Customer Success Is Our Mission

Coherent Detection with Asynchronous GmAPD

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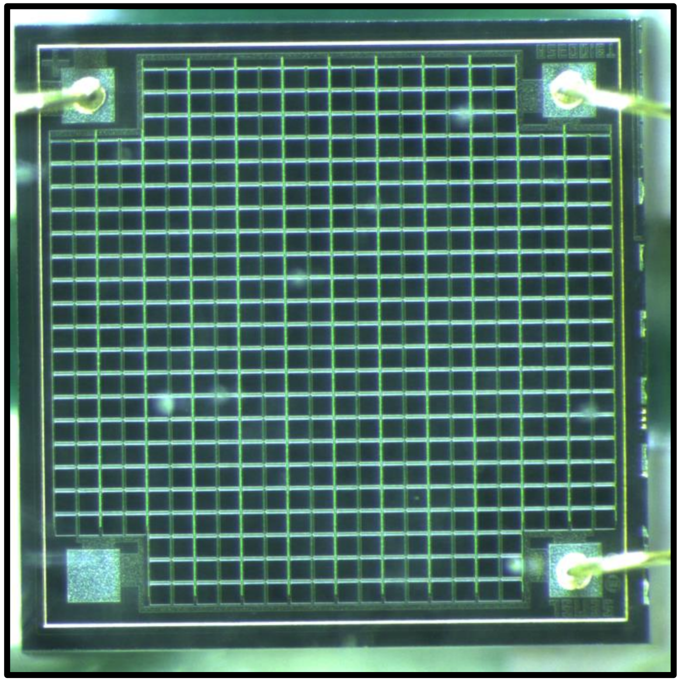
Presentation Outline

- Overview and motivation
- Derivation of CNR, blocking loss relation
- Simulation experiments
- Laboratory experiments
- Summary

What is a Photon Counting Receiver:

- Used when return signal is comprised of single photon events
  - Low source power, distant objects
  - Signal consists of 2D photo-event locations and times
- Multiple pulses are typically integrated for reliable detection. Poisson statistics are key aspect of signals.
- Detector properties such as reset time and dark count rate are important considerations
  - Reset time- detector pixel cannot record another event until reset
  - Dark count rate sets lower limit on the signal level

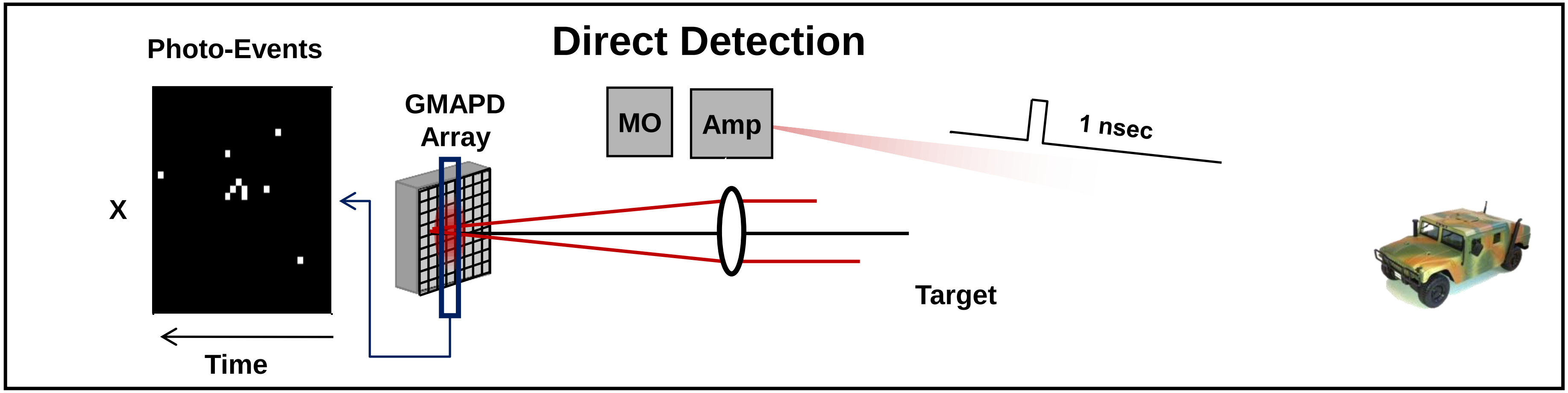


SensL Inc. 2D GmAPD Array (macro-pixel)

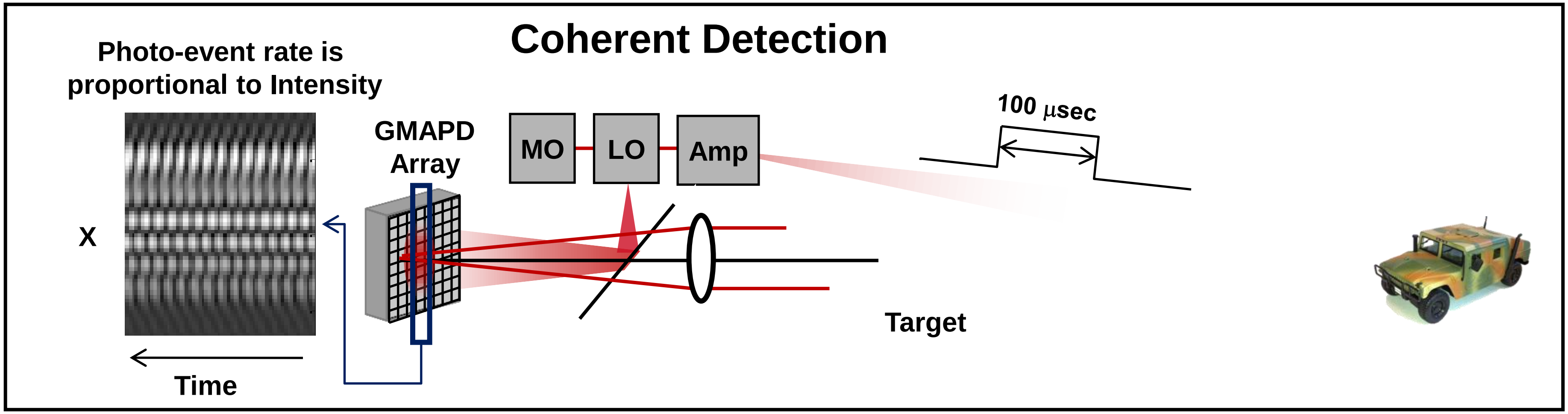
Comparison of Direct and Coherent Detection:

- GMAPD arrays are typically used for direct detection ladar
- Here we consider their use for coherent detection

Direct Detection



Coherent Detection



Why Geiger Mode Detection for Coherent Applications

Linear coherent detection:

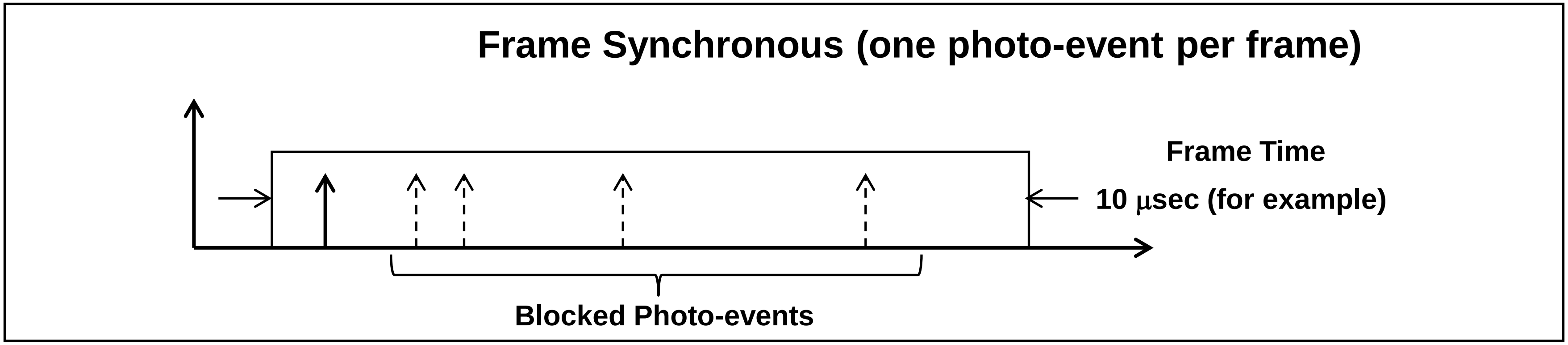
- 2-D linear detector arrays for coherent detection are complicated
  - ROICS for high-density, high-bandwidth linear detection are difficult to implement
  - Each detector (or small cluster) requires a high-speed A/D converter
  - Volume of data is large
- Linear detectors do perform better than GmAPDs- no blocking loss

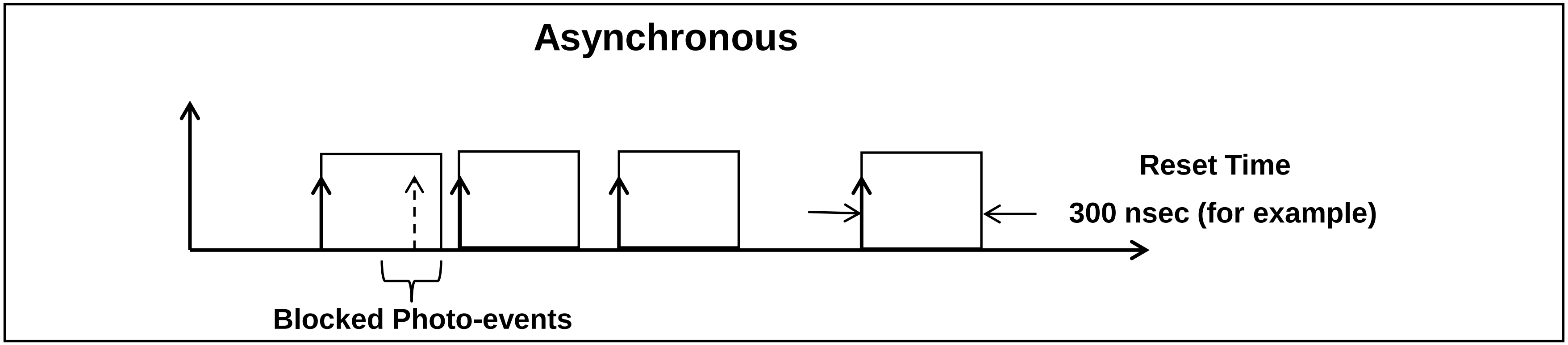
GmAPD coherent detection:

- GMAPD detector arrays already exist in 2-D array format
- The output of the GMAPD is already digital, so no additional A/D required
- GMAPD will typically NOT perform as well as the linear counterparts
- Next-generation asynchronous readout architecture overcomes many of the shortfalls of the previous frame-synchronous devices

Coherent Detection with Asynchronous GmAPD Detector

- Next generation of GMAPD detectors will operate in asynchronous mode (as opposed to frame synchronous)
- Result is improved reset time

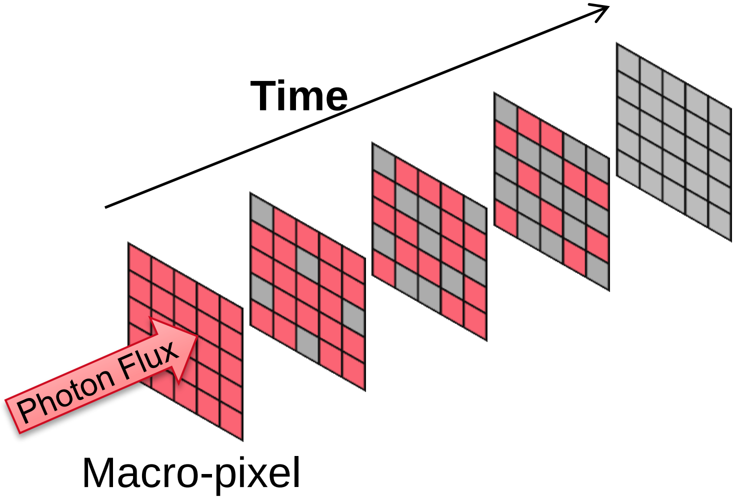




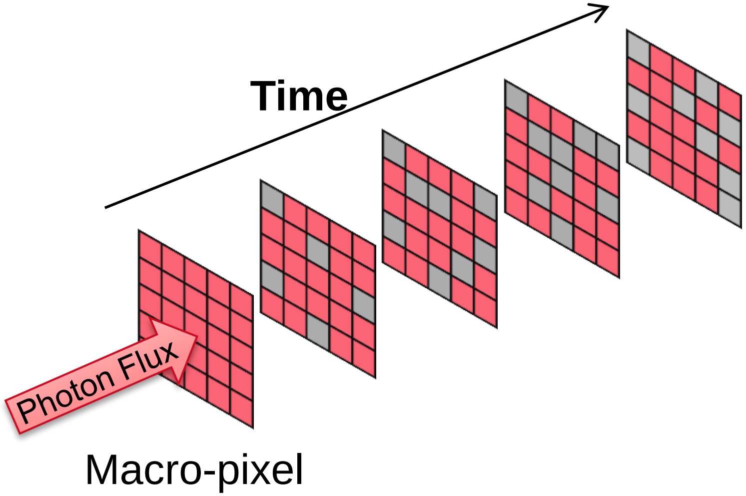
GmAPD Macro-Pixel Saturation or Blocking Loss

- Detectors are comprised of *macro-pixels* to increase dynamic range
- Traditional frame-synchronous continues to loose sensitivity as the number of detections continue until the array is reset (every ~ 50 μs)
- Asynchronous arrays reset pixels individually ~ 0.5 μs after a detection event
  - Creates a flow of pixels being reactivated countering saturation

Frame Synchronous:
Infrequent reset results in blocking efficiency that approaches 0



Asynchronous:
Reaches a balance- detectors reset at rate near photon flux



GmAPD Function Described by Differential Equation

- Expanding on the work of Luu and Jiang (Appl. Optics, v45, No. 16, p3798 2006), we write the expression for the rate of change of the active pixels in the macro-pixel,

$$N'(t) = -PDE \cdot \lambda(t) \cdot \frac{N(t)}{N_0} - N(t) \cdot DCR + \frac{N_0 - N(t)}{T_R}$$

