Two-Dimensional Opto-Electronic Interconnect Processor

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Agenda

- The Problem
- Motivation
- Digital Halftoning
- Opto-Electronic Digital Halftoning Processor
- Component Characterization
- Summary

The Problem

- **Problem**

  -- given a continuous tone input image, $x(m,n)$ with intensity values in the interval $x(m,n) \in [0,1]$, where $[a,b] = \{x: a \leq x \leq b\}$, find a bilevel image $y(m,n)$ constrained to $y(m,n) \in \{0,1\}$, such that some predefined distortion measure $d(x,y)$ is minimized.

- **Digital Halftoning**

  -- an algorithmic process which creates the *illusion* of a continuous tone image from the judicious arrangement of binary picture elements.

- **Error diffusion**

  -- a method of quantization in which the error associated with the nonlinear quantization process is diffused within a local region and subsequent filtering techniques employed in an effort to improve some performance metric such as signal-to-noise ratio.

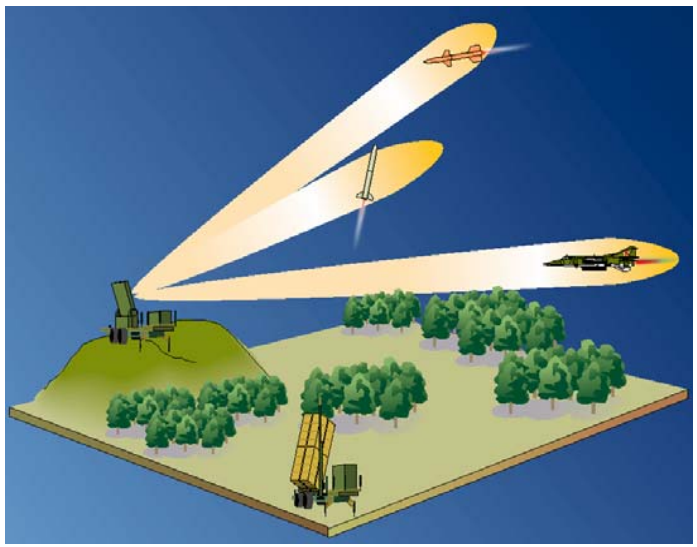
- **Goals**

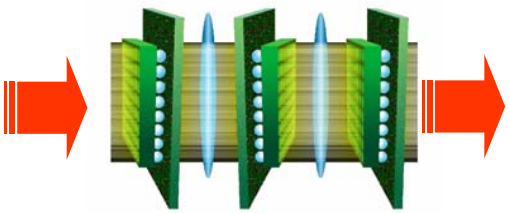
  -- improve halftone image quality
  -- reduce the computational complexity of error diffusion
  -- provide a means of implementing arbitrary size and shape diffusion kernels

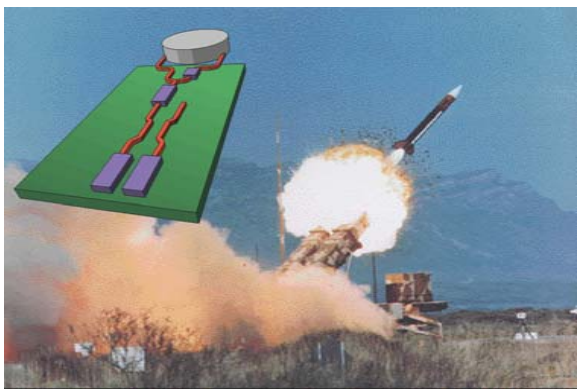
Motivation

Acquiring, processing, and transporting massive amount of information are of critical importance in military applications.

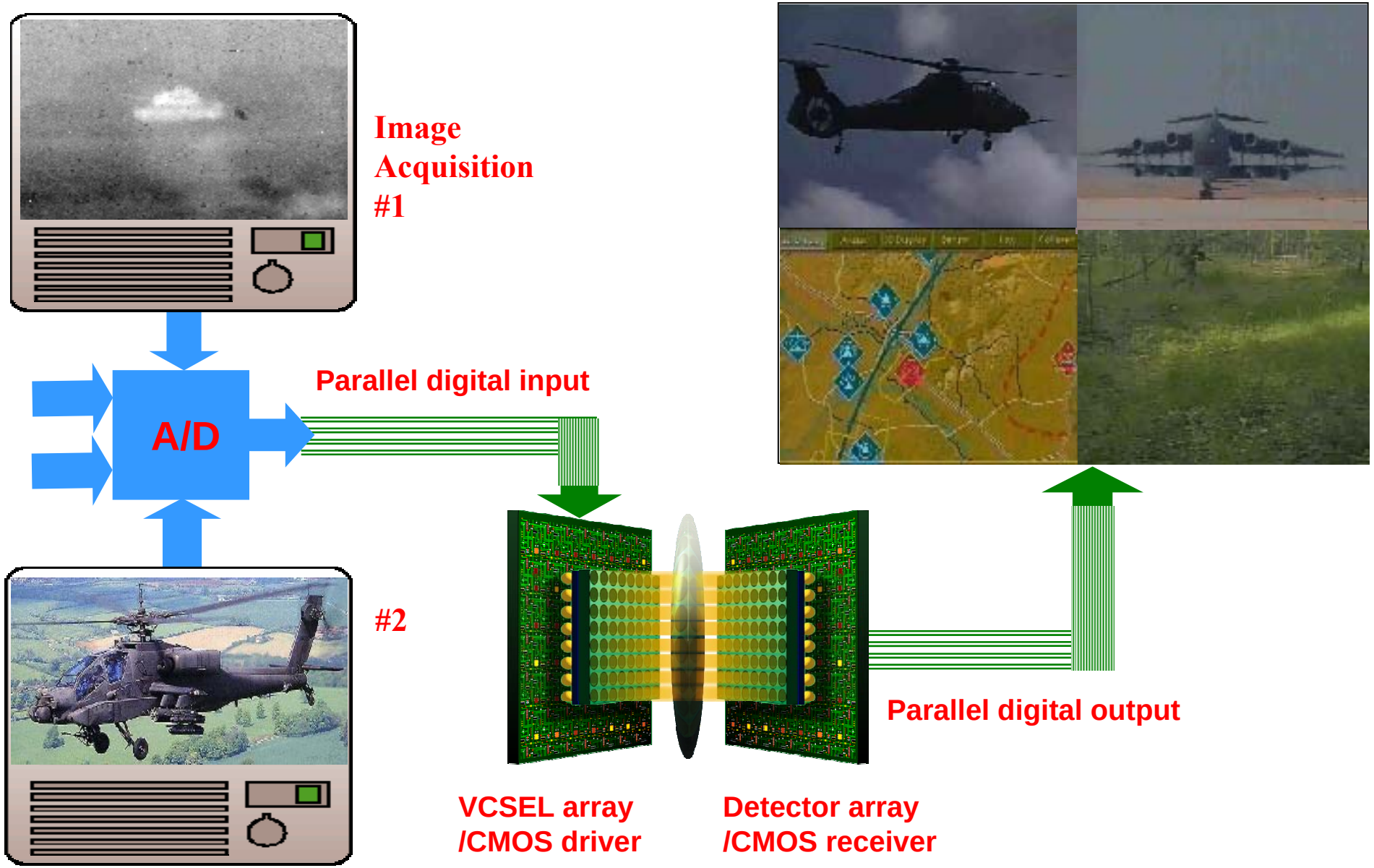
Advanced optoelectronic (OE) interconnects provide the promising solution for future high-bandwidth chip-to-chip, board-to-board data communication



