A millimeter-wave hyper-spectral device based on Lumped Element Kinetic Inductance Detectors

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November 10, 2022

\textbf{ABSTRACT}

Context. Millimetre-wave astronomy is an important tool for cosmology. In this context, the Line Intensity Mapping (LIM) technique has been proposed to map in three dimensions the specific intensity due to line (e.g. [CII], CO) emission. This mapping is particularly interesting to study the primordial galaxies as a function of redshift. LIM observations are typically carried out on single dish telescopes, since it is not required to resolve the individual objects.

\textbf{Aims.} Hyper-spectral integrated devices have the potential to replace the current Fourier transform, or the planned Fabry-Perot-based instruments to achieve efficient, i.e. large field-of-view, line intensity mapping at millimeter and sub-millimeter wavelengths. The aim is to perform hyper-spectral mapping, with a spectral resolution \( R = \lambda / \Delta \lambda = 100 \sim 1000 \), over large, i.e. thousands of beams, instantaneous patches of the Sky. The device that we have developed allows avoiding moving parts, complicated and/or dispersive optics or tunable filters to be operated at cryogenics temperatures.

\textbf{Methods.} We have designed, fabricated and tested an innovative integrated hyper-spectral device sensitive in the 80-90 GHz range. It contains nineteen horns and sixteen spectral-imaging channels, each selecting a frequency band of about 0.1 GHz. A conical horn antenna, coupled to a planar superconducting filter, collects the radiation. A capacitively coupled Lumped Element Kinetic Inductance Detector (LEKID) is then in charge of dissipating and sensing the super-current established in the filter.

\textbf{Results.} The prototype is fabricated with only two photo-lithography steps over a commercial mono-crystalline sapphire substrate. It exhibits a spectral resolution \( R = \lambda / \Delta \lambda = 800 \). The optical noise equivalent power is in the observational relevant \( 10^{-17} \text{W}/\sqrt{\text{Hz}} \) range. The device, as expected from 3-D simulations, is polarisation-sensitive, paving the way to spectro-polarimetry measurements over very large instantaneous field-of-views.

\textbf{Key words.} Instrumentation, detectors, millimeter-wave, spectrometer, superconductivity

1. Introduction

The Line Intensity Mapping (LIM) technique \cite{Kovetz2017}, \cite{Dumitru2019} aims to map the specific intensity due to line (e.g. [CII], CO) emission. Such a mapping, if achieved with spectrally-resolving instruments, allows to disentangle the line emission as a function of the redshift. The end result is thus a three-dimensional view of the observed region. LIM observations are typically carried out on single dish telescopes, since the goal is not to resolve the individual objects but on the opposite to maximize the mapping speed, i.e. enhancing the sensitivity and the field-of-view (FoV).

One possible technique is to use low-temperature on-chip spectrometers \cite{Volpert2022}, \cite{Karkare2015}, \cite{Bryan2015}, \cite{Karkare2020}, \cite{Endo2019}, \cite{Chowdhury2022}, aiming to achieve intermediate resolution, i.e. \( R = \lambda / \Delta \lambda = 100 \sim 1000 \). The main limitation is, despite the recent dramatic improvements, the number of available readout electronics channels. In the near future, it will not be possible to cover, with this technique, the large instantaneous FoV that are required for the planned LIM experiments. On top of that, for technological reasons the existing devices exhibit relatively low overall quantum efficiency. Similar spectral resolutions, over large FoV, are currently achieved using FTS (Fourier transform spectrometers) \cite{CONCERTO2020}, \cite{Monfar2021}. The drawback is in this case represented by the higher optical background per pixel, translating into lower per-pixel sensitivity. Furthermore, the optical design is complicated, requiring for example large moving mirrors at room temperature.

An efficient alternative that has been proposed is the use of Fabry-Perot elements operating at low temperatures. This is for example planned for the EoR-Spec project \cite{Cothard2020}. In this case the observing frequency is swept by the settable narrow-band Fabry-Perot filter to reconstruct the spectrum. This approach is compatible with large FoV, i.e. thousands spatial pixels simultaneously on the sky, and does not suffer from the high per-pixel load limitation. The drawback lies in the narrowness of the instantaneous bandwidth.

In this work we present the design, fabrication and optical characterisation of an innovative hyper-spectral device based on Lumped Kinetic Inductance Detectors (LEKID). Our HYPKID prototype focal plane targets the so-called "3-mm atmospheric window". The extension to higher frequencies, e.g. 2-mm and 1-mm windows, is feasible. With respect to the existing on-chip spectrometers the advantages of the HYPKID are: a) the larger number of spatial pixels, i.e. larger instantaneous field-of-view; b) the easy fabrication, comparable to the well-proven LEKID imaging arrays \cite{Adam2018}.
The HYPKID fabrication process is made by only two photolithographic steps and does not require the deposition of dielectrics. The incoming signal, at a frequency comprised between 80 GHz and 90 GHz, does not have to be guided through a planar transmission line. On top of the already cited advantages, this allows a decisive gain in the overall quantum efficiency.

