Submillimeter Spectroscopy with μ-Spec

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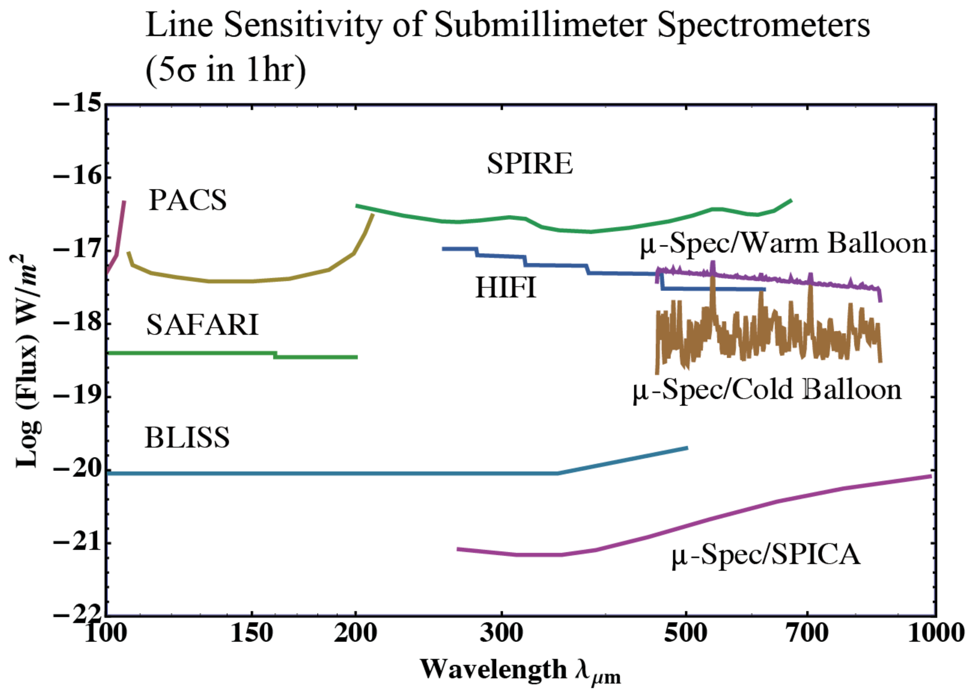
Scientific Motivation:

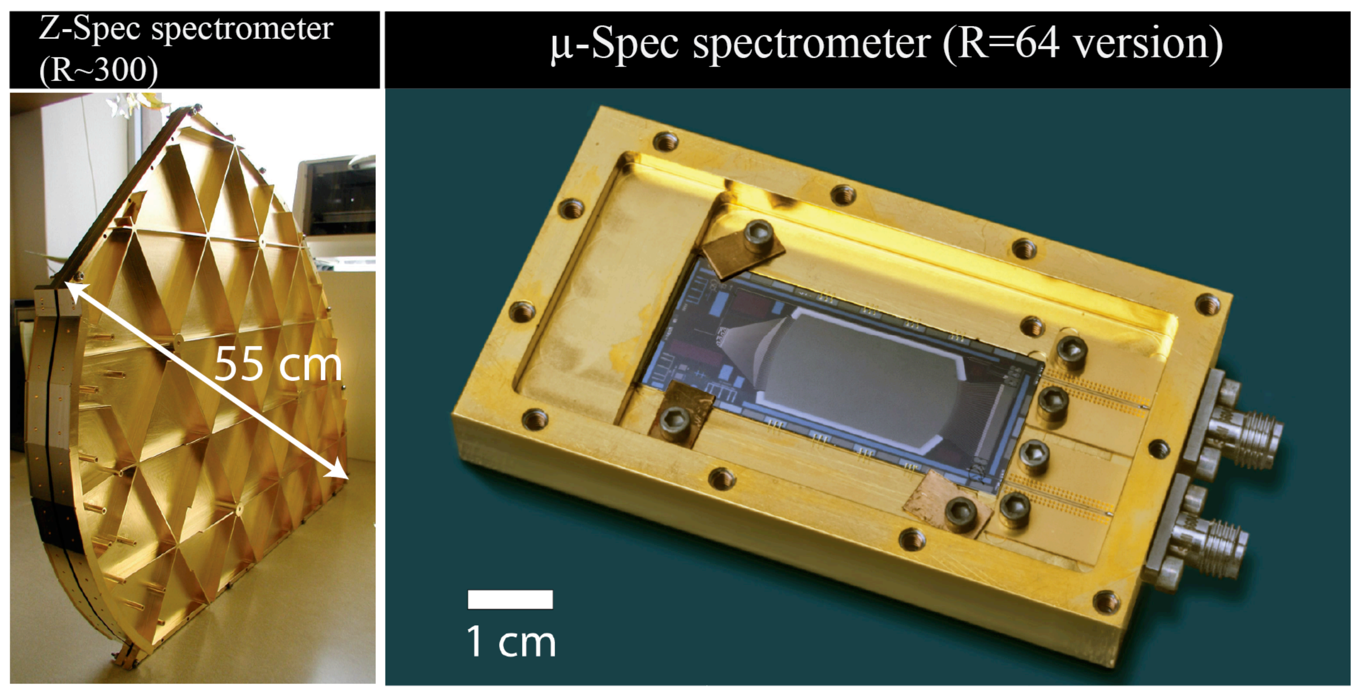
The far-infrared/sub-millimeter part of the spectrum contains a wealth of information about the content and history of our universe. This information is encoded in a wide range of molecular lines and fine structure lines. Observations of such spectral lines allow us to explore galaxies at high redshifts. Strong fine structure lines of abundant elements (C, N, and O) allow us to trace obscured star formation and AGN activity into the high redshift universe. We can measure galaxy redshifts, and determine their elemental abundances and physical conditions out to redshifts of z>~ 5. Our ability to fully explore this rich spectral region has been limited, however, by the size and cost of the cryogenic spectrometers required to do these sensitive measurements.

