Superconducting Nanowire Single Photon Detectors for Deep Space Optical Communication

Applied Superconductivity Conference

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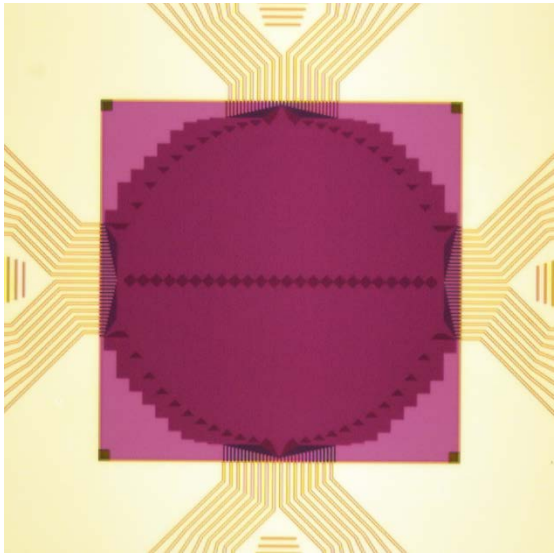
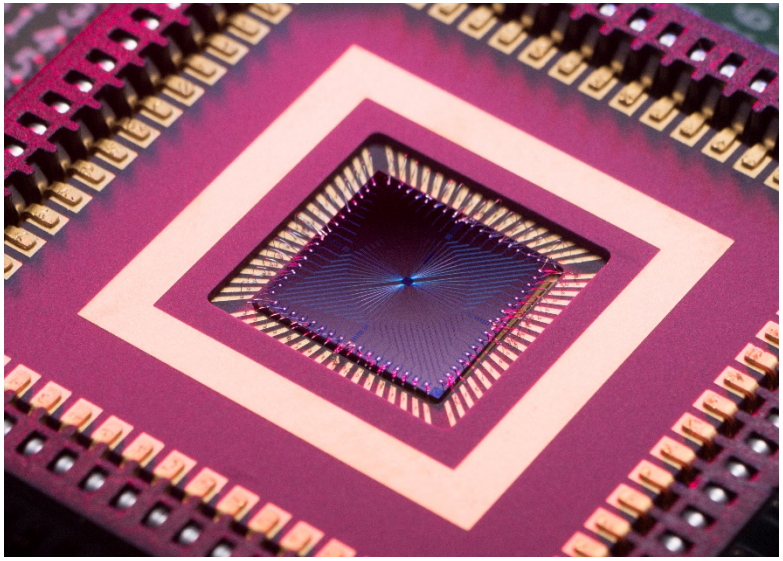
- SNSPDs are the **highest performing** single photon detectors available in the infrared (efficiency, count rate, timing jitter, dark counts)
- They operate at deep cryogenic temperatures (~1 K) and are being developed for use on the **ground** for deep space optical communication
- SNSPD arrays with **sufficient active area** to couple to a 5-meter telescope and support **gigacount-per-second** count rates are a **completely new technology.**



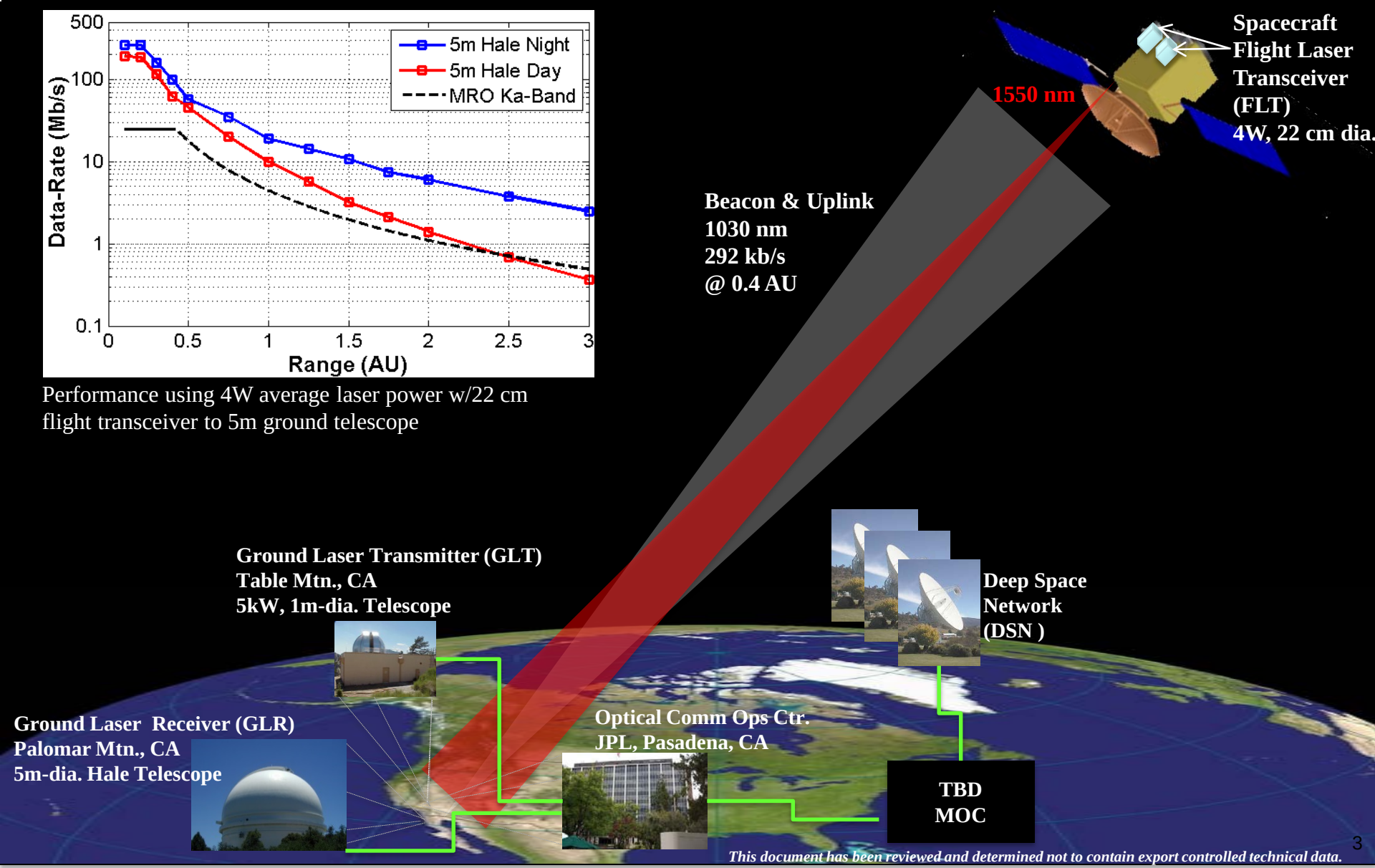
64-pixel WSi SNSPD array with 320-µm diameter active area



64-pixel SNSPD array bonded in chip carrier package

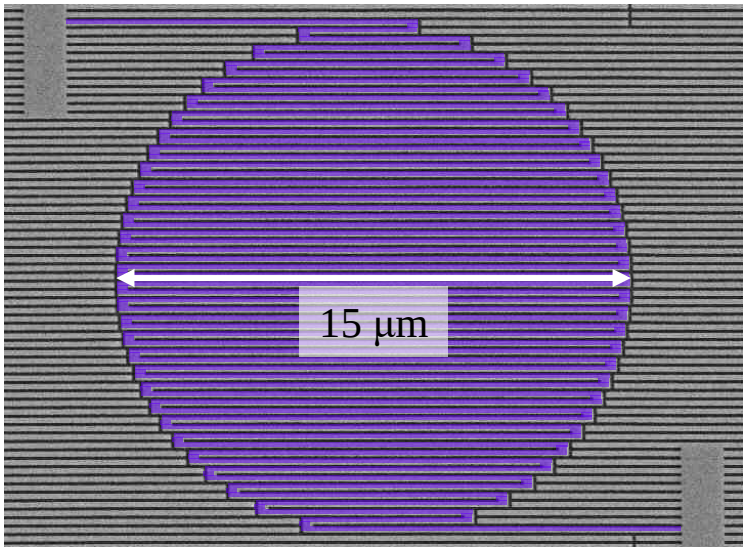
DSOC Project Overview

Performance using 4W average laser power w/22 cm flight transceiver to 5m ground telescope



This document has been reviewed and determined not to contain export controlled technical data.

Device Physics and Concept



Electron microscope image of single pixel SNSPD

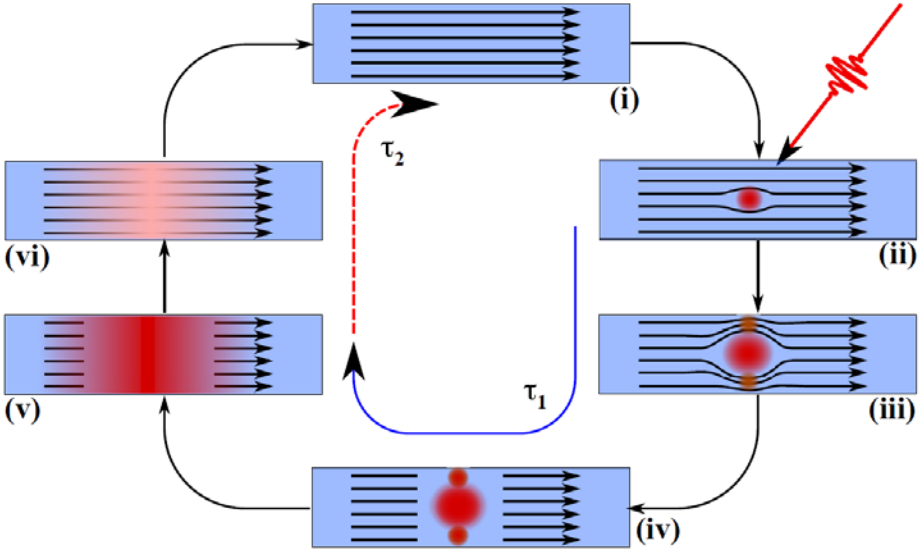
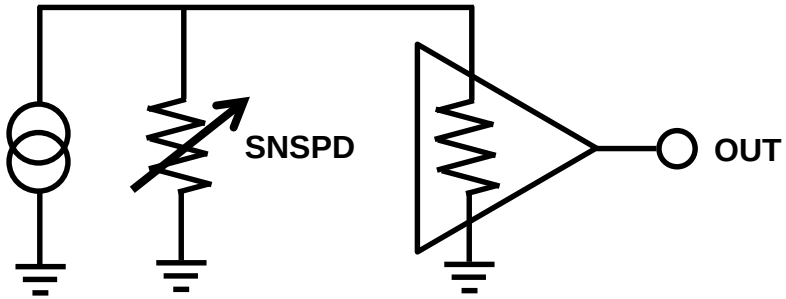


