Optical Sampling Scope

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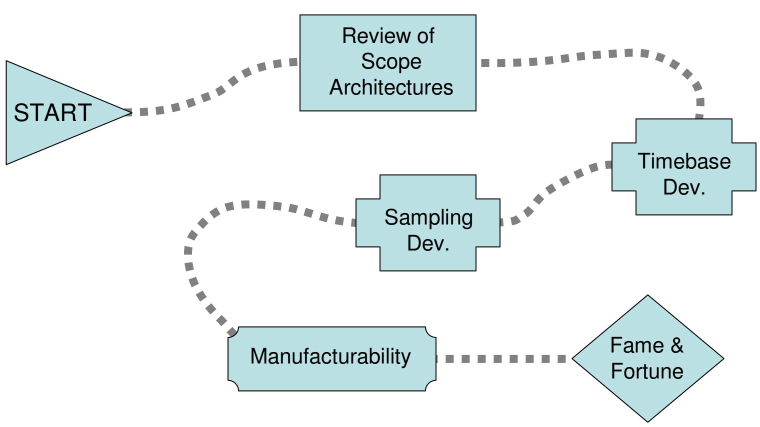
Outline

The Optical Sampling Scope Development Cycle



Project Kick-Off

Optical Sampling Scope

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

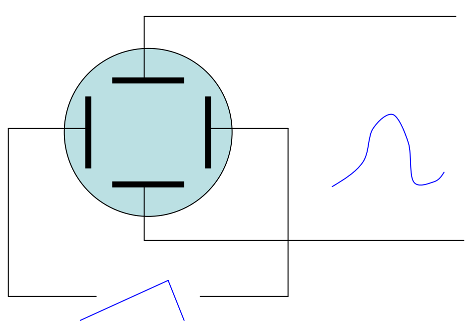
Need for a new, fast instrument capable of measuring ~2ps pulses

