Integrated Optics for Submillimeter Spectroscopy: Introducing μ-Spec

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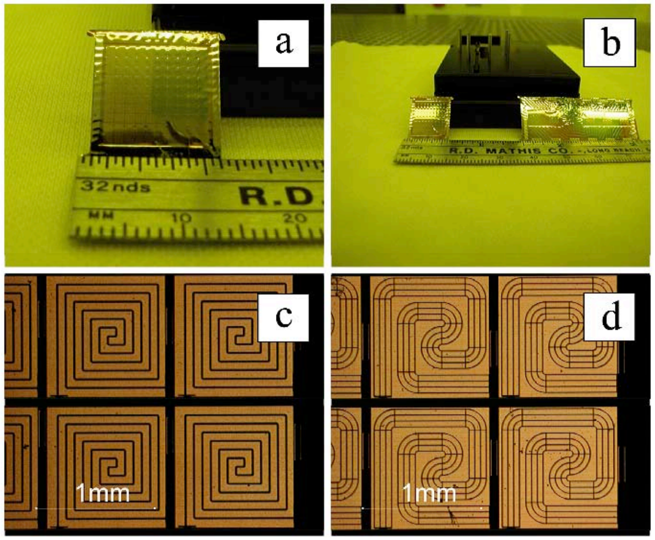
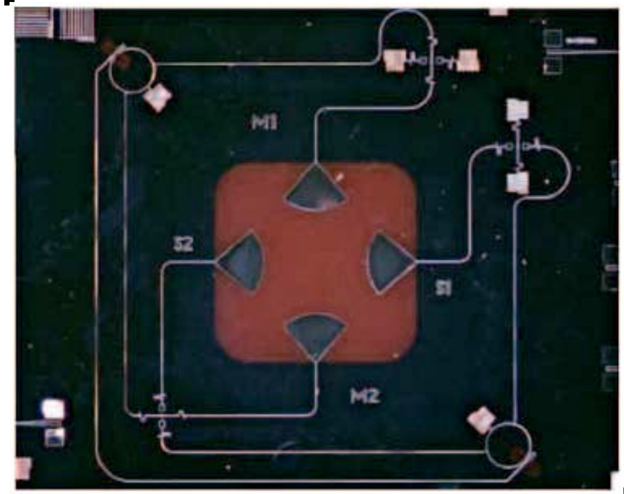
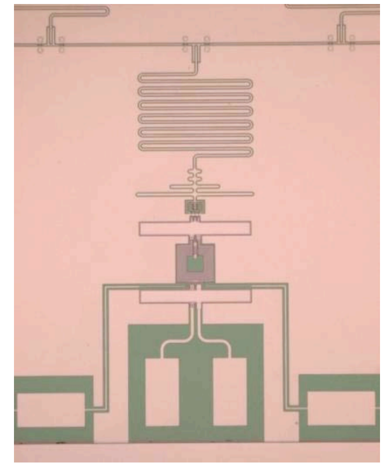
Goddard Microwave Design Capabilities



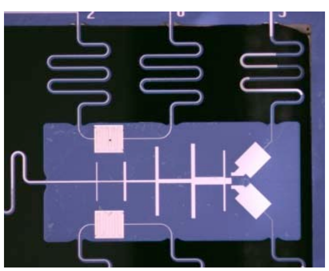
Microwave Kinetic Inductance Detector with Selective Polarization Coupling



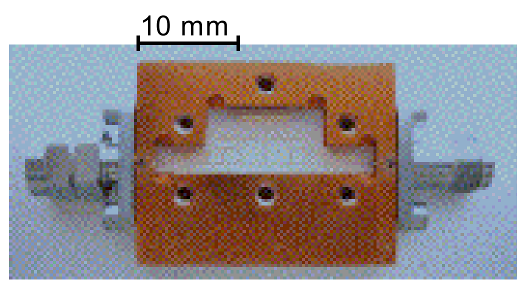
CMBpol Detector



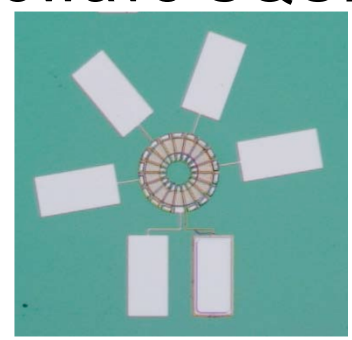
Microwave SQUID



Broadband TES Termination

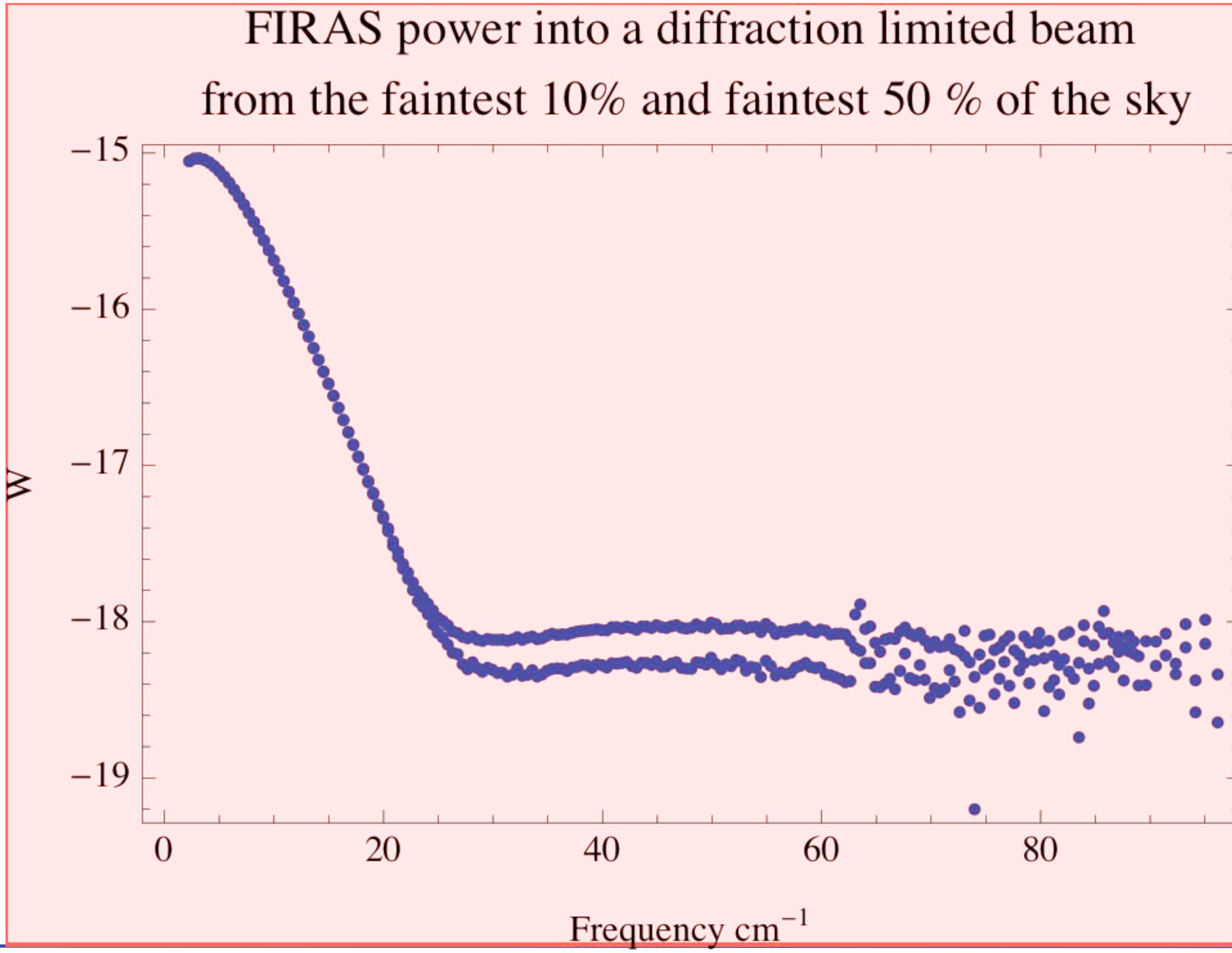


Thermal Blocking Filter

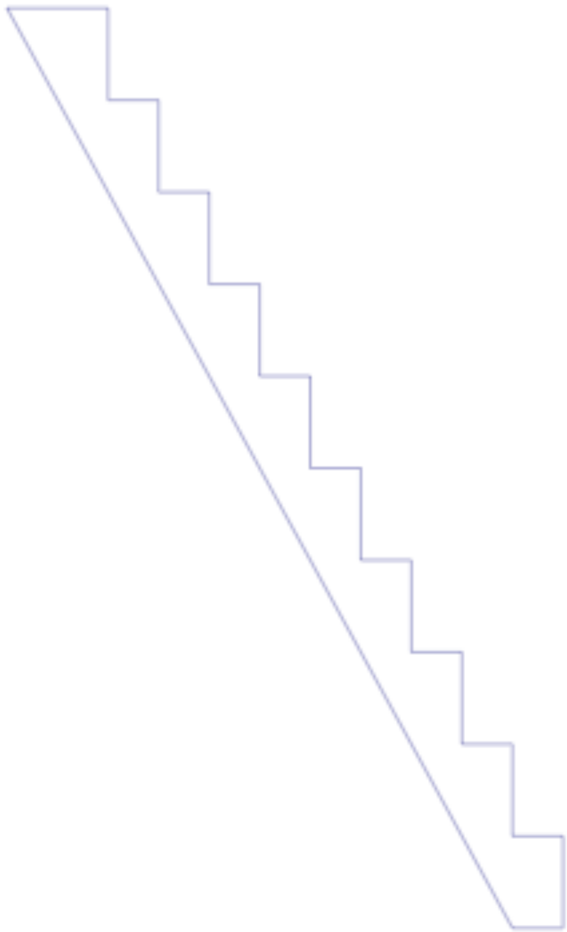


Planar Transformer with high μ material

The Space Environment



Grating Operation



Plane wave scatters off grating

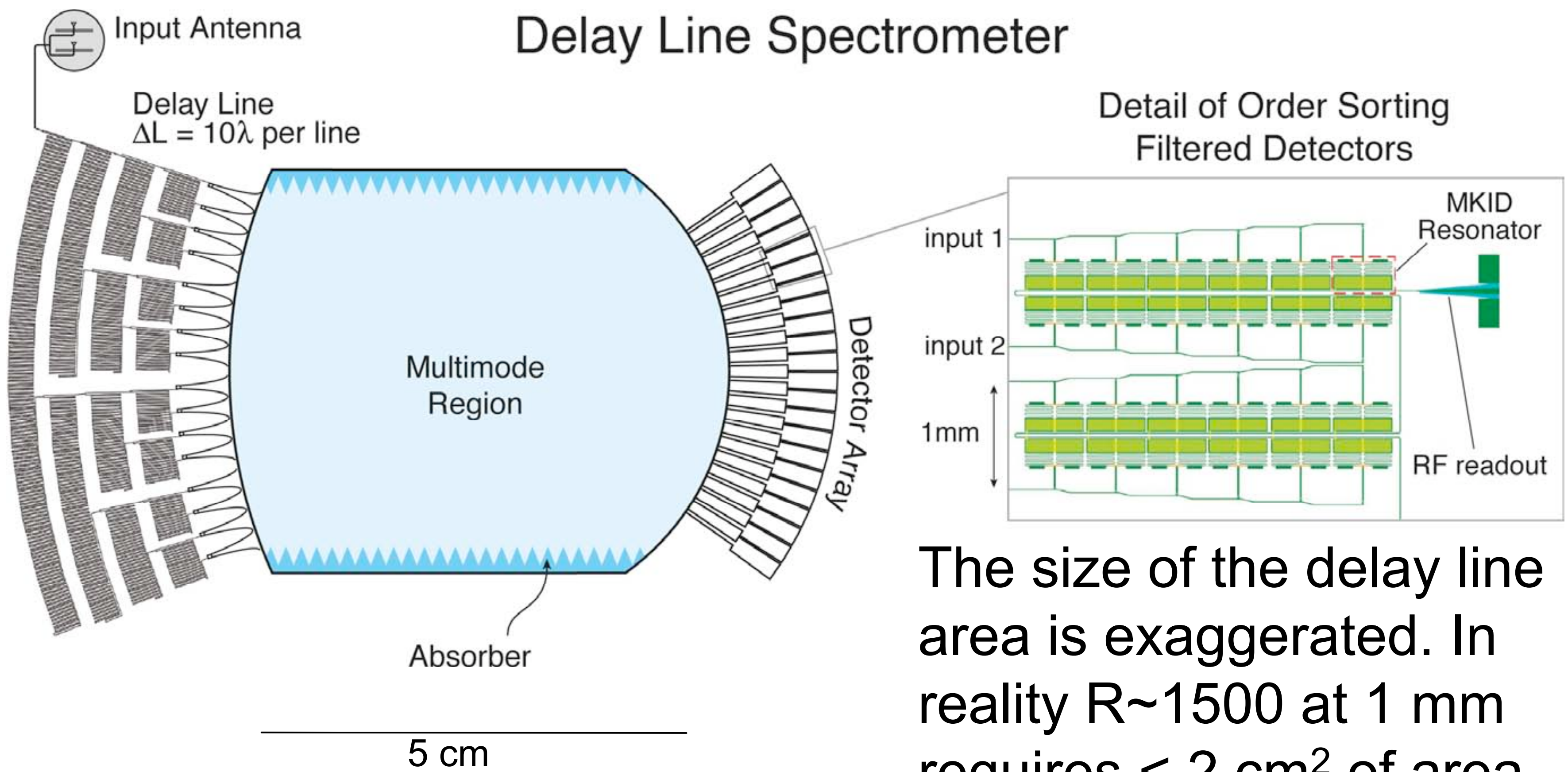
Grating divides amplitude into n equal parts with progressively increasing phase shift

Different Frequencies propagate as plane waves with different k-vectors

Grating Spectrographs

- Resolving power is set by total phase delay, which is of the order of the size of the instrument. Must be large for high resolution.
- Focal surface must have of order N detectors for full sampling of an octave at resolving power N. Since detectors must be of order λ in size, the transverse dimension must be large, similar to the length
- So: Spectrograph must be of order N λ x N λ