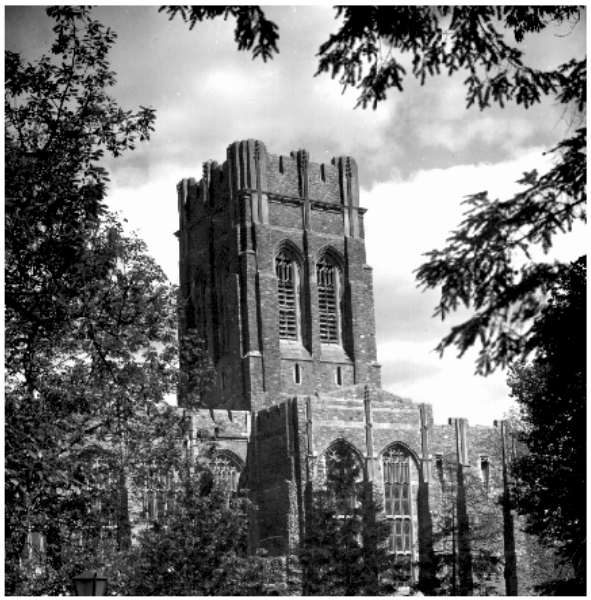




Parallel Image Transfer and Processing through Optoelectronic Interconnects

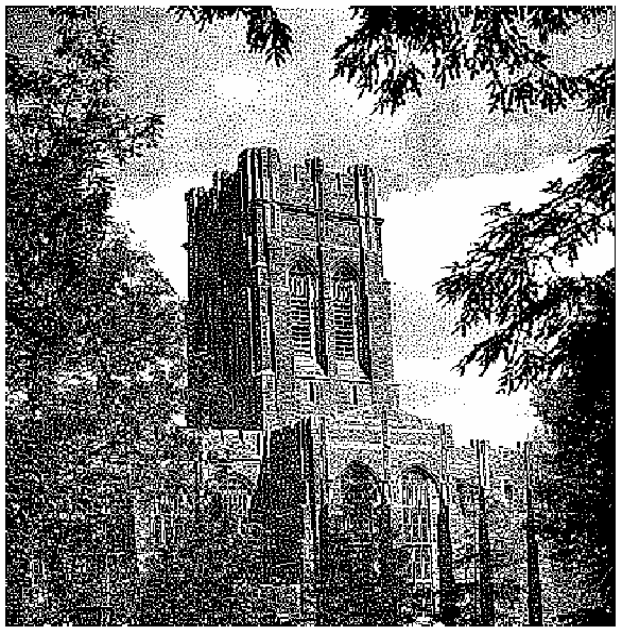


Digital Image Halftoning



Continuous-tone input image

- **Maps**
- **Images**



Binary-valued output image

- **Lossy compression**
- **Reduced data-rate requirement**

Goal: Create illusion of continuous image using binary data

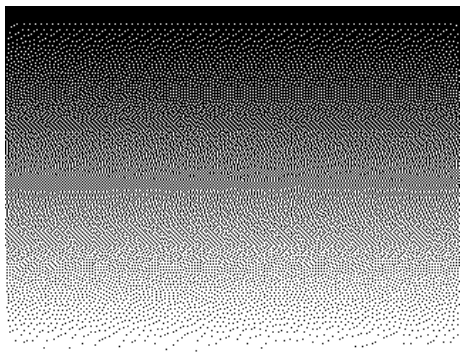
Halftoning Methods

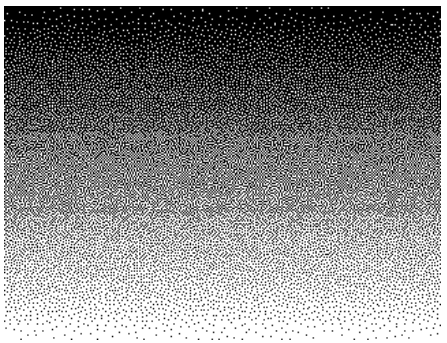
Source

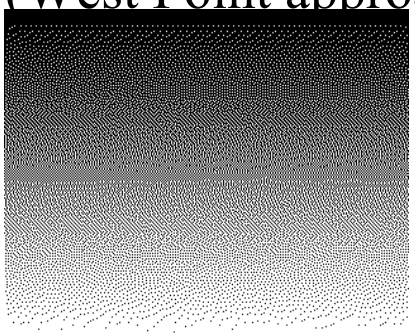
Conventional
Ordered Diffusion

Iterative
Convolution

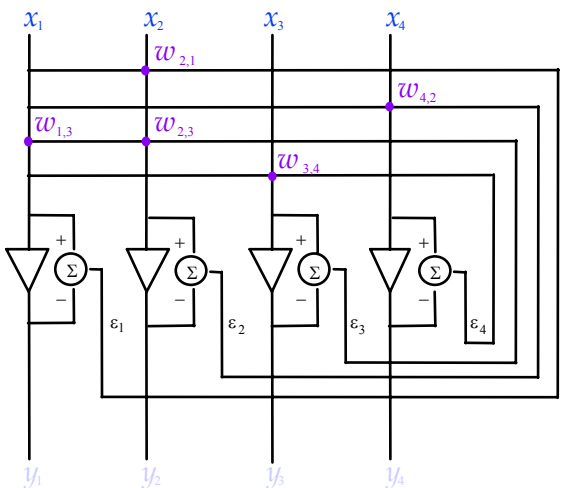
Error Diffusion
(West Point approach)







Error Diffusion Neural Network



In equilibrium, the *error diffusion neural network* satisfies

$$\mathbf{u} = \mathbf{x} + \mathbf{W}(\mathbf{y} - \mathbf{u}) = \mathbf{x} + \mathbf{W}\mathbf{y} - \mathbf{W}\mathbf{u}$$

which results in an equivalence to the Hopfield-type network

$$(\mathbf{I} + \mathbf{W})\mathbf{u} = \mathbf{x} + \mathbf{W}\mathbf{y}$$

$$\mathbf{u} = (\mathbf{I} + \mathbf{W})^{-1}(\mathbf{x} + \mathbf{W}\mathbf{y})$$

Therefore, the energy function can be written as

$$E = -\mathbf{y}^T\mathbf{A}\mathbf{W}\mathbf{y} - 2\mathbf{y}^T\mathbf{A}\mathbf{x}$$

where

$$\mathbf{A} = (\mathbf{I} + \mathbf{W})^{-1} \qquad \mathbf{A}\mathbf{W} = \mathbf{I} - \mathbf{A}$$

Therefore

$$E = -\mathbf{y}^T(\mathbf{I} - \mathbf{A})\mathbf{y} - 2\mathbf{y}^T\mathbf{A}\mathbf{x} = -\mathbf{y}^T\mathbf{y} + \mathbf{y}^T\mathbf{A}\mathbf{y} - 2\mathbf{y}^T\mathbf{A}\mathbf{x}$$

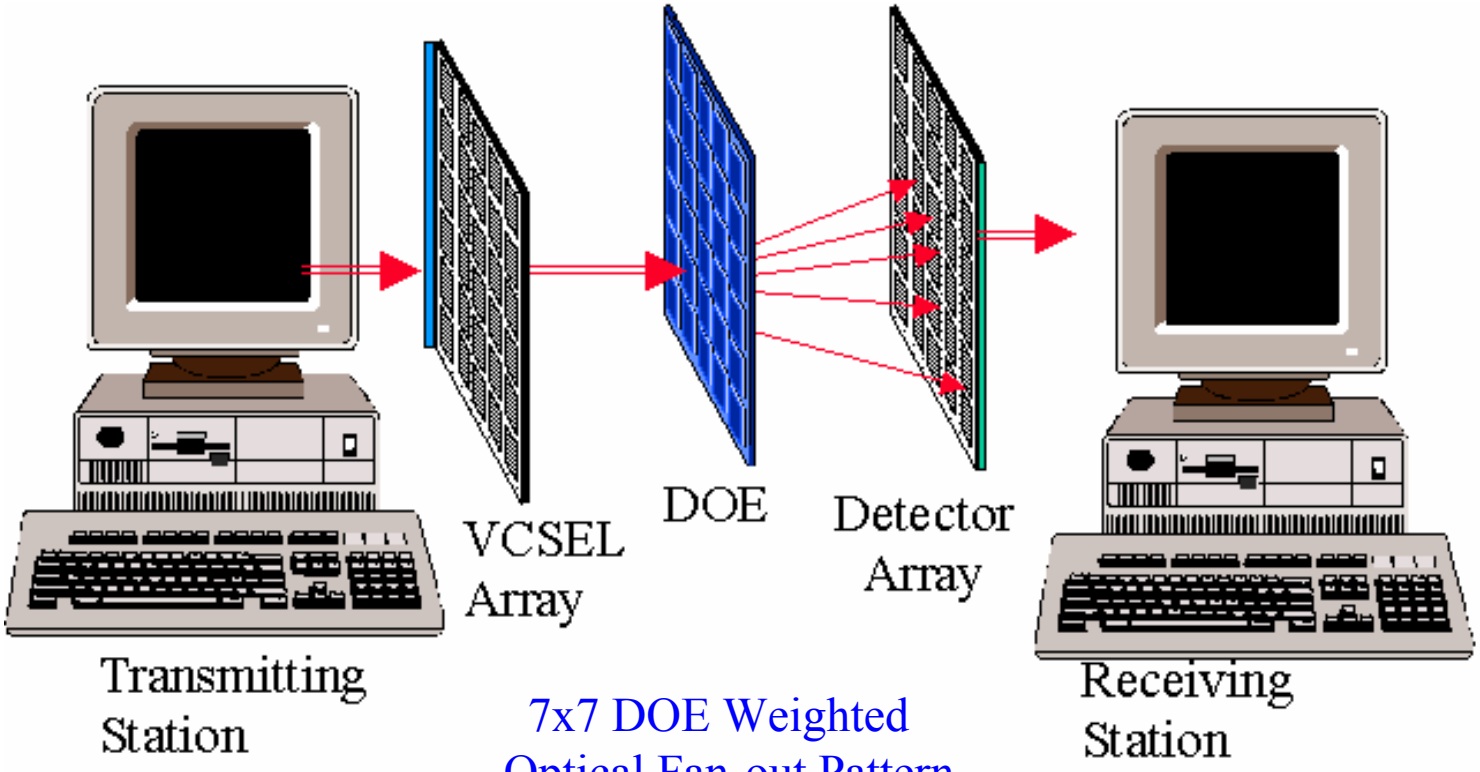
We can write an alternate form of the energy function

$$E' = E + \underbrace{\mathbf{y}^T\mathbf{y} + \mathbf{x}^T\mathbf{A}\mathbf{x}}_{constant} = \mathbf{y}^T\mathbf{A}\mathbf{y} - 2\mathbf{y}^T\mathbf{A}\mathbf{x} + \mathbf{x}^T\mathbf{A}\mathbf{x} = \underbrace{(\mathbf{y} - \mathbf{x})}_{error}{}^T\,\mathbf{A}\underbrace{(\mathbf{y} - \mathbf{x})}_{error}$$

