National Aeronautics and Space Administration

Early Stage Technology Workshop

Astrophysics and Heliophysics

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Waveguide-Integrated MKIDs for on-chip cryogenic spectrometers in the infrared

Jet Propulsion Laboratory
Matt Shaw
Microdevices Engineer

TECHNOLOGY DRIVES EXPLORATION

Non-Proprietary

Company/Research Overview

- Jet Propulsion Laboratory, Pasadena, CA
- Founded 1936 by Caltech, under contract with NASA since 1958
- Federally Funded Research and Development Center (no block funding)
- > 5000 employees

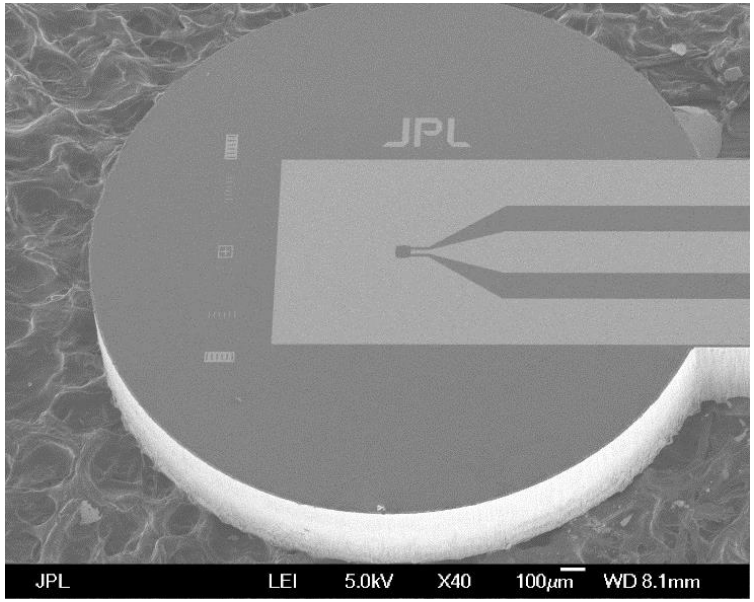
Overview of Technology

- Waveguide-integrated NIR MKIDs
- A building block toward an on-chip cryogenic spectrometer in the NIR (1 – 5 μm)
- TRL-1
- Represents the first step toward a practical, robust technology for making low-cost, low-mass cryogenic spectrometers in the NIR.

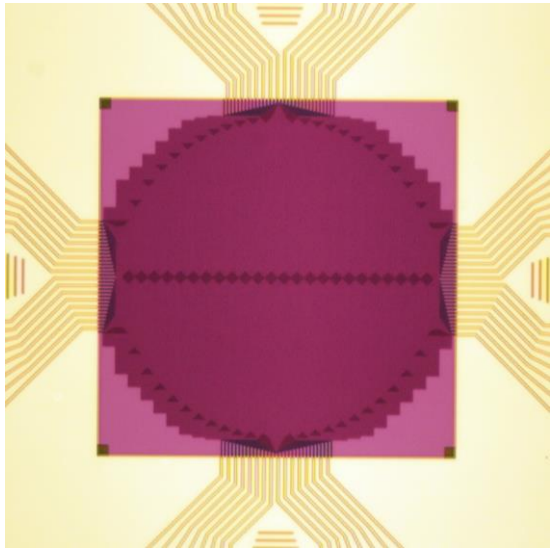
Superconducting WSi Nanowire Detectors

Superconducting Nanowire Single Photon Detectors

- Time correlated single photon counting, UV-5 µm
- > 90% efficiency at 1.5 µm
- ~100 ps time resolution
- Sub-Hz intrinsic dark rates
- 40 ns dead time
- Arrays as large as 64 pixels
- 1 K operating temperature
- Primary applications are space-based optical communication and quantum optics



Single-Pixel SNSPD Chip



64-pixel SNSPD Array

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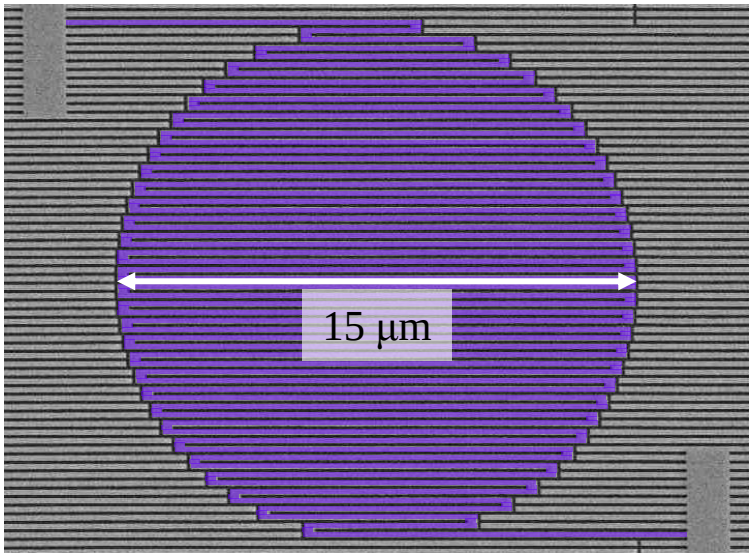
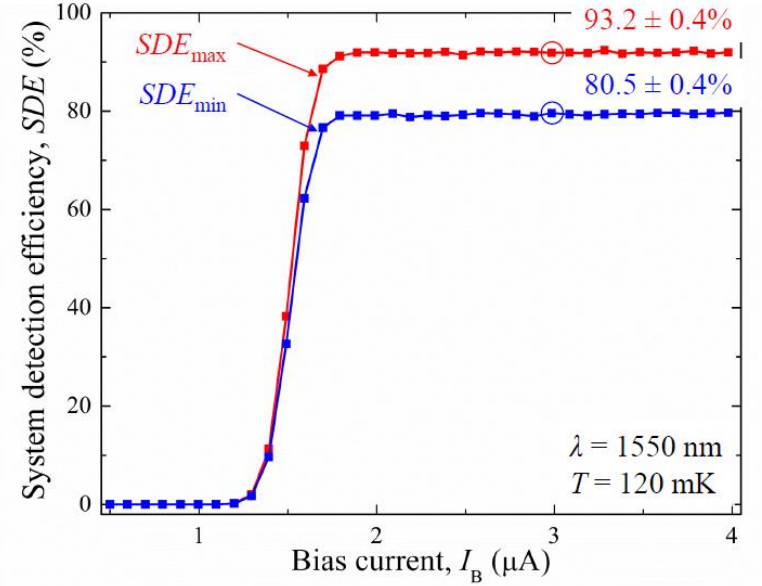
- Primary applications are space-based optical communication and quantum optics
- No intrinsic energy resolution



Single-Pixel SNSPD Element



Non-Proprietary

Currently Funded Projects

SNSPD

Integrated Photonics

MKID

Deep Space Optical Communication

Large-format SNSPD arrays for optical communication demonstration ground terminal

320-micron, 64-256 pixel SNSPD arrays

Free-space coupling

Cryogenic readout electronics

Quantum Key Distribution

Fiber-coupled arrays for high-rate counting over telecom fiber

All-optical nanowire fabrication process (optical lithography of nanowires)

Jointly funded with NIST Boulder

Supporting work toward a quantum communication demonstration from ISS

High Operating Temperature SNSPDs

Developing MgB2 SNSPDs for operation in the ~25K range

Tc of HPCVD deposited thin films is 36K

Opens up many new opportunities for airborne and space applications

UV SNSPDs Quantum Computing

Developing SNSPDs in optical cavity optimized for 370 nm

Integrating with ion traps in the same cryostat

Jointly funded with NIST

Eventually will try to integrate with ion chips directly

Cryogenic Readout Circuits

Custom SiGe MMIC performing A/D conversion and digital logic at 40K stage on 8 GHz clock