μ-Spec Allows Dramatic Reduction in Spectrograph Size

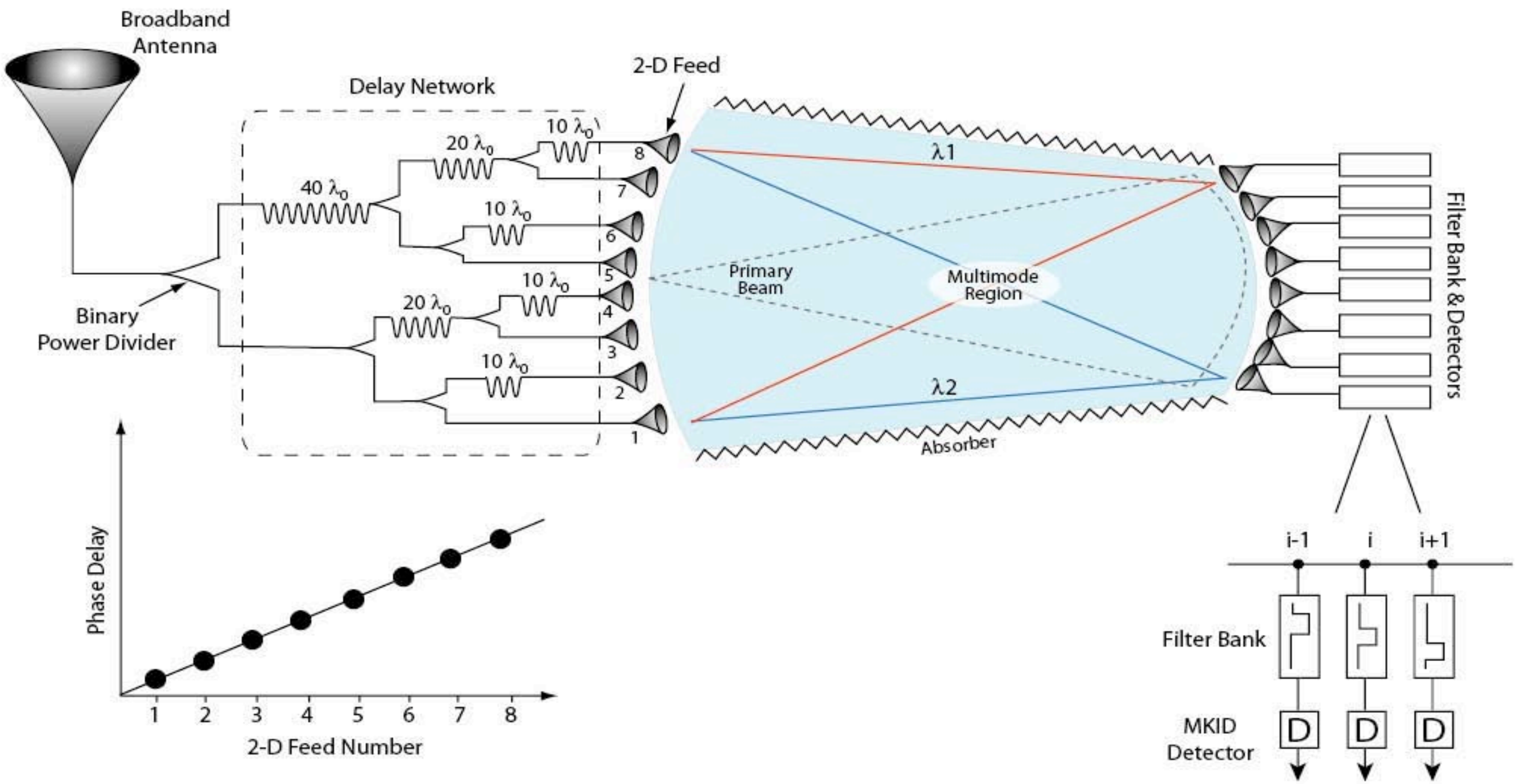


The size of the delay line area is exaggerated. In reality R~1500 at 1 mm requires < 2 cm^2 of area.

Key Technology – low loss transmission lines

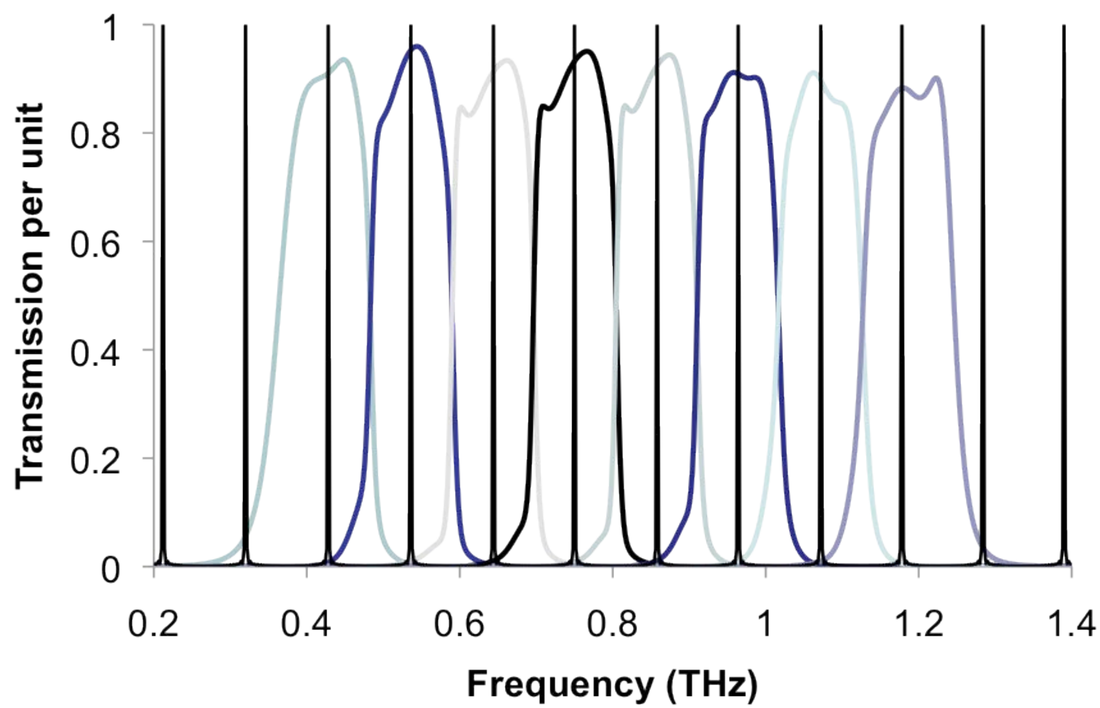
- Superconductors with single crystal Si dielectric
- Bulk loss of Si is low enough

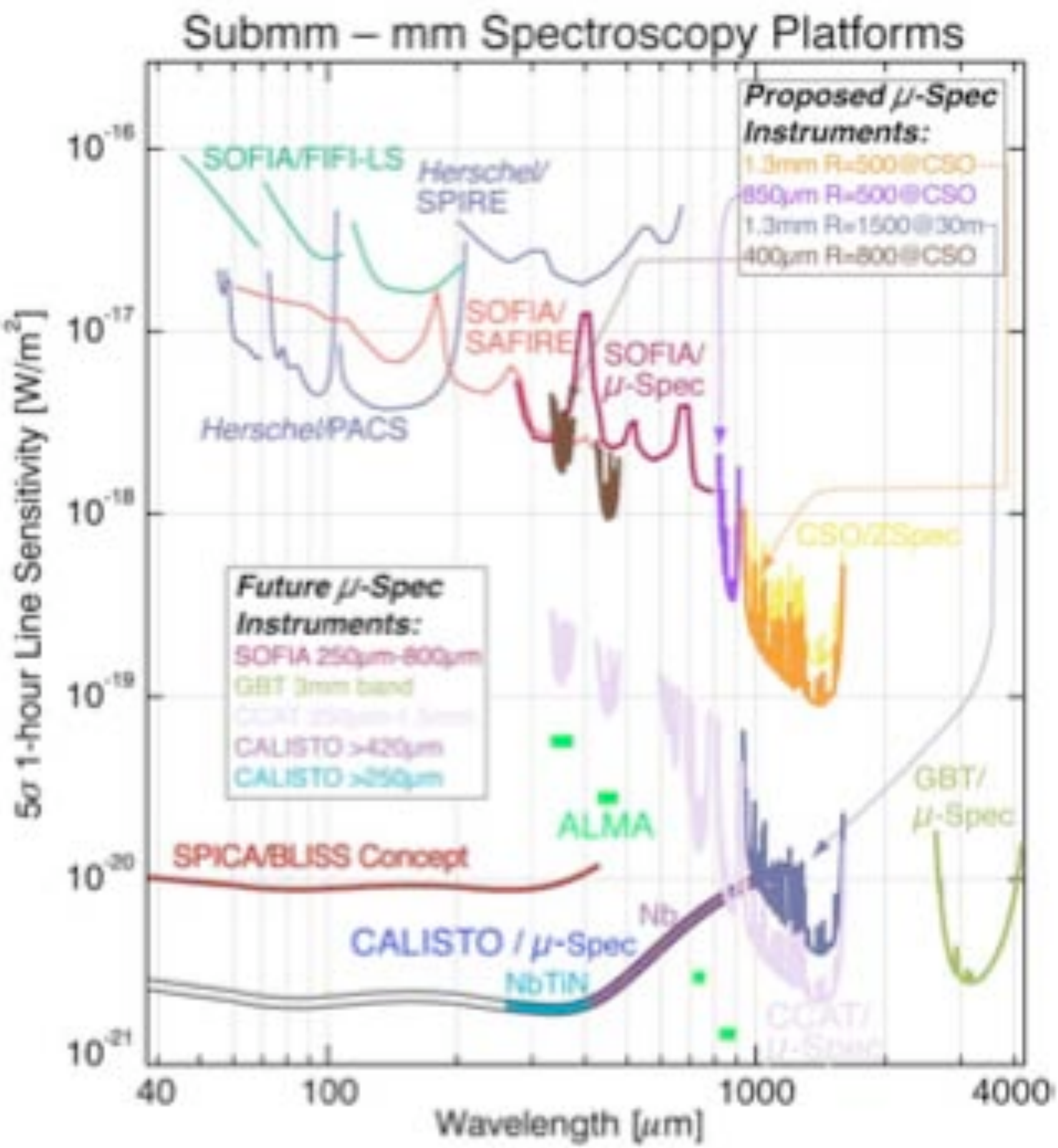
µ-Spec Concept



Output Filter Bank

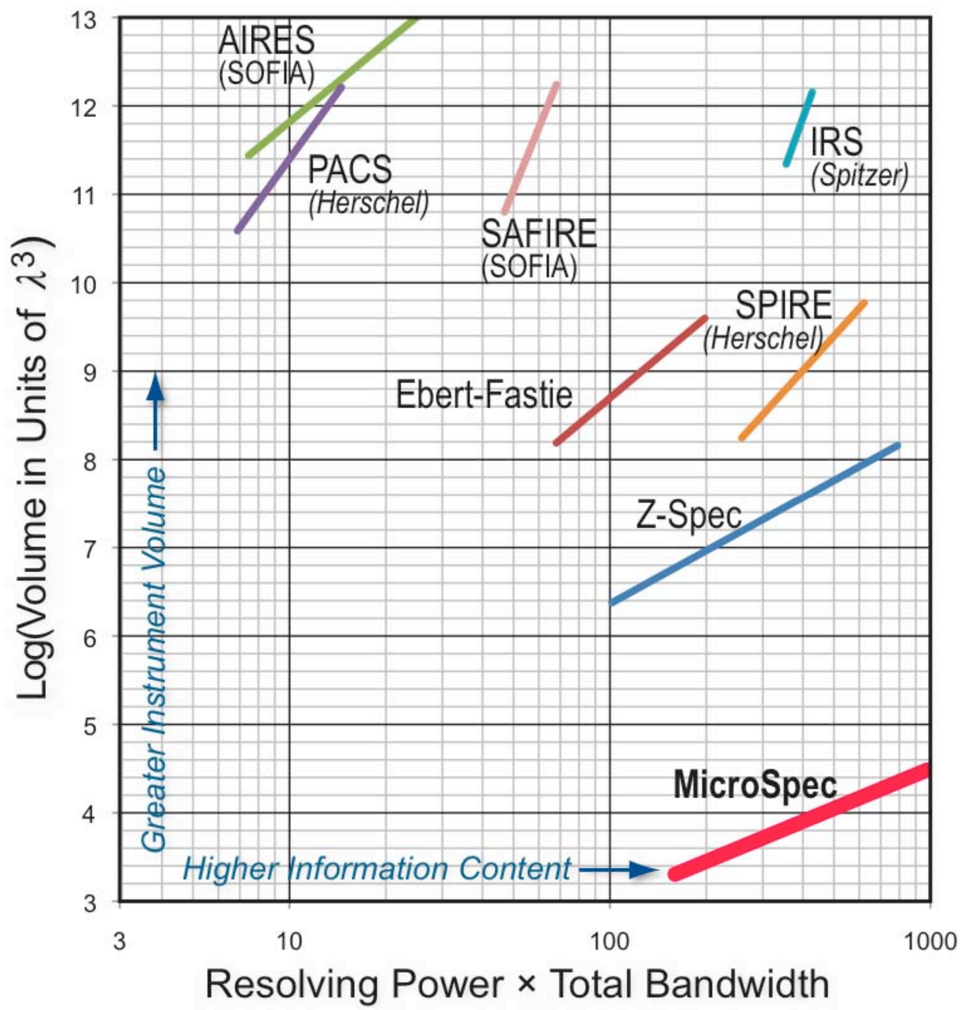
- Each output of the spectrometer receives signals at different wavelengths from different orders of the grating
- Each output has a channelizing filter bank which directs the different orders to their detectors.





