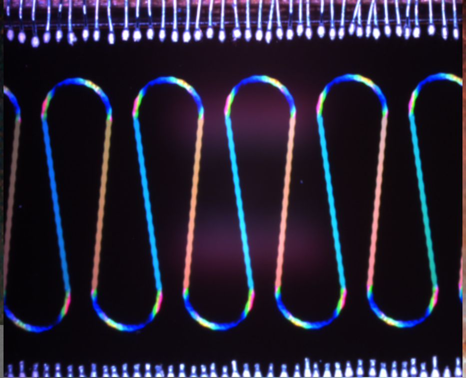

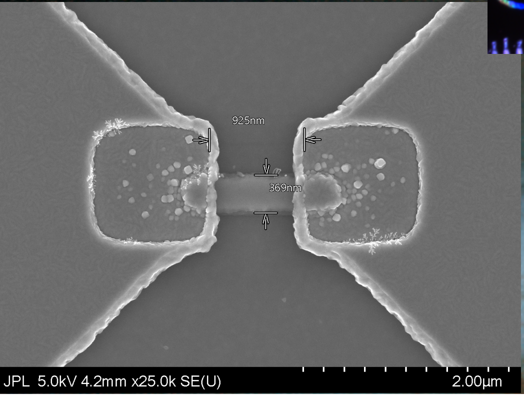

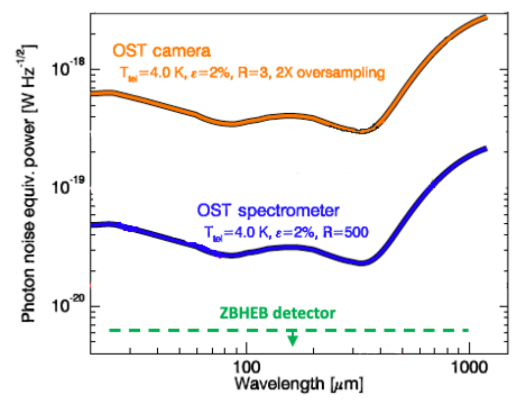

Virtual Research Presentation Conference

Array scalable zero-bias far-IR detector with high sensitivity and dynamic range

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Program: Topic

Assigned Presentation # RPC-106

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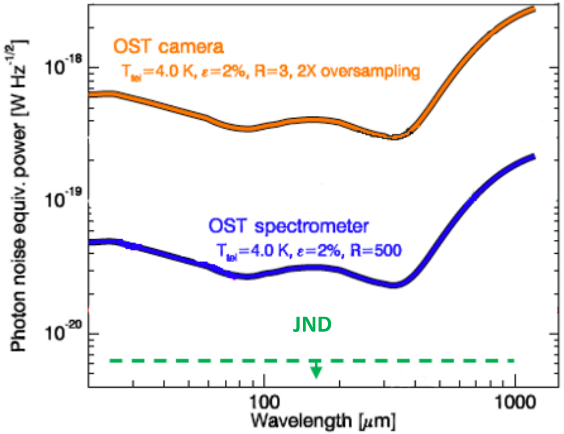
Tutorial Introduction

Abstract

We develop an ultrasensitive far-IR detector – Johnson Noise Detector (JND) – which is a hot-electron bolometer based on the normal metal. Beside the advantage of high sensitivity, the JND does not require any dc or microwave bias, has a very large dynamic range of 60-100 dB and can be operated at arbitrary temperature in the 0.05-9 K range, depending on the radiation background. The combination of the the high sensitivity is unique as very sensitive detectors usually have a very limited dynamic range and low saturation optical power. Johnson Noise Thermometry (JNT) allows the Frequency Domain Multiplexed (FDM) readout of up to 1,000 JNDs using a single broadband quantum-limited (QL) parametric LNA, a filter-bank channelizer, and a single transmission line between the detector array and room temperature electronics. The JND readout uses microwave noise power emitted by the bolometer as the measure of the sensor electron temperature, T_e. The thermal responsivity is determined by both the electron-phonon cooling and microwave-photon mediated cooling. The latter is critical at 50-100 mK. The ultimate detector Noise Equivalent Power NEP ~ 10^{-21} W/Hz$^{1/2}$ @ 50 mK. This low NEP is required for the moderate resolution spectrometers ($R = \nu/\delta\nu \sim 1000$) on a future space telescope (e.g., Origins Space Telescope – OST) with cryogenically cooled primary mirror ($T_{mirror} \approx 5$ K).

Detector sensitivity requirements for Origins Space Telescope spectrometers



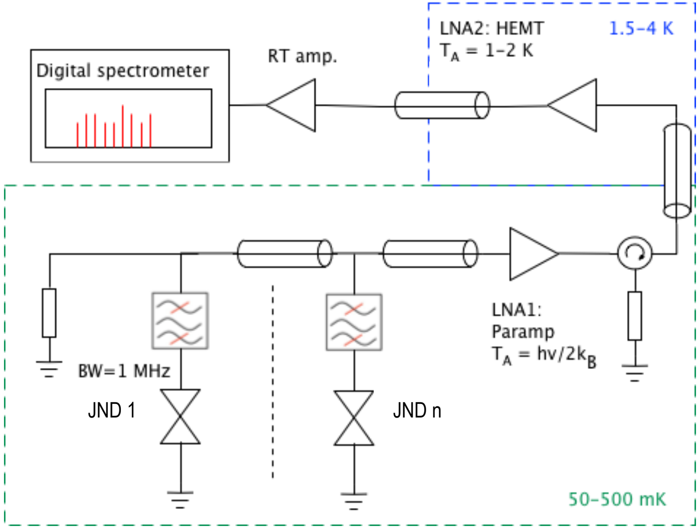
(adopted from Ref. 1)

Problem Description

- Due to its extremely low radiation background determined by the galactic emission, OST sets extraordinary sensitivity requirements (NEP < 10^{-19} W/Hz$^{1/2}$) which cannot be met by any practical detectors yet. The problem becomes even more severe as the OST spectrometers require arrays of several 1000s detectors. Efforts in several labs to achieve needed detectors are ongoing but this will definitely take long time and there is no obvious leading technology.
- Currently, three technologies have demonstrated promising NEP results. They are Transition-Edge Sensor (TES) [2,3], Kinetic Inductance Detector (KID) [4,5], and Quantum Capacitor Detector (QCD) [6]. However, none of these has been demonstrated in a practical instrument. A significant issue with such detector is the low saturation power preventing the deployment of the detector anywhere except the ultimate space telescope with cold mirror. JND is very different in the way. The same detector can be used on any high-background platform including ground based telescope.
- NASA's current push is the OST concept as a part of the 2020 Decadal Survey in Astronomy and Astrophysics. Both "Large-format, low-noise and ultralow-noise Far-IR direct detectors" covering roughly a spectral range of 30-600 µm with NEP down to 3×10^{-21} W/Hz$^{1/2}$ and "Cryogenic readouts for large-format Far-IR detectors" with at least a 1000 pixels per amplifier channel multiplexing ratio are among the top technological priorities identified in the recent 2017 Program Annual Technology Report of Cosmic Origins Program Office, Astrophysics Division, NASA's Science Mission Directorate, in support of the OST instrument suite. Our detector array approach addresses one of the Tier 1 Technology Gaps identified in the 2019 Astrophysics Division Space Mission Directorate's Astrophysics Biennial Technology Report named "Large-Format, Low-Noise and Ultralow-Noise Far-IR Direct Detectors." JPL has a strong interest in far-IR astronomical instrument and has been historically very strong with the development of new detectors in this range. The current effort is well aligned with these trends.

Methodology

- The approach is to use a small thin-film normal-metal AuPd hot-electron device with Nb superconducting contacts and to employ JNT as an FDM low-noise readout [7]. The approach is unique and has not been pursued by anybody. At sub-Kelvin operating temperature (our target is T = 50 mK), the model predicts an NEP ≈ $(1\text{-}2)\times10^{-21}$ $W/Hz^{1/2}$ for the 0.3µm x 0.15µm x 17nm devices currently available.



- Each JND detector element is connected to the same low-noise L-band amplifier (LNA) through a bandpass (BW = 0.2-1 MHz). All filters have different center frequencies thus making an FDM for the broadband white Johnson noise generated by the detectors. The impinging far-IR radiation heat up the electrons in the detector thus increasing the Jonson noise. All filter outputs are fed into a single transmission line which is the only connection from the JND array to the room-temperature electronics.
- The first stage LNA is the Kinetic Inductance Parametric Amplifier (KIPA) [8] which is nearly quantum-noise limited. The total bandwidth optimal for accommodation of ~ 10^3 JND elements is about 1.5 GHz (L-band).
- In contrast to other sensitive detectors, the JND does not exhibit the hard saturation by a large signal. The detector and the KIPA together are expected to have a ~ 100-dB dynamic range.

The Goal

Our goal was to developed and built the essential components needed for implementation of the JND detector array and carry out electrical NEP measurements with a prototype JND detector.

The components been developed include

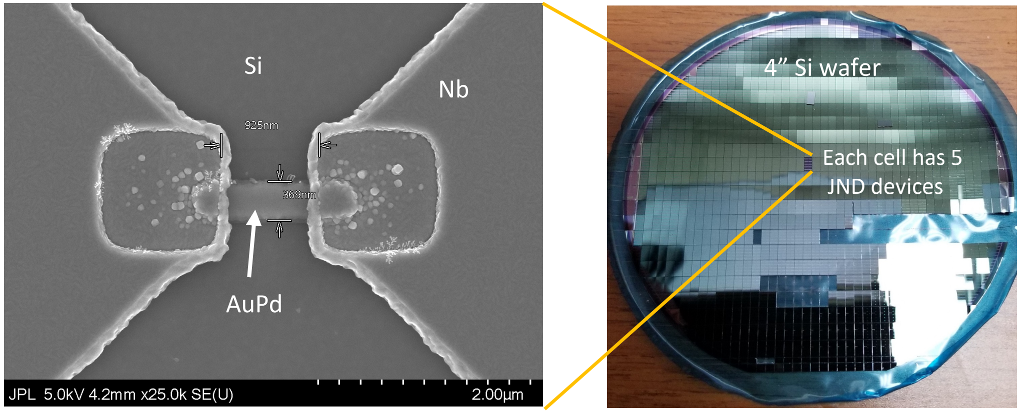
- Submicron-size normal-metal JND devices
- L-band KIPA
- Ultra narrow band-pass filters (Q ~ 1000)

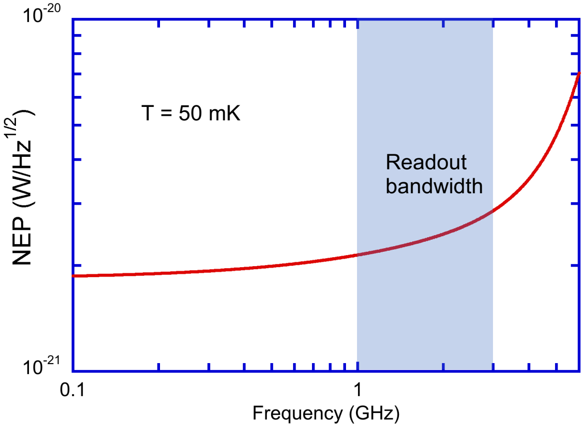
The ultimate NEP $\approx 2\times10^{-21}$ W/Hz$^{1/2}$ is an extremely challenging goal and the plan was to approach it gradually, using different combinations of the LNA (the HEMT amplifier, $T_A \approx 1$K, to start with) and the bandpass filter.

Results: AuPd JND Devices

JND devices were fabricated by thermal evaporation of 17-nm AuPd film of a Si wafer. Using, UV projection lithography and e-beam lithography, devices with dimensions in the range of 0.5µm × 0.15µm to 1µm×0.3 µm were achieved. The resistance of the cold devices is close to 50 Ohm. AuPd bridges are terminated by superconducting Nb leads in order to prevent the diffusion of thermal energy which would deteriorate the sensitivity of the detector.

These devices are optimal in their parameters for achieving the lowest possible NEP for this type of detector. Our model [7] predicts NEP as low as 2×10^{-21} W/Hz$^{1/2}$ at low readout frequency. The degradation of the NEP with frequency is due to the extinction of Johnson noise (Wien’s limit for 1D blackbody radiation).



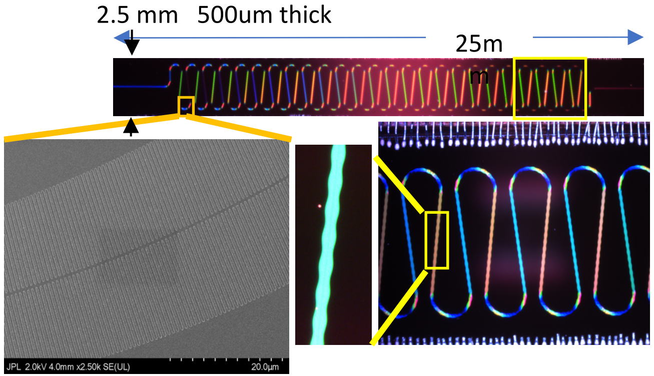


Results: L-band KIPA & s/c diplexer/filter

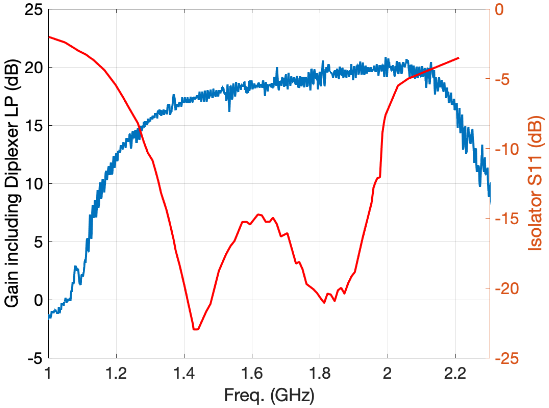
Kinetic Inductance Parametric Amplifier is a very important element for this work since it the NEP of JND is inversely propositional to the noise temperature of the readout amplifier. KIPA has demonstrated the quantum noise limited noise temperature of $hf/2k_B$ which is the fundamental minimum. In FY20, we achieved the L-band (1.2-1.9 GHz) version of KIPA with the large gain of up to 20 dB. This is a 3-wave mixing mode microstrip device pumped at 6.6 GHz.

Also, a superconducting diplexer/filter has been developed. This component is needed for limiting the KIPA bandwidth and minimizing losses (maximizing sensitivity).

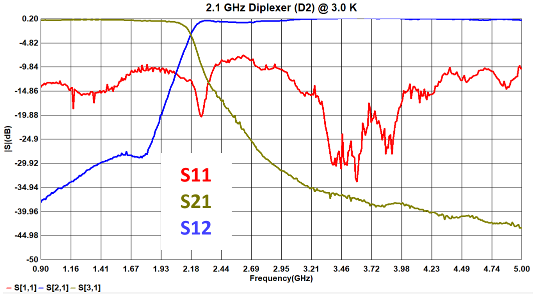
L-band KIPA



KIPA's gain including isolator's loss

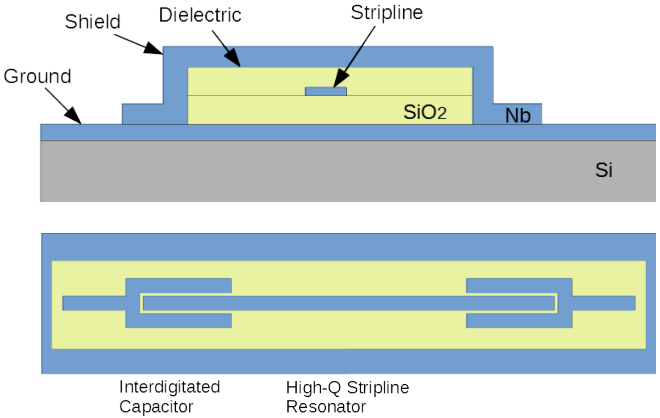


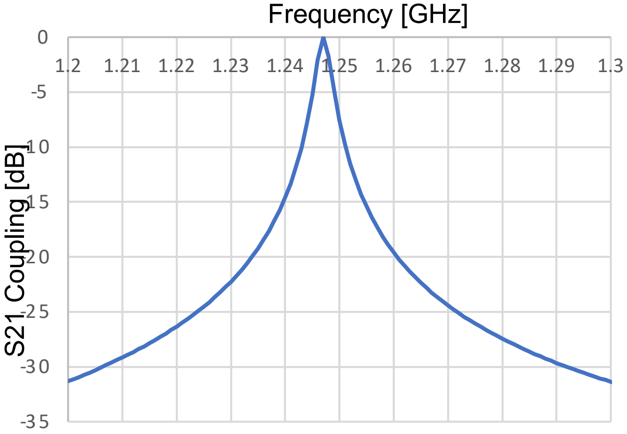
Superconducting diplexer



Results: Ultra Narrowband Superconducting Filters

In order to achieve the comb filter with ~ 10^3 channels for multiplexing an array of JND detectors, we designed high-Q bandpass filters using shielded superconducting microstrip lines. The comb would cover the range between 1 GHz and 3 GHz where the NEP would be the lowest.

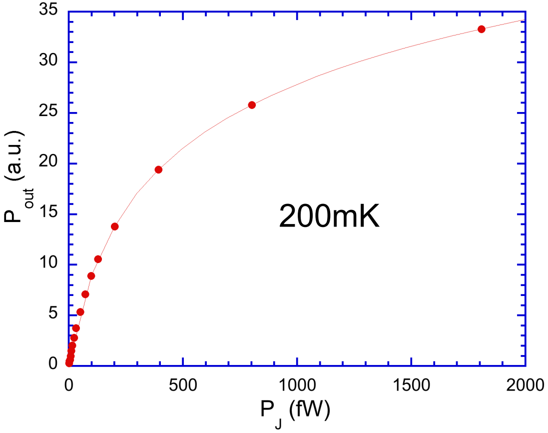


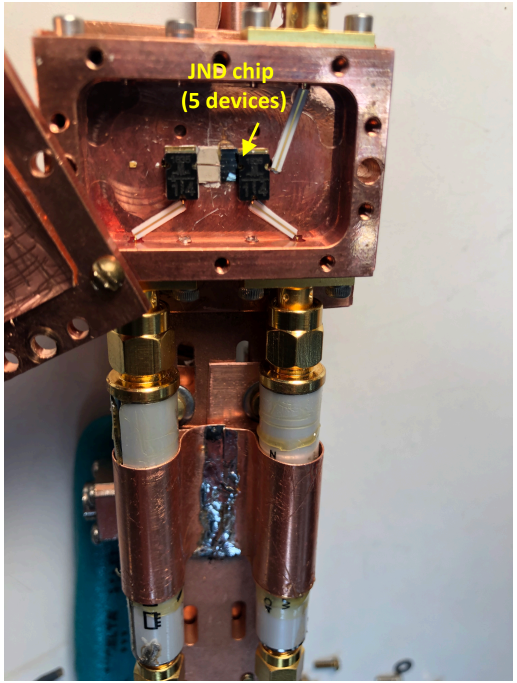


Shown HFSS simulation:
Strip width 20μm
Strip thick 2μm
Dielectric SiO_2 ; ε=4.0
Dielectric bottom 2μm
Dielectric top 4μm
Resonator length 60mm
3 fingers/capacitor
Finger length 3500μm
Finger gap 2μm
3dB Bandwidth = 3MHz

Results: Electrical NEP Test

- An experimental test setup for electrical NEP measurements includes a shielded box holding the JND device and two chip cryogenic bias-T's, a coaxial band-pass filter (f_0 =1.38 GHz, BW = 50 MHz), an L-band cryogenic isolator and a HEMT LNA ($T_A \approx$ 1K). The JND assembly connects to the LNA via the NbTi superconducting coax to minimize the microwave loss. DC bias wires are filtered using cold 10-kOm resistors and 80-MHz lowpass filters to prevent loading of the devices by the 300-K thermal noise.
- The dc bias is needed for NEP characterization only. The procedure is to substitute the far-IR power with the small Joule power (ΔP_J) and measure the change of the output microwave noise power (ΔP_{out}) and the rms value of the noise power in the 1-Hz signal bandwidth $<P_{out}>$. Then the detector responsivity $S = \Delta P_{out} / \Delta P_J$. The ratio of $<P_{out}>/S$ gives electrical NEP.
- So far, NEP ~ 10^{-17} W/Hz$^{1/2}$ has been measured at 300 mK that is consistent with the theory prediction. The experimental technique needs further improvement and troubleshooting of potential issues at lower temperatures.





Significance of the results and next steps

The importance of the FY20 results is as follows:

- Optimal (ultimately small, 50-Ohm resistance) JND devices have been achieved;
- An L-band parametric amplifier with high gain based on the kinetic inductance has been further optimized by adding a superconducting band-limiting diplexer;
- Shielded superconducting filters with Q ~ 1000 suitable for frequency domain multiplexing of a 1000-pixel JND array have been designed;
- Electrical NEP measurements of the new JND device with a 1-K LNA have been carried out.

Overall, we are getting closer to having this new detector technology validated via demonstration of the extremely low NEP value required by OST. Our next step is to continue this development effort under the NASA’s APRA program.

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