$\mathbf{W}$ - sparse and circulant

$\mathbf{A}$ - full-rank

Opto-electronic Processor Setup



7x7 DOE Weighted
Optical Fan-out Pattern

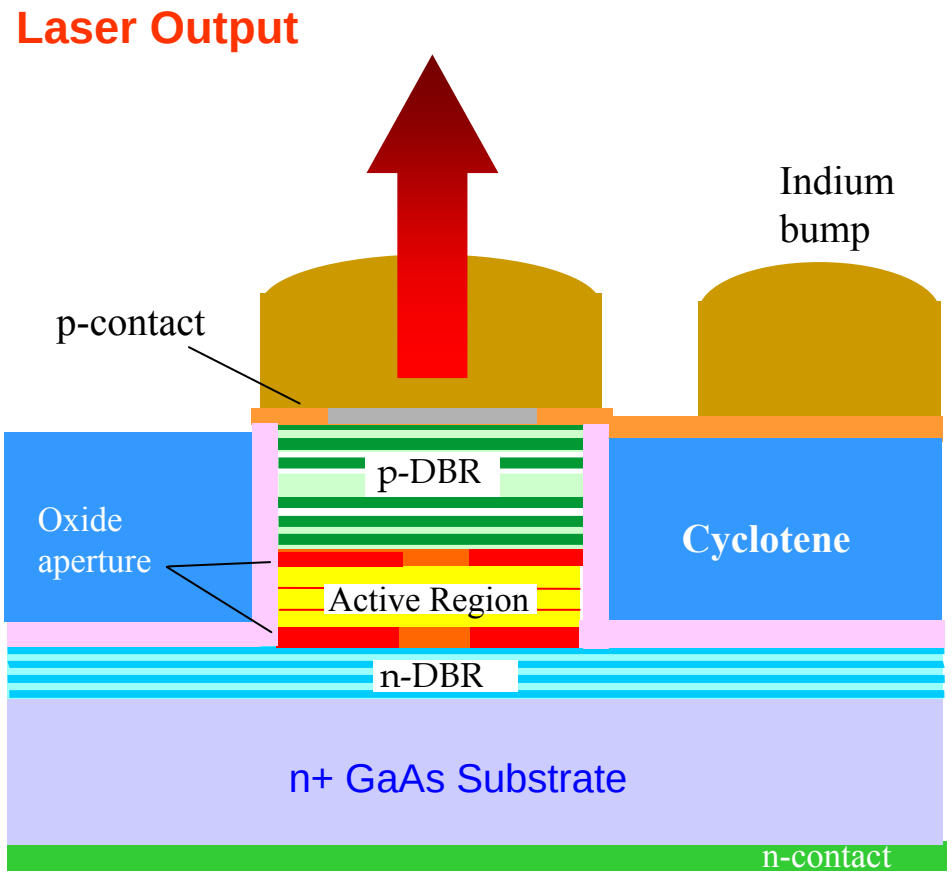
- **Maps**
- **Images**

Binary-valued output image with adequate quality.