Superconducting nanocryotron logic

Commercialization

Collaborating with two US small businesses to help commercialize WSi SNSPD technology

Waveguide Devices

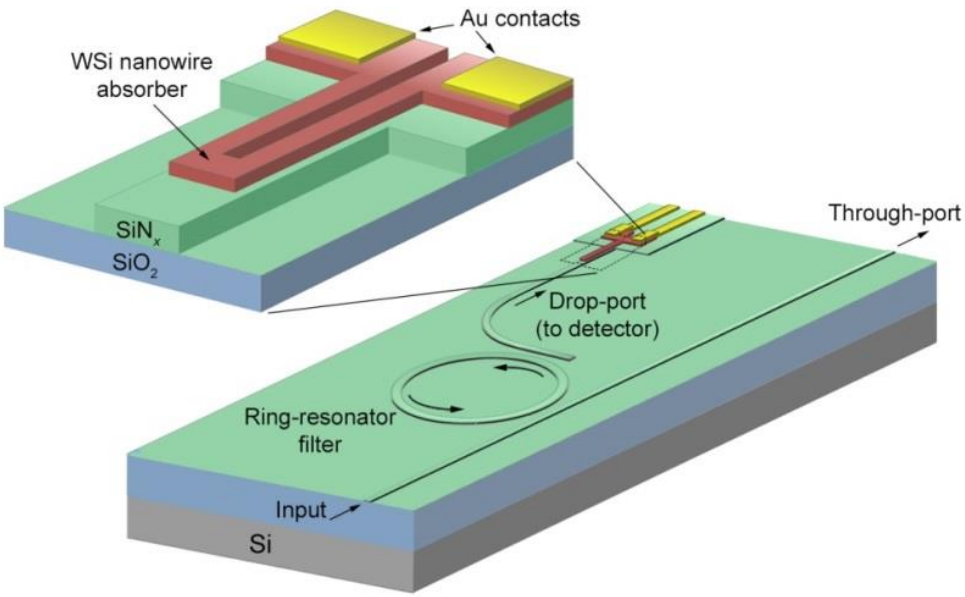
Waveguide SNSPDs for wavelength multiplexed quantum communication

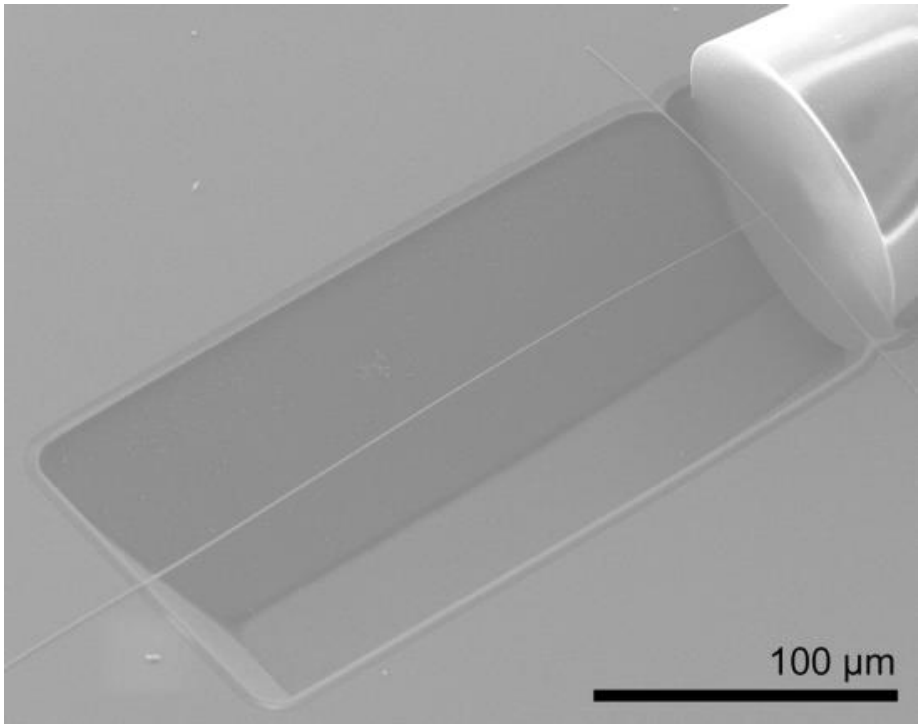
Waveguide MKIDs for on-chip mid-IR cryogenic spectrometer