Maximum bandwidth available in Sampling Scopes was ~60GHz

Scope Review

Oscilloscope

Graphical tool to display the time evolution of electrical signals



Vertical Channel

Provides the amplitude axis

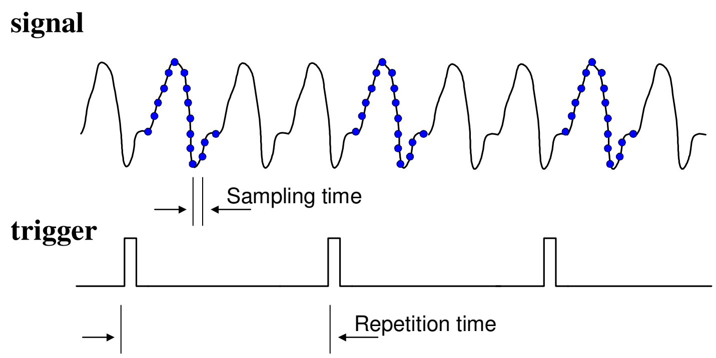
Horizontal Channel = Timebase

Provides the time axis

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

Real-Time Scope

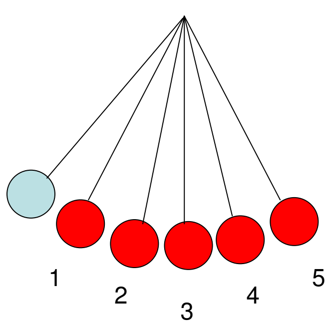
Timebase



• Stable Clock, Fast Sampling

Real-Time Scope

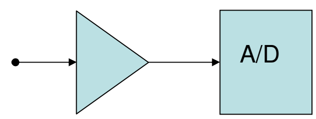
Analogy
Recording a pendulum movement



Movie

Real-Time Scope

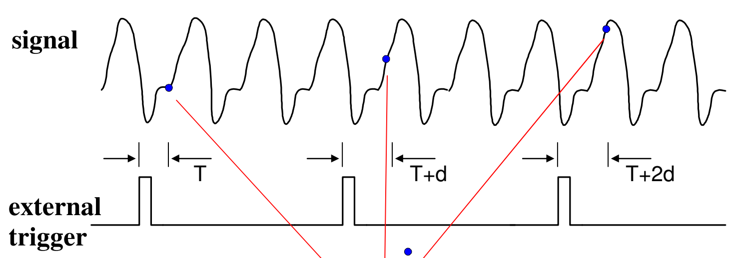
Vertical Channel



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

Time-Equivalent Scope

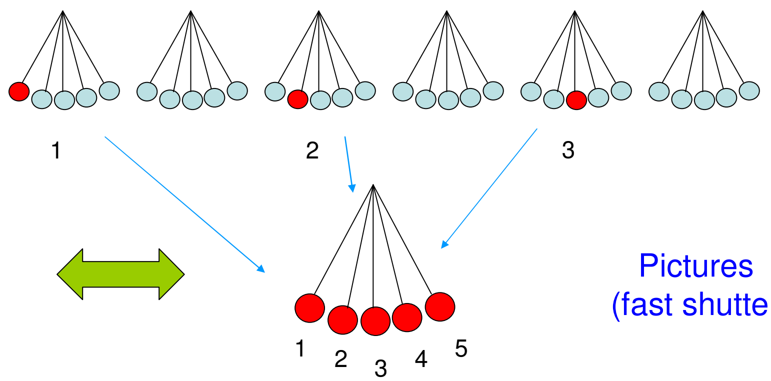
Timebase



Stable Clock
Stable delay
Fast Trigger

Time-Equivalent Scope

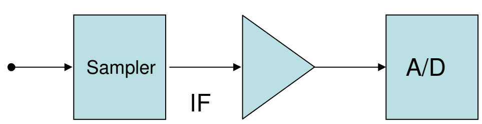
Analogy
Recording a pendulum movement



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

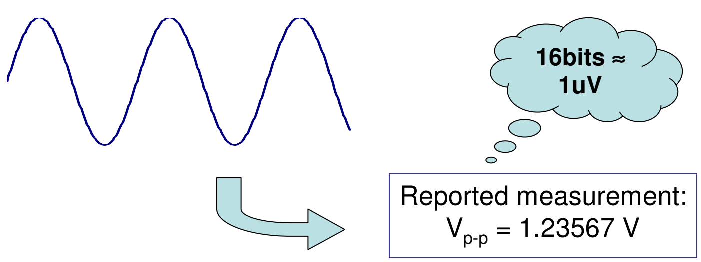
Important Specifications

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

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

Vertical Channel

Amplitude Accuracy

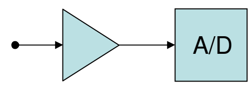


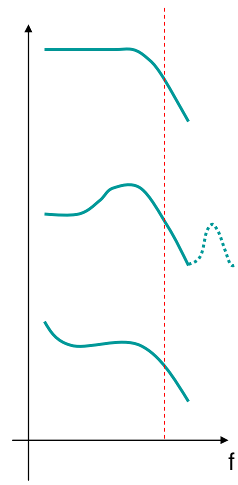
Accuracy Spec = <noise> + % <measurement>

Vertical Channel

Channel Bandwidth

Simplified Channel Diagram:





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

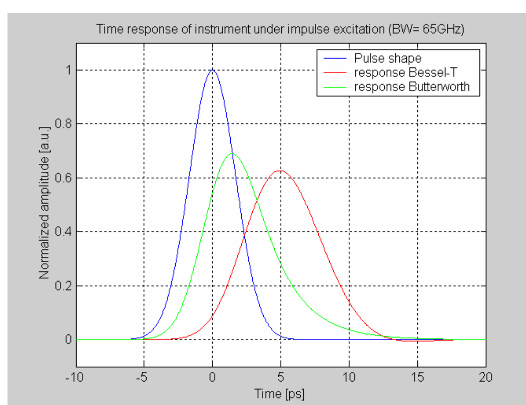
Rule of thumb: Scope BW = 2 Signal BW ?

Vertical Channel

Channel Bandwidth Simulation

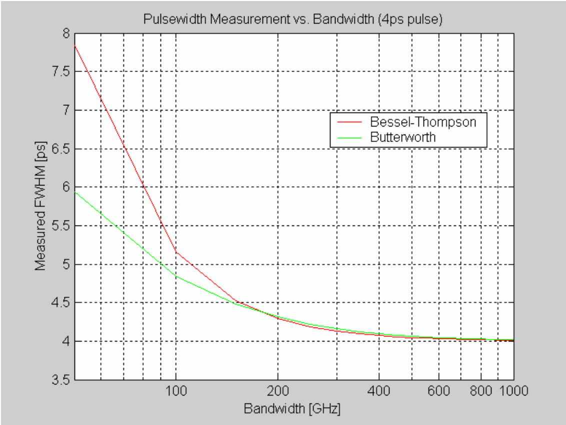
Input:
4ps Gaussian pulse
(BW ~ 110GHz)

Instrument bandwidth: 65GHz



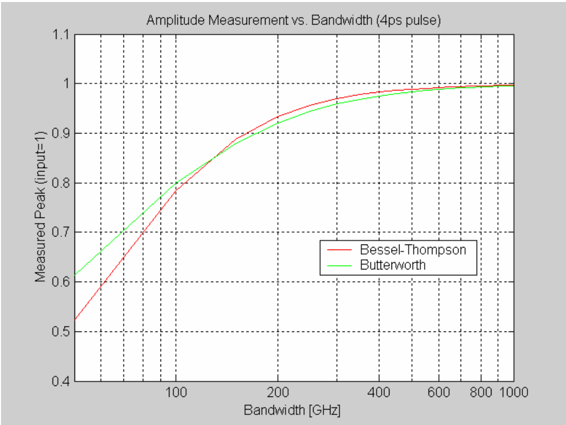
Vertical Channel

Channel Bandwidth Simulation (cont.)



Vertical Channel

Channel Bandwidth Simulation (cont.)



Scope Characteristics

Important Specifications

• Vertical Channel

⇨ Amplitude Accuracy
⇨ Noise
⇨ Channel Bandwidth

• Timebase

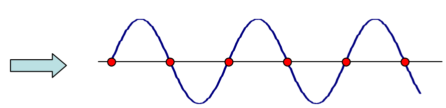
⇨Time Accuracy
⇨ Bandwidth
⇨ Sampling Rate
⇨ Jitter
⇨ Trigger Bandwidth

Timebase

Sampling Rate

Nyquist: sampling rate $\geq$ 2 fmax (signal)

⇒ Sample at least 2 points of the max frequency signal

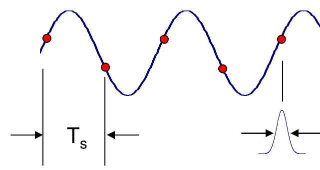


Rule of thumb: Scope BW = Sampling Rate / 4

Timebase

Sampling Period and Sampling Window

20GSa/s
⇨50ps sampling period
⇨ BW?