Sensitivity of an R=512 μ-Spec as compared to other instruments. For the space-based μ-Spec on SPICA photon-counting detectors have been assumed in the calculation.



Enabling technology:

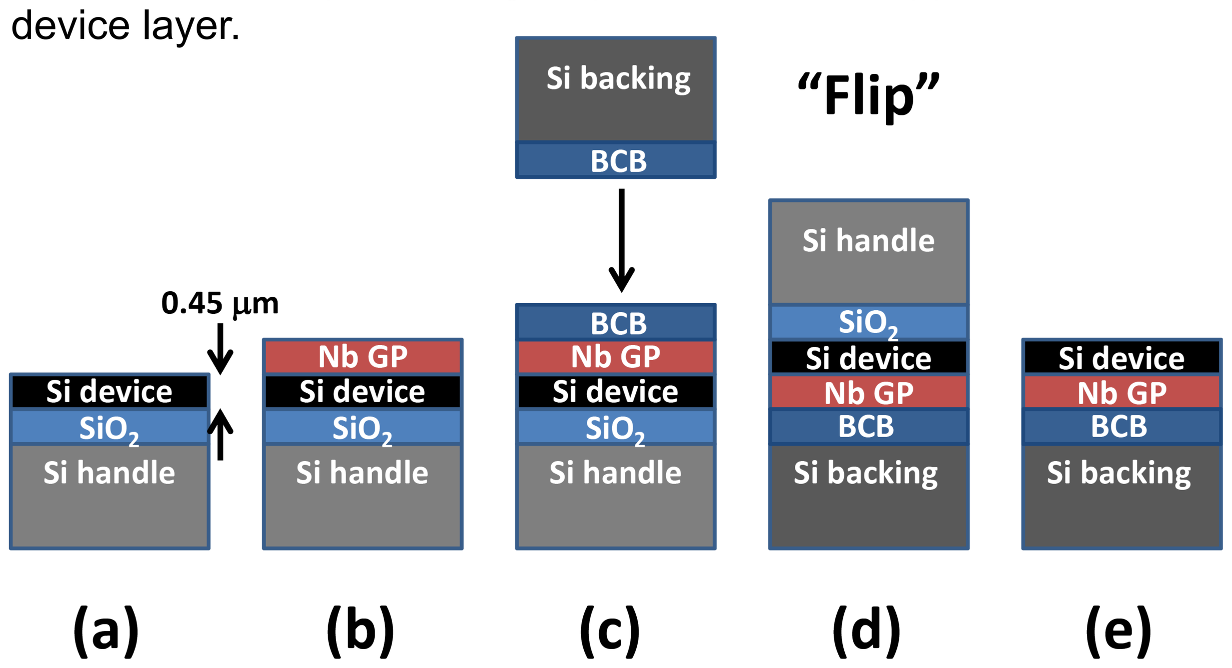
We are developing an **extremely compact** (~10 cm^2), submillimeter spectrometer, called μ-Spec. This high performance instrument will enable a wide range of spectroscopy flight missions, which would have been impossible due to the large size of current instruments with the required spectral resolution and sensitivity. Orders of magnitude reduction in the mass and volume of our spectrometer is achieved by using superconducting microstrip transmission lines with **single crystal silicon dielectric** substrates provided by SOI wafers.