Key term for Asynchronous GmAPD

where $\lambda(t)$ is the photon flux for the heterodyne detection given by,

$$\lambda(t) = \frac{N_S+N_{LO}}{CPI}\left(1 + \frac{2\sqrt{\eta_{HET}N_SN_{LO}}}{N_S+N_{LO}} cos(2\pi f_{IF}t + \phi)\right)$$

and f_{IF} is the heterodyne beat frequency

$N_0 \equiv$ Number of pixels in the macropixel

$N(t) =$ Number of active pixels

$T_R \equiv$ Single pixel reset time

$CPI \equiv$ Coherent Processing Interval

$DCR \equiv$ Dark Count Rate

$N_S \equiv$ Number of signal photons per CPI

$N_{LO} \equiv$ Number of LO photons per CPI

$PDE \equiv$ Probability of a photon creating a photo - electron

$\eta_{HET} \equiv$ Heterodyne mixing efficiency

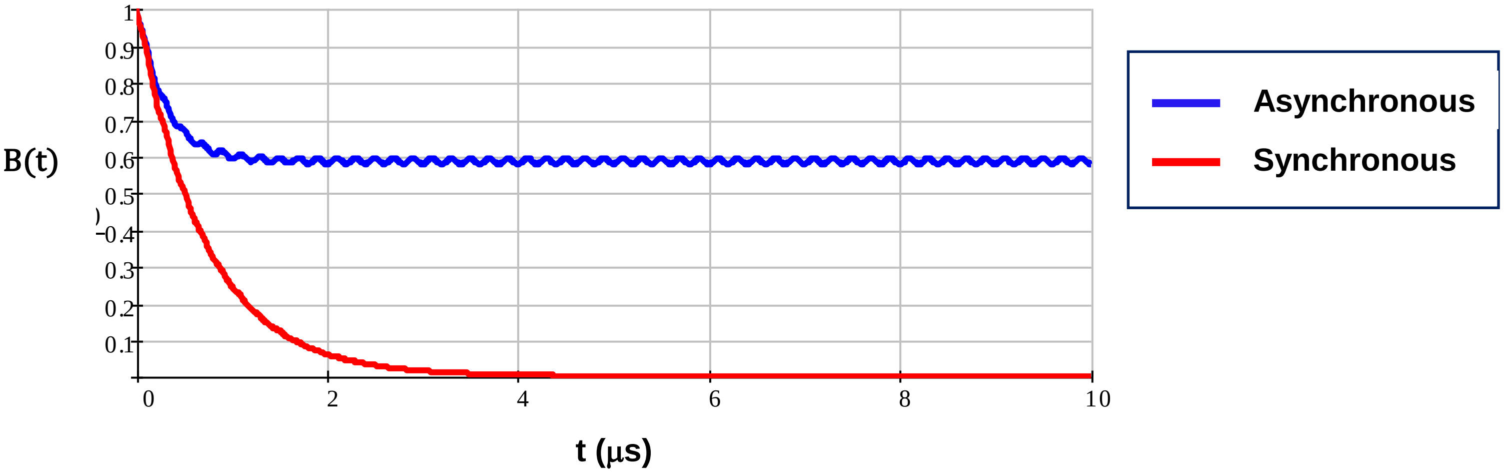
Blocking Efficiency Obtained by Solving Diff. Eq.

- Blocking efficiency, B, is the relative # of active detectors in the macro-pixel

$$B(t) = {}^{N(t)}/_{N_0}$$

- Plot below shows numerical solution
- As expected, the Blocking Eff. for the synchronous case goes to zero, but for the asynchronous case, it reaches a nonzero steady state

Values
$N_0 = 25$
CPI = 10 μsec
$N_S = 100$
$N_{LO} = 1000$
$DCR = 10^5$
PDE = 0.30
$\eta_{HET} = 0.30$
f = 5 MHz
$T_R = 500$ nsec



Raytheon

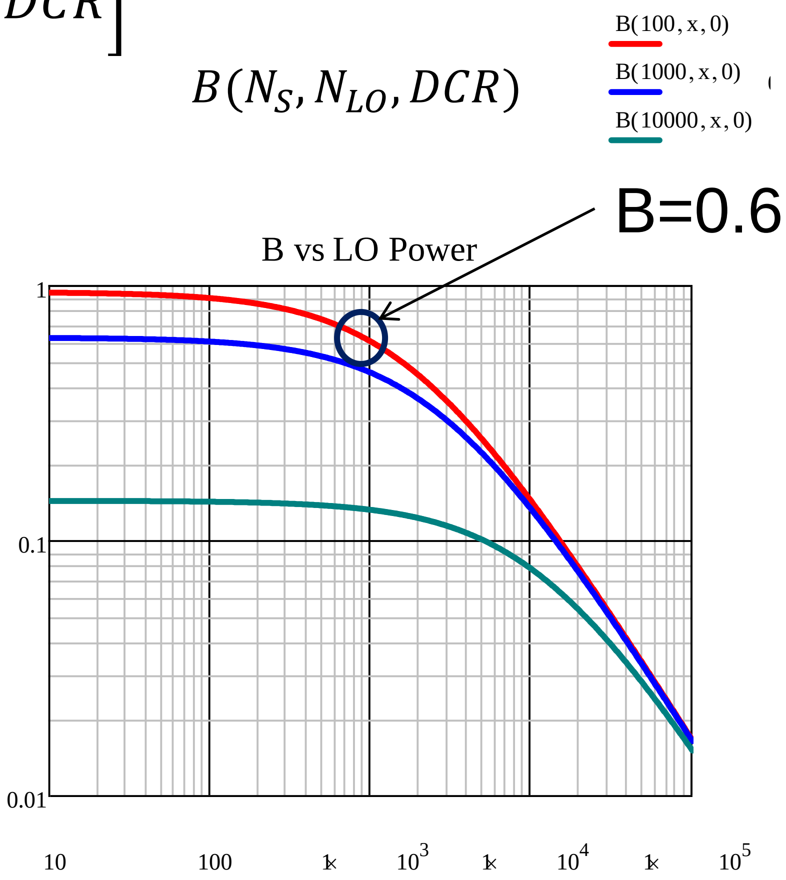
Steady State Operation: $dN(t)/dt = 0$

- Steady state Blocking Efficiency $N(t)/N_0$

$$B = \frac{1}{1 + T_R\left[\frac{(N_S + N_{LO})PDE}{CPI \cdot N_0} + DCR\right]}$$

$B(N_S, N_{LO}, DCR)$

Parameter	Value
Detectors in Macro Pixel	**N_0 = 25**
Coherent Processing Interval	**CPI = 10 μsec**
Incident Signal Photons	**$N_S = 10^2, 10^3, 10^4$**
Incident LO Photons	**N_{LO} = variable**
Dark Count Rate for Macro Pixel	**0 kHz**
Photon Detection Efficiency	**PDE = 0.30**
Heterodyne Efficiency	**η_{HET} = 0.30**
Interference Frequency	**f = 5 MHz**
Asynchronous Reset Time	**T_R = 500 nsec**
Blocking Factor	**B = plotted**

