



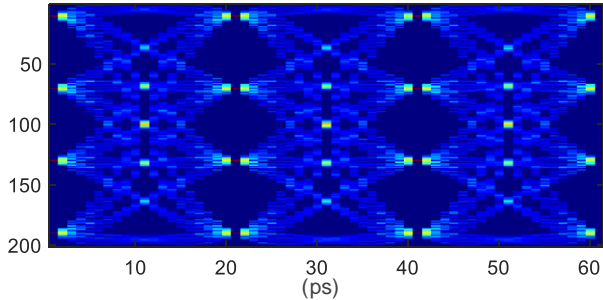
Worst-Case OM3

100Gbps OM3 30m without pre-distortion, *averaged eye*

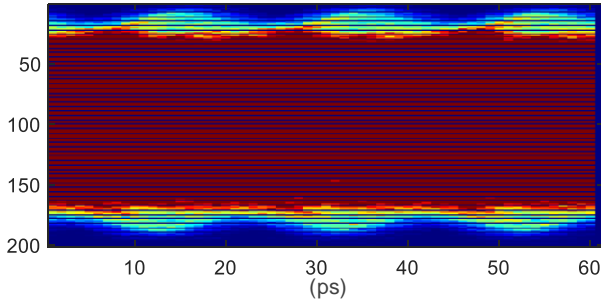
Mathematical Signal (R.C)



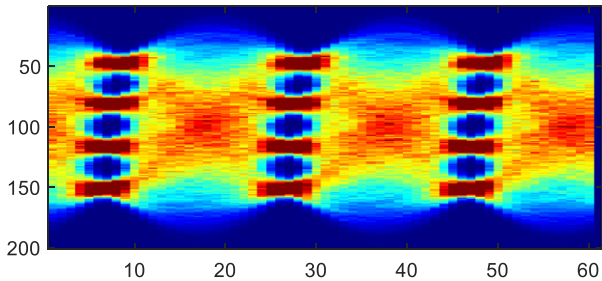
Pre-distorted



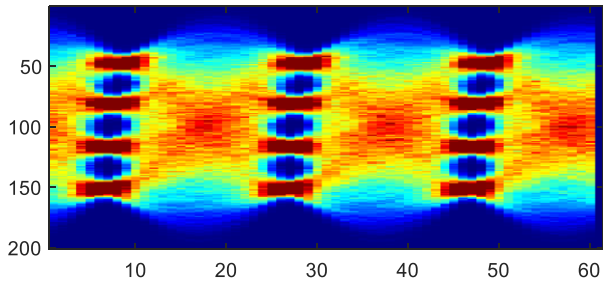
Received by the Scope



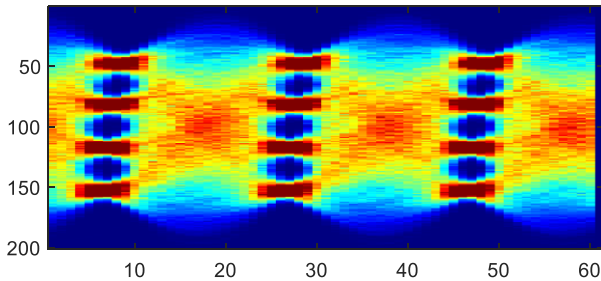
Equalized, FFE with 13 taps



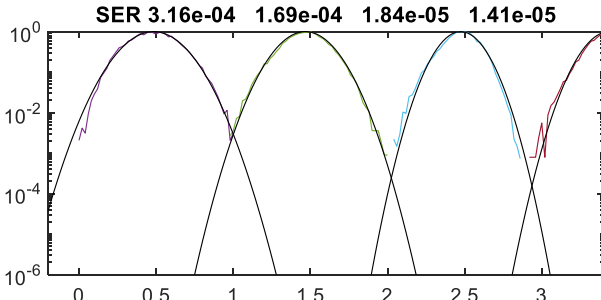
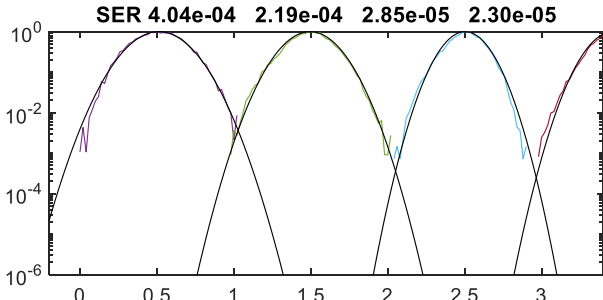
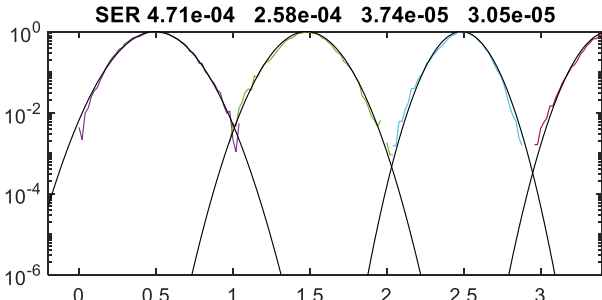
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps

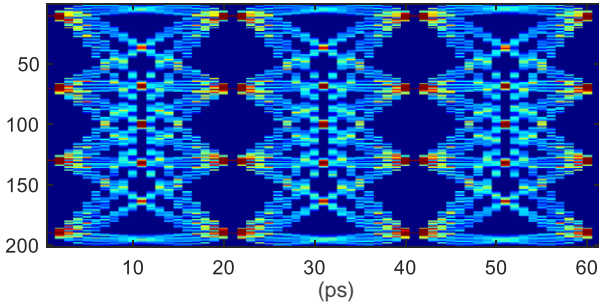


Histograms, and Symbol Error Rate

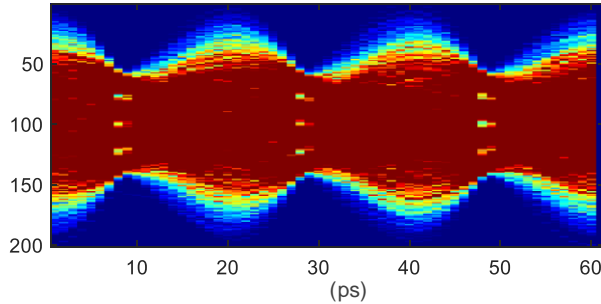


100Gbps OM3 30m with pre-distortion, *averaged eye*

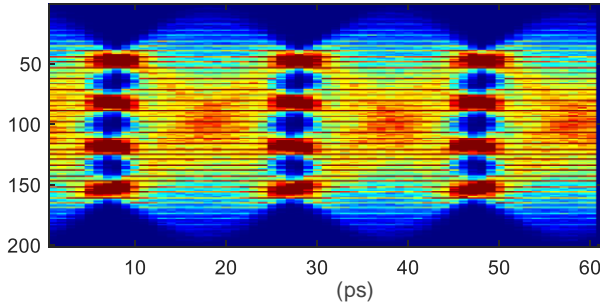
Mathematical Signal (R.C)



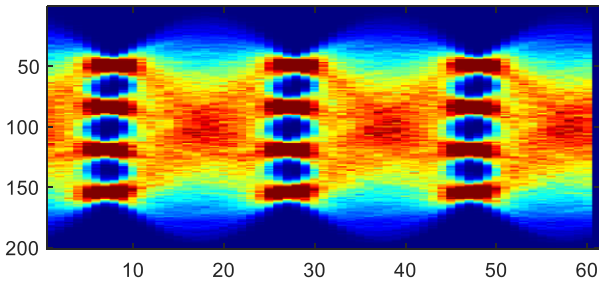
Pre-distorted



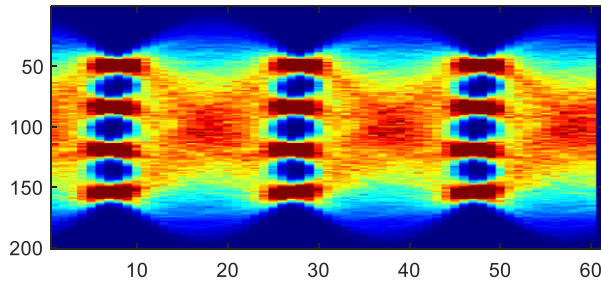
Received by the Scope



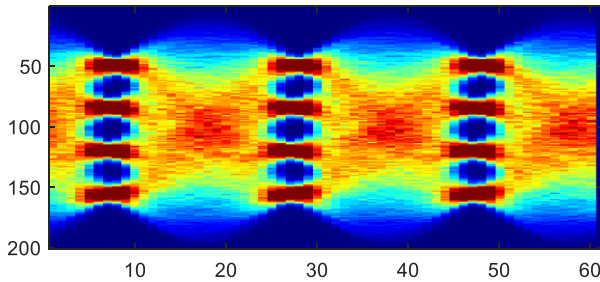
Equalized, FFE with 13 taps



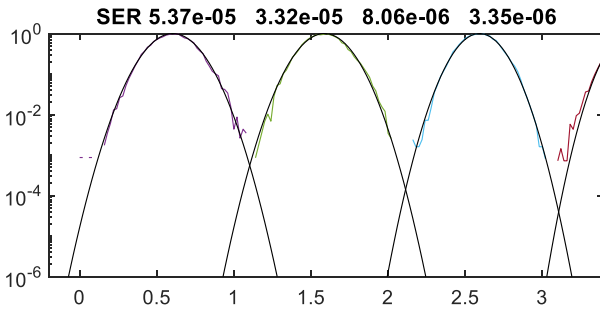
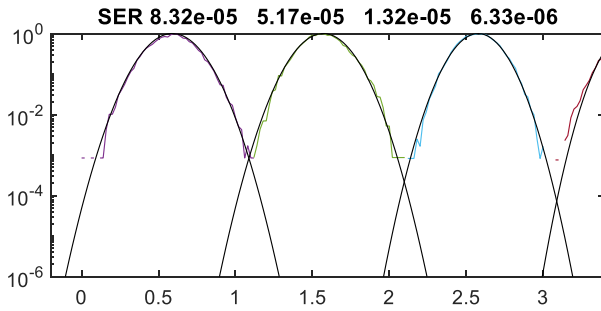
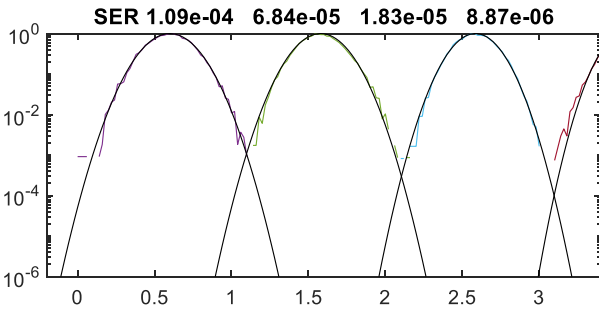
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps

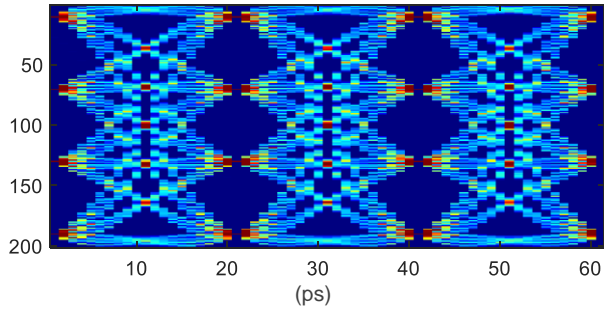


Histograms, and Symbol Error Rate

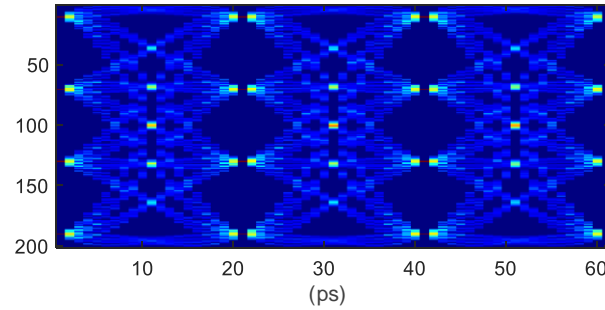


100Gbps OM3 50m without pre-distortion, *averaged eye*

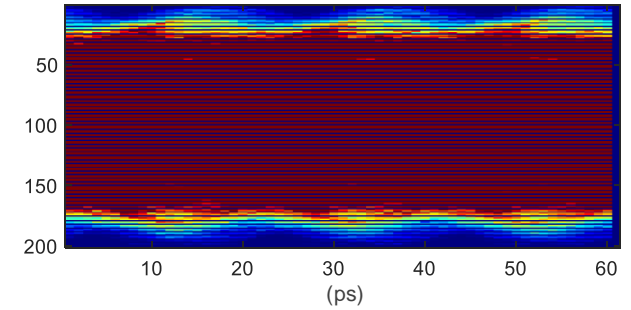
Mathematical Signal (R.C)



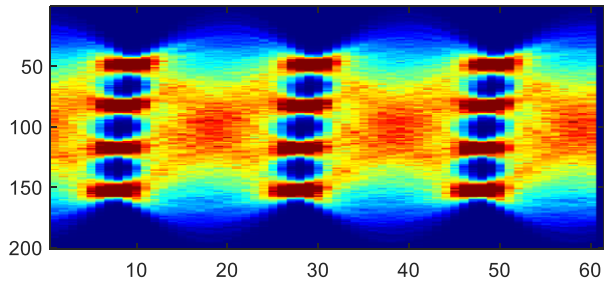
Pre-distorted



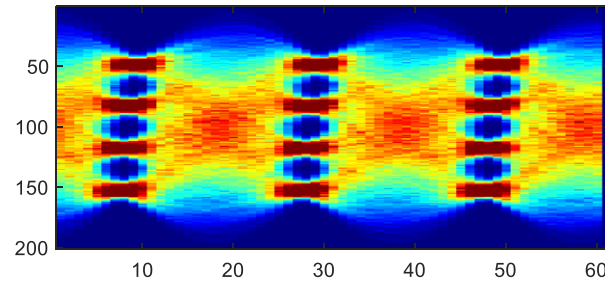
Received by the Scope



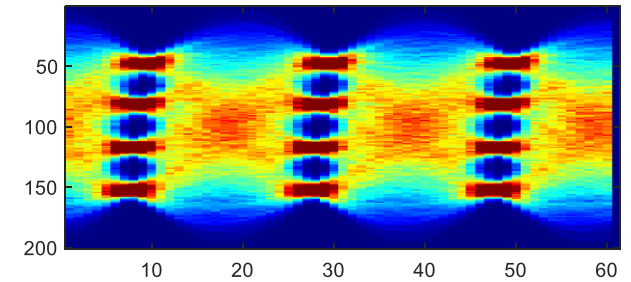
Equalized, FFE with 13 taps



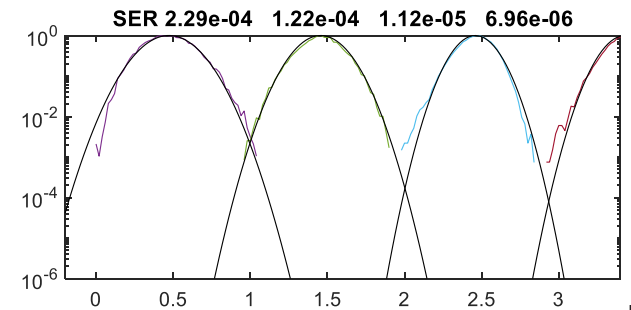
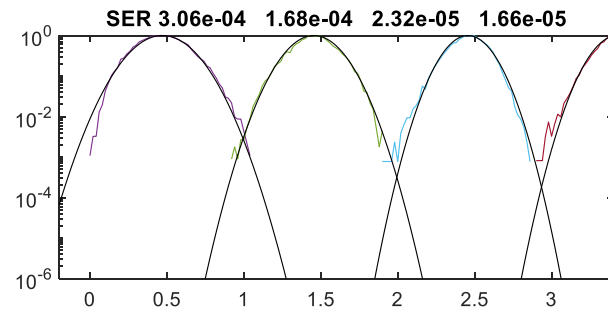
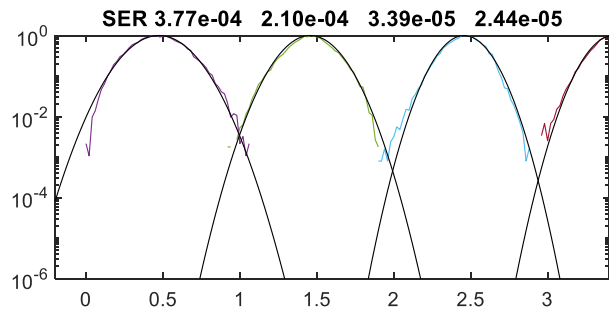
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps

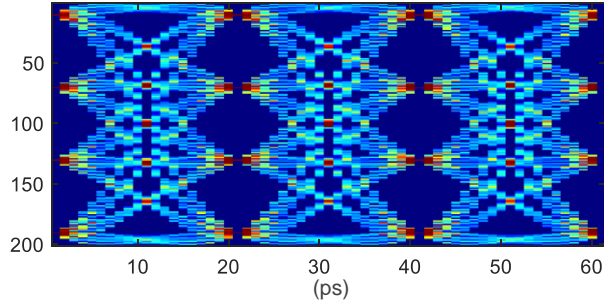


Histograms, and Symbol Error Rate

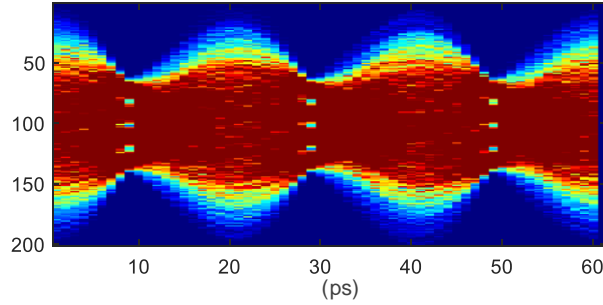


100Gbps OM3 50m with pre-distortion, *averaged eye*

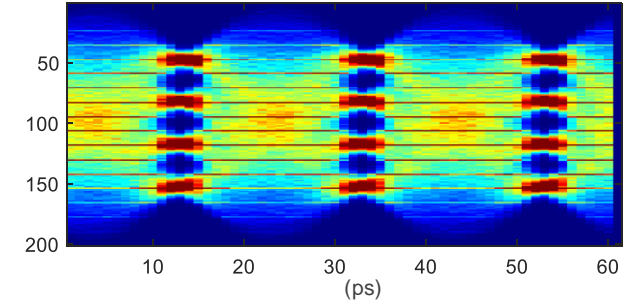
Mathematical Signal (R.C)



