PAM-4信号的产生与分析

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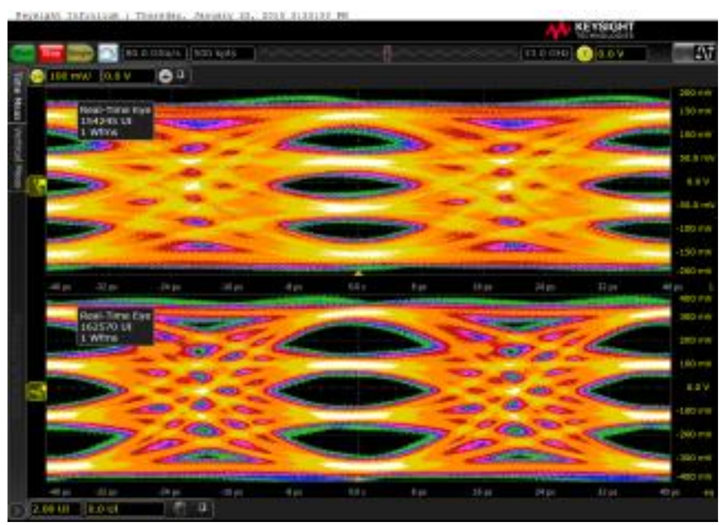

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- PAM-4信号及其挑战
- PAM-4信号的分析
- PAM-4信号的产生
- 总结

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网络带宽趋势：100G→400G→1T

研发
2014

部署实施
2018

1 Tb/s

线路速率: 100+ Gb/s

调试方式: ??
(28Gbaud PAM-8,
16-QAM, DMT or ??)

400 Gb/s

线路速率: 56 Gb/s

调制方式:
56G NRZ
28Gbaud PAM-4

100 Gb/s

线路速率: 25 Gb/s

调制方式:
25/28Gb/s NRZ

研发
2017?

部署实施
2022?

研发
2010

部署实施
2015

KEYSIGHT TECHNOLOGIES

100G现有常见标准

	Interface	Type	Data rate	Chan.	Reach	Notes
IEEE 802.3ba/bm	100GBASE-ER4	Optical, 1310nm SM	25.78125 Gb/s	4	40 km	
	100GBASE-LR4	Optical, 1310nm SM	25.78125 Gb/s	4	10 km	
	100GBASE-SR4	Optical, 850 nm MM	25.78125 Gb/s	4	?? km	
	CAUI-4	Electrical, Chip-to-module	25.78125 Gb/s	4	25 cm	re-timed
IEEE 802.3bj	100GBASE-KR4	Electrical, PCB	25.78125 Gb/s	4	1 m	
	100GBASE-CR4	Electrical, cable	25.78125 Gb/s	4	??	
	100GBASE-KP4	Electrical, PCB	25.78125 Gb/s	4	??	PAM-4
	100GBASE-CP4	Electrical, cable	25.78125 Gb/s	4	??	PAM-4
T11	32G Fibre Channel	Optical, 850 nm MM, Optical, 1300 nm SM	28.05 Gb/s	1 1	100 m 10 km	
OIF	CEI-25G-LR	Electrical, multi-board	19.9 – 25.8 Gb/s 19.9 – 28.05 Gb/s	1-n	686 mm	
	CEI-28G-SR	Electrical, daughter board		1-n	300 mm	
	CEI-28G-VSR	Electrical, chip-to-chip		1-n	150 mm	
Infiniband	EDR		25.0 Gb/s	1, 4, 12	tbd	

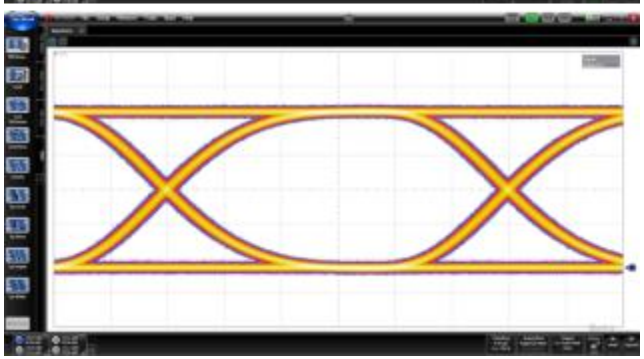
迈向下一代400G的网络带宽

– 对于400GbE，56 Gb/s的链路数据速率将成为其主要的推动者

– 56 Gb/s的链路数据速率，可以有两种实现方式：

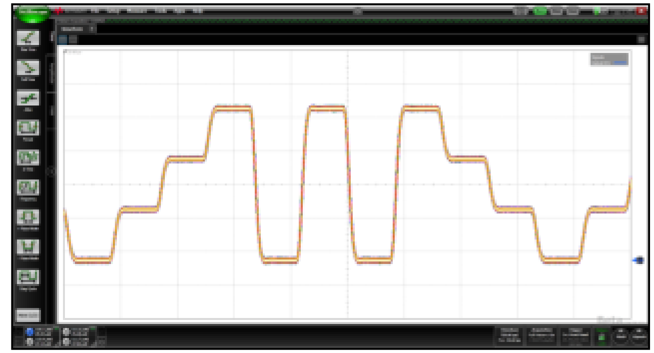
- 56G NRZ
  + 无需新的技术 – 直接由25/28G链路速率向上演进
  - 难以解决信道的损耗与反射问题
  - 抖动预算更加紧张 – 17.8 ps UI
- 28 Gbaud PAM-4
  + 信号损耗问题在28 Gb/s NRZ阶段已经得到解决
  - 线性的Tx与Rx – 更复杂，芯片价格更高，耗电更大
  - 损失9.6 dB的可用信噪比
  - 全新的挑战 – 少有经验可供借鉴
- 两种实现方式都会被用来实现400GbE

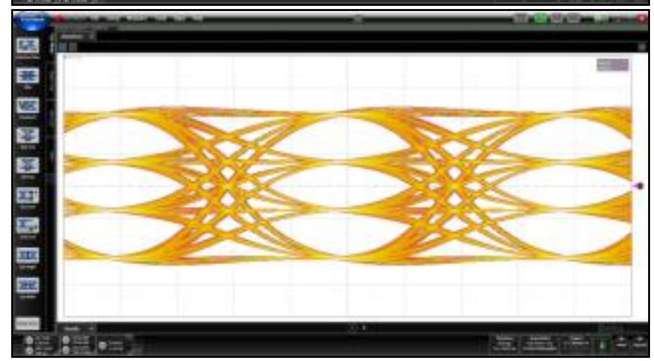
NRZ (非归零码) vs. PAM-4 (脉冲幅度调制)



- 2个幅度电平
- 每一个符号传输一比特的信息
- 28 GBaud NRZ = 28 Gb/s

PAM-4





- 4个电平幅度
- 每一个符号传输两比特的信息
  - ✓ 对于相同的波特率，具有2倍的吞吐率
  - ✓ 28 GBaud PAM-4 = 56 Gb/s
- 信噪比降低，更易受到噪声的影响
- 更加复杂的TX/RX设计，更高的成本

KEYSIGHT TECHNOLOGIES

和PAM-4有关的标准进展

– 已完成的标准

a. IEEE 802.3-2014 clause 94 (25.78 Gb/s as 13.6 GBaud PAM-4 in 1m backplane)
   - Low adoption rate – limited advantages over clause 93 – 25.78G NRZ

– 正在开发/讨论的标准

a. **OIF-CEI-4.0 (56G)** – lane enabler basis for standards below.
   a. OIF-CEI-56G-XSR-PAM-4 (Extra Short Reach interface)
   b. OIF-CEI-56G-VSR-PAM-4 (Very Short Reach interface)
   c. OIF-CEI-56G-MR-PAM-4 (Medium Reach interface)
   d. OIF-CEI-56G-LR-PAM-4 (Long Reach interface)

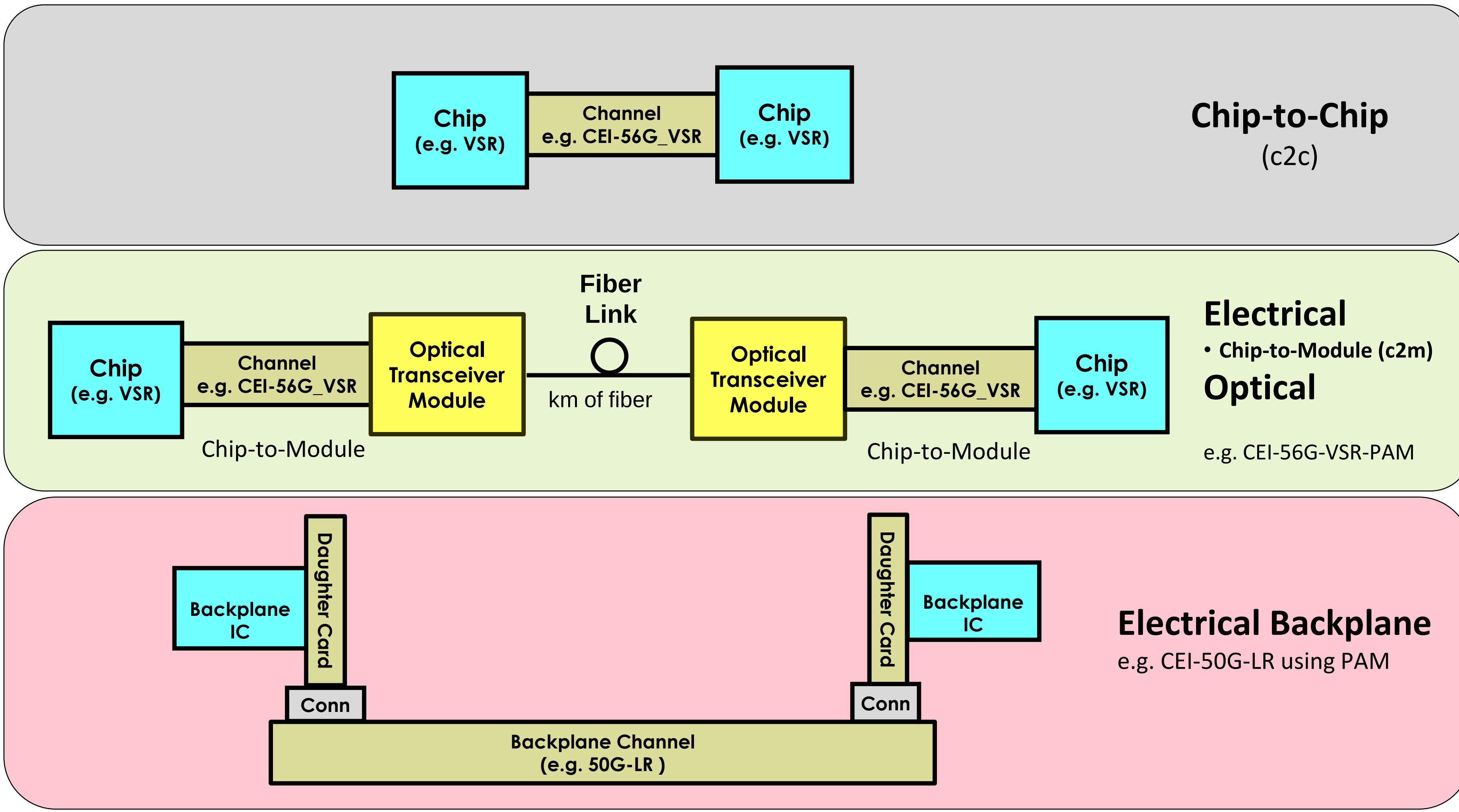
b. **IEEE 400G Ethernet (P802.3bs) / CDAUI-8 – Electrical + Optical SM 1310nm**