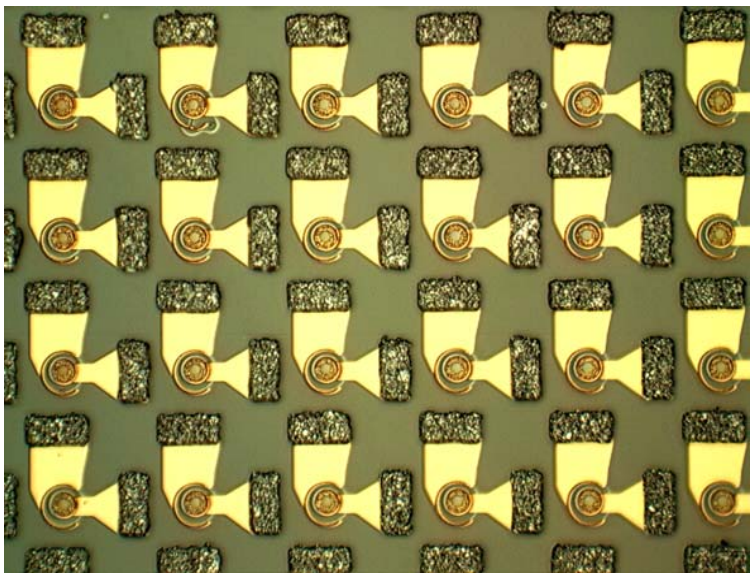
Detectors will initially be CCD

Digital Image Halftoning Scheme

850 nm Top-Emitting VCSEL

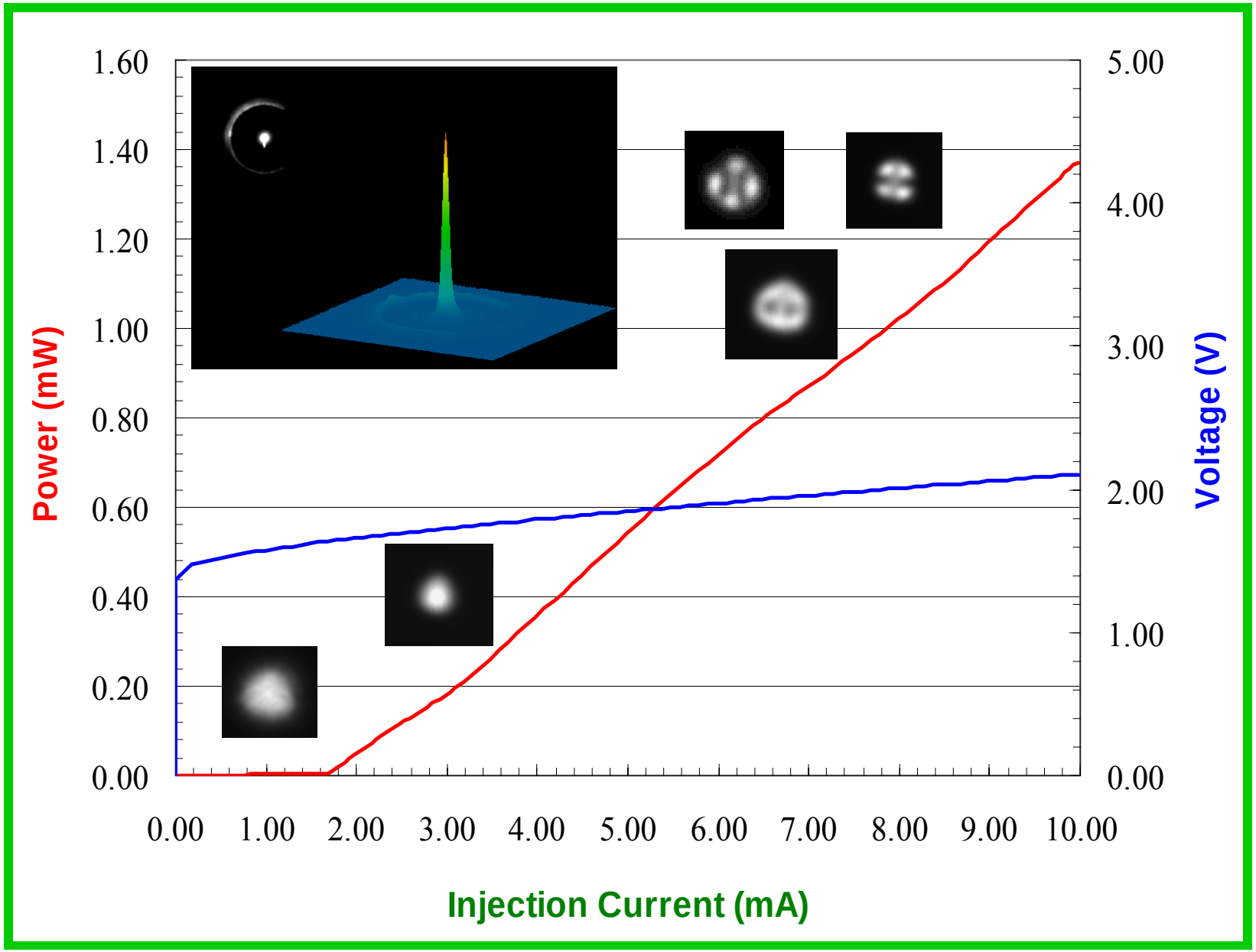


Cross-sectional view of a VCSEL device



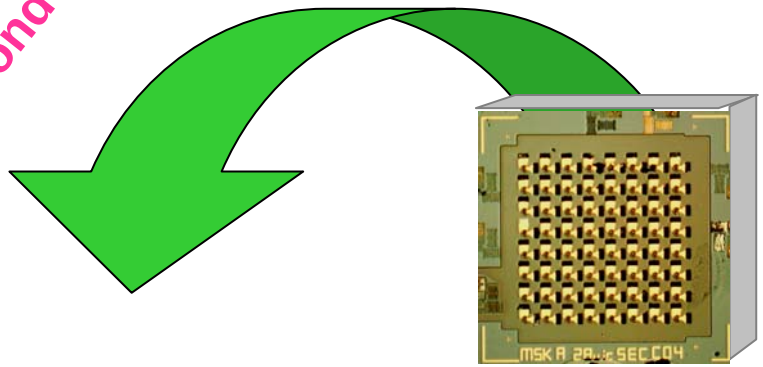
Top view of the partial 8x8 VCSEL array
125 mm pitch, 32 mm mesa