Submm – mm Spectroscopy Platforms
Proposed μ-Spec Instruments:
1.3mm R=500@CSO
850μm R=500@CSO
1.3mm R=1500@30m
400μm R=800@CSO
SOFIA/FIFI-LS
Herschel/ SPIRE
SOFIA/ SAFIRE
SOFIA/ μ-Spec
Herschel/PACS
Future μ-Spec Instruments:
SOFIA 250μm-800μm
GBT 3mm band
CALISTO >420μm
CALISTO >250μm
ALMA
GBT/
SPICA/BLISS Concept
CALISTO / μ-Spec
Nb
NbTiN
5σ 1-hour Line Sensitivity [W/m²]
Wavelength [μm]

Context

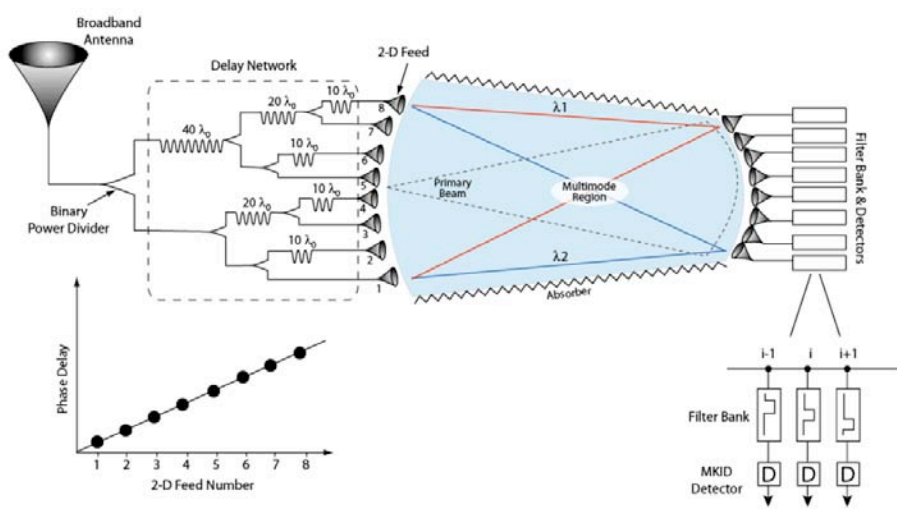


MicroSpec (μ-Spec), the instrument being proposed, is orders of magnitude smaller than present instruments of comparable performance.

Adapted from a Matt Bradford slide.

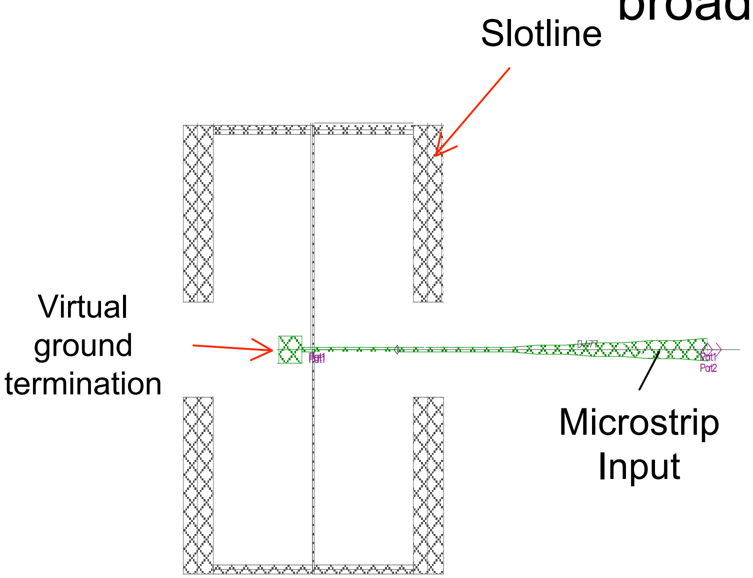
Microwave Technology Implementations

- Ultra-broadband antenna
- Front-back microstrip transition
- Channelizing filter
- Plane-wave absorber
- Low Noise Equivalent Power (NEP) Microwave Kinetic Inductance Detector (MKID)

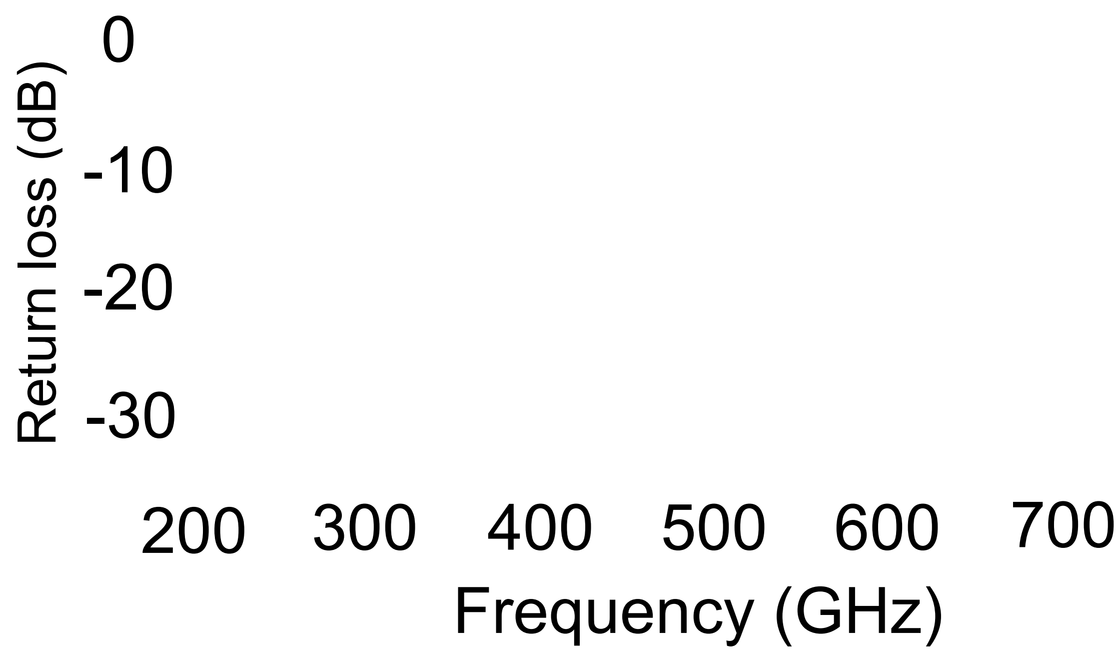


Ultra-broadband Slot Antenna

New slotline antenna design use slotline-to-microstrip transition & slotline impedance transformation concept to generate an ultra-broadband antenna

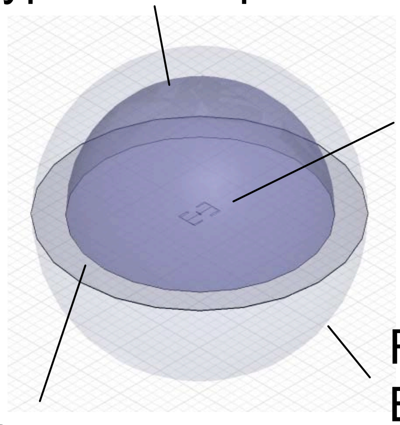


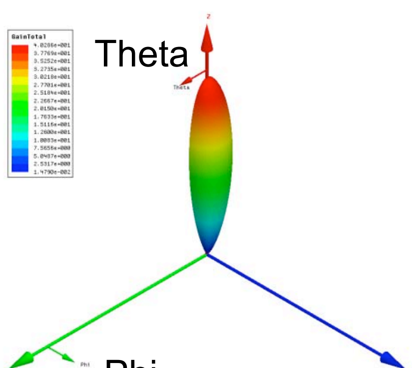
Slotline Antenna on 1.5 µm Silicon Substrate



Frequency Response of the Slotline Antenna

Broadband Slot Antenna Simulation

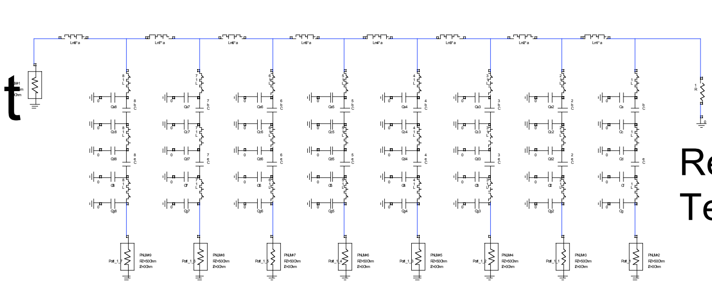




Slotline Antenna Gain Response at 650 GHz

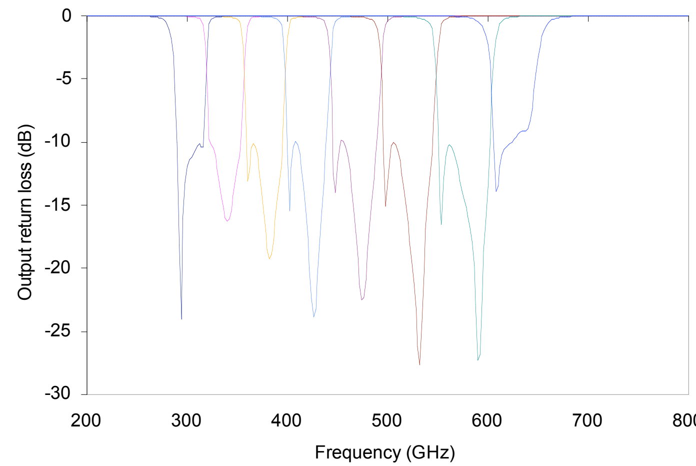
Channelizing Filter

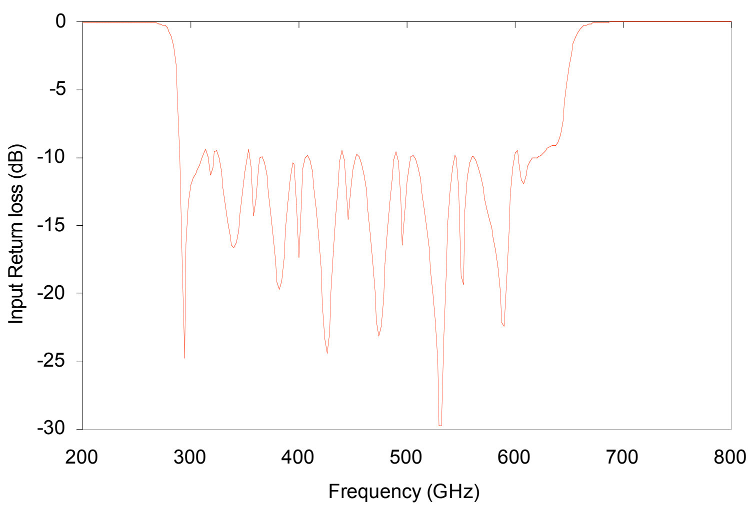
Input



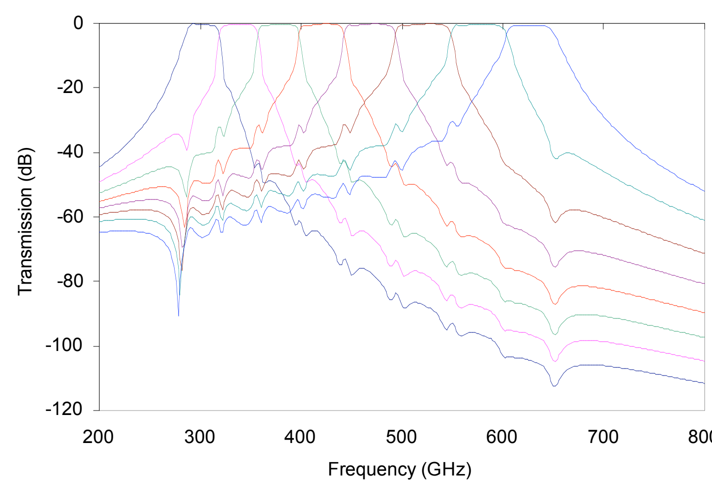
Resistor Termination

Eight output channels





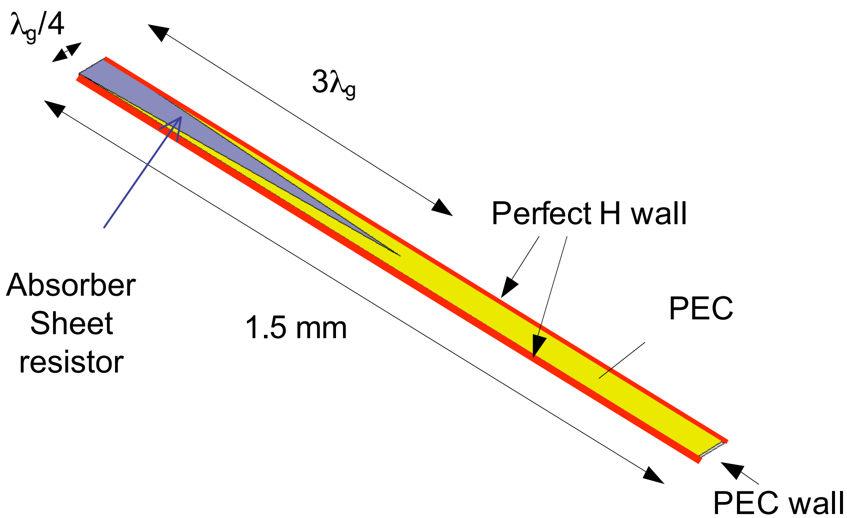
Input Return Loss

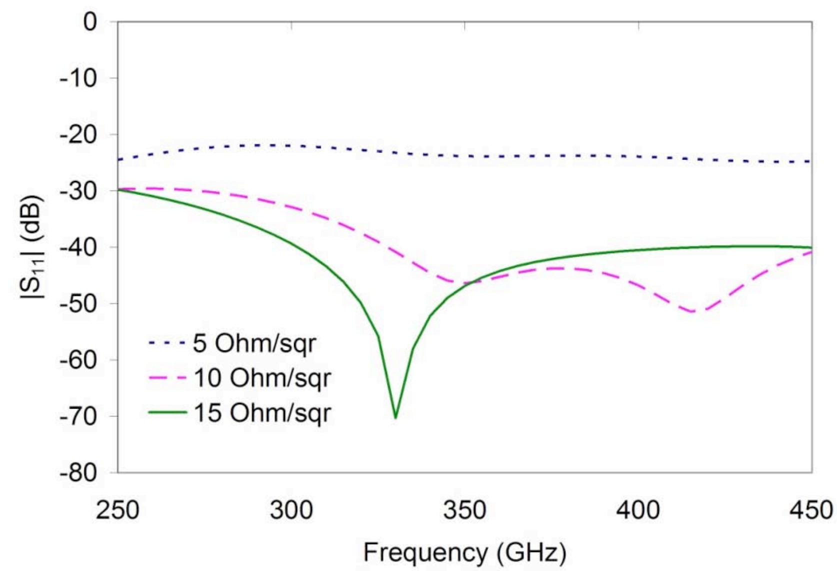


Filter Transmission & Return Loss

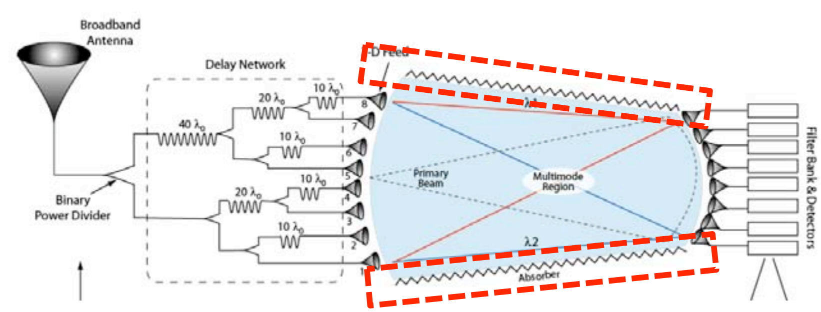
Interesting spectrophotometer by itself!

Plane wave absorber



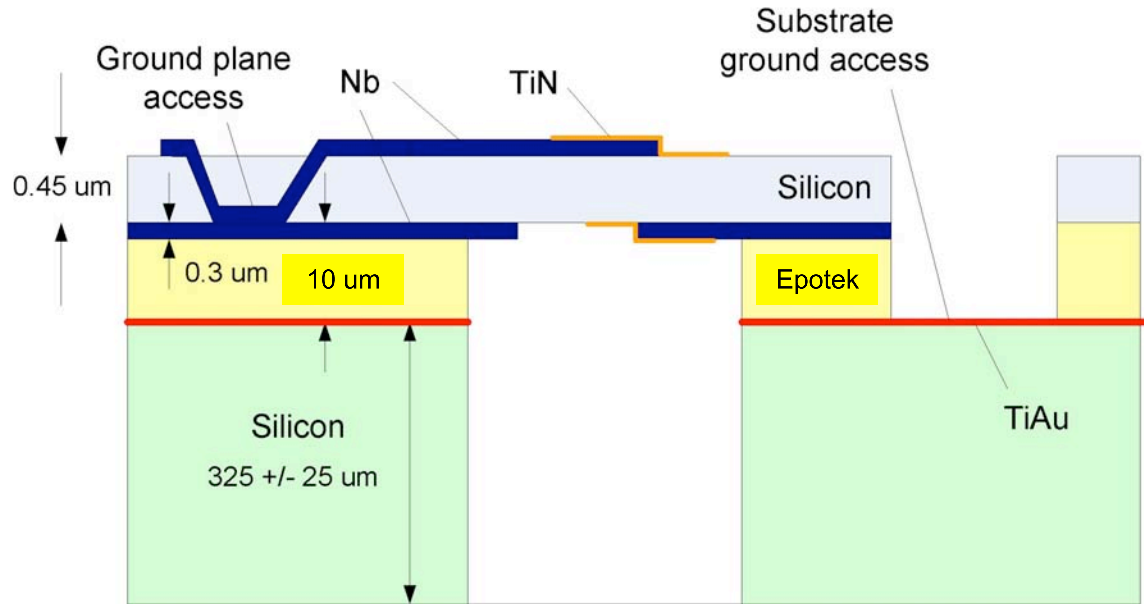


Unit cell model of the absorber on 0.45 um single-crystal Silicon substrate

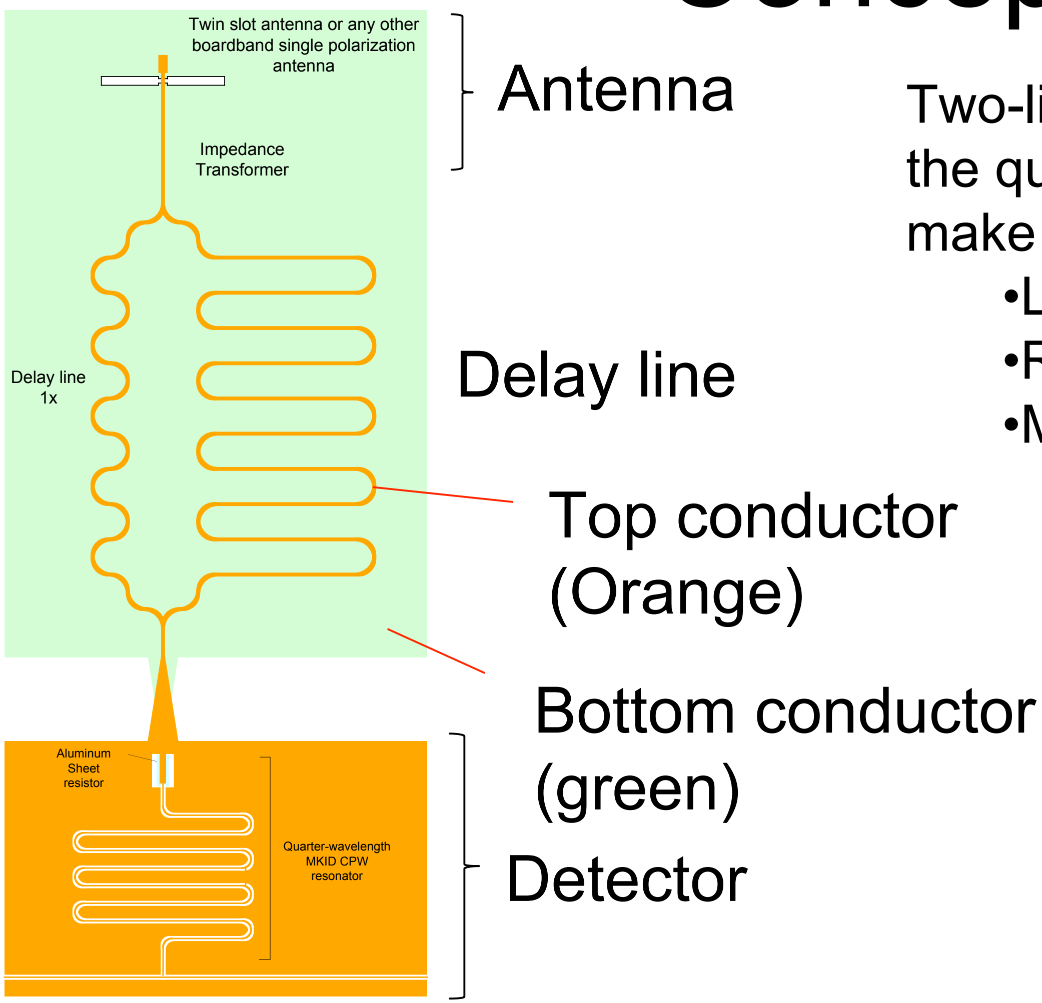


Fabrication Stack up

Material	Thickness
TiN	55 nm
Nb	0.3 µm
Silicon	0.45 µm
Nb	0.3 µm
TiN	55 nm
Epotek	10 µm
Degenerately Doped Silicon	325 µm +/- 25 µm



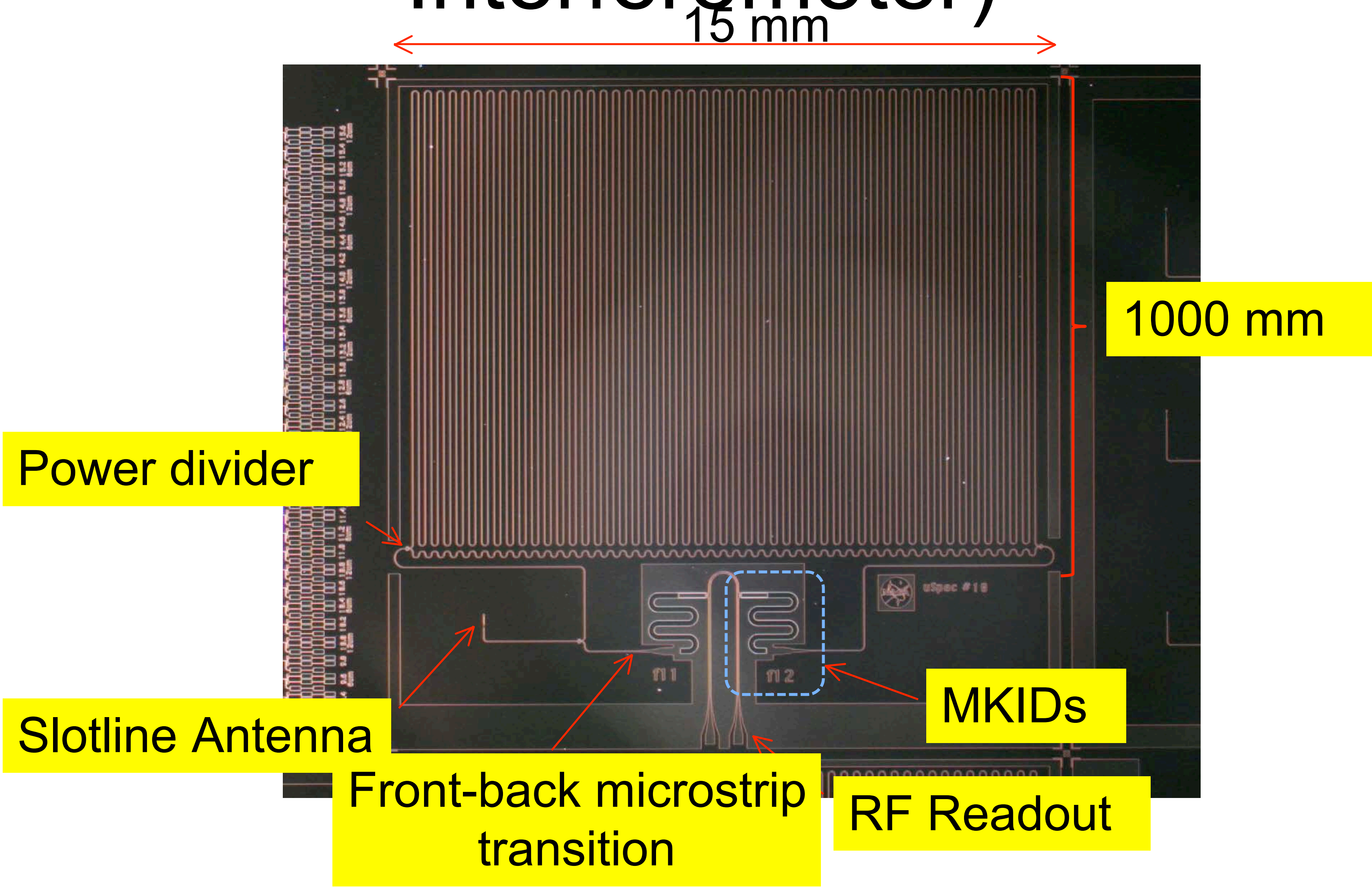
Two-line Interferometer Concept



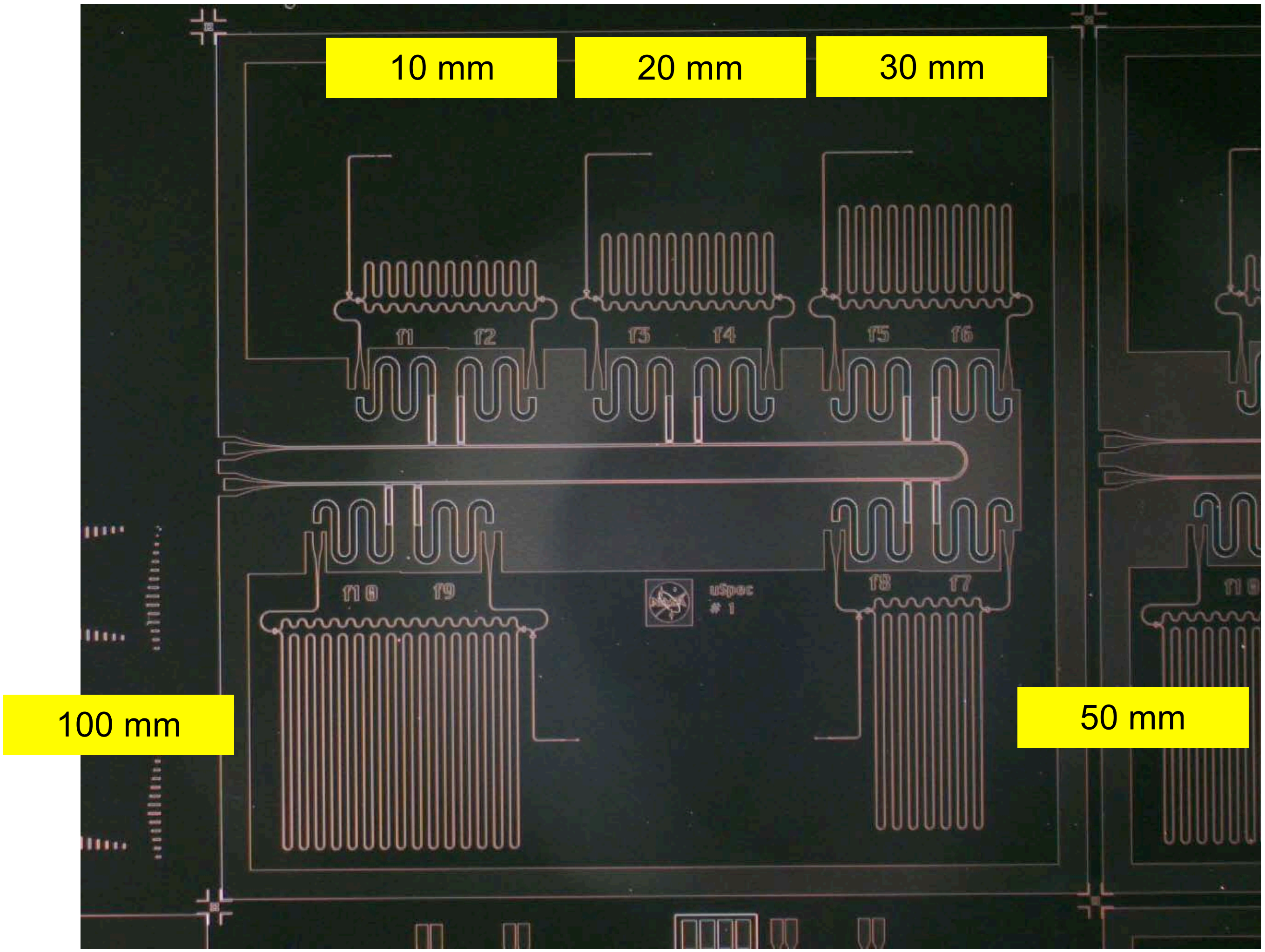
Two-line interferometer : determine the quality of the dielectric used to make the uSPEC

