你所不知道的直接数字合成

Zhang Xin

Agenda

- Challenge for coherent 100G/400G
- Design and build reference coherent transmitter
- Considerations for ideal coherent receiver
- Summary

Challenges for 100G/400G

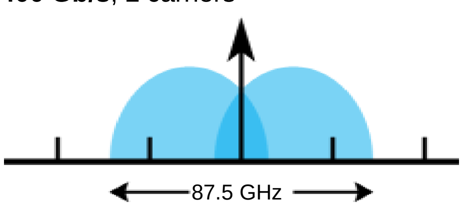
- Even as 100G coherent optical systems are being deployed, architecture for 400G systems and beyond are in development
- Current proposals vary considerably from the number of carriers, to the carrier spacing, to the modulation format used
- High accuracy complex modulation scheme more than QPSK
- The test and measurement system must have the flexibility to support any combination of system parameters

Example Industry Approaches to 400G and Beyond

- No industry consensus on how to build superchannels
- Vendors differ on characteristics as basic as carrier count and carrier spacing to what modulation format should be used

system rate	# of carriers	modulation format
400 Gb/s[1]	2	DP-16QAM
500 Gb/s[2]	5	DP-QPSK
500 Gb/s[3]	10	DP-QPSK
1.0 Tb/s[4]	10	DP-QPSK
1.5 Tb/s[5]	8	DP-16QAM

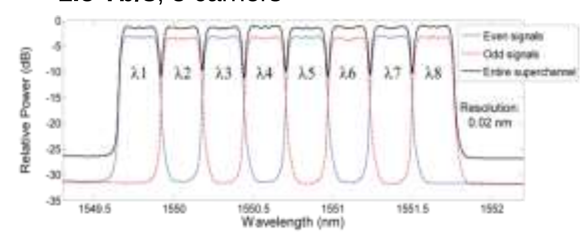
400 Gb/s, 2 carriers



500 Gb/s, 10 carriers

1.0 Tb/s, 10 carriers

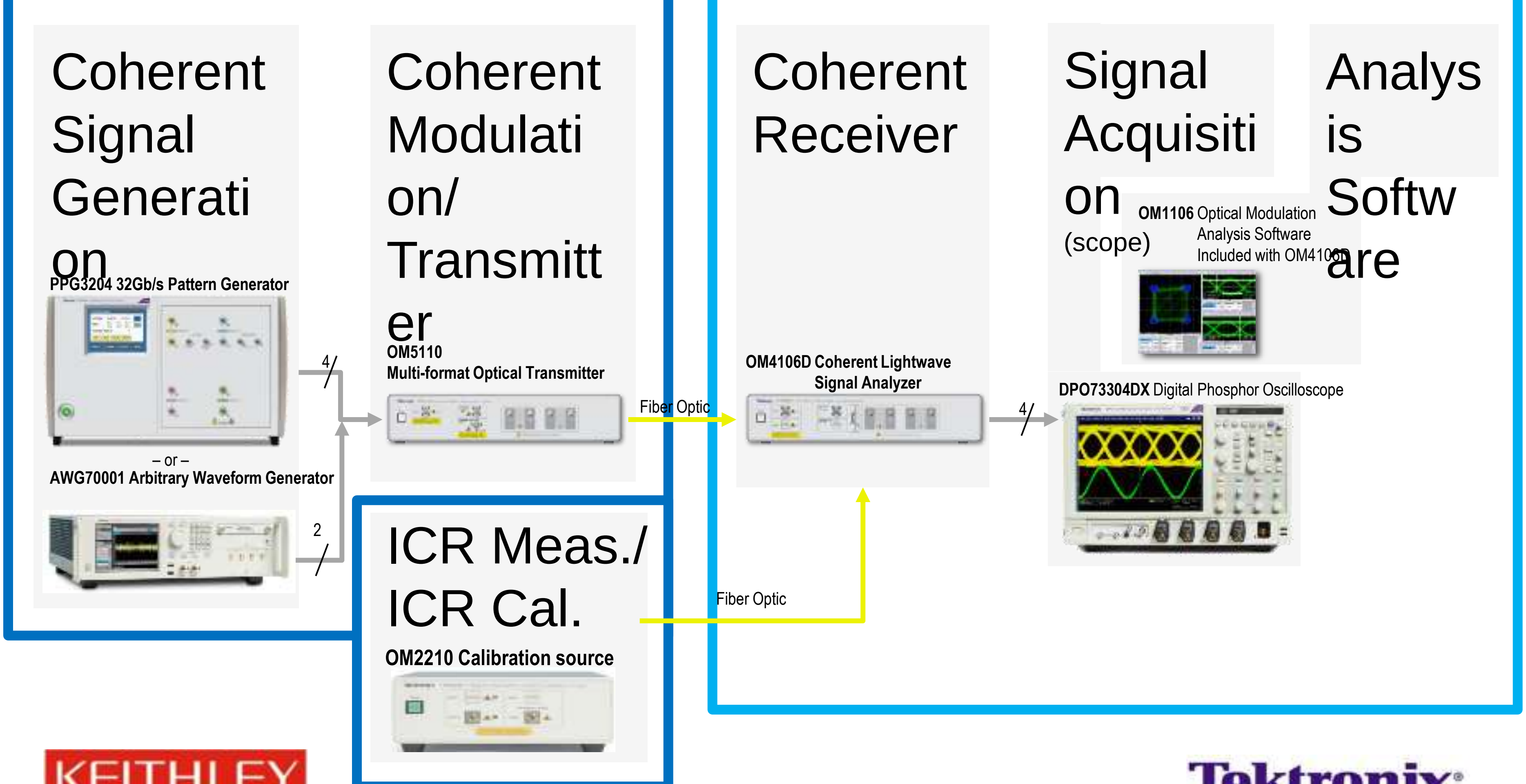
1.5 Tb/s, 8 carriers



Sources: [1]Beyond 100G, Fujitsu Network Communications, Inc.
[2]Dawn of the Terabit Age, Infinera Corporation
[3]Coherent Super-Channel Technologies, OSA Webinar, Infinera Corporation
[4]Super-Channels: DWDM Transmission at100Gb/s and Beyond, Infinera Corporation
[5]1.5-Tb/s Guard-Banded Superchannel Transmission over 56 × 100-km (5600-km) ULAF Using 30-Gbaud Pilot-Free OFDM-16QAM Signals with 5.75-b/s/Hz Net Spectral Efficiency, Alcatel-Lucent, Bell Labs

Coherent Optical T&M Platform

Tektronix offers complete end-to-end testing of coherent modulation formats.



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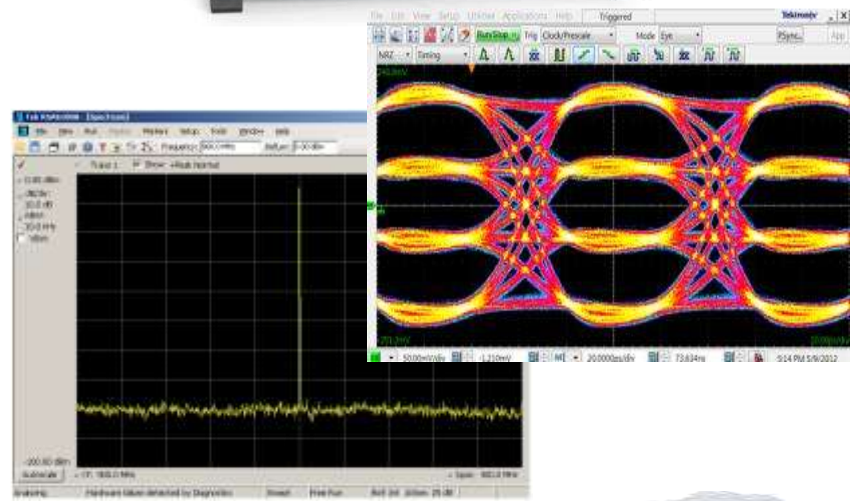
Tektronix

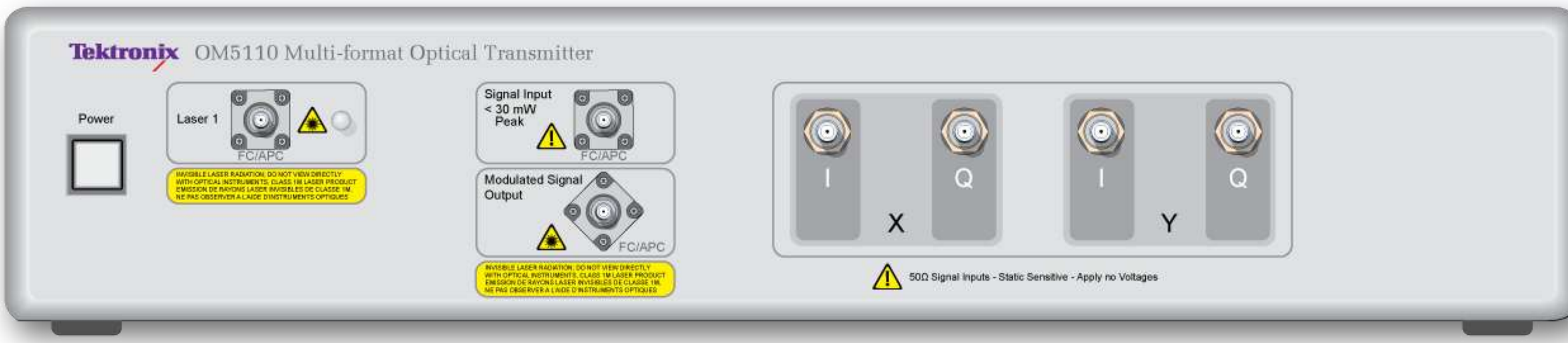
AWG70000A Arbitrary Waveform Generators

- Wideband RF signals at carrier up to 20GHz
- 10 bit Vertical Resolution
  - Allows for multi-level and signal compensation(PAM 4~16)
- 50 GS/s DAC
  - Can generate signal up to and above 32GBaud



"The sampling rate of 50 GS/s combined with the ability to synchronize two AWGs enabled us to generate 30-GBaud signals per optical carrier, with a data rate of 233 Gb/s, more than twice the previous record. The performance and signal purity of the AWG70000 more than met our requirements for this demanding experiment." –
S. Chandrasekhar, Bell Labs

OM5110 Tektronix Coherent Optical Modulator

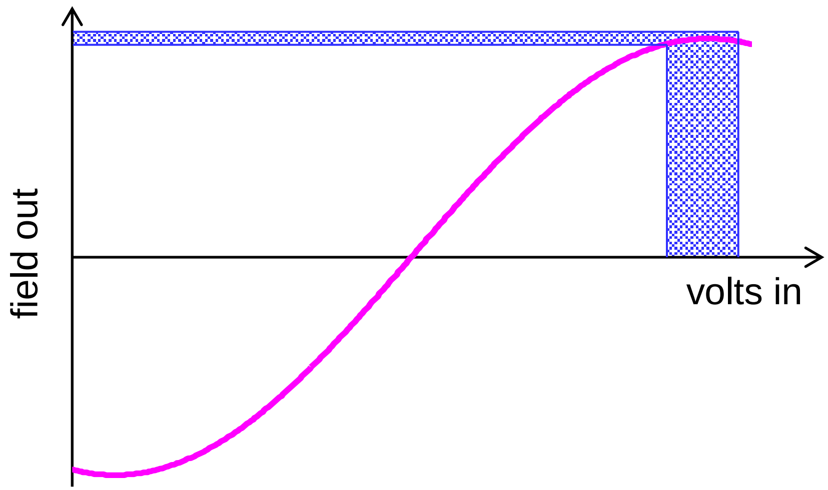


- 46 GBaud Coherent optical transmitter offers modulation of common complex modulation formats such as BPSK, DP-QPSK, PM-16QAM.
- Built-in C- or L-band lasers offer setup convenience. Instrument also supports use of external lasers.
- Instrument can be placed under control of Tektronix optical modulation analysis software and offers both manual and automatic bias control.

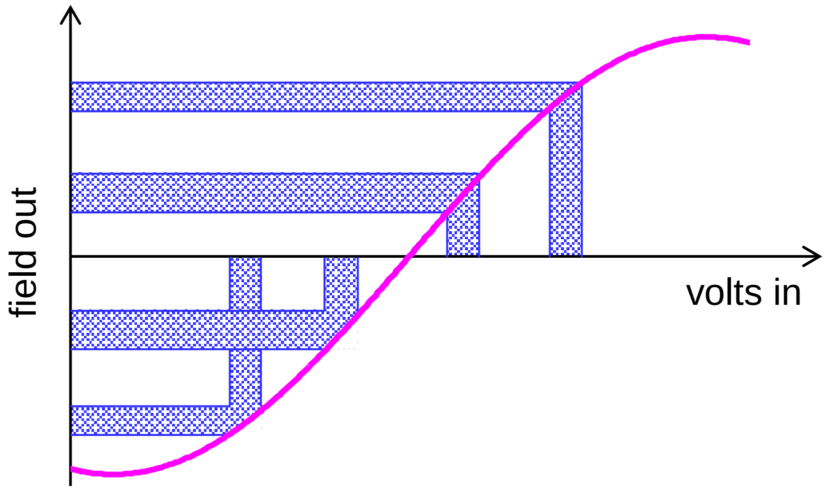
Challenges upgrading from QPSK to QAM

- For 20 years external optical modulators (typically $LiNbO_3$ Mach-Zehnder) have successfully generated **binary** signals
  - OOK, BPSK and QPSK are all examples of binary modulation
- Drive amplifiers operated with output stage in saturation
  - gives clean 2-level signal even if frequency response of linear stages is not flat
- Mach-Zehnder has natural sine-shaped response
  - hides ISI in drive signal, impact of non-flat frequency response of modulator

Binary modulation



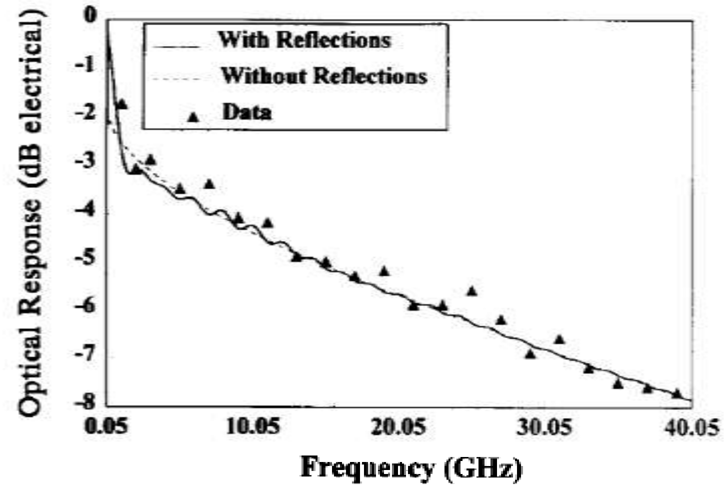
Multilevel modulation



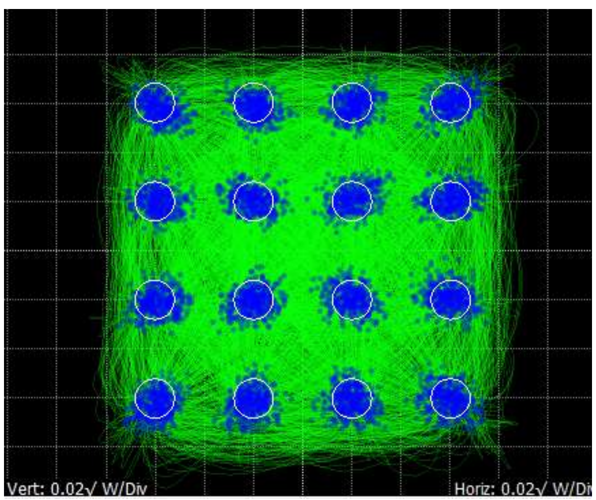
- **With multilevel modulation response of amp + modulator no longer hidden**