I-V-L Characteristics of 850 nm Top-Emitting VCSELs

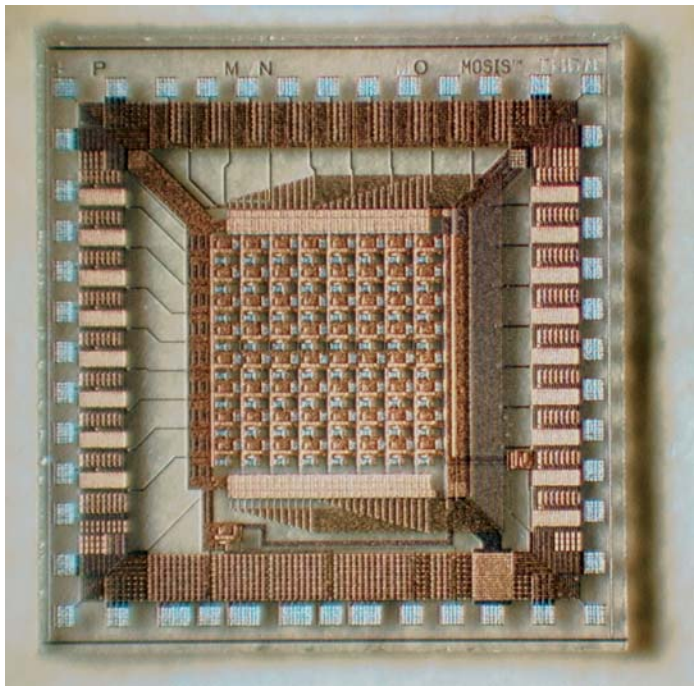


8x8 VCSEL-CMOS Driver array Hybridization

flip-chip bond



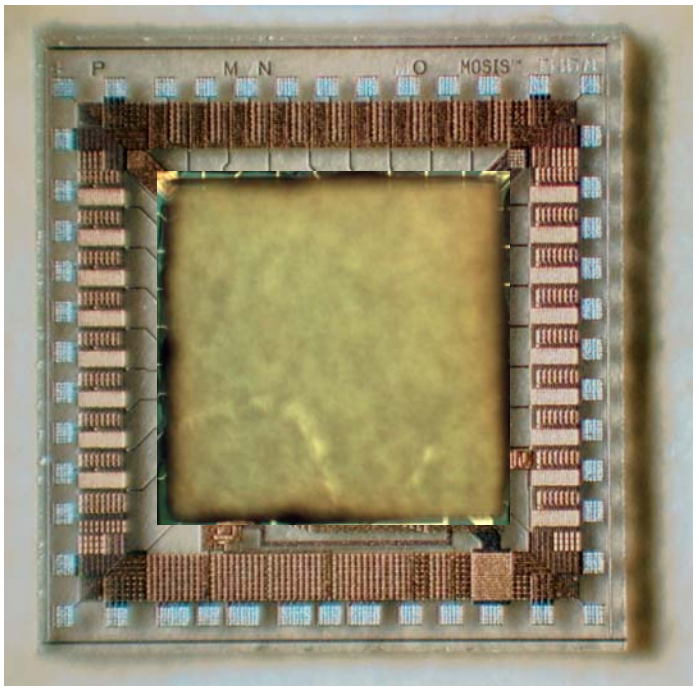
Top-emitting
VCSEL array chip



2.5 mm

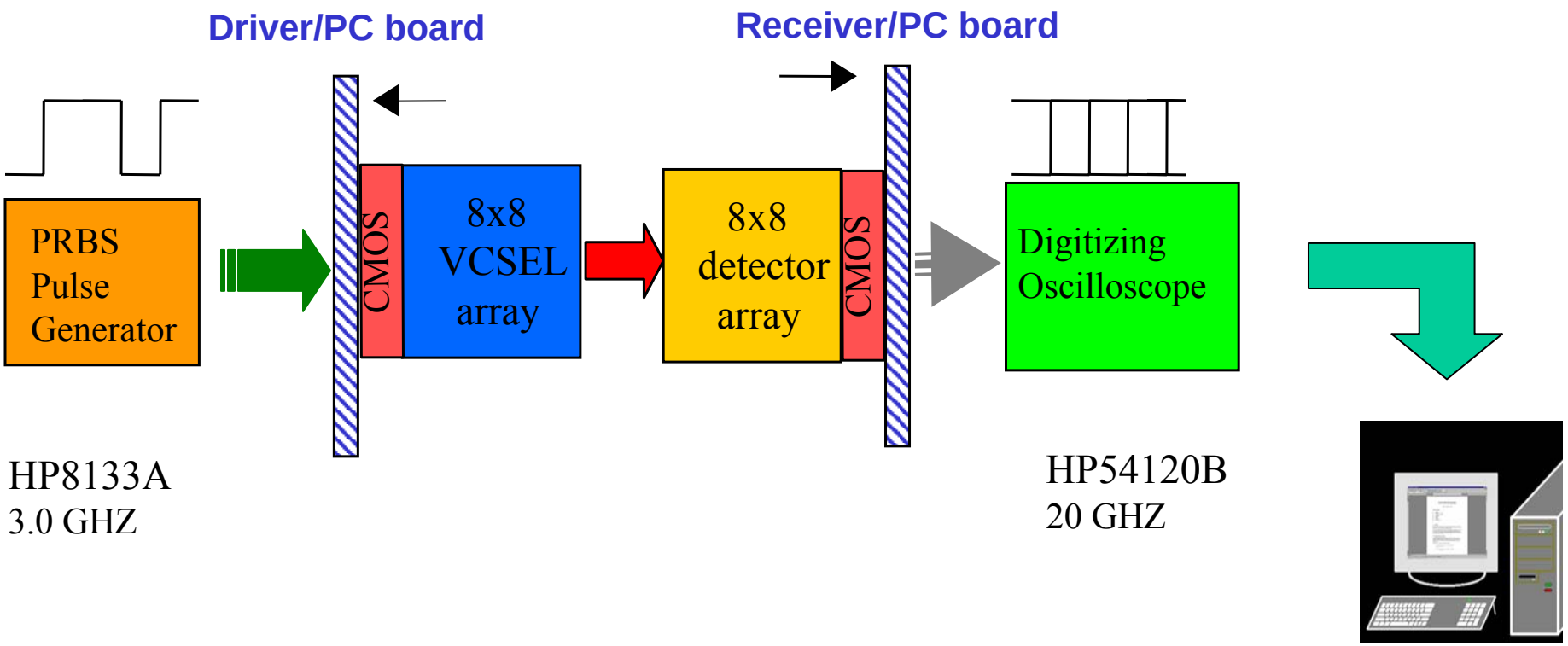
CMOS driver chip

RDI- M8 Flip-chip bonder



VCSEL array flip-chip bonded on the CMOS driver

Bit-Error-Rate Measurement & Calculation



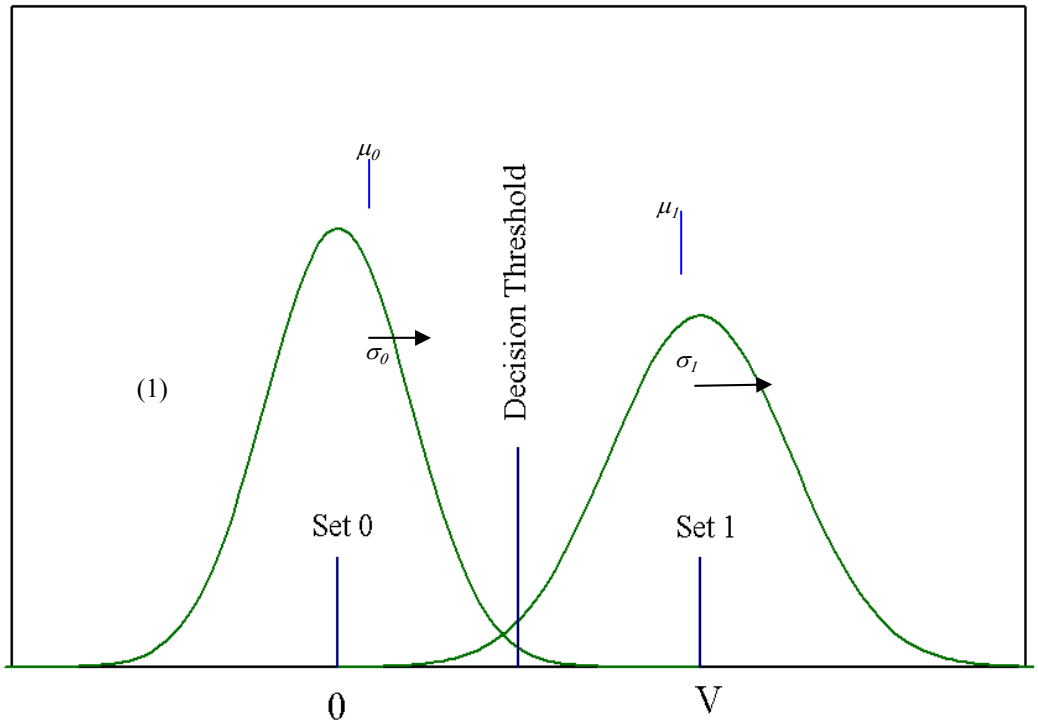
Multi-channel parallel VCSEL data Interconnect

Eye Diagram

Bit-Error-Rate Measurement & Calculation

$$BER = P_T(0)P_R(1|0) + P_T(1)P_R(0|1) = \tfrac{1}{2}(P_R(1|0) + P_R(0|1))$$

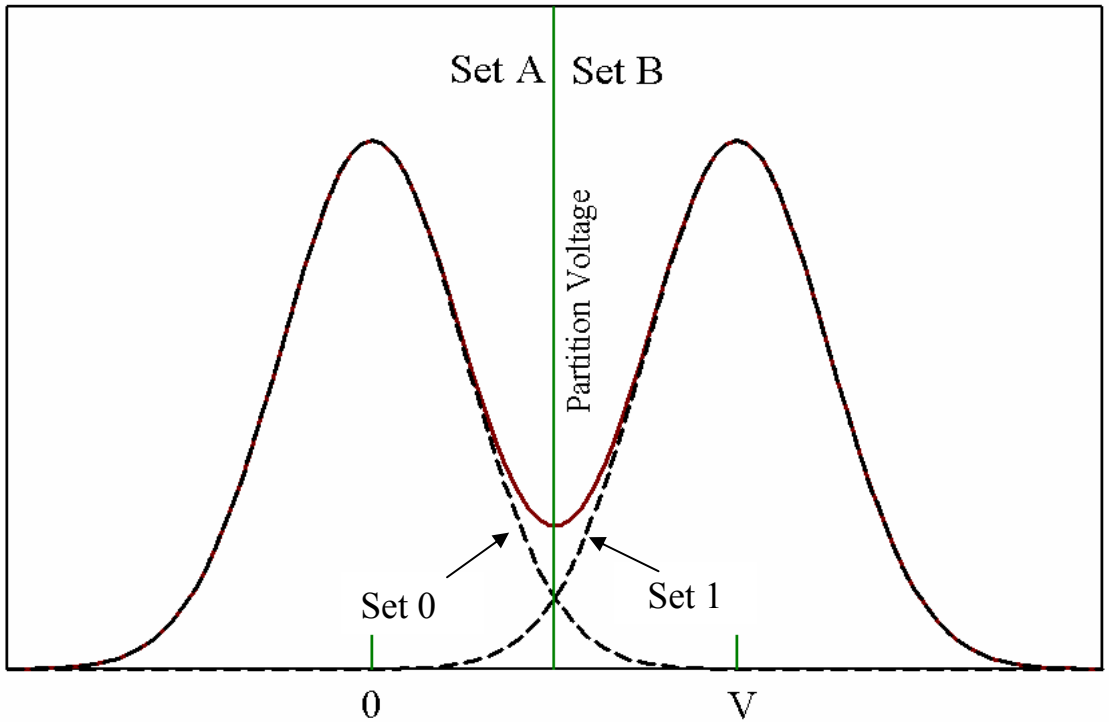
,



Two different Gaussian distributions with standard deviations σ_0 and σ_1, centered at μ_0 and μ_1, separated by a voltage of V, which are denoted Set 0 and Set 1, respectively.
The BER is represented by the areas of the tails of each set past the decision threshold.
Acknowledgement: John and Paul Shen for analysis of BER.

Bit-Error-Rate Measurement & Calculation

$$P(t) = \frac{1}{\sqrt{2\pi}}\left(\frac{1}{\sigma_0} e^{-\frac{t^2}{2\sigma_0^2}} + \frac{1}{\sigma_1} e^{-\frac{(t-V)^2}{2\sigma_1^2}}\right)$$



Two equal Gaussian distribution curves representing Set 0 and Set 1, and the skewed distribution seen in Set A and Set B, divided by a partition voltage.

Bit-Error-Rate Measurement & Calculation

$$BER = \frac{1}{2}\left(\int_{V/2}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_0} e^{-t^2/2\sigma_o^2} dt + \int_{-\infty}^{V/2} \frac{1}{\sqrt{2\pi}\sigma_1} e^{-(t-V)^2/2\sigma_1^2} dt\right)$$

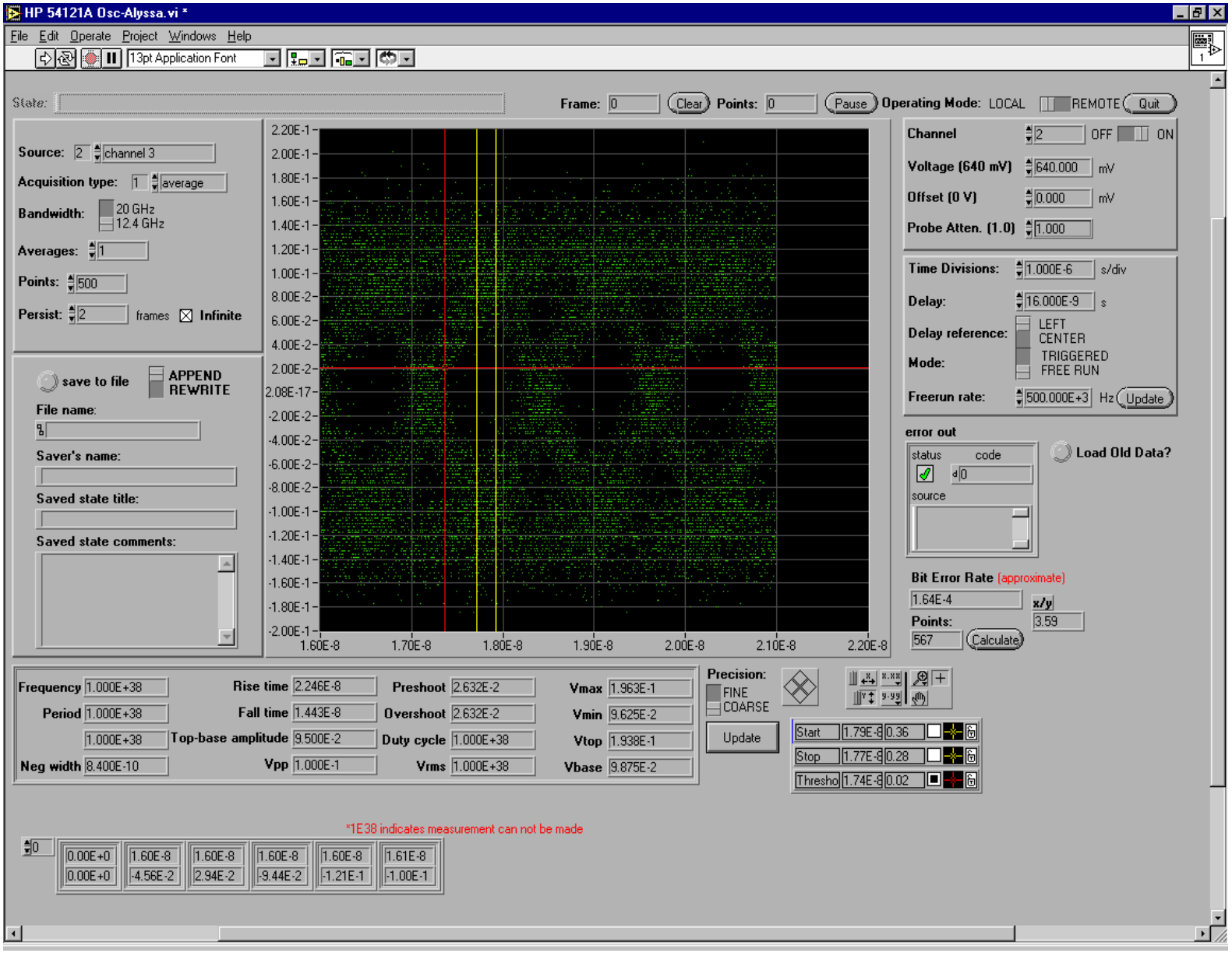
***erf*(*x*) -- the error function**

$$BER = \frac{1}{4}\left(erf\left(\frac{V}{2\sqrt{2}\sigma_0}\right) + erf\left(\frac{V}{2\sqrt{2}\sigma_1}\right)\right)$$

$$BER = \frac{1}{2} erf\left(\frac{V}{\sqrt{2}(\sigma_0 + \sigma_1)}\right)$$

optimum BER

Bit-Error-Rate Measurement & Calculation



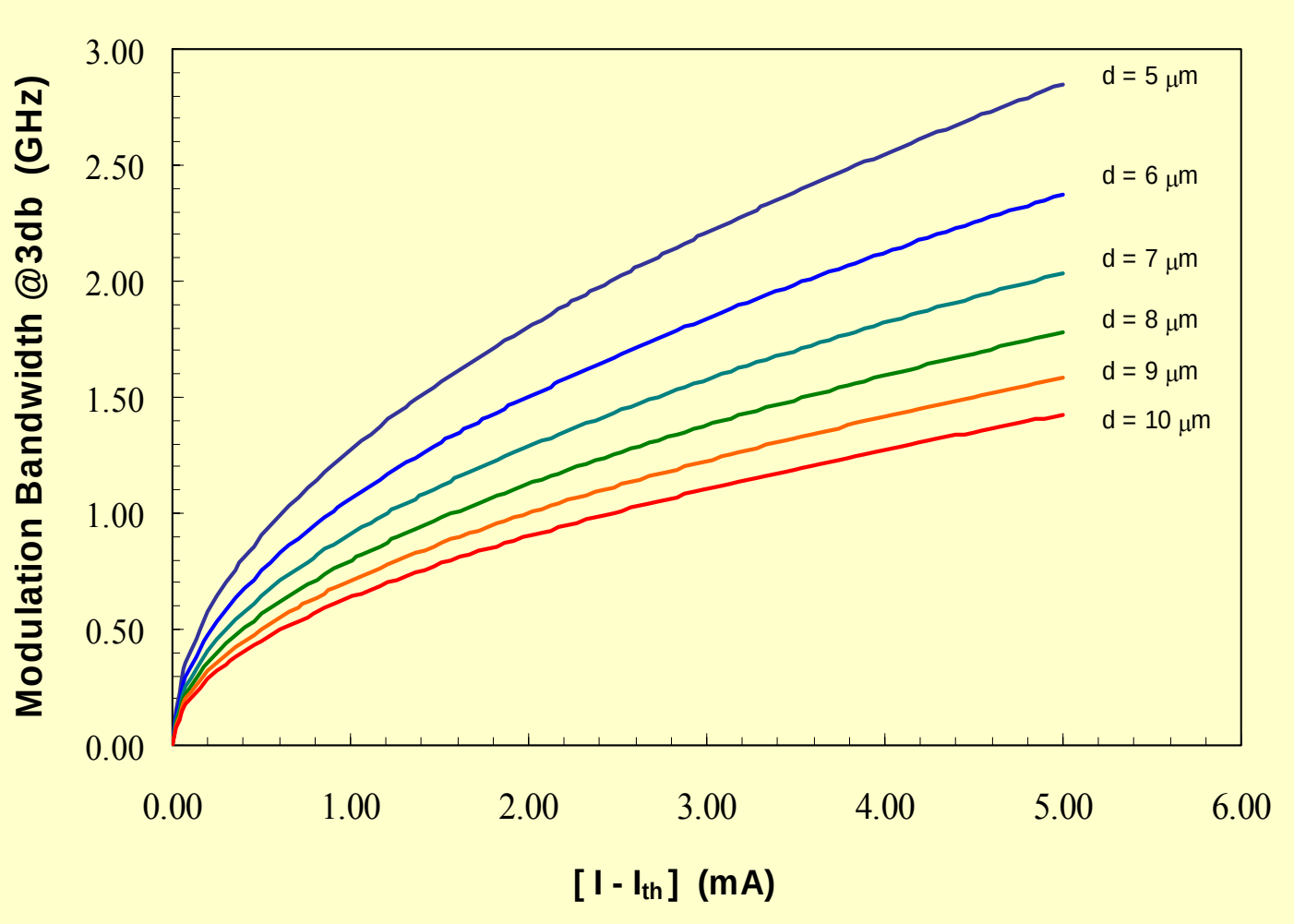
LabView program for BER measurement

Modulation Bandwidth of the VCSEL

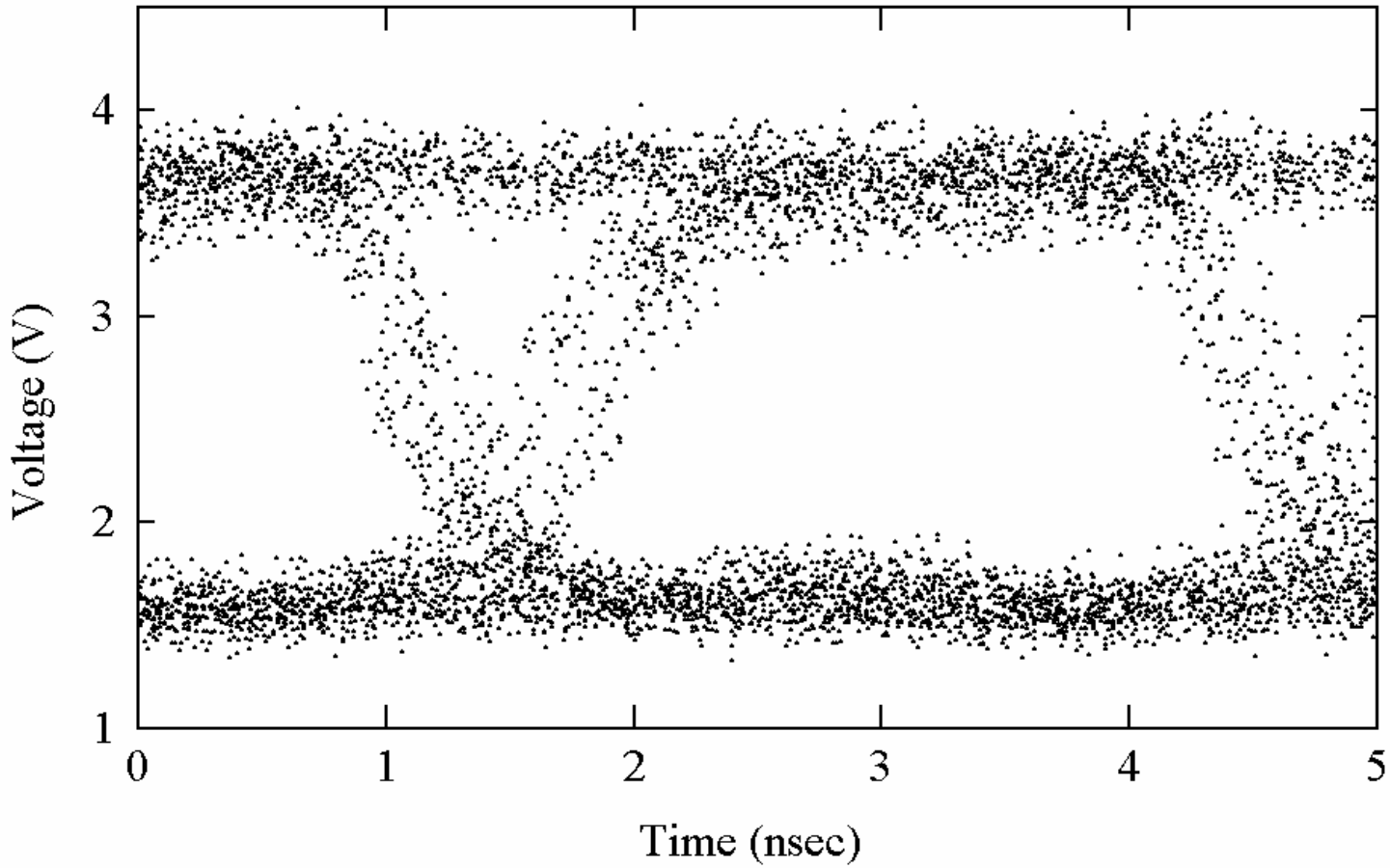
$$f_R = \frac{1}{2\pi}\sqrt{\eta_i v_g \frac{\Gamma}{V}\frac{\partial g}{\partial N}\frac{(I - I_{th})}{q}}$$