- Loss
- Resolving resolution
- MKID detection capability

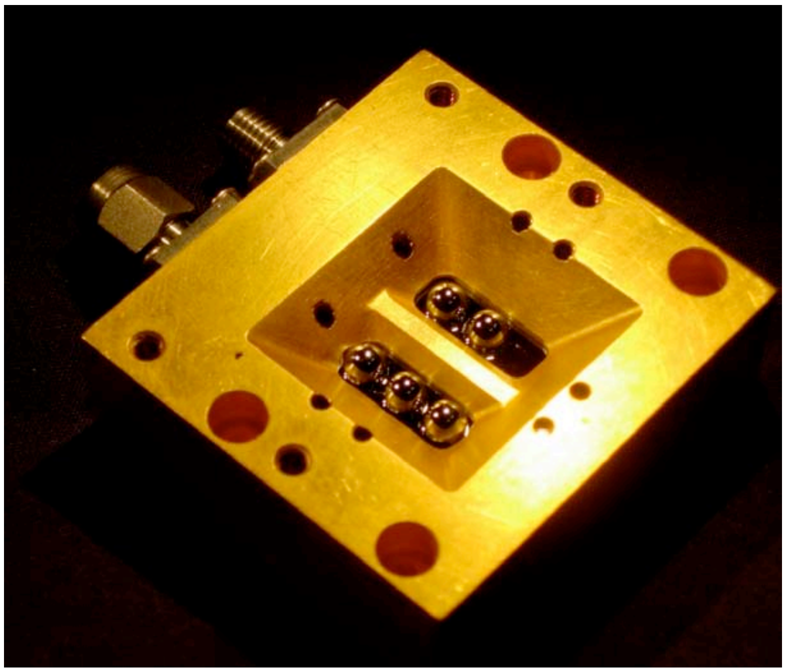
Fabricated Devices (Two-Line Interferometer)



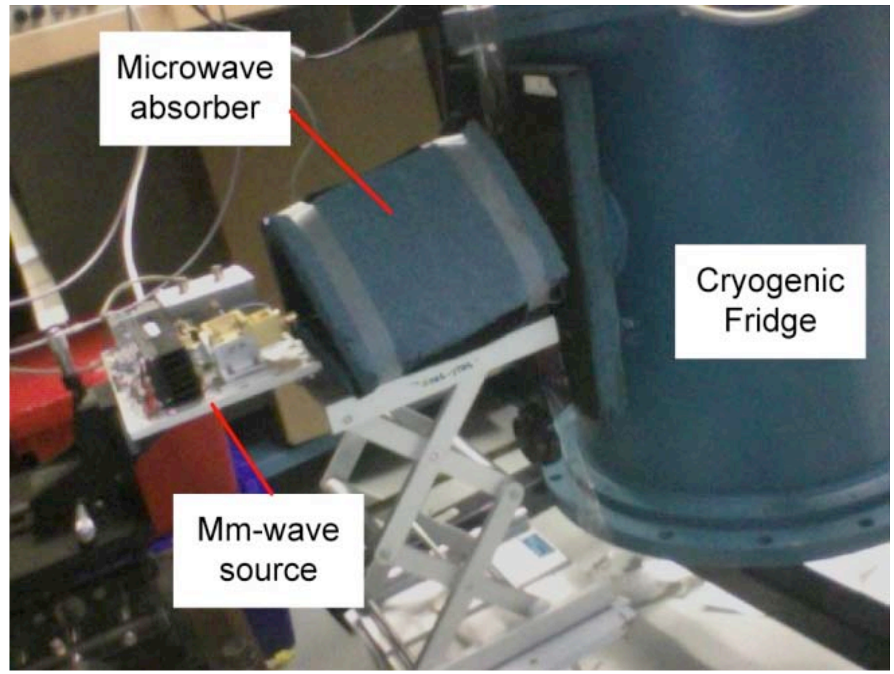
Fabricated Two-line Interference Device



Hardware Implementation

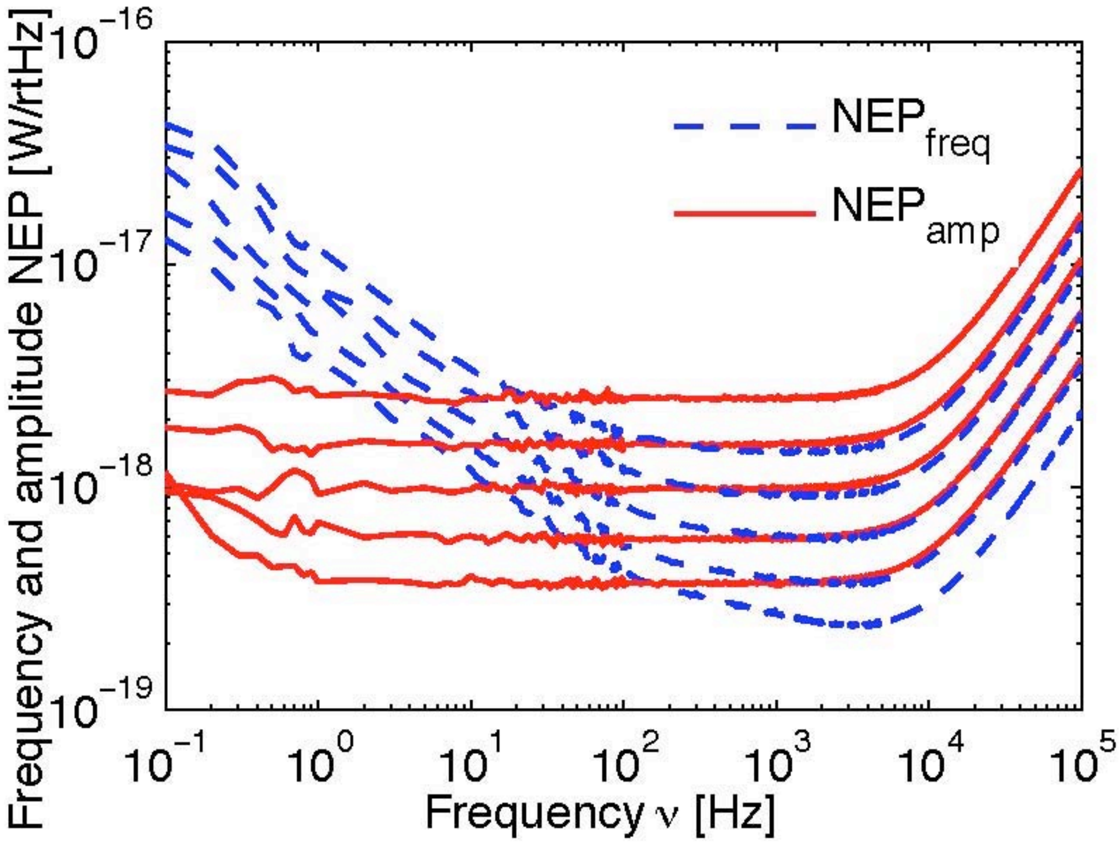


Two-line Interferometer Package



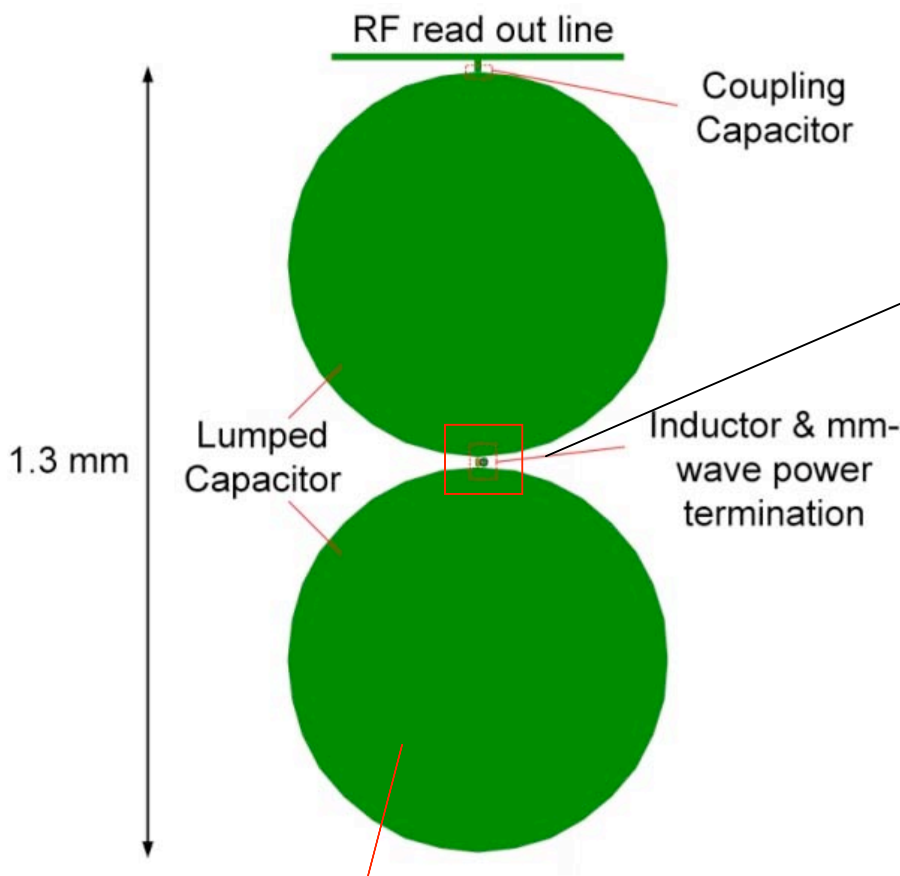
Two-line Interferometer Test Setup

Caltech/JPL MKID Noise



$\tau = 200\ \mu s$, NEP $\sqrt{\tau} = 0.035$ eV (35 μm)

Low NEP Detector Development

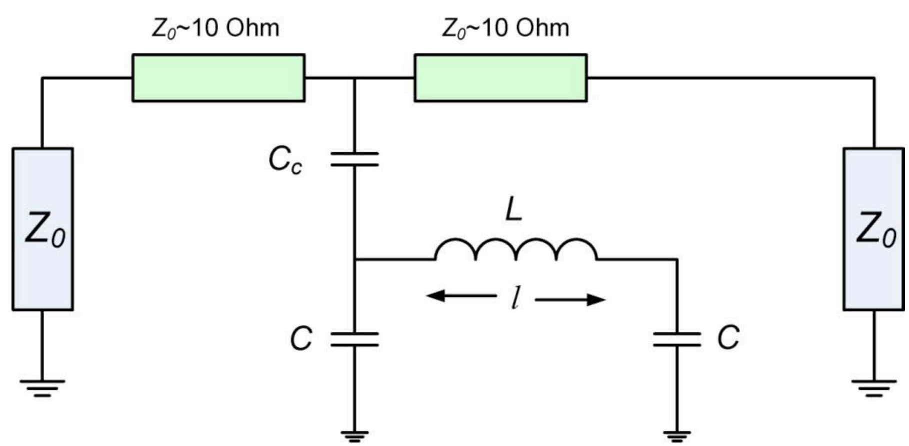


Top metal layer

$f_r = 1/(2\pi\sqrt{LC})$

NEP ~ 2.5x 10^{-20} W/√Hz!
Should count mm photons!