Illustration of SNSPD photon detection process



SNSPD device readout concept

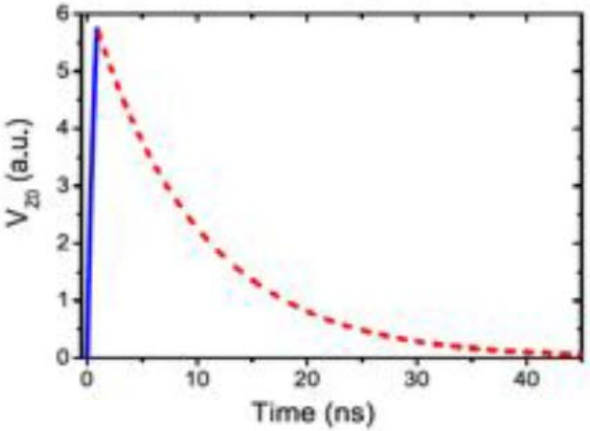
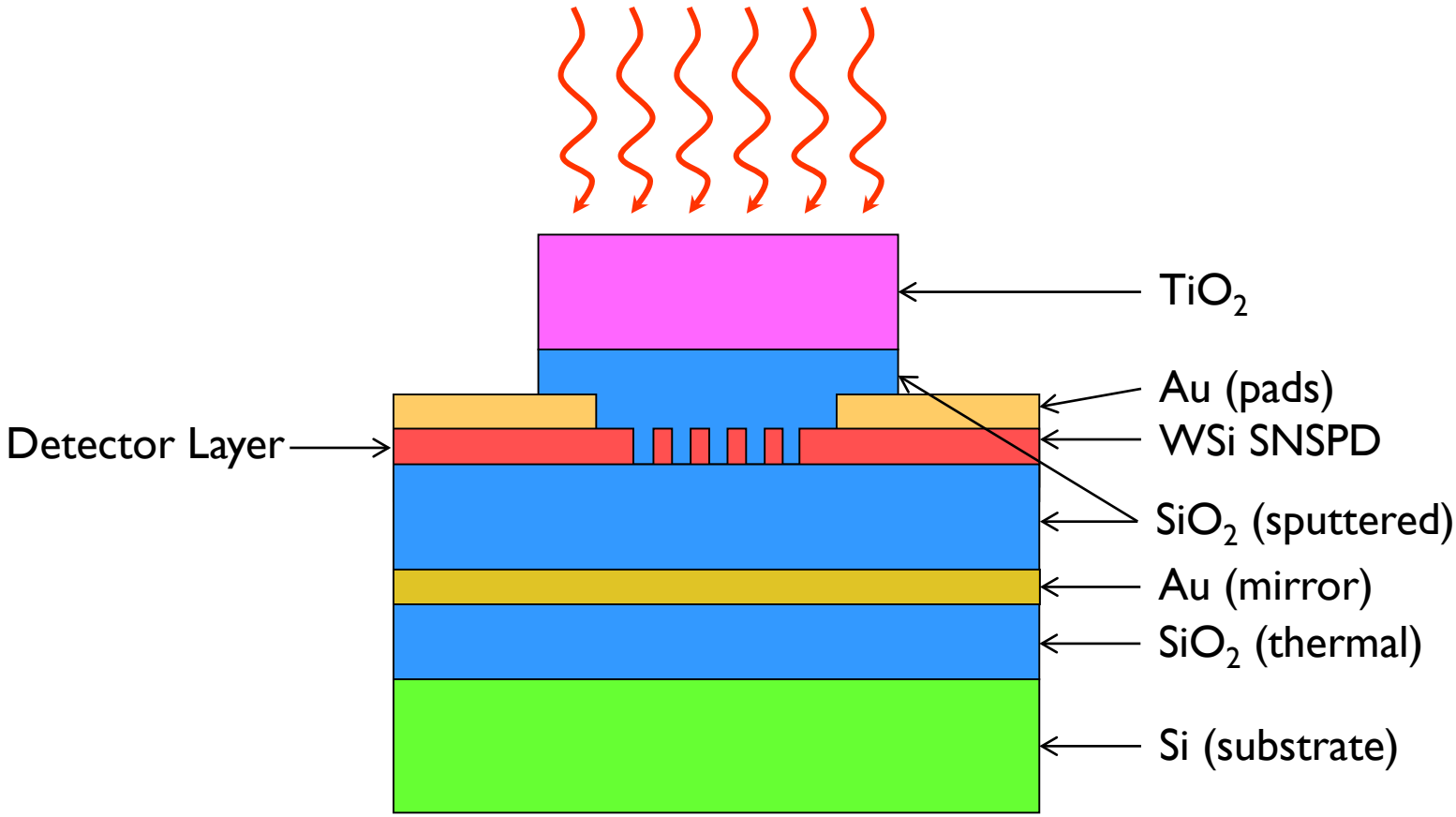


Illustration of SNSPD electrical output pulse

Optical Cavity to Enhance Absorption



- Photosensitive nanowire element is embedded in a vertical quarter-wave cavity
- Enhances detection efficiency from 20% to >90%

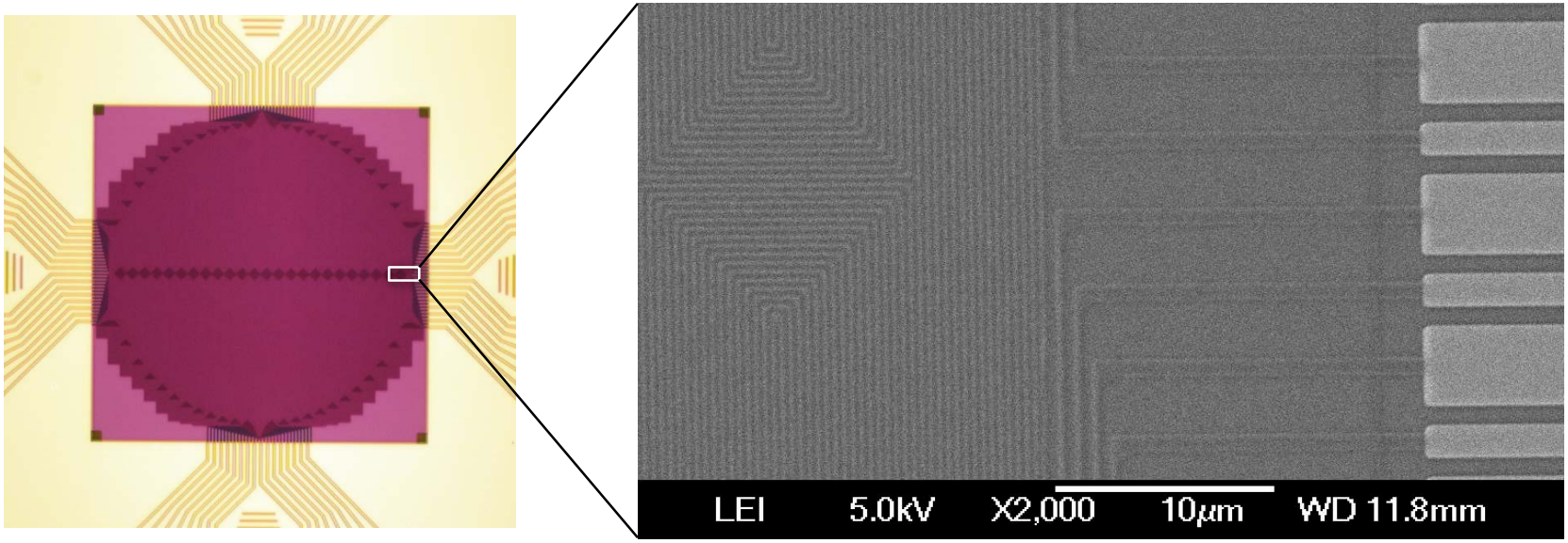
SNSPD Performance Requirements

	DSOC Requirement	Progress to date	Capability Acheived
Detection Efficiency	>50% minimum >70% desired	93% (fiber-coupled single pixel) 55% (uncalibrated, 320 µm array)	✓
Timing Jitter	150 ps (1-σ)	46 ps (1-σ) (320 µm array)	✓
Dark Counts	< 10 kcps / pixel free space coupled	< 7 kcps / pixel (320 µm array)	✓
Maximum Count Rate	550 Mcps (264 Mbps, 12º SEP, 0.16 AU)	1.3 Gcps (320 µm array, extrapolated)	✓
Active Area	320 µm diameter (50 µrad seeing, Palomar daytime)	320 µm diameter	✓
Numerical Aperture	f/1.2	f/4	X

