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Citation for published version (APA):

Neto, A., Iacono, A., Gerini, G., Baselmans, J. J. A., Yates, S., Baryshev, A., & Hoevers, H. F. C. (2009). Leaky lens based UWB focal plane arrays for sub-mm wave imaging based on kinetic inductance detectors. In *Proceedings of 3rd European Conference on Antennas and Propagation 2009, EuCAP 2009, 23-27 March 2009, Berlin, Germany* (pp. 1824-1827). Institute of Electrical and Electronics Engineers.

Document status and date:

Published: 01/01/2009

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Leaky Lens Based UWB Focal Plane Arrays for Sub-mm Wave Imaging Based on Kinetic Inductance Detectors

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Abstract— This work highlights some of the results of a cooperation between TNO and SRON (Space Research Organization Netherlands) which is now going on with renewed efforts since almost two years. A novel strategy for broad band focal plane array design is proposed. Its purpose is to couple the radiation from a Large F/D reflector system to an array of Kinetic Inductance detectors that are being investigated at SRON to be used in Space science missions such as SPICA [1]. To maximize the benefits from using their BW properties one idea is to use Leaky Lens based array elements, as imaging pixels, however other possibilities are also envisaged.

I. INTRODUCTION

All the existing quasi-optical systems that are characterized by large F/D are designed to operate efficiently over narrow frequency bands. That is because in order for the entire system to be efficient, i.e. in terms of spill over, the final feeds should be characterized by high directivities. While there are antennas that present large BW and high directivities, in most cases these properties are achieved at the cost of a poor phase center stability over the frequency which eventually destroys the efficiency of the reflector system. As a consequence now days the most common trend, at least in the cm wave regimes, is to use complicated feeding networks, effectively realizing the narrow beams via phased array technology. The cost and complications associated to such technological solutions, important also in the lower frequency regimes, appear formidable at THz regimes. Clearly it is in principle possible to oversize the optical system in such a way that spill over is not felt as a problem any more, by essentially accepting a very low aperture efficiency. However this comes at great costs and a solution that allows for a better aperture efficiency would be widely preferable.

Recently, UWB Leaky Lens antennas have been proposed [2]. These lenses are truly amazing instruments as they allow, at least on one plane, stable phase centers and directive patterns independently from the frequency, while maintaining low cross polarization levels. The reason for these properties is the particular type of radiation mechanism adopted. The

leaky radiation occurring when a slot is etched at the interface between two different dielectric media is effectively a broad band form of Cherenkov radiation. The performances of the non-planar version of the Leaky Lenses have been demonstrated to be acceptable over a decade of BW and excellent over a 1:3 BW. In this paper, we will propose a focal plane architecture that is suited to host broad band lens antennas as imaging elements. Whether they are Leaky Lenses or more standard types resonant type of structures is not an essential feature for the specific application this consortium has in mind. However what is essential is that the feed arrangements be suited to be used in conjunction with KID type resonators. A key novel element of the TNO/SRON design is the integration of both antenna and detector in the same CPW structure, so hosting the dissipationless low frequency resonator (GHz) readout signal while absorbing the high frequency (THz) incoming radiation. Progress on the development using prototypes narrow band directive antenna/lens combination at 670GHz is here presented.

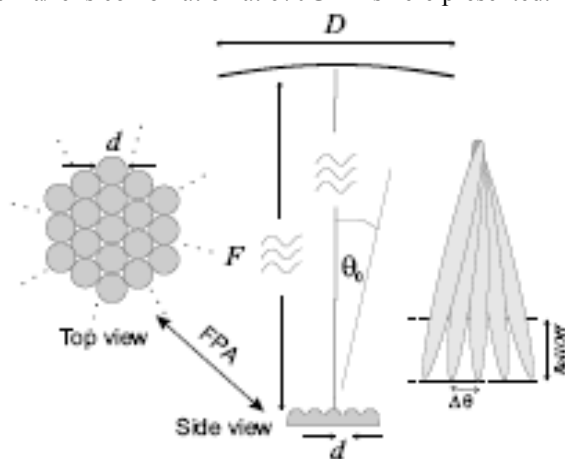


Fig. 1 Schematic view of a reflector system and focal plane suited to host feeds for multiple beam imaging.