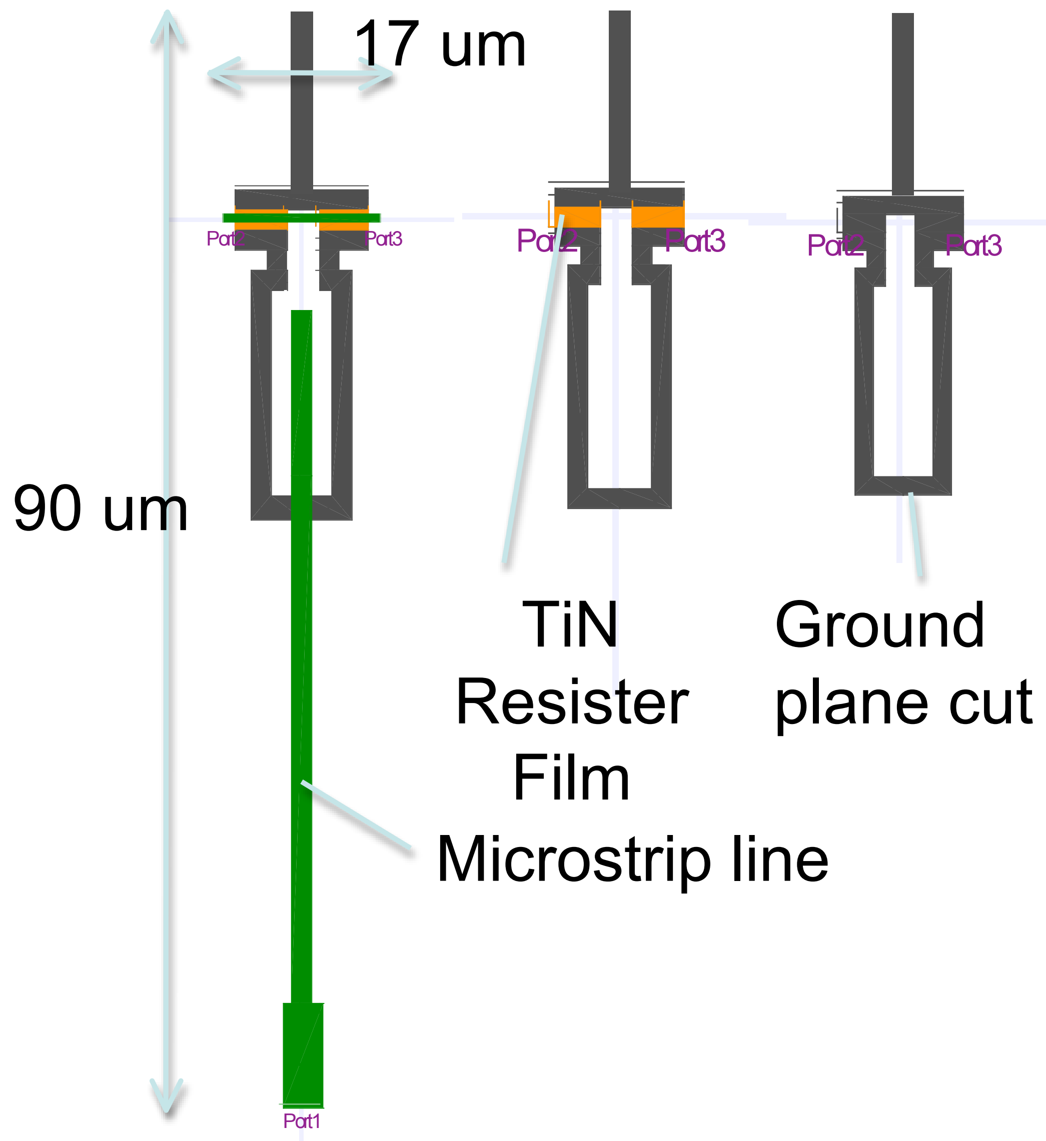
Infra-red absorber circuit



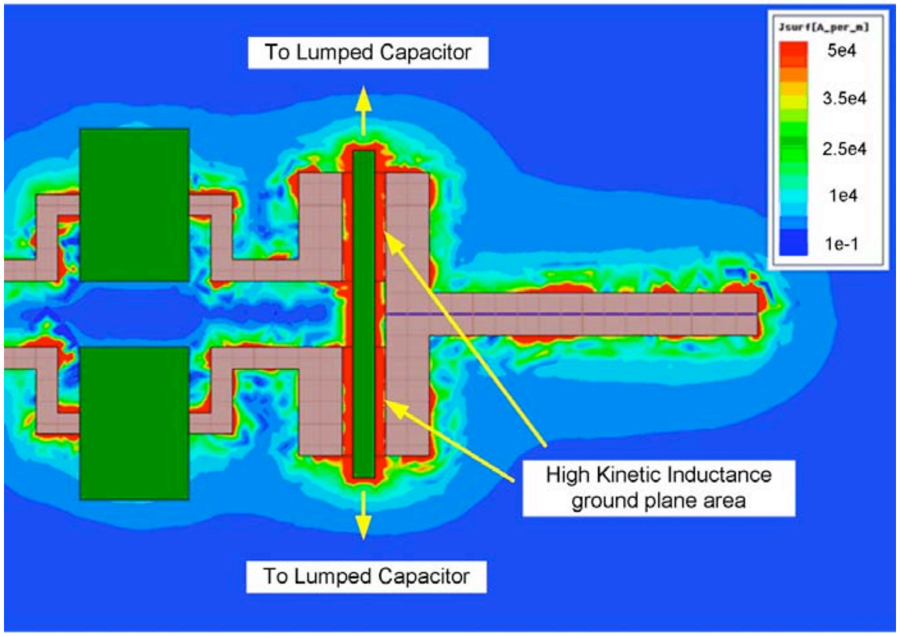
Equivalent Circuit Model

Low Volume Detector Design

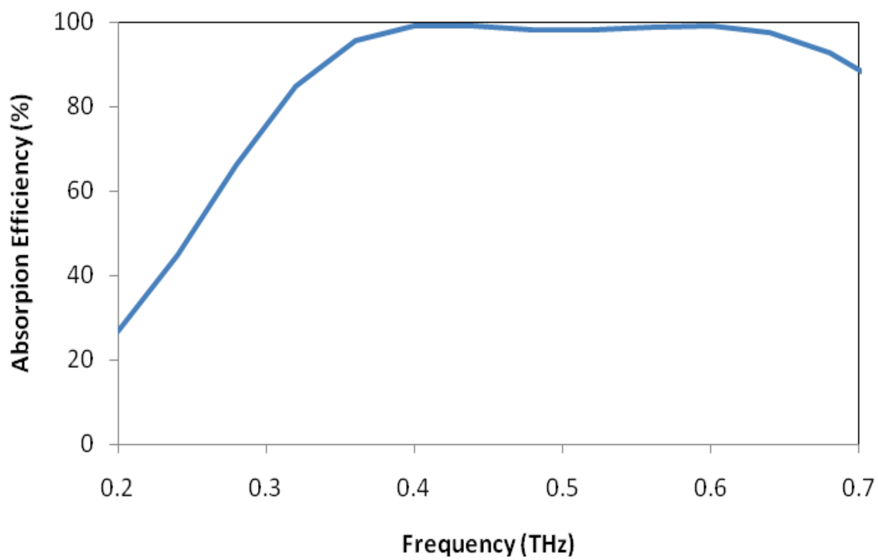
- CPW provide broadband termination for Ti-N sheet resistor
- Compact design with short resistor termination
- Cut-out slot prevent current from flowing around the resistor termination at RF frequencies
- Matching capacitor enhances the isolation level between the CPW input and the Resonator



Detector Termination Frequency Response

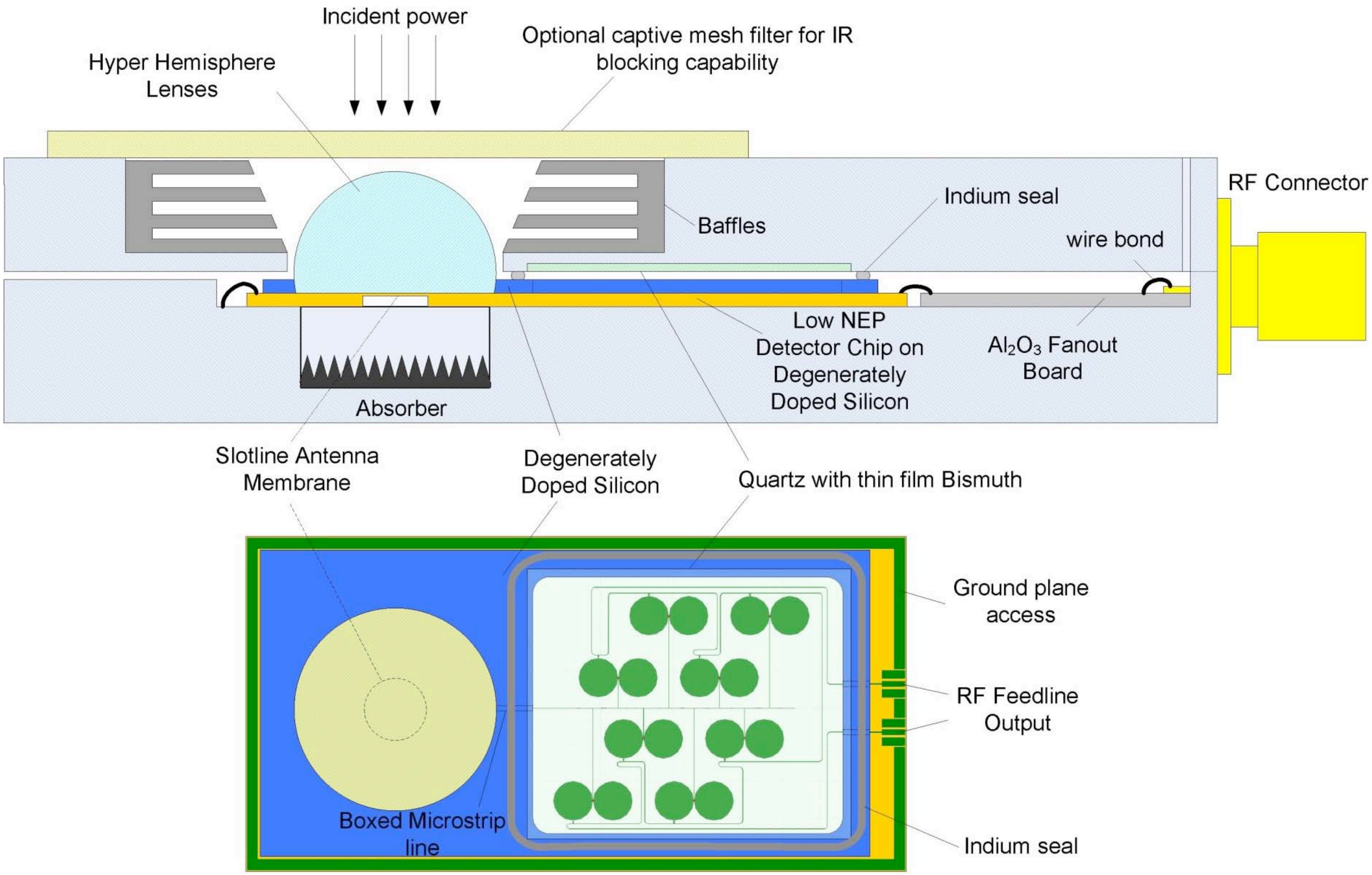


Simulated current density (A/m) of the ground plane with high kinetic inductance around the at 4 GHz



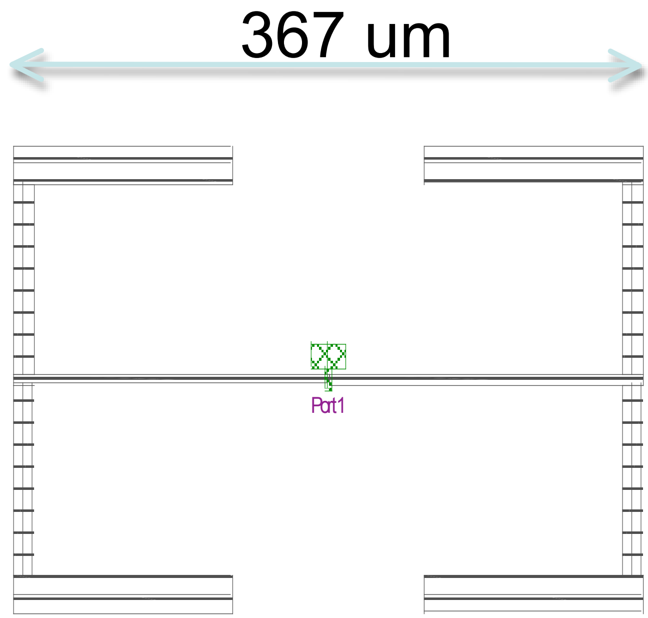
Frequency response of the detector termination

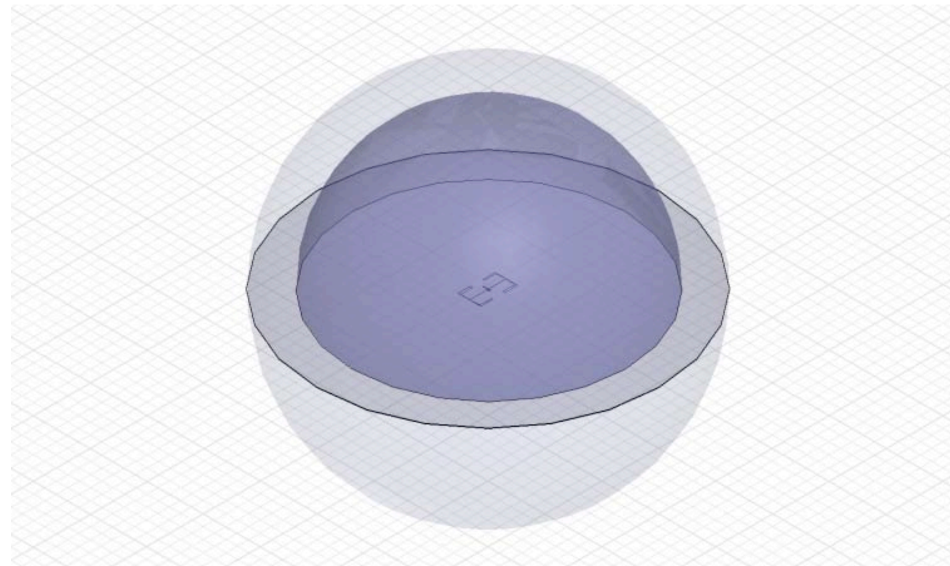
Detector Packaging



Top view of the Low NEPDetector Chip

Broadband Antenna

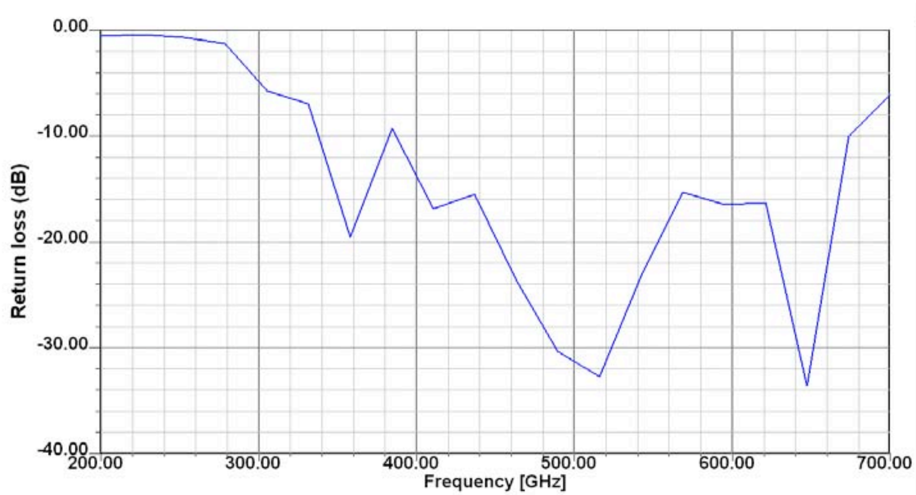




Physical layout of the Microstrip-feed Slotline Antenna

Slot antenna setup with hyper-hemisphere lens : Si sphere radius = 1 mm, Radiation sphere radius = 1.2mm

Antenna Radiation Pattern and Frequency Responses



Antenna Return loss Response

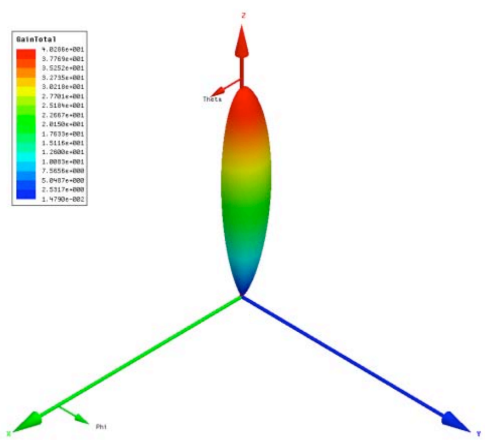
Antenna gain at 650 GHz

Antenna Radiation Pattern

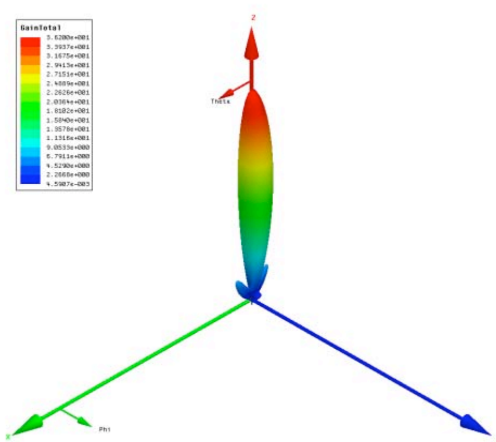
Antenna gain at 350 GHz - 3dB
Beam width ~ 19 degree