c. **64G Fiber Channel** (highly leveraged from (a) and/or (b) above). **Electrical + MM 850nm**

d. **InfiniBand 600G HDR** (highly leveraged from (a) and/or (b) above).

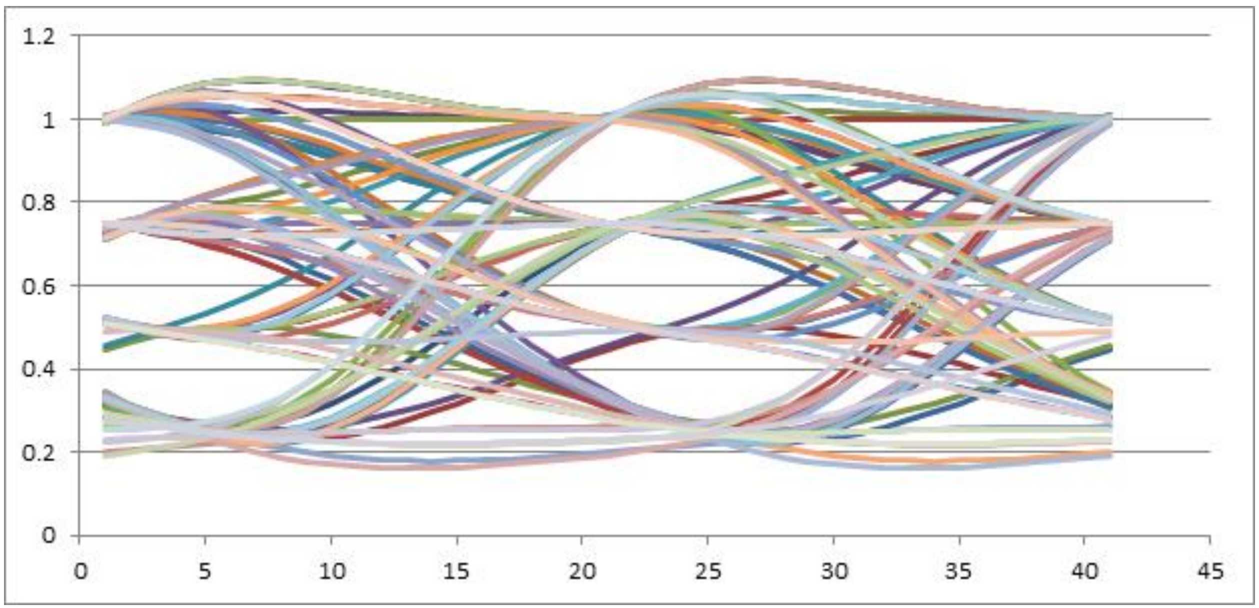
典型的PAM-4通信系统

Transmitter, Channel & Receiver

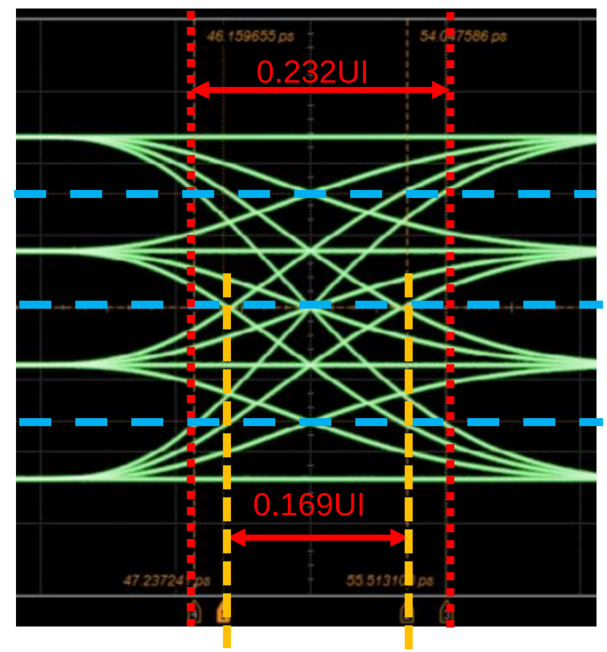


从NRZ到PAM-4

- PAM-4固有的ISI问题，需要接收机对码型相关抖动不敏感
- 新问题：...
  - 线性驱动的VCSELs的3个眼图具有时间迟滞
    - 上面的眼到达时间比下面的快
    - 每个眼图需要独立的采样判决时间延迟

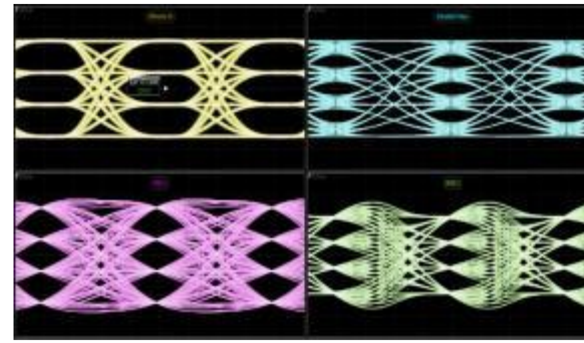


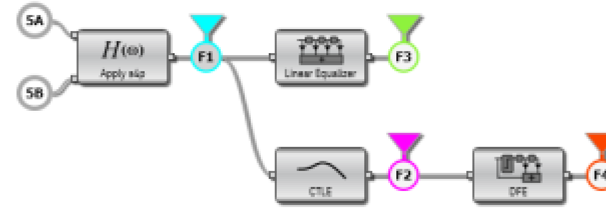
PAM-4

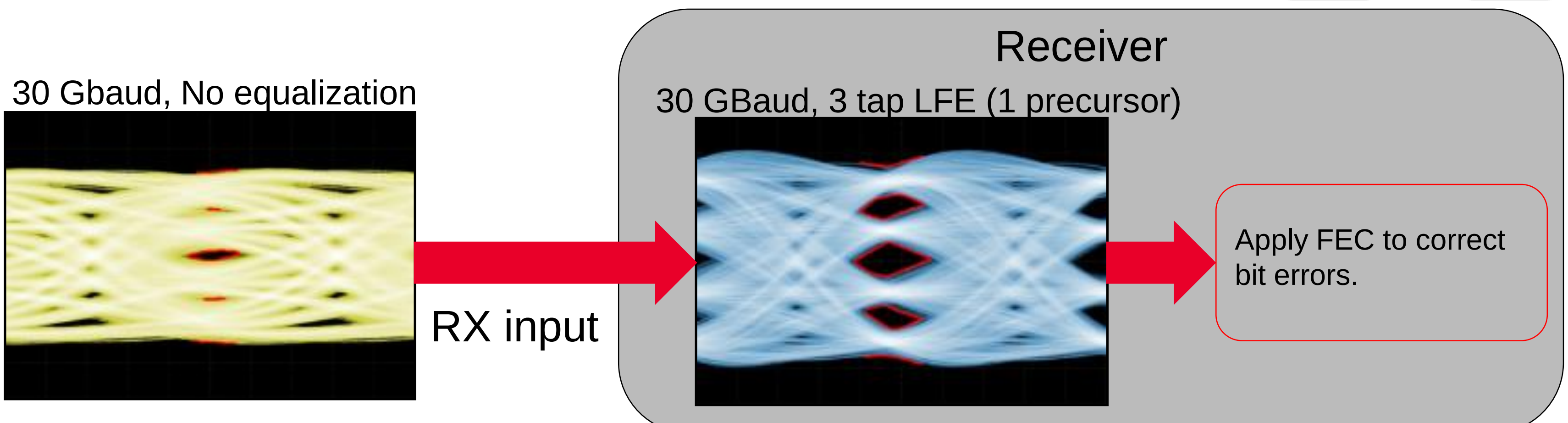


PAM-4的均衡

- 接收端需要使用均衡算法以使闭合的眼图重新张开并继而进行前向纠错（FEC）处理
- 可以是以下均衡方式的组合：
  - Linear Feedforward Equalizer (FFE/LFE)
  - Continuous Time Linear Equalizer (CTLE)
  - Decision Feedback Equalizer (DFE)