II. REPORT ON THE NARROWER BAND DESIGN RESULTS

A. Requirements from the SPICA mission

Three main requirements have been proposed by the scientists for the SPICA mission instruments that, when realized, would constitute major breakthrough with respect to the already advanced state of the art of sub-mm wave frontends. While the main *sensitivity* requirement (noise equivalent power $NEP < 10^{-19}$) is essentially associated to the receiver technology, the other two major requirements are the *number of pixels* (in the order of the thousands) and the *BW*. Overall a decade BW is considered interesting for SPICA, however due to this bandwidth previously being considered impractical SPICA is at the present time proposed to be divided in three separate bands so requiring three separate instruments. A single broadband option would give significant advantages in weight and simplicity for SPICA, so developments would be considered in this design phase of the mission. While SRON proposes KIDS for the sensitivity issue [3],[4], TNO proposes Dielectric lenses for the BW Kilo-elements focal plane array. In the rest of this paper we will imagine a focal characterized by F/D in order of 10, and accordingly d approximately $10 \lambda_0$ with reference to Fig. 1, even if $F=2*D$ would probably suffice for a thousand element array. The large F/D makes the focal plane larger and hence easier to build for THz imaging (SPICA $\lambda_0 \sim 30..210 \mu\text{m}$). A bandwidth of operation in the order of 15% used for the first prototypes. Novel designs which aim for 1:2 (octave) bandwidth and so compatible with the current baseline design for SPICA are being delivered to SRON as the paper is being written. Additionally, development and testing of the proposed leaky Lenses with a 1:10 BW is foreseen. However, they will be implemented at a later stage as the necessity to demonstrate the feasibility of the lens array concept has taken a more important role in these phase of the work rather than demonstrating the BW potentials.

B. Kinetic Inductance Detectors

Kinetic Inductance Detectors were originally proposed at Caltech by the Group of Jonas Zmuidzinas [3], and significant work has taken place on the device physics (e.g. see [5] and citing articles) and potential performance [4]. However, their basic working is relatively simple (see Fig. 2). A through line is realized in CPW technology and connected to an input (1) and output (2) and the transmission from port (1) to (2) or S_{21} is measured in the frequency range of $\sim 3..8$ GHz enabling use of many standard microwave components and instruments. If the line is coupled to a resonant circuit, the S_{21} will be significantly lower at the resonant frequency, with the stop frequency band depending on the propagation properties of the transmission line that realizes the resonance. The concept is that if the line is realized in a clean superconducting material kept at low temperatures (100mK for aluminum) then the resonant circuit is essentially lossless at the readout frequency. However, THz radiation will dissipate on propagation which modifies [3] the resonant frequency and

loss in the resonant circuit and hence modulating the transmission of the readout signal with the incoming THz flux. The resonant circuit here is a thin film capacitively coupled CPW $\frac{1}{4}$ wavelength resonator of $\sim 100\text{nm}$ Aluminum or Tantalum on high purity Silicon or Sapphire substrate, enabling usable Q factors ($f/(2\Delta f)$ of the resonance) up to 1 million, i.e. low loss at readout frequency. A THz antenna is electrically small at the readout frequency, so can be integrated into the resonator with only a small modification of its impedance (see below). However, in the THz, the resonator is electrically long and lossy, so acts as an infinite lossy transmission line to absorb (and hence detect) the THz radiation.

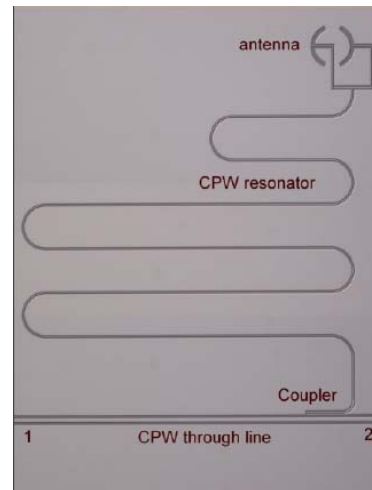


Fig. 2 the through line in the bottom of the picture, the resonating quarter wavelength (at GHz frequencies) line realized in Coplanar waveguide, and the twin arc slot antenna

C. Sub-mm wave First Implementation

After the preliminary scaled design of the antenna which we reported in [6], it was decided to manufacture a high frequency prototype of at 670 GHz to investigate and demonstrate the novel radiation coupling with KIDs developed at SRON. For the purposes of SPICA it is chosen that the frequency be high enough to demonstrate feasibility in the THz regime but low enough for the entire manufacturing to be done with optical lithography. The coupling from the 670GHz sub-mm wave generator to the resonator line happens via the antenna and this demonstration is one of the purposes of this work. See Fig. 2 which shows the through line in the bottom of the picture, the resonating quarter wavelength (at GHz frequencies) line realized in Coplanar waveguide, and the twin arc slot antenna that couples the CPW to the THz radiation.