sampling period ≠ sampling window

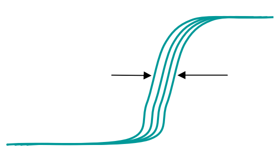
Evident in Time-Equiv. Scopes

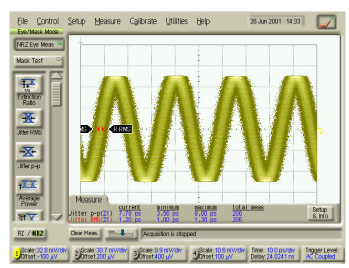
Origin of Rule of Thumb

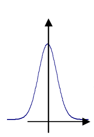
Timebase

Jitter Bandwidth

Jitter = time uncertainty

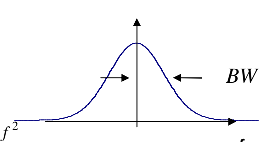






$\sim e^{-\frac{t^2}{2\sigma^2}}$

FT



$\sim e^{-2\pi^2\sigma^2 f^2}$

$$BW = \frac{1}{\pi\sigma}\sqrt{\frac{\ln 2}{2}}$$

Timebase

Timebase Accuracy

Accuracy Spec = <jitter> + % <measurement>

1ps RMS jitter ⇨ 187GHz

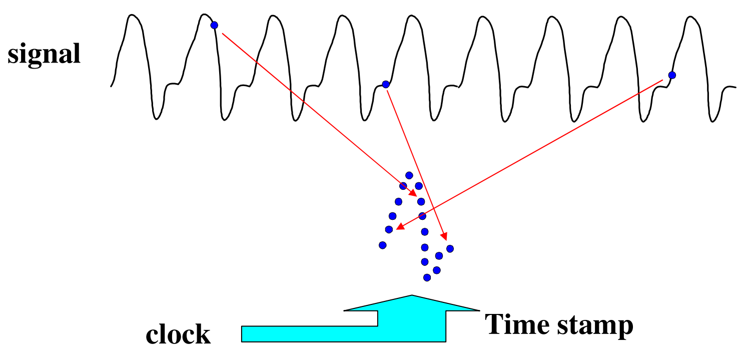
Timebase Development

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.

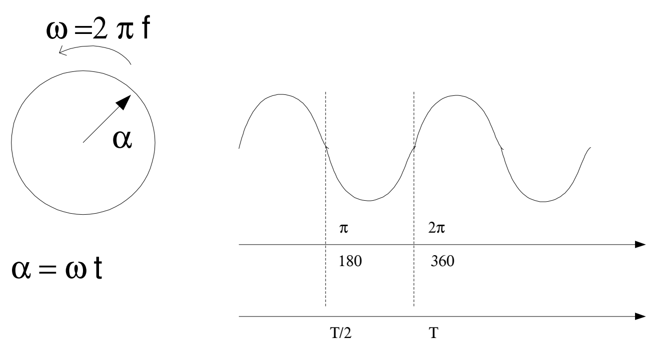
Random Timebase



time stamp for each sample estimated from clock

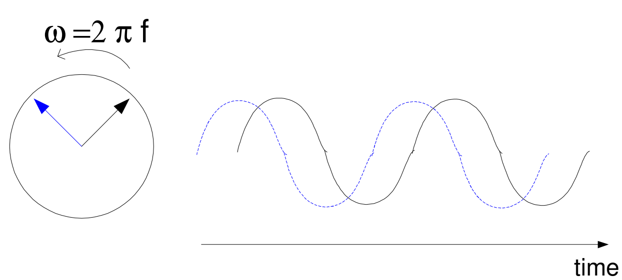
Random Timebase

Time Stamp Estimation



Random Timebase

Time Stamp Estimation



Quadrature

Random Timebase

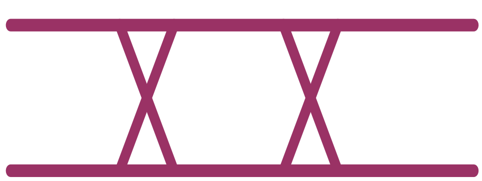
Applications & Limitations

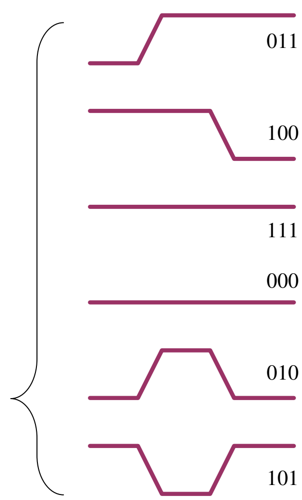
- **Low Jitter Floor**
- **High Accuracy**
- **External Clock Available**
- **Good Quality Clock**
- **Time Stamp limited to one Clock Period**

Ideal for Eye Diagram Analysis

Eye Diagram Analysis

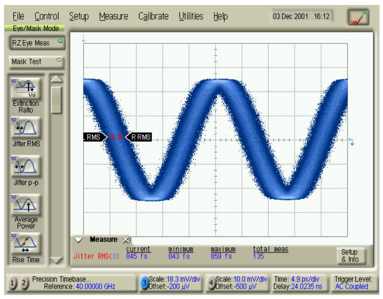
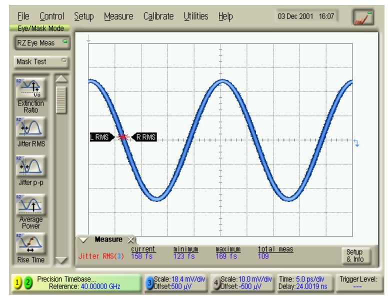
- Oscilloscope is triggered with a synchronous clock.
- The bits in the data stream do not have identical periods, so the screen shows a multivalued signal representing the superposition of data values



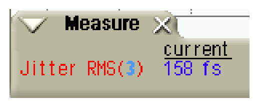


Random Timebase

86107A Results

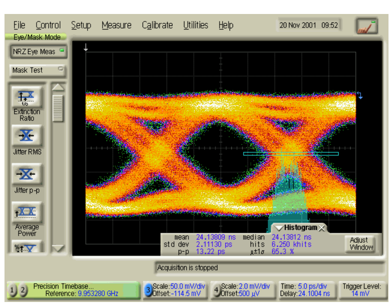
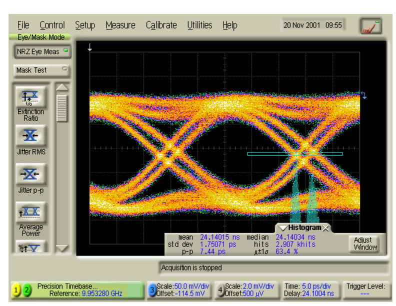