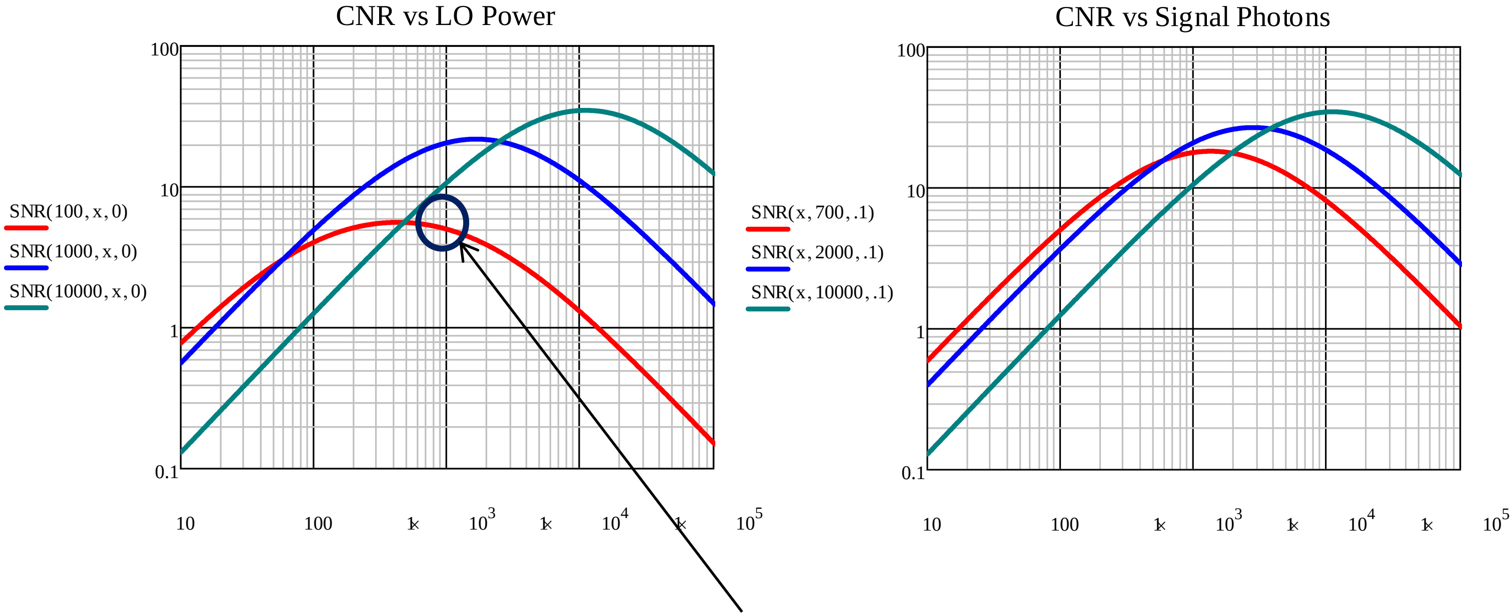


Steady State Operation: CNR

- CNR plotted vs LO power and signal photons

$$CNR = \frac{PDE \cdot B \cdot \eta_{HET} N_S N_{LO}}{N_S + N_{LO} + N_0 \cdot B \cdot CPI \cdot DCR/PDE}$$

Values
$N_0 = 25$
CPI = 10 μsec
$N_S = 10^2, 10^3, 10^4$
N_{LO} = 700, 2000, 10000
DCR= 0, 10^5
PDE = 0.30
η_{HET} = 0.30
f = 5 MHz
T_R = 500 nsec
B = calculated

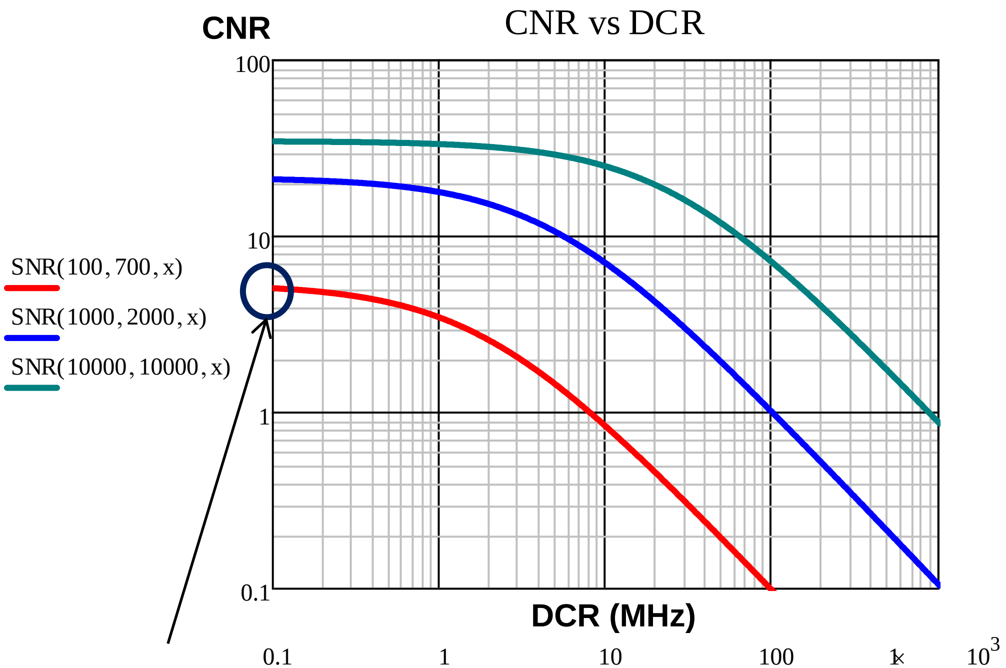


CNR=4.9 (DCR=0)

Steady State Operation: CNR

- For N_0=100 signal photons hitting the detector
  - Linear mode CNR is ~9 (9 signal photo-electrons per CPI)
  - CNR ≅ 4.8 for asynchronous GmAPD with DCR = 100 kHz
  - CNR value > 0.5 x Ideal