- No afterpulsing
- No crosstalk

Current State of the Art

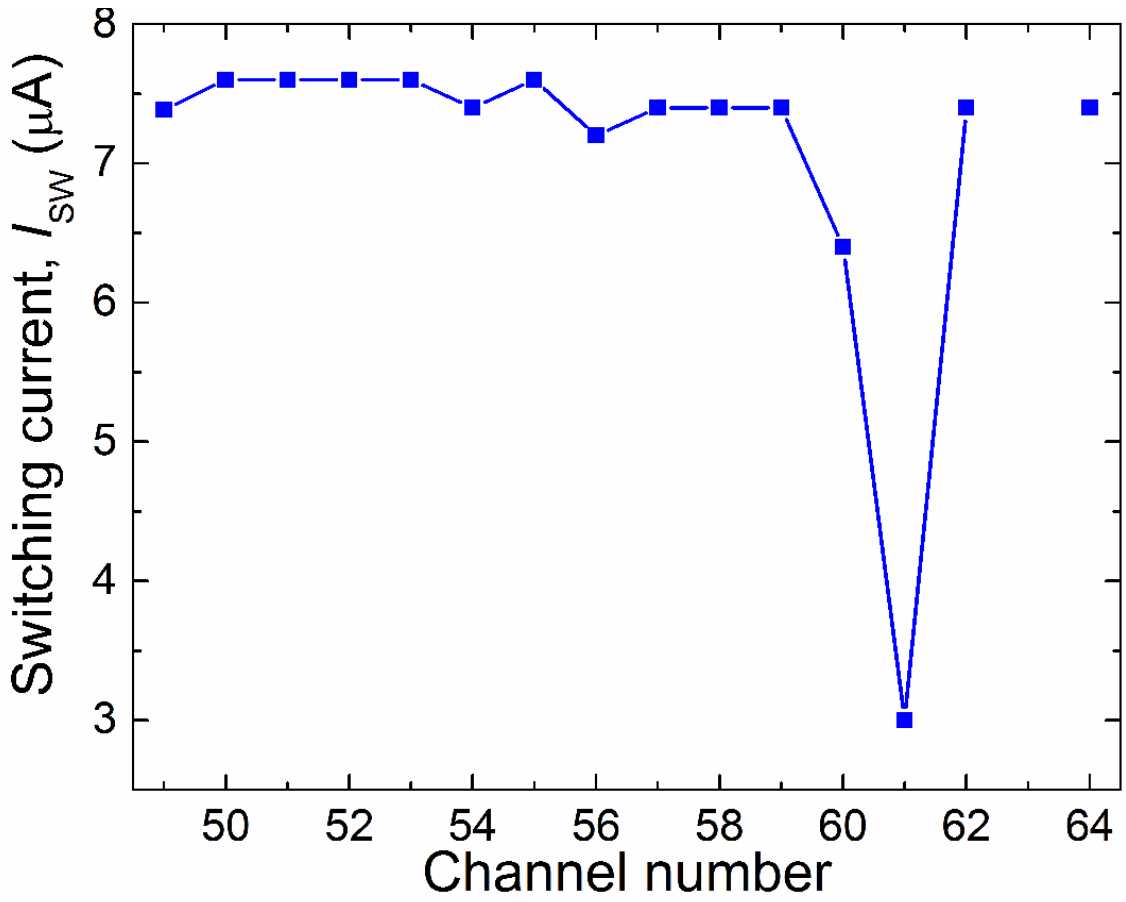
- In FY16, we have developed a prototype SNSPD array with high enough performance to use in end-to-end laboratory tests in advance of PDR
- 320-µm diameter active area, 4 active quadrants, 16 co-wound wires per quadrant
- 10% nanowire fill factor: 4.5 x 160 nm wires on a 1.6 µm pitch
- ~55% efficiency measured on a single quadrant, 31 out of 32 measured nanowires are working
- Meets DSOC project requirements for maximum count rate, timing jitter, and dark counts
- More work is needed to develop array with high efficiency at a wide cone of angles



64-pixel WSi SNSPD array with 320-µm active area

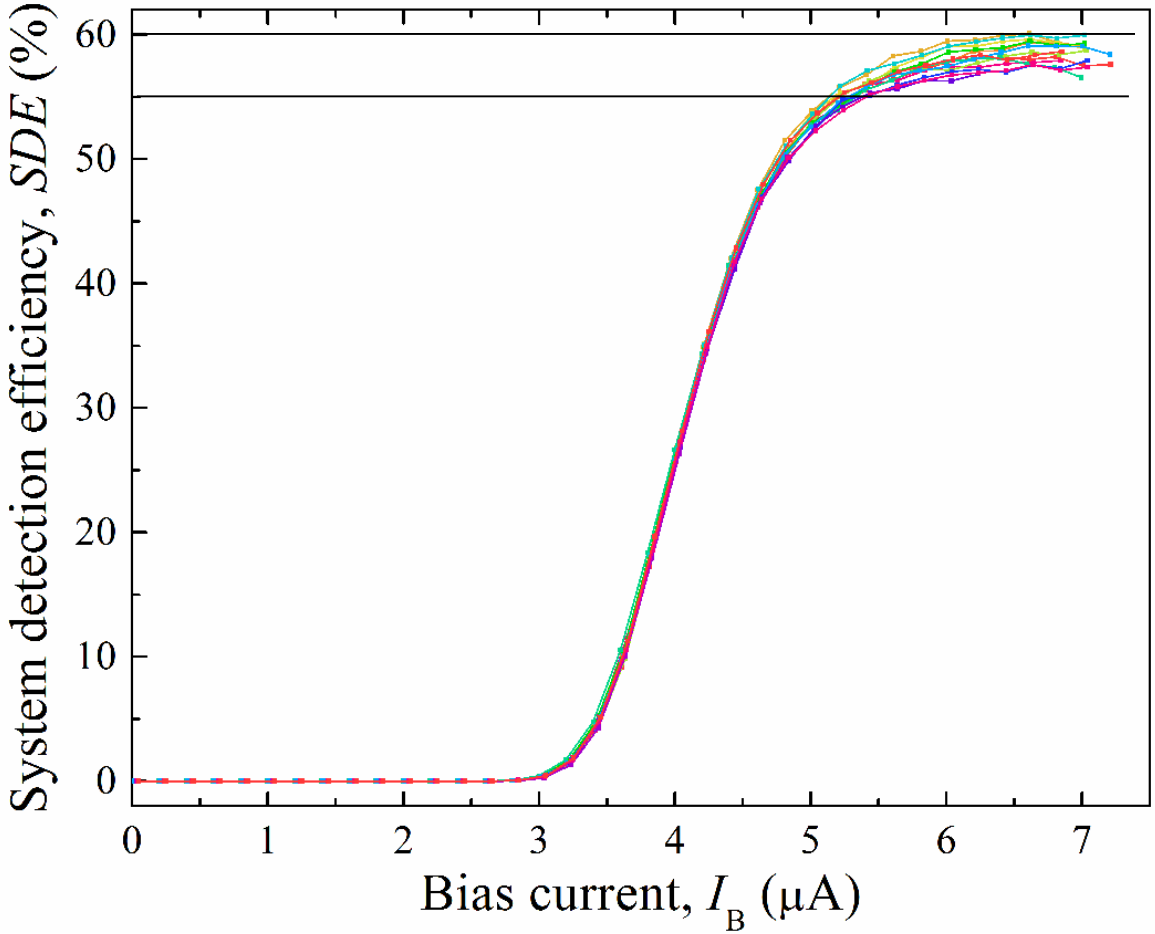
SEM image of 64-pixel 320-µm array

Switching Current Measurements



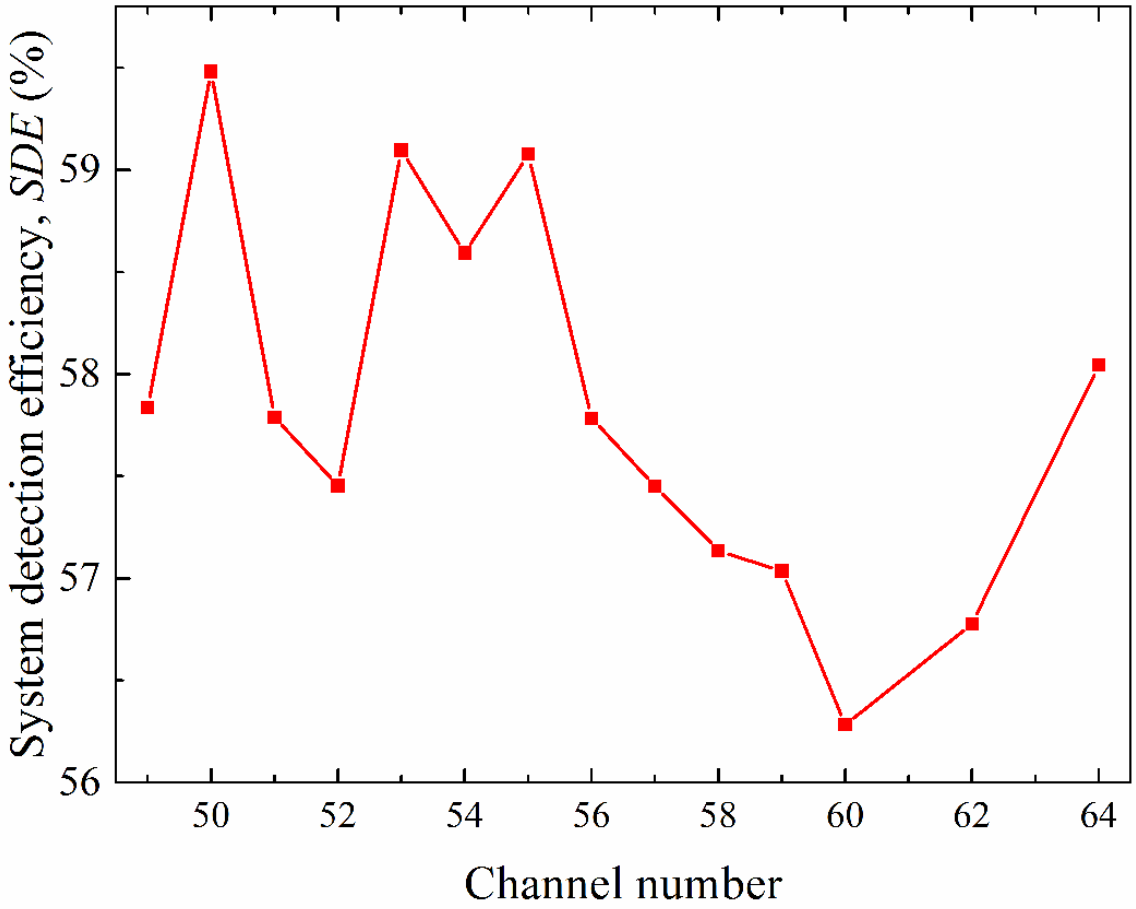
- Switching currents are very uniform, indicating high device uniformity across the array
- Operating current can be high enough to enable high-SNR readout
- 31 out of 32 devices are working properly

Efficiency Measurements



- 30 out of 32 measured pixels are working (14 are shown here)
- Total quadrant efficiency is 55%, measured with slow f/4 beam (theory predicts 76%)
- Measurement is not properly calibrated, numbers should be treated as preliminary