40GHz Sinewave



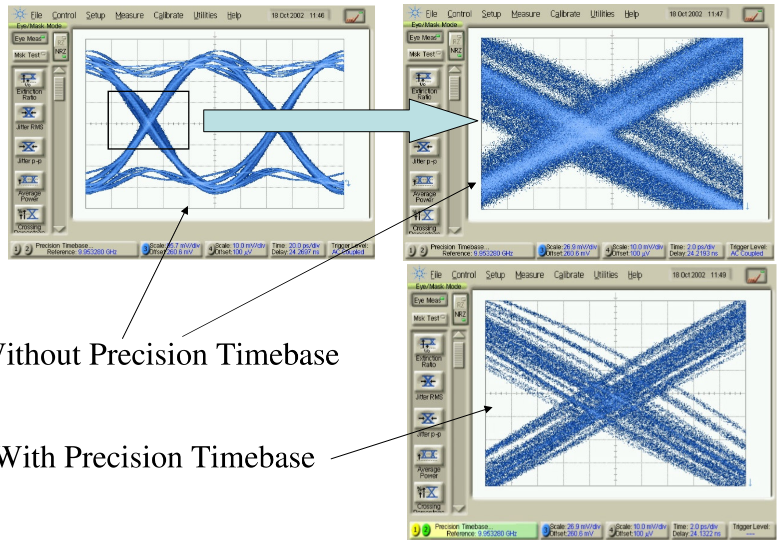
Random Timebase

86107A Results

40GHz Eye Diagram

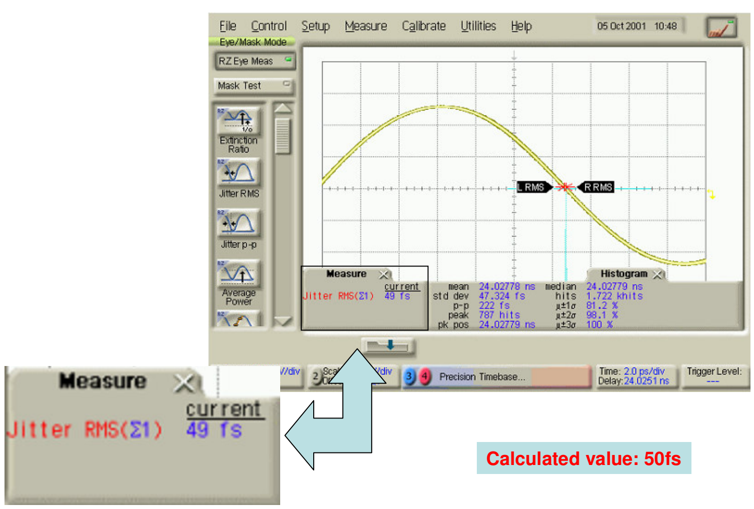
86107A Results (cont.)



Without Precision Timebase

With Precision Timebase

Random Timebase Extreme



Calculated value: 50fs

Sampling Development

Sampling Development

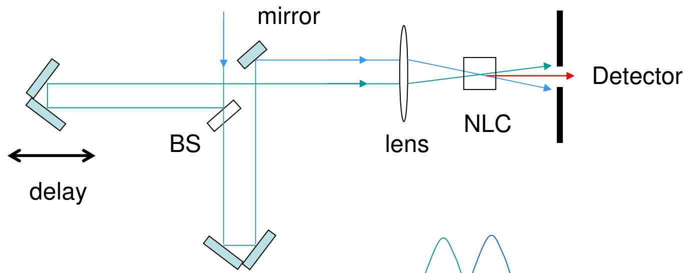
Input: ⇨ **optical / fiberized**
⇨ **wavelength ~ 1550nm**

Sampling Options

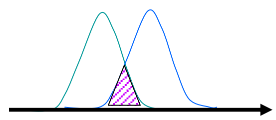
- **Photodiode + Electrical sampling**
- **Optoelectronic Sampling**
- **Optical Sampling**

Autocorrelation

Measure a pulse with itself



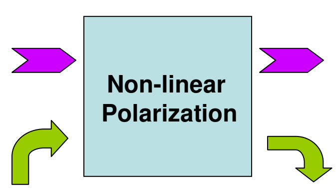
Intensity Autocorrelation



Autocorrelation

Non-Linear Crystal

$E\,e^{i\omega t}$ → **Non-linear Polarization** → $E\,e^{i\omega t}\,;\,E\,e^{i2\omega t}$