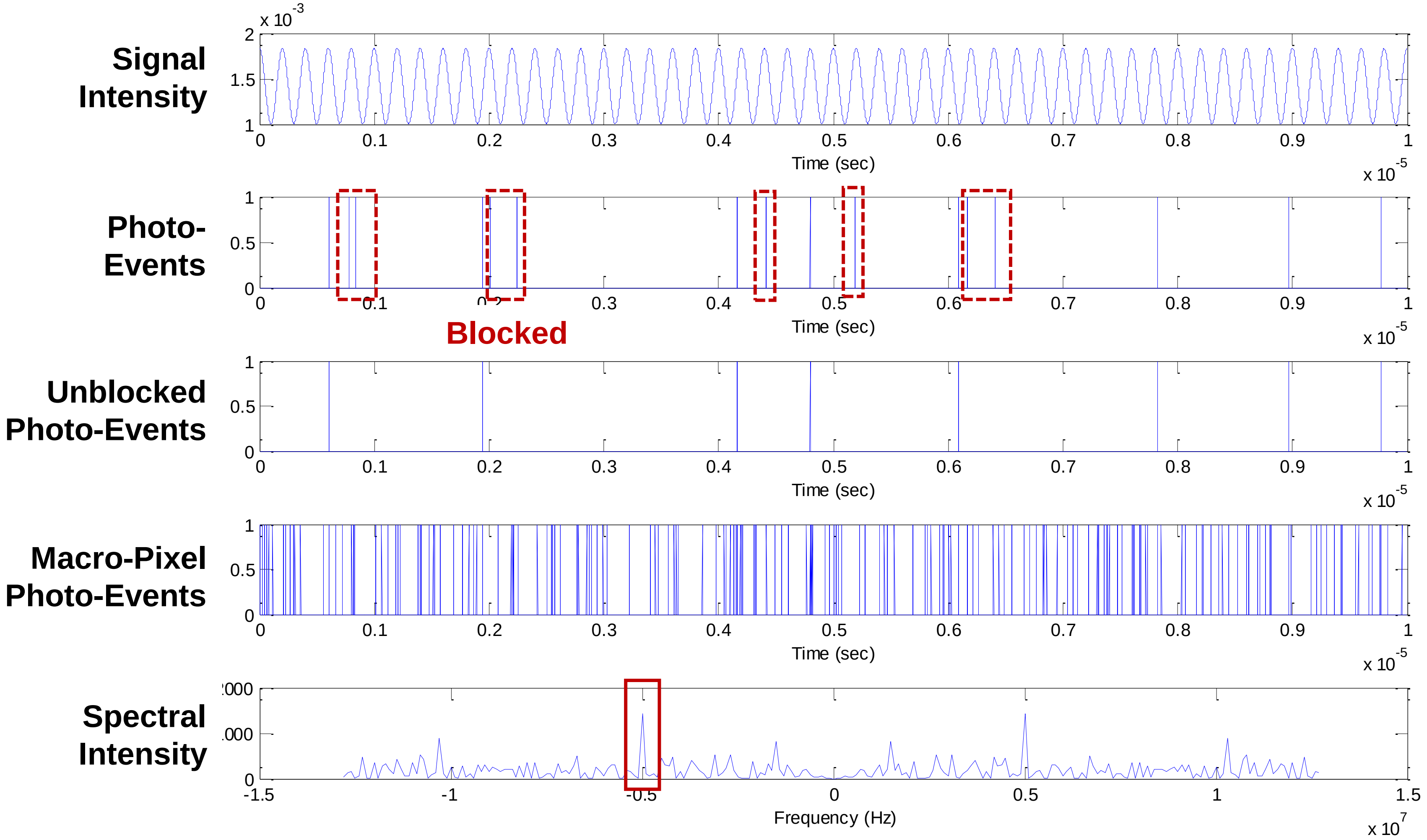
Values
N_0 = 25
CPI = 10 μsec
N_S = 10^2, 10^3, 10^4
N_{LO} = 700, 2000, 10000
DCR= variable
PDE = 0.30
η_{HET} = 0.30
f = 5 MHz
T_R = 500 nsec
B = calculated
CNR = plotted



CNR=4.8
(DCR=100 kHz)

Simulation Results- Asynchronous

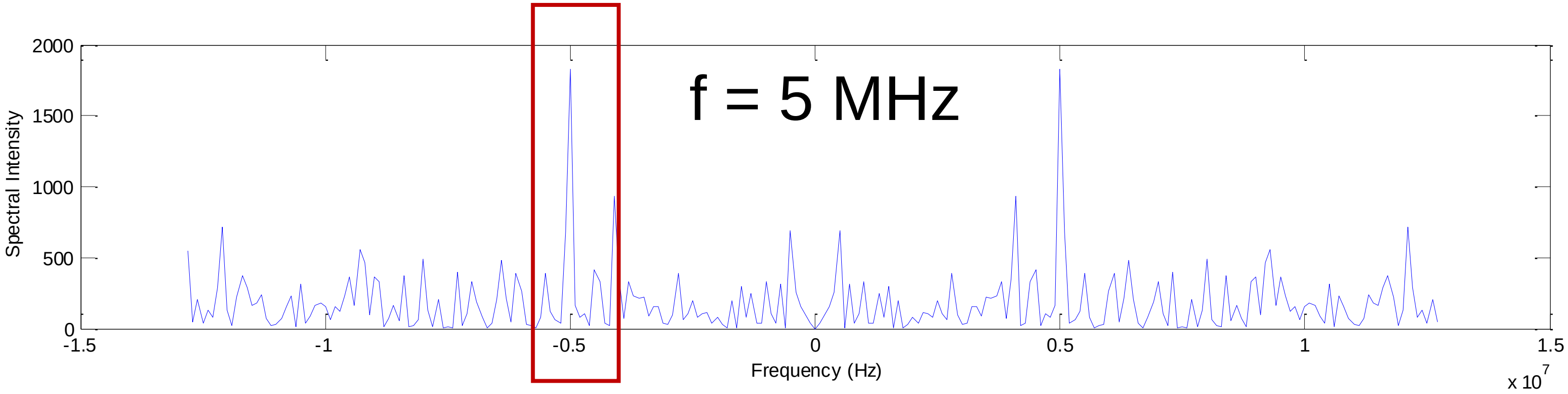
- Simulations performed by applying blocking rule to pixel signals
- Blocking factor B = 0.58

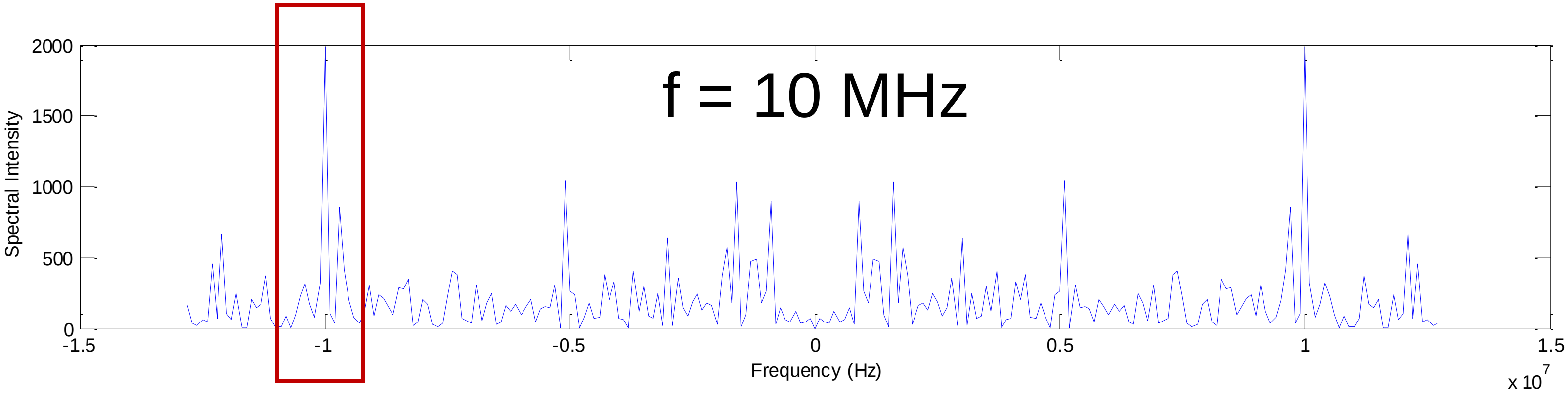


Simulation Results- Asynchronous

- Frequency content retained even with T_R = 500 nsec
  - Conventional wisdom would indicate cutoff of 2 MHz
  - Information retained via clock precision

Values
N_0 = 25
CPI = 10 µsec
N_S = 300
N_{LO} = 1000
DCR= 10^5
PDE = 0.30
η_{HET} = 0.30
f = 5, 10 MHz
T_R = 500 nsec
B = 0.55
CNR = 11.3

