Outline

The Optical Sampling Scope Development Cycle

START

Review of Scope Architectures

Timebase Dev.

Sampling Dev.

Manufacturability

Fame & Fortune
Optical Sampling Scope

40Gb/s Optical transmission was coming
300 GHz fiber link demonstrated

Need for a new, fast instrument capable of measuring ~2ps pulses

Maximum bandwidth available in Sampling Scopes was ~60GHz
Scope Review

Oscilloscope

Graphical tool to display the time evolution of electrical signals

- **Horizontal Channel = Timebase**
  - Provides the time axis

- **Vertical Channel**
  - Provides the amplitude axis

- **Real-Time**
- **Time-Equivalent (Sequential)**
Real-Time Scope

Timebase

signal

trigger

Sampling time

Repetition time

- Stable Clock, Fast Sampling

Real-Time Scope

Analogy
Recording a pendulum movement

Movie
Real-Time Scope
Vertical Channel

- Stable, Linear Amplification
  ⇒ DC and AC
- Low noise
- Acquire data in time < Sampling Time
  ⇒ Fast A/D conversion

Time-Equivalent Scope
Timebase

- Stable Clock
- Stable delay
- Fast Trigger
Time-Equivalent Scope

Analogy
Recording a pendulum movement

Pictures (fast shutter)

Time-Equivalent Scope

Vertical Channel

- Stable, Linear Amplification
  - DC and AC (not RF)
- Low noise
- High BW data sampler
- Low sampling rate
Scope Characteristics

Important Specifications

- Vertical Channel
  - Amplitude Accuracy
  - Noise
  - Channel Bandwidth

- Timebase
  - Time Accuracy
  - Bandwidth
  - Sampling Rate
  - Jitter
  - Trigger Bandwidth

Vertical Channel

Amplitude Accuracy

Reported measurement: \( V_{pp} = 1.23567 \text{ V} \)

Accuracy Spec = \(<\text{noise}> + % <\text{measurement}>\)
Vertical Channel

Channel Bandwidth

Simplified Channel Diagram:

-3dB point of Frequency Response
Does not provide enough information

Rule of thumb: Scope BW = 2 Signal BW

Vertical Channel

Channel Bandwidth Simulation

Input:
4ps Gaussian pulse
(BW ~ 110GHz)

Instrument bandwidth: 65GHz
Vertical Channel

Channel Bandwidth Simulation (cont.)

[Graph showing pulse width measurement vs. bandwidth for different filters: Bessel-Thompson and Butterworth.]
### Scope Characteristics

**Important Specifications**

- **Vertical Channel**
  - Amplitude Accuracy
  - Noise
  - Channel Bandwidth

- **Timebase**
  - Time Accuracy
  - Bandwidth
  - Sampling Rate
  - Jitter
  - Trigger Bandwidth

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#### Timebase

**Sampling Rate**

Nyquist: sampling rate \( \geq 2 \cdot f_{\text{max}} \) (signal)

- Sample at least 2 points of the max frequency signal

Rule of thumb: Scope BW = Sampling Rate / 4
Timebase

Sampling Period and Sampling Window

20GSa/s
⇔ 50ps sampling period
⇔ BW?

Sampling period ≠ sampling window

Evident in Time-Equiv. Scopes
Origin of Rule of Thumb

Timebase

Jitter Bandwidth

Jitter = time uncertainty

\[ \sim e^{-\frac{t^2}{2\sigma^2}} \]

\[ \sim e^{-2\pi^2 f^2 \sigma^2} \]

\[ BW = \frac{1}{\pi \sigma} \ln \frac{2}{2} \]
Timebase

Timebase Accuracy

Accuracy Spec = <jitter> + % <measurement>

1ps RMS jitter $\oplus$ 187GHz

Timebase Development
Random Timebase

**Standard Timebase:**
Internal clock provides the time stamp of the sample

**Random Timebase:**
External clock
Measure clock to determine time stamp of sample
Internal clock not synchronized with external one.

time stamp for each sample estimated from clock
Random Timebase

Time Stamp Estimation

\[ \omega = 2 \pi f \]

\[ \alpha = \omega t \]

Random Timebase

Time Stamp Estimation

Quadrature
Random Timebase

Applications & Limitations

• Low Jitter Floor
• High Accuracy
• External Clock Available
• Good Quality Clock
• Time Stamp limited to one Clock Period

Ideal for Eye Diagram Analysis

Eye Diagram Analysis

• Oscilloscope is triggered with a synchronous clock.
• The bits in the data stream do not have identical periods, so the screen shows a multivalued signal representing the superposition of data values

011
100
111
000
010
101
86107A Results (cont.)