Efficiency Measurements



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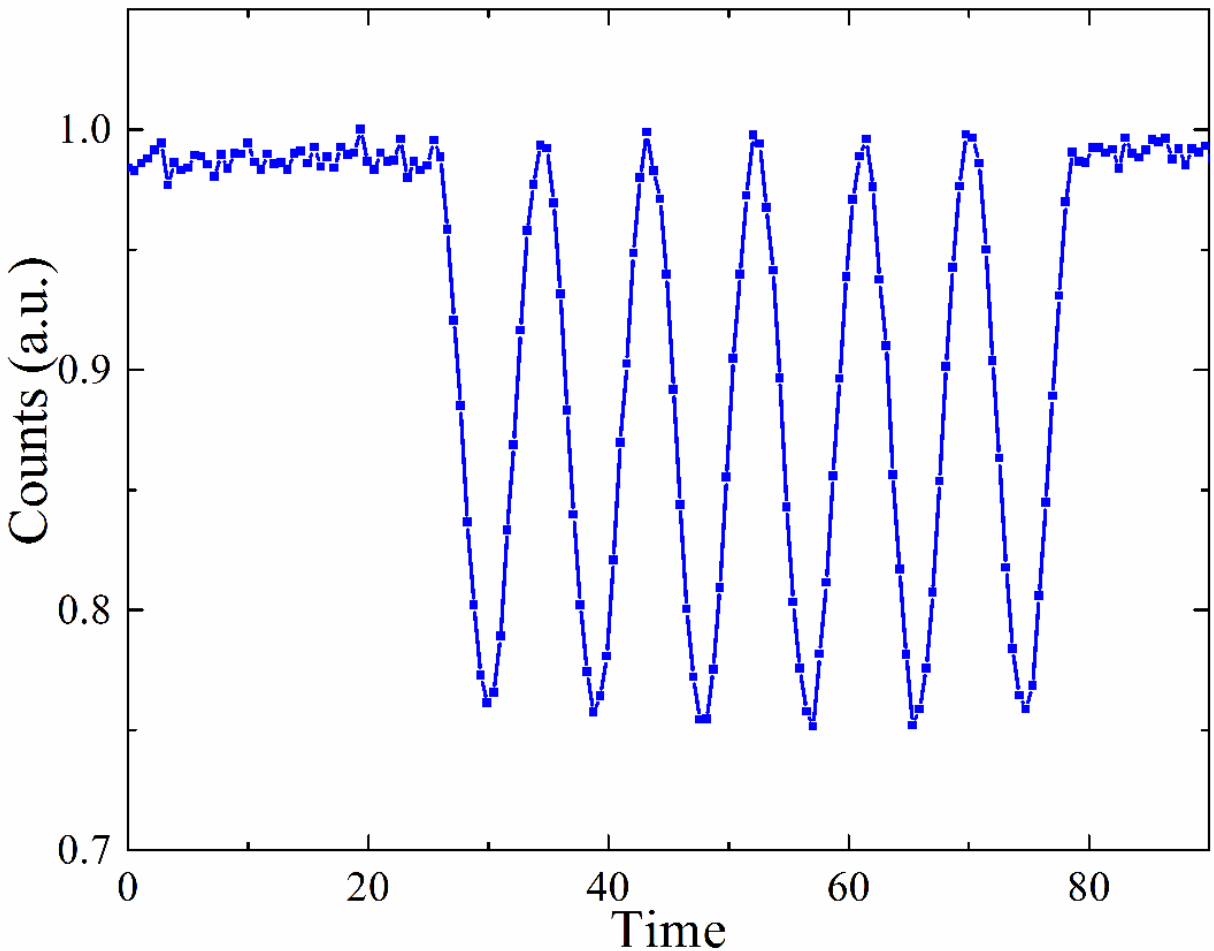
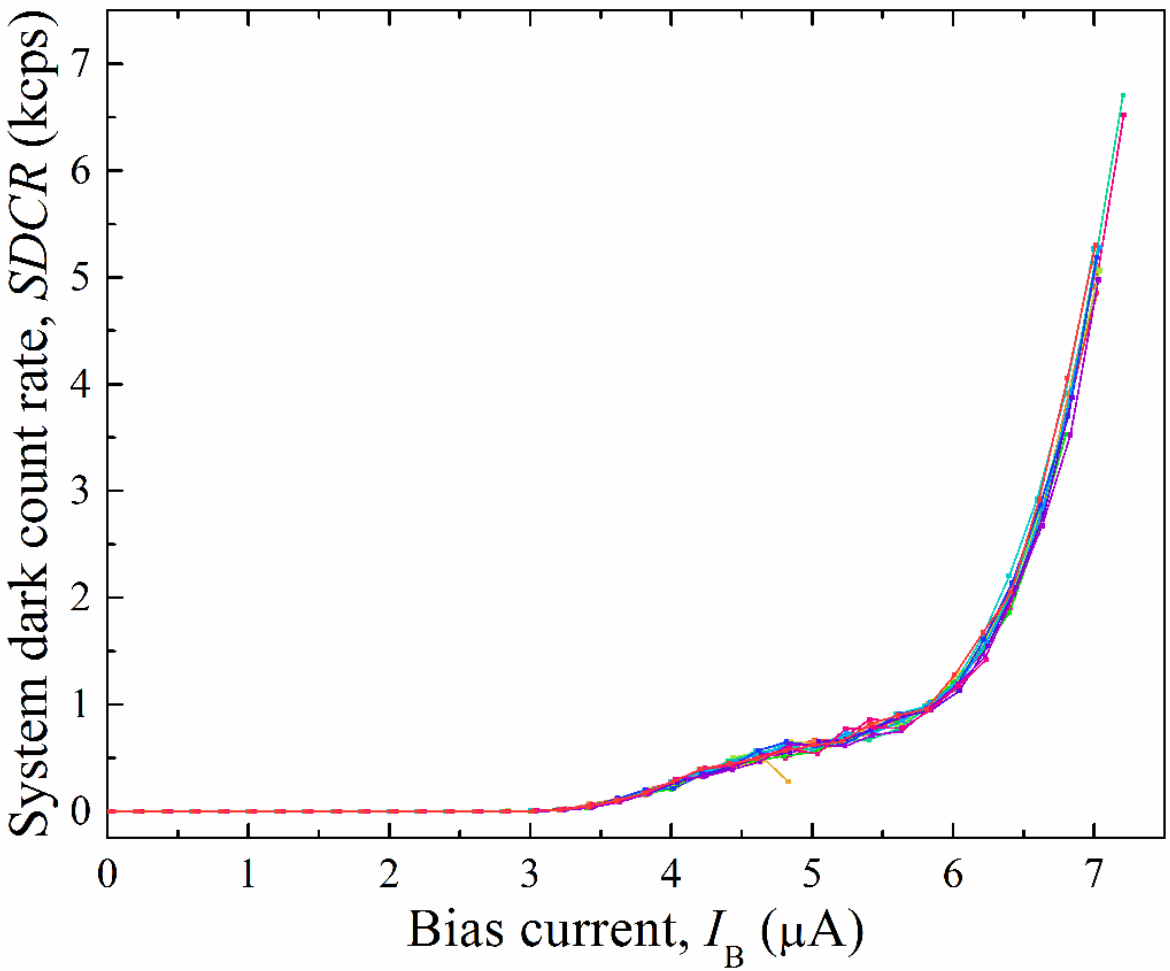
Polarization Dependence of Efficiency



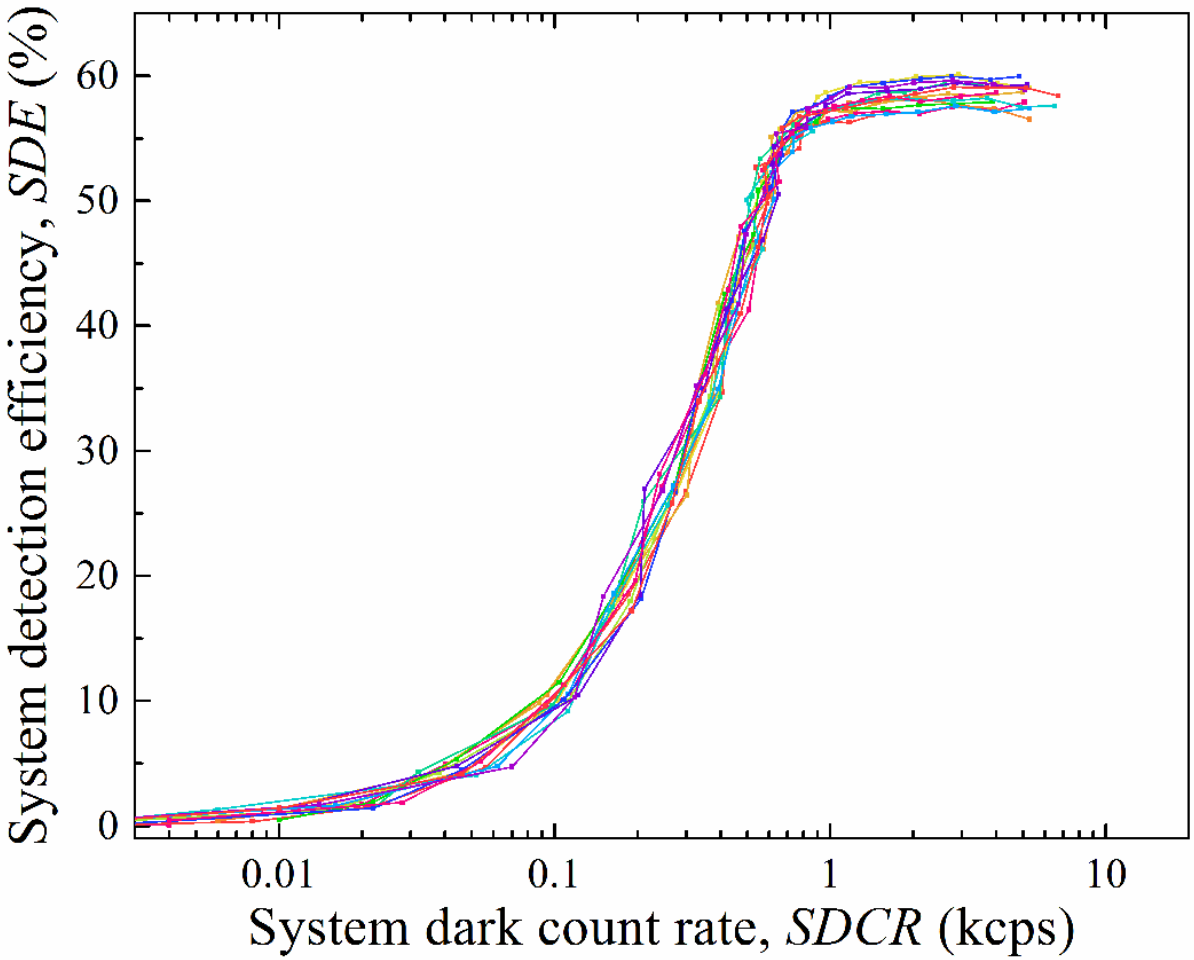
- 25% variation between TE and TM polarizations
- RCWA theory predicts only 18% variation between polarizations

