Characterization of the Visible Light Photon Counter for optical communications on a photon-starved channel

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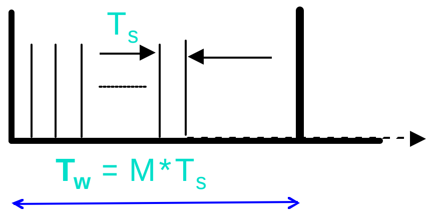
Outline

- **Photon Counting: good for deep space optical communications**
- **The Visible Light Photon Counter (VLPC): what and why**
- **Test Configuration Overview: JPL's detector characterization facility**
- **VLPC Signal Processing: analog signal chain and digital analysis**
- **VLPC Characterization: pulse response, gain, noise, linearity**
- **Receiver Signal Processing: front end architecture**
- **Ongoing work and Summary**

Photon Counting for Deep Space Optical Comm

T_s Slot Width
T_w Frame (word) Time
M Alphabet Size



Detector Class	Examples	Photon Capacity Limit
phase insensitive amplifier	parametric amplifier, Raman amplifier, laser amplifier	1.44
dual quadrature sensitive	coherent heterodyne	1.44
single quadrature sensitive	coherent homodyne, degenerate parametric amplifier	2.88
photon counting	photomultiplier tube, cooled avalanche photodiode, hot electron superconducting	hν/2kTln2 (for instance, 69 bits /photon at 1 µm & 150K)

$$C = B\left[\log_2\left(1+\frac{1}{M}\right)+\frac{1}{M}\log_2(1+M)\right] \xrightarrow{PPM\,encoding} C = \frac{B}{M}\log_2 M$$

from Brillouin's "negentropy principle"

$$P_{avg} = \frac{B_{bit/s}\, N_{photon/bit}\, h\nu}{\eta_{link}\,\eta_{detector}}$$

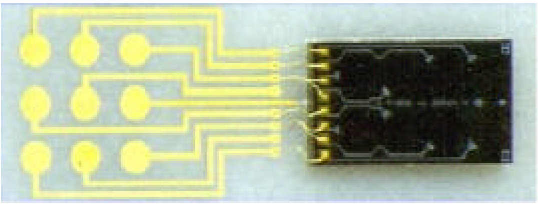
bits/second; photon energy; average laser power; link loss; quantum efficiency

- **Photon counting can yield a higher channel capacity than phase-sensitive detectors**
- **Deep Space Optical Communications requires data encodings that maximize the (bits/sec) per (Joule/sec) metric**
- **PPM Encoding with Photon Counting detection is an attractive solution**

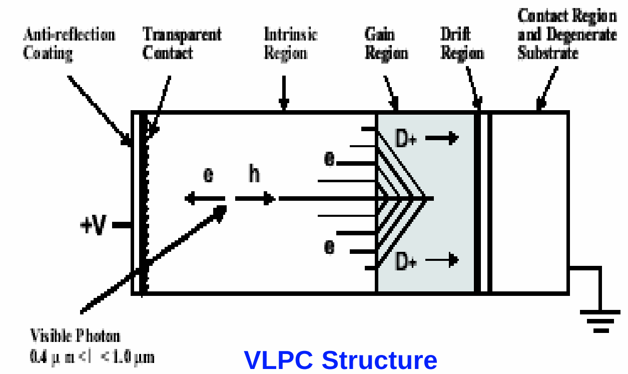
Higher efficiency means a choice of:
- Lower transmitter power
- Smaller receive aperture
- Higher data rate

Visible Light Photon Counter

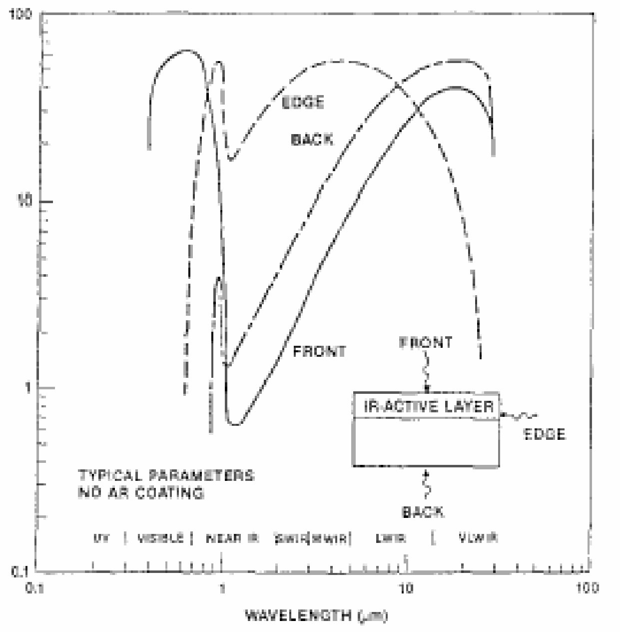
8-detector VLPC chip
1-mm diameter detector area