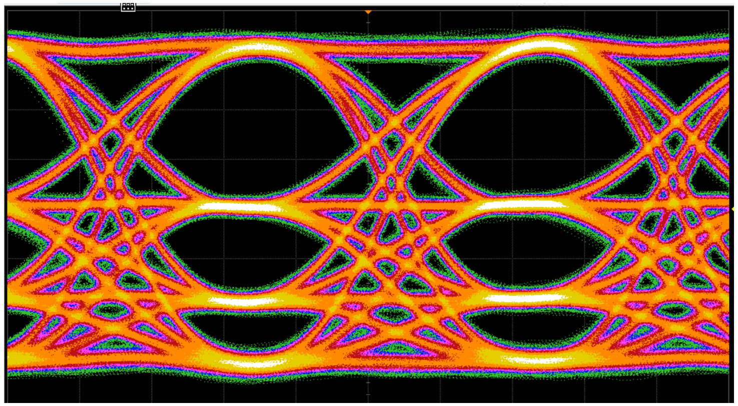




其它损伤对PAM-4接收机带来的挑战

非线性——最下方的眼图存在幅度压缩

- 各个眼图具有不一致的有效信噪比



相对于均匀分布的误码，前向纠错（FEC）对于突发误码的能力有限

- 传统的BERT不对突发误码进行测量
- 码型位置直方图可以提供一定的信息，但无法完全描述突发误码

PAM-4仍是新生事物，对标准和技术的了解仍处在学习阶段。
我们还需要时间了解哪些损伤会造成问题

新的测试将被重新定义测试发射机(Tx)输出
新的压力类型将被重新定义测试接收机(Rx)输入

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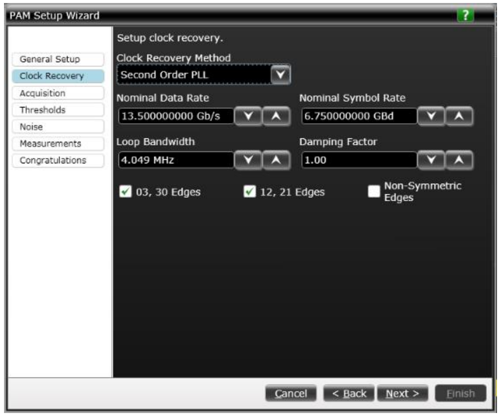
PAM-4测试所面临的挑战

– 时钟恢复 (CR) – 用以跟踪低频抖动，触发示波器

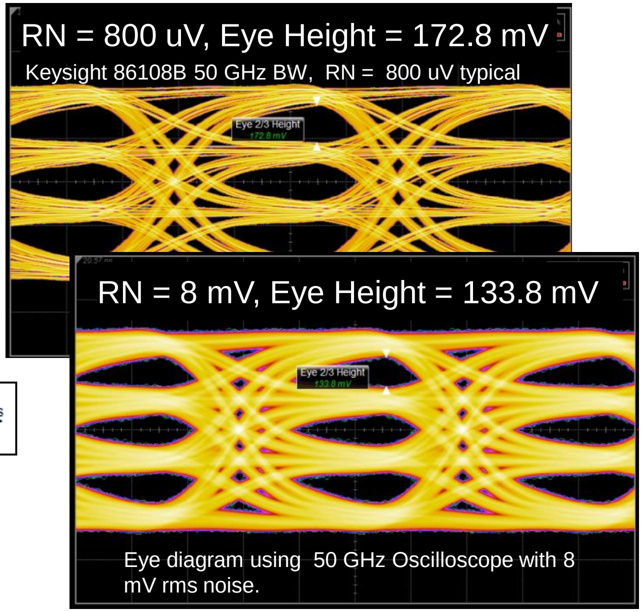
- 实时示波器采用软件时钟恢复方式
  - 具备跳变电平限定功能的软件时钟恢复算法，支持基于0-3/3-0 与 1-2/2-1 电平的跳变沿进行时钟恢复
- 采样示波器采用硬件时钟恢复方式
  - Keysight现有的硬件时钟恢复方式支持用于PAM-4信号



– 噪声

- 噪声会降低眼张开度，影响到系统的BER性能
- 来自DUT Tx的随机噪声（RN）与来自示波器的RN进行平方和再开根号的运算，才得到显示信号的RN
- 缓慢的跳变沿速度(slew rate, S) 会使噪声的影响由于AM/PM的转换效应而表现为抖动
- 采样示波器可以提供相同带宽下最低的本底噪声（通常比具有相同带宽的实时示波器低5-10倍）

$$Jitter_{rms} = \frac{RN_{rms}}{S}$$



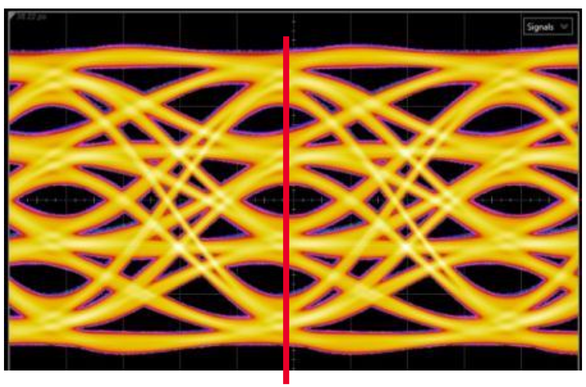
PAM-4的测试挑战——全新的算法

PAM-4大部分测试项目需要新的测量方法和算法

- **哪里是定时测量的参考点？这取决于被测件Rx的设计**

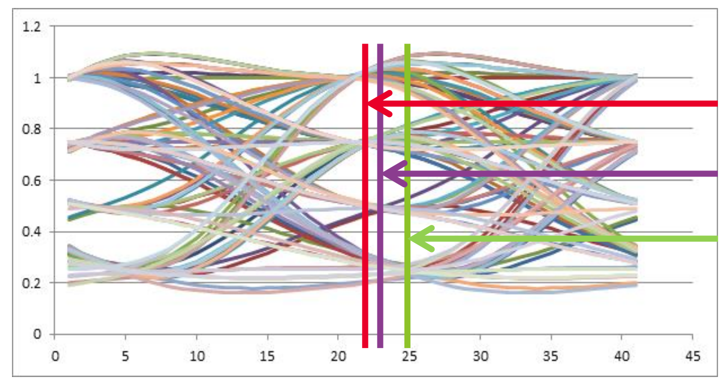
单一的定时参考点（例如：中间眼）

- 对于3个切片采用相同的Rx采样时刻
- Rx的设计最为简单，但有可能不能得到最好的SER性能



独立的定时参考点（针对每一个眼）

- 每一个切片具有独立的定时/延迟
- 可以得到较好的SER性能，但Rx设计复杂

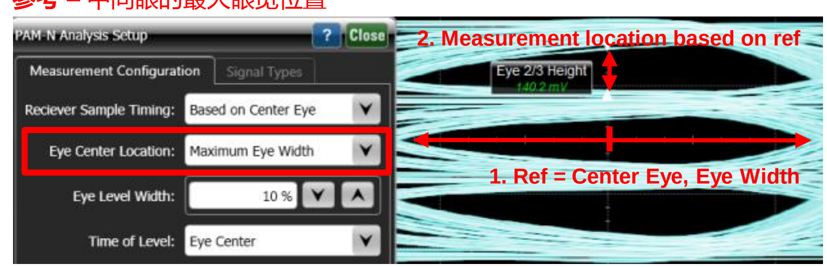


- **参考眼的“中心”如何确定？**
  - 最大眼宽的位置…或…
  - 最大眼高的位置…或…
  - 其它的确定方法?

例如：OIF-CEI 56G-VSR PAM-4

✓ 提议：中间眼，最大眼宽位置

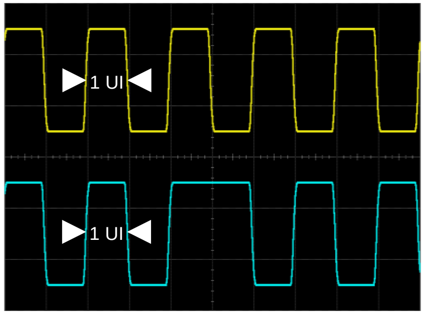
参考 – 中间眼的最大眼宽位置



PAM-4测试码型

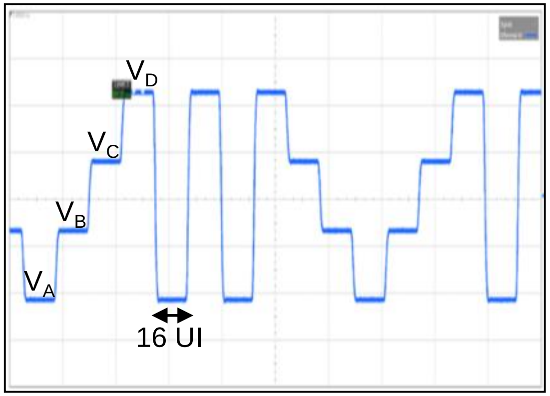
- Reference: IEEE Std 802.3bj-2014, Amendment to IEEE Std 802.3™-2012 as amended by IEEE Std 802.3bk™-2013

PAM-4 transmitters must be capable of generating:



- **JP03A Test Pattern**
  - Repeating {0,3} sequence
- **JP03B Test Pattern**
  - {0,3} repeated 15 times, {3,0} repeated 16 times