Dark Counts vs Bias



- ~ 1 kcps *per pixel* at the back of the plateau (background limited)
- 6-7 kcps per pixel at the front of the plateau (intrinsic)
- < 10 kcps per pixel required for DSOC

Dark Counts vs Bias



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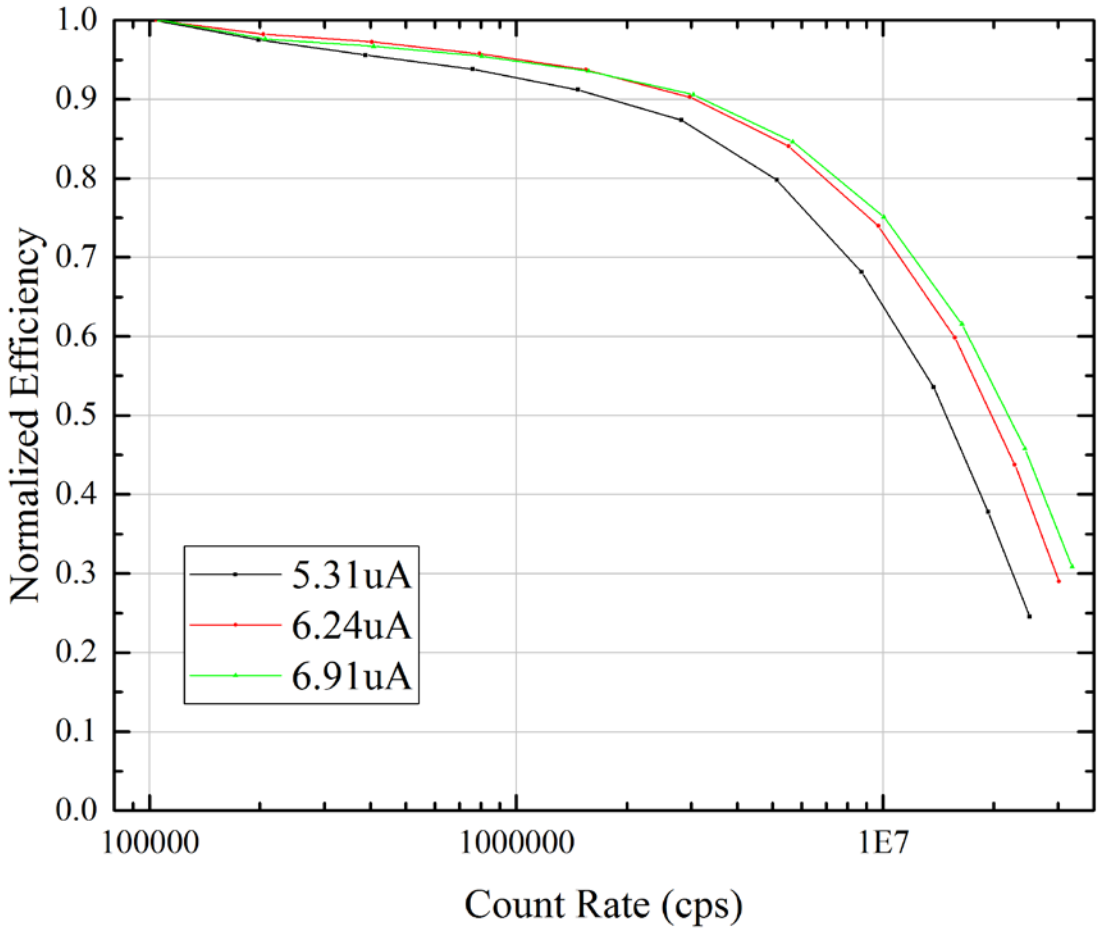
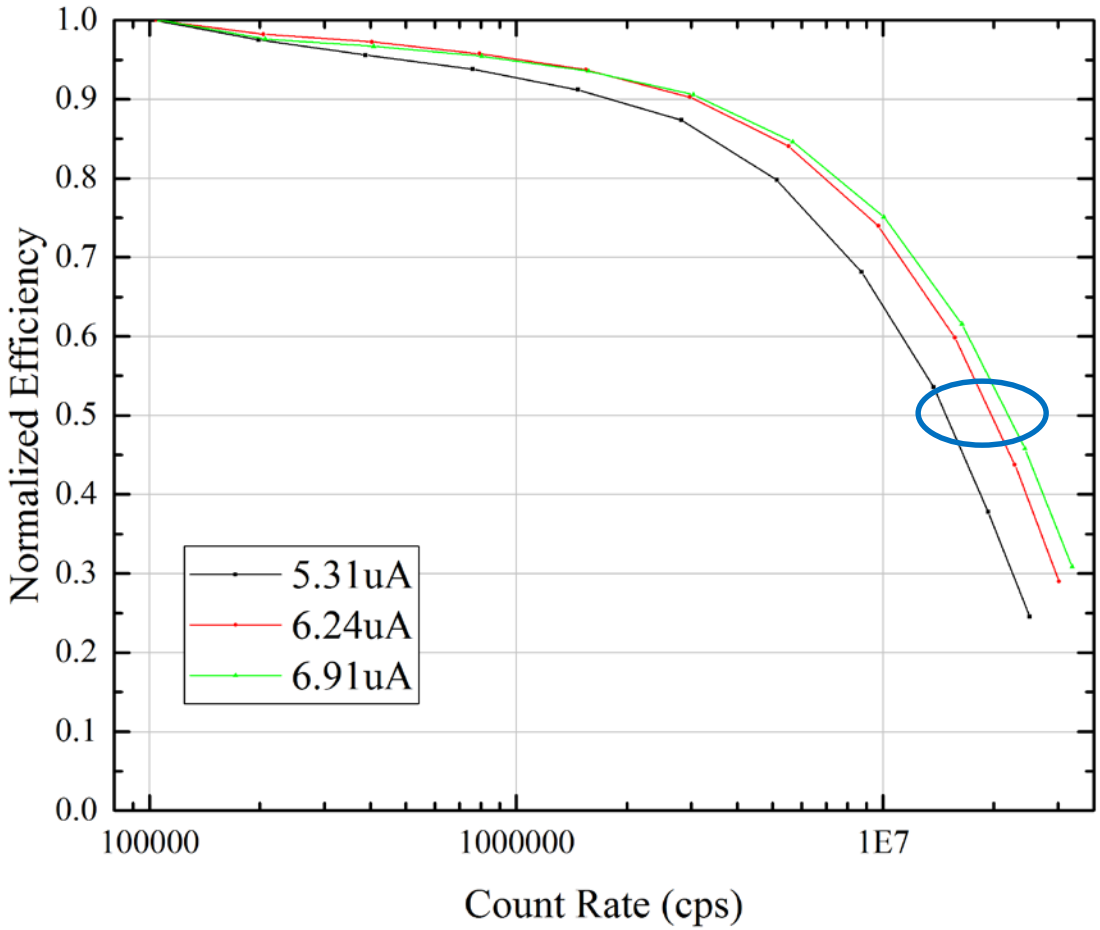
Maximum Count Rate



- 3dB MCR of 15 Mcps at the back of the plateau, 22 Mcps at the front
- Data taken through prototype DC coupled cryogenic amplifier chain at 40K (crucial)
- For 60 working pixels, this gives an array MCR of 900 Mcps at the back, 1.3 Gcps at the front