M. Petroff and M. Stapelbroek
IEEE Trans. Nuclear Sci., **36**, 158, (1989)



VLPC Structure



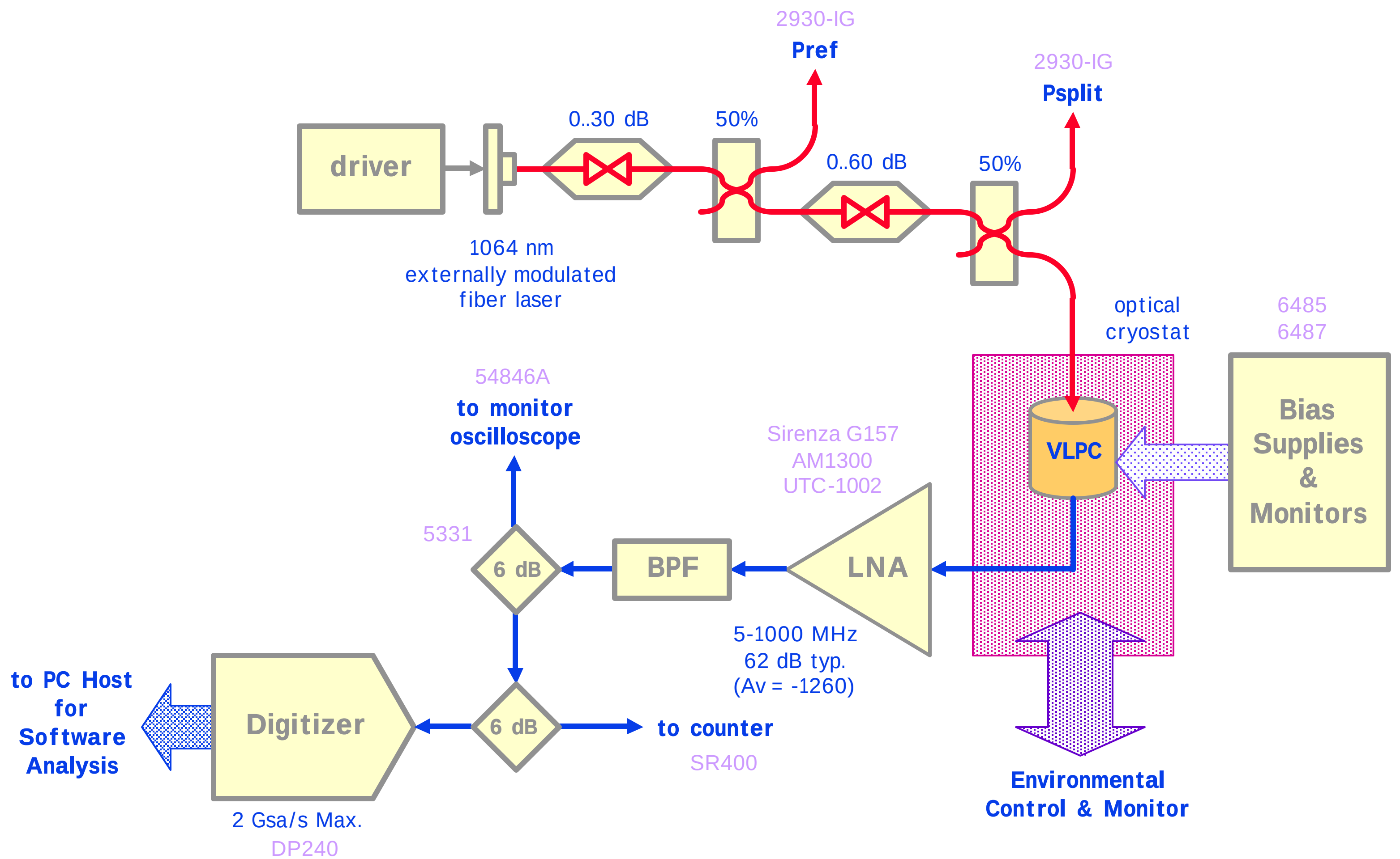
Si:As Detector Detection Efficiency

- **The VLPC is a variant of a Si:As detector with avalanche gain that was developed by DRS Technologies for use in Fermilab's D0 detector**
  - The combination of intrinsic Si and extrinsic As absorption gives a spectral response from 0.4 to 28 microns
  - Operating temperature range is typically 6 to 10K
- **A non-Markovian gain process allows the device to exhibit a gain variance near one**
  - With a typical gain of 20000 to 40000 this means photon counting with photon number resolution!