Challenges upgrading from QPSK to QAM

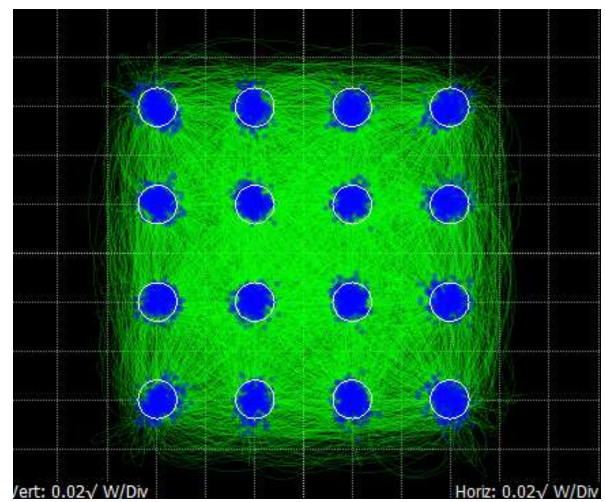
- Lithium niobate modulator has structure in its frequency response at low frequencies
  - skin loss in microstrip electrode
  - phase matching of backward travelling wave component
- Example (right) is for z-cut Ti-diffused waveguide
  [Gopalakrishnan et al., JLT, vol. 12, 1994, p. 1807-1819]
- 28 Gbaud 16-QAM optical signals
  - Examples use clean (<4% EVM) electrical signal



Without equalization: EVM = 9%



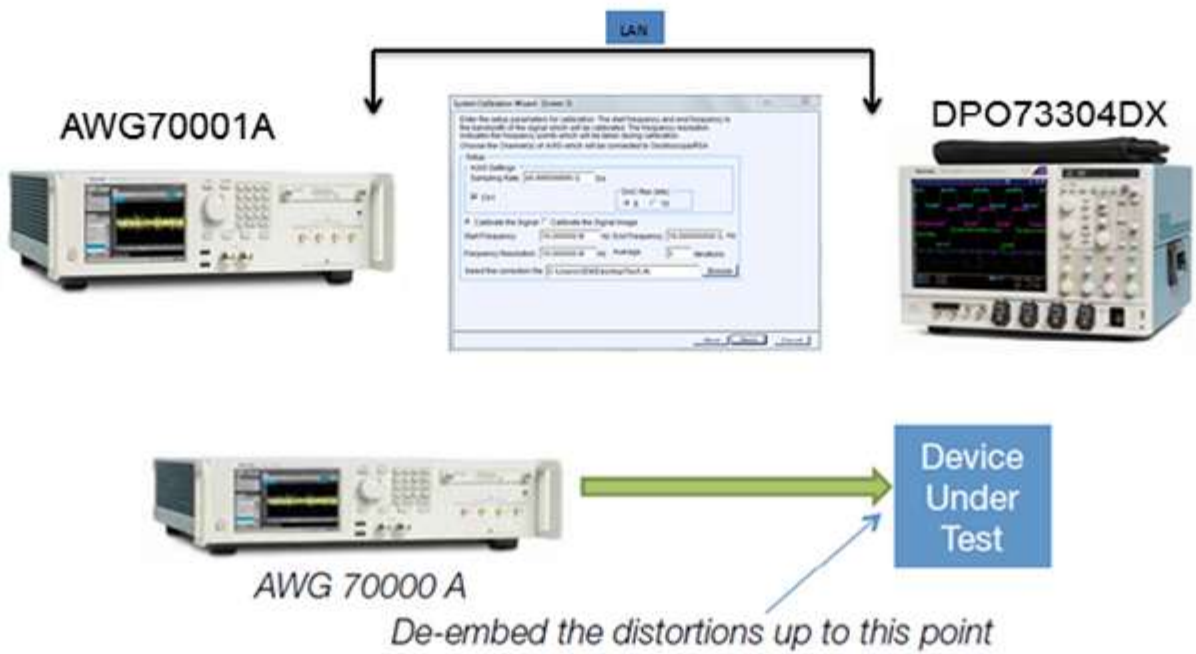
With equalization: EVM = 6.4%



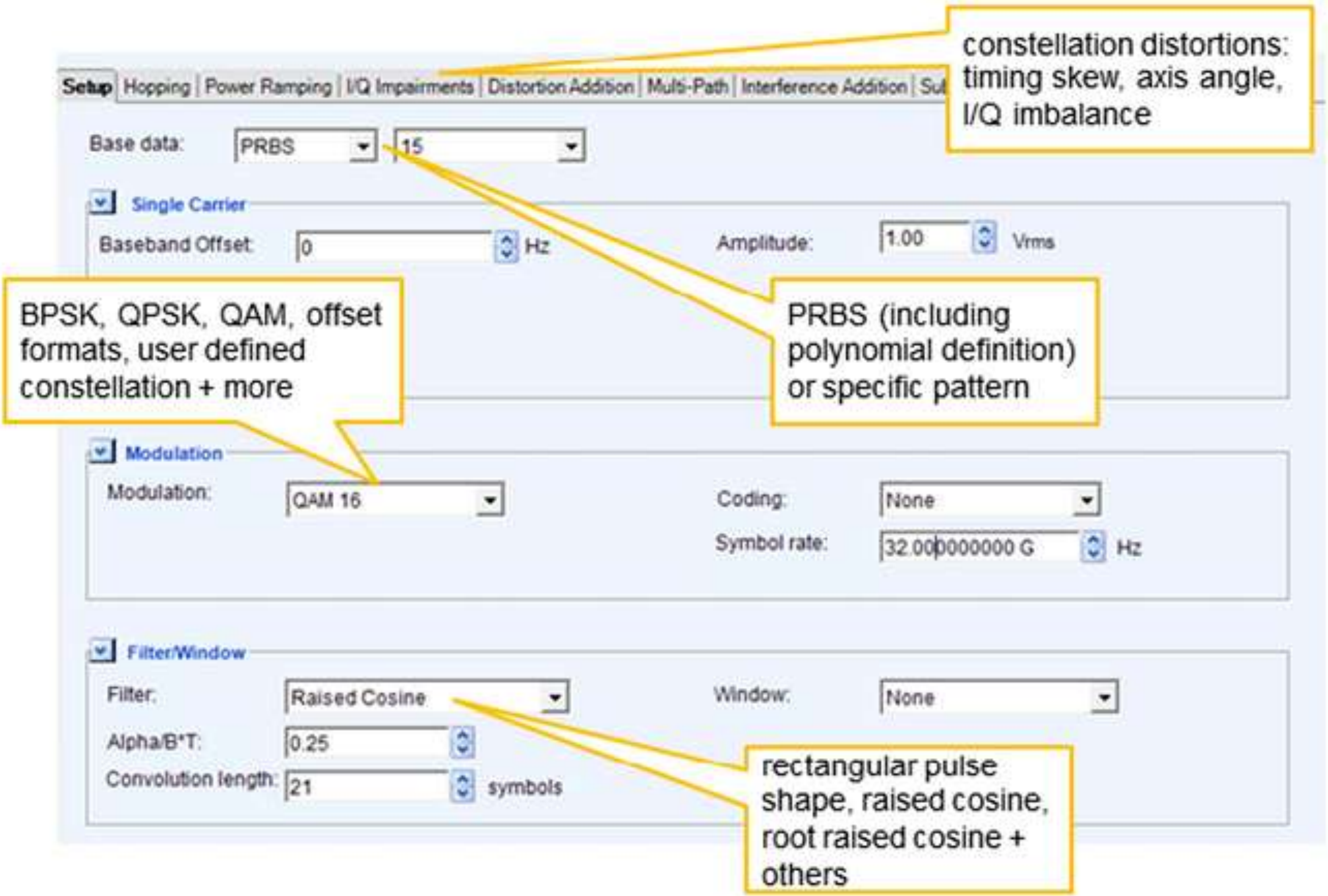
- **Equalized drive signal is better than usual 4-level drive signal for 16-QAM**

Pre-compensation in RFXpress for Coherent Modulation and transmission

- Calibration is performed using RFXpress from Tektronix
- SignalVu/OUI software running on DPO73304DX is used to measure the EVM

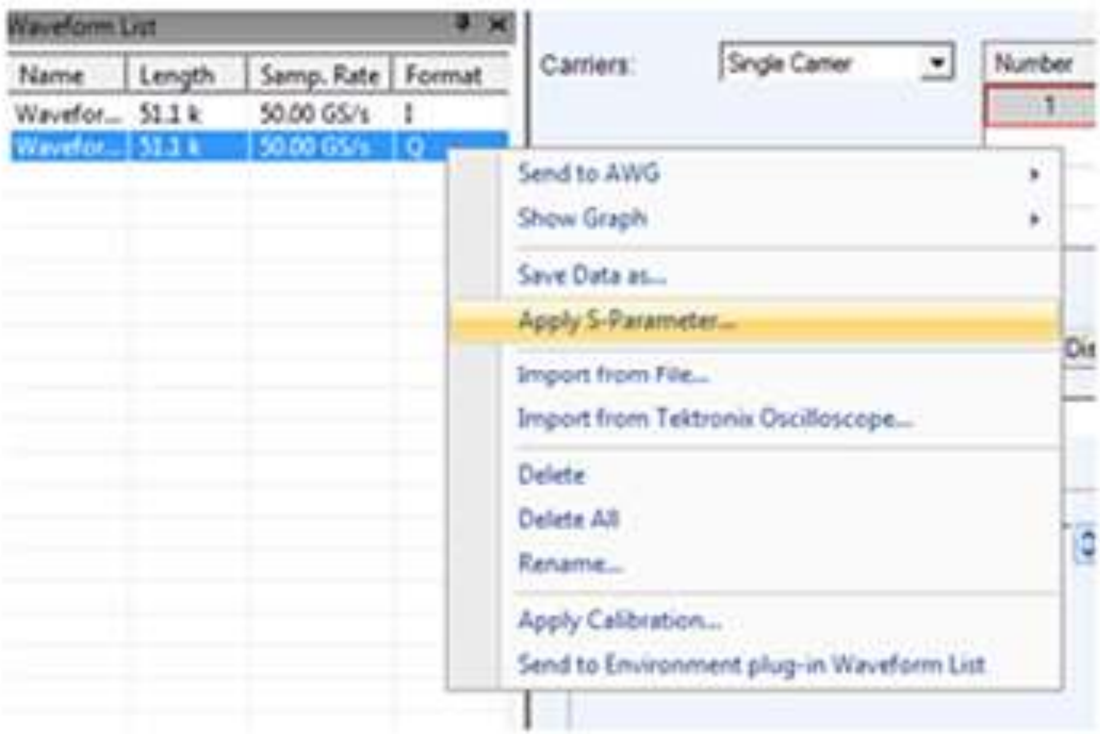


Using RFXpress design waveform



Using RFXpress design waveform

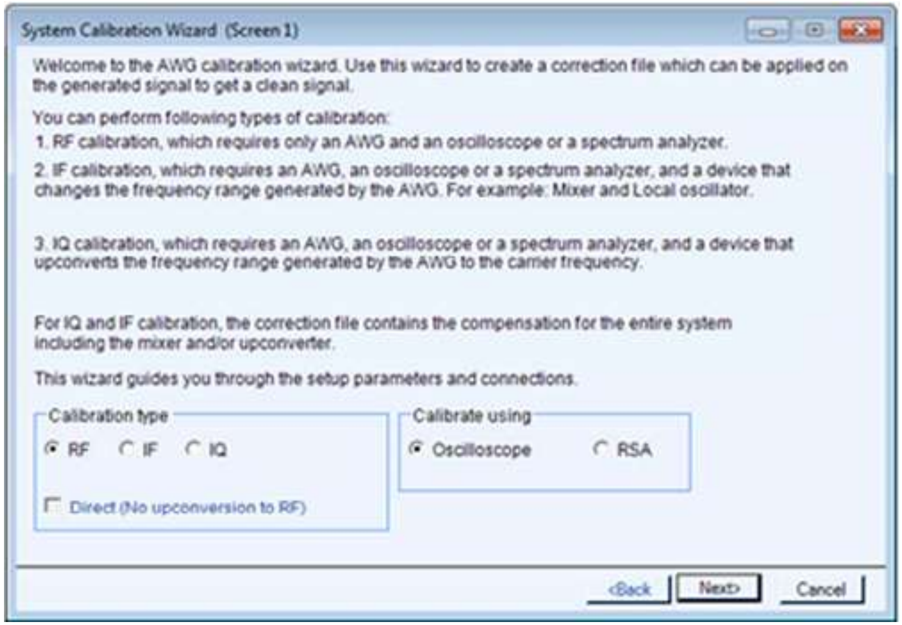
- Apply correction, either from the file supplied by Tektronix or user's own calibration
  - Corrections for multiple hardware elements can be applied in turn, e.g. first AWG then optical transmitter



Using RFXpress design waveform

- RFXpress included calibration wizard, to obtain calibration of AWG + following hardware
- Connects directly to AWG & oscilloscope, sends test waveforms, acquire results, and process them to give calibration file

1. RFXpress is used to create baseband 32Gbaud QSPK signal
2. RFXpress ‘RF’ Calibration used to create the correction coefficients.
3. Signal is connected to scope to find roll off point and correction coefficients are send back to RFXpress
4. RFXpress is used again to recreate the signal with correction coefficients/pre-compensation applied
5. Final waveform is downloaded to AWG70001A for transmission