Maximum Count Rate



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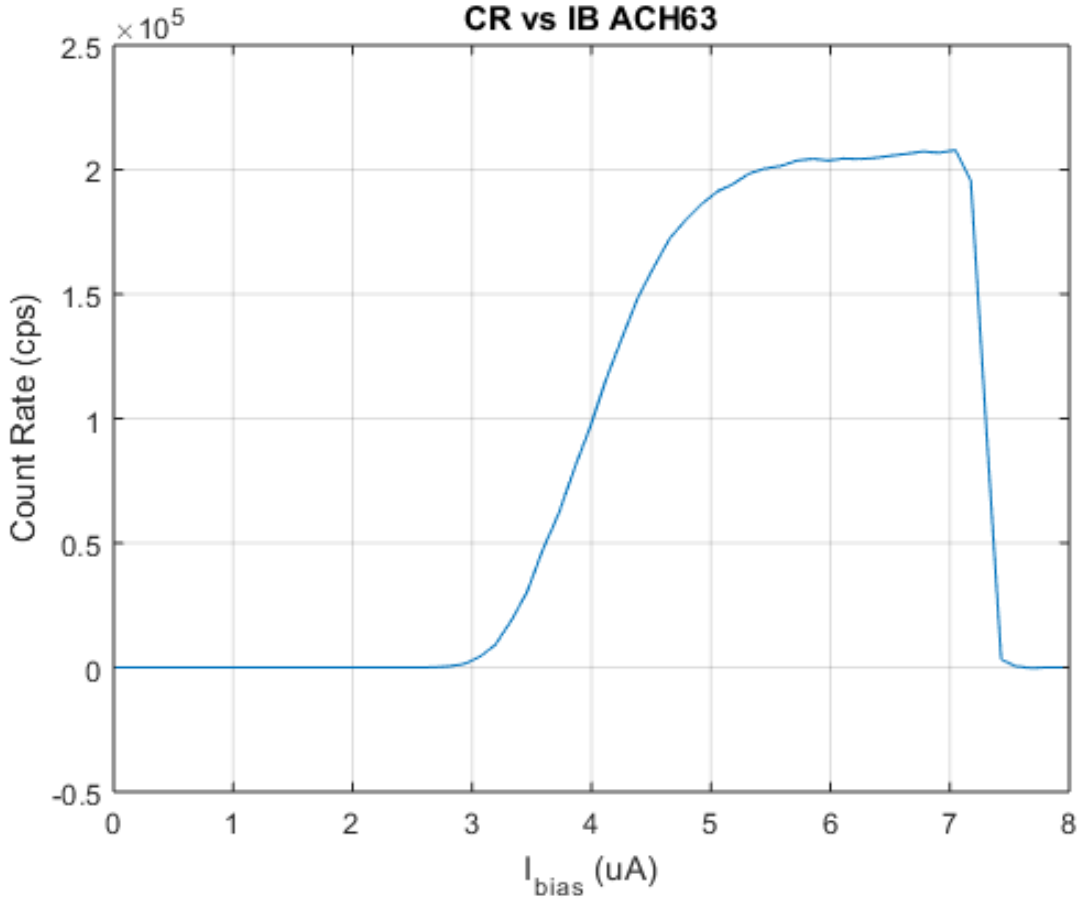
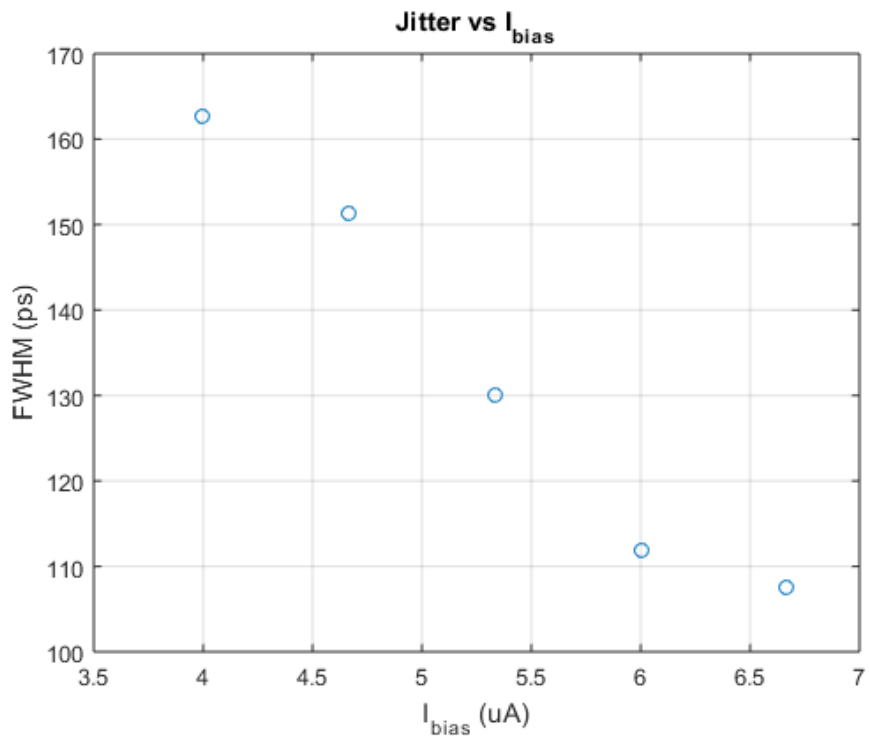
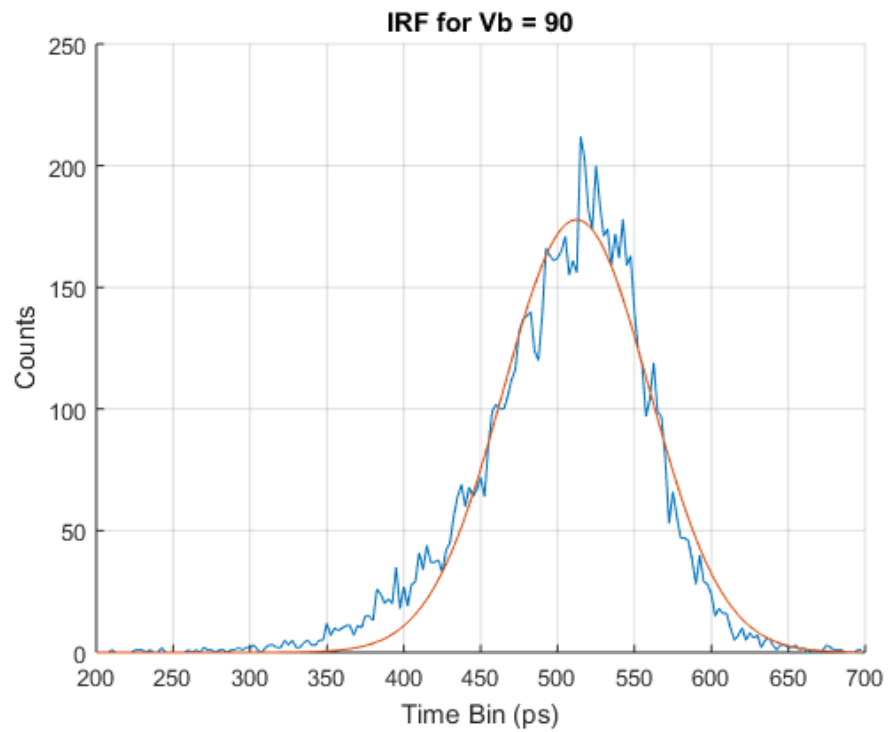
Counts vs. bias through cryoamps



- Count rate vs. bias curve shows plateau through cryogenic amplifier
- Device does not enter regime of relaxation oscillation
- Current splitting through amplifier circuit appears negligible

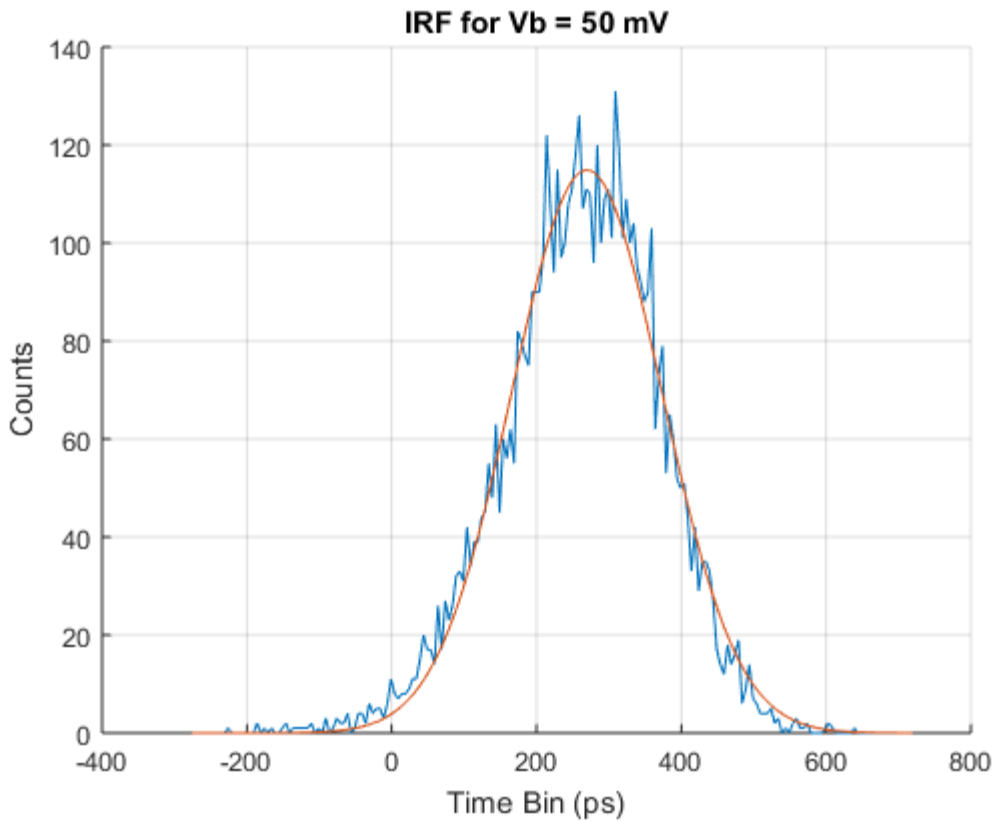
Timing Jitter through Cryoamps





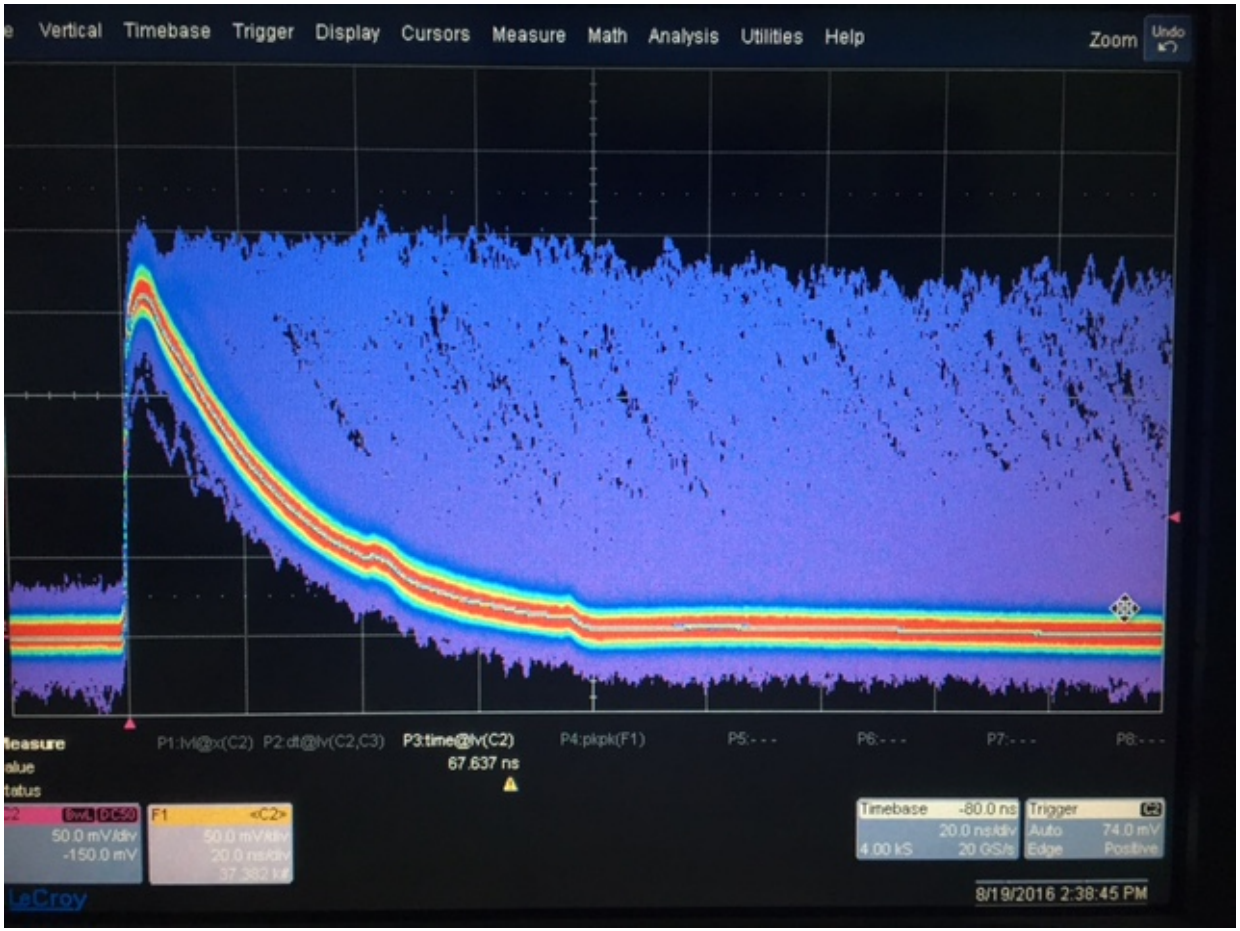
- Timing jitter 162 – 108 ps FWHM across the plateau, or 69 – 46 ps 1-sigma
- Easily meets DSOC requirement of 150 ps 1-sigma
- Non-Gaussian behavior of tails is likely due to non-uniform polarity response of amplifier
- Scaling suggests that readout SNR is the dominant jitter mechanism
- SNSPD jitter is negligible in RSS with jitter in Voxtel TDC (~200 ps)