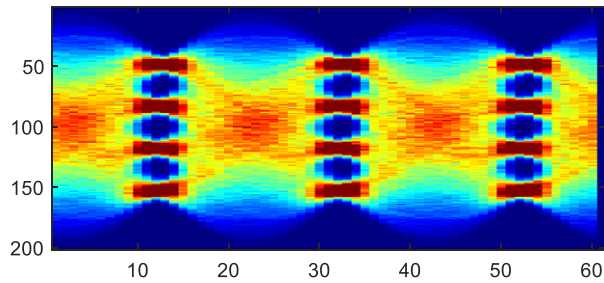
Pre-distorted



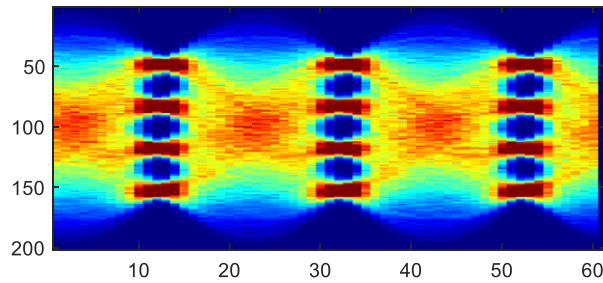
Received by the Scope



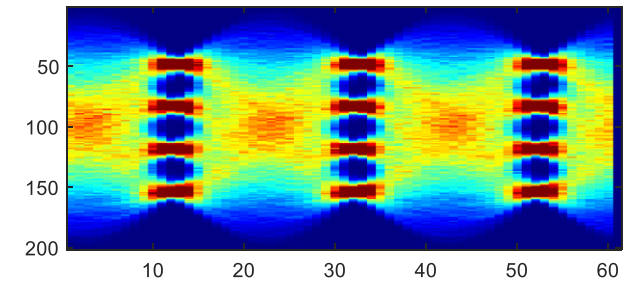
Equalized, FFE with 13 taps



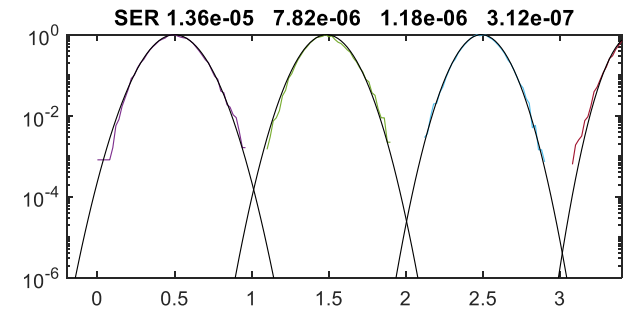
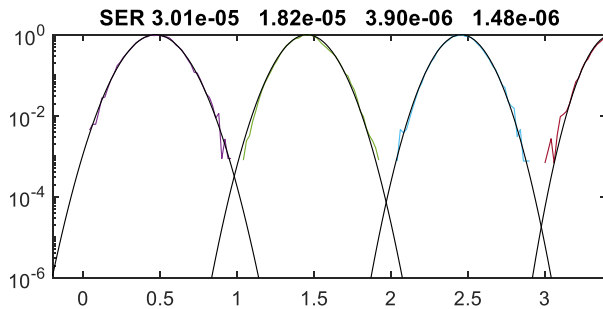
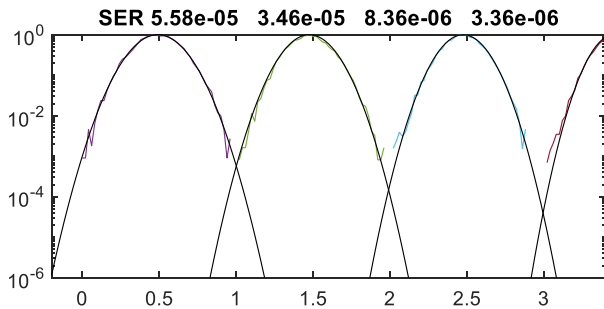
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps

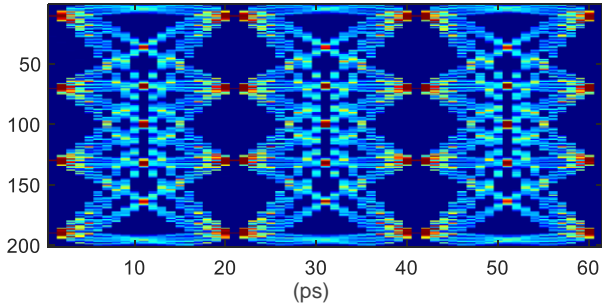


Histograms, and Symbol Error Rate

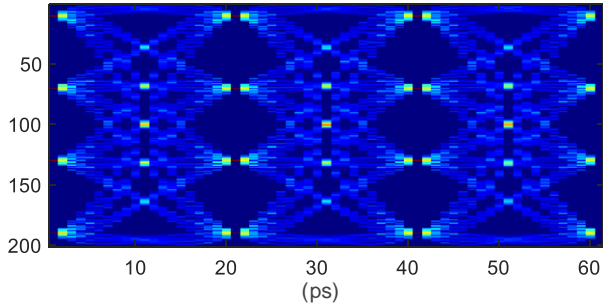


100Gbps OM3 100m without pre-distortion, *averaged eye*

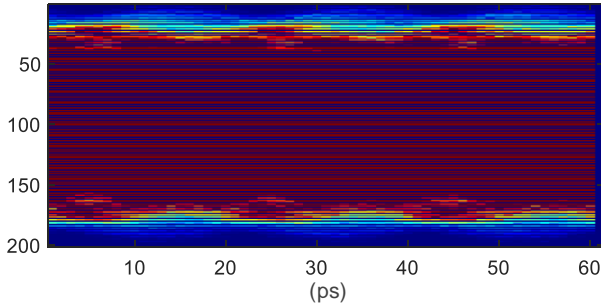
Mathematical Signal (R.C)



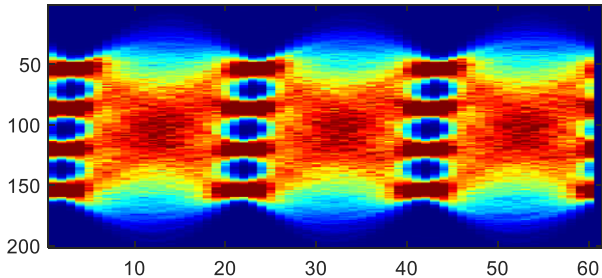
Pre-distorted



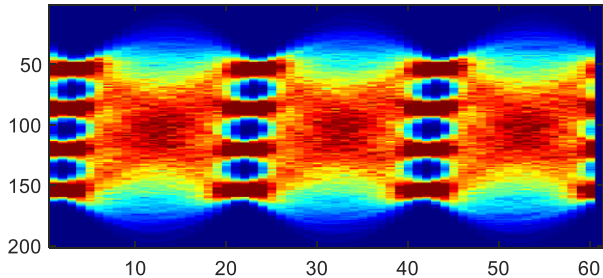
Received by the Scope



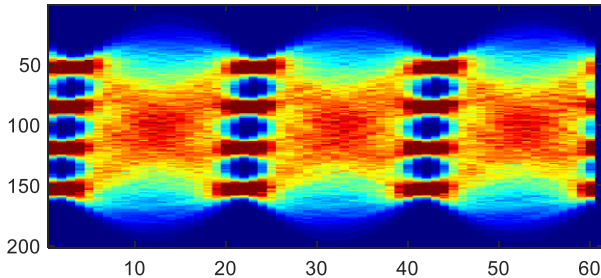
Equalized, FFE with 13 taps



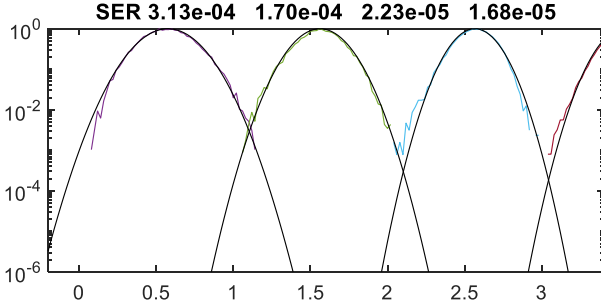
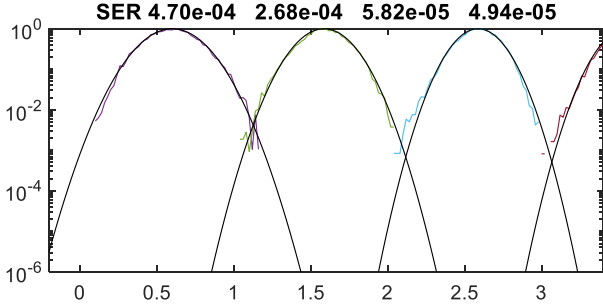
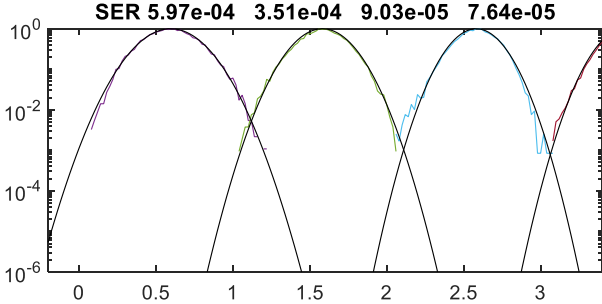
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps

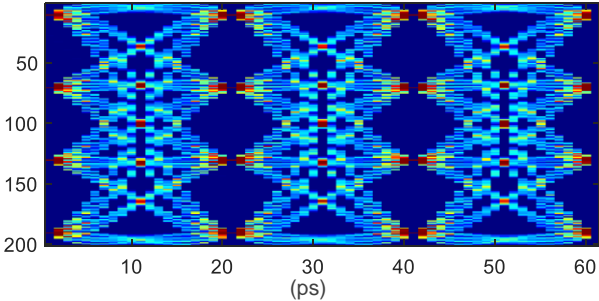


Histograms, and Symbol Error Rate

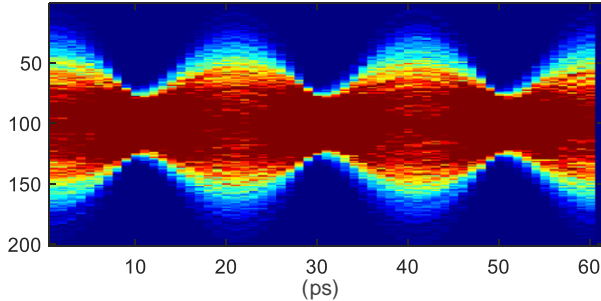


100Gbps OM3 100m with pre-distortion, *averaged eye*

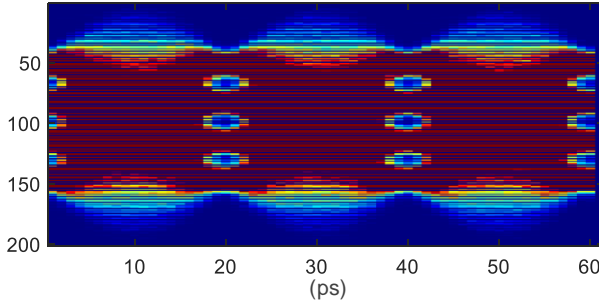
Mathematical Signal (R.C)