VPLC for Photon Counting Optical Comm

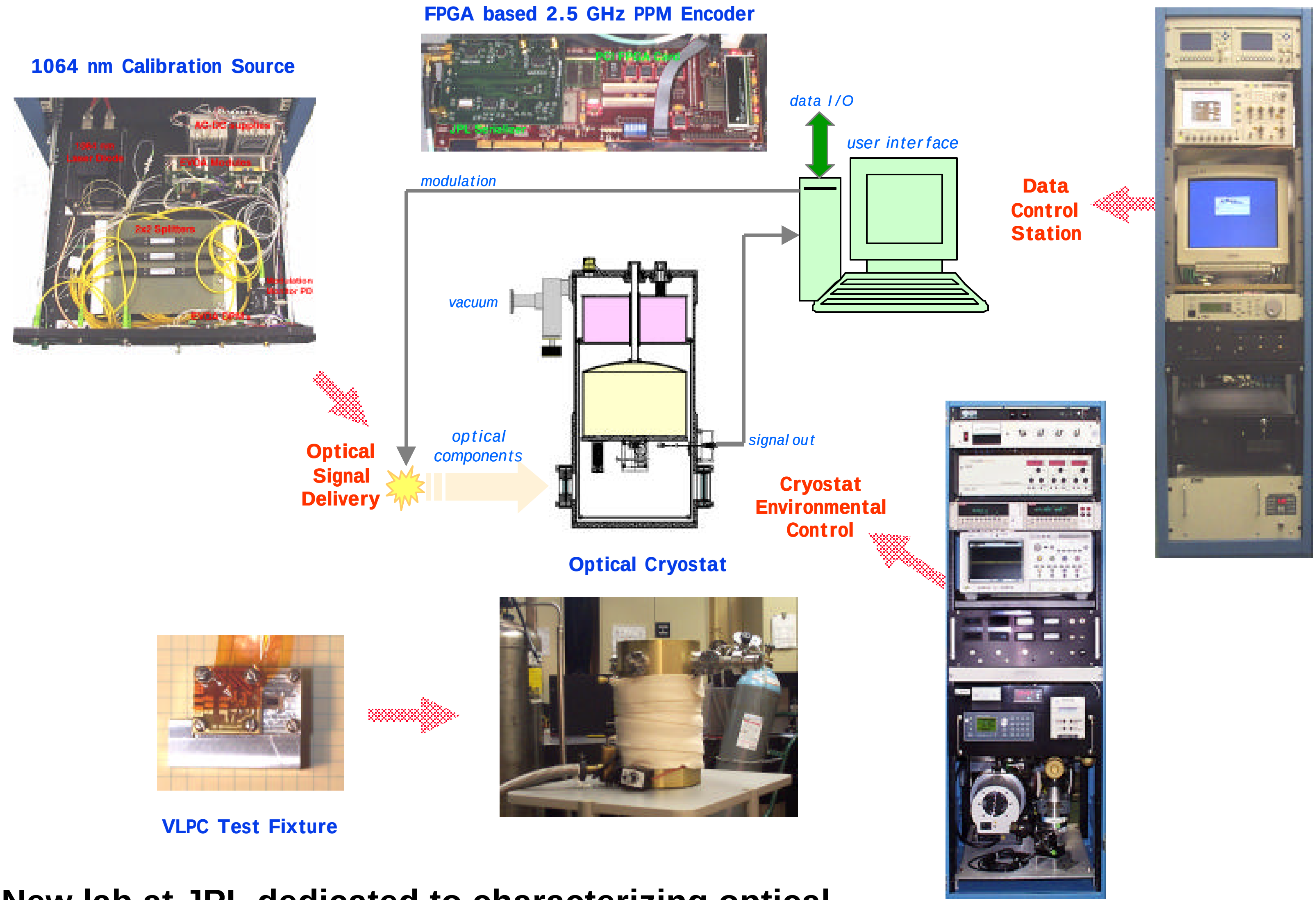
- **If you want to photon count in the visible, and can cool to < 10K, the VLPC is a great detector!**
- **Unfortunately, for 1 to 1.5 micron optical communications, where there are good laser sources, the detection efficiency is poor, as this falls between the intrinsic Si and extrinsic As absorption bands**
- **However, the VLPC is an excellent device to demonstrate high rate photon counting optical communications while other photon number devices with enhanced near-IR response are being developed**
  - Such as:
    - arrays of Geiger mode InGaAs/InGaAsP avalanche photodiodes
    - hybrid photomultiplier tubes with InGaAs/InGaAsP photocathodes
    - Si:As detectors with a separate absorber layer
    - InGaAs/InGaAsP MIS avalanche detectors

VLPC Test Configuration



- **The test configuration emulates deep space receive signal levels (pW) with CW background and a GHz rate intensity modulated optical data stream**
- **The detector output is typically digitized and post-processed in near-real time**

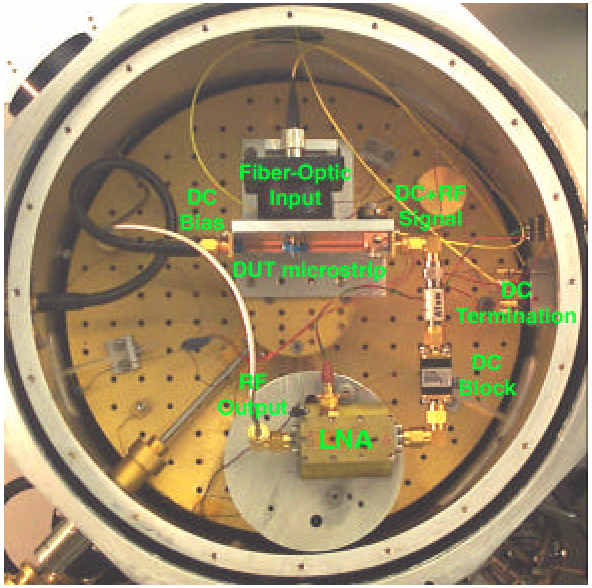
Detector Characterization Facility



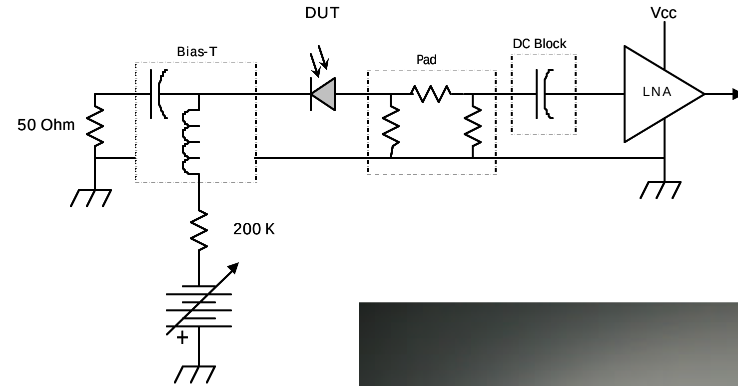
- **New lab at JPL dedicated to characterizing optical detectors for deep space optical communications**

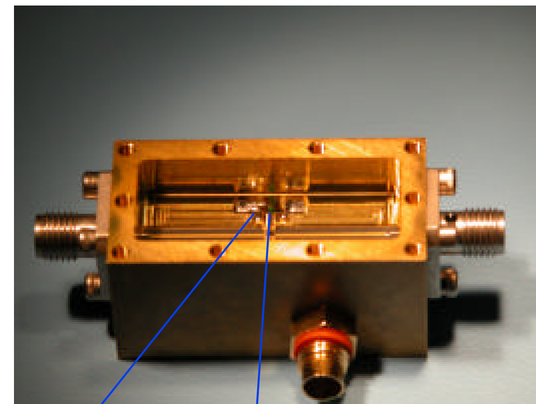
VLPC Analog Signal Chain

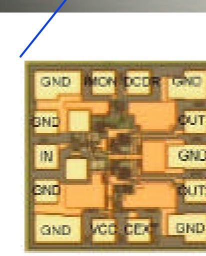
Optical Cryostat Layout with Cryogenic LNA