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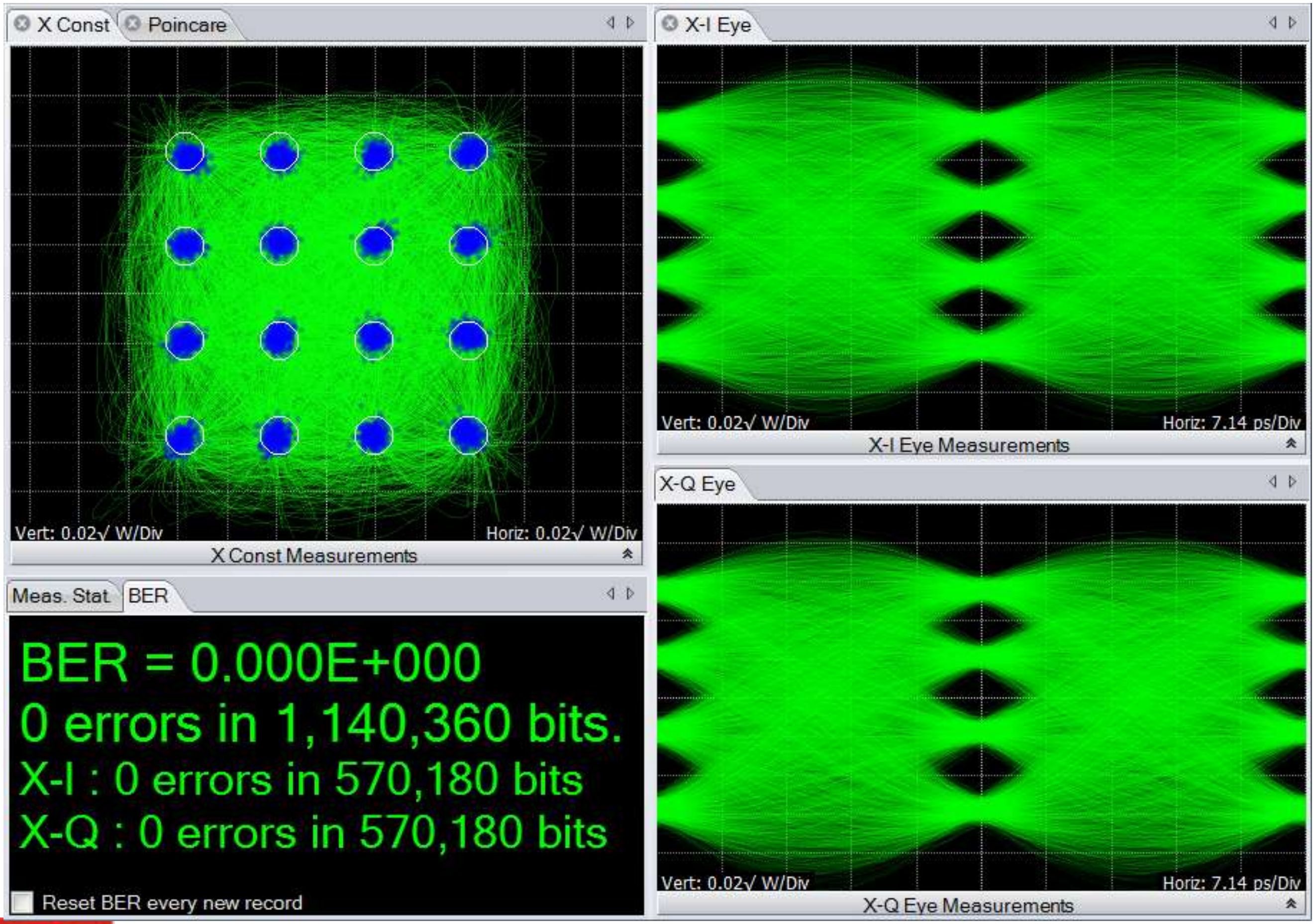
Examples of equalized OM5110 transmitter output

- 28 Gbaud 16-QAM optical signal
- EVM = 5.8%



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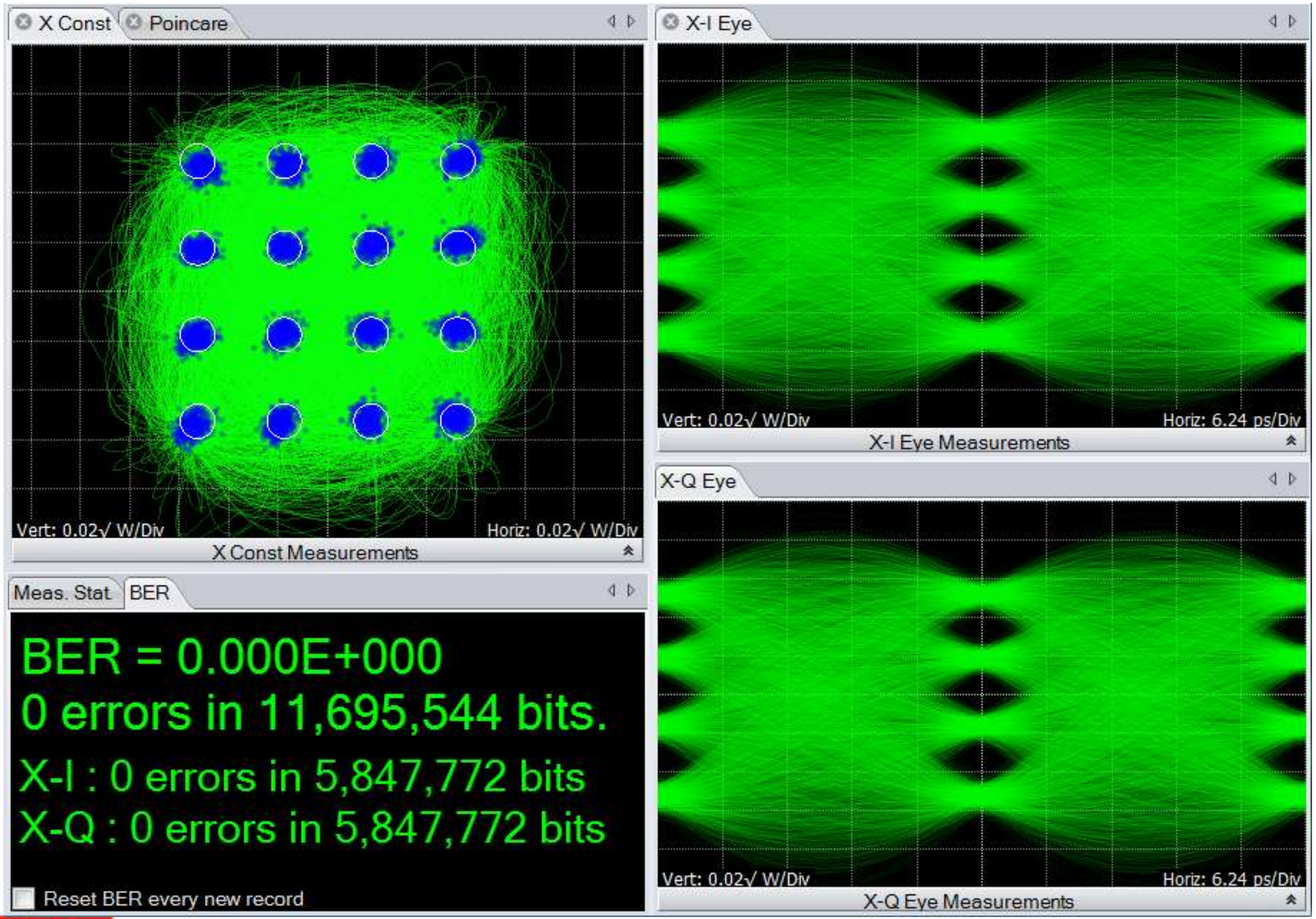
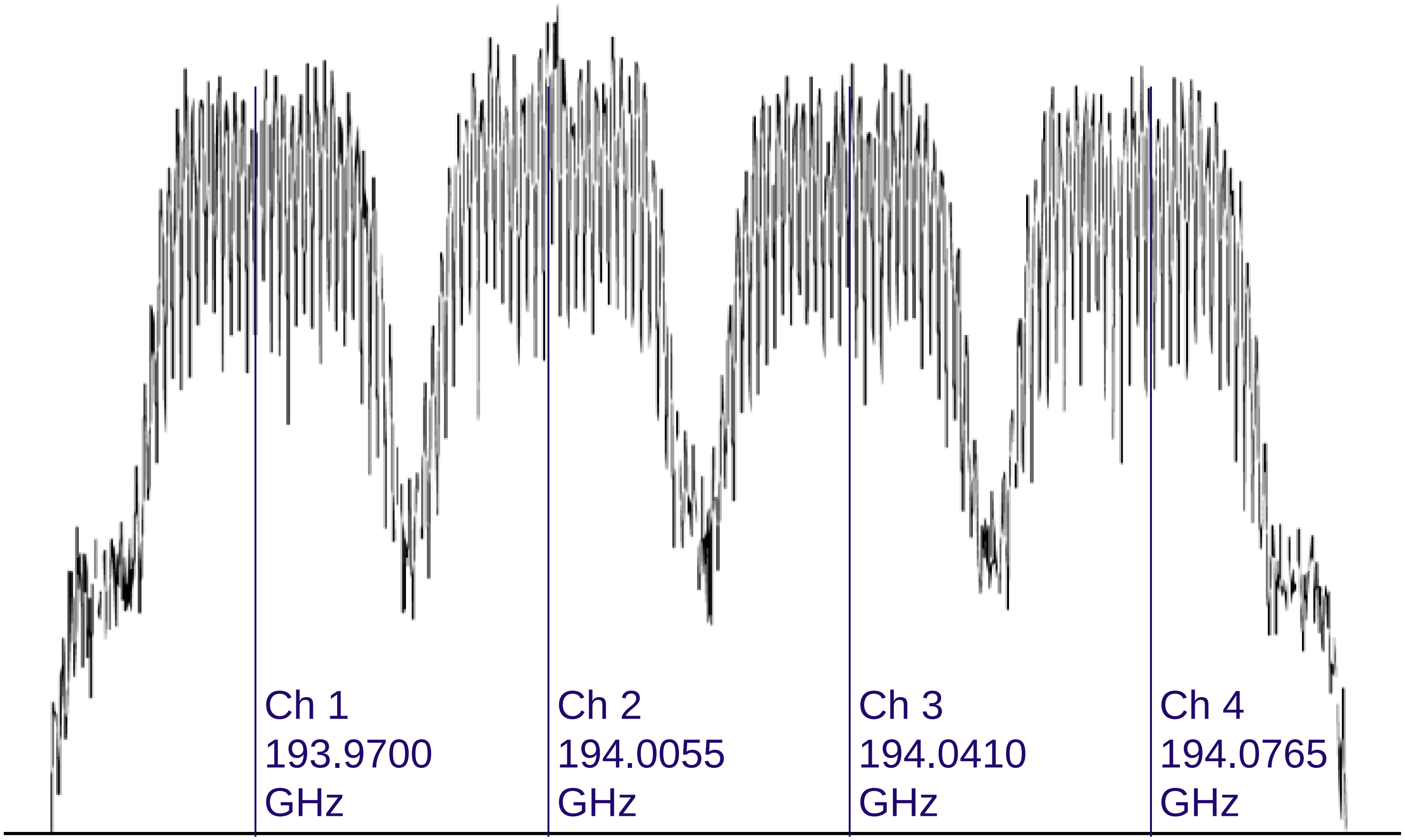
Examples of equalized OM5110 transmitter output