Timing Jitter through 300K amplifiers



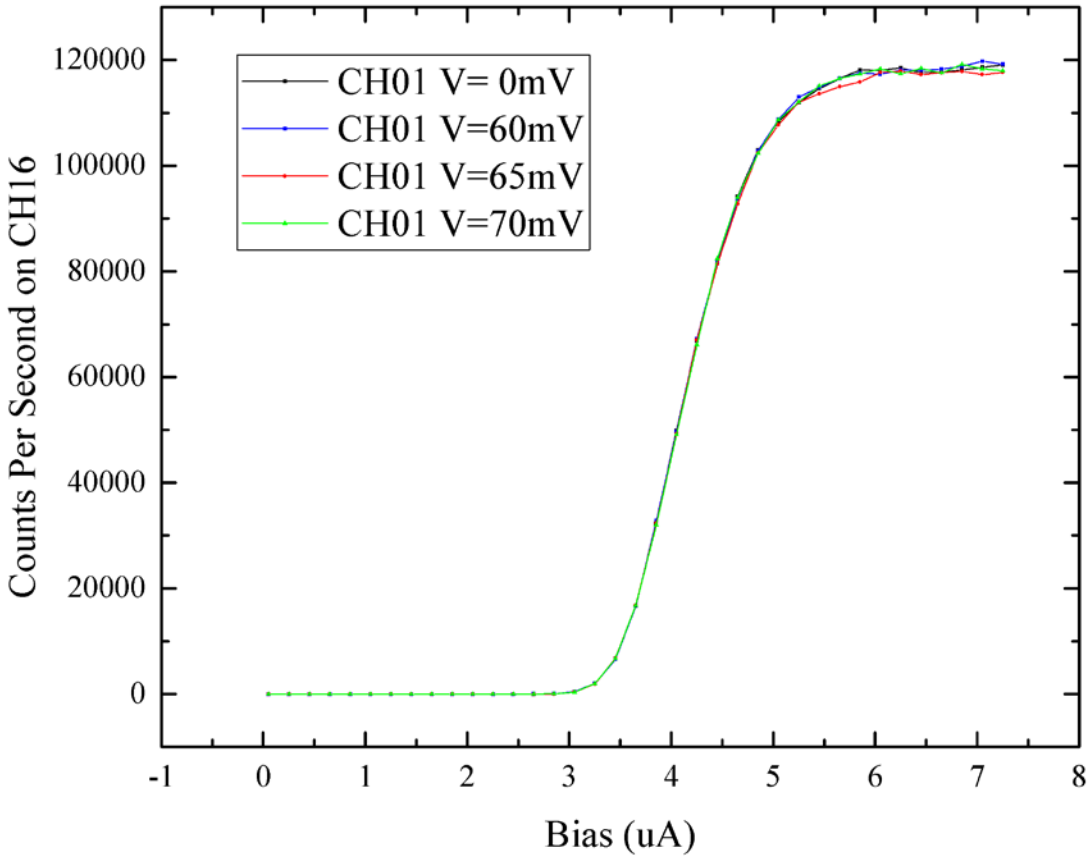
- Room temperature 2x mini-circuits ZFL-1000LN+ amplifier chain
- Gaussian tails are restored
- Jitter is 244 ps FWHM, or 104 ps 1-sigma

No Measurable Afterpulsing



- No afterpulsing is observable from persistence traces (shown) or interarrival time histogram
- Some latching effects are seen at the highest bias currents, but not enough to impact MCR

No Measurable Crosstalk

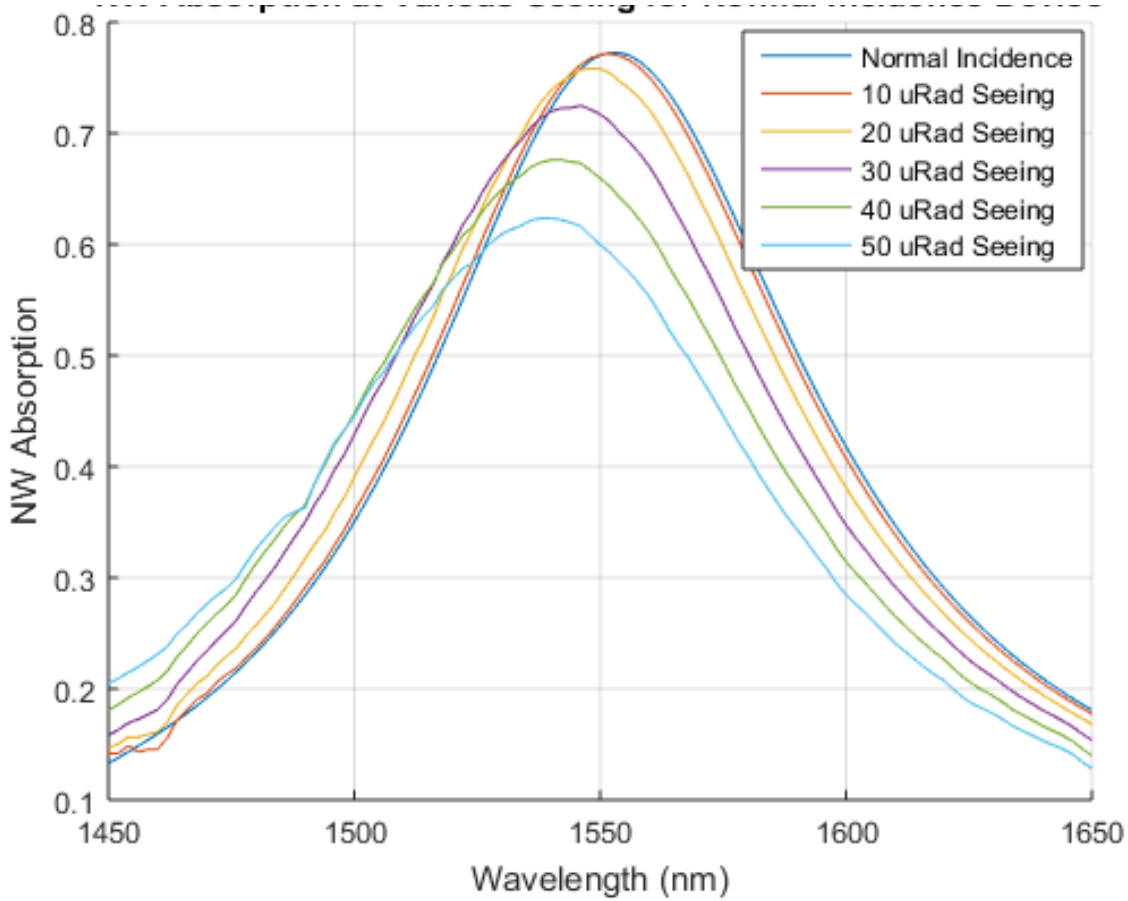


- No crosstalk is observed with 10% nanowire fill factor co-wound arrays
- Severe crosstalk was observed with 20-40% fill factor co-wound arrays
- No crosstalk was observed with 20-40% fill factor “pizza” arrays
- In 2014, no crosstalk was observed with 160-µm 40% fill factor “rectangular” arrays

Challenges Overcome

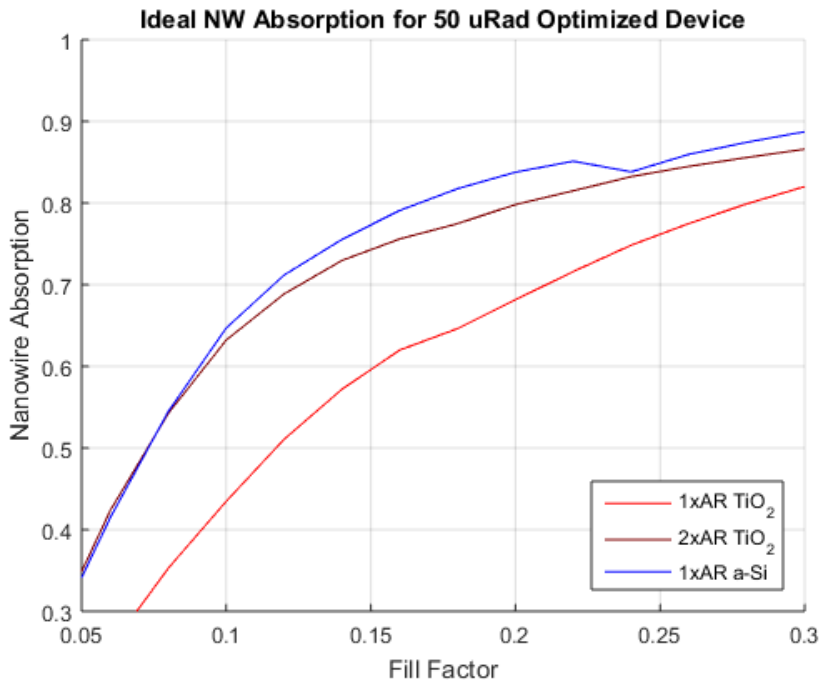
- **Anomalous series resistance in device leads (FY15)**
  - Caused detectors to afterpulse and latch
  - Solved by switching to superconducting Nb leads
- **Poor device yield, many constricted wires in array**
  - Problem was traced to resist process used to pattern leads
  - Solved in short term by using a discontinued resist (ARCH 8250)
  - Process development continues to find a sustainable solution
- **Low switching currents, lack of plateau**
  - Mastery of wire dimensions and WSi deposition parameters (stress, thickness, etc)
  - Deposition in a shared sputtering chamber makes this problem still unresolved
- **Severe crosstalk between wires**
  - Extensive study revealed that crosstalk was thermal rather than electrical in nature
  - Solved by reducing nanowire fill factor to 10% and/or using “pizza” geometry
- **Low maximum count rate**
  - Developed DC-coupled cryogenic amplifier chain