Our demonstrated prototype R=64 μ-Spec instrument is shown above as compared to the state-of-the-art, Z-spec.

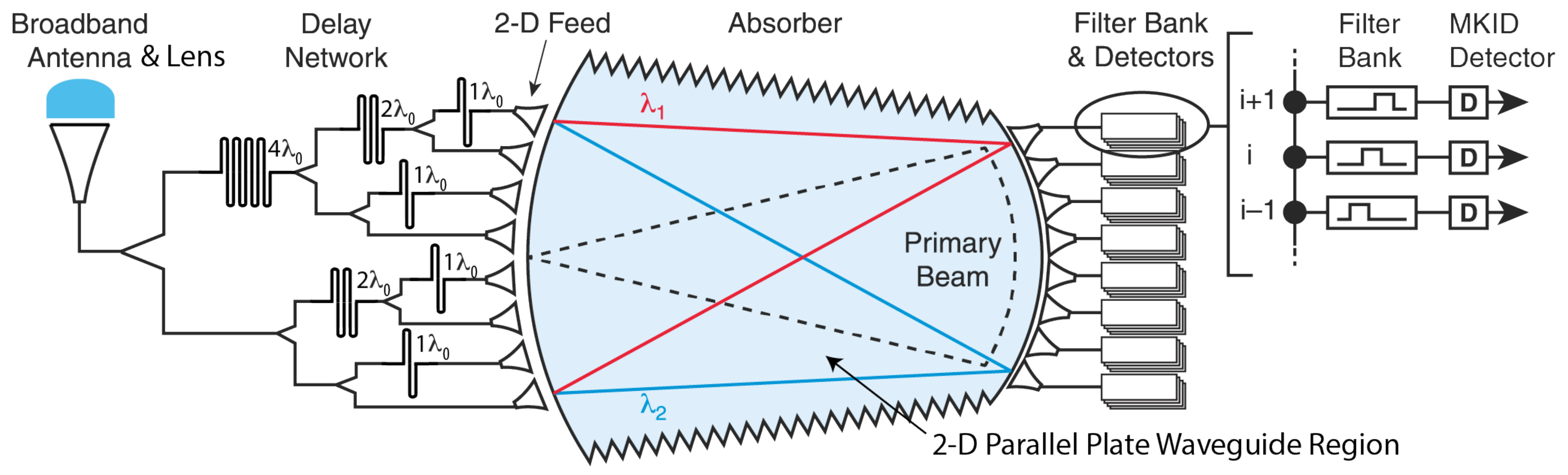
Fabrication Process:

The "single flip" bonding process used to fabricate R=64 μ-Spec. (a) One begins processing a Silicon- On-Insulator (SOI) wafer with a 0.45 μm thick device layer. (b) The Nb ground plane is deposited and lifted off. The wafer is (c) bonded to an intrinsic Si backing wafer with an epoxy, BCB and (d) flipped. (e) The SOI handle wafer is removed and the remainder of processing steps occur on the opposite side of the device layer.



Instrument Overview:

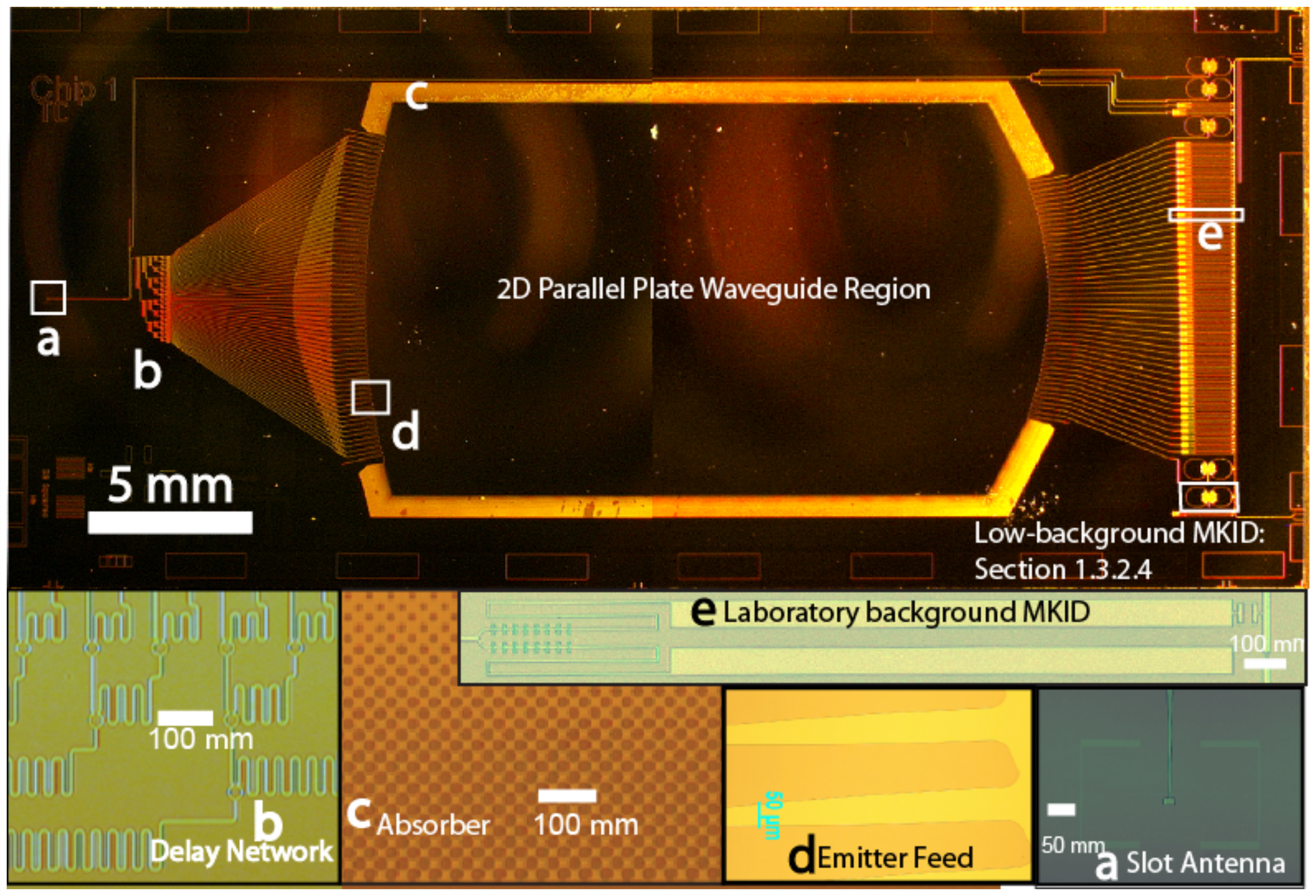
The sub-mm signal is coupled onto a low-loss microstrip transmission line by a broadband lens/antenna. A network of delay lines and dividers creates a synthetic grating which focuses different wavelengths of light on each of the output detector channels [1]. The outputs are connected to a bank of order-sorting filters to disentangle the various orders. The detectors are **Microwave Kinetic Inductance Detectors (MKIDs)** [2] which are naturally frequency multiplexed and are read out with a single microwave line.



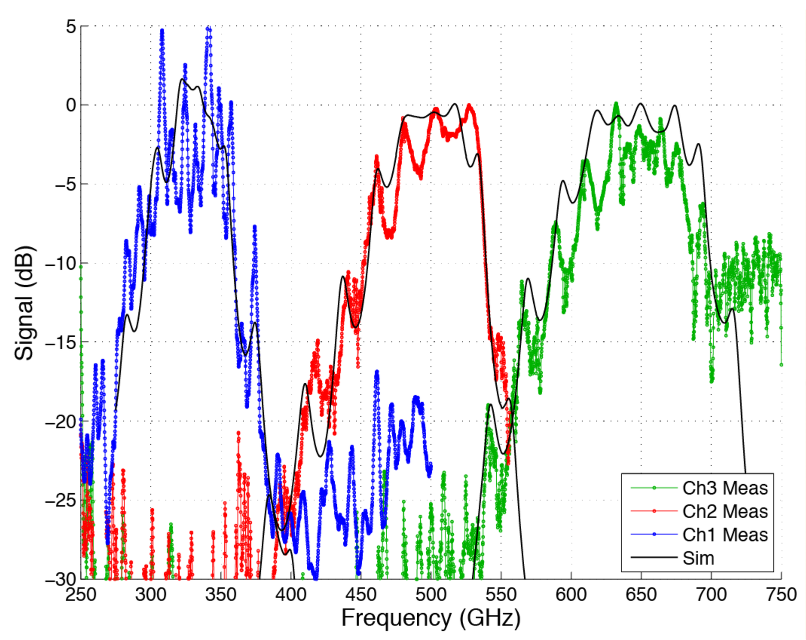
μ-Spec is the analog of a grating spectrometer. This results in several advantages:

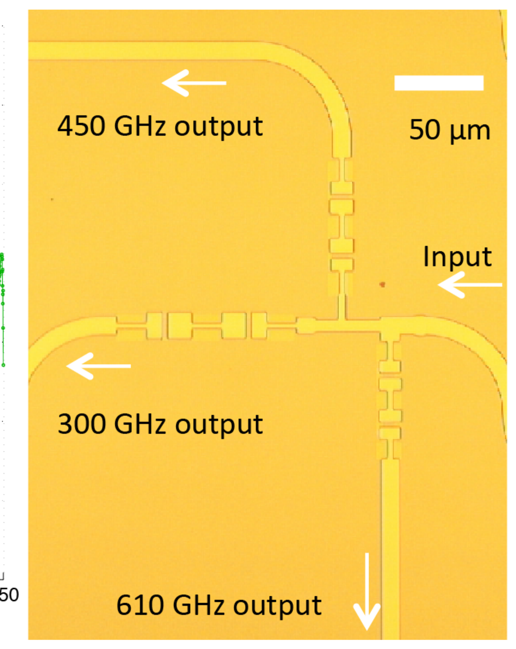
- ✓ Wavelength of each channel is determined by design.
- ✓ Sampling of wavelength space can be uniform.
- ✓ Spectral function is [sin(x)/x]^2 as compared to Lorentzian (e.g. Fabry-Perot or filter-bank based instruments) where larger wings make high-contract spectroscopy more difficult.
- ✓ An array of μ-Spec modules will have uniform response among different modules.

Spectrometer components:



Channelizing Filters: Measured and simulated filters. Ripples are due to impedance mismatch between MKIDs and the filters and are not intrinsic to filter performance. There is a 5- 10% frequency shift between measured and simulation due to uncertainties in fabricated linewidths.