Microstrip Biasing Topology

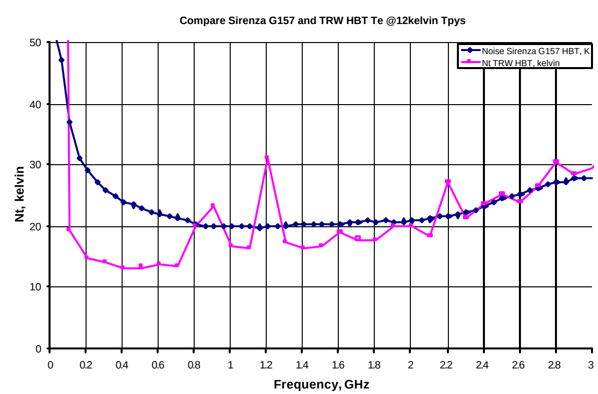






InGaP LNA in 12 GHz Chassis

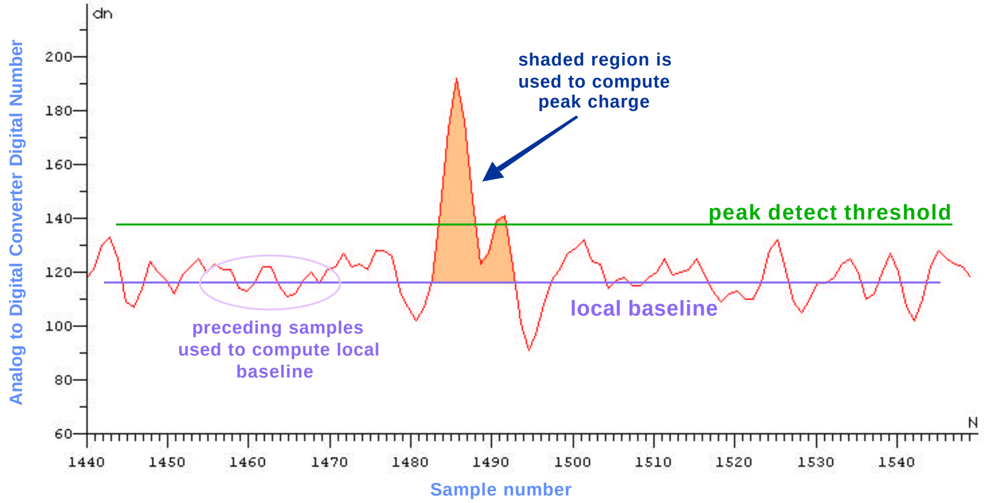
- **The initial preamplifier is also cooled to < 15K to minimize additive thermal noise for detector calibration**
- **A microstrip architecture allows the detector and amplifier to be physically separated**



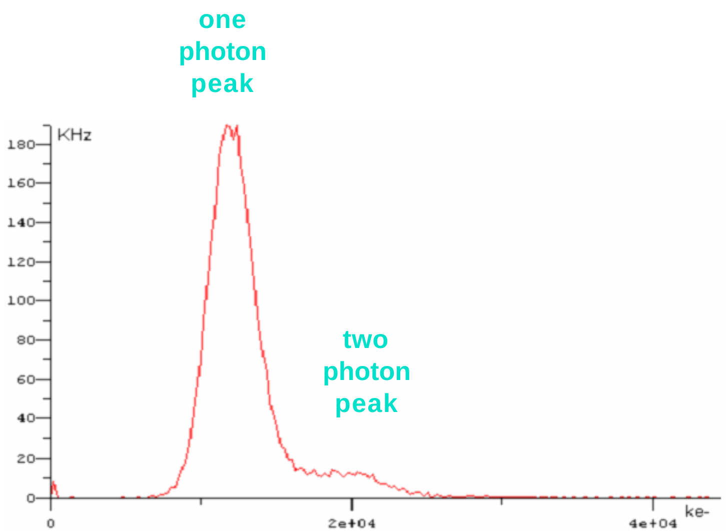
Commercial chip (Sirenza) with ultra-low noise and multi-GHz bandwidth that can operate at cryogenic temperatures

Digital Analysis

- **In addition to time domain displays and Fourier analysis, pulse height and pulse area histograms are essential to characterize the detector performance**
  - detector gain and excess noise are derived from pulse area histograms
  - dark rate and photon counting linearity are derived from thresholded peak height histograms
  - other histograms: pulse width distribution and interarrival time