Lunar Ranging

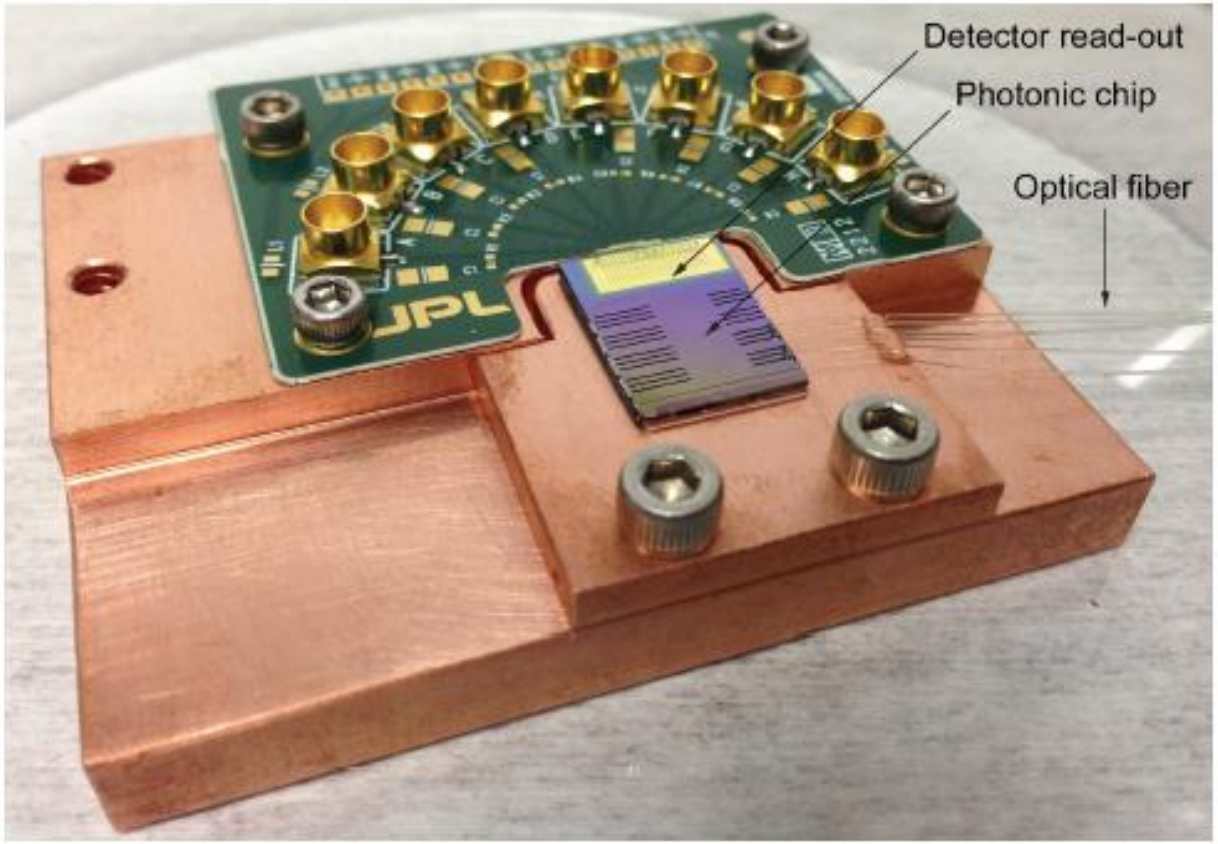
On-chip Waveguide Integrated SNSPDs

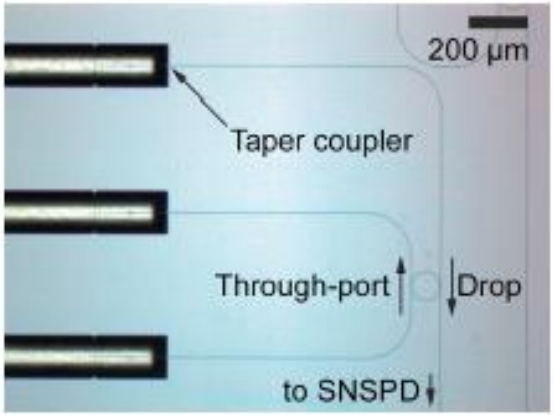
- WSi SNSPDs coupled to SiN waveguide photonics platform
- Integration with low-loss broadband optical couplers (Collaboration w/ Painter Group, Caltech)
- Integration with on-chip ring resonators or echelle grating to form channelizing spectrometer or DWDM receiver for QKD
- Can realize a robust, on-chip cryogenic spectrometer, particularly in the mid-IR
- Promising preliminary results

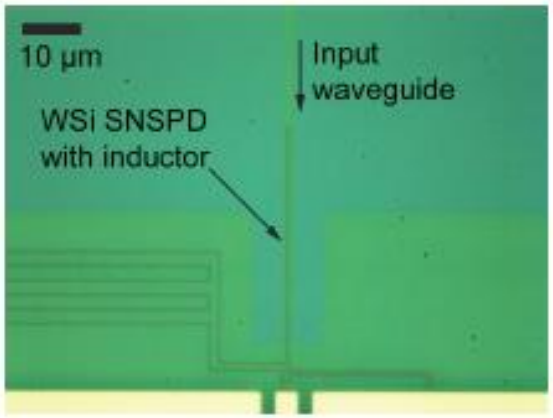




On-chip Waveguide Integrated SNSPDs







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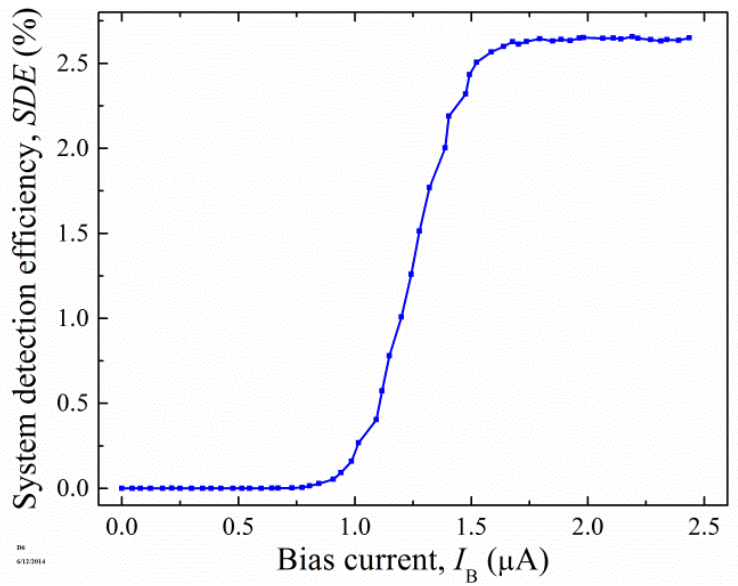

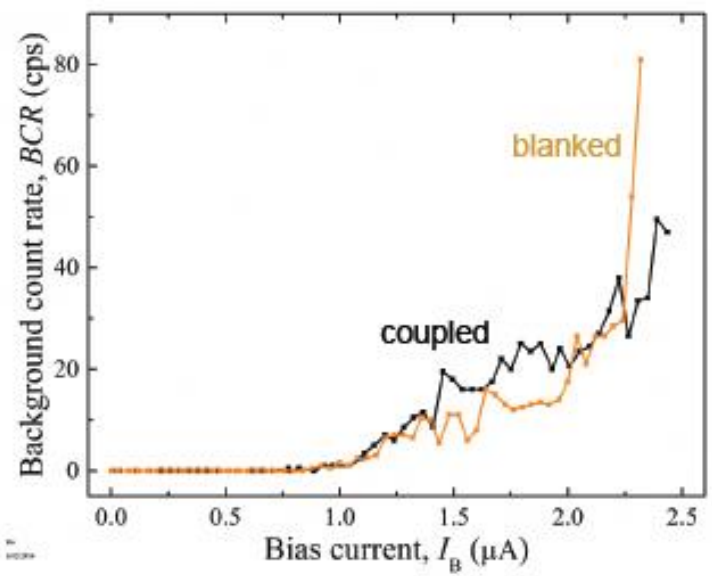

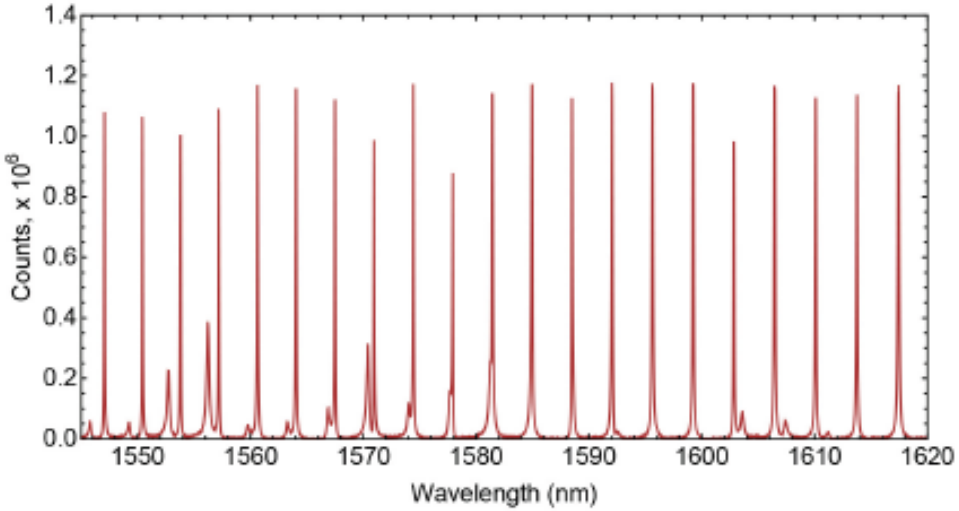

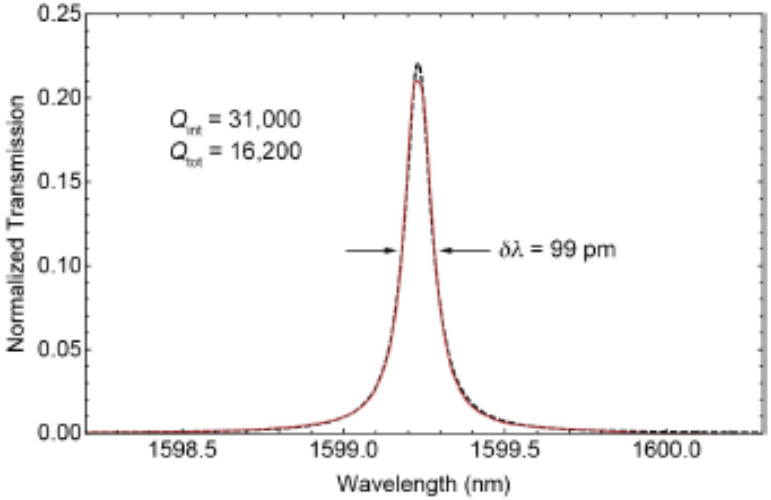

Applications of Waveguide Detectors

- **Wavelength-multiplexed receivers for quantum communication**
- **On-chip heralded single photon sources**
- **On-chip cryogenic spectrometers**