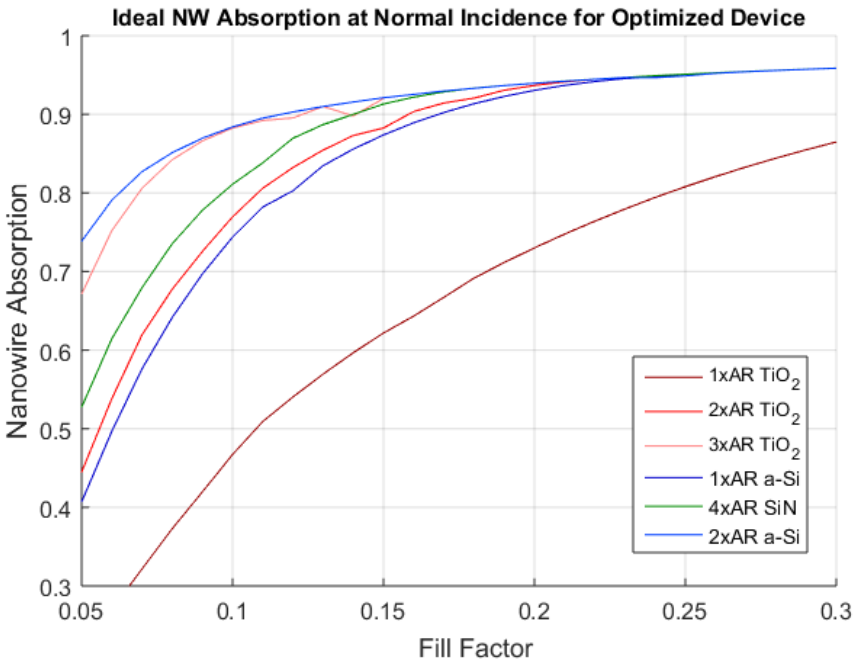
Predicted Behavior for Realistic Beams



- Theoretical optical absorption in nanowires for TE polarization, optimized 2x TiO2 AR coating
- RCWA theory includes diffraction effects, typically overestimates efficiency by ~7%
- Theory estimates 77% for perfectly collimated beam at 1550nm, 60% at 50 µrad seeing.
- Suggests this design will **not** meet 50% efficiency requirement for realistic seeing conditions

Efficiency vs Fill Factor Tradeoff

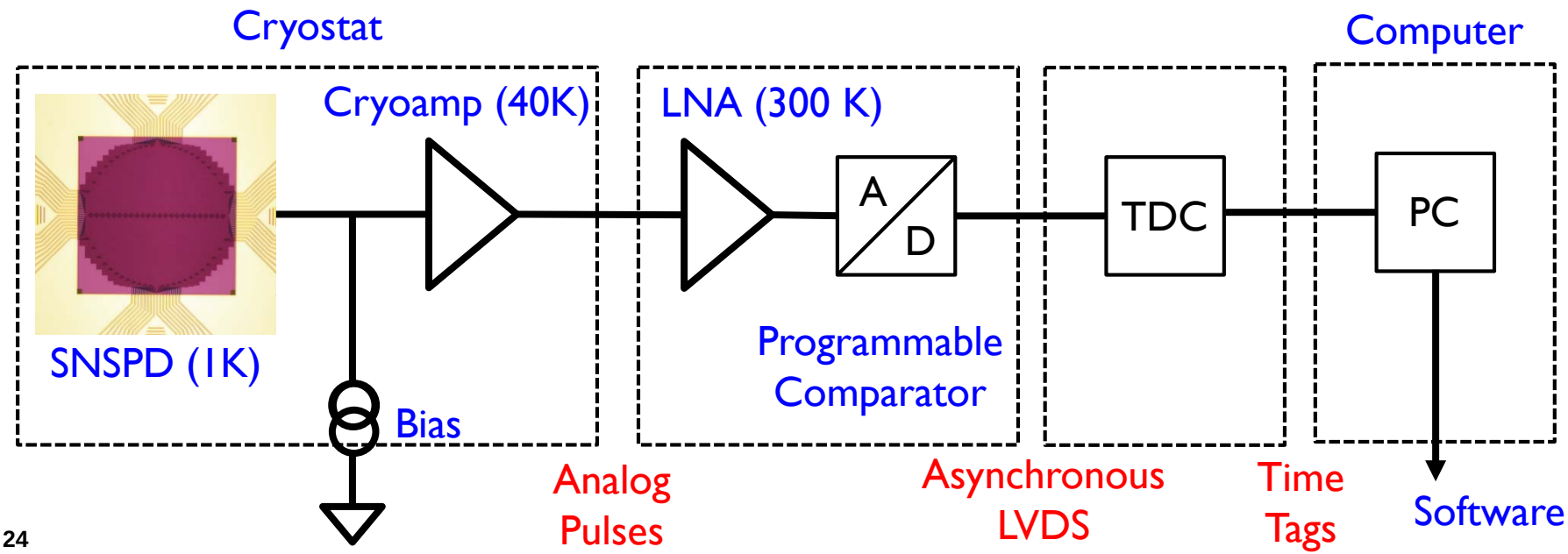




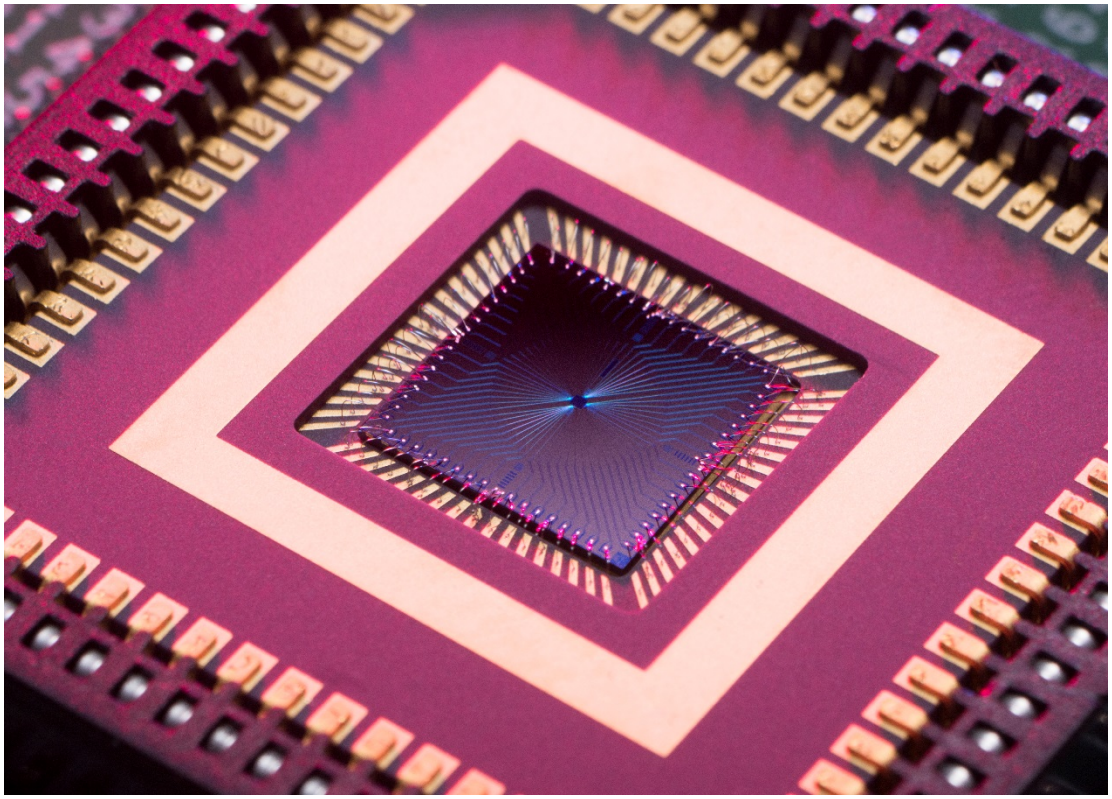
- RCWA simulations showing the tradeoff between efficiency and fill factor for fast and slow beams
- Efficiency falls quickly below 10% fill factor
- More advanced AR coatings can be used to recover efficiency at low fill factors (higher Q)

SNSPD Readout Concept

- Reading out a 64-pixel SNSPD array is a nontrivial engineering challenge
- To maintain high time resolution and maximum count rate, each pixel requires its own readout channel with ~2 GHz bandwidth
- At the end of FY15, we switched from an approach based on cryogenic mixed-signal readout chips (custom SiGe “channel combiners”) to an FPGA-based 64-channel asynchronous time tagger concept, minimizing cryogenic electronics whenever possible
- This decision was made to minimize system complexity, risk, and cost to the DSOC project.
- We are now building a laboratory testbed to support end-to-end communication tests
- All testbed readout components will be in hand by the end of FY16



Conclusion



- SNSPD development for DSOC has come a long way since start of GCD funding in 2011
- Proof of concept SNSPD array suitable for DSOC is good enough for end-to-end testing
- Much work remains to be done to design, build, and field a ground detector instrument