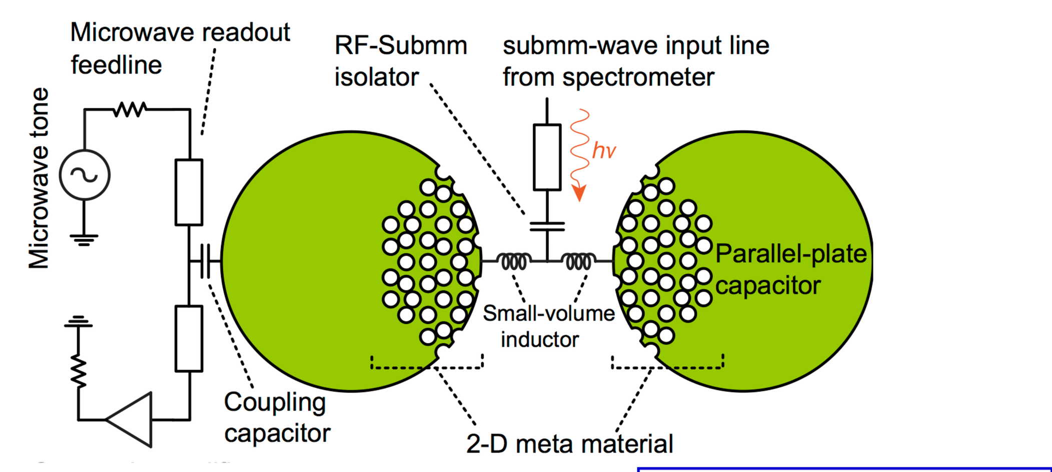


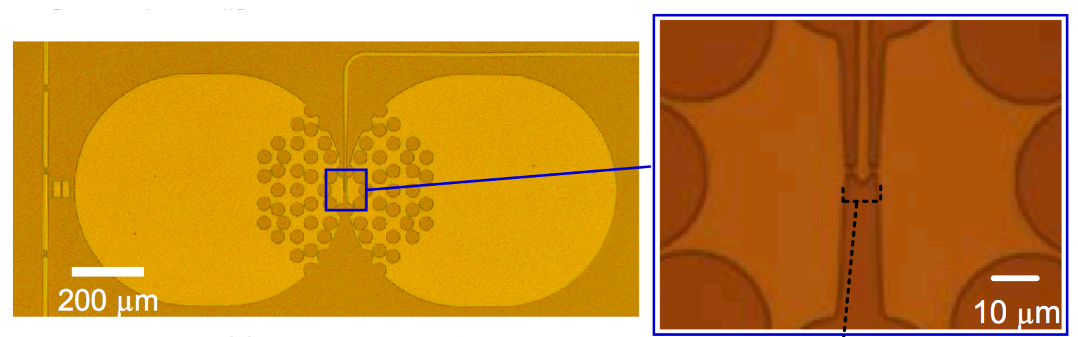


Ultra-sensitive Detectors:

Operation on a cold space telescope requires sensitivities of ~ 10^{-20} W/rt Hz. To achieve this we are addressing three main challenges in this regard:

1. Maximizing responsivity to photons by reducing kinetic inductor volume
2. Minimizing two-level system (TLS) noise from capacitor by confining E fields in crystalline dielectric in parallel-plate capacitor design [3]
3. Eliminating stray radiation coupling and leakage by providing highly protected integrated optics using microstriplines, avoiding cuts in ground plane, and in-line coaxial thermal blocking filters.