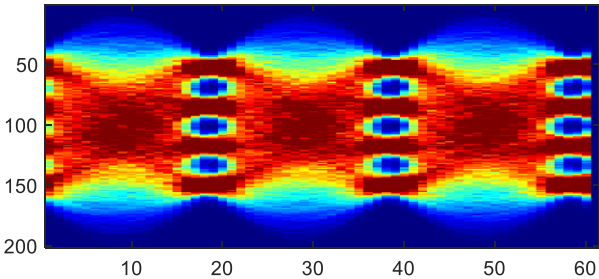
Pre-distorted



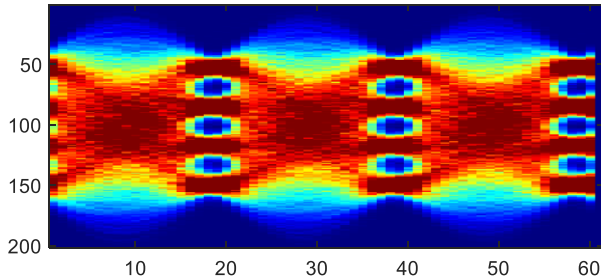
Received by the Scope



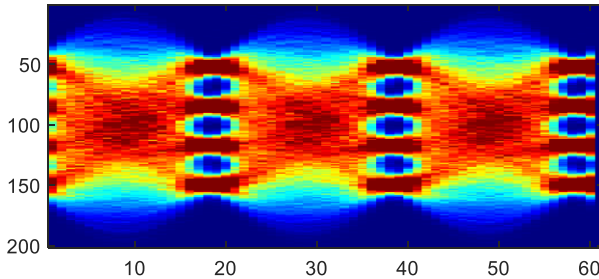
Equalized, FFE with 13 taps



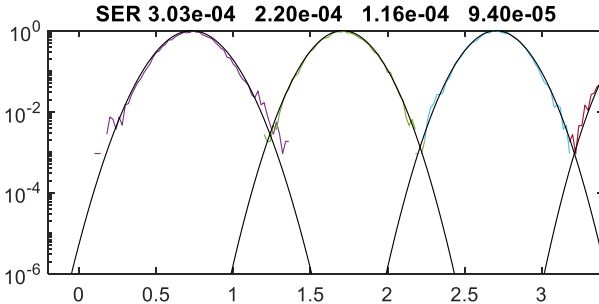
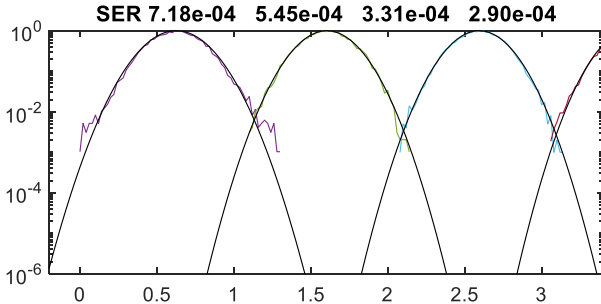
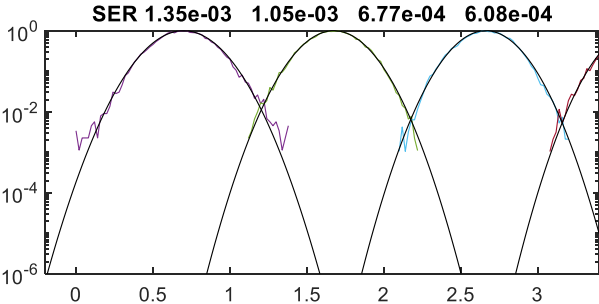
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps



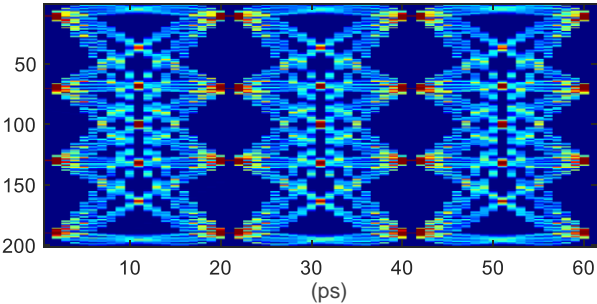
Histograms, and Symbol Error Rate



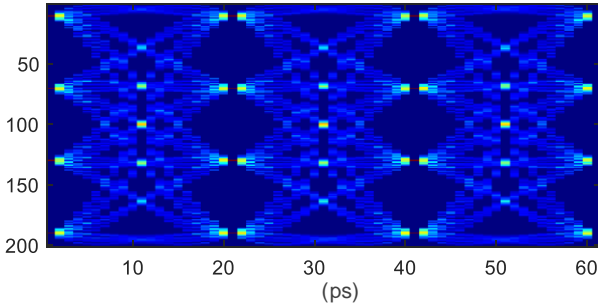
Worst-case OM4

100Gbps OM4 30m without pre-distortion, *averaged eye*

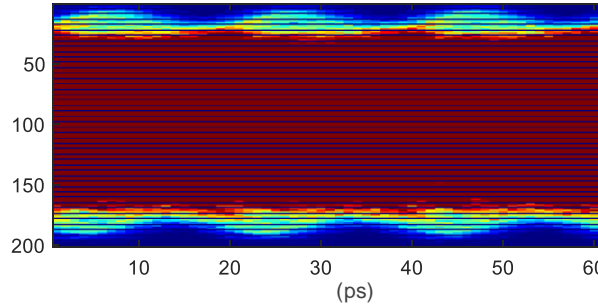
Mathematical Signal (R.C)



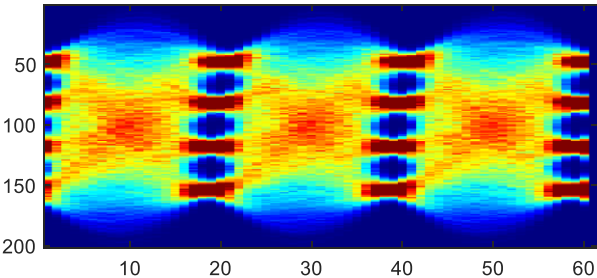
Pre-distorted



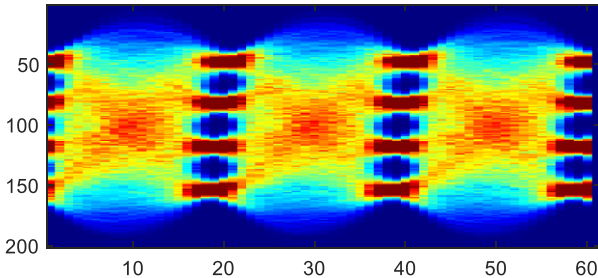
Received by the Scope



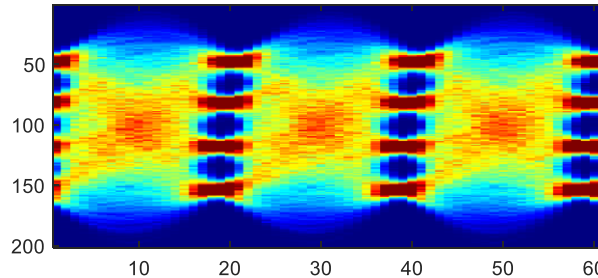
Equalized, FFE with 13 taps



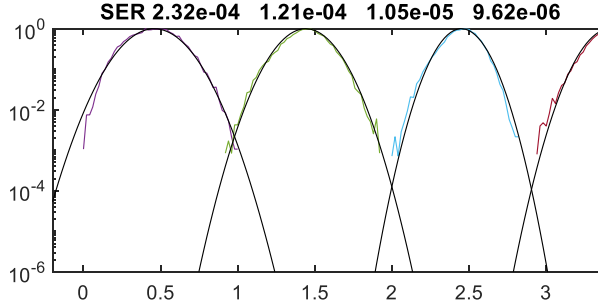
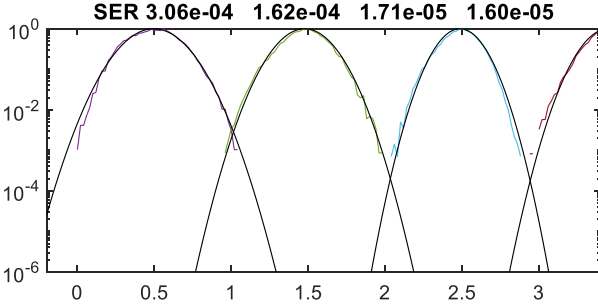
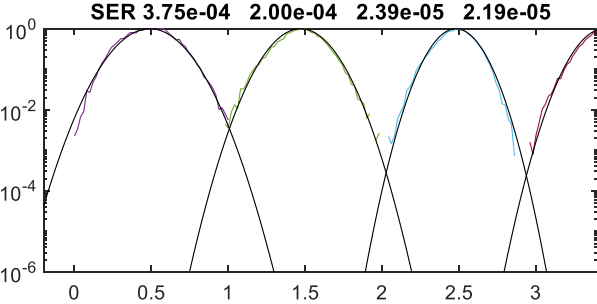
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps

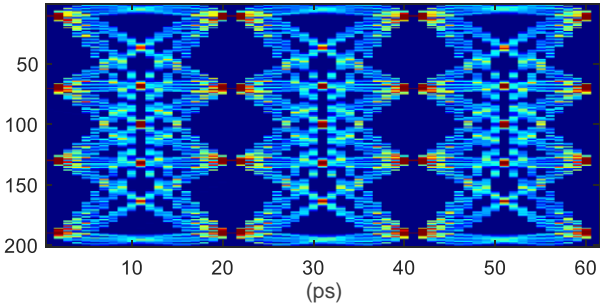


Histograms, and Symbol Error Rate

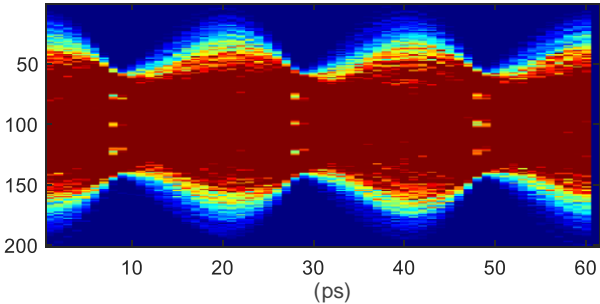


100Gbps OM4 30m with pre-distortion, *averaged eye*

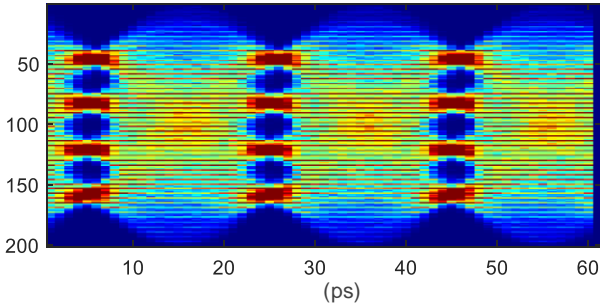
Mathematical Signal (R.C)



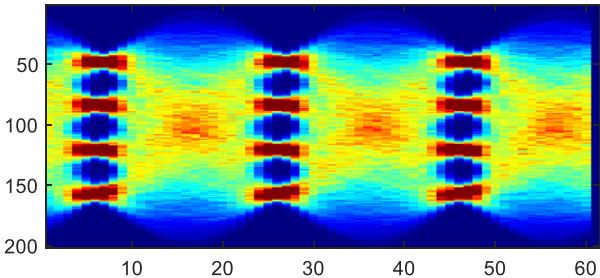
Pre-distorted



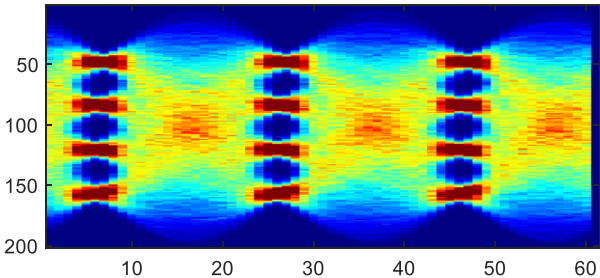
Received by the Scope



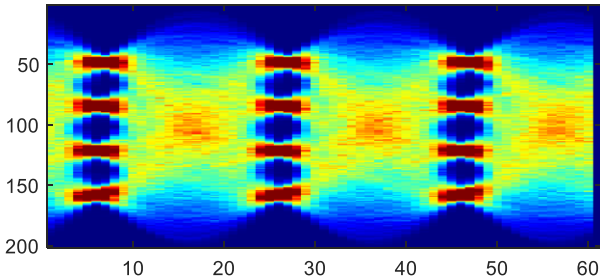
Equalized, FFE with 13 taps



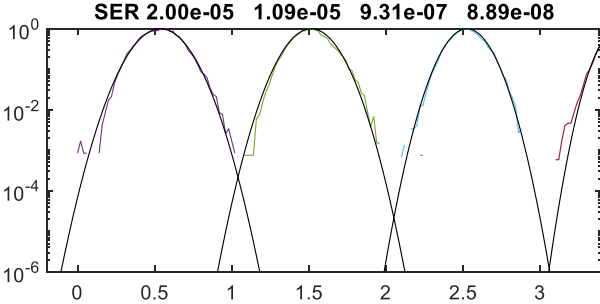
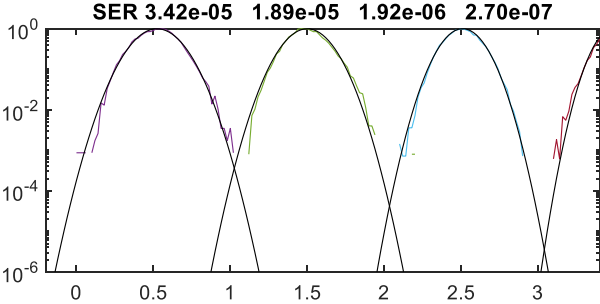
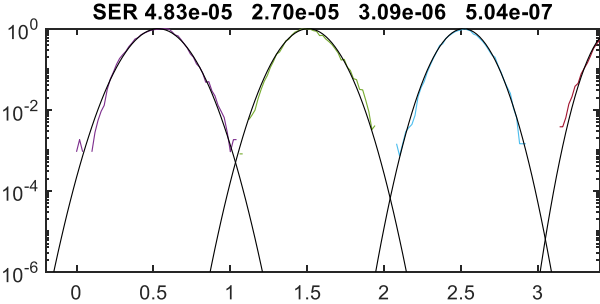
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps

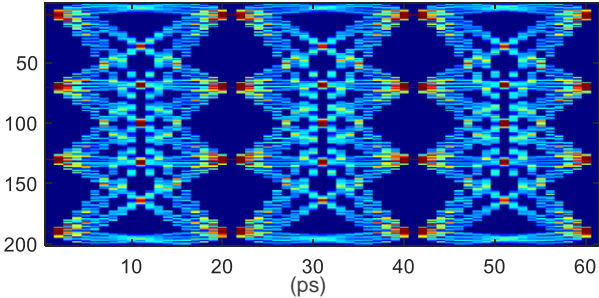


Histograms, and Symbol Error Rate

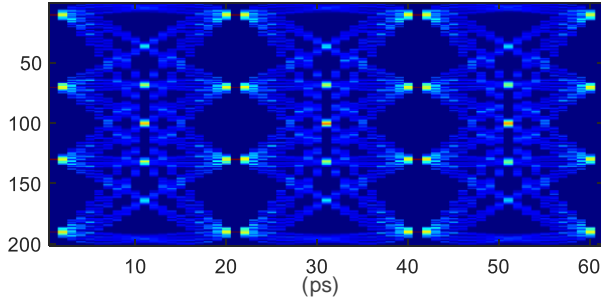


100Gbps OM4 50m without pre-distortion, *averaged eye*

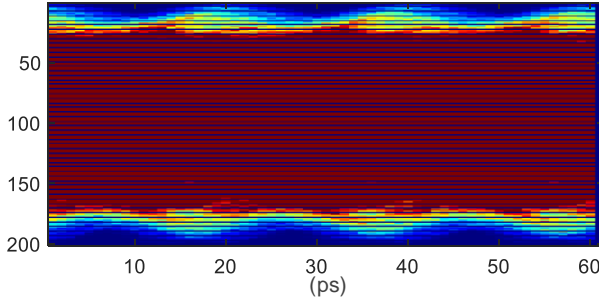
Mathematical Signal (R.C)