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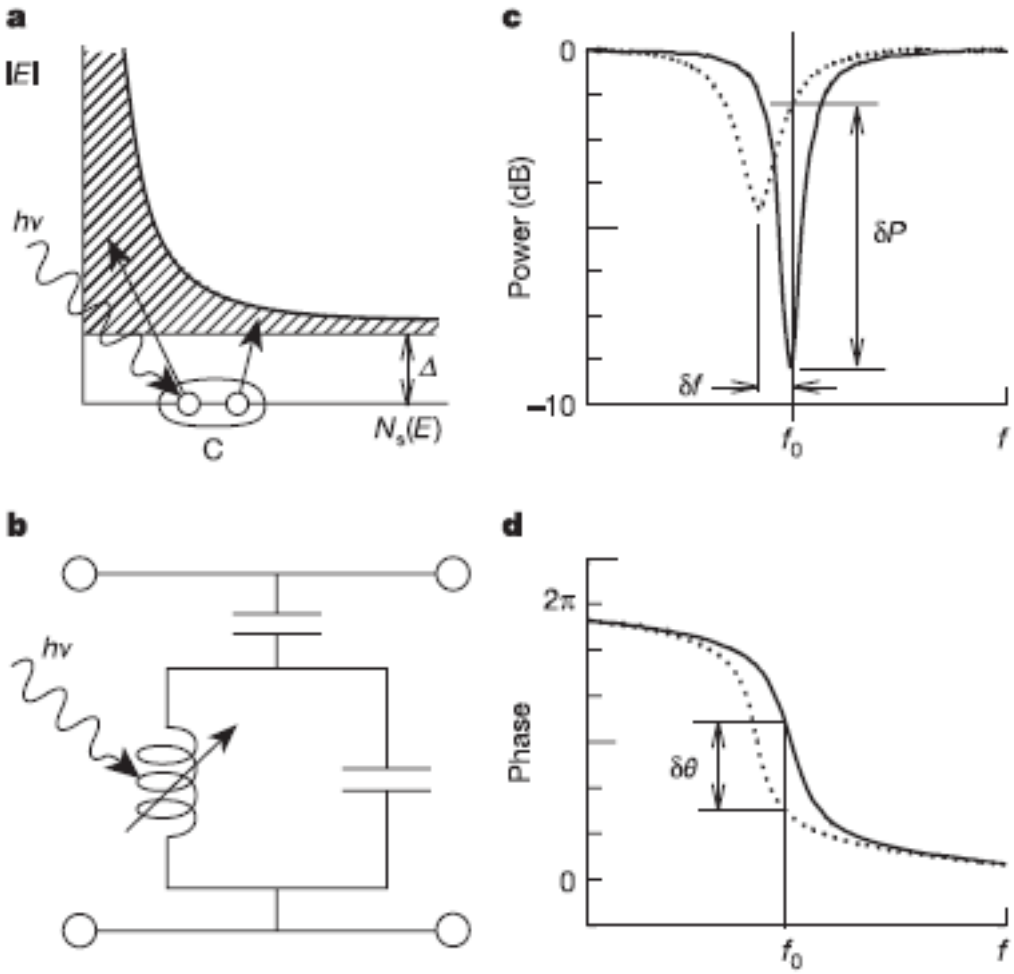
- **On-chip heralded single photon sources** **SNSPD**
- **On-chip cryogenic spectrometers**

Applications of NIR Waveguide Detectors

- **Wavelength-multiplexed receivers for quantum communication** **SNSPD**
- **On-chip heralded single photon sources** **SNSPD**
- **On-chip cryogenic spectrometers** **MKID**

Microwave Kinetic Inductance Detectors



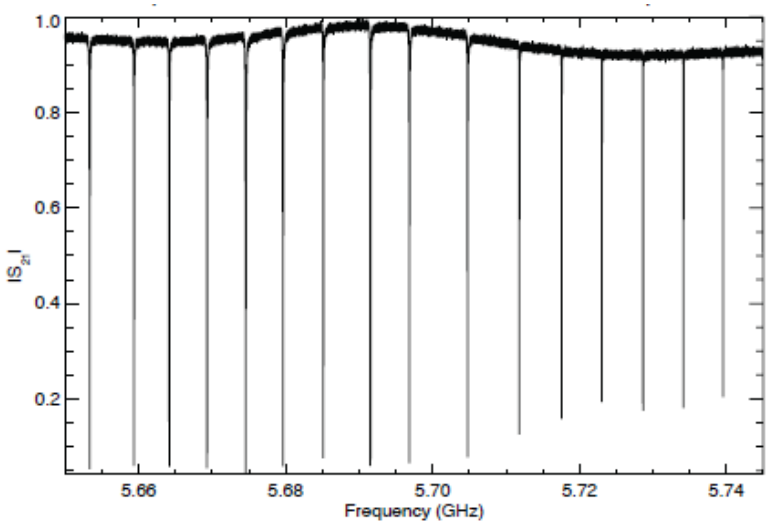
Day et al, *Nature* (2003)

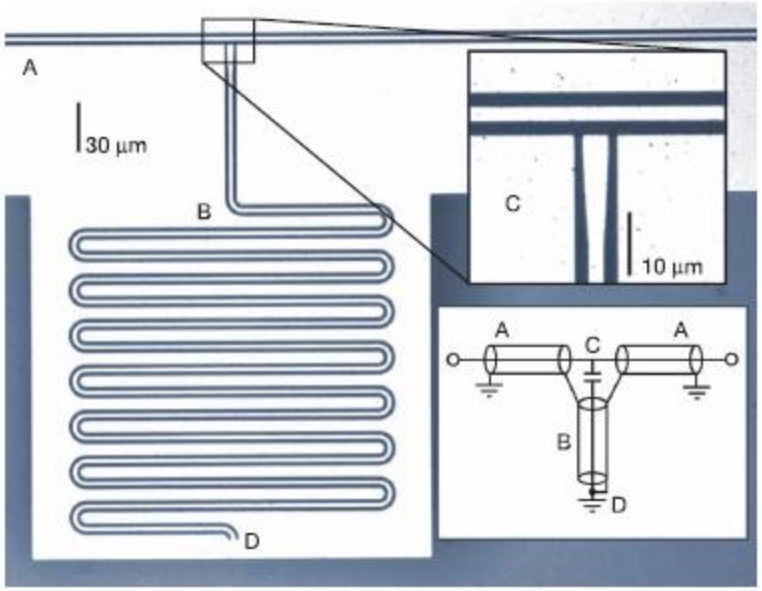
Microwave Kinetic Inductance Detectors

- Frequency multiplexing allows thousands of superconducting detectors to be read out through a single RF feedline