- 32 Gbaud 16-QAM optical signal
- EVM = 6.5%



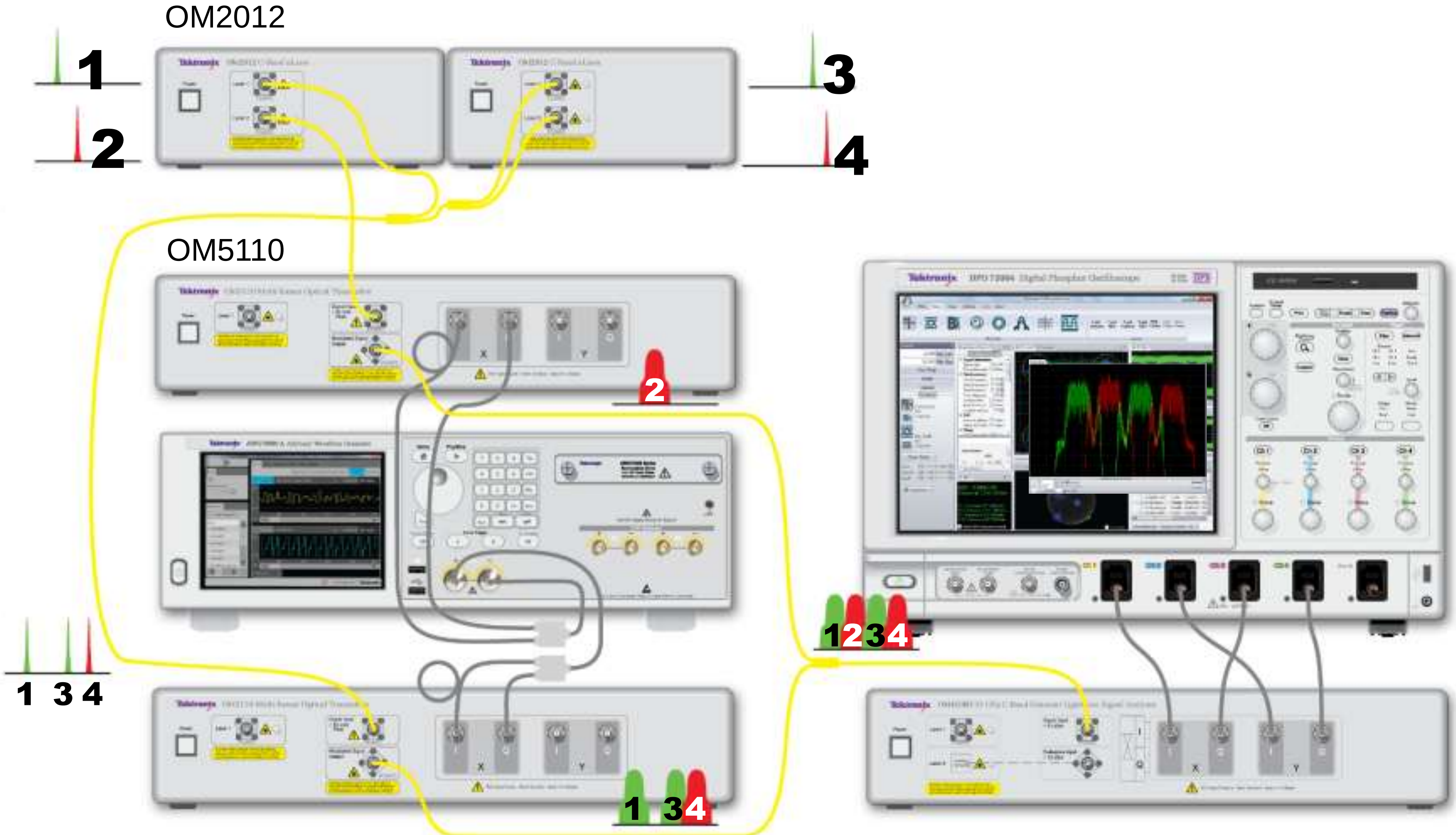
400G Multi-Carrier Super-Channel

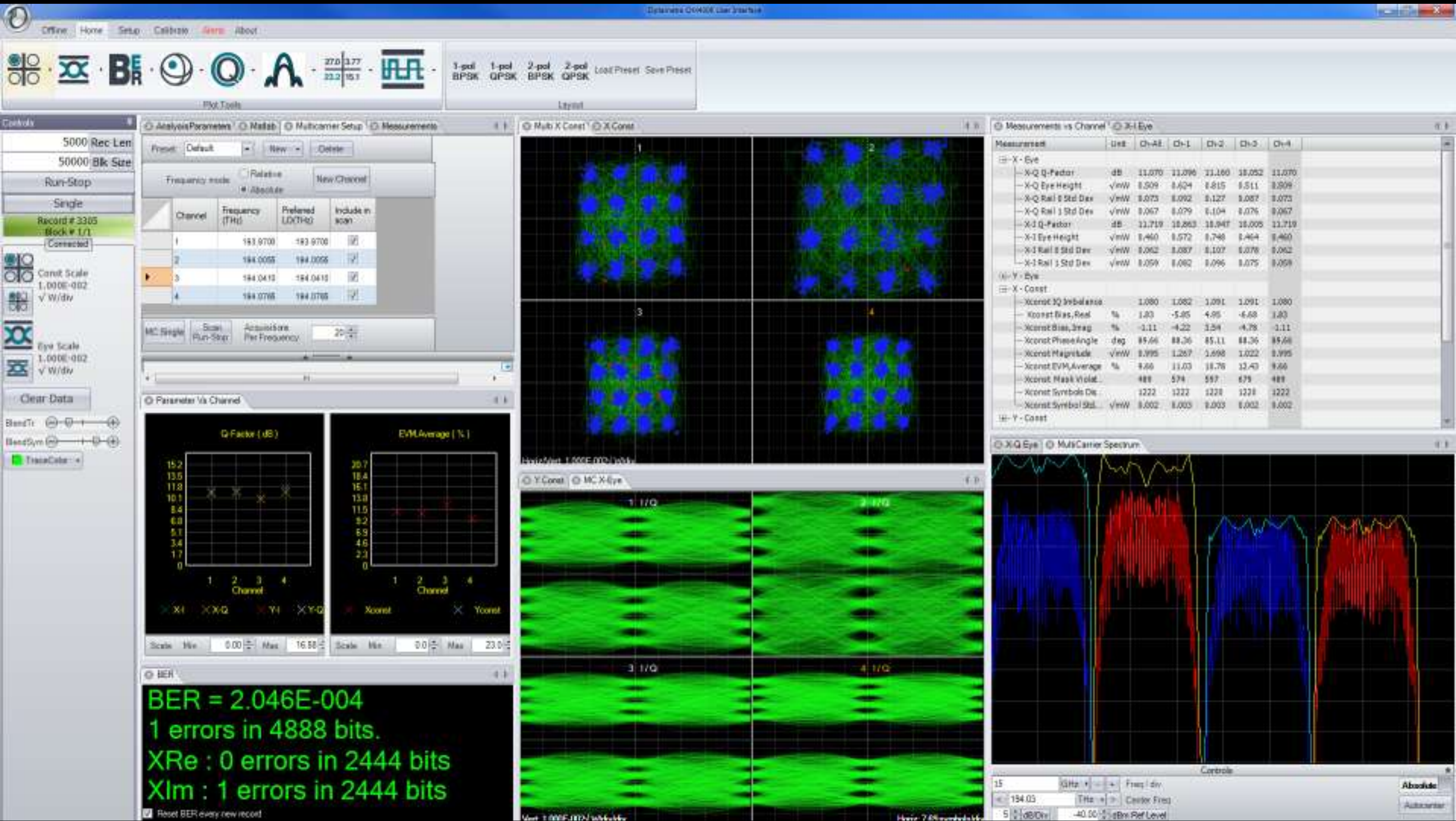
Example: Spectrum of 4-Carrier Super-Channel



400G Multi-Carrier Super-Channels

Demo on OFC2

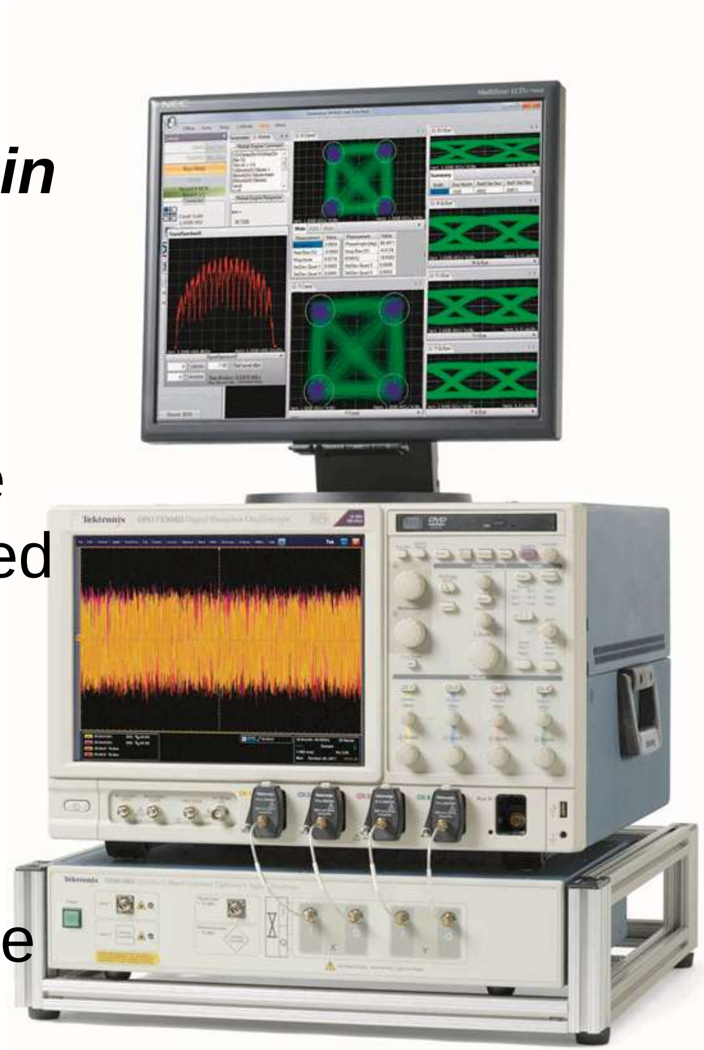




Offline
Home
Setup
Calibrate
About
1-pol BPSK
1-pol QPSK
2-pol BPSK
2-pol QPSK
Load Preset
Save Preset
Plot Tools
Layout
Controls
5000 Rec Len
50000 Blk Size
Run-Stop
Single
Connected
Const Scale
Eye Scale
Clear Data
Multi X Const
Measurements vs Channel
Parameter Vs Channel
Q-Factor (dB)
EVM Average (%)
Channel
BER
BER = 2.046E-004
1 errors in 4888 bits.
XRe : 0 errors in 2444 bits
XIm : 1 errors in 2444 bits
MultiCarrier Spectrum

OM4106D 33 GHz Coherent Lightwave Signal Analyzer

Complete and open solutions to complex measurement challenges in long-haul fiber-optic communications



- Advanced dual-polarization in-phase and quadrature receiver with integrated signal and reference tunable laser sources
- Open-architecture MATLAB-based computational engine offers :
  - powerful phase-recovery analyze
  - polarization, bit-error rates
  - record/playback
- Intuitive graphical user interface controls frequently used instrument

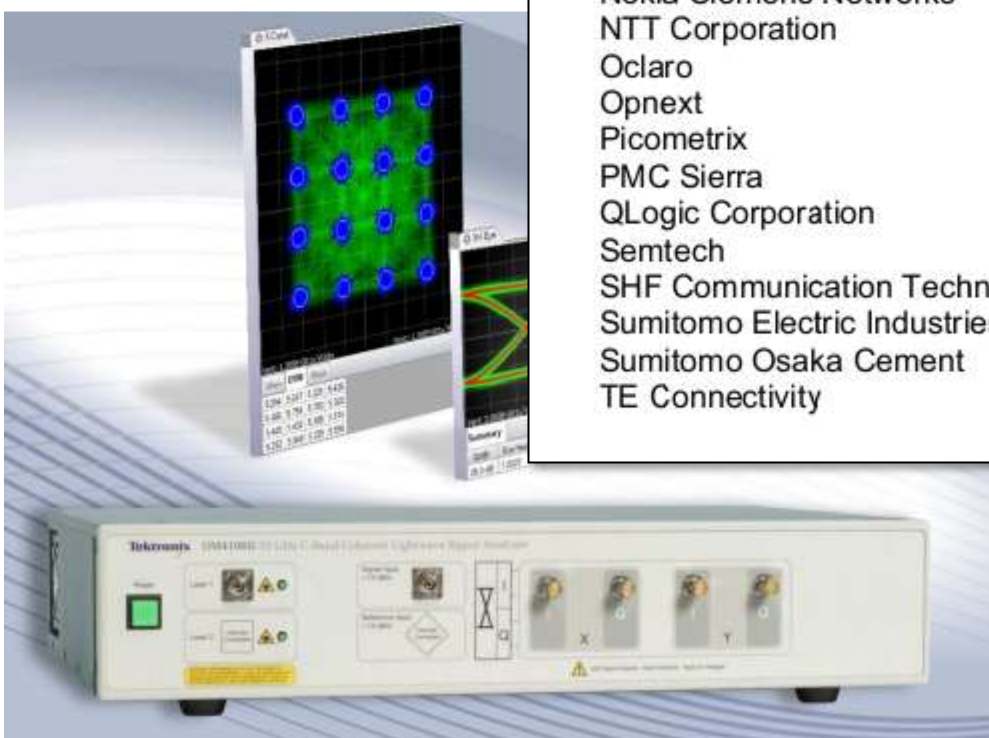
Tektronix OM4000 series ‘ICR’ compliance with OIF

- Only the T&M vendor in OIF member list
- First instrumentation ICR in the world

OIF OPTICAL INTERNETWORKING FORUM

IA # OIF-DPC-RX-01.1
IA for Integrated Intradyne Coherent Receivers

NEC
NeoPhotonics
Nokia Siemens Networks
NTT Corporation
Oclaro
Opnext
Picometrix
PMC Sierra
QLogic Corporation
Semtech
SHF Communication Technologies
Sumitomo Electric Industries
Sumitomo Osaka Cement
TE Connectivity
Tektronix
Telcordia Technologies
Tellabs
TeraXion
Texas Instruments Iain Robertson
Time Warner Cable
TriQuint Semiconductor
u2t Photonics AG
Verizon
Vitesse Semiconductor
Xilinx
Xtera Communications
Yamaichi Electronics Ltd.
ZTE Corporation



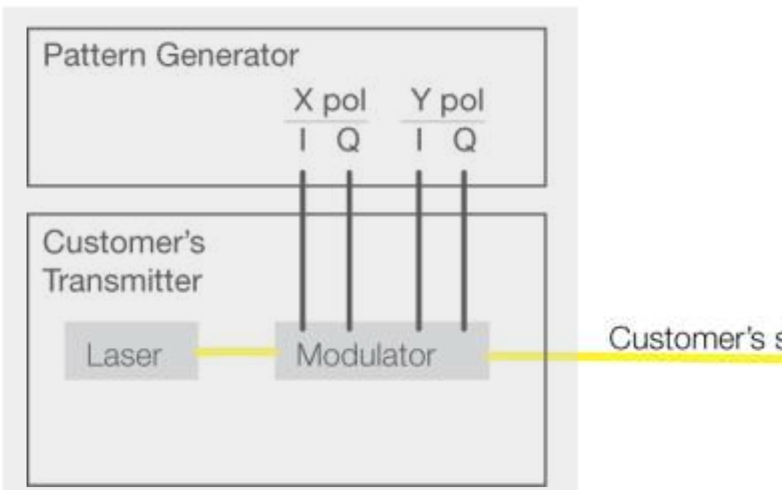
Tektronix

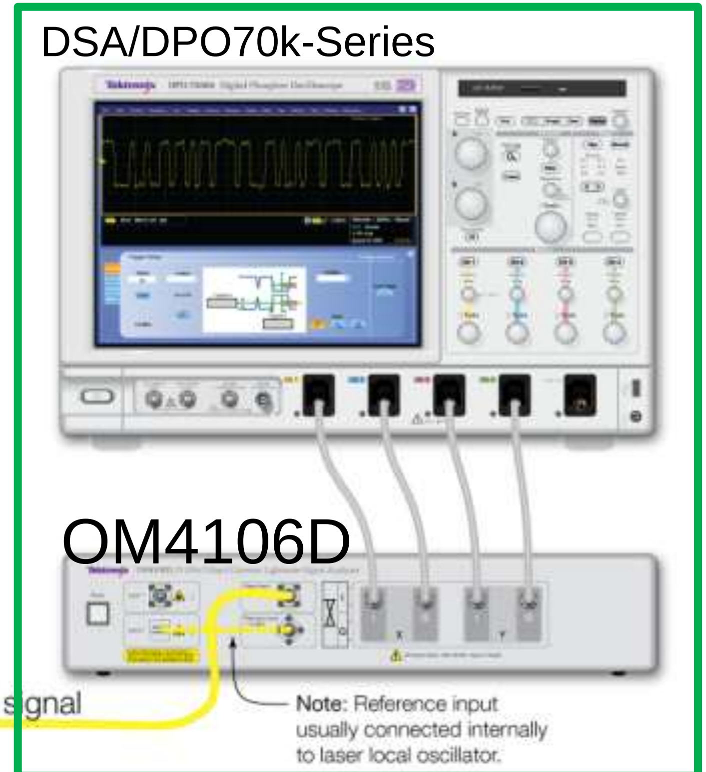
Example Real Time Scope Configuration

Note: Ethernet connections not shown. All instruments assumed to be connected to same network.