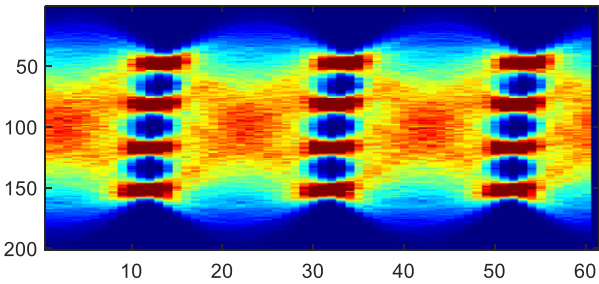
Pre-distorted



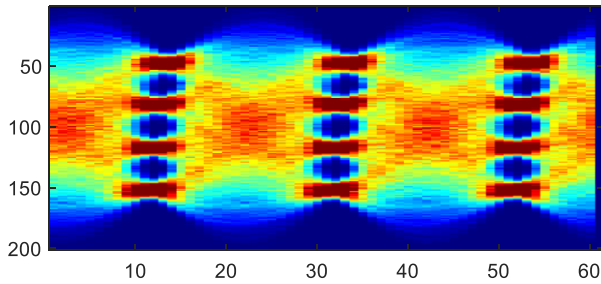
Received by the Scope



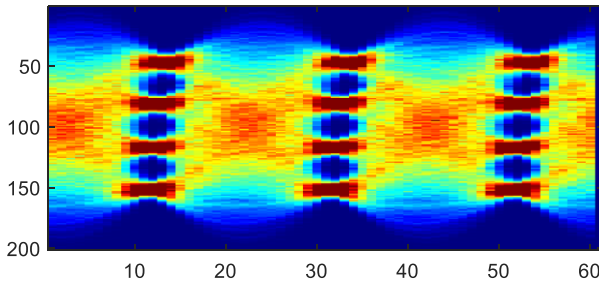
Equalized, FFE with 13 taps



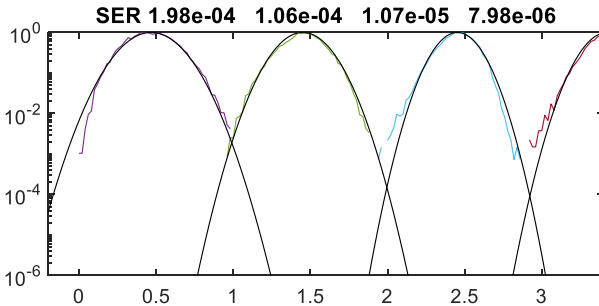
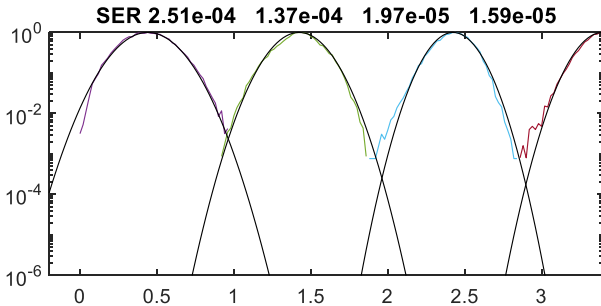
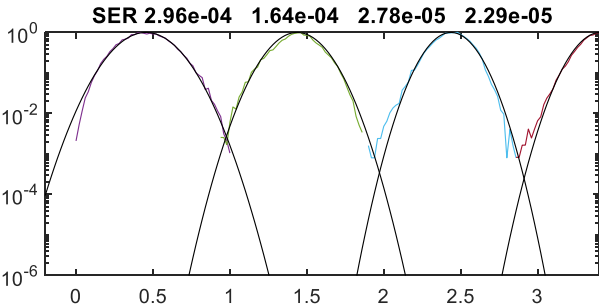
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps

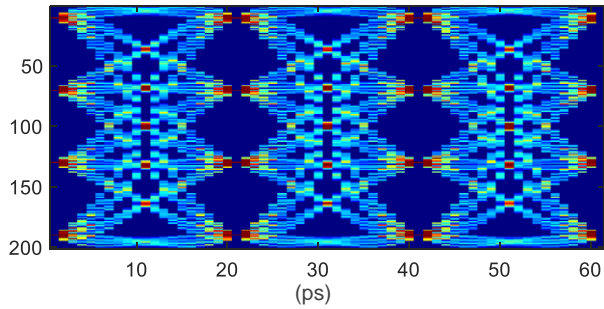


Histograms, and Symbol Error Rate

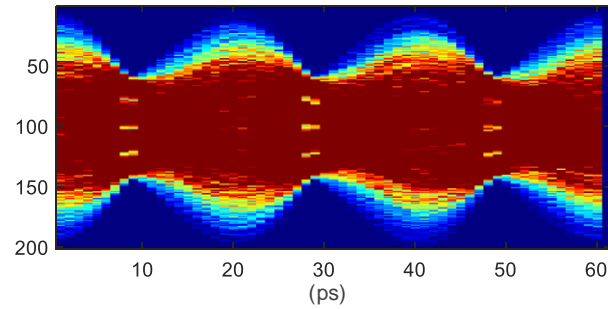


100Gbps OM4 50m with pre-distortion, *averaged eye*

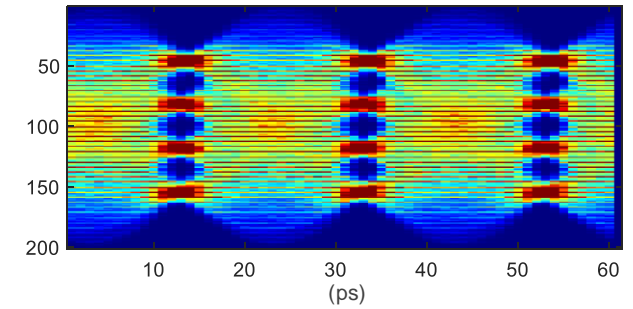
Mathematical Signal (R.C)



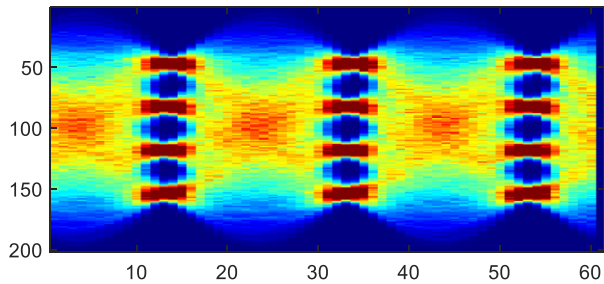
Pre-distorted



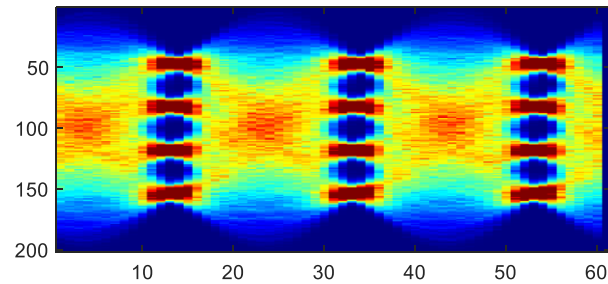
Received by the Scope



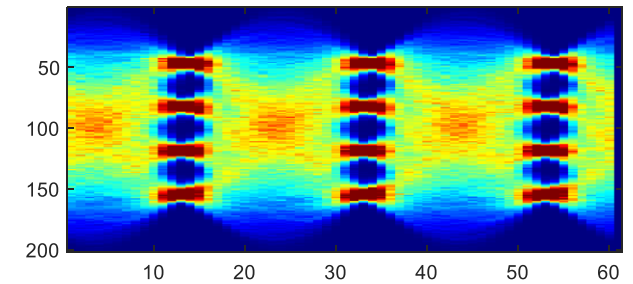
Equalized, FFE with 13 taps



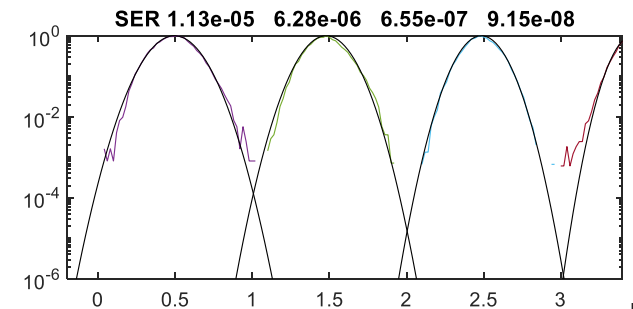
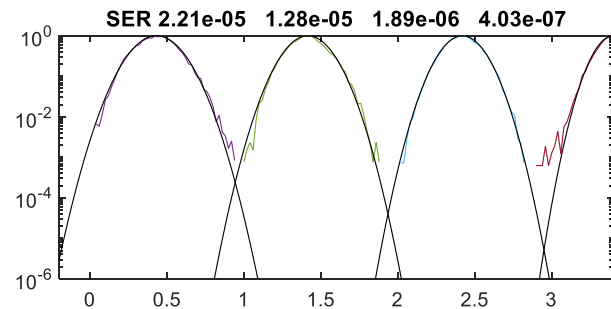
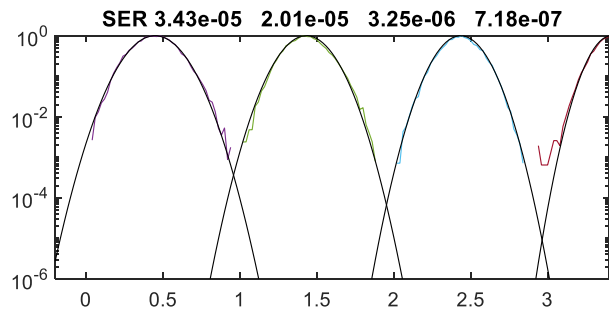
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps

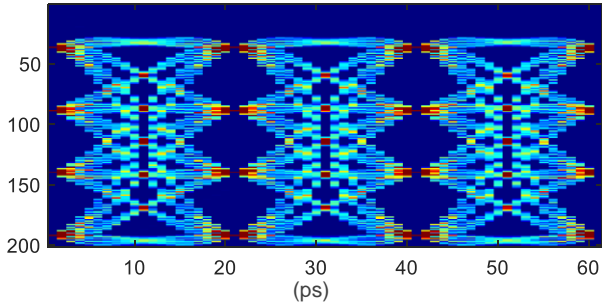


Histograms, and Symbol Error Rate

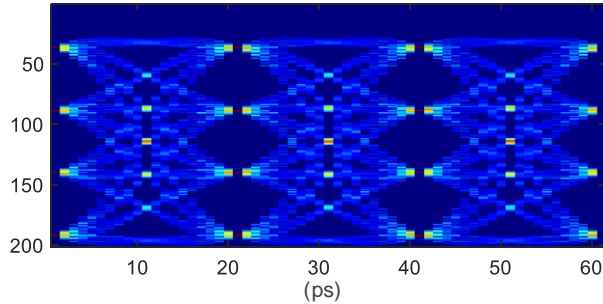


100Gbps OM4 100m without pre-distortion, *averaged eye*

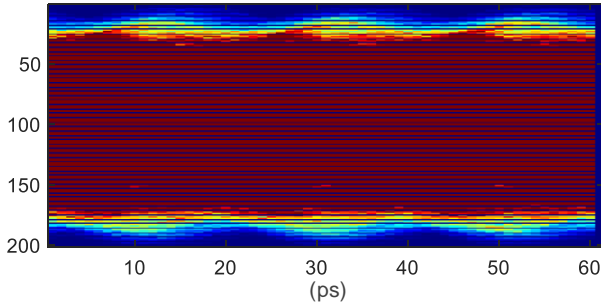
Mathematical Signal (R.C)