Modulation Bandwidth:
$f_w \approx 1.55 f_R$ (-Relaxation resonance frequency)

η_i - internal quantum efficiency,
v_g - group velocity,
Γ/V - modal volume
$\partial g/\partial N$ - differential gain
I_{th} - current threshold of the device
q - electronic charge

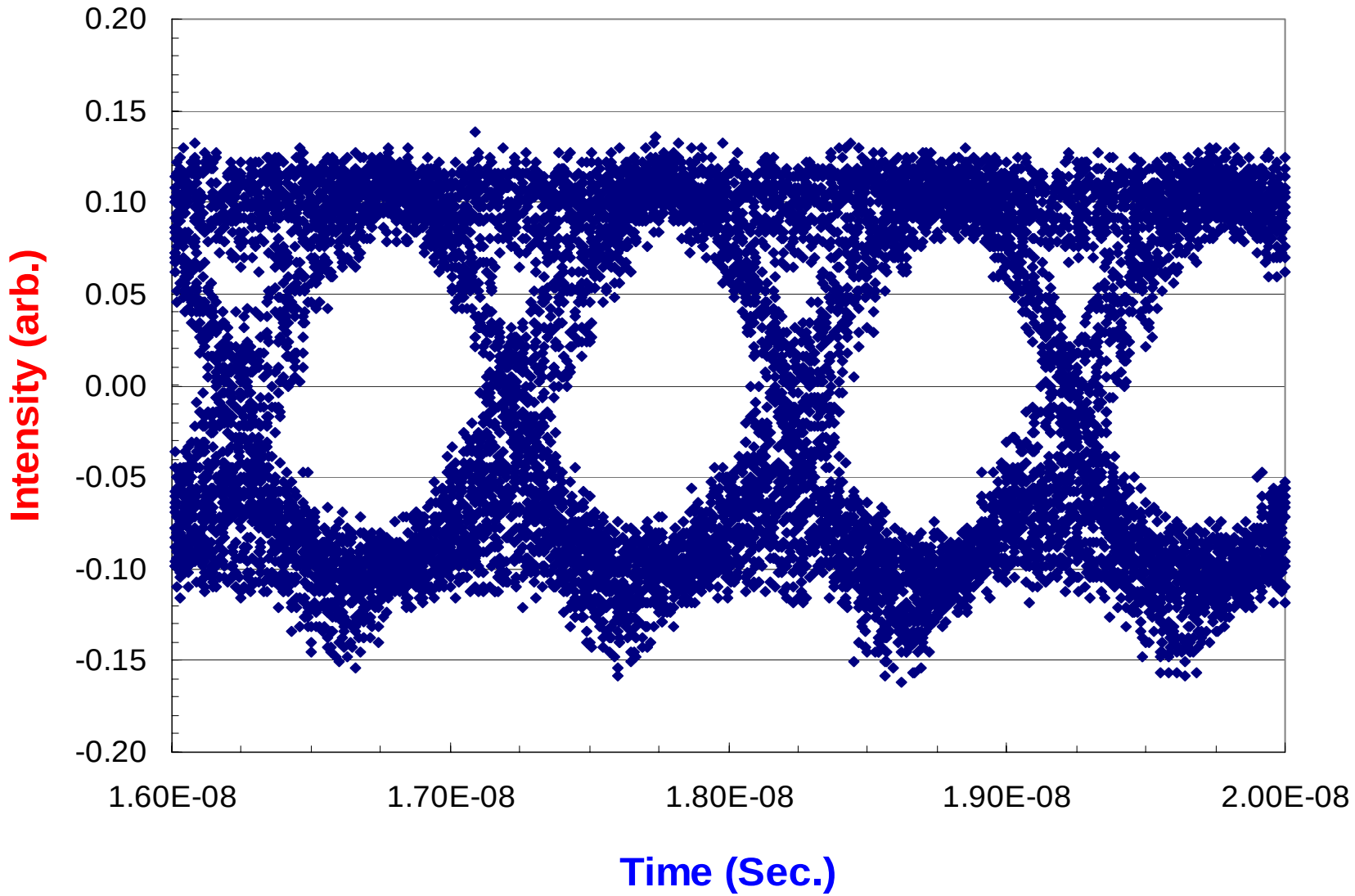


Bit-Error-Rate Measurement & Calculation



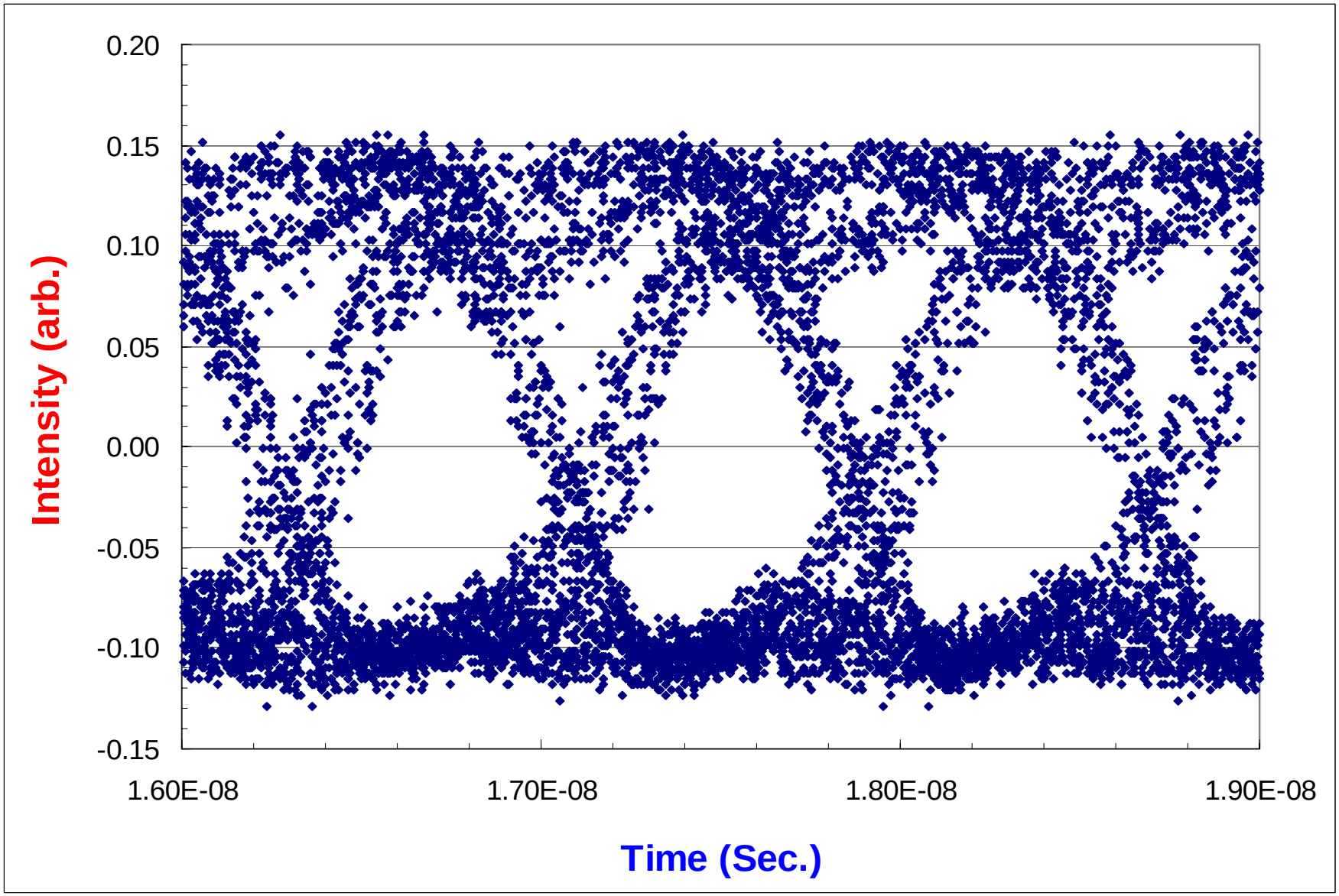
An eye diagram of a 300 Mb/s transmission. The BER for this eye diagram is 10^{-16}.