The HYPKID, in terms of focal plane efficiency, compatibility with large FoV, photon noise and mapping speed, is exactly equivalent to a Fabry-Perot instrument.

2. Design and Fabrication

Our prototype HYPKID device has been designed for and fabricated on a two inches 100 \( \mu \)m-thick monocrystalline C-plane sapphire substrate. It contains nineteen horns; sixteen of them with spectral capabilities and three for continuum measurement. A schematic view, including a picture, is presented in figure 1.

The incoming signal is collected by an array of nineteen smooth conical horn antennas disposed over an hexagonal pattern. The 12 mm long horn ends up in a portion of cylindrical waveguide with a diameter of 2.5 mm. The cutoff frequency is around 70 GHz, and the antenna is expected to be single-mode \((T_{E_{11}})\) until the onset of the \(TM_{01}\) mode above 91 GHz. For sixteen horns, the waveguide itself radiates, on the other end, toward the c-shape filters that provide the spectral capabilities. The vacuum gap is of approximately 700 \( \mu \)m, to be further optimised for the next generation of devices.

The co-planar superconducting filters are coupled to the LEKID that dissipate the mm-wave signal via generation of quasi-particles. The resonance frequencies of the LEKID are affected by the change of their kinetic inductance. A single Ghz (microstrip) readout line is frequency-multiplexing the sixteen channels on a single electronics IN/OUT pair of coaxial cables. The readout rate for the HYPKID tests is fixed at 46 Hz. The superconducting filters are half wave planar resonators. The length of each of the sixteen filters is varied to cover the 80-90 GHz range. The coupling quality factor of each filter with the mm-wave microstrip is adjusted to target a bandwidth of 0.1-0.2 GHz. The filters shape aims at maximizing the current next to the LEKID, and optimising the dissipation efficiency in the detector.

To establish the possible use of the c-shaped millimeter-wave planar filter as efficient termination for the horn-waveguide we have simulated the structure using CST Studio Suite®. The Titanium-Aluminium LEKID is defined in the simulation as an ohmic sheet with a resistance of 2 \( \Omega \) per square. The Aluminium filter on the other hand has a purely imaginary impedance of 2 \( \Omega \) per square to reproduce the kinetic inductance. In a first simulation, presented in the figure 1b, we have calculated the fraction of the power flowing into the waveguide that is dissipated into the LEKID and is thus expected to contribute to the signal. At the filter resonance peak and for the current prototype device we expect an efficiency of around 50%. This confirms that the device that we propose is an efficient option, especially compared to the existing on-chip spectrometers that exhibit lower quantum efficiencies. The cross-polarised signal is predicted at around 5%. From our simulations we expect, after optimisation of the device geometry, a conversion efficiency of up to 80%.

The figure 1c shows the simulated surface current in the metal layers, i.e. LEKID and filter. The plots evidence the polarisation selectivity of the device. The c-shape filter absorbs mostly the InPol direction of the electric field. The cross-polarised signal is mainly due to the direct absorption into the LEKID inductive meander that is exposed to the waveguide output.

The resonant frequency of each LEKID is tuned by adjusting the length of the meander (L) and one of the fingers of the capacitor (C). The resonance frequencies range between 1.5 GHz and 1.8 GHz. The internal quality factor \( Q_i \) (material) and the coupling quality factor \( Q_c \) (design) are both in the 10^5 range. The LEKID, as in our standard imaging devices (Adam et al. 2018), are coupled to a 50 \( \Omega \) micro-strip readout-line.

Three types of superconducting materials have been used to fabricate the HYPKID: pure aluminium (20 nm), titanium-aluminium bi-layer (10 nm / 25 nm) and aluminium cover with gold (200 nm / 200 nm). The pure aluminium superconductor (Al) is a lossless conductor for frequencies smaller than its spectroscopy gap 2\( \Delta_{Al}/h \) \(~110\) GHz. It is used for the (lossless) c-shape filters and patterned via standard UV lithography and lift-off. The titanium-aluminium bi-layer (TiAl) aims to dissipate the radiation for frequencies higher than its spectroscopic
At the peak of the filter resonance the fraction of incoming power that is dissipated and contributes to the signal is of around 50%. The FWHM of the resonance is compatible with a spectral resolution $R = 450$. The predicted cross-polarisation signal is around 5%.

It is evident that the radiation collection is achieved in the filter for the InPol case, while it is mostly happening directly in the LEKID inductive meander for the CrossPol situation.

The TiAl bi-layer is also used for the GHz microstrip readout line. This layer too is patterned using standard UV lithography, followed by diluted HF etching. The aluminum covered with Au is used for the ground plane on the back-side of the substrate. The Au layer is crucial to ensure a good thermalisation of the device (and thus a fast time constant), whereas the thick Aluminium ensures a high-quality (superconducting) electrical ground plane.

3. Experimental set-up

The hyper-spectral device is mounted in a custom optical dilution refrigerator (mm-wave camera) with a base temperature of 60 mK. The camera is directly derived from the NIKA (Néel IRAM KID Arrays) instrument (Monfardini et al. 2011), and also described in Chowdhury et al. (2022).

For characterisation, we have adopted a commercial mm-wave source coupled to a pyramidal emission horn. The mm-wave source is polarised and can be set in the range 75-110 GHz with Hz-like frequency precision. It is however not calibrated in intensity. In order to attenuate the signal entering the cryostat we insert, in front of the input lens, five Eccosorb$^\text{TM}$ sheets. Each sheet attenuates the signal by a factor around 25. The total attenuation is thus estimated around $10^7$.

The signal per channel of the spectrometer is defined as the frequency shift of the corresponding LEKID. In previous publications, we have demonstrated the linear proportionality between the absorbed power and the frequency shift (Swenson et al. (2010), Calvo et al. (2013)). The frequency shift of the LEKID is measured using a dedicated multiplexing electronics (Bourrion et al. 2013), synchronized with the mm-source.

4. Results and discussion

As a result of a complete characterisation cycle, we show in figure 4 the HYPKID pixels responses and the corresponding spectral resolution. Thirteen out of the sixteen designed channels are functional, showing a very clear peaked spectral response in the range 78-88 GHz. Due to the optics constrains (size of the focal plane), the external horns are expected to experience some degree of vignetting, explaining part of the response scatter.

As expected from the simulations described above, the device is polarisation selective. The un-filtered background is...
clearly detected in the CrossPol direction at an amplitude of around 2 kHz, while it is much less pronounced in the InPol scientifically useful direction. In this polarisation direction the integrated un-filtered background contributes to the signal for less than 10% over the whole band. This is achieved thanks to the orthogonal polarisation absorption of the filter and the LEKID.

The measured spectral resolution of our prototype HYPKID, shown on a pixel-per-pixel base in the figure is around $R \approx 800$. This value is slightly higher than the simulation prediction ($R \approx 450$).

The Noise Equivalent Power (NEP) corresponds to the power producing a signal-to-noise ratio of one in one Hz output bandwidth. It is calculated as:

$$\text{NEP} = \frac{P \cdot N}{\delta f} = \frac{P}{(S/N)}$$

where $\delta f$ is the frequency shift (Hz) of the LEKID resonance generated by the change of the optical power load $P$ (the power per pixel) and $N$ is the noise spectral density expressed in $W/\sqrt{Hz}$. $S/N$ is the signal-to-noise ratio, per unit bandwidth, measured for the detection of $P$.

On average, the noise $N$ is of the order of a few $Hz/\sqrt{Hz}$. The HYPKID signal-to-noise (S/N) ratio is in the range $10^3 \div 10^4$. Since the mm-wave source is not amplitude calibrated, we have compared the HYPKID (S/N) ratio to the one measured on a previously characterised array (Catalano et al. 2020). This array, with an NEP in the low $10^{-17}W/\sqrt{Hz}$ range measured using black-body sources, has been mounted in the same position as the HYPKID and measured under identical optical conditions. From the comparison, we conclude that the prototype HYPKID NEP sits also in the $10^{-17}W/\sqrt{Hz}$ order of magnitude. More precise estimations of the sensitivity require further studies and optimisations of our testing setup, and will be presented in future publications.

5. Conclusions

We have designed, fabricated and tested a new hyperspectral imaging device operating in the astronomically relevant millimetre-wavelength band. Our device is characterised by a straightforward design and fabrication process, readily compatible with large field-of-view, i.e. thousands beams (pixels), arrays.

The first prototype confirmed the soundness of this innovative device, showing good performance in terms of spectral resolution ($R \approx 800$), polarisation selection and sensitivity, i.e. NEP in the $10^{-17}W/\sqrt{Hz}$ range. The direct comparison of the performance with our on-chip spectrometer (Chowdhury et al. 2022), operating in the same band and characterised in the same way, confirms the decisive gain in quantum efficiency predicted by the electro-magnetic simulations.

The optical sensitivity figures are already interesting for the HYPKID to be considered for the next generation of experiments targeting Line Intensity Mapping observations.

The device being polarisation-sensitive, the hyper-spectral properties can be combined to polarisation measurements. For example, by introducing in the beam a polarisation modulator, i.e. a fast rotating half-wave plate (Pisano et al. 2022). A 45-degrees polariser (splitter) can be inserted to illuminate simultaneously two polarisation-sensitive focal planes in a very compact configuration.

We plan to build on the promising results presented in this paper and elaborate further optimised hyper-spectral devices operating up to 300 GHz.

Acknowledgments

We acknowledge the specific contribution of the engineer G. Garde to the device holder and the overall support of the Cryogenics, Electronics and NanoFab groups at Institut Néel and LPSC. The fabrication of the device described in this paper was conducted at the PTA Grenoble micro-fabrication facility. This work has been partially supported by the French National Research Agency through Grant No. ANR-16-CE30-0019 ELODIS2, the LabEx FOCUS through Grant No. ANR-11-LABX-0013, the EU Horizon 2020 research and innovation program under Grant Agreement No. 800923 (SUPERTED) and Grant Agreement No. 78821 (CONCERTO).

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