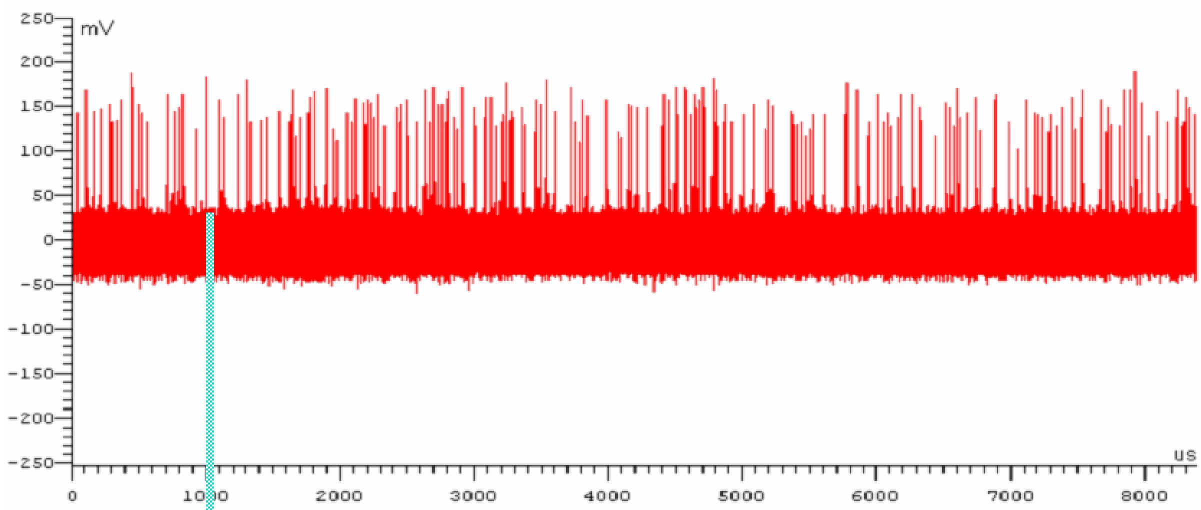


Sampled Data

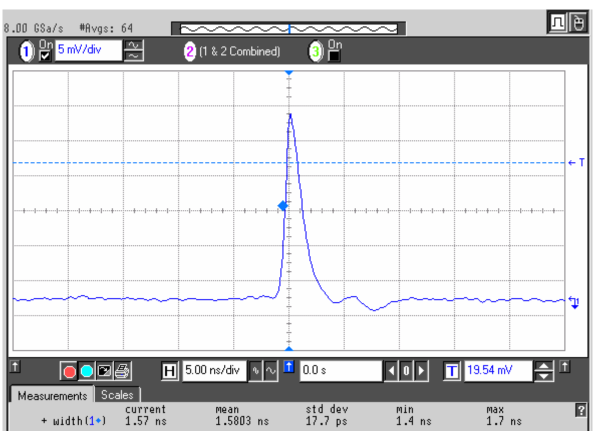


Pulse Area Histogram

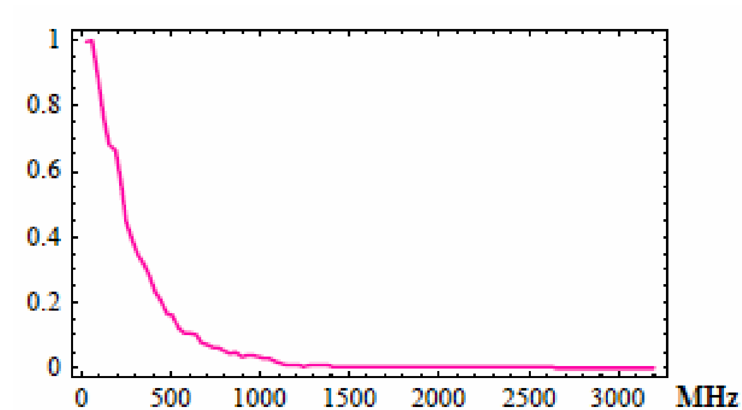
Temporal Pulse Response



1064 nm CW Illumination



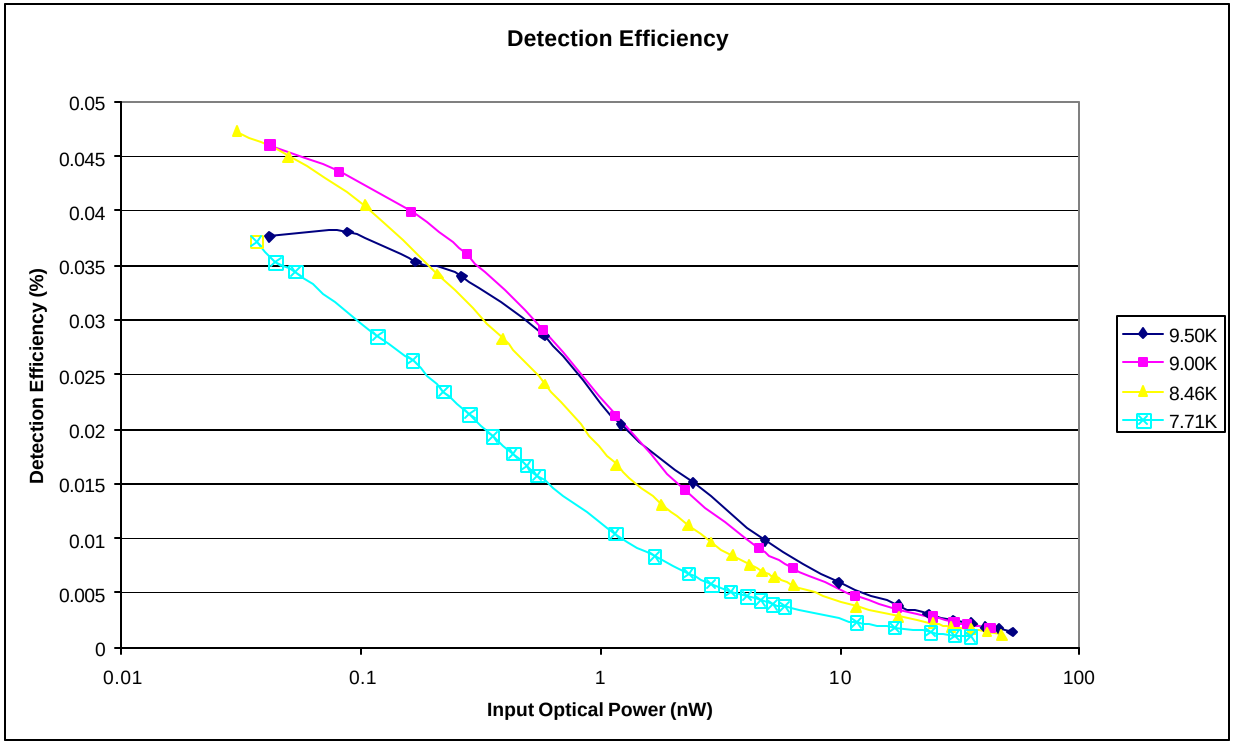
VLPC Single Photon Response



Normalized Power Spectrum

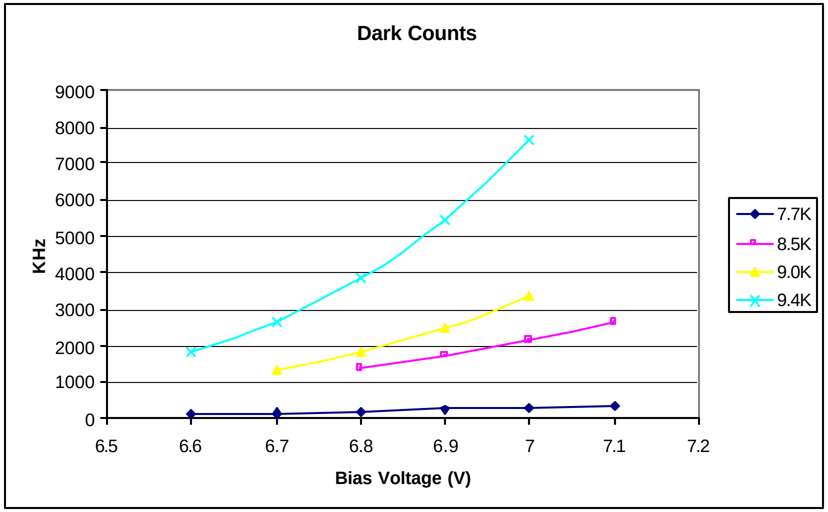
- **Single photon output pulse is typically about 1 ns wide with 30000 electrons**

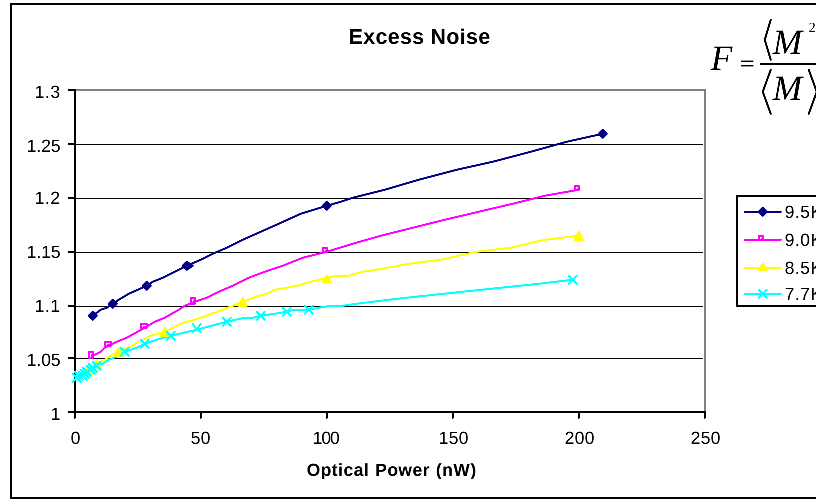
VLPC 1064 nm Detection Efficiency

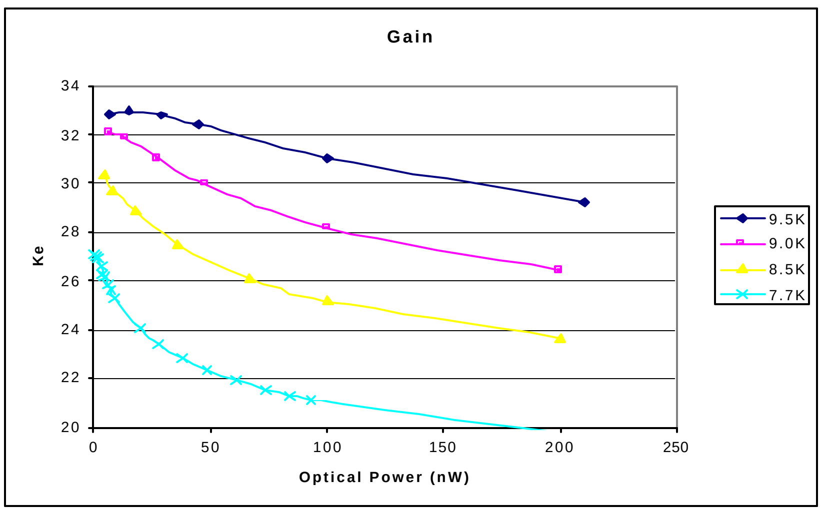