Local Laser:

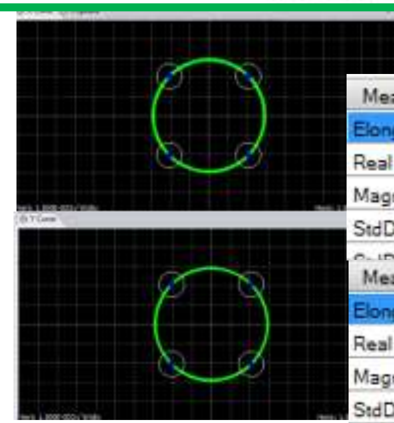
Wavelength Range: C+L
Output power:14.5dBm
Power adjustable: 0.01dBm
Gridding: 12.5GHz





Receiver:

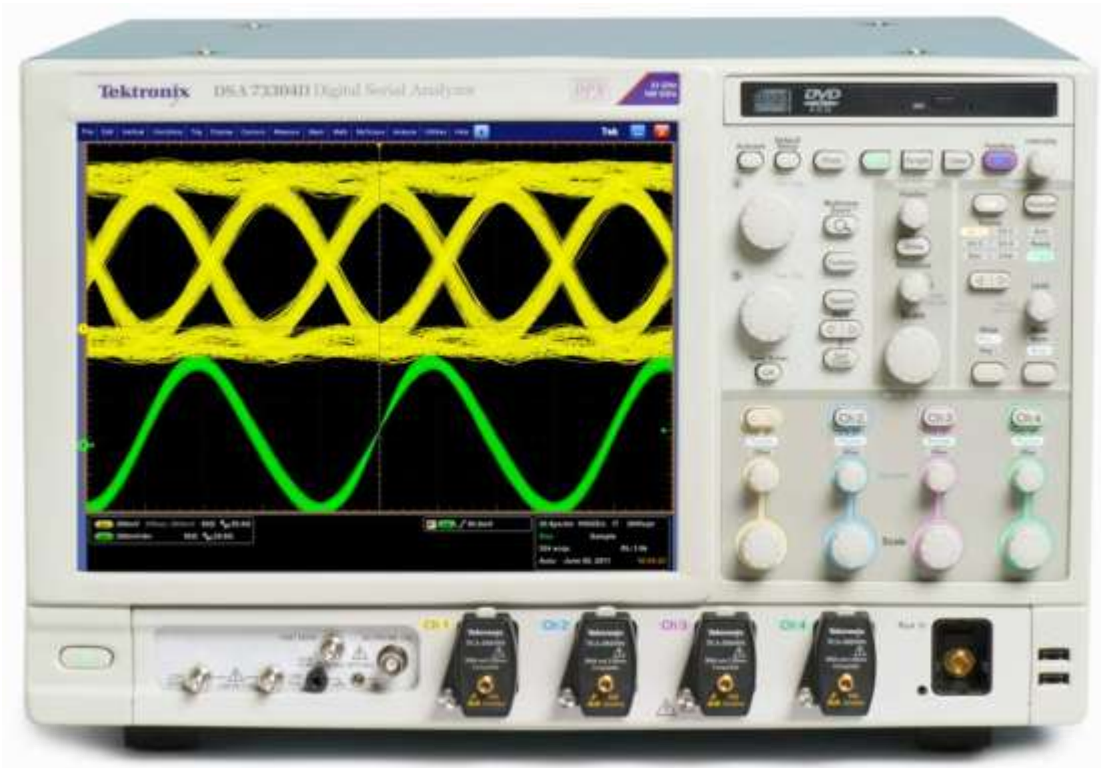
Linewidth tolerance:>5MHz
Linear receiver
EVM floor: <2% (with scope)
BER limit : >10e-2
Analysis sample : >1M pts



Measurement	Value	Measurement	Value
Elongation	1.0007	PhaseAngle (deg)	89.9848
Real Bias (%)	0.1438	Imag Bias (%)	0.0113
Magnitude	0.0439	EVM(%)	1.6808
StdDev Quad 1	0.0005	StdDev Quad 2	0.0005

Measurement	Value	Measurement	Value
Elongation	0.9992	PhaseAngle (deg)	90.0127
Real Bias (%)	0.0457	Imag Bias (%)	0.1101
Magnitude	0.0438	EVM(%)	1.4228
StdDev Quad 1	0.0004	StdDev Quad 2	0.0004

Introducing the DPO/DSA70000DX Series



- Industry leading combination of **33** GHz bandwidth and **100** GS/sec sample rate
- **6.25mV/div** the most accurate vertical resolution
- Most flat frequency response ±**0.5dB**

The World's Most Accurate Oscilloscope

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Full Automatically Measurements over 50+ items

- Optical Field
  - Wavelength range
  - Polarization ER
  - Laser phase noise
  - PDL/ PMD/ CD
- Electrical Field
  - Quadrature phase angle
  - Constellation bias.
  - Eye crossing points
  - Std. dev. by quadrant
  - I/Q skew
  - Total skew
- System
  - Q-factor
  - EVM, noise-loaded BER
- Time Domain

AnalysisParameters | Matlab | Measurements | X vs T

Measurement	Value	Mean	Min	Max	StdDev	Unit	Count
X - Eye							
Y - Eye							
X - Const							
Xconst IQ Imbalance	0.962	1.001	0.939	1.051	0.036		1611
Xconst Bias,Real	1.02	-0.89	-4.60	1.70	1.31	%	1611
Xconst Bias,Imag	-3.23	-1.17	-4.08	2.71	1.07	%	1611
Xconst PhaseAngle	90.76	90.00	88.60	91.64	0.48	deg	1611
Xconst Magnitude	0.725	0.715	0.587	0.739	0.027	√mW	1611
Xconst EVM,Average	12.03	11.73	10.62	16.49	0.56	%	1611
Xconst Mask Violat...	31	34	10	210	14		1611
Xconst Symbols Dis...	1379	1379	1379	1380	0		1611
Xconst Symbol Std....	0.002	0.002	0.001	0.003	0.000	√mW	1611
Y - Const							
Yconst IQ Imbalance	0.997	1.000	0.972	1.018	0.010		1611
Yconst Bias,Real	0.81	0.51	-0.70	1.86	0.37	%	1611
Yconst Bias,Imag	-0.87	-0.15	-1.77	1.32	0.62	%	1611
Yconst PhaseAngle	90.25	90.00	88.78	91.36	0.40	deg	1611
Yconst Magnitude	0.810	0.809	0.671	0.829	0.029	√mW	1611
Yconst EVM,Average	9.39	8.68	7.41	14.73	0.73	%	1611
Yconst Mask Violat...	4	3	0	87	5		1611
Yconst Symbols Dis...	1379	1379	1379	1380	0		1611
Yconst Symbol Std....	0.002	0.002	0.001	0.003	0.000	√mW	1611
X - Trans							
X-Q Crossing Point	47.71	48.04	45.67	50.17	0.88	%	1611
X-Q Skew	-2.12	-2.58	-3.39	-1.66	0.39	ps	1611
X-Q Risetime	24.41	24.02	22.85	25.26	0.58	ps	1611
X-Q Falltime	23.48	23.33	22.49	24.13	0.22	ps	1611
X-Q Overshoot	-1.88	-1.64	-3.81	0.09	0.58	%	1611
X-Q Undershoot	-1.60	-0.72	-2.02	0.62	0.42	%	1611
X-I Crossing Point	49.96	49.24	45.99	53.08	2.01	%	1611
X-I Skew	-2.65	-2.57	-3.40	-1.72	0.39	ps	1611
X-I Risetime	23.40	23.92	22.64	25.42	0.69	ps	1611

Clear Statistics

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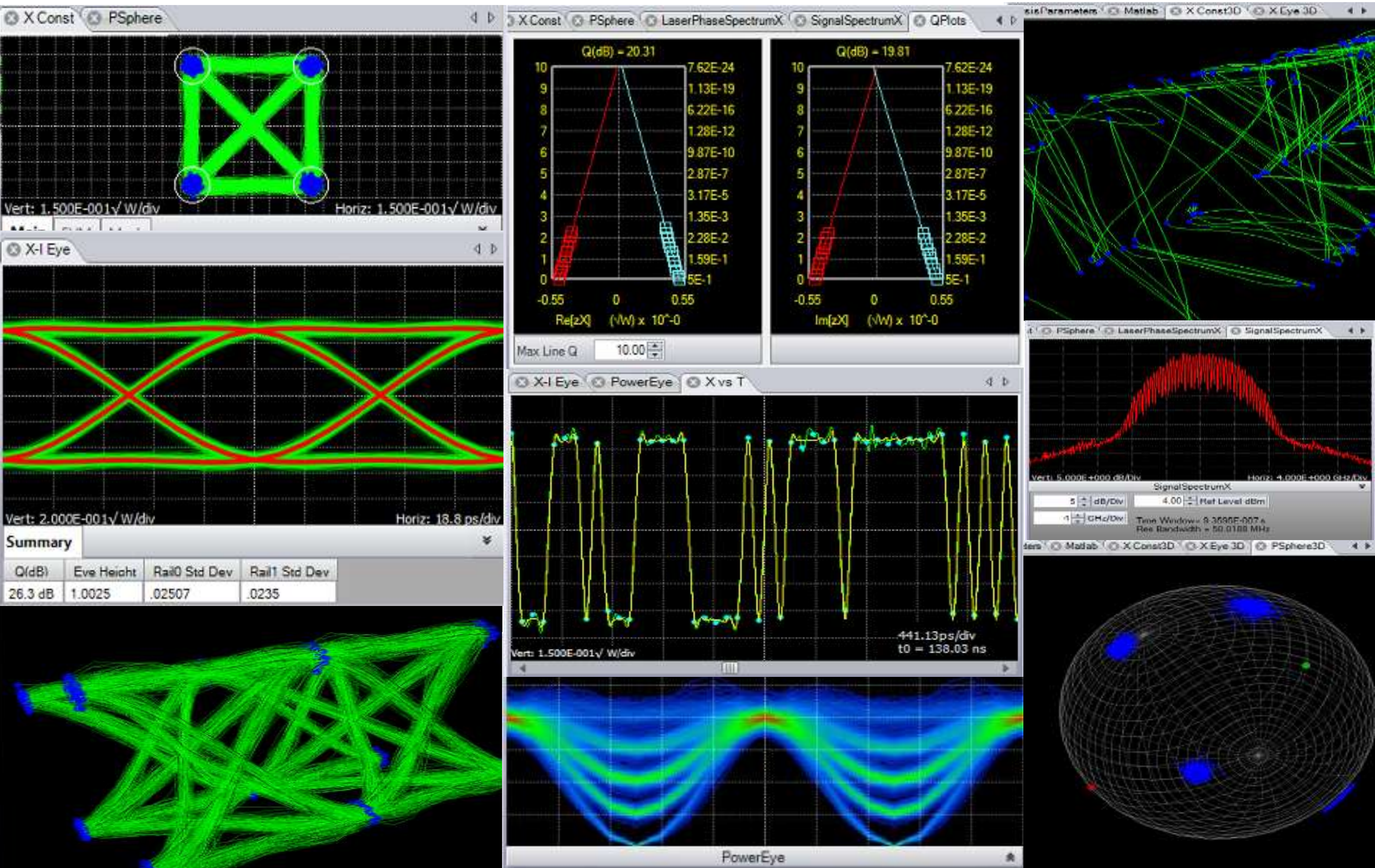
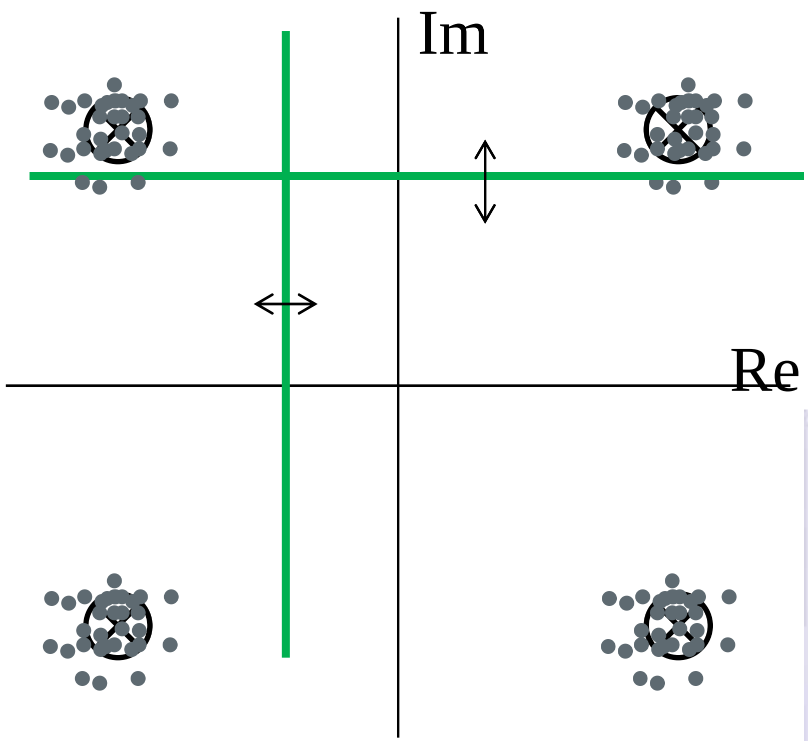
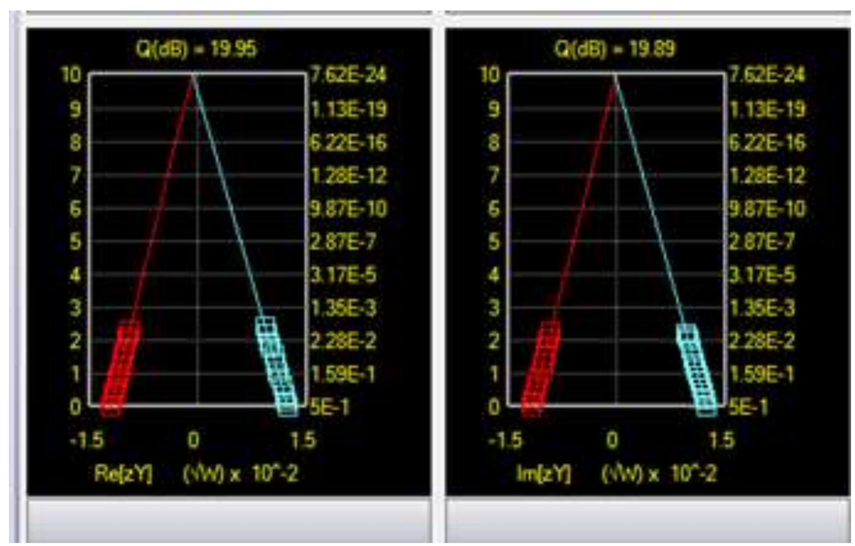
Comprehensive Diagrams