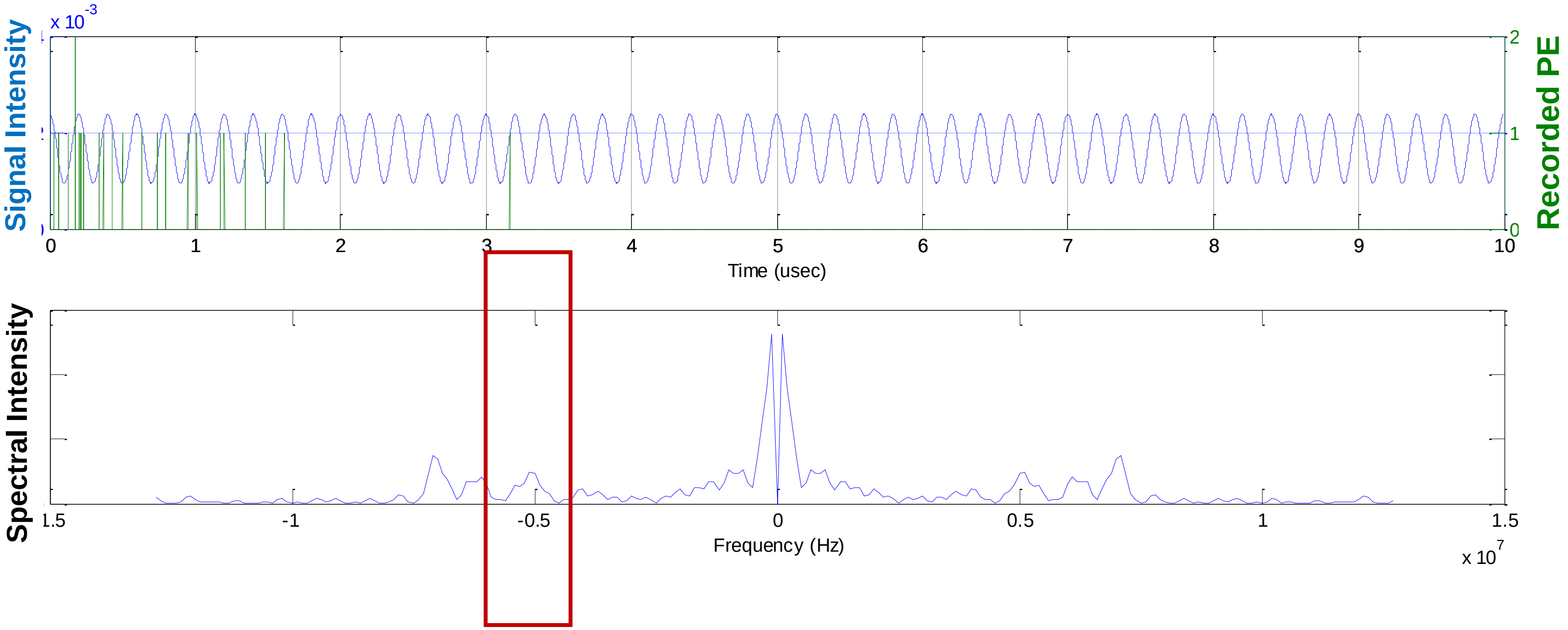




Simulation Results- Synchronous

- Frame-synchronous detector has high blocking loss and does not retain frequency information
  - Realized blocking loss B = 0.0627

Values
N_0 = 25
CPI = 10 µsec
N_S = 300
N_{LO} = 1000
DCR= 10^5
PDE = 0.30
η_{HET} = 0.30
f = 5 MHz
T_R = NA
B = 0.0627

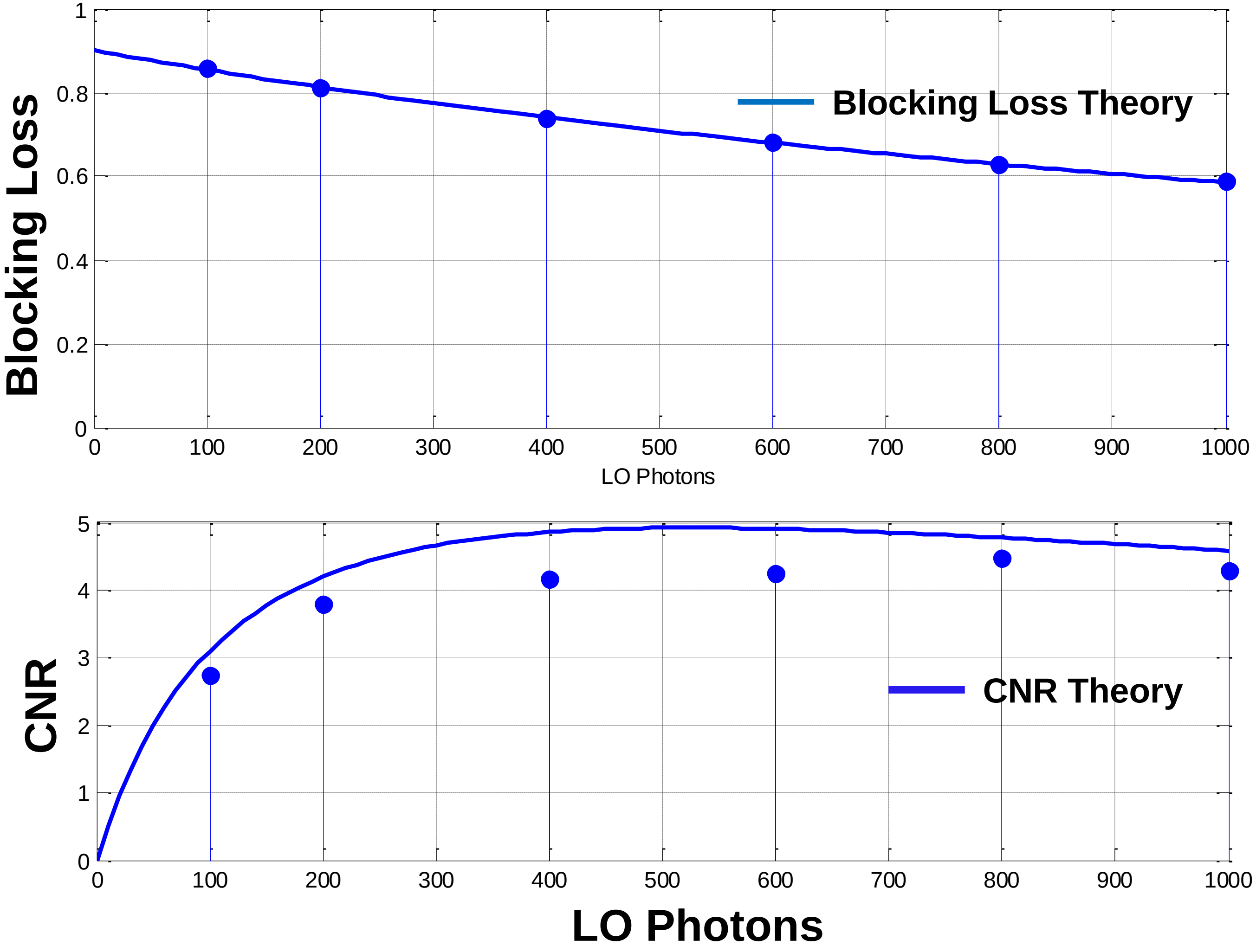


f = 5 MHz
Peak diminished and broadened

Comparison of Simulation to Theory

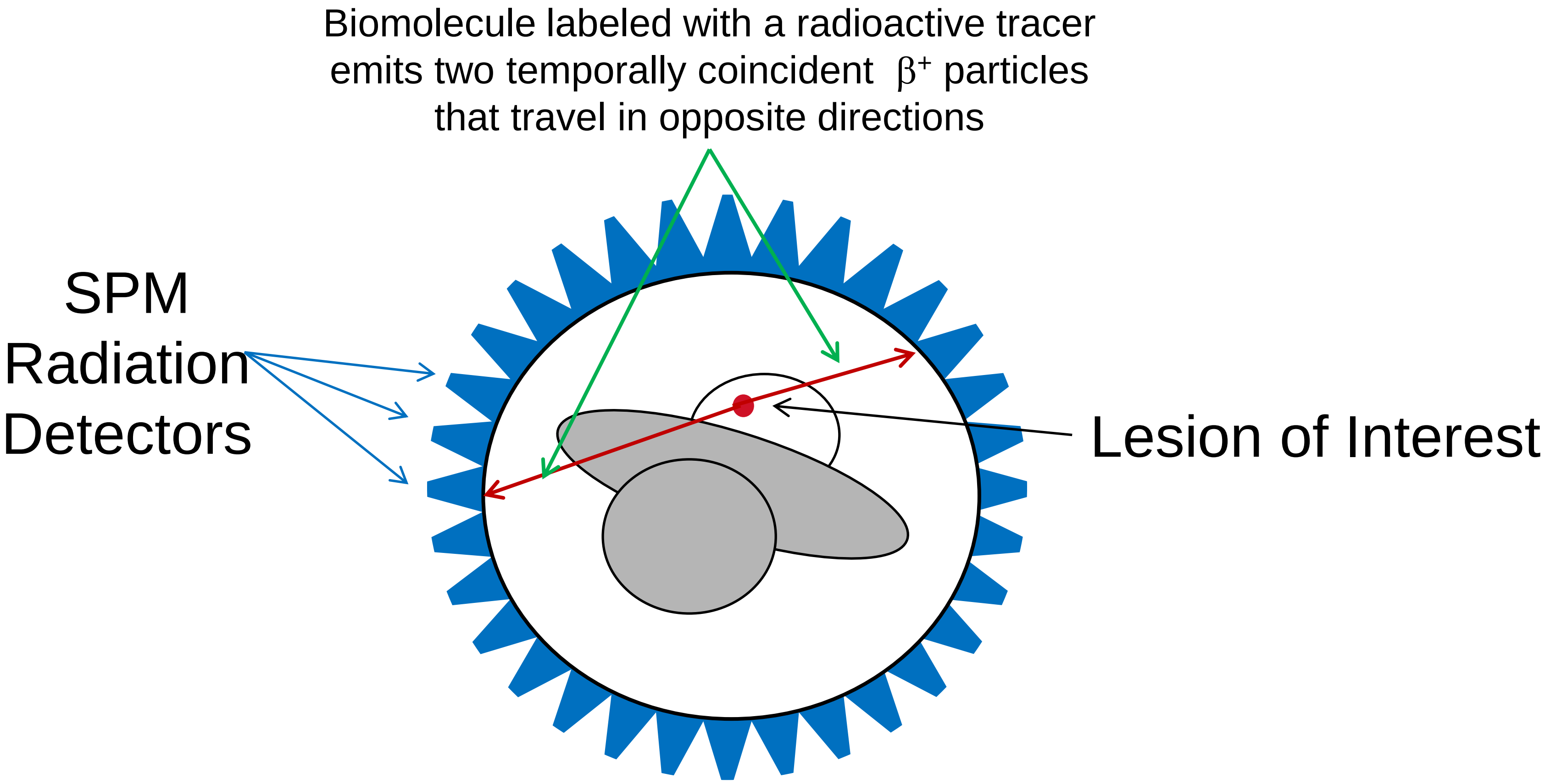
- Simulation matches blocking and gives lower CNR values than theory
- Theory is for steady state, simulation includes transients

Values
N_0 = 25
CPI = 10 μsec
N_S = 100
N_{LO} = Variable
DCR= 10^5
PDE = 0.30
η_{HET} = 0.30
f = 5 MHz
T_R = 500 nsec



Experiments- Silicon Photo Multiplier (SPM)

- SPMs are used in Time-of-Flight Positron-Emission-Tomography (ToF-PET) to detect entangled beta particles



Biomolecule labeled with a radioactive tracer emits two temporally coincident β^+ particles that travel in opposite directions

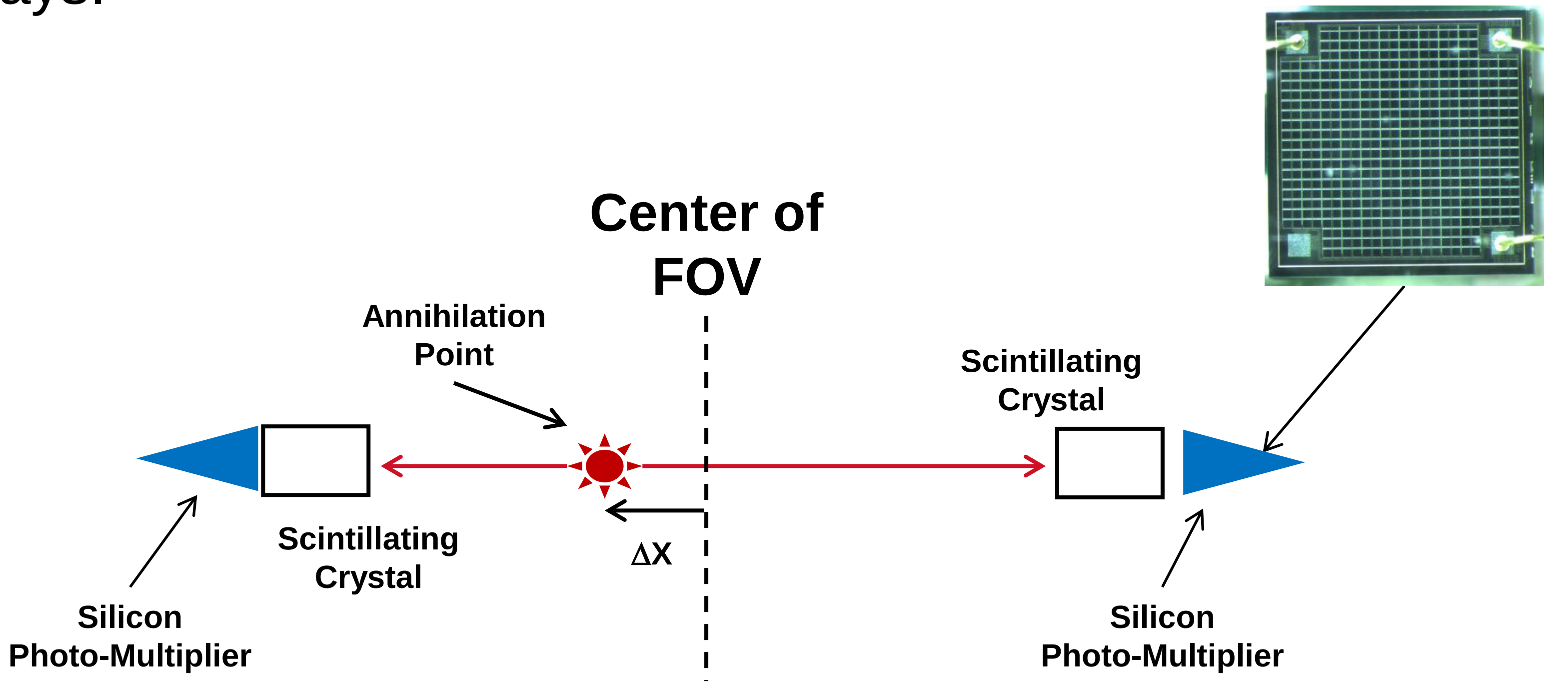
SPM Radiation Detectors

Lesion of Interest

V. C. Spanoudaki and C. S. Levin, “Photo-Detectors for Time of Flight Positron Emission Tomography (ToF-PET),” Sensors, 10, 2010.

