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# Far infrared imaging spectrometers for the next generation astronomical instruments

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***Abstract*—Advances in far infrared astronomy have been, and will be, defined by instrument capabilities. Especially relevant is the development of imaging spectrometers for the wavelength range of 0.03-3 mm, which are not available at all at this moment. We will discuss recent advances in this field: First, we discuss the development of miniature on-chip spectrometers, that can operate in a 0.09-1 THz by using lossless superconducting circuits to create miniature spectrometers. For higher frequencies this is not possible due to material limitations, moreover instruments have to be operated in space due to the opacity of the atmosphere. Recent proposals for new missions focus on space-based observatories with optics cooled down to 4K, which offer unprecedented spectral imaging speeds, but require large arrays of extremely sensitive detectors. In the second part of this paper we will discuss the development of microwave Kinetic Inductance detectors with a sensitivity of NEP ≈ $3.1 \cdot 10^{-20}$ W/√Hz, sufficient for these applications.**

## I. Introduction

RADIATION in the far-infrared (FIR) part of the electromagnetic spectrum, loosely defined as the 0.03-3 mm wavelength range, represents about half the energy generated in the universe since the Big Bang and includes information from processes mostly invisible at other wavelengths. Further advances in FIR astronomy would especially benefit from the development of imaging spectrometers: Instruments capable of creating 3D data of significant part of the sky, where 2 dimensions are spatial, and the 3rd dimension of the datacube consist of the spectral information of the radiation detected at each spatial position.

## II. Results

For ground-based astronomy the atmosphere only admits radiation for wavelengths longer than 0.3 mm. Using radiation dispersion or Fourier Transform Spectrometers in combination with large detector arrays are impractical due to the long wavelengths of 3-0.3 mm, resulting in very large instruments. This problem can be elegantly be circumvented by fabricating on-chip filterbanks, originally proposed in [1]. These systems take advantage of the fact that superconductors like NbTiN allow lossless circuits up to a frequency of 1.1 THz (wavelengths down to 0.27 mm). The first astronomical observations were performed with the instrument Deshima on the ASTE telescope in Chile [2]. This was a prototype validating the technology. We are now in the final integration state of Deshima-2, a broad band (215-430 GHz) spectrometer with a resolution R=500. In the top panel of Fig.1. we show an

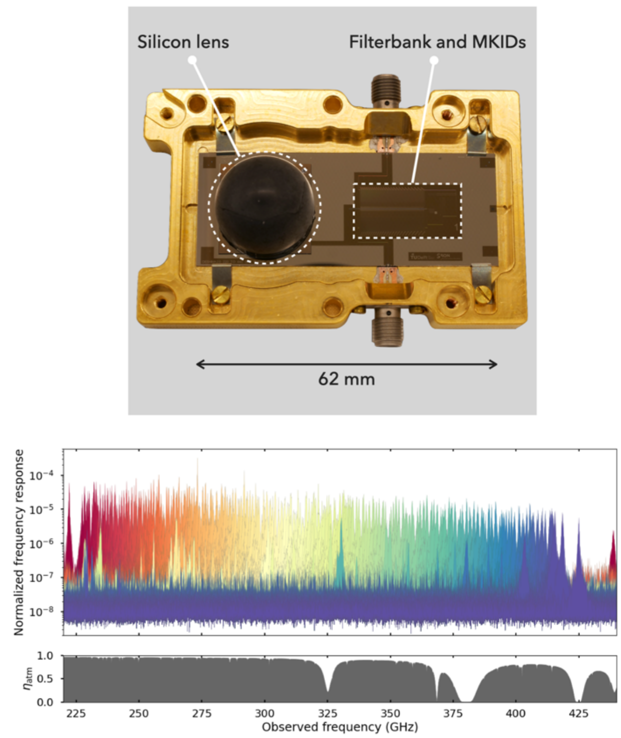


**Fig. 1.** Top: Photograph of the Deshima-2 on-chip spectrometer holder and chip. Bottom: Measured spectral response of the spectrometer, showing the individual detector responses coloor coded, as well as the atmosphereic

image of the on-chip spectrometer chip, showing the Si lens, equipped with stycast anti-reflection coating. In the focus of the lens is a leaky-wave antenna coupling the radiation to a long, lossless coplanar waveguide transmission line to the filterbank. The filterbank consists of 370 band pass filters, each coupled to a microwave kinetic inductance detector (MKID). Hence each MKID will detect only radiation in a narrow band. This is illustrated in the bottom panel of Fig.1: Each color-coded curve represents the response of an individual MKID to a frequency sweep of a continues wave source coupled to the lens. The design of this filterbank is discussed in great detail in [3].