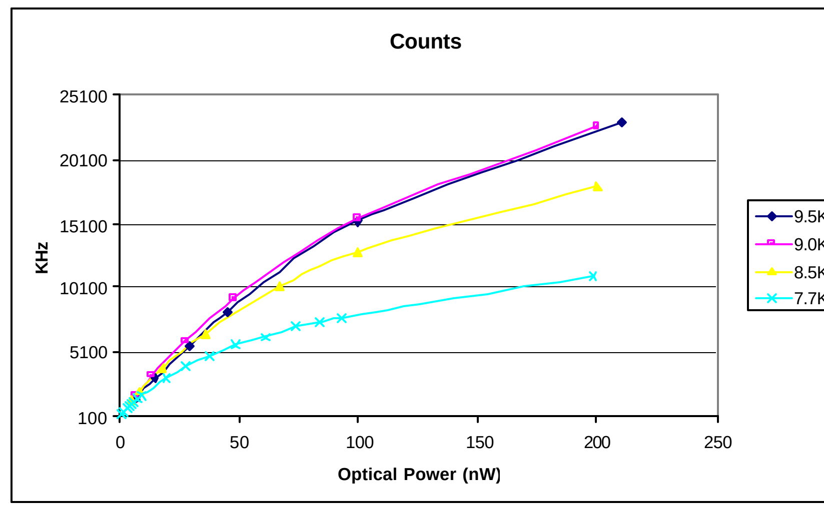
- **As expected, detection efficiency at 1064 nm is very poor**
  - However, electrical output pulse was verified to be independent of wavelength, so this wavelength can be used to verify optical communications performance
  - Observed loss in detection efficiency at high incident flux rates (many 10’s of MHz detected photons) is due to loss of gain from space charge effects
- **We prefer to use 1064 nm as most of our calibrated sources and detectors are at that wavelength**