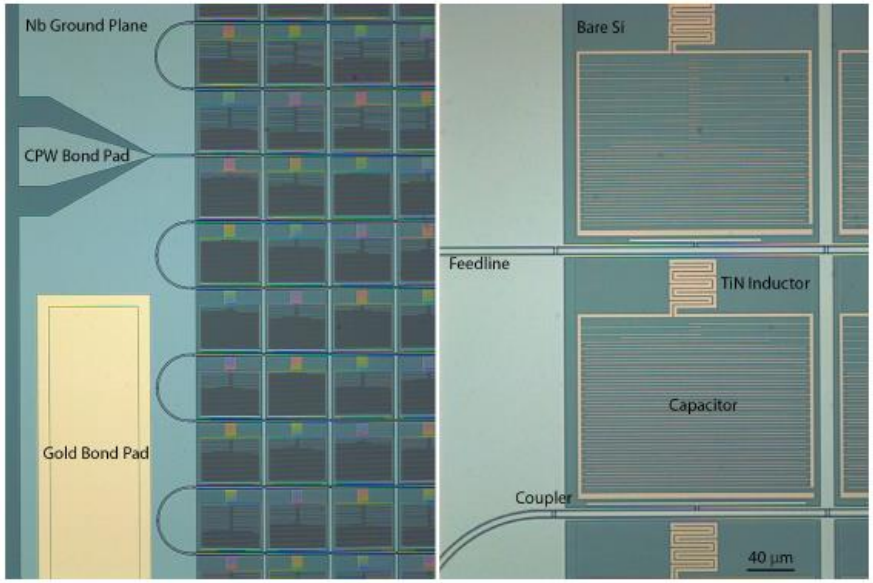
- NEP ~10^{-19}, Single photon counting in the NIR