Ground based observations are possible up to 1 THz, but even there they suffer from the limited transmission of the atmosphere. Hence, going to space is advantageous, and for frequencies above 1 THz even essential. Here spectroscopy is only possible with quasi-optical front ends such as gratings, which are relatively compact due to the shorter wavelengths. Another important advantage of space missions is that the telescope optics will cool down to temperatures of order 50K-

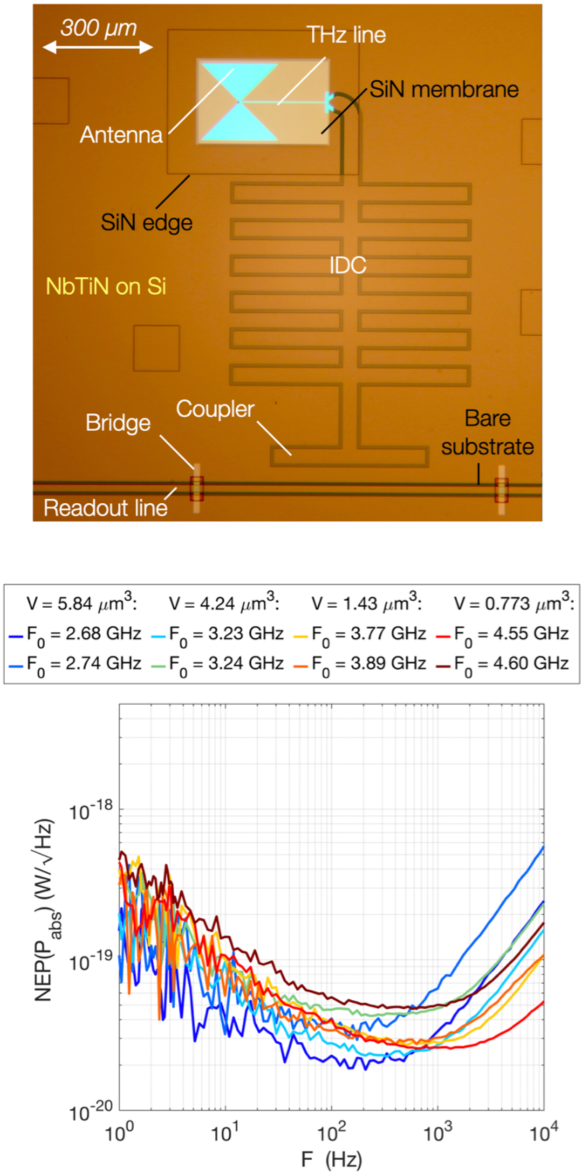


**Fig. 1.** Top: Micrograph of a single detector. It consists of a NbTiN CPW line loaded with an interdigitated capacitor (IDC) coupled to the readout line via a coupling structure. Its shorted end consists of an aluminium section fabricated on a thin SiN membrane, highlighted by the use of backlighting in the micrograph. Bottom: Measured NEP for 8 detectors, with different aluminium lengths resulting in different aluminium volumes as indicated in the legend.

80K, reducing the telescope self-emission in the THz frequency range. However, the radiation flux due to the universe itself is extremely weak, and even a 50K telescope will self-emit orders of magnitude more flux than the background radiation of the universe itself. Since thermal radiation is quantized, radiative loading creates a noise signal on the detectors, limiting the detector sensitivity. To reach a radiative load less than the universe background, allowing what is called 'background limited radiation detection', requires cooling the telescope down to 4K. This is technologically feasible, but such an observatory sets extreme requirements to the detector sensitivity: A detector noise equivalent power NEP $\approx 3{\cdot}10^{-20}$ W/√Hz is needed for a R = 500 spectrometer. MKIDs are a very interesting detector technology for these applications: They allow for large arrays, are relatively simple and have been used in many ground based and balloon based observatories. Additionally, they have a relatively high technological readiness for operation in space [4], but until very recently did not reach the required sensitivity. We present a new MKID design, where radiation coupling and absorption take place in a small aluminium volume fabricated on a 100 nm SiN membrane, which is embedded in a NbTiN resonator. A leaky-wave lens-antenna couples the radiation to a very small aluminium transmission line where radiation absorption occurs A micrograph of the device, without lens, is given in the top panel of Fig. 2. We obtain a mean NEP $\approx 3.1{\cdot}10^{-20}$ W/√Hz for 8 detectors measured using a thermal calibration source filtered in a narrow band around 1.5 THz [6]. This is sufficient for the most demanding applications in future space-based observatories with cryogenically cooled telescopes. At negligible power falling on the detector, which is the case at these NEP values, the spectral shape of the NEP is limited by 1/f noise, limiting the performance at low modulation frequencies. The measured data is given in the bottom panel of Fig.2. When we increase the radiation load on the detector to an absorbed powers of 53 aW, the NEP becomes limited by the radiation background to a NEP $\approx 1{\cdot}10^{-19}$ W/√Hz. At these and higher power levels the detector noise becomes white down to 1 Hz. The antenna design, device geometry and assembly allow scaling to frequencies up to $\lesssim$ 8 THz. Importantly, creating kilo-pixel arrays from the presented device design is possible using the same readout technology and system integration as discussed in Ref. [4].

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