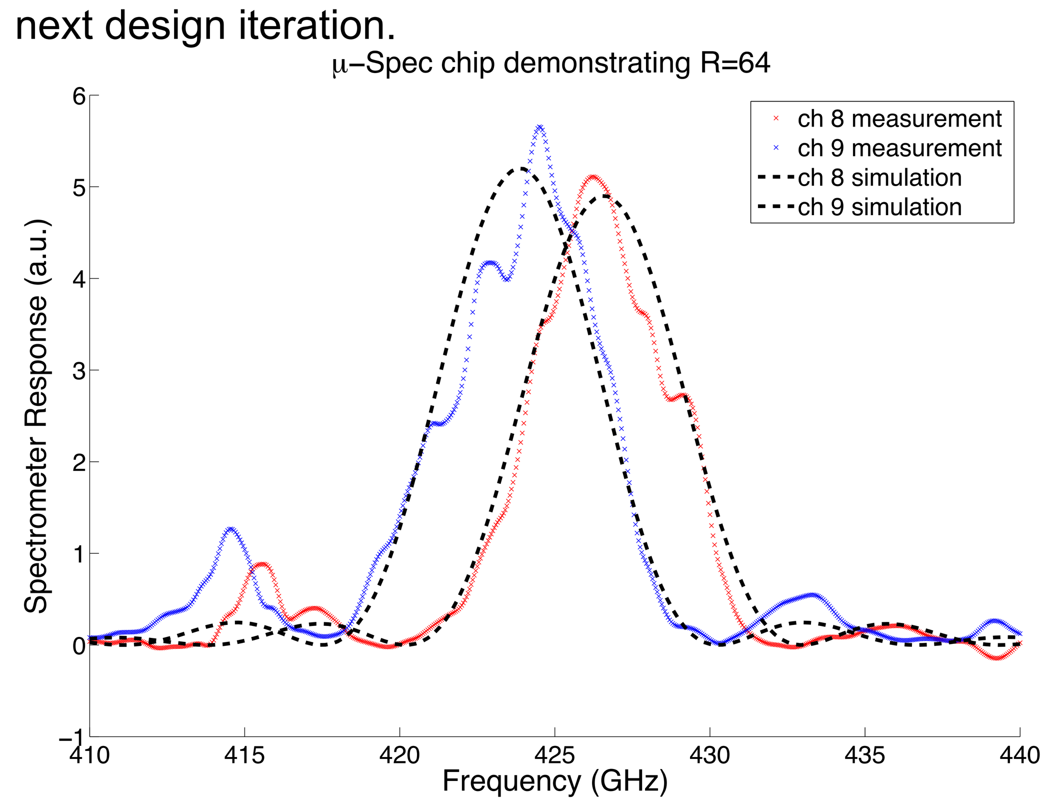


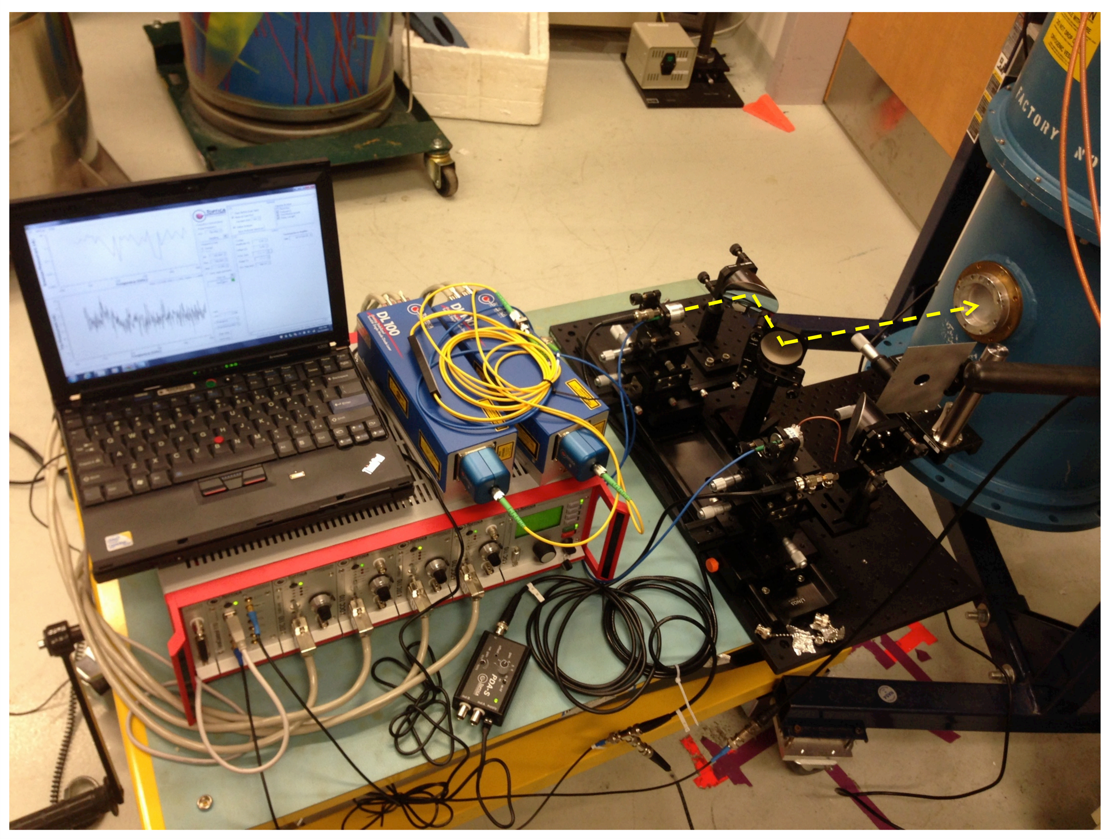
Photograph of fabricated MKID detector for low background loading

Small-volume inductor/submm absorber

Measured Spectrometer Response

We measured the response of several channels in the R=64 μ-Spec to submillimeter light using a tunable photomixer source. Below is the response of two adjacent channels demonstrating the design resolution and ±1 GHz absolute frequency location. There is no evident loss as expected from limits set by 2-line interference measurements for our transmission lines. The origin of the fine structure is reflections in the MKID absorber pad material (MoN trilayer), which will be replaced by Al in the next design iteration.





References

[1] Cataldo, G., W.-T. Hsieh, W.-C. Huang, et al., "Micro-Spec: an ultracompact, high-sensitivity spectrometer for far-infrared and submillimeter astronomy." Applied Optics **53** (6), pp. 1094 (2014)

[2] J. Zmuidzinas, "Superconducting microresonators: Physics and applications," Annual Review of Condensed Matter Physics, **3** (1), pp. 169 (2012)

[3] O. Noroozian, J. Gao, J. Zmuidzinas, H. G. LeDuc, and B. A. Mazin, "Two- level system noise reduction for Microwave Kinetic Inductance Detectors," in Low Temperature Detectors LTD 13, ser. AIP Conference Proceedings, **1185**, pp. 148 (2009)