Antenna gain at 500 GHz

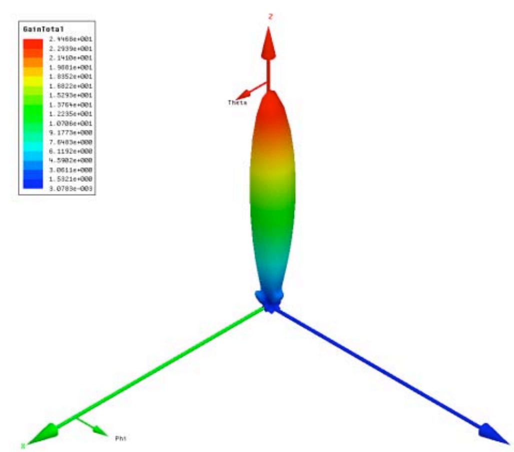
Slot Antenna 3D Radiation Pattern



350 GHz



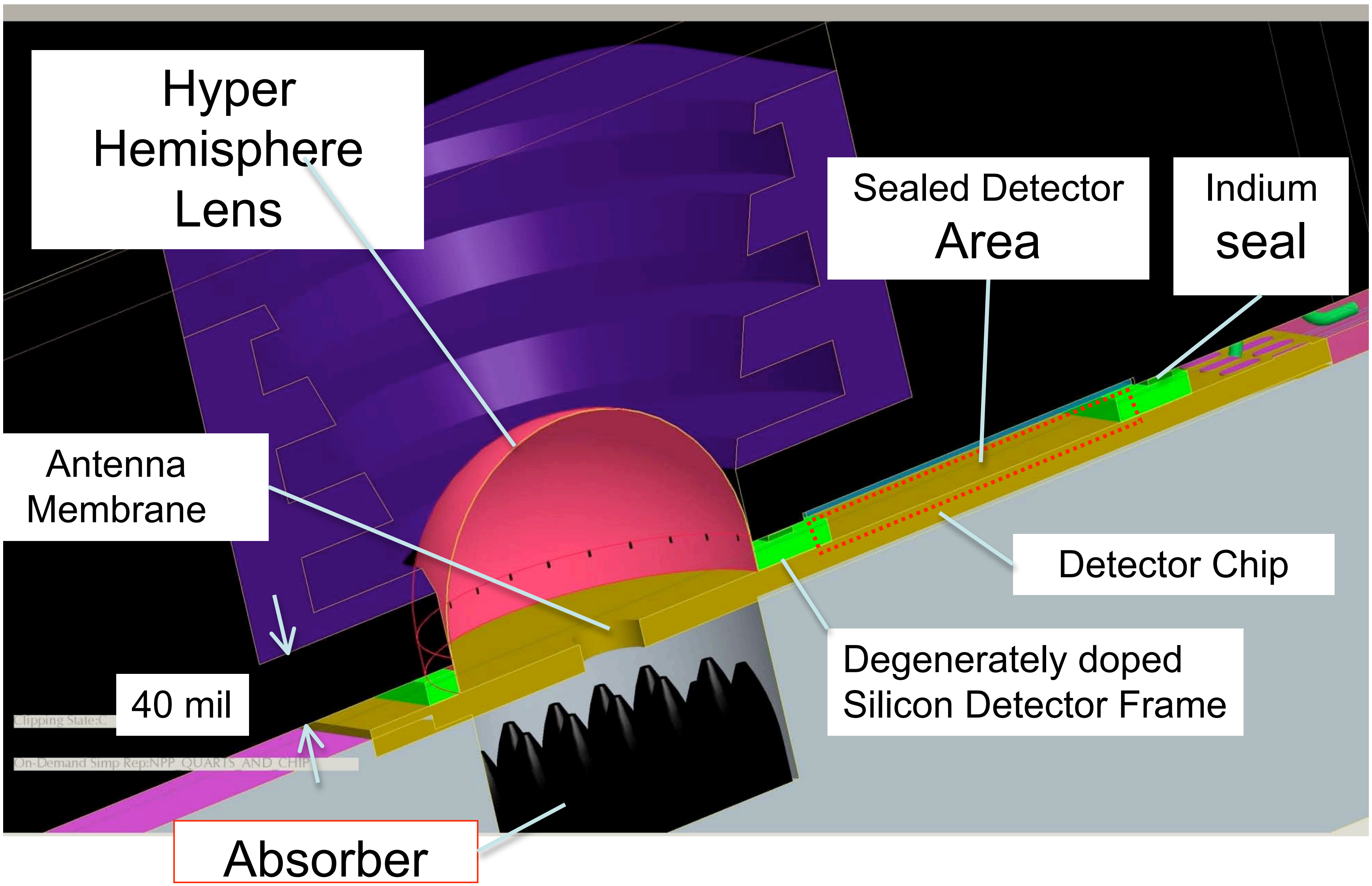
500 GHz



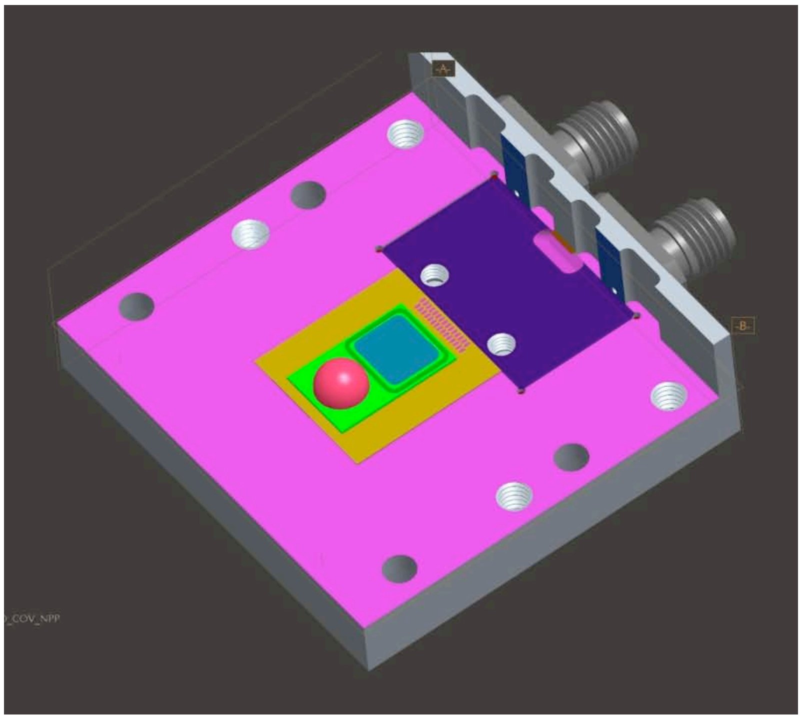
650 GHz

3D Radiation Pattern of the Low-NEP Slot antenna at 300, 500 and 650 GHz

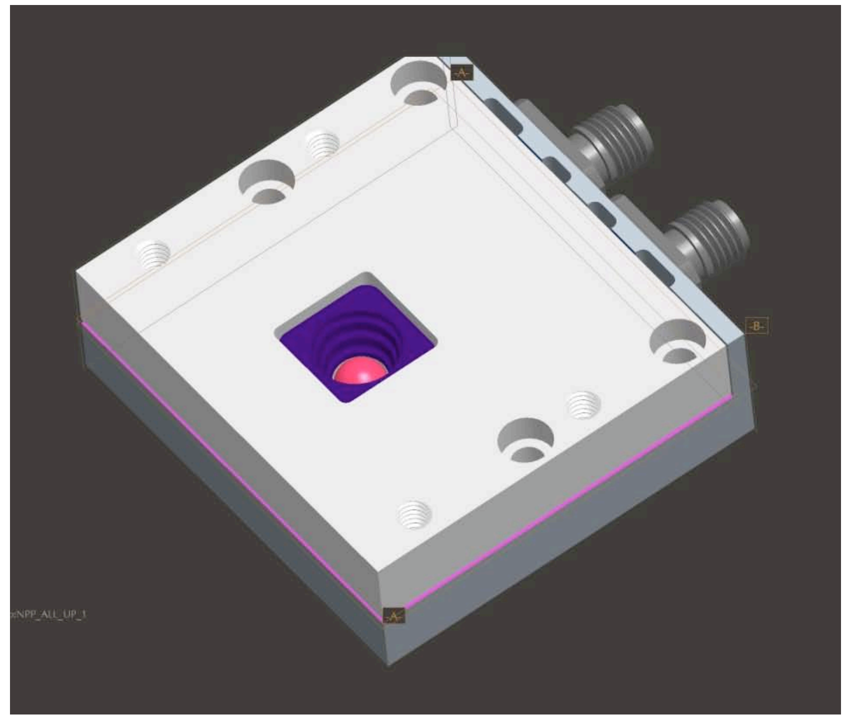
Low NEP Detector Optical Interface Area



3D View of the detector package



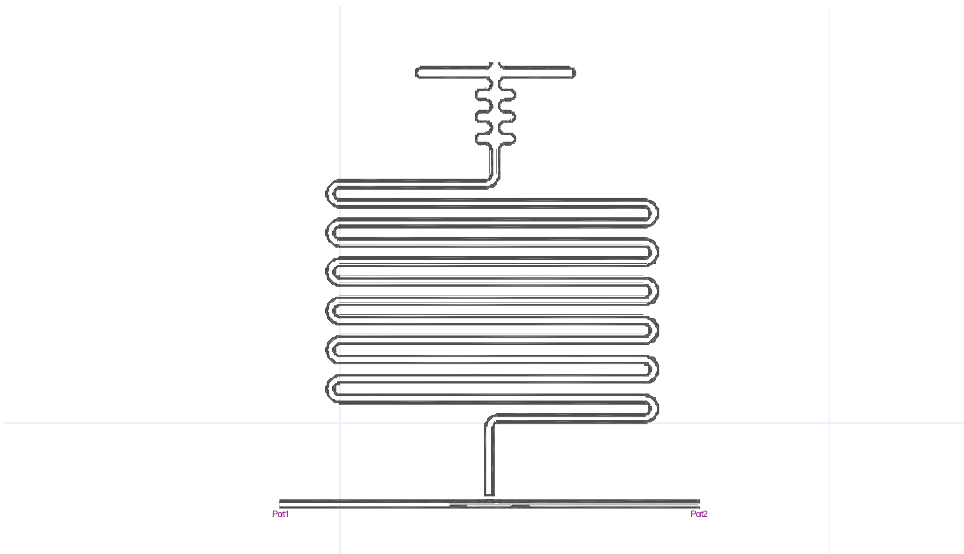
Detector Assembly without cover



Detector Assembly with cover

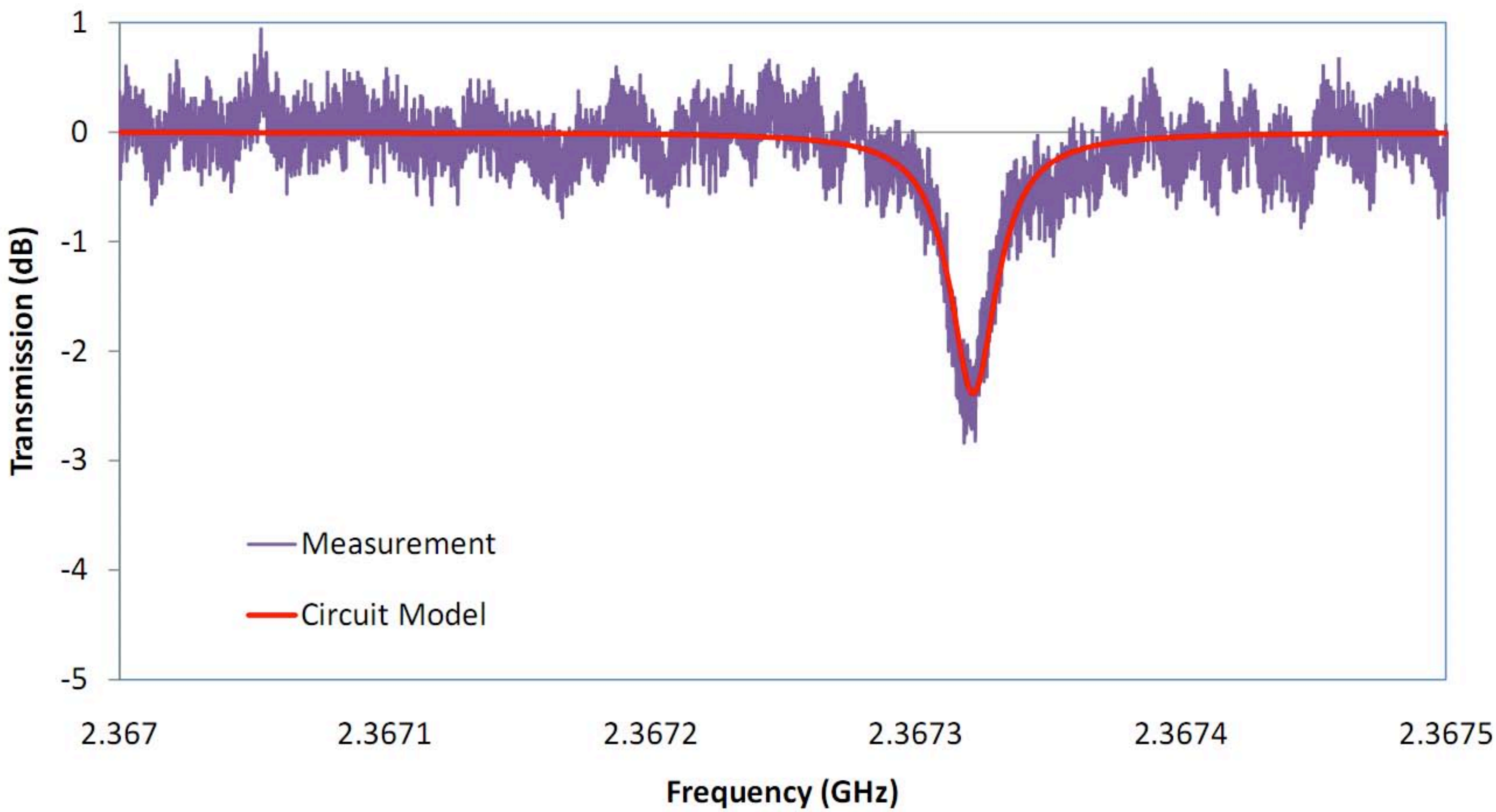
Substrate Characterization

- TiN Resonator
- MoN Resonator



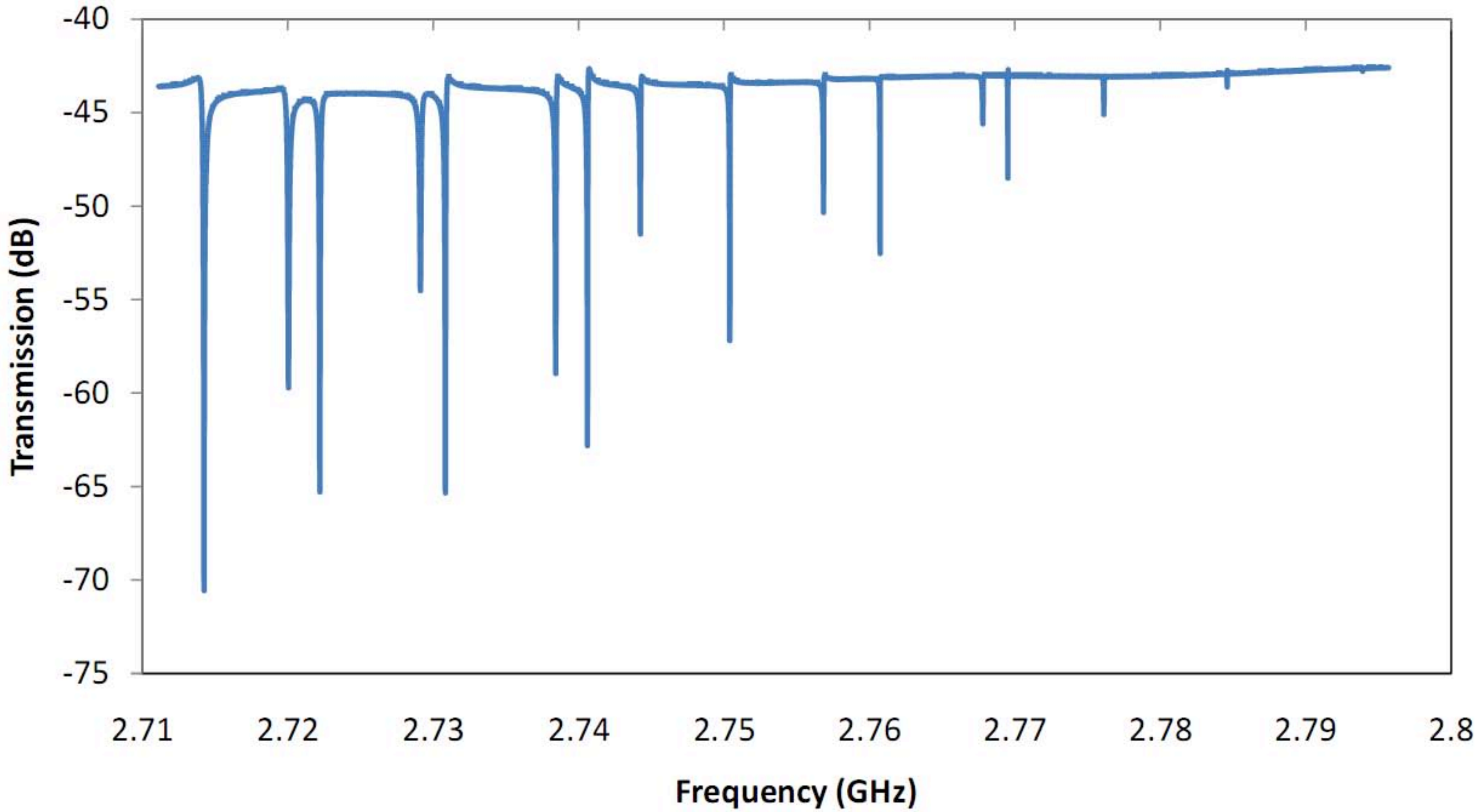
CPW resonator under investigation

TiN Measurement Results



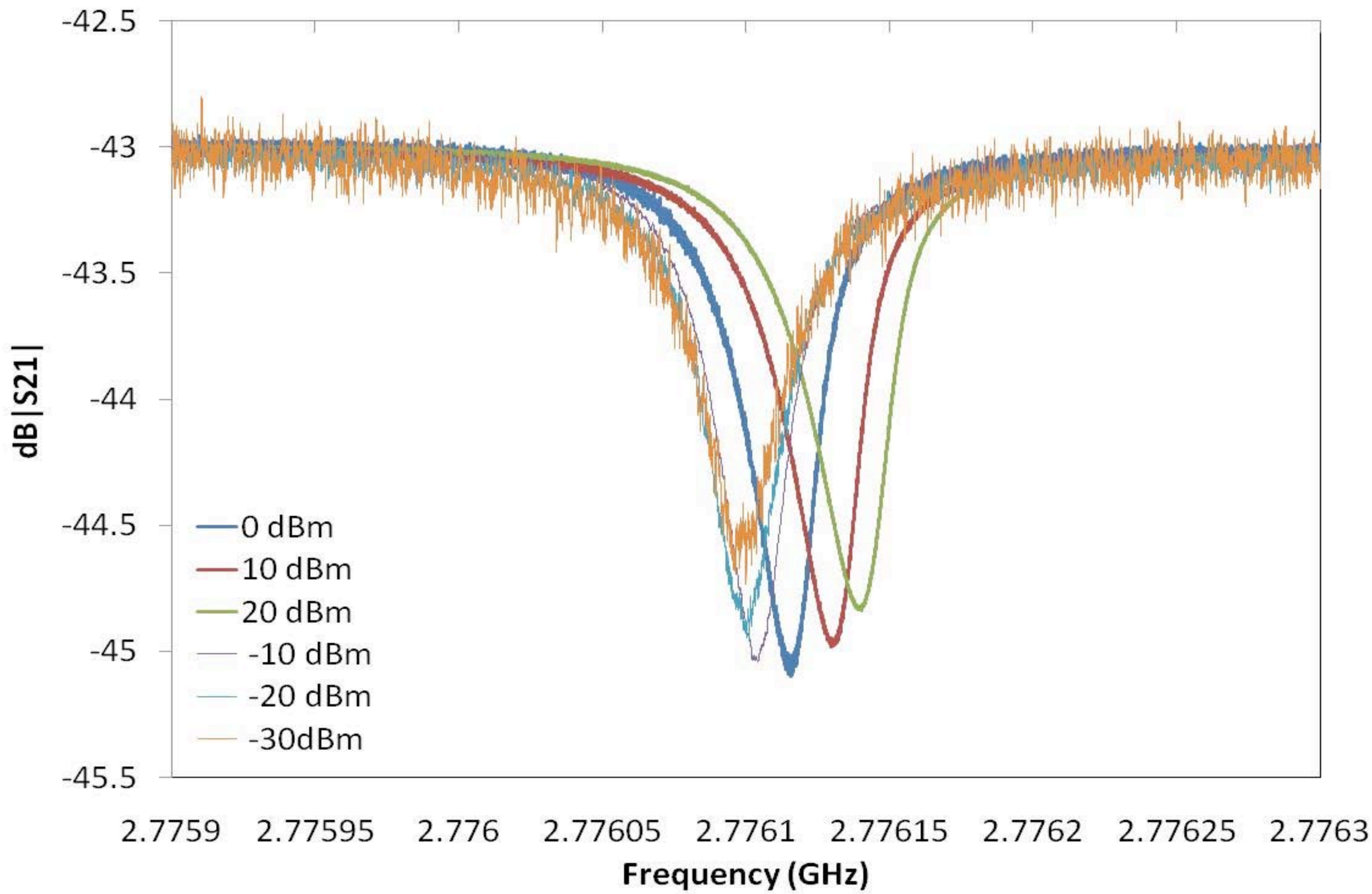
Measured and circuit model frequency response of the CPW resonator: Extracted Coupling Q = 394,553 Extracted Internal Q = 126,954

MoN Resonator Frequency Response at 0.4 K

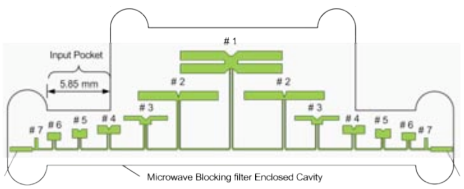


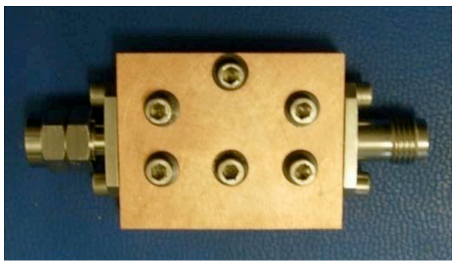
Frequency response of the MoN CPW resonators test structure containing 16 resonators Q_c ranges from 10^4 to 10^8.

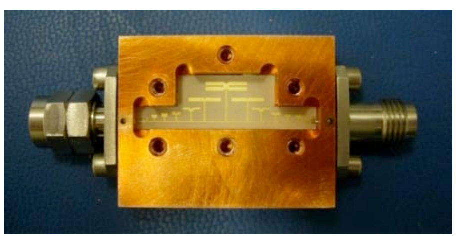
Shift in resonator frequency due to input power level (-50 to -100 dBm)

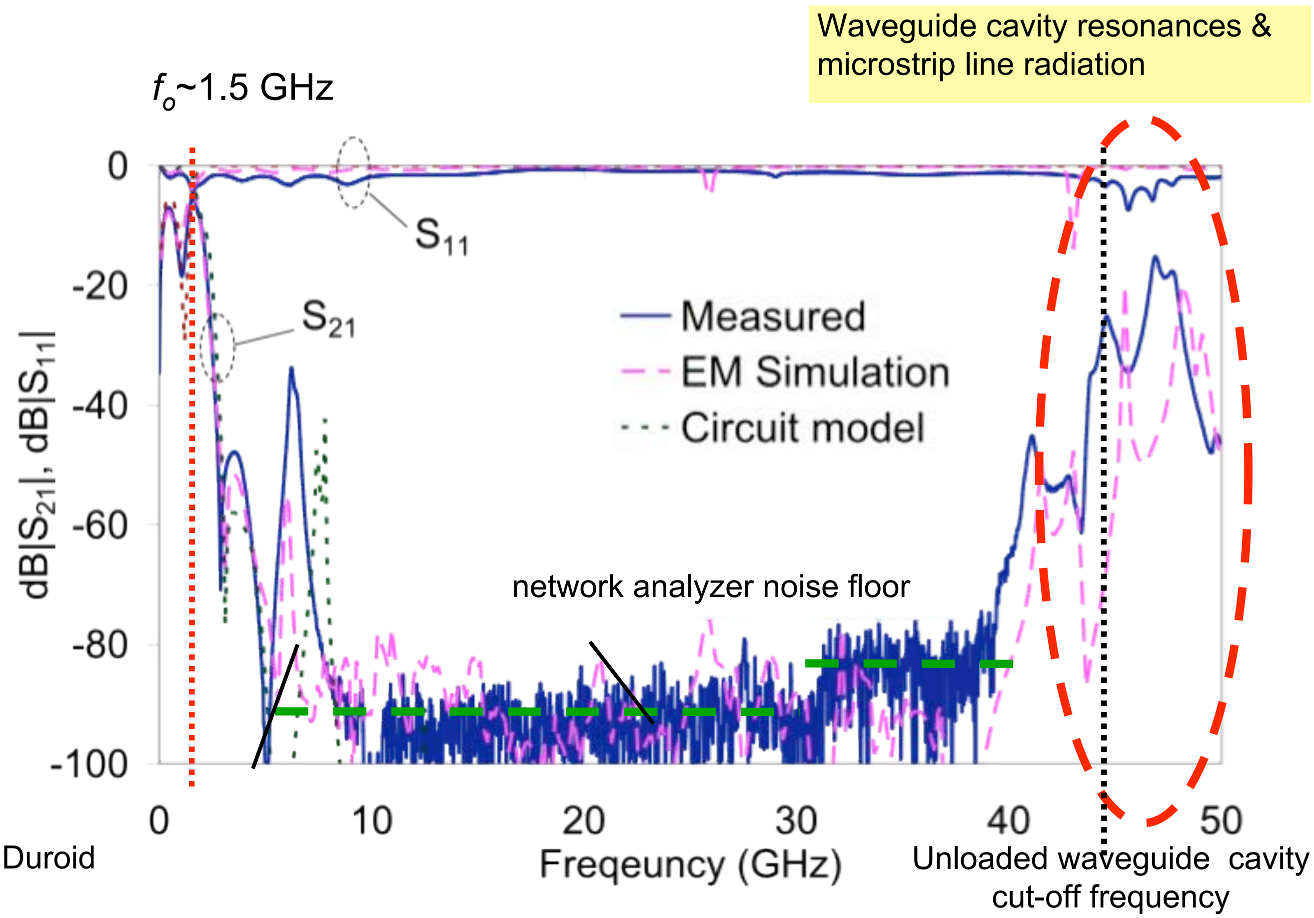


Thermal Blocking Filter: GHz…









Thermal Blocking Filter on ~125um Duroid
Measured DC parameters:
- Capacitance ~ 22.4pF
- Inductance ~ 49nH (@1MHz)
- Series Resistance ~ 0.92ohm (@300K)
- Series Resistance ~ 0.27ohm (@4K)