Without Precision Timebase

With Precision Timebase

Random Timebase Extreme

Calculated value: 50fs
Sampling Development

Sampling Options

• Photodiode + Electrical sampling
• Optoelectronic Sampling
• Optical Sampling

Input: ⇒ optical / fiberized
     ⇒ wavelength ~ 1550nm
Autocorrelation

Measure a pulse with itself

Intensity Autocorrelation

Non-Linear Crystal

\[ E e^{i\alpha} = E e^{i\alpha}; E e^{i2\alpha} \]

\[ E e^{i\alpha t} + E e^{i\alpha t} \]

\[ E e^{i(\alpha t + \beta)}; E e^{i(\alpha t - \beta)} \]

Analogy with non-linear device
Autocorrelation

- Autocorrelation Trace

- FWHM = 646 fs
- Hyperbolic Secant Square
  - 0.648*FWHM = 419 fs
- Gaussian
  - 0.707*FWHM = 457 fs
Sampling Development

Cross-Correlation

![Cross-Correlation Diagram]

- Sampling pulse
  - ~ 400fs (~ 1THz)
- Signal Sample

Sampling Development

Sampling Pulse Issues

- **Sampling wavelength ≠ Input wavelength** (to avoid spectrum ‘Holes’)
  - Sum Frequency Generation

- **Bandwidth**
  - Short Pulse Laser (~200fs)
Sampling Development

Crystal Issues

- Efficiency
  - Periodically Poled Crystal (PPLN)
- Spectral Coverage
  - Chirped Poling
- Sensitivity
  - High Power Laser
- Power constrains in Crystal
  - Doping

Sampling Development

Vertical Channel

Sum Frequency Generation

Input signal

Dichroic beamsplitter

Non-linear crystal

APD

Sampling Scope
Manufacturability

Challenge:
Convert our Breadboard, that was distributed on an optical table into a manufacturable product.

We have the technology…
… if only we had the 6 million dollars

(this may be funny only for the older guys who used to watch the “6 million dollar man” show)
Optical Sampling Scope

Manufacturability

What does it mean?

- Off-the-shelf components
- Reliable suppliers (for one-of-a-kind)
- Rugged design
- To be assembled by non-experts
- Testable to guaranteed specifications
- Environmental Performance

Prototype 1
Optical Sampling Scope

Desired Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Requirement</th>
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<tr>
<td>Noise Level</td>
<td>&lt; 100uV RMS</td>
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<tr>
<td>Wavelength</td>
<td>~1550 nm (25nm window)</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>&gt; 600 GHz</td>
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</table>

Testing Required

Optical Sampling Scope

Noise Tests

![Graph showing noise tests with Input Power (W) on the x-axis and Signal to Noise Ratio (SNR) on the y-axis. The graph includes markers for High Gain and Low Gain, with values for RMS Dark Noise @ 1550nm (High Gain: 40uW, Low Gain: 300uW) and Shot Noise.]
Sampling Development

Wavelength Coverage

-6 nm
11 nm
22 nm

35C
55C
75C

Wavelength Coverage

Sampling Development

Linearity

low gain
high gain
Optical Sampling Scope

Bandwidth Test

Impulse Response:

Autocorr. FWHM : 680fs
PW (Gaussian) = 480fs

Measured: 650 fs
Sampling window: 440fs
BW (Gaussian): 980GHz
Optical Sampling Scope

Impulse Response:

- Autocorr. FWHM: 680fs
- PW (Gaussian) = 480fs
- Measured: 630 fs
- Sampling window: 410fs
- BW (Gaussian) > 1THz
Results

Optical Sampling Scope

40Gbps RZ Optical Signal

Standard Electrical Sampling (50GHz)  Optical Sampling (800GHz)
Bit period is less than 3 picoseconds!
The End

Additional Info
Random Timebase Example

40GHz signal
10GHz Clock
4.1GHz sampling rate (freerun)

Random Timebase Example

0 500 1000 1500 2000 2500
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

time [ps] signal sampling

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Random Timebase Example

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<th></th>
<th>Input Phase</th>
<th>Time [ps]</th>
<th>Amplitude</th>
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<td>0.40</td>
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Note: The graph shows the input signal and reconstructed samples over time.