Exclusive:
Measuring TX Constellation Imperfections: Q-factor

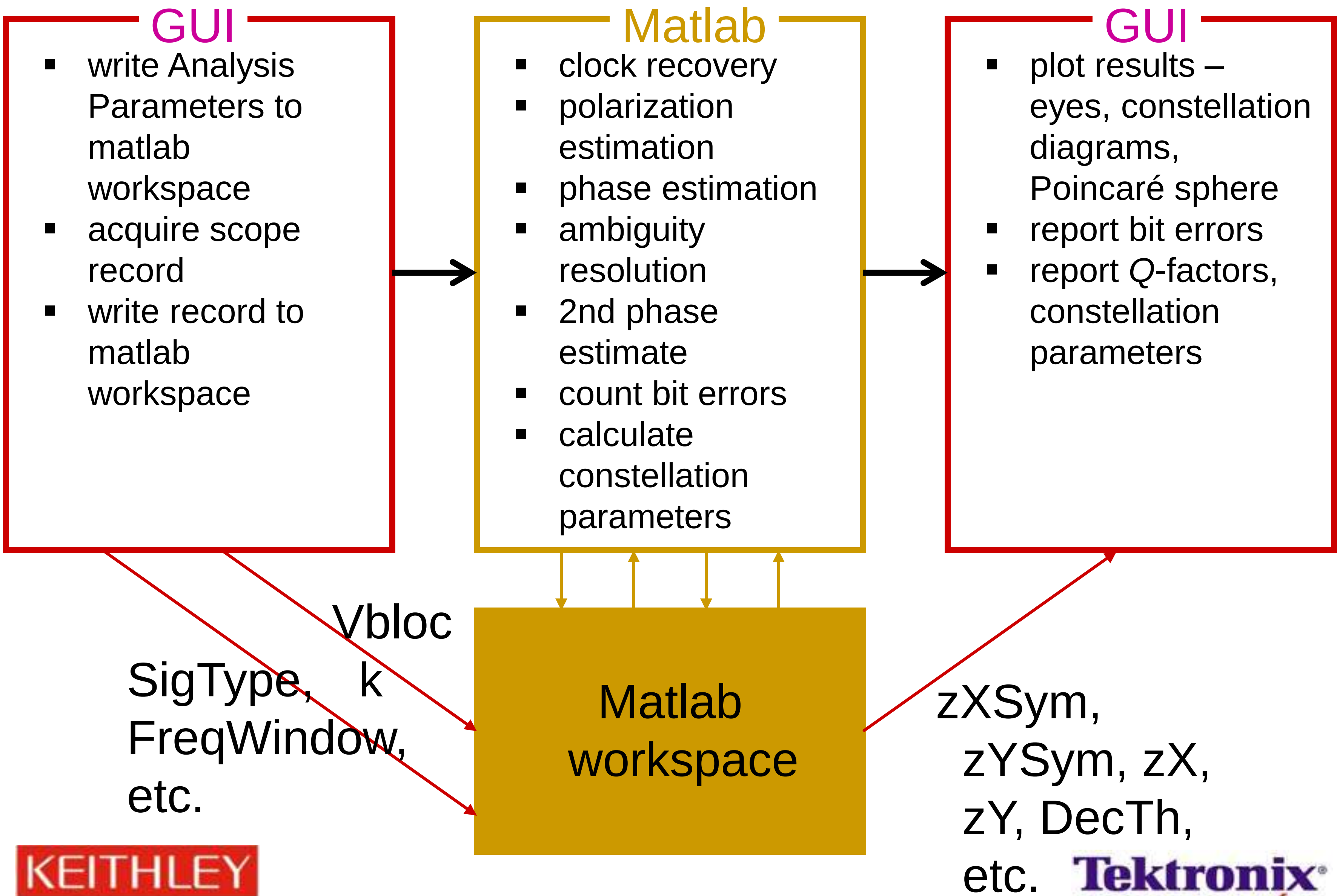


- Counts errors as decision threshold is moved.
- Errors fitted to error function in “Q-space”
- → Plot, max-Q and



Open All Algorithms for Power User with Matlab™

Interaction Between GUI and Matlab



Example Industry Approaches to 400G and Beyond

- No industry consensus on how to build super-channels – no one architecture fits all requirements.
- Vendors differ on characteristics as basic as carrier count and carrier spacing to what modulation format should be used.

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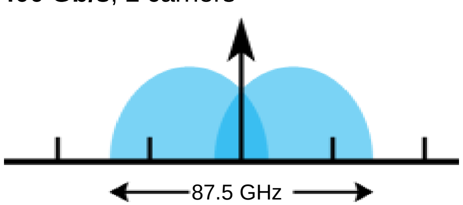
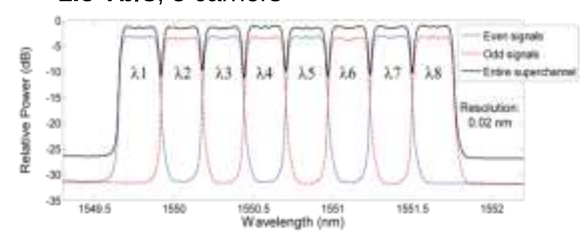
400 Gb/s, 2 carriers



500 Gb/s, 10 carriers

1.0 Tb/s, 10 carriers

1.5 Tb/s, 8 carriers



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[4]Super-Channels: DWDM Transmission at100Gb/s and Beyond, copyright 2012, Infinera Corporation
[5]1.5-Tb/s Guard-Banded Superchannel Transmission over 56 × 100-km (5600-km) ULAF Using 30-Gbaud Pilot-Free OFDM-16QAM Signals with 5.75-b/s/Hz Net Spectral Efficiency, Alcatel-Lucent, Bell Labs

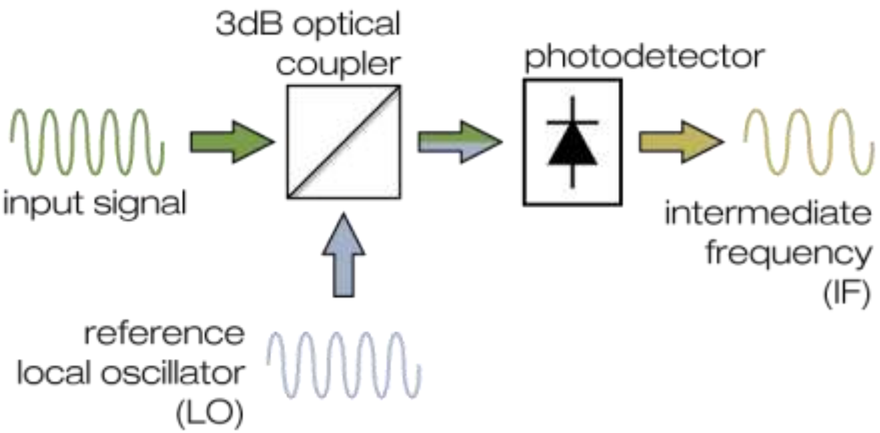
Example Industry Approaches to 400G and Beyond

system rate	# of carriers	modulation format	system bandwidth	req'd scope bandwidth
400 Gb/s[1]	2	DP-16QAM	87.5 GHz	44 GHz
500 Gb/s[2]	5	DP-QPSK	190 GHz	**95 GHz**
500 Gb/s[3]	10	DP-QPSK	190 GHz	**95 GHz**
1.0 Tb/s[4]	10	DP-QPSK	375 GHz	**188 GHz**
1.5 Tb/s[5]	8	DP-16QAM	260 GHz	**130 GHz**

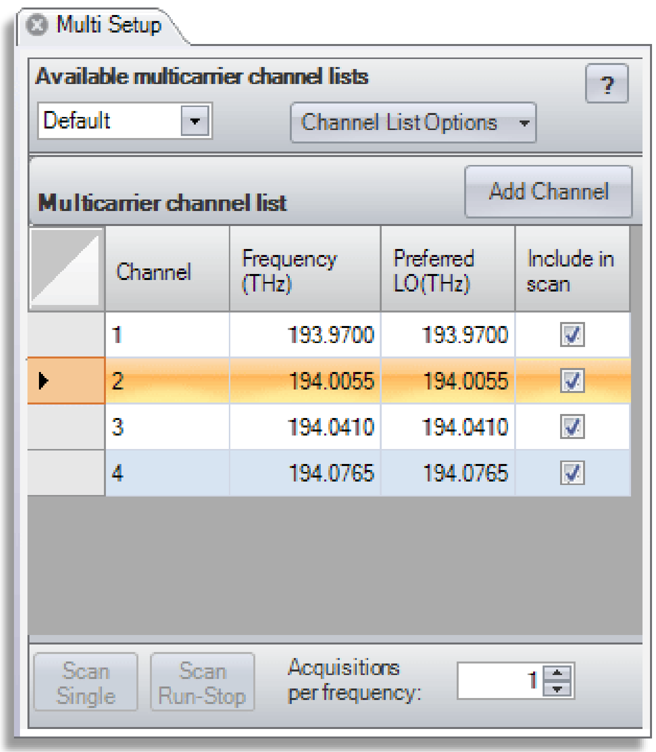
Tektronix recently announced a 70GHz real-time oscilloscope(ATI Technology),
but current oscilloscopes still do not have sufficient bandwidth to capture an entire super-channel with a single acquisition.

Acquiring Super-Channels – Local Oscillator Tuning

- Coherent detection works by combining the input signal with a local oscillator.
- The local oscillator frequency determines the center of the frequency range that is detected.
- By sweeping the local oscillator, different frequency ranges can be captured in sequence.



Acquiring Super-Channels – Configuration

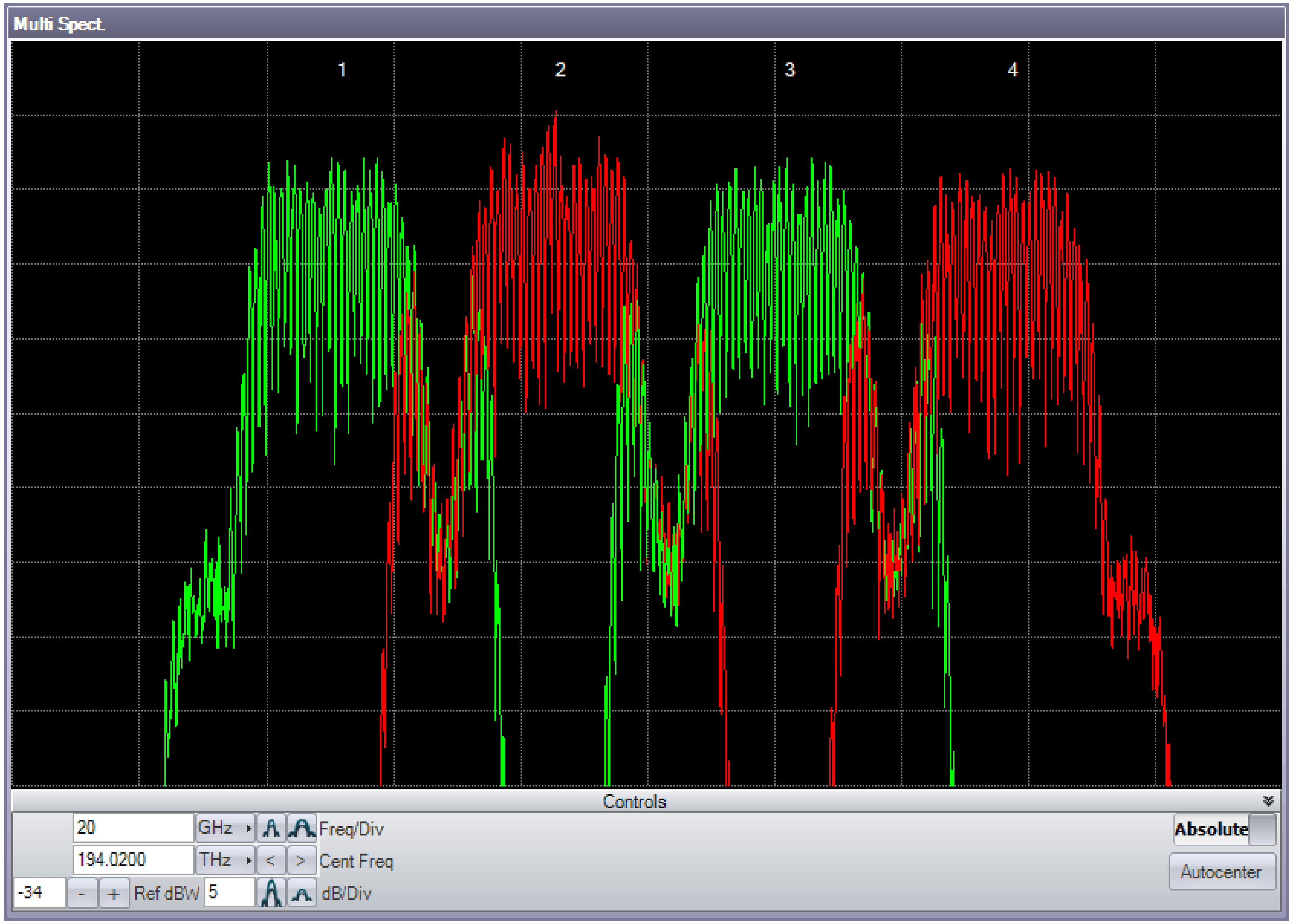


Example

- 4 Carrier Super-Channel
- Center frequencies spaced at 35.5 GHz:

Channel 1: 193.9700 GHz
Channel 2: 194.0055 GHz
Channel 3: 194.0410 GHz
Channel 4: 194.0765 GHz