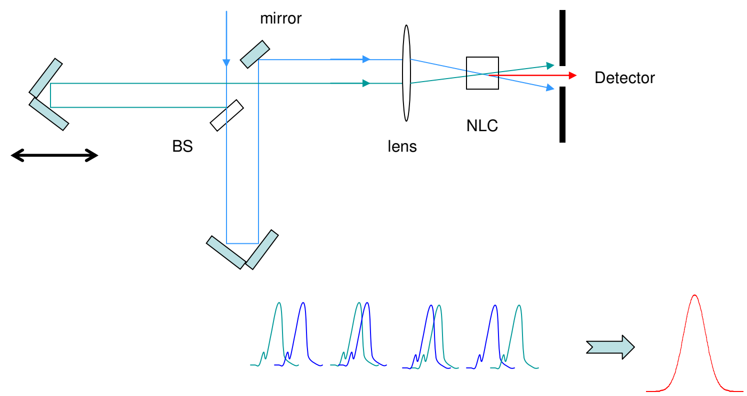


$E\,e^{i\omega_1 t} + E\,e^{i\omega_2 t}$

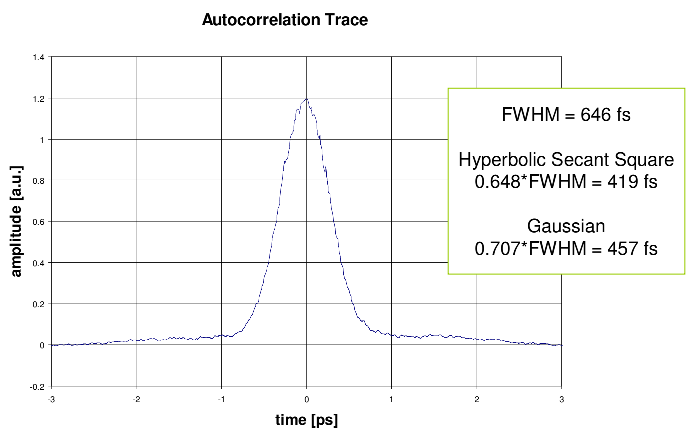
$E\,e^{i\omega_1 t}\,;\,E\,e^{i\omega_2 t}\,;\,E\,e^{i2\omega_1 t}\,;\,E\,e^{i2\omega_2 t}\,;$
$E\,e^{i(\omega_1+\omega_2)t}\,;\,E\,e^{i(\omega_1-\omega_2)t}\ldots$

Analogy with non-linear device

Autocorrelation

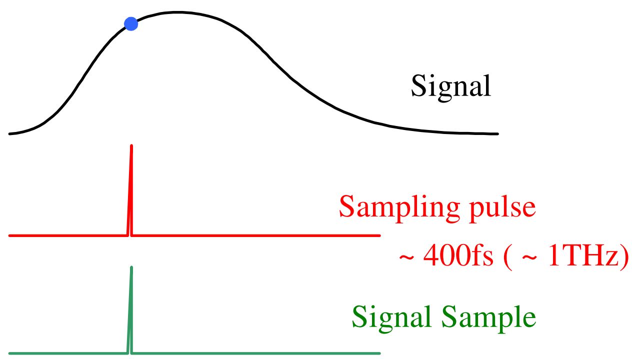


Autocorrelation



Sampling Development

Cross- Correlation



Sampling Development

Sampling Pulse Issues

- **Sampling wavelength ≠ Input wavelength**
  (to avoid spectrum 'Holes')
  ⇨ Sum Frequency Generation

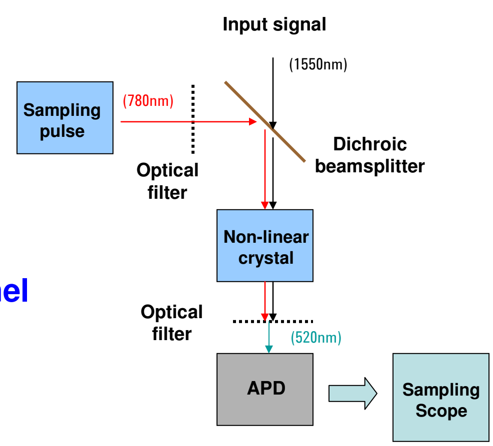
- **Bandwidth**
  ⇨ Short Pulse Laser (~200fs)