  030303030303030303030303030303**0330**30303030303030303030303030303030



- **Transmitter Linearity Test Pattern**
  - ➢ The transmitter linearity test pattern is a repeating 160-symbol pattern with a sequence of 10 symbol values each 16 UI in duration. {–1,–1/3,+1/3,+1,–1,+1,–1,+1,+1/3,–1/3}
  - ➢ 10 consecutive symbols mitigates the impact of ISI on "Level" measurements (V_A, V_B, V_C, V_D)
  - ➢ Level Separation Mismatch Ratio (RLM) $R_{LM} = \frac{6 \cdot S_{min}}{V_D - V_A}$
- **Quaternary PRBS13 Test Pattern (QPRBS13)**
  - ➢ The QPRBS13 test pattern is a repeating 15548-symbol (338 training frame words) sequence

Will these be leveraged into future IEEE/OIF PAM-4 Standards? Probably some leverage…

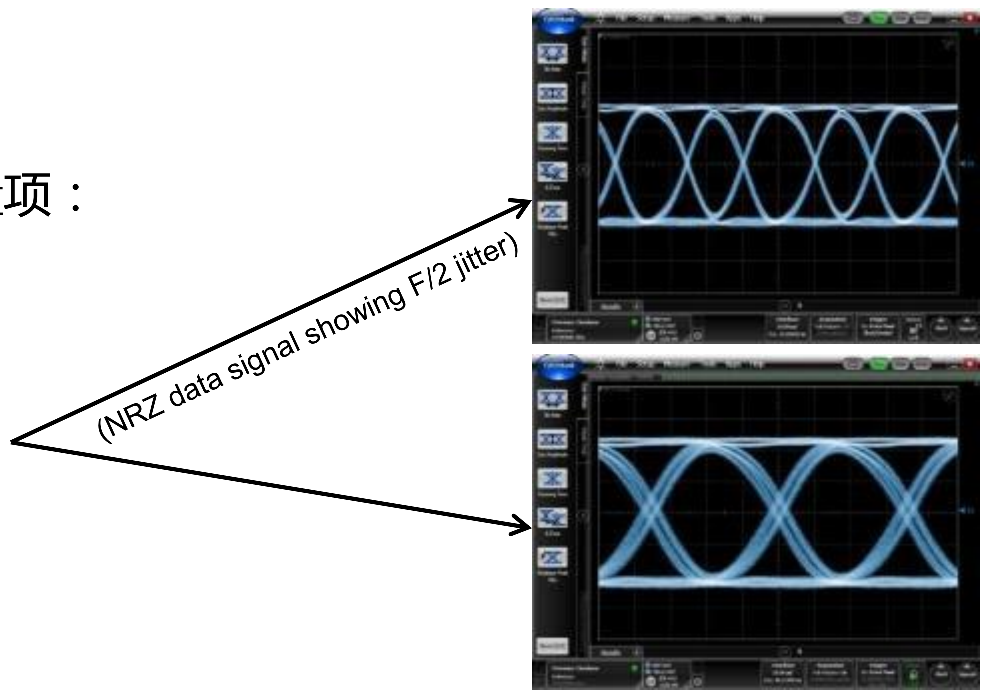
JP03B测试码型
适合于哪些测试项？

– JP03B是一个62比特长并带有相位反转的时钟码型

- {0,3}重复15次，{3,0}重复16次
  0303030303030303030303030303**0330**303030303030303030303030303030

– JP03B适合于如下测量项：

- Random Jitter (RJ)
- Periodic Jitter (PJ)
- Even-Odd (F/2) Jitter



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发射机线性测试码型

10个符号的序列，每个符号持续16个UI

– **测试每一个“电平” (V_A, V_B, V_C, V_D)**
  - 平均电压（对于光信号，则为功率）
  - 噪声
  - 及其他…

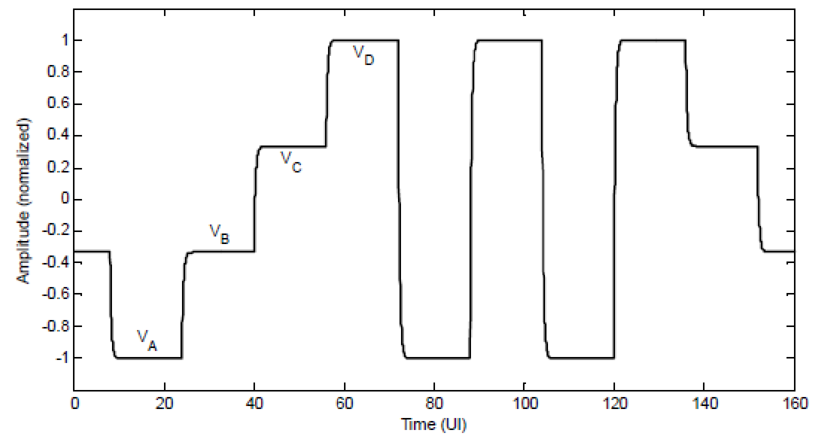

Figure 94–18—Transmitter linearity test pattern

– **分析发射机的线性**
  - Per IEEE Std 802.3bj™-2014 (Amendment to IEEE Std 802.3™-2012 as amended by IEEE Std 802.3bk™-2013), measure:
    - ✓ 最小信号电平，*Smin*
    - ✓ 有效符号电平，*ES*1 及 *ES2*
    - ✓ 电平间隔失配比，*RLM*

$$S_{\min} = \frac{\min(V_D - V_C, V_C - V_B, V_B - V_A)}{2}$$

$$V_{avg} = \frac{V_A + V_B + V_C + V_D}{4}$$

$$ES_1 = \frac{V_B - V_{avg}}{V_A - V_{avg}} \qquad ES_2 = \frac{V_C - V_{avg}}{V_D - V_{avg}}$$

$$R_{LM} = \frac{6 \cdot S_{\min}}{V_D - V_A}$$

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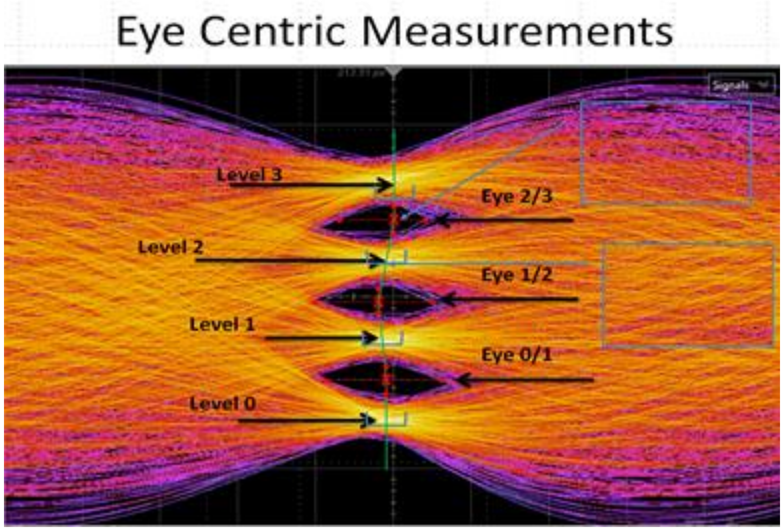
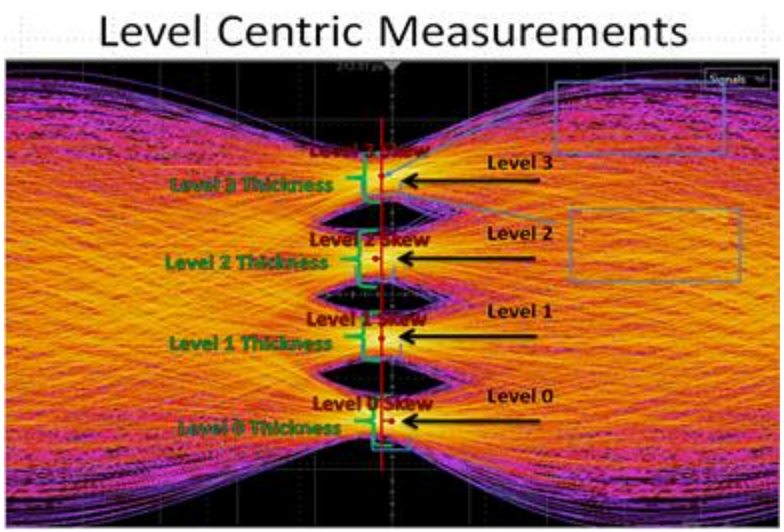
QPRBS13 – 眼图测试

四进制PRBS13测试码型

– 基于眼图的测量项目：

- Eye Height
- Eye Width
- Eye Skew
- EW and EH likely to be specified at a relatively high probability (e.g. EW @ 1E-6)
- Level – mean, “thickness”, and skew at the points of minimum ISI.

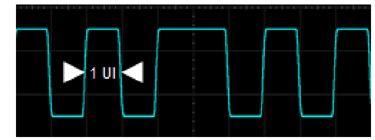




TX 测试方法 – 以IEEE 802.3bj Clause 94为例

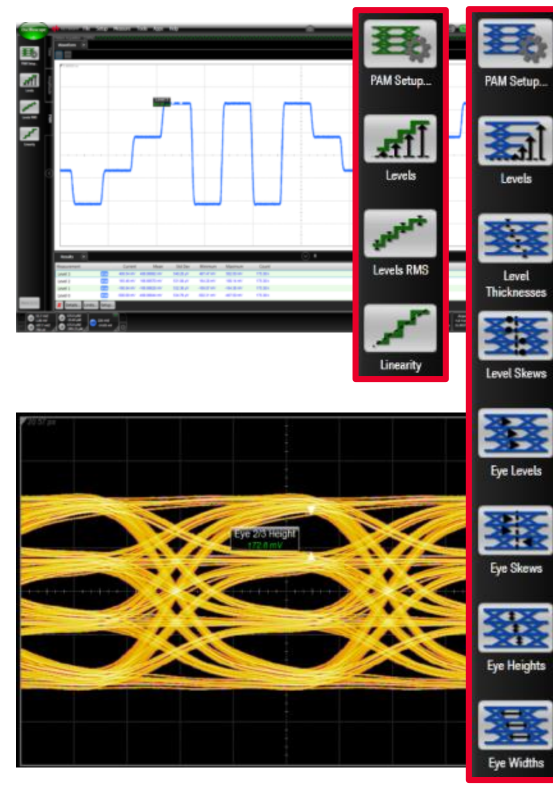
IEEE 802.3bj Clause 94 针对Tx的测试可以归纳为如下3个步骤：

1. **利用JP03B码型测试抖动参数**
   测量RJ, Periodic Jitter, Even-Odd Jitter (EOJ, or F/2)



2. **基于“发射机线性测试码型”测试PAM-4信号的电平、噪声以及电平线性度等指标：**
   - 电平（电压或功率）
   - 噪声
   - 线性度 (R_{LM}, Ratio Method,…)

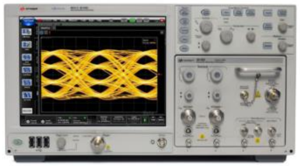
3. **基于QPRBS13码型及均衡算法（例如CTLE）测试眼图相关的参数：**
   - Eye Width @ 1E-6
   - Eye Height @ 1E-6
   - Eye Skew

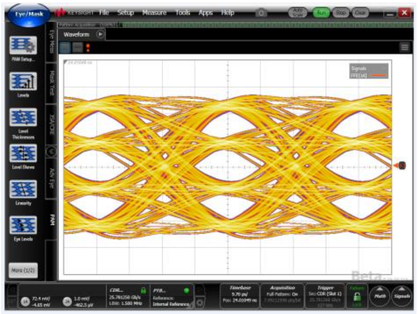


Keysight 对于PAM-4信号的测试方案

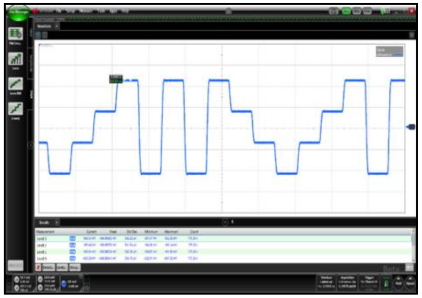
Keysight 在2015年初第一个向市场推出了基于采样示波器和实时示波器的PAM-4信号分析测量软件：

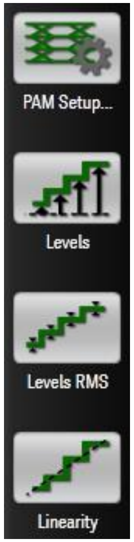
- 86100D-9FP for the 86100D DCA-X





- N8827A/B PAM-4 Analysis Software for RT scopes





这些软件选件执行规范所要求的基本的PAM-4参数测量，但不会自动设置与控制示波器，不会将测试结果与任何规范文本进行比较。

利用Keysight N8827A分析工具进行PAM-4测试

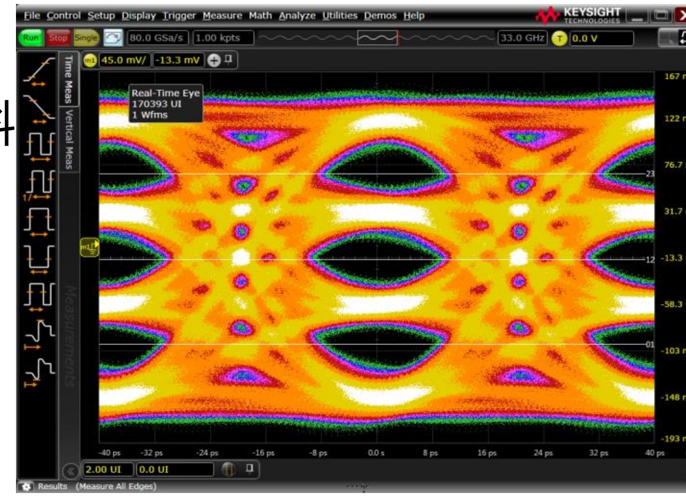
Infiniium示波器上基于眼图和电平测量的软件工具

– PAM-4实时眼图测量：

- 每一个PAM-4眼的眼高、眼宽和相对眼偏斜

– PAM-4波形测量：

- 每一个电平的均值、RMS值及“厚度”
- 每一个阈值的数据TIE
- PAM-4信号所具有的6种跳变类型的上升/下降时间
- 支持CTLE、FFE与DFE均衡

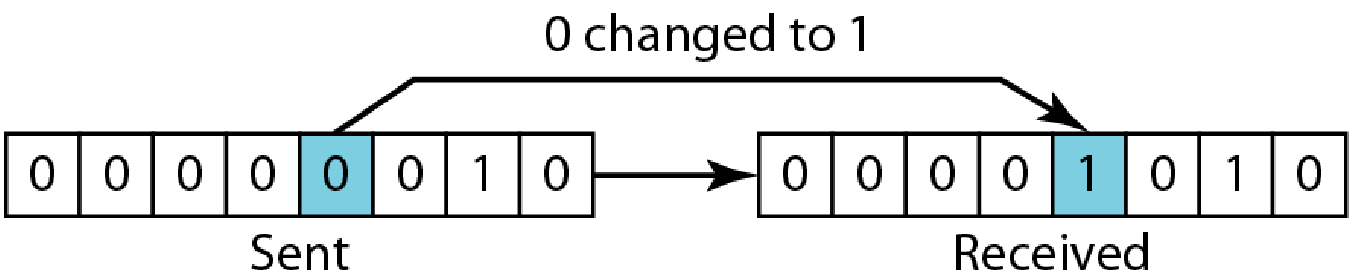


Results (Measure All Edges)

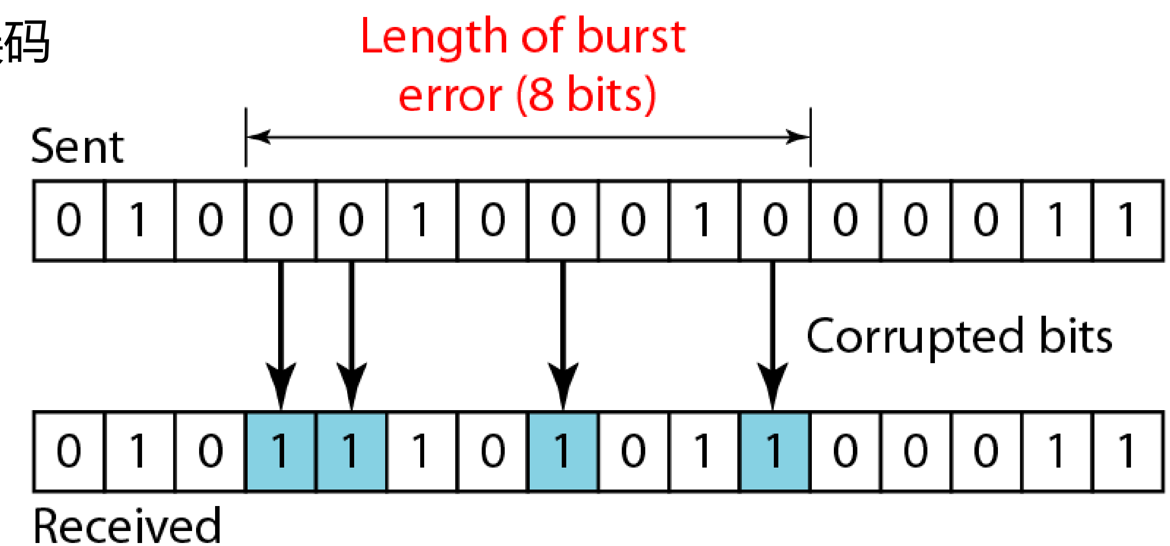
Measurement	Current	Mean	Min
Eye 2/3 Width(m	12.6202 ps	0.0 s	12.6202 ps
Eye 1/2 Width(m	15.5048 ps	0.0 s	15.5048 ps
Eye 0/1 Width(m	13.2212 ps	0.0 s	13.2212 ps
Eye 2/3 Height(n	29.2 mV	0.0 V	29.2 mV
Eye 1/2 Height(n	36.9 mV	0.0 V	36.9 mV
Eye 0/1 Height(n	31.3 mV	0.0 V	31.3 mV
Eye 2/3 Skew(m1	721.2773 fs	0.0 s	721.2773 fs
Eye 1/2 Skew(m1	-793.8863 fs	0.0 s	-793.8863 fs
Eye 0/1 Skew(m1	72.6090 fs	0.0 s	72.6090 fs
Eye 2/3 Level(m1	72.2 mV	0.0 V	72.2 mV
Eye 1/2 Level(m1	-15.0 mV	0.0 V	-15.0 mV
Eye 0/1 Level(m1	-98.5 mV	0.0 V	-98.5 mV
Level 3 Mean(m1	117.7 mV	0.0 V	117.7 mV
Level 2 Mean(m1	30.6 mV	0.0 V	30.6 mV
Level 1 Mean(m1	-59.7 mV	0.0 V	-59.7 mV
Level 0 Mean(m1	-149.1 mV	0.0 V	-149.1 mV
Level 3 RMS(m1)	8.6466 mV	0.0 V	8.6466 mV
Level 2 RMS(m1)	7.7473 mV	0.0 V	7.7473 mV
Level 1 RMS(m1)	7.3821 mV	0.0 V	7.3821 mV
Level 0 RMS(m1)	9.6787 mV	0.0 V	9.6787 mV