- > 10 years of development in submillimeter and optical astronomy





Early MKID, JPL / Caltech

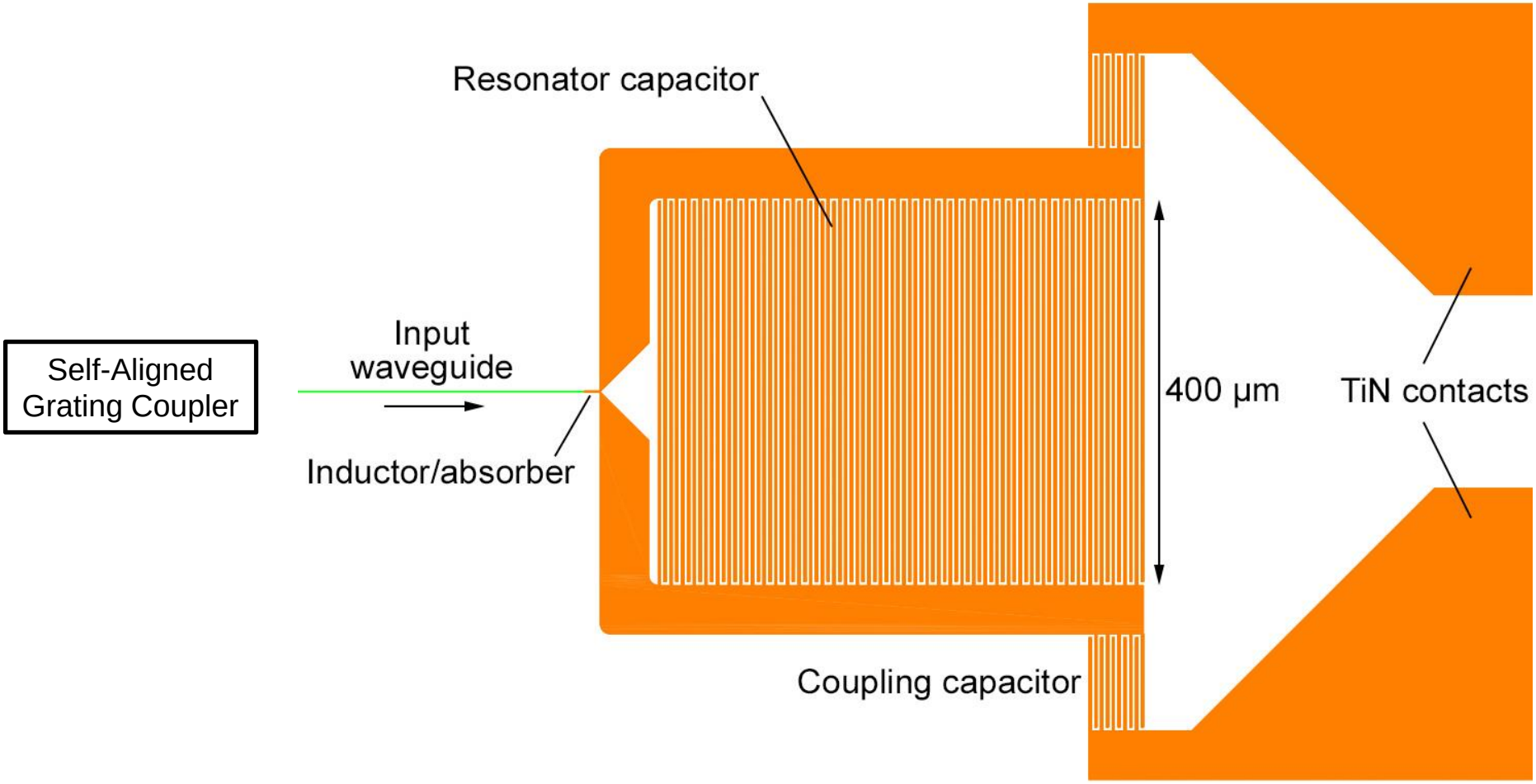


2024 Pixel MKID Array, Mazin Group, UCSB

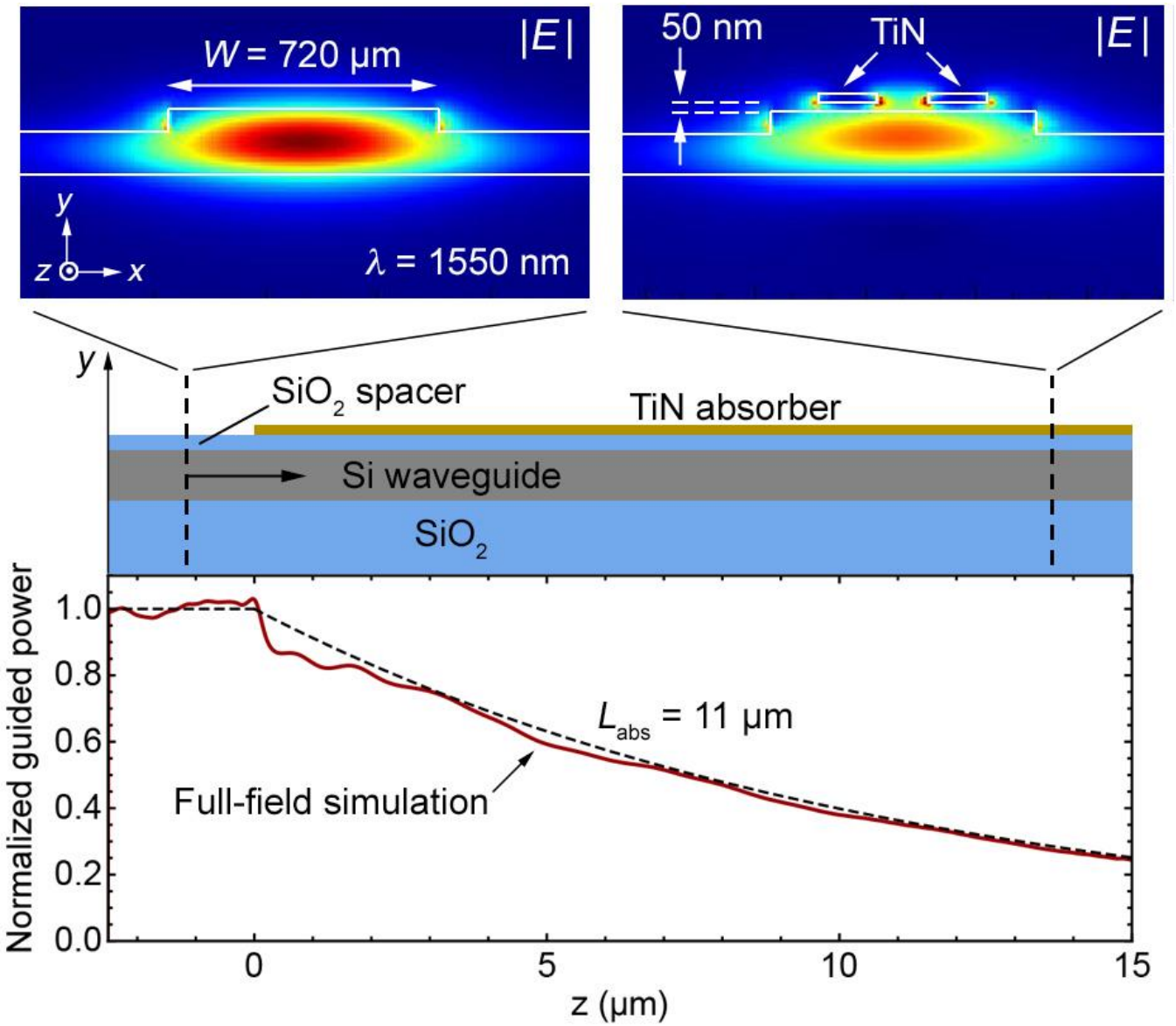
Non-Proprietary

Waveguide-integrated MKIDs

- MKID fabricated on silicon waveguide towards a NIR on-chip spectrometer
- Funded by STMD Center Innovation Fund (CIF)

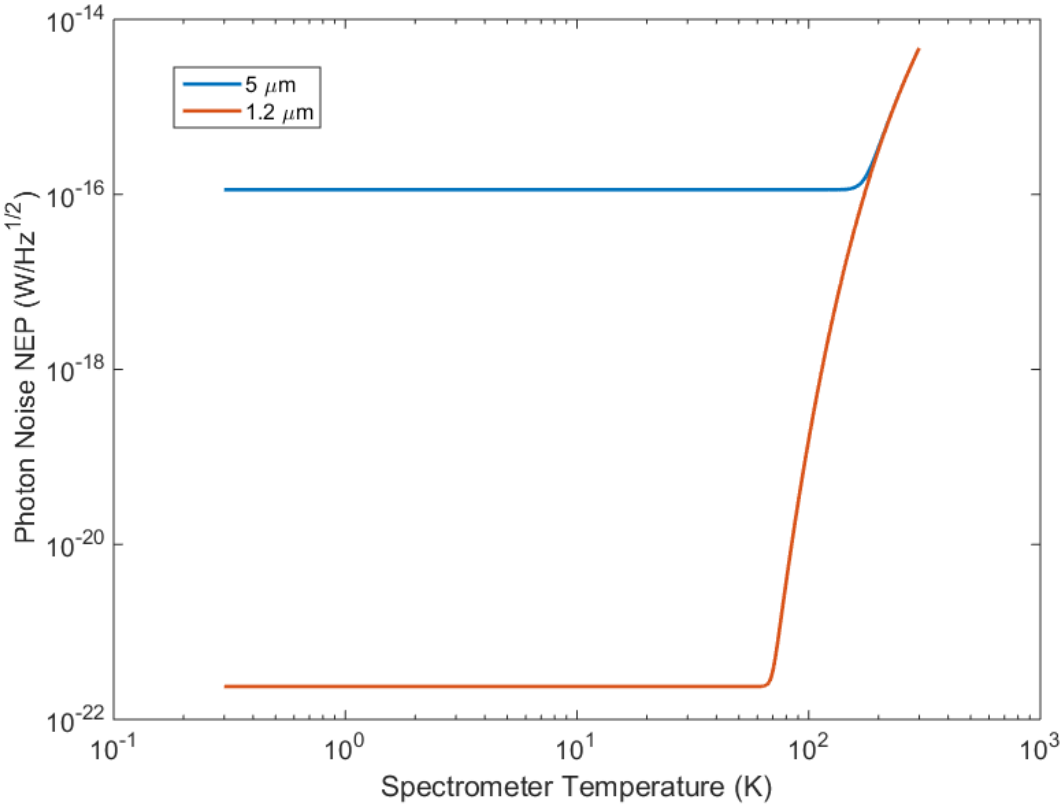


Waveguide-integrated MKIDs



Why Cryogenic Spectrometers?

In the NIR (1-5 µm), cryogenic spectrometers offer orders of magnitude more sensitivity than at 300K.



Ideal channelizing spectrometer w/ R=1000, 1.2 – 5 µm, 300K source

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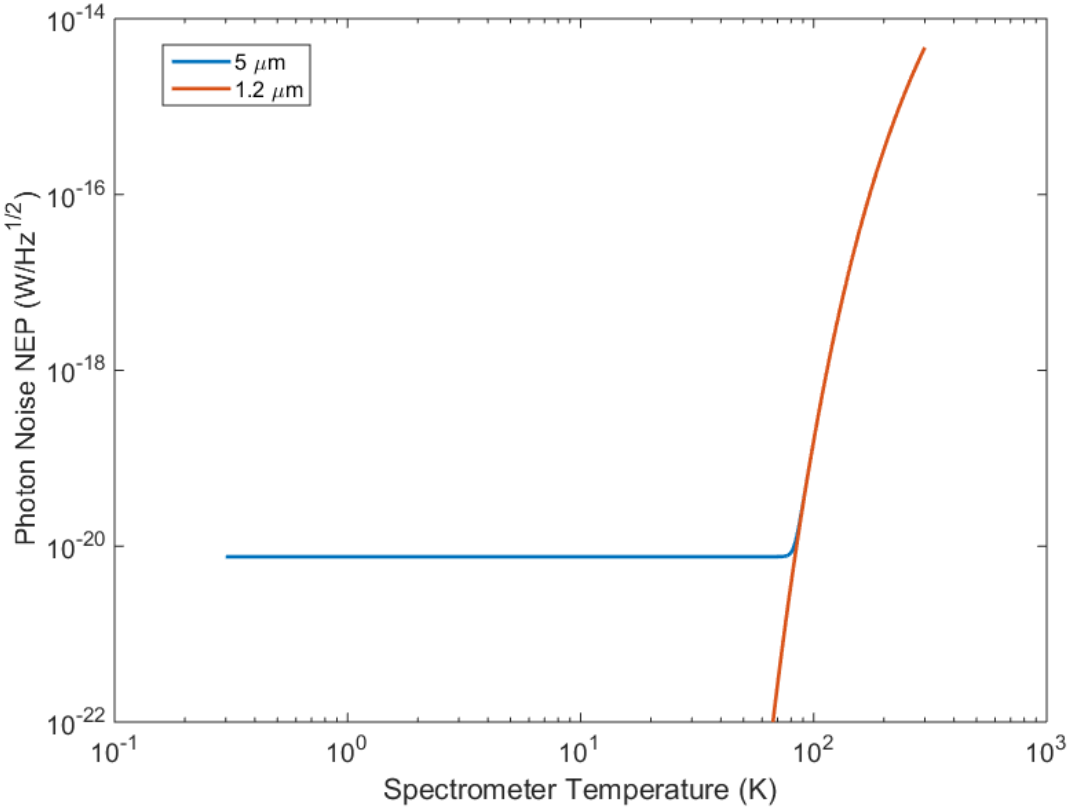