Sampling Development

Crystal Issues

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

Sampling Development



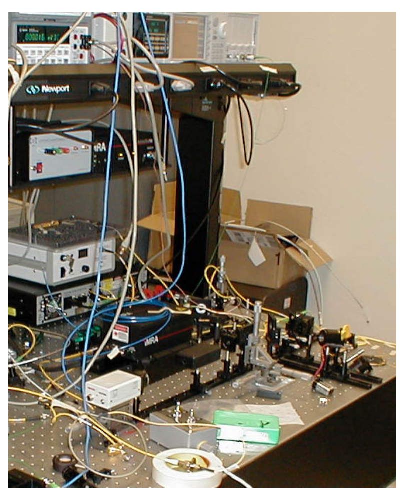
Vertical Channel

Sum Frequency Generation

Manufacturability

Optical Sampling Scope

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

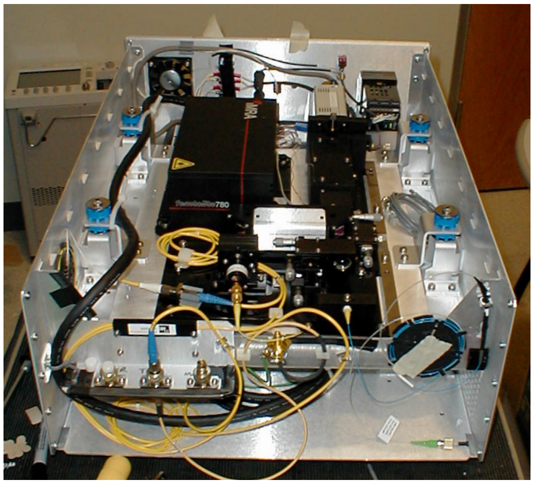
Manufacturability

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

Optical Sampling Scope

Prototype 1



Optical Sampling Scope

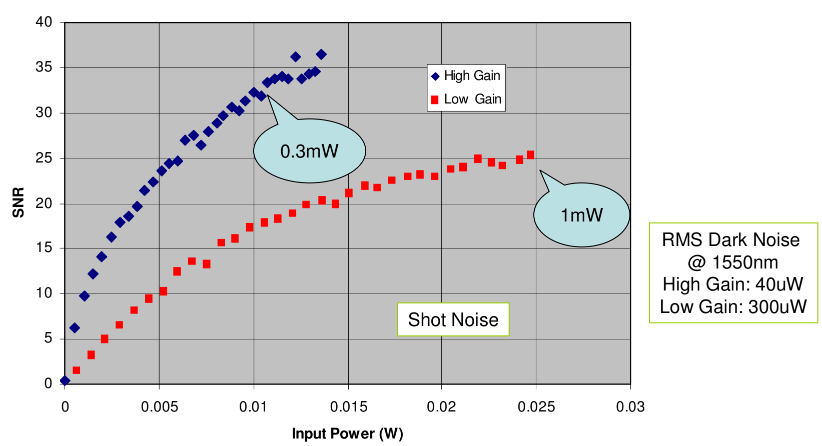
Desired Specifications

Noise Level	< 100uV RMS
Wavelength	~1550 nm (25nm window)
Bandwidth	> 600 GHz

Testing Required

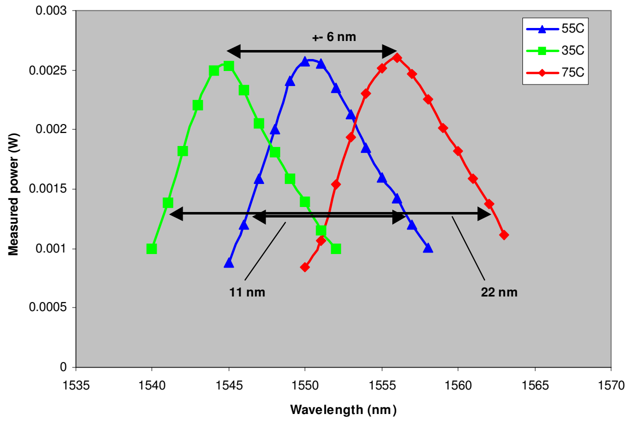
Optical Sampling Scope

Noise Tests



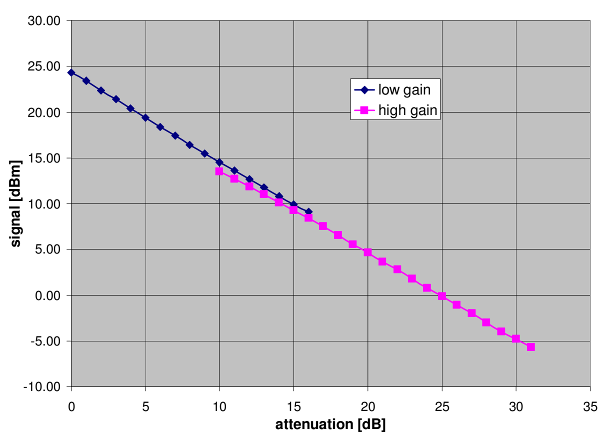
Sampling Development

Wavelength Coverage



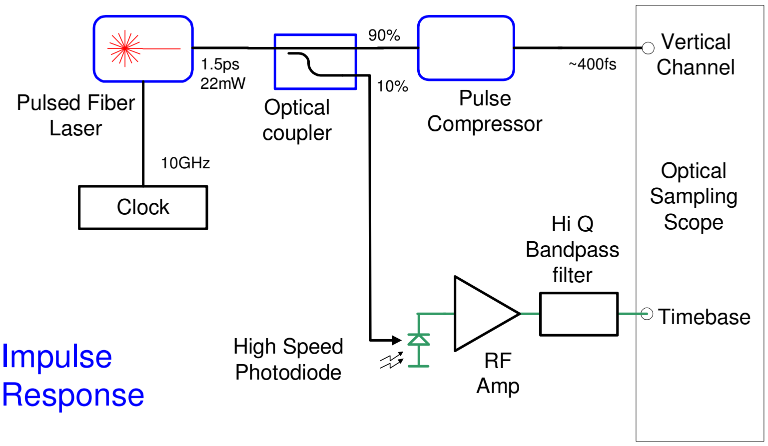
Sampling Development

Linearity



Optical Sampling Scope

Bandwidth Test



Impulse Response

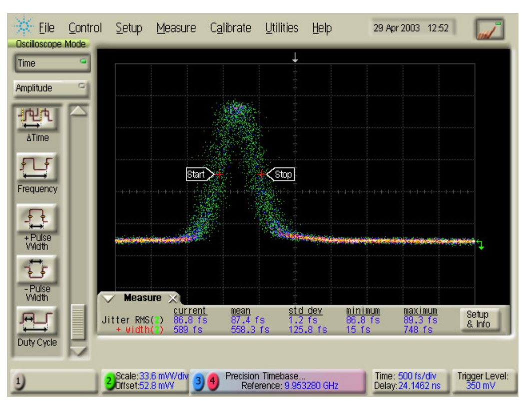
Optical Sampling Scope

Bandwidth Test

Impulse Response:

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

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

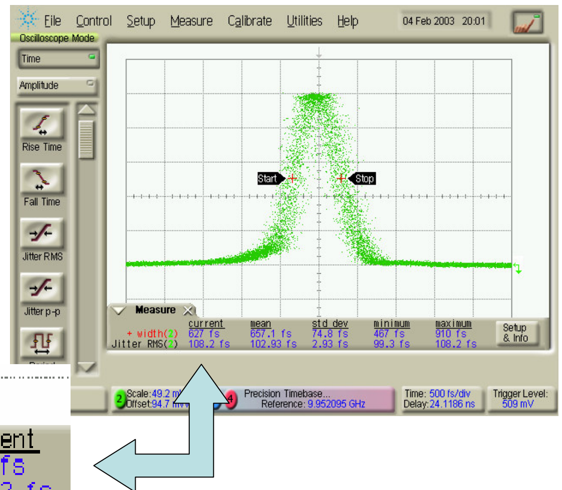


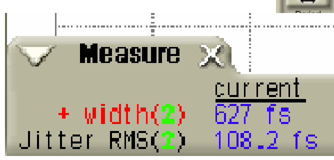
Optical Sampling Scope

Impulse Response:

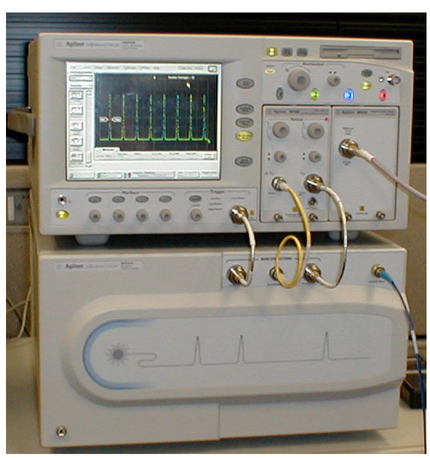
Autocorr. FWHM : 680fs
PW (Gaussian) = 480fs

Measured: 630 fs
Sampling window: 410fs
BW (Gaussian)> 1THz





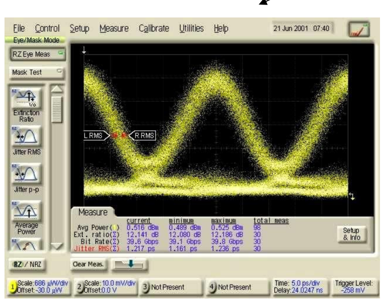
Optical Sampling Scope



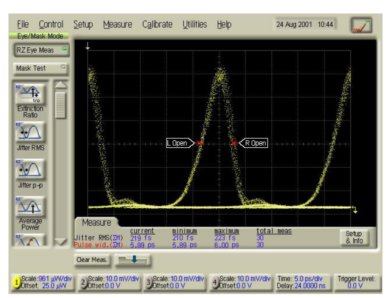
Results

Optical Sampling Scope

40Gbps RZ Optical Signal

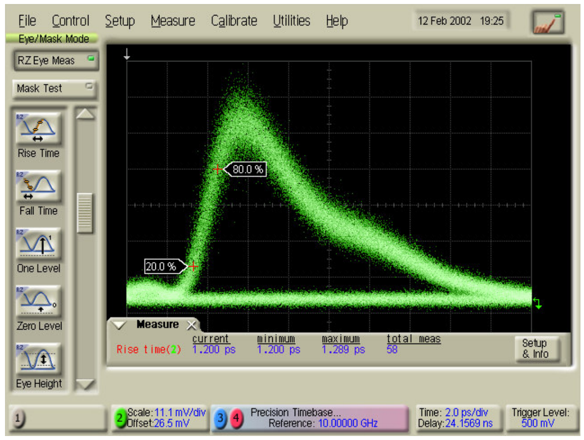


Standard Electrical Sampling (50GHz)



Optical Sampling (800GHz)

Optical Sampling Scope



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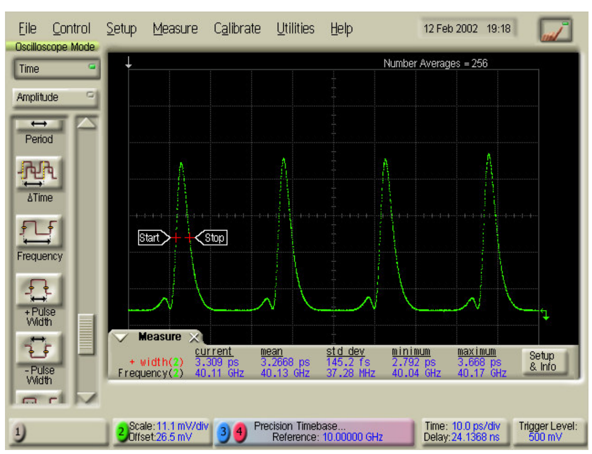
Optical Sampling Scope



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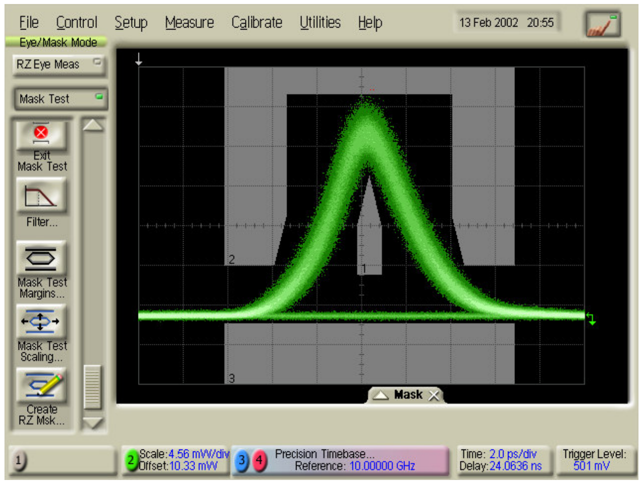
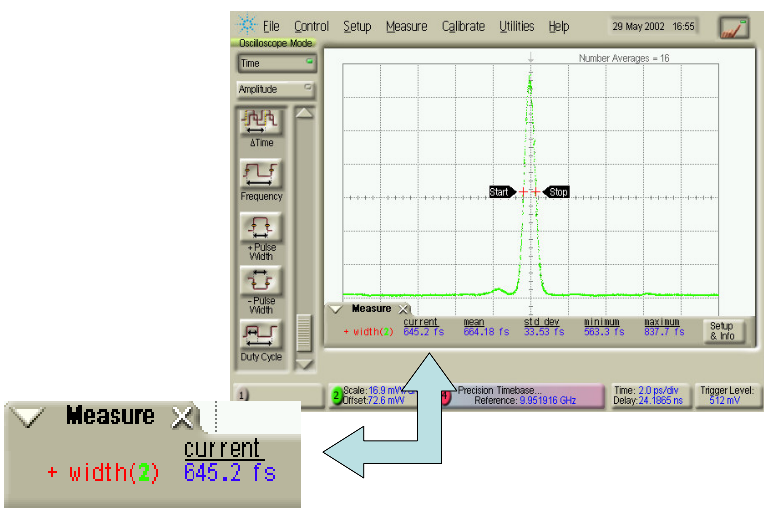
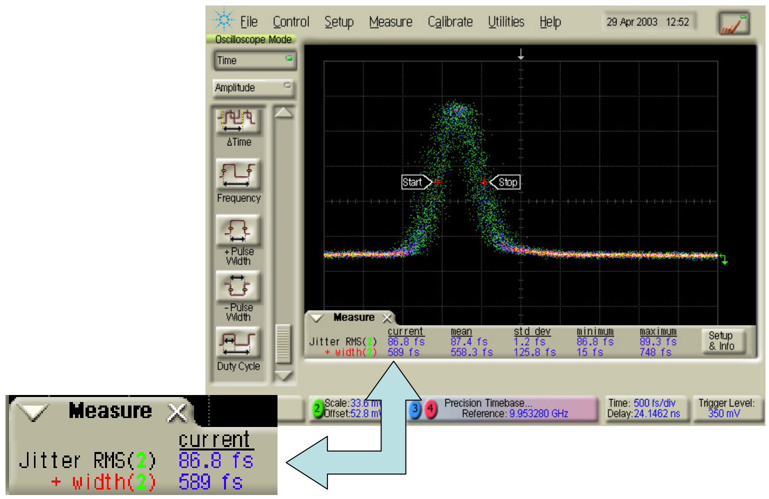
Optical Sampling Scope