VLPC 1064 nm CW Performance





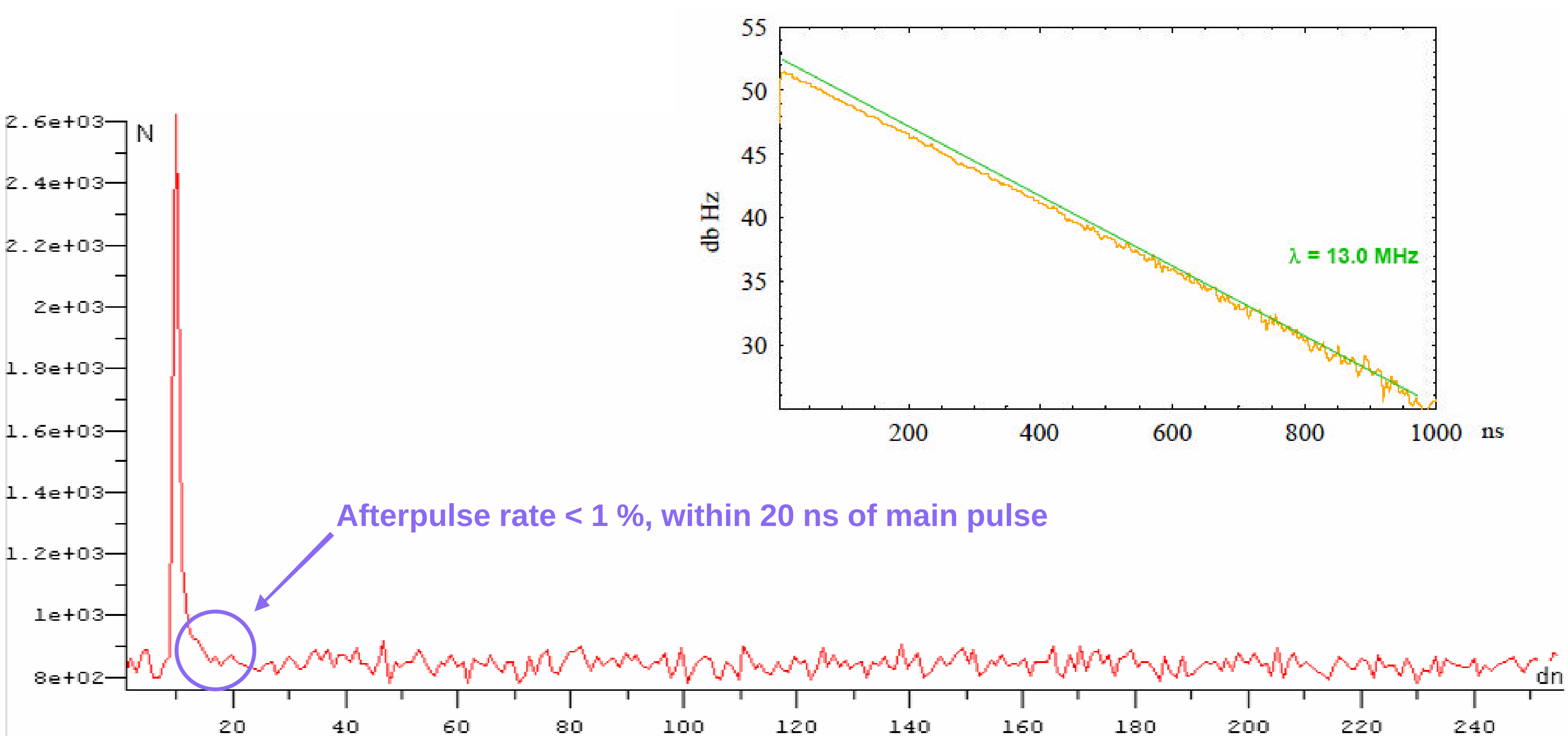




- **0.5 dB compression point at 17 MHz at 9.5K, for instance**
  - 5 dB compression at 50 MHz at 9.5K