Ideal channelizing spectrometer w/ R=1000, 1.2 – 5 µm, 100K source

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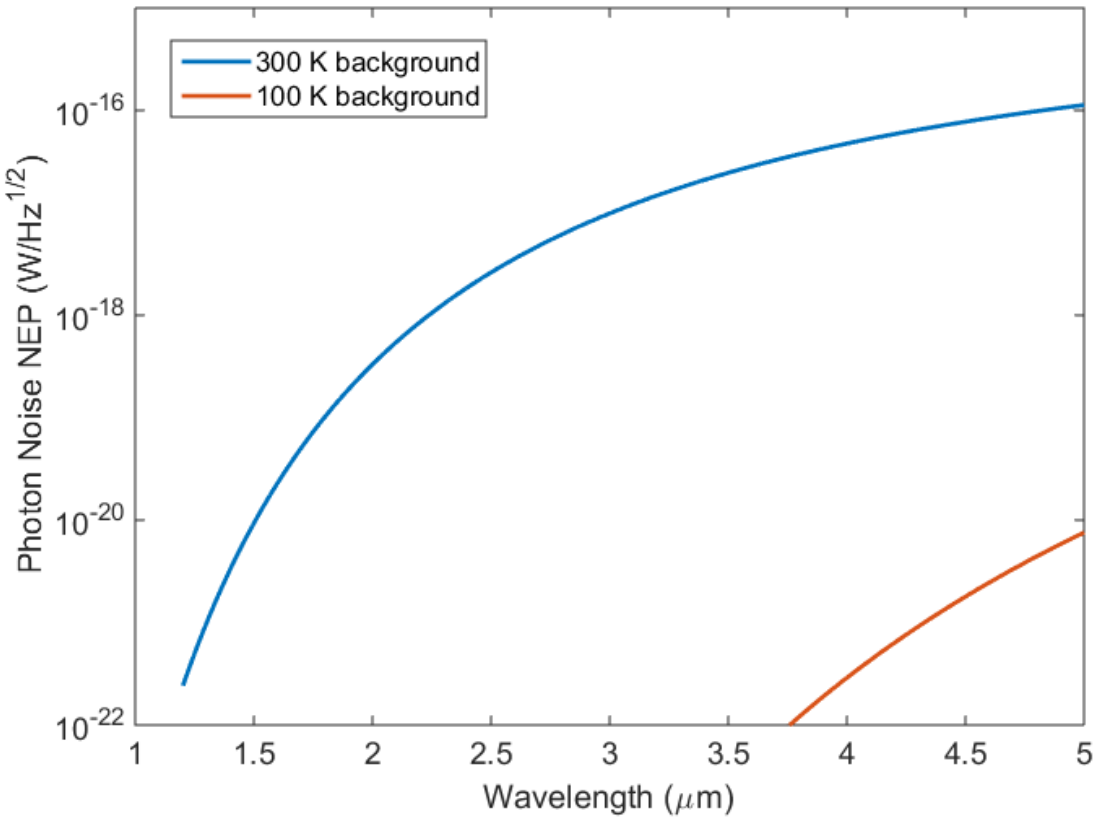
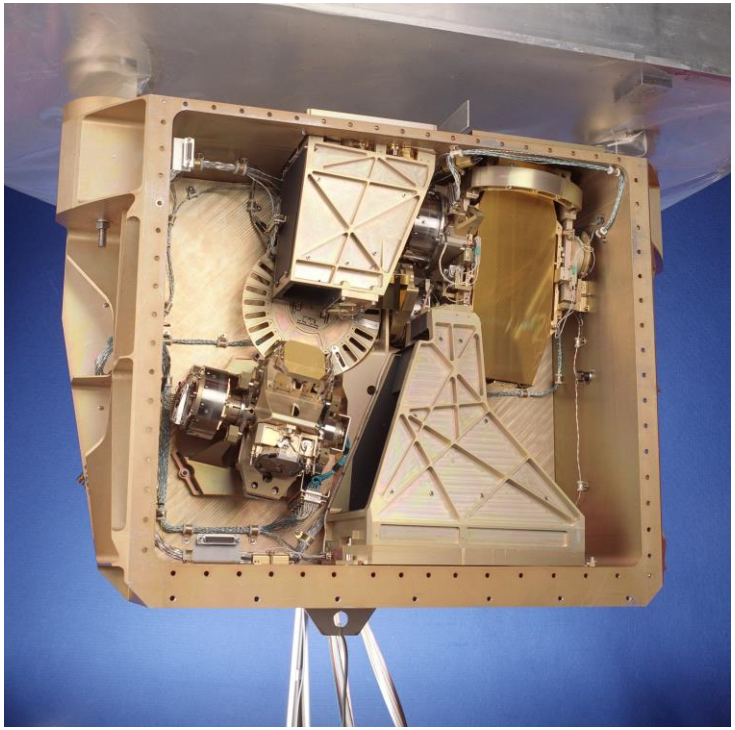


Ideal channelizing spectrometer w/ R=1000, 1.2 – 5 µm, 100K source

Why Not Cryogenic Spectrometers?

- Cryogenic alignment of bulk optics is required
- Very costly, complex instruments for “big science”
- Mostly used in the mid-IR and longer



VISIR cryogenic spectrometer, ESO

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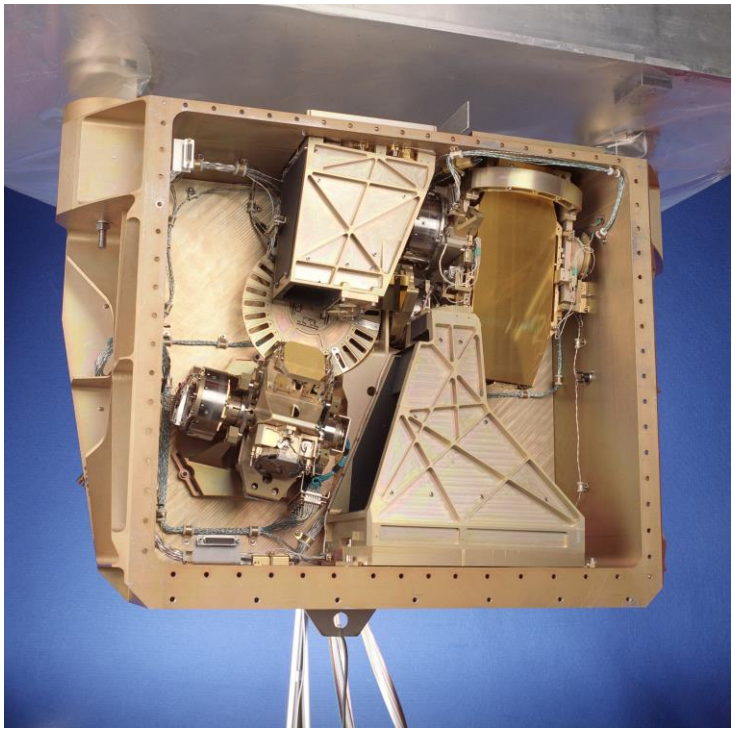
BUT…

- What if we could make a technology that gave the SNR advantage of a cryogenic spectrometer, but could fit in the palm of your hand?
- What can we learn and leverage from telecom photonics?