Optical Sampling Scope

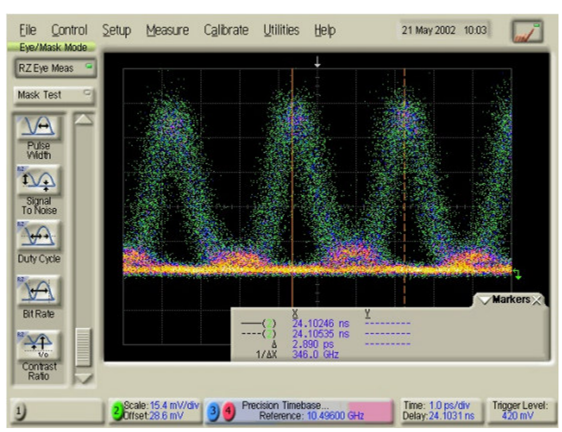


Optical Sampling Scope



Optical Sampling Scope

346Gbps RZ Optical Signal



Bit period is
less than
3 picoseconds!

The End

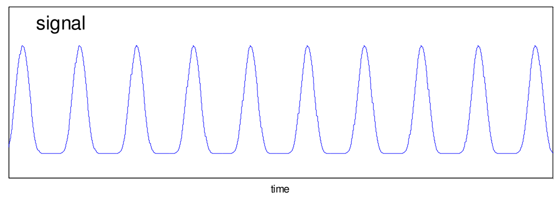
Additional Info

Random Timebase Example

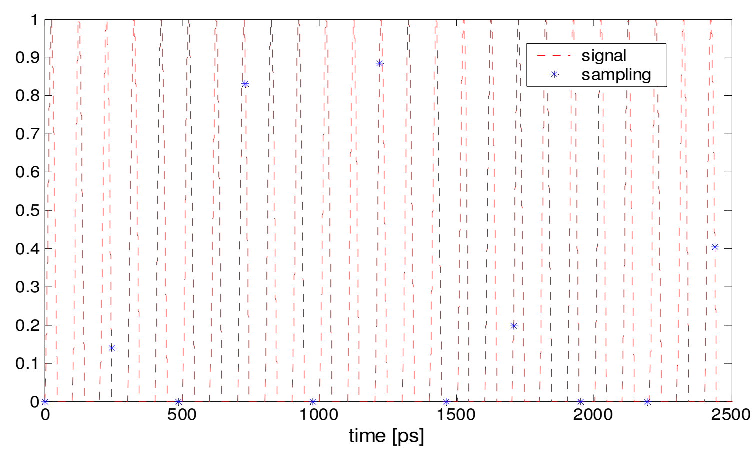
40GHz signal

10Ghz Clock

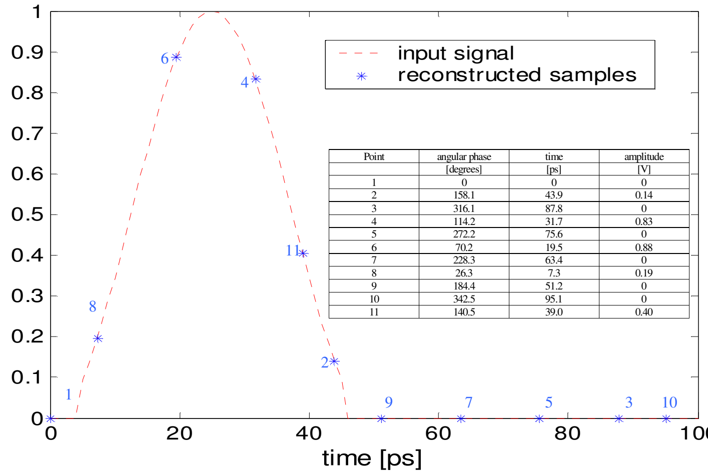
4.1GHz sampling rate (freerun)



Random Timebase Example



Random Timebase Example



Point	angular phase	time	amplitude
	[degrees]	[ps]	[V]
1	0	0	0
2	158.1	43.9	0.14
3	316.1	87.8	0
4	114.2	31.7	0.83
5	272.2	75.6	0
6	70.2	19.5	0.88
7	228.3	63.4	0
8	26.3	7.3	0.19
9	184.4	51.2	0
10	342.5	95.1	0
11	140.5	39.0	0.40