前向纠错（Forward Error Correction）
误码类型

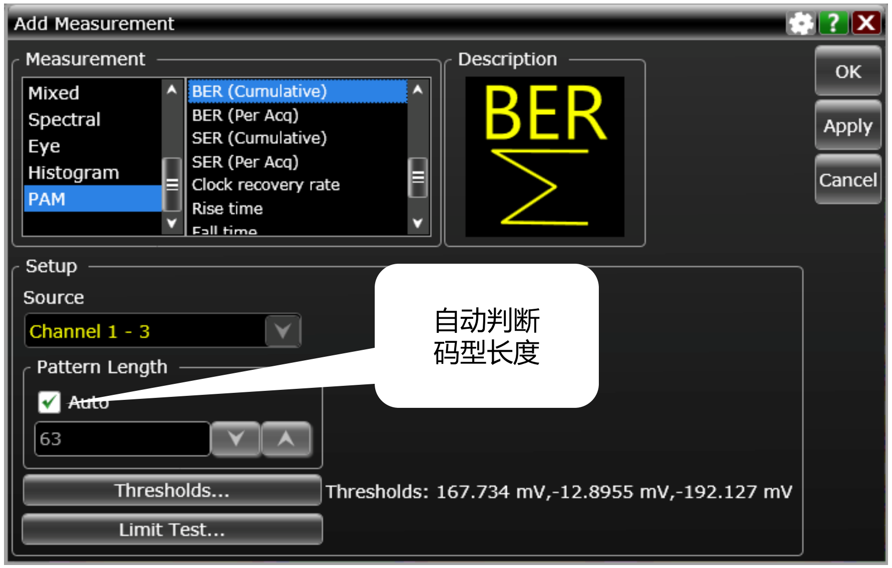
– 单一比特误码



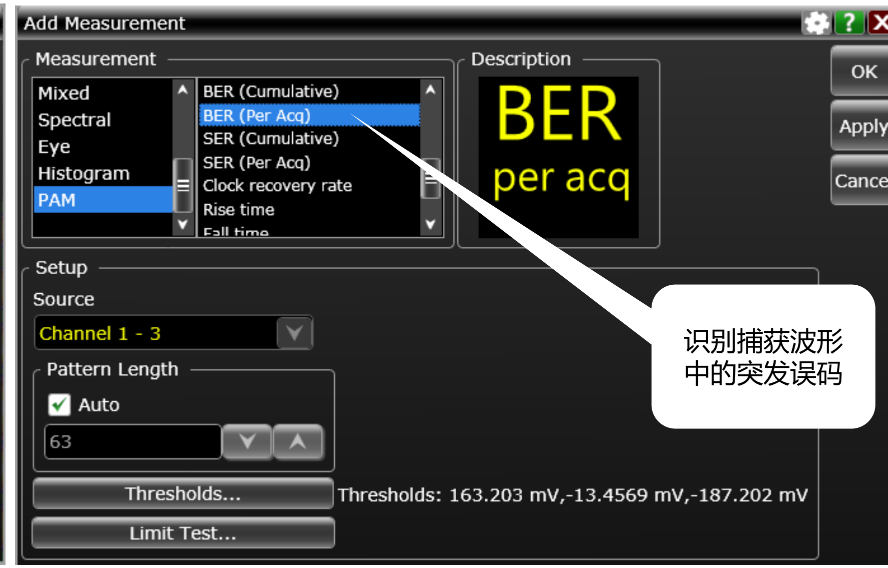
– 突发误码



误码率测量（ BER ）



BER (Cumulative)
显示示波器多次捕获
波形中总的误码率



BER (Per Acq) 显示
每一次捕获波形中
的误码率

在实时示波器上设置BER测试

Measurement	Current	Fail Max	Fail Min	Mean	Min	Max	Range (Max-Min)	Std Dev	Count
BER, Per Acq(1-3	1.62090E-05	0	0	1.62090E-05	1.62090E-05	1.62090E-05	0.0E+00	0.0E+00	1
Eye 2/3 Width(1-	0.0 s	0	0	0.0 s	0.0 s	0.0 s	0.0 s	0.0 s	1
Eye 1/2 Width(1-	60 fs	0	0	60 fs	60 fs	60 fs	0.0 s	0.0 s	1
Eye 0/1 Width(1-	0.0 s	0	0	0.0 s	0.0 s	0.0 s	0.0 s	0.0 s	1

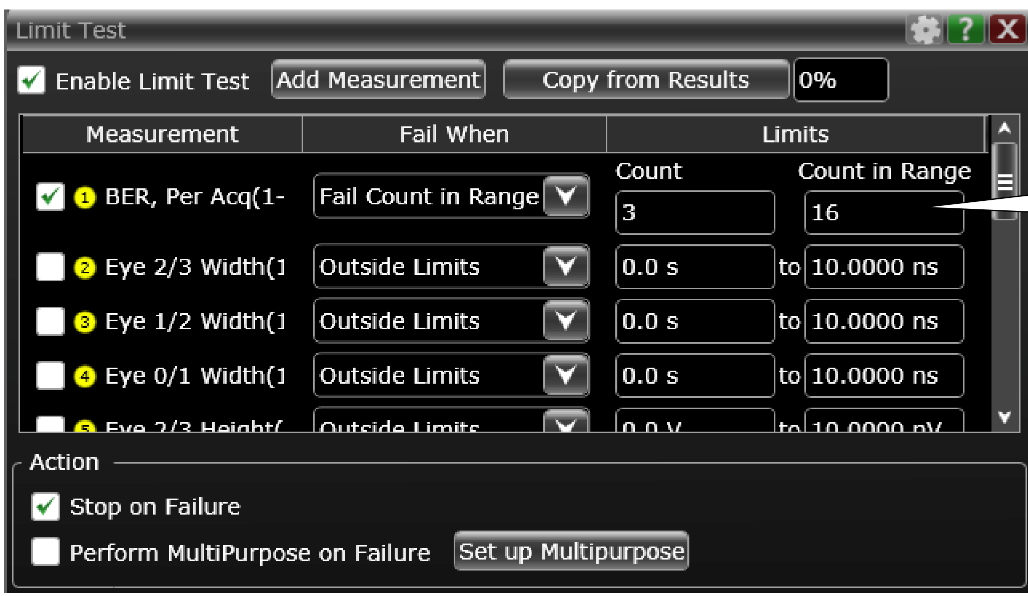
BER测量功能

– 支持测量：累积BER/SER，以及单次捕获的BER/SER

– BER统计值（无预设限值）、BER 10E-5, 10E-6, 10E-7.

– 单次捕获BER测量，支持对单次捕获波形中出现突发误码的情况进行触发

– PAM-4眼图展开，及BER误码位置浏览功能（显示波形出现误码的位置）



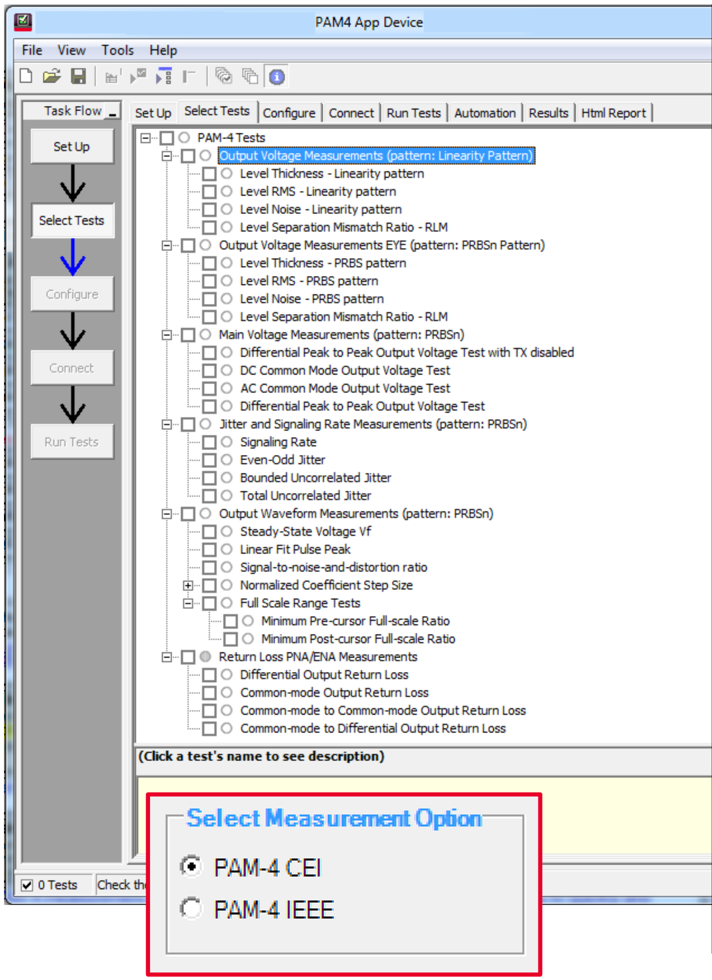
突发误码可以用"在Y个比特序列范围内出现X个误码"的方式进行定义

定位出现误码的波形位置

实时示波器允许在出现误码时重新展开眼图

最新的 PAM-4 测量应用软件

针对采用PAM-4的新兴标准的“预兼容”应用



- **N1085A PAM-4 Measurement App**
  for Ethernet and OIF-CEI (for the 86100D DCA-X)

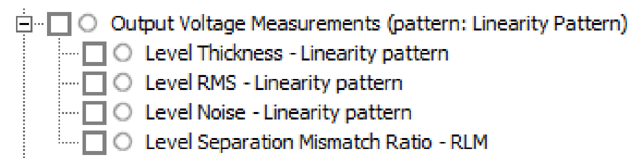
- **N8836A PAM-4 Measurement App**
  for Ethernet and OIF-CEI (for the real-time scopes)

Keysight PAM-4测量应用

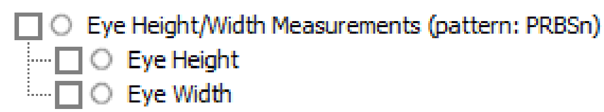
支持超过20个测试项目

Provides comprehensive coverage of all PAM-4 tests that are specific to the Clause you are testing. You may click on all tests, a group of tests or individual tests. The full test name appears in the test list, and is also shown in the test results and reports. A description of the test and reference to the Standard / IA are shown for each test.