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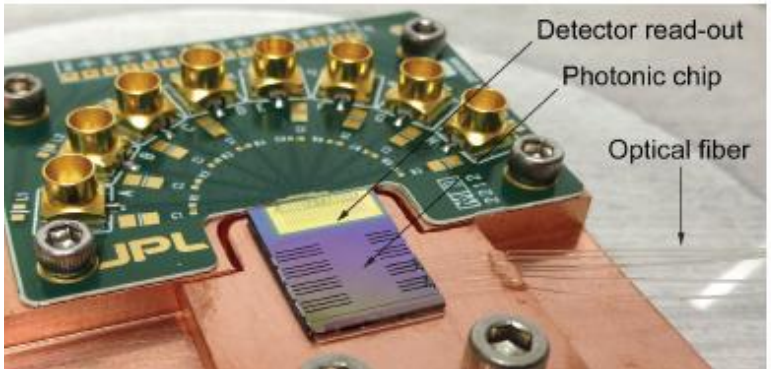
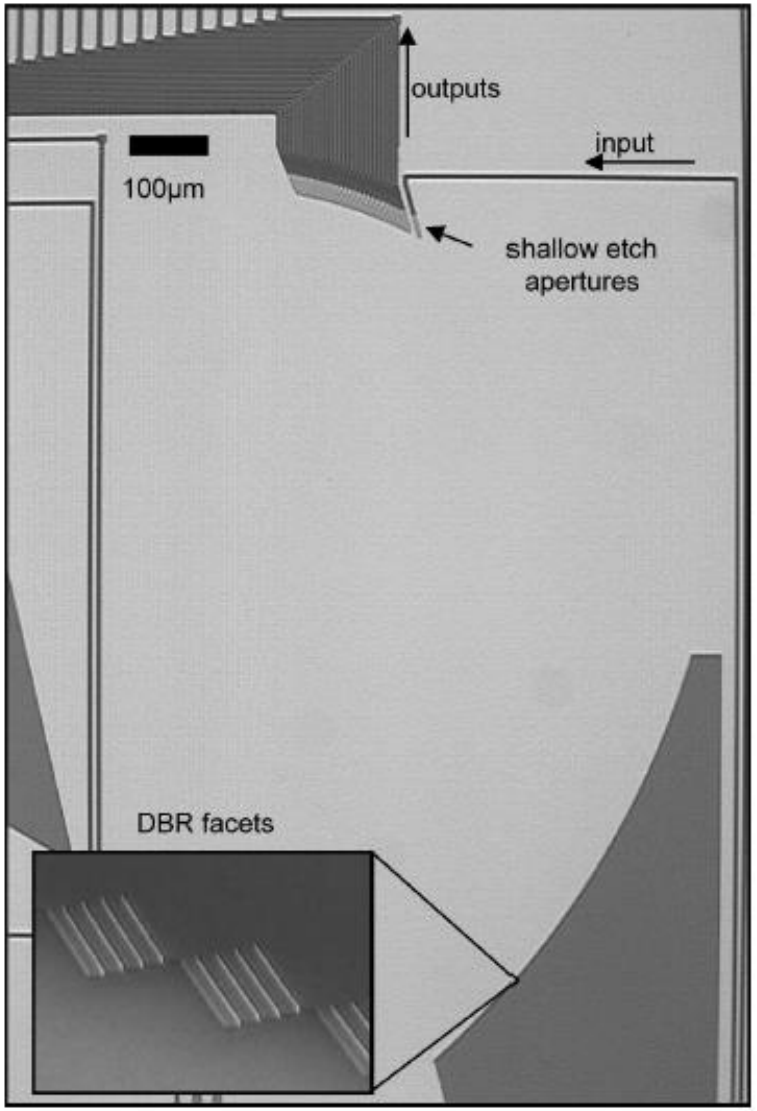
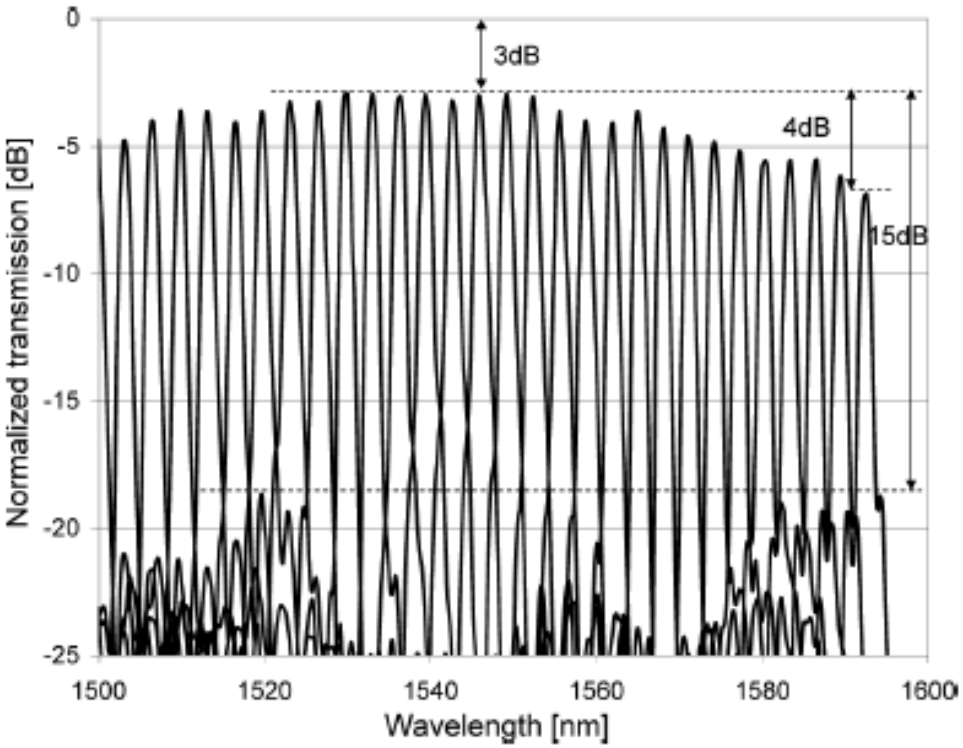


Planar Concave Gratings

- Powerful tools have been developed in Silicon Photonics for DWDM





Baets et al, U. Ghent (2010)

- Demonstrations have been performed at 2.1 µm, 3.8 µm

on-Proprietary

Necessary Components

- Waveguide integrated detectors operating from 1.2 – 5 µm
- Fine spectrometer elements. R > 1000
- Coarse spectrometer elements. R ~ 5
- Efficient, broadband fiber-to-waveguide couplers
- Low-loss mid-IR waveguides

Necessary Components

- Waveguide integrated detectors operating from 1.2 – 5 µm
  Waveguide MKIDs. Semiconductor Detectors?

- Fine spectrometer elements. R > 1000
  Planar concave gratings, arrayed waveguide gratings, SWIFTS

- Coarse spectrometer elements. R ~ 5
  Nanophotonic mode splitters, low-order gratings

- Efficient, broadband fiber-to-waveguide couplers
  Inverse nanotaper couplers. Cryogenic self-alignment?

- Low-loss mid-IR waveguides
  Silicon on Sapphire waveguides, ZrF fiber, Chalcogenide fiber

Non-Proprietary

Current Development Status of Technology

Technology is in its infancy. Considerable research and development in mid-IR photonics is necessary. However, the path appears feasible.

What will it cost to advance this technology? (ROM cost)

- ~$1M to advance the individual components
- ~$1M to integrate everything together into a spectrometer

Why should NASA, Industry, and other government agencies invest in this technology?

- Orders of magnitude more sensitivity
- Makes cryogenic spectroscopy practical for small spacecraft, laboratory experiments

Target Technology Market Applications

- Laboratory Chemistry
  - Any application where sensitivity is a limiting factor
  - Gains are particularly strong for cryogenic samples
- Space-based astrophysics
  - Solid-state spectroscopy of interstellar ices
  - With 77K detectors, could be feasible for cubesat missions
- Ground-based astronomy
  - Simpler, cheaper IR spectroscopy instruments

Contacts

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  - (626) 487-7019
  - http://microdevices.jpl.nasa.gov

Summary of Key Points

- Cryogenic spectrometers offer the potential for orders of magnitude improvements in sensitivity in the 1-5 micron range
- On-chip photonics can be used to make these devices practical and inexpensive
- Waveguide-coupled MKIDs are the first step along this path.

Back-up charts