Acquiring Super-Channels – Captured Spectrum



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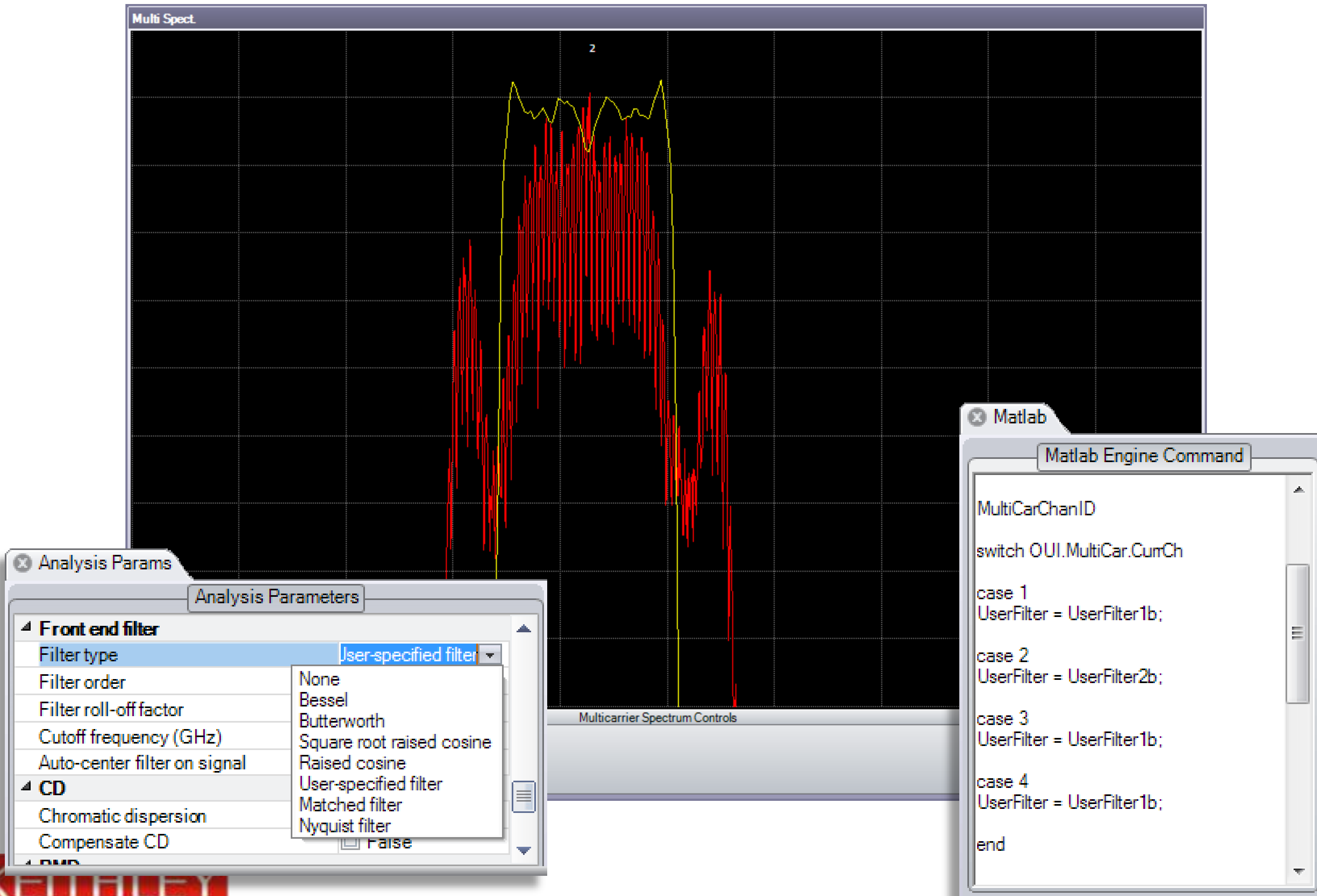
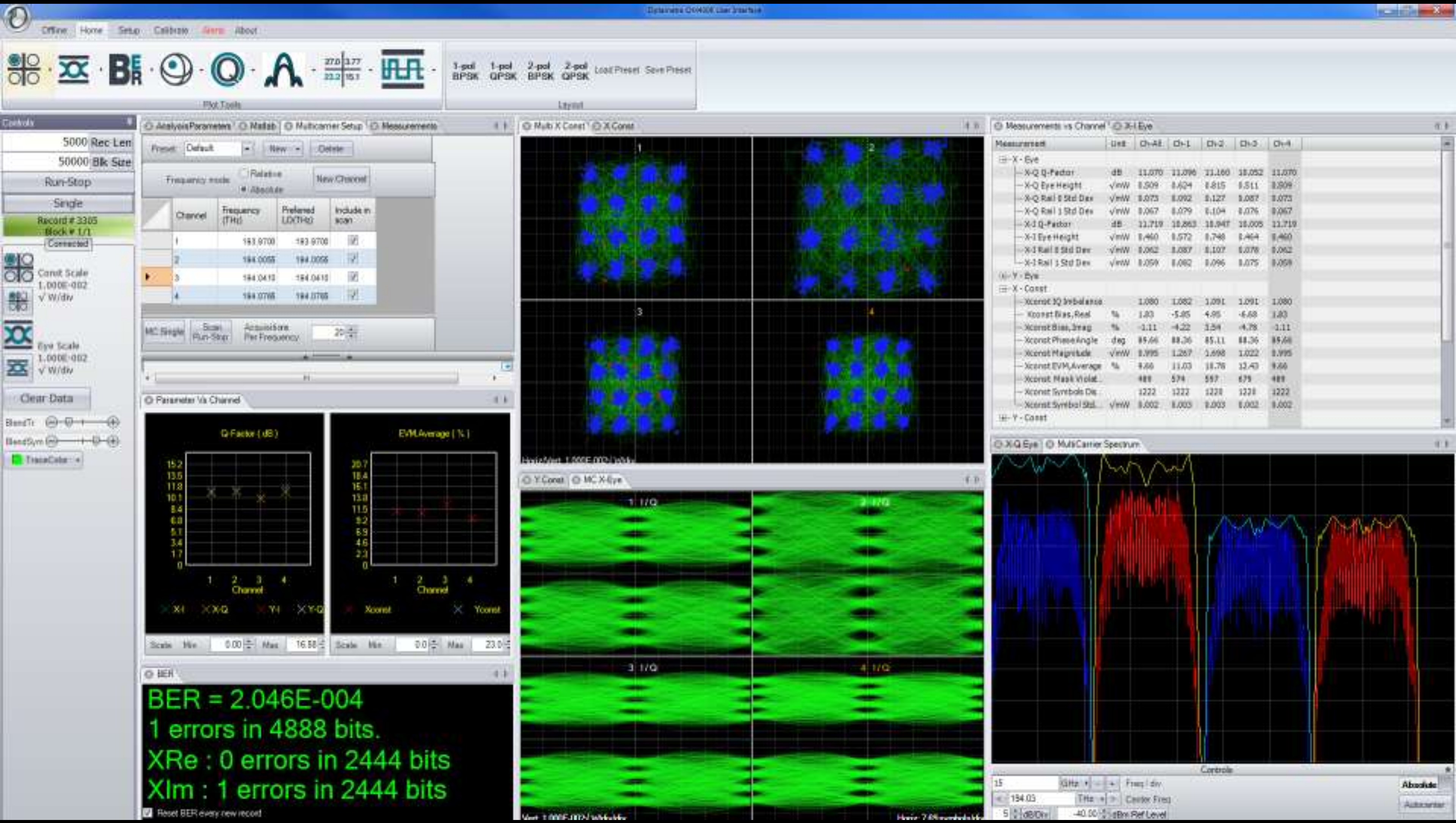
Acquiring Super-Channels – Digital Channel Filtering




Offline
Home
Setup
Calibrate
About
Plot Tools
1-pol BPSK
1-pol QPSK
2-pol BPSK
2-pol QPSK
Load Preset
Save Preset
Layout
Controls
5000 Rec Len
50000 Blk Size
Run-Stop
Single
Connected
Clear Data
Multicarrier Setup
Measurements
New Channel
Channel
Frequency (THz)
Preferred LO(THz)
Include in scan
Parameter Vs Channel
Q-Factor (dB)
EVM Average (%)
Channel
BER
BER = 2.046E-004
1 errors in 4888 bits.
XRe : 0 errors in 2444 bits
XIm : 1 errors in 2444 bits
Reset BER every new record
Measurements vs Channel
MultiCarrier Spectrum

Integrated Measurement Results

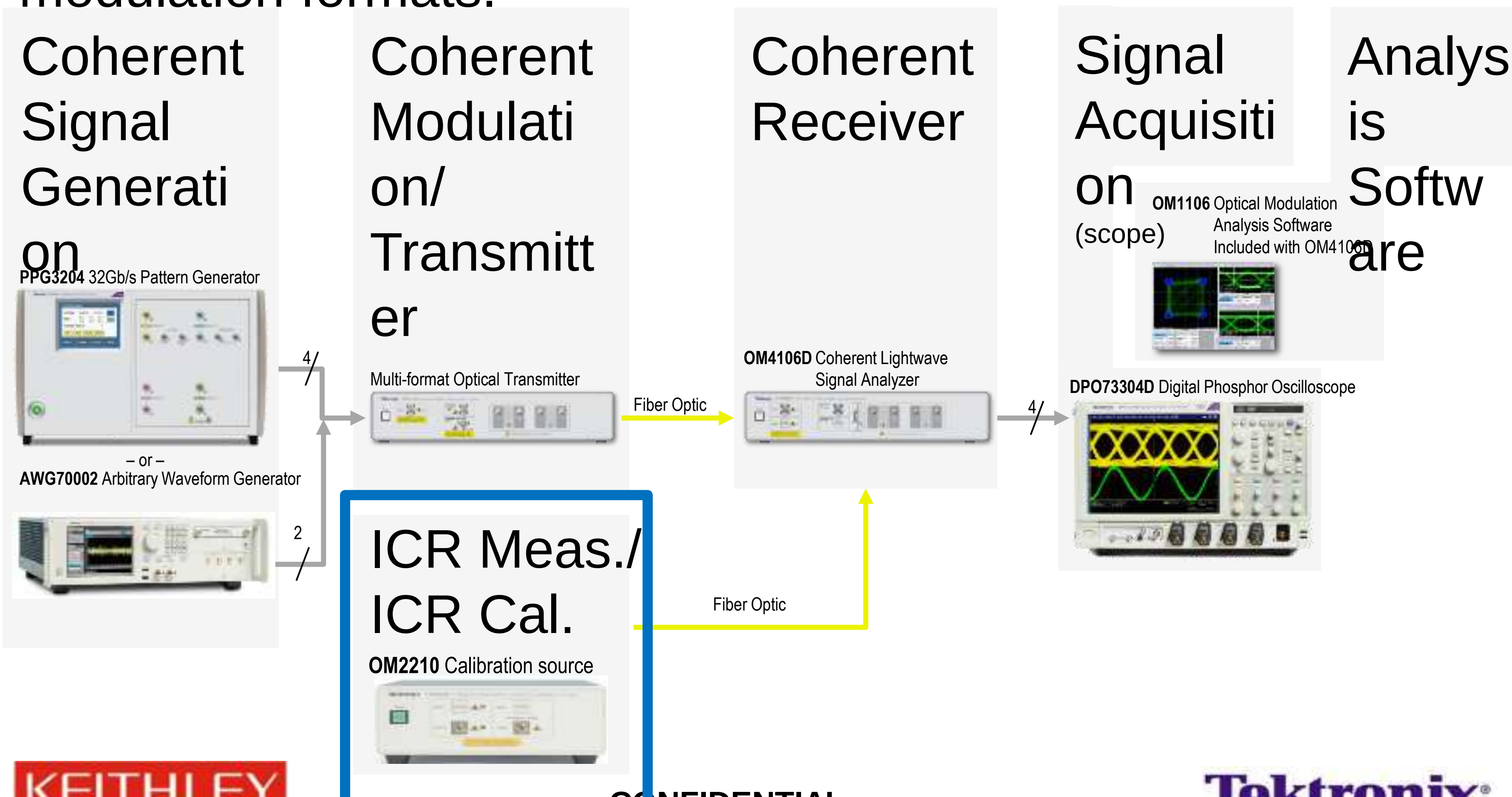
- Integrated measurement results can be viewed for each channel side-by-side
- Eye diagrams, constellation diagrams, and optical spectrum plots can be viewed individually by channel or with all channels superimposed for easy comparison

Meas. vs. Chan.

Measurement	Unit	Ch-All	Ch-1	Ch-2	Ch-3	Ch-4
⊟ X - Eye						
X-Q Q-Factor	dB	11.937	11.937	10.703	11.721	11.448
X-Q Eye Height	√mW	1.614	1.614	1.975	1.390	1.252
X-Q Rail 0 Std Dev	√mW	0.216	0.216	0.311	0.195	0.166
X-Q Rail 1 Std Dev	√mW	0.207	0.207	0.275	0.160	0.163
X-I Q-Factor	dB	12.148	12.148	10.740	11.528	11.878
X-I Eye Height	√mW	1.443	1.443	1.823	1.242	1.147
X-I Rail 0 Std Dev	√mW	0.180	0.180	0.294	0.163	0.149
X-I Rail 1 Std Dev	√mW	0.190	0.190	0.236	0.179	0.149
⊞ Y - Eye						
⊟ X - Const						
Xconst IQ Imbalance		1.091	1.091	1.094	1.093	1.095
Xconst Bias,Real	%	2.48	2.48	-6.05	1.97	2.32
Xconst Bias,Imag	%	1.42	1.42	5.28	0.97	0.57
Xconst Phase Angle	deg	89.30	89.30	89.70	89.64	89.54
Xconst Magnitude	√mW	3.231	3.231	4.209	2.801	2.558
Xconst EVM,Average	%	6.93	6.93	7.72	7.52	7.35
Xconst Mask Violat...		41	41	66	45	45
Xconst Symbols Dis...		1,234	1,234	1,234	1,234	1,234
Xconst Symbol Std....	√mW	0.006	0.006	0.008	0.005	0.005
⊞ Y - Const						
⊞ X - Trans						
⊞ Y - Trans						
⊞ Pow - Trans						
⊟ XY Measurements						
Sig Freq Offset	MHz	674.2	674.2	-199.6	306.0	55.2
Signal Baud Rate	GHz	25.99	25.99	25.99	25.99	25.99
PER	dB	...	...	...	...	...
PDL	dB	...	...	...	...	...
⊞ PMD						

Coherent Optical System

Tektronix offers complete end-to-end testing of coherent modulation formats.

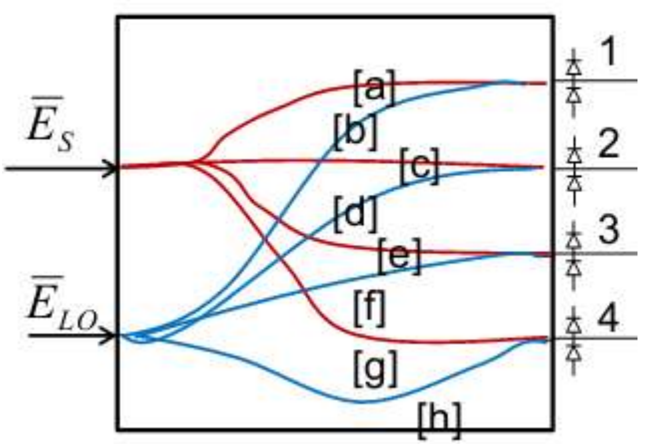


Optical hybrid calibration

$$\mathbf{V} = [H]\mathbf{E}$$

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{23} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix} \begin{bmatrix} E_{xr} \\ E_{xi} \\ E_{yr} \\ E_{yi} \end{bmatrix}$$

$$\mathbf{E} = [H]^{-1}\mathbf{V}$$



Apply Ex or Ey, measure phase angle

- How to set Ex? Ey?
- What about crosstalk effect on angle?