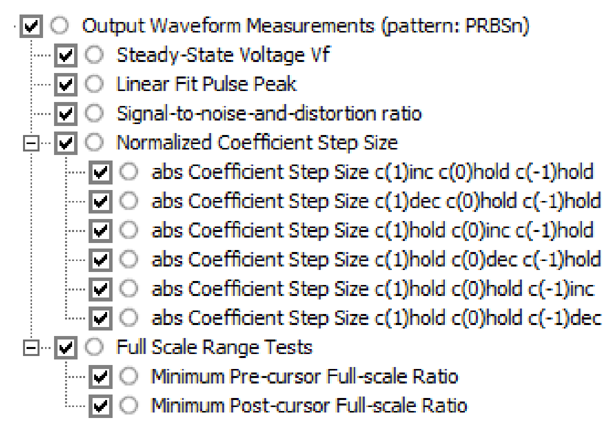
- **Linearity (RLM) and Level Measurements**



- **Eye Width (EW), Eye Height(EH) Measurements**



- **Output Waveform Measurements**



Plus

- **Jitter and Signaling Rate Measurements** (JP03A/JP03B pattern)
- **Return Loss Measurements** (using ENA/PNA, or N1055A TDR)

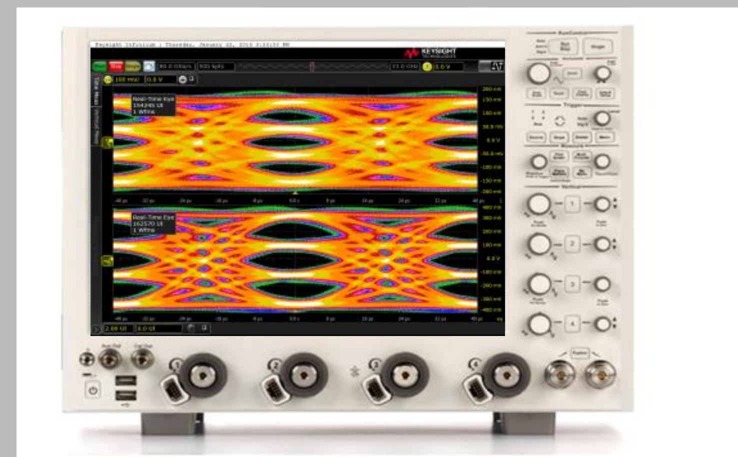
基于示波器的PAM-N测试方案-电信号

✓ **Best for <u>validating / characterizing</u> PAM-4 designs.**
(best signal fidelity due to lower noise).

<u>Electrical – Sampling Scope</u>
(includes built-in clock recovery and precision timebase)
Keysight 86100D DCA-X with 86108B

- Channels: 2
- Bandwidth: 50 GHz
- Jitter: <45 fs rms typ.
- Electrical Clock Recovery – integrated HW Clock Recovery works with PAM-N signals up to 32 Gbaud
- 86100D-9FP PAM-4 Analysis Software
- N1085A PAM-4 Measurement App for Ethernet and OIF-CEI

✓ **Best for <u>troubleshooting</u> PAM-4 designs.**



<u>Electrical – Real-time Scope</u>
Keysight DSO Z-Series

- Channels 2-4
- Bandwidth: up to 63 GHz
- Sample Rate: Up to 160 GSa/s
- PAM-4 Serial Data Analysis Wizard
- Software Clock Recovery (specify transitions for CR)
- N8827A PAM-4 Analysis Software w/ BER!
- N8836A PAM-4 Measurement App for Ethernet and OIF-CEI

基于示波器的PAM-N测试方案-光/电信号

<u>Optical (add Electrical/TDR remote heads)</u>

Agilent 86100D DCA-X with 86105D-281

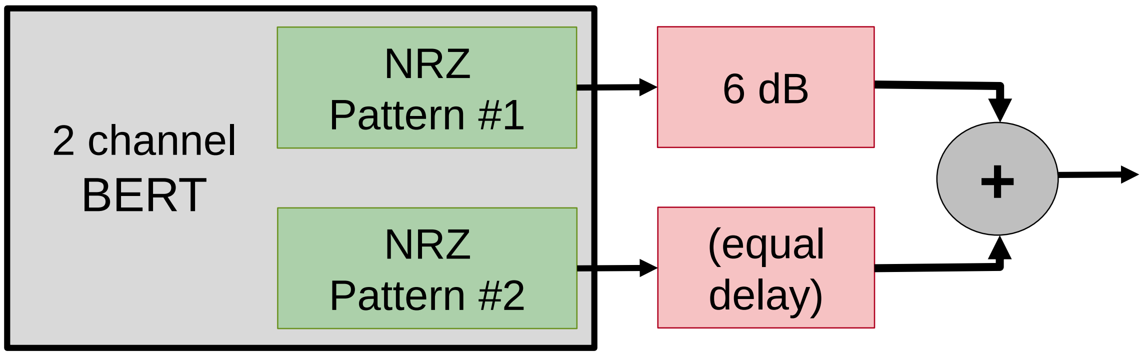
- Channels: Up to 2 optical per module, 8 electrical
- Bandwidth: 34 GHz (optical), 60 GHz (electrical)
- Jitter: < 85 fs rms typ. (with 86100D-PTB)
- N1070A Optical Clock Recovery (external)
    - 32 Gbaud Single Mode
    - 14 Gbaud Multimode
- Electrical Remote Heads
    - N1045A 60 GHz Electrical Only
    - N1055A 50 GHz Electrical with TDR/TDT
- 86100D-9FP PAM-4 Analysis Software
- N1085A PAM-4 Measurement App for Ethernet and OIF-CEI

目录

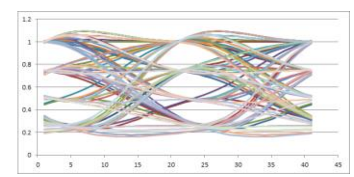
- PAM-4信号及其挑战
- PAM-4信号的分析
- **PAM-4信号的产生**
- 总结

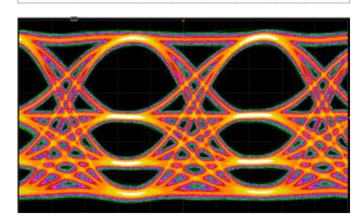
输入(Rx)测试 – PAM-4 信号产生
传统的NRZ 码型发生器

通过2路NRZ PPG合成：通过功分器将2路不同幅度权重的NRZ信号合成1路PAM-4



+ 长用户码型
+ “Drives like a BERT” – very responsive to stress control changes
+ 更快的上升时间
- 有限的压力注入(SJ, RJ, BUJ, Even/Odd, SI, RI, etc.)
  - Long lead time for new stress capability – if possible as all
- 更高的成本 – 每个PAM-4信号需要2路高性能的码型发生器。





输入(Rx)测试 – PAM-4 信号产生选择
任意波发生器

最新一代AWG可以产生PAM-N 信号，速率高达32Gbaud

+ 不局限于PAM-4 – 能产生任何幅度调制信号（PAM-8,…）

+ 能产生任何压力 – 抖动，幅度干扰，迟滞，非线性，...
  - Future proof – 标准会要求新的抖动压力类型
  - AWG可以通过模拟器运算产生各种新的压力

+ 较小的尺寸 – 较低的成本
  - 在单块板卡上实现高达4 个PAM-N通道

- 有限的用户码型
  - 但是可以产生所有目前标准定义的PAM-4测试码型

- 较慢的上升时间
  - 足够快——模拟接收机测试的通道

AWG与传统BERT的定时分辨率

– 传统BERT的定时单位是UI (Unit Interval)
  - 以整数表示的比特、去加重抽头宽度等
  - 以小数表示的定时抖动 (mUI)

– AWG的定时分辨率与UI无关联
  - 预失真模拟定时分辨率 << 采样间隔
  - 去加重抽头宽度不受整数UI的限制

AWG-Keysight M8195A & M8196A

NEW

M8195A

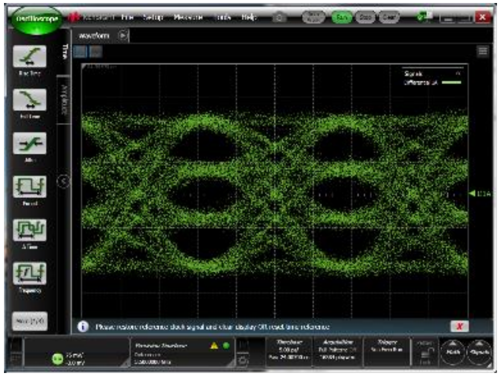
- Up to 65 GSa/s
- 25 GHz BW
- Up to 4 ch.
- 8 bit resolution

- Applications
  - 32 GBaud PAM-4
  - Coherent optical
  - RF with > 4 GHz modulation BW