Bit-Error-Rate Measurement & Calculation



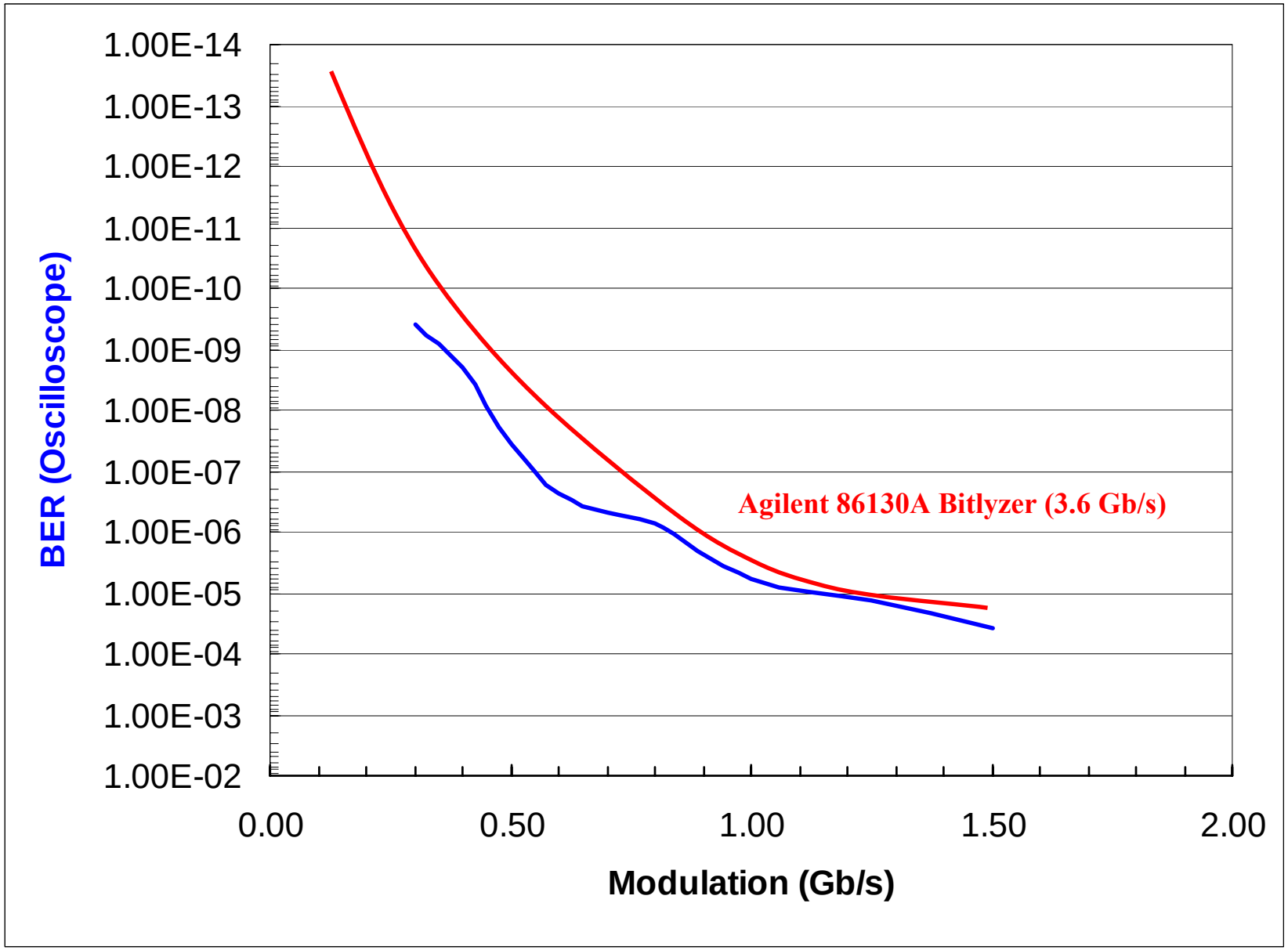
An eye diagram of 1.0 Gb/s transmission. BER --- 10^{-9}.

Bit-Error-Rate Measurement & Calculation



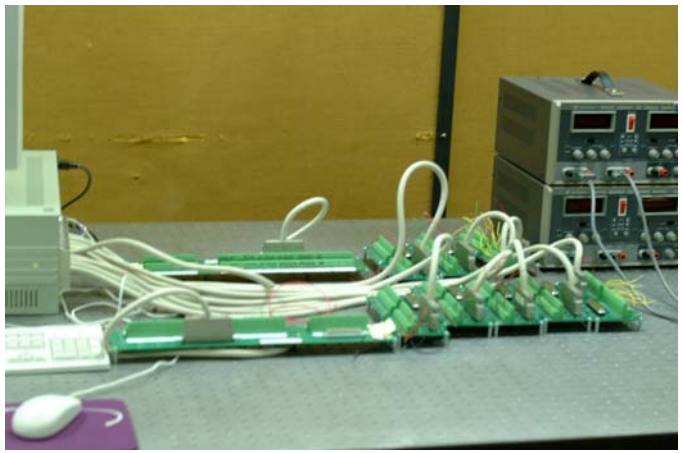
An eye diagram of 1.25 Gb/s transmission. BER --- 10-5.

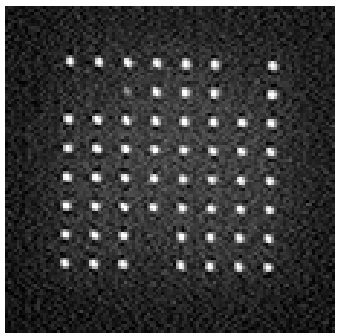
Bit-Error-Rate Measurement & Analysis



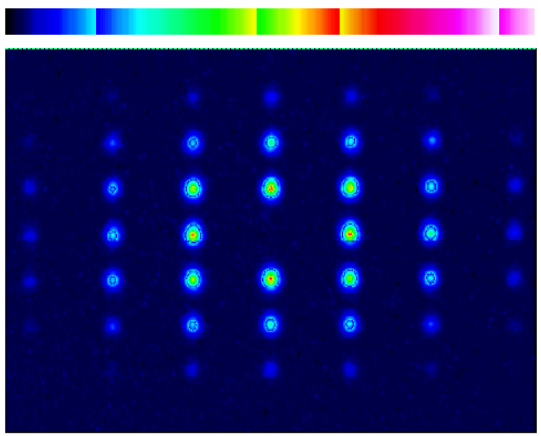
Opto-electronic Processor Preliminary Results

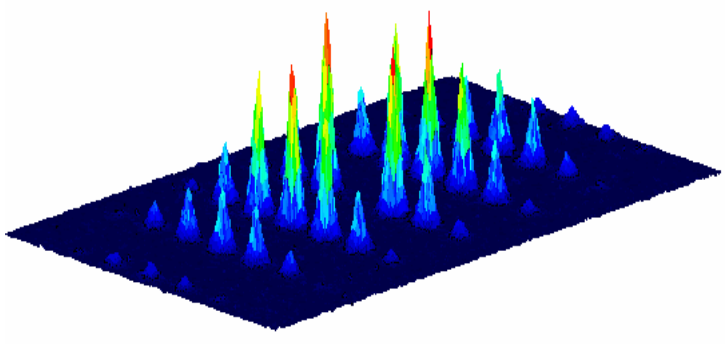
- **Diffractive Optical Element fanout achieved**
- **Parallel VCSEL lighting accomplished**
- **Computer control of 1 VCSEL onto CCD**





ARL VCSEL #3 21 JUL 2004





Opto-electronic Processor Future Work

- **Full implementation of digital halftoning system under computer control using VCSEL and detector arrays**
- **Analysis of halftoning system performance**

SUMMARY

1. Free-space SOS optical interconnect system was developed for parallel data transmission and processing.

2. A method for direct measurement of BER using eye diagram was investigated and compared with the results from a BER Tester.

3. Data rate up to 1.25 Gb/s/ch (minimum) was measured from the interconnects array.

4. The interconnects operates at 3.2 –3.5 V.
   Power consumption: VCSEL emitter – 15 mW/ch
   Photoreceiver < 5 mW/ch