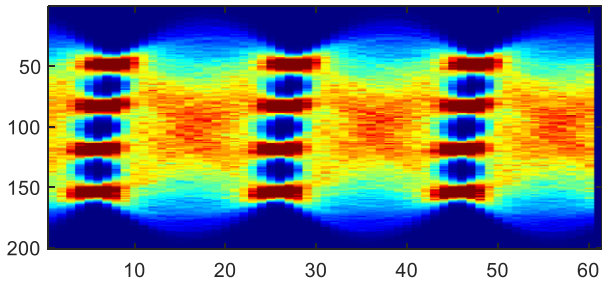
Pre-distorted



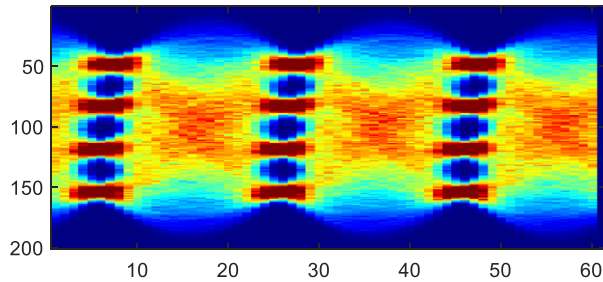
Received by the Scope



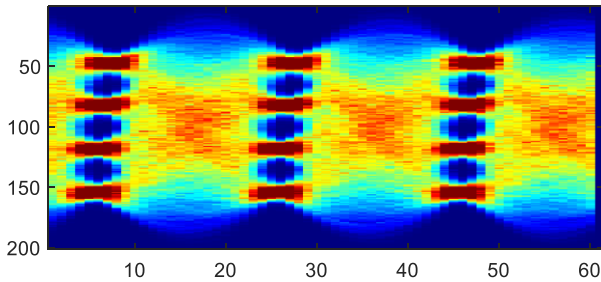
Equalized, FFE with 13 taps



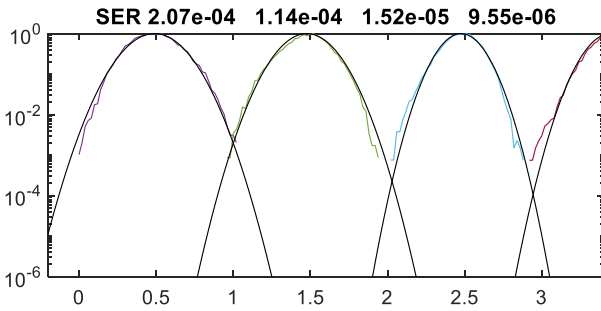
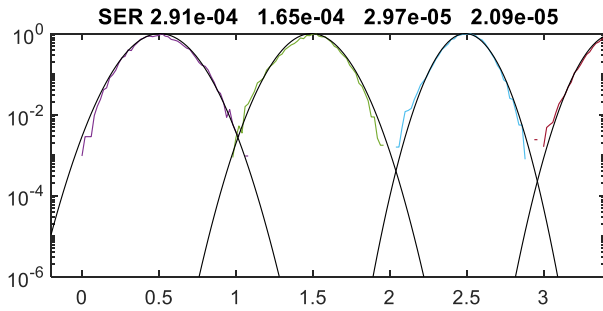
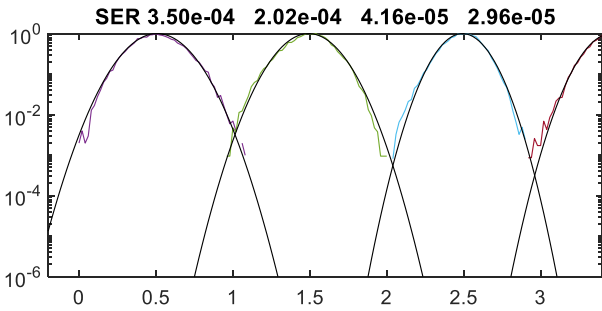
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps

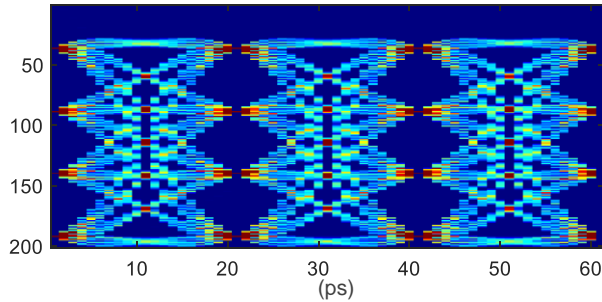


Histograms, and Symbol Error Rate

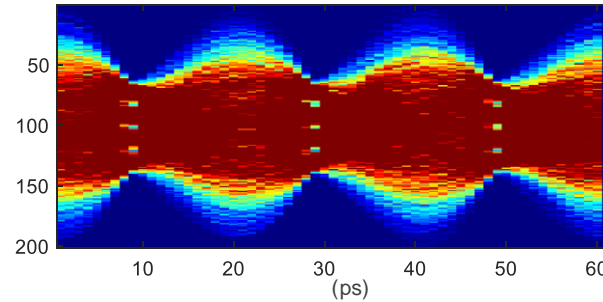


100Gbps OM4 100m with pre-distortion, *averaged eye*

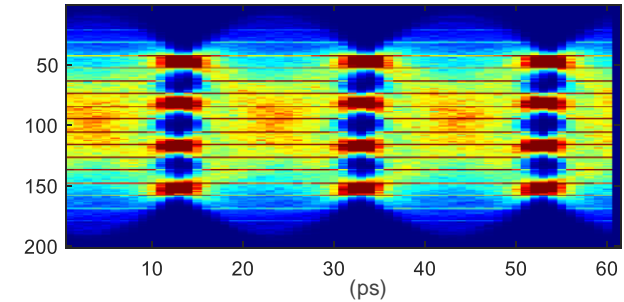
Mathematical Signal (R.C)



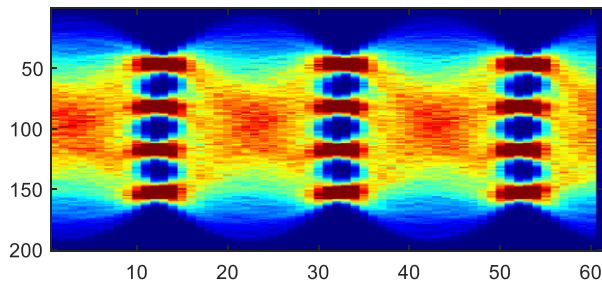
Pre-distorted



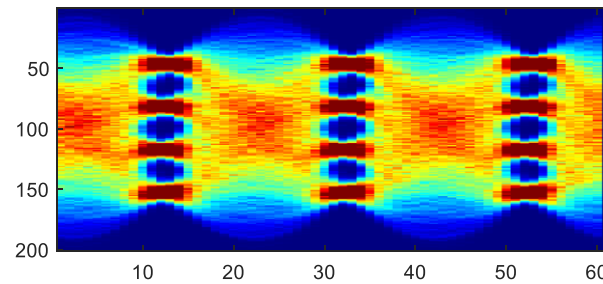
Received by the Scope



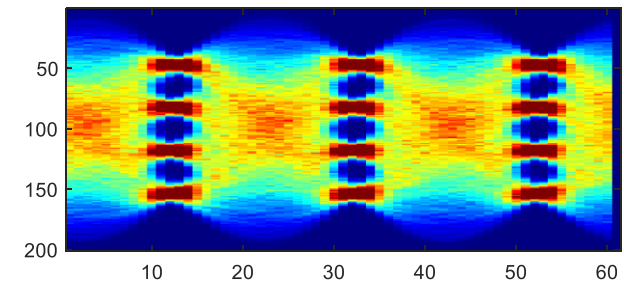
Equalized, FFE with 13 taps



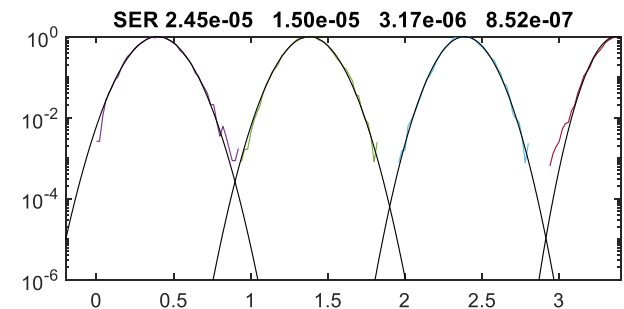
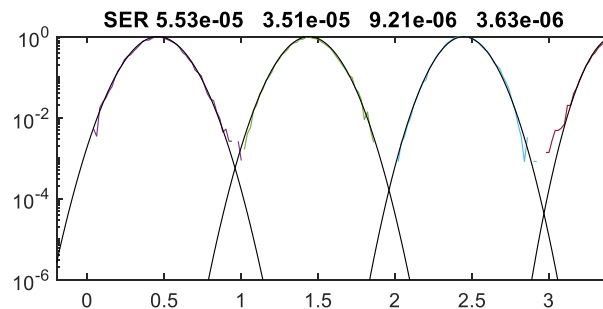
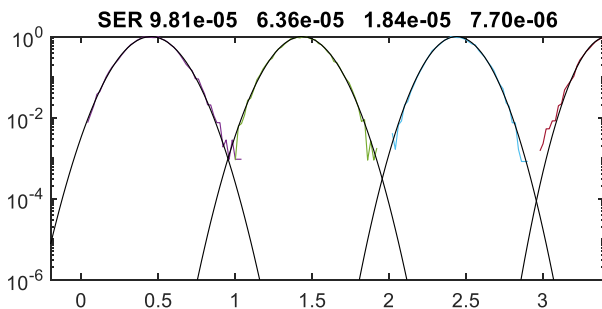
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps



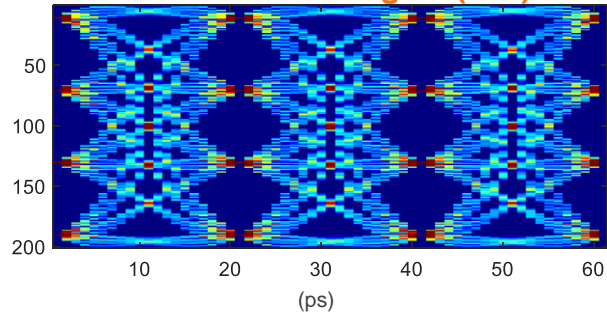
Histograms, and Symbol Error Rate



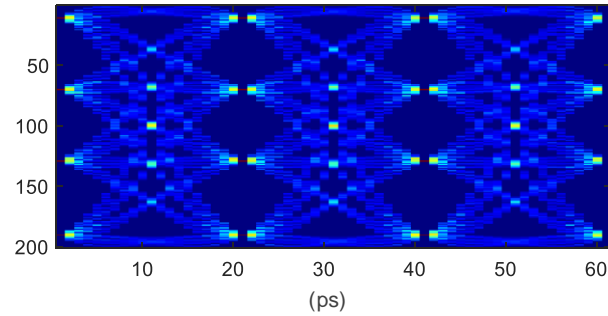
Eye degradation for non-averaging for 100m worst case OM4

100Gbps OM4 100m without pre-distortion, *noise included*

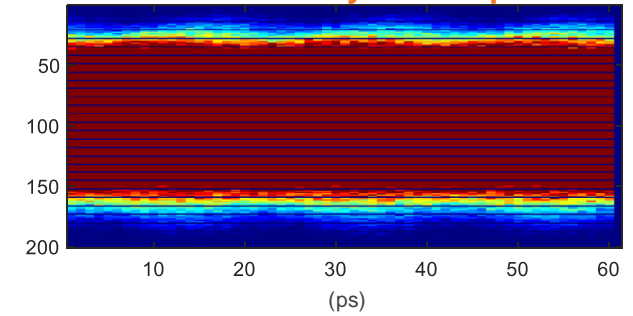
Mathematical Signal (R.C)



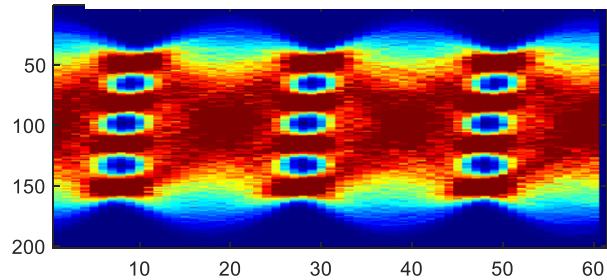
Pre-distorted



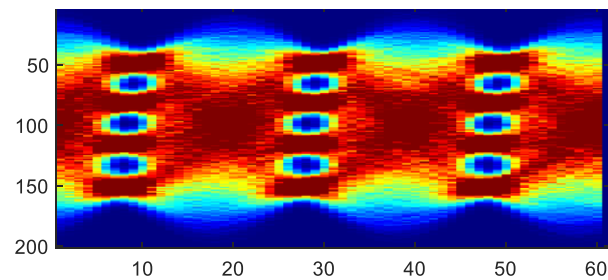
Received by the Scope



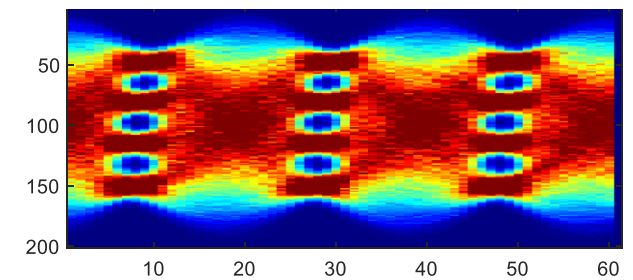
Equalized, FFE with 13 taps



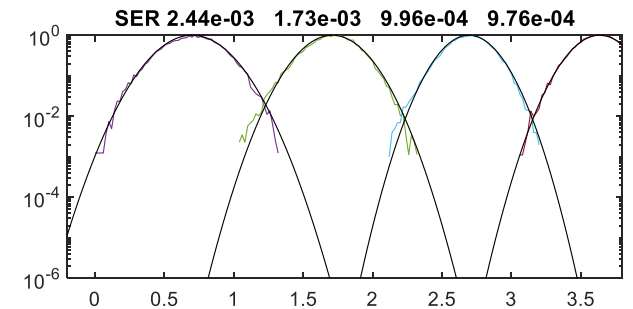
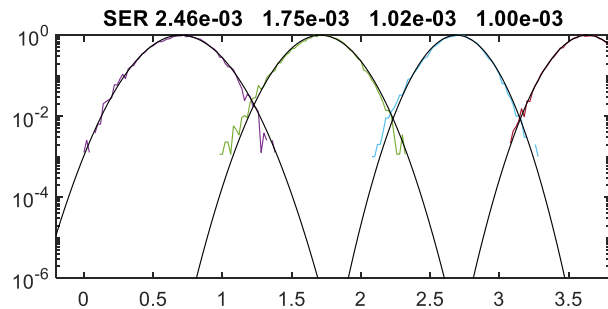
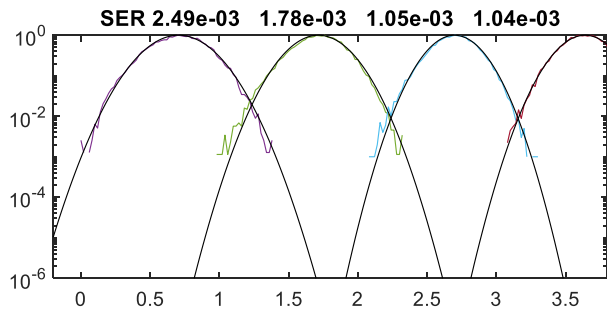
Equalized, FFE with 15 taps



Equalized, FFE with 17 taps

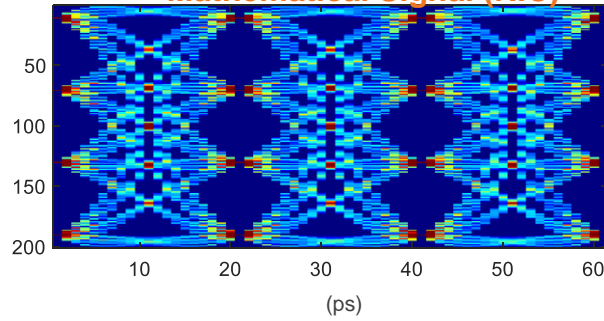


Histograms, and Symbol Error Rate

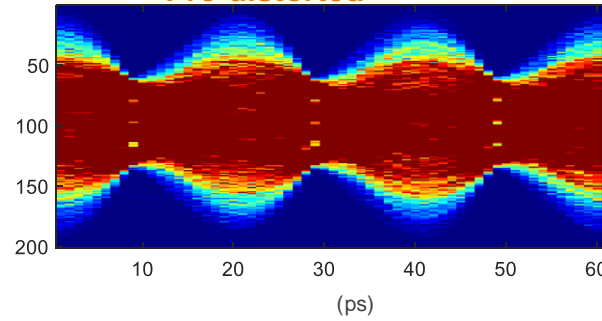


100Gbps OM4 100m with pre-distortion, *noise included*

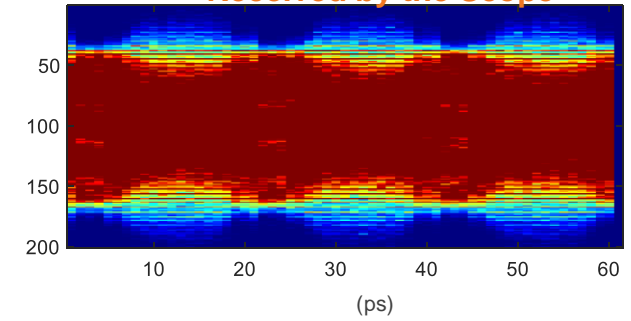
Mathematical Signal (R.C)



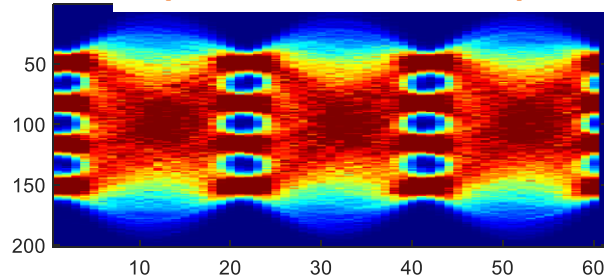
Pre-distorted



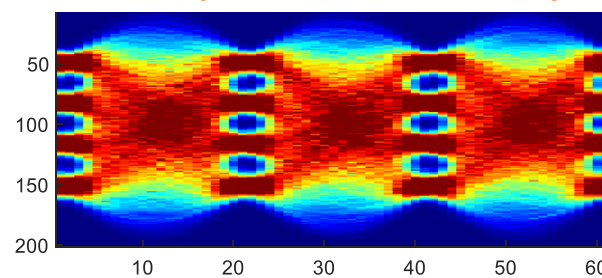
Received by the Scope



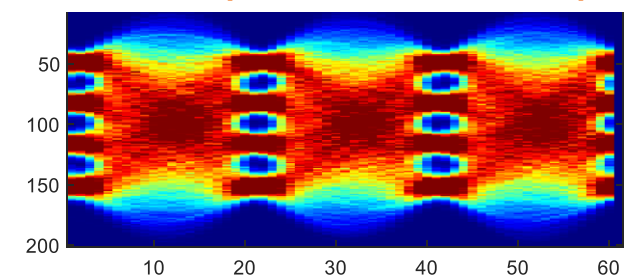
Equalized, FFE with 13 taps



Equalized, FFE with 15 taps



Equalized, FFE with 17 taps



Histograms, and Symbol Error Rate