Photon Counting Linearity

Photon Interarrival Times

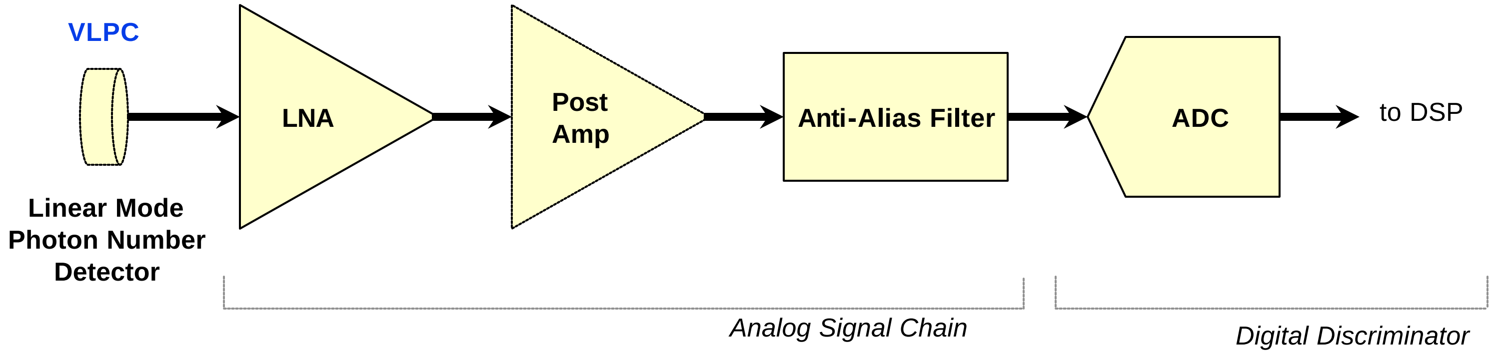


VLPC Arrival Rate Histogram

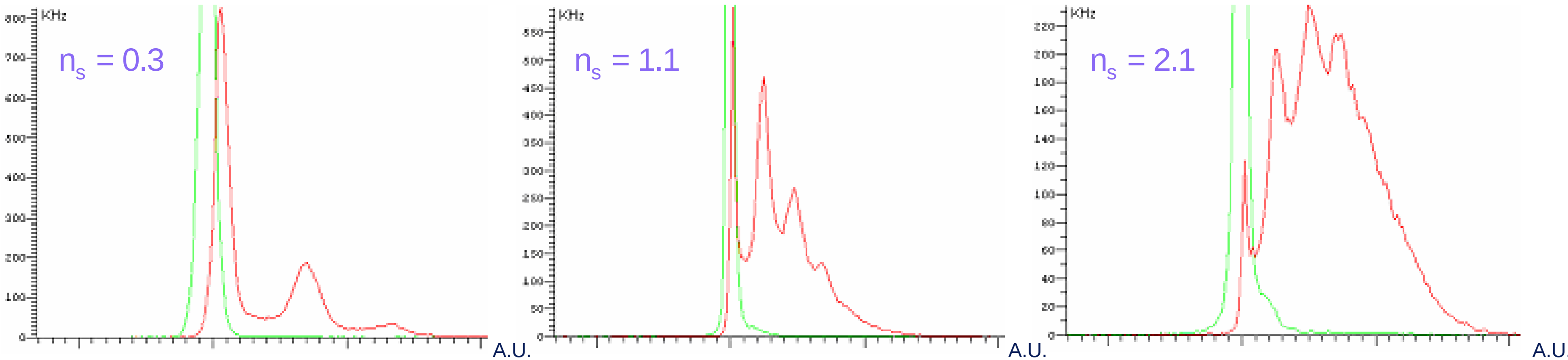
- **Exponential interarrival time distribution is expected for CW illumination**

Receiver Front-End Architecture

- **A flexible photon counting receiver front-end can be constructed by analog sampling of the detector output**
  - The pulse discriminator function is emulated by digital signal processing (DSP)
  - This is more flexible than a pure hardware solution, comprising a comparator and counter, for instance
    - DSP can implement FIR signal filtering, for instance
  - Note: a Geiger mode avalanche photodiode may be considered as having a hardwired “comparator” stage that implements a discriminator with only zero or greater than zero resolution

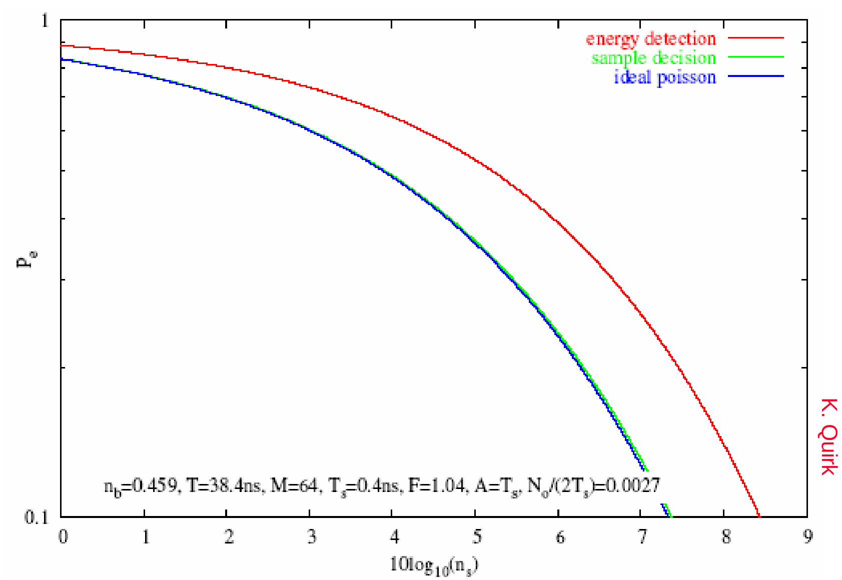


Slot Energy Histograms



note: horizontal scale on slot energy histograms varies between plots

- **Slot histograms represent the sum of signal and noise generated charge in a PPM slot**
- **Thresholding converts the slot integrated charge levels (“energy”) into a photon number**
- **Subsequent processing of the photon number signal is essentially “noise free”**



comparison of thresholded vs. non-thresholded signal processing for an example MLCD link

Ongoing Work

- **Work is in progress to acquire symbol (no FEC coding) and bit (FEC decoded) error rate data using the VLPC as the detector for a software digital receiver for comparison with theoretical predictions**

- **Testing with the VLPC has established techniques that are now being used to characterized newer high bandwidth photon number resolving detectors with enhanced near-IR sensitivity**
  - VLPC with PtSi layer added to improve near-IR absorption
  - Intevac HPMT with InGaAs or InGaAsP photocathode
    - This has now demonstrated 34% single photon detection efficiency at JPL, for instance

Summary

- **A photon counting / photon number resolving detector can be used with a PPM encoded laser source to implement a high efficiency, high data rate optical communications link**
- **The VLPC is an excellent photon number resolving detector for the 0.4 to 28 micron spectral range (although poor in the 1 to 2 micron range)**
  - High bandwidth with large area
  - High gain with very low excess noise
  - Can handle high flux rates: many 10's of MHz per mm^2
  - Although < 10K operation is problematic for many applications
- **Other detector technologies are rapidly maturing that will be able to provide similar performance in the 1 to 1.5 micron regime**