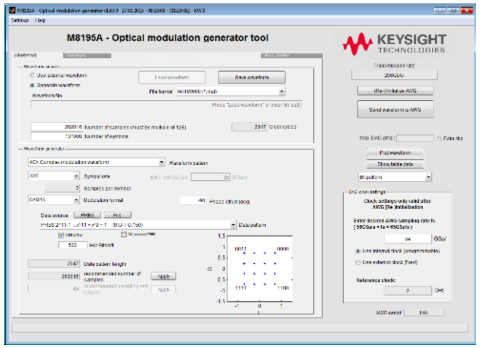
M8196A

- Up to 92 GSa/s
- 32 GHz BW
- 4 channels
- 8 bit resolution
- limited playtime

- Applications
  - 56 GBaud PAM-4
  - Coherent optical



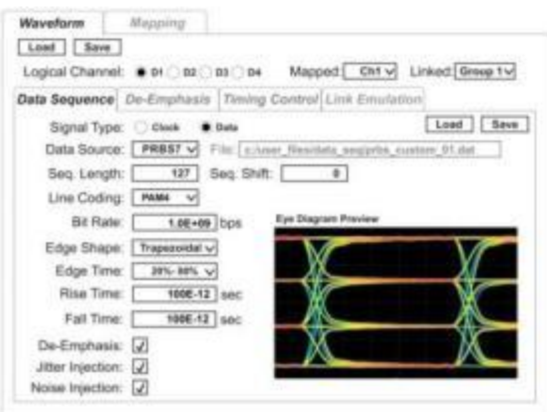
56 GBaud PAM-4 (92GSa/s)



Go where you have never been able to test before:
in speed, in bandwidth and in channel density. *Explore your possibilities*

M8195A 65 GS/s AWG PAM-N 码型发生器

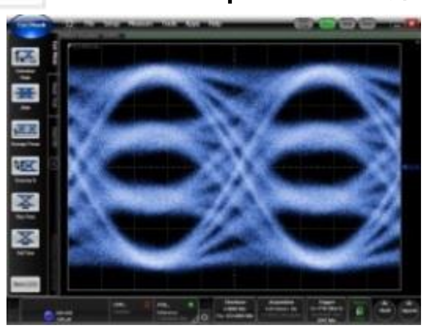
1 – 4 通道
65 GS/s – 8 bit
25 GHz 模拟带宽
固有抖动RJ：<200 fs typ. (32G NRZ)
差分输出幅度：2 Vpp (diff)
内存：最大可选16GS (up to 2^24-1 resp. 2^31)

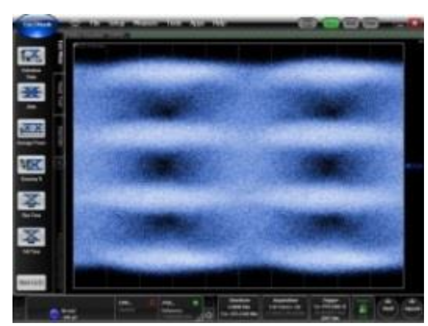


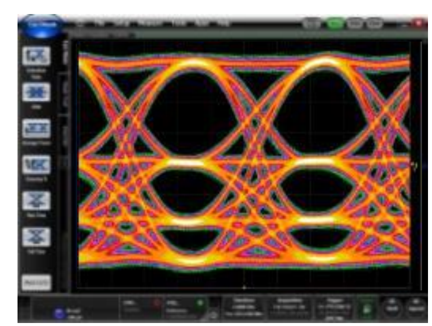
Industry leading source for PAM-4

支持 PAM-4、PAM-8 和其他高阶调制类型：
支持相干OFDM、QAM-N

无需外部硬件，直接注入各种"压力"损伤：
上升时间、ISI、抖动、DCD、noise，…
Future proof – 新的压力类型会在将来被定义

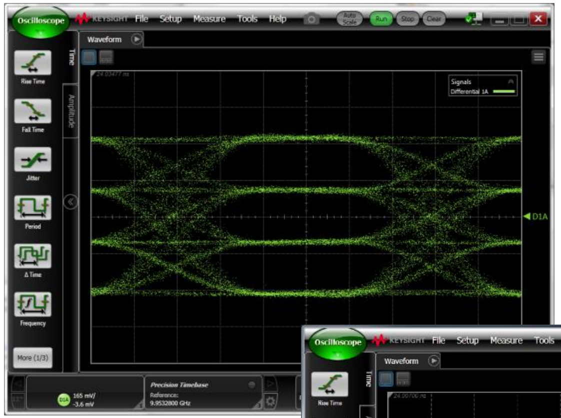




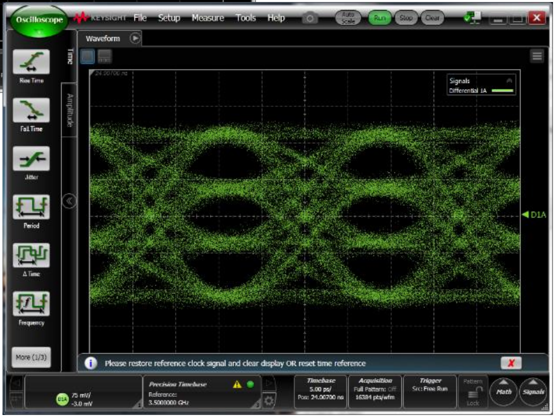


Keysight M8196A AWG

- Highest speed = **92 GS/s**
- Extremely high bandwidth = **32 GHz**
- High channel density =
  Up to **4 synchronized channels**
- Differential outputs:
  - Amplitude up to 1 $V_{pp(se)}$ (2 $V_{pp(diff.)}$),
  - Voltage window -1.0 … +2.5V
- **8 bit resolution**
- Rise/Fall times **below 9 ps**
- 512 kSa memory



20 GBaud PAM4



56 GBaud PAM4

不仅仅只是抖动!

生成不同的“压力”波形更加便捷

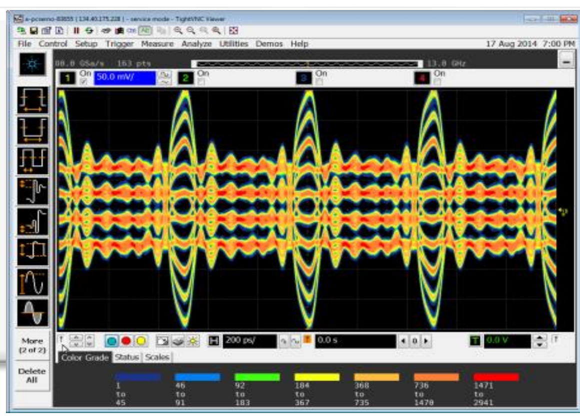
– PAM-4链路涵盖很多全新的技术，哪些信号损伤会在接收端导致信号误码还需要持续的摸索与实验

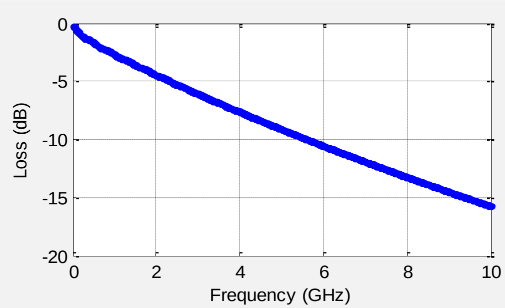
– AWG的“任意”特性，允许用户在数分钟内产生各种各样的波性损伤或压力

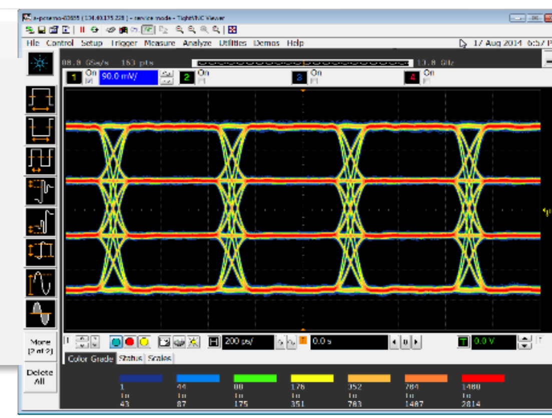
  • 除了定时抖动之外，还可以包括线性、时间偏斜等幅度相关的信号损伤

– 去加重可以直接合并在生成的码型波形中

– 可以方便的进行线缆/夹具的去嵌入以及信道的模拟，无需在信号路径上增加额外的硬件以实现信号损伤。





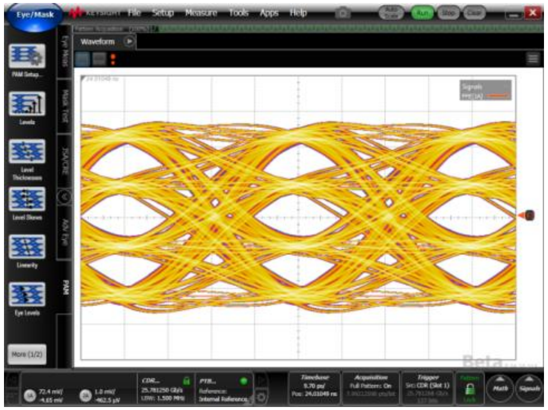


KEYSIGHT TECHNOLOGIES

目录

- PAM-4信号及其挑战
- PAM-4信号的分析
- PAM-4信号的产生
- **总结**

PAM-4 小结



- PAM-4 signaling will be an enabler for 400G links
- Transition from NRZ to PAM-4 is revolutionary
  - Many new challenges - New science
- Required Tx measurements and Rx stress types will change
- Keysight provides leading tools for PAM-4 Simulation, Tx and Rx Characterization
  - Tx Characterization Oscilloscopes
    - Keysight 86100D DCA-X sampling oscilloscope
      - N1010A FlexDCA remote access analysis/simulator
      - N1085A PAM-4 Measurement Application for Ethernet and OIF-CEI
    - Keysight DSAZ 63 GHz real-time oscilloscope
      - N8827A PAM-4 Measurement Tool With BER
      - N8836A PAM-4 Measurement Application for Ethernet and OIF-CEI
  - Rx Characterization:
    - Keysight M8195A/M8196A AWG, 81490A optical transmitter, N1010A FlexDCA

Thank you for your time!