REFERENCE: U-Yen, K. and Wollack, E.J., "Compact Planar Microwave Blocking Filter," 2008, 38th European Microwave Conference, Amsterdam, Netherlands, in press.

μ-Spec: Features

- Is the first fully integrated high performance spectrometer system
- Can couple to large two dimensional arrays of detectors in a very small volume
- Can operate up to 700-1200 GHz
  - Set by available superconductors
- Can provide R ~500 by fabrication tolerances, > 1500 by delay line trimming
- Can be mass produced
- Optics can be highly corrected to provide diffraction limited imaging of the spectrum

Status

- All basic elements have been produced
  - Nb transmission lines with single crystal Si dielectric show low loss
    - $Q_{dielectric}$ > 1000 at 35 GHz
  - Tolerances are acceptable
    - R~500 possible by tolerance alone
  - No other complicated circuit elements
  - Relatively simple fabrication process
    - Needs only 3 metal layers

Benefits of Integrated Optics

- Compact
- Provide highly protected environment for photon counting detectors
  - Single mode in, power divided
  - Microstrip has low loss
  - Highly filtered interfaces
  - Can be almost completely boxed at operating temperature.

Summary

Integrated optics provide ideal environment for low-NEP photon counting detectors in the THz region

Provide practical technique for using large arrays of detectors for THz spectrometers

Enables very compact instruments; > 100 spectrometers, > 10^5 pixels

Instrument mass/volume/power dominated by electronics