Silicon Photo-Multiplier

- Lesion location is determined by recording time-of-flight difference for scintillated photo-events
- ToF-PET (and particle physics) is driving the development of advanced SPMs as alternative to photomultiplier tubes
- Size of SPM pixels is mm rather than 10s of microns for GMAPD arrays.



Center of FOV

Annihilation Point

Scintillating Crystal

Scintillating Crystal

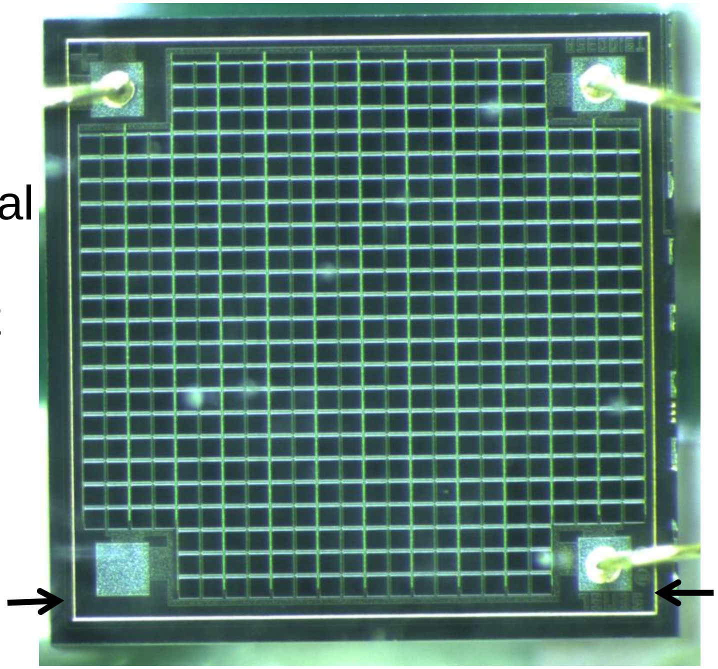
ΔX

Silicon Photo-Multiplier

Silicon Photo-Multiplier

Silicon Photo-Multiplier

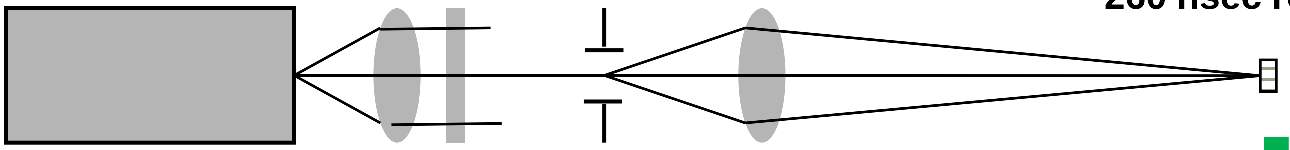
- **Technical Highlights:**
  - 260 nsec reset time
  - 0.250 nsec time-of-flight resolution
  - 0.100 nsec signal rise time Gain and optical response uniformity <+-10%
  - Available from Sensl Inc. in surface mount (SMT) package
    - 0.25mm, 1mm, 3mm, and 6mm active detector area



Device from: Sensl Inc.
1 pixel = 576 (24 x 24), parallel GMAPDs

Experimental Setup

- Evaluated detector response from temporally modulated LED
- With a dead time of 260 ns, the fastest Nyquist sampling rate is 1.9 MHz.
- Macropixel detects modulation at ~50 times the Nyquist frequency of a single pixel.



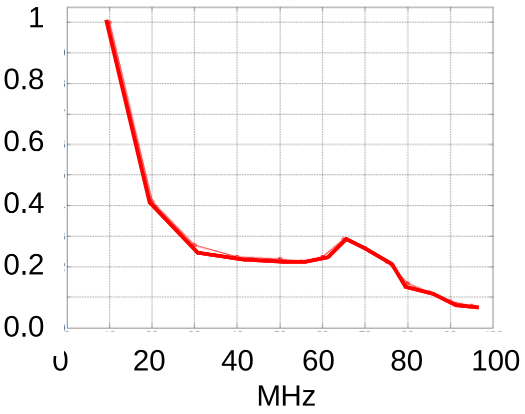
Thorlabs Modulated LED
405 nm: 10 to 90 MHz

IRIS

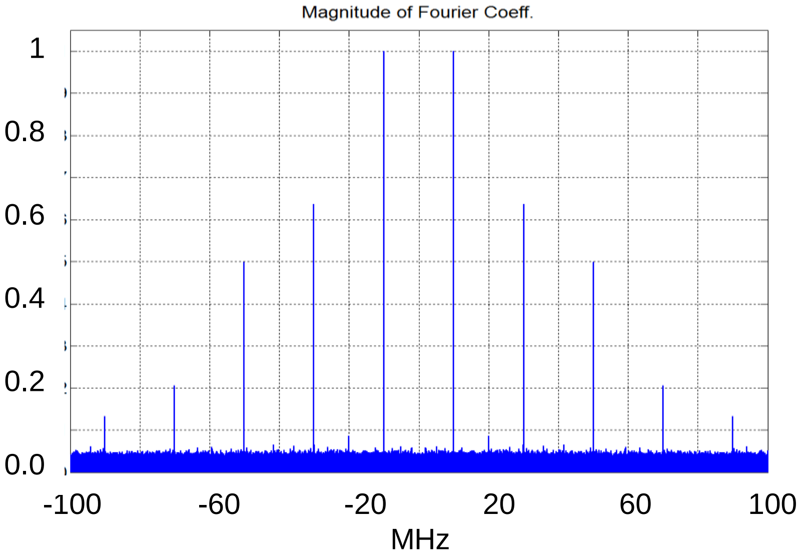
Sensl Detector:
260 nsec reset time

$$I(t) = I_1 + I_2 \sin(2\pi f t)$$

Modulation Depth



Magnitude of Fourier Coefficient



Summary

- Asynchronous GmAPD detectors show promise for coherent detection
- Macro-pixel composed of several individual GmAPDs
- Formulas for blocking loss and CNR derived
  - Performance approaches that of a linear detector
  - Allows coherent detection with array of detectors
  - Optimal LO level ≅ Signal level
- Frequency response >> 1/reset time
- Simulations in good agreement with theory
- Experiments with Silicon Photo-Multipliers are underway