Or

Apply E1 and E2, find all hybrid parameters

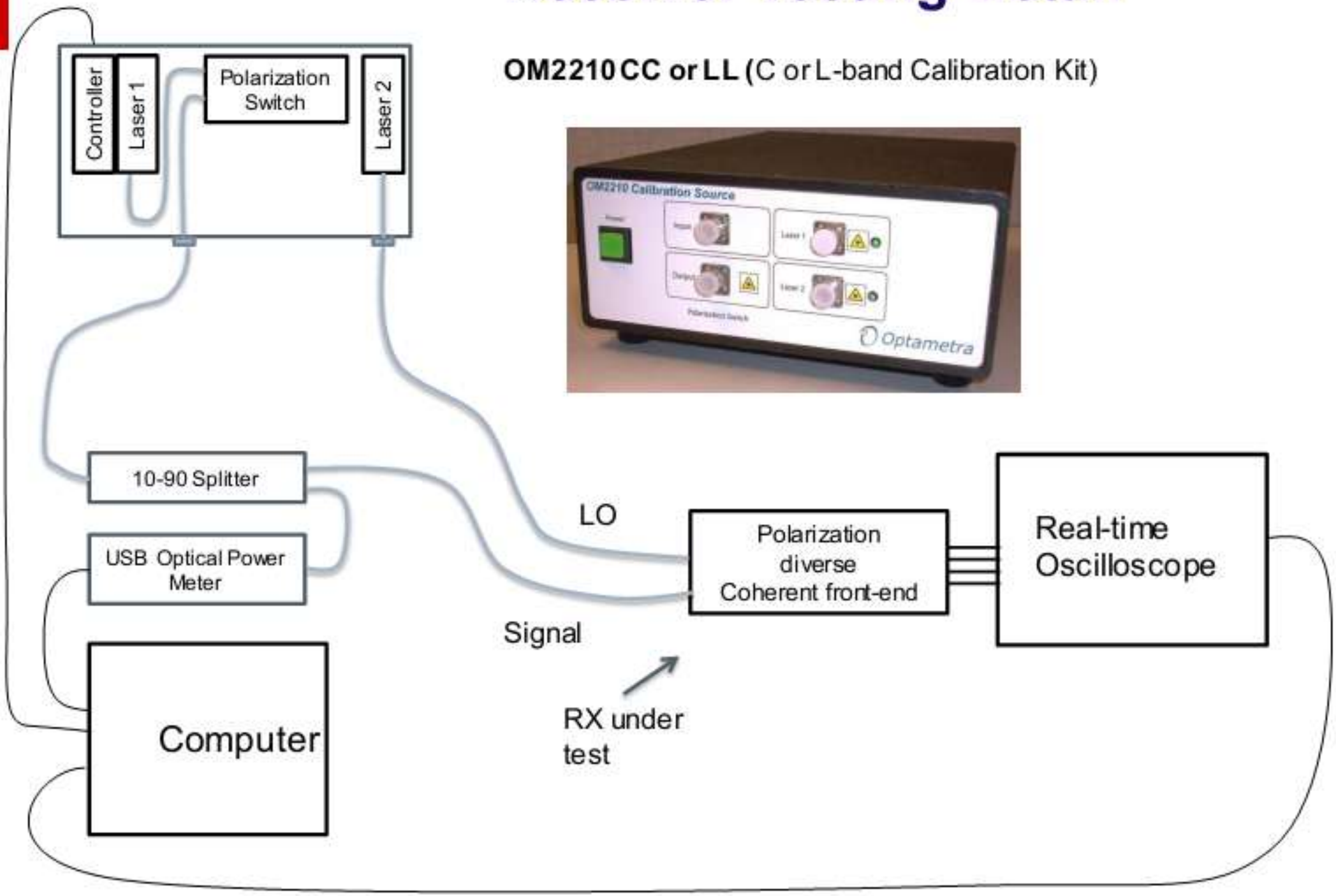
- E1·E2 = 0 (new coordinate system)
- Rotate back to hybrid system

Entire H is needed to find H^{-1}

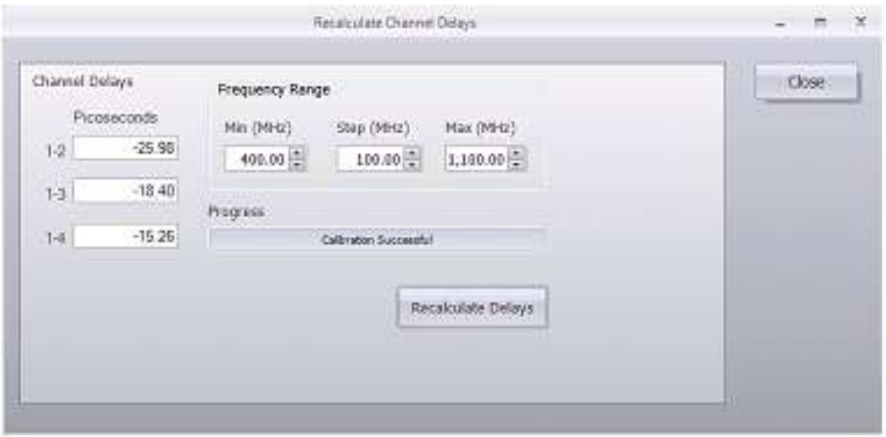
This gives full impact of finding E given V

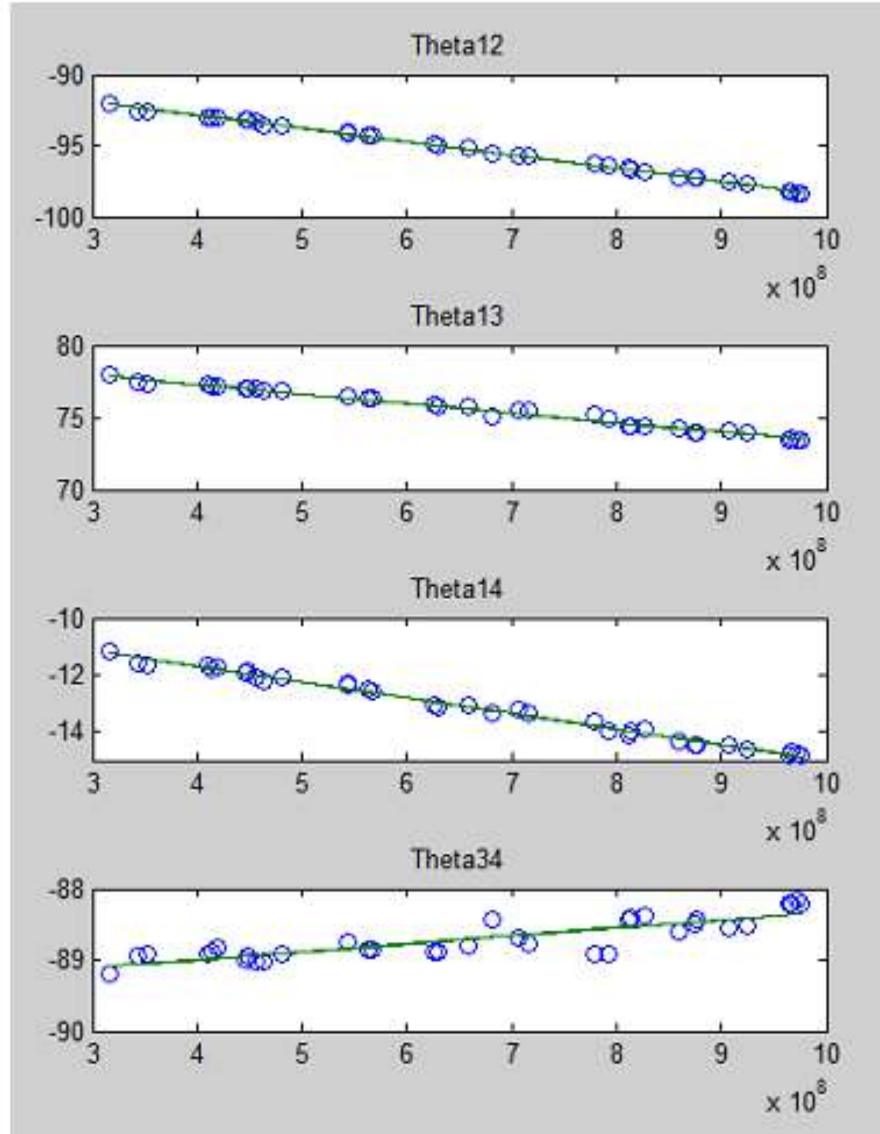
Receiver Testing Detail

OM2210 CC or LL (C or L-band Calibration Kit)



4-Channel Skew Measurement





- User sets up heterodyne Frequency Sweep Range
- Relative phase plotted vs. frequency
- Average slope provides the Channel Delay

```
Status =

      ChDelay: [0 -2.5981e-011 -1.8396e-011 -1.5257e-011]
      MinFreq: 3.1548e+008
      MaxFreq: 9.7618e+008
  rmsErrDeg12: 0.0983
  maxErrDeg12: 0.2504
  rmsErrDeg13: 0.1741
  maxErrDeg13: 0.4614
  rmsErrDeg34: 0.1407
  maxErrDeg34: 0.3690
```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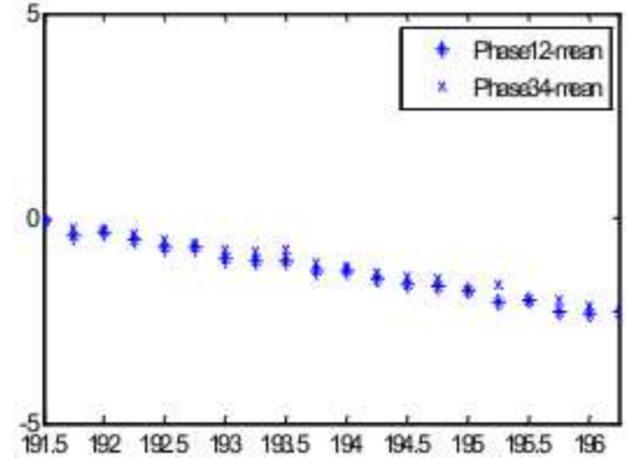
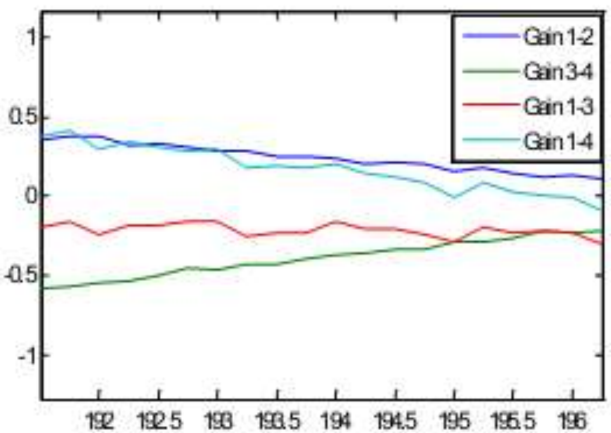
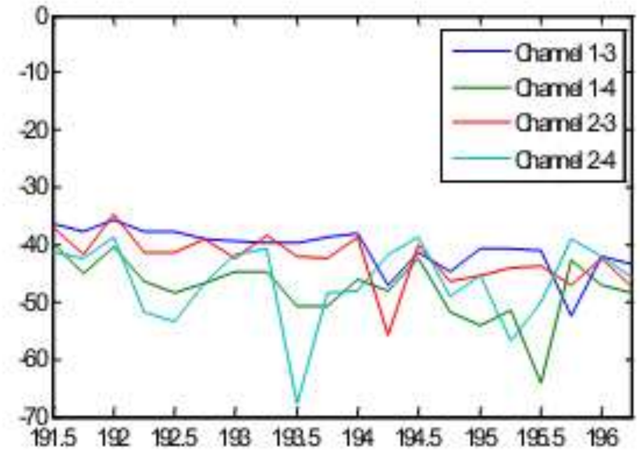
Example RX Measurement Results

Quadrature phase vs. wavelength
Gain vs. wavelength
Crosstalk vs. wavelength







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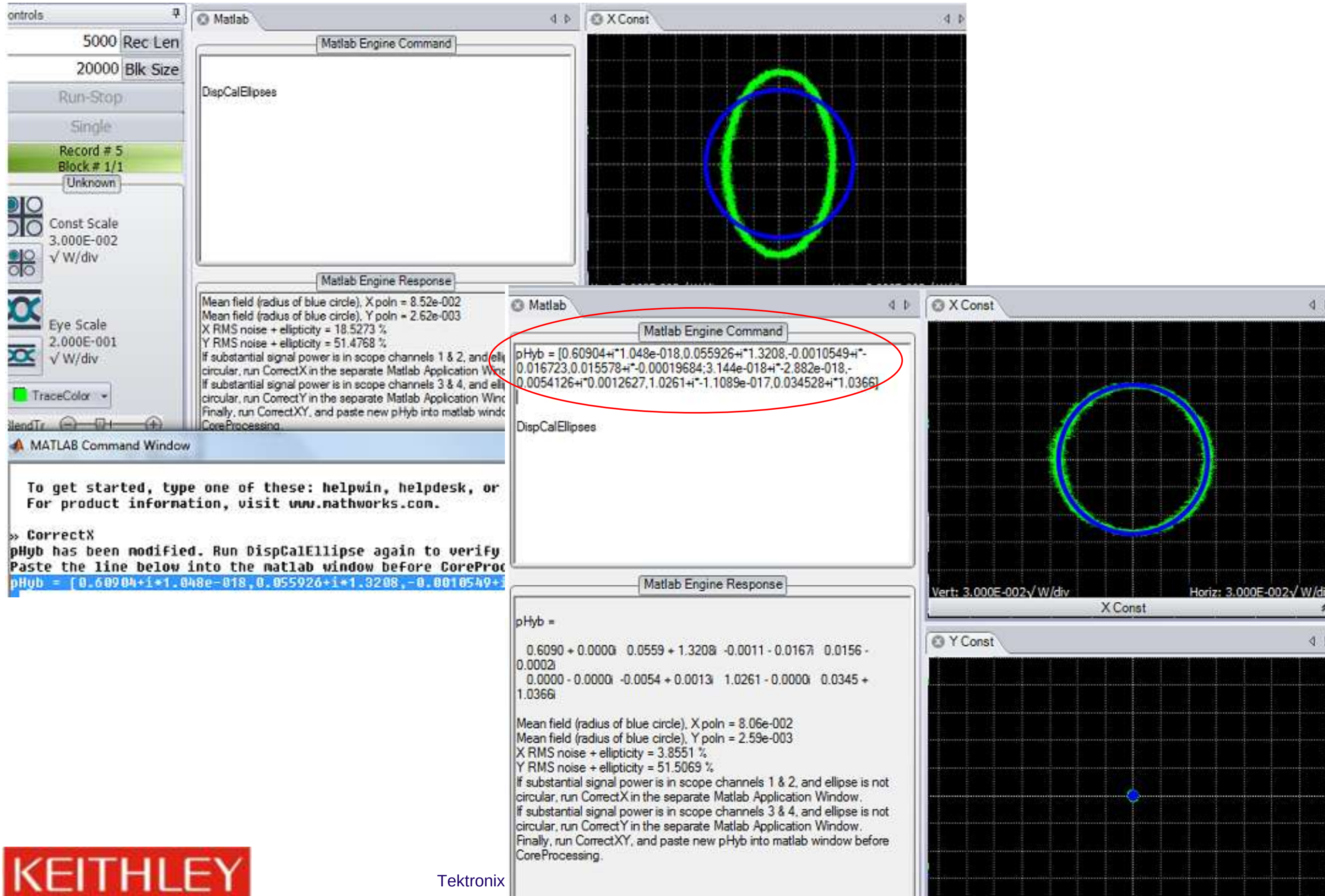
Customized ICR testing with Hybrid Cal



Tektronix Coherent Optical T&M Platform

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Thanks!