A two slot structure with each of them excited with a CPW line is used. The two lines are then connected in parallel to achieve a unique feed. Note that the common feeding line, or filter, has been chosen to present characteristic impedance equal to 50 Ohm. Each of the two slots will present a real part of the impedance which is roughly 100 Ohm. Accordingly each of the lines connecting the two slots to the common

feeding line will present approximately 100 Ohms also. The impedance bandwidth is in the order of 15%.

D. Measurement Set Up

Most of the work in the year went into the preparation of the measurement set up. The details are focus of this communication as they will be the object of more dedicated contributions. The basics are that for optical tests antenna-coupled KIDs are aligned and glued to a silicon lens, and then mounted in sample holder (Fig. 3) inside a 300mK base temperature cryostat with optical access (Fig. 4) for a 670GHz sub-mm wave source (band selected to reject stray room temperature radiation). Tantalum devices are used since they are good devices at 300 mK and the high optical load of this setup. Final devices should use aluminum, but this requires lower base temperature of 100mK and lower optical load.

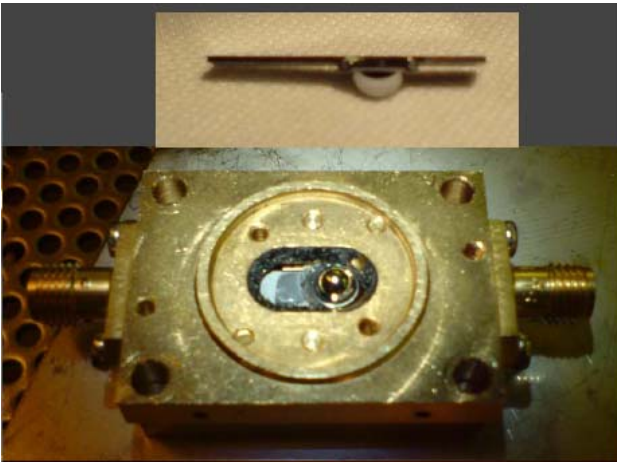


Fig. 3 The sample holder and a side view showing the synthesized elliptical lens antenna glued to the sample.

A beam pattern can be measured by scanning an external radiation source outside the cryostat window and measuring the device response as a function of position.

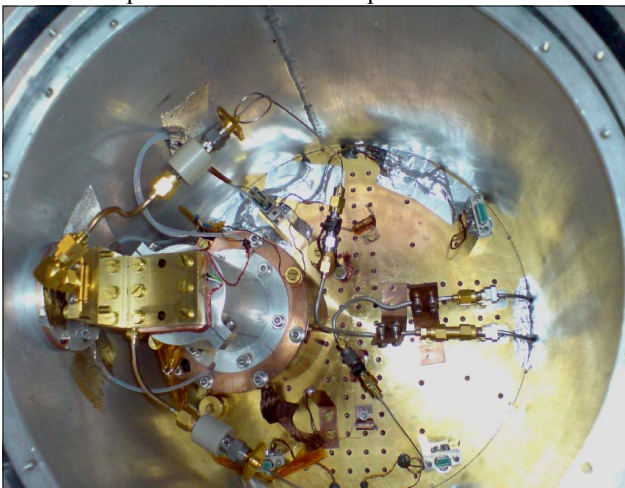


Fig. 4 The sample holder and a side view showing the synthesized elliptical lens antenna glued to the sample.

E. Air bridges

The first radiation patterns detected by the KIDs were very broad due to radiation coupling to the KID itself via a slotline mode. This will couple to any optical system (and adjacent pixels) in a complex manner so should be suppressed. This requires the use of airbridges spaced at least $\frac{1}{4}$ the effective (THz) wavelength apart on the KID, a standard technique in the microwave (GHz) range, but none trivial for these devices which are fabricated using optical lithography. The exact details will be presented elsewhere, but they have been realized (see Fig. 5) using a shaped photoresist profile with the photoresist removed after deposition and processing of a bridge layer. The bridges are made of aluminum, where here the priority was to demonstrate good bridge fabrication. However, Al has a lower transition temperature than Ta so the performance of these devices cannot be electrically calculated as in [4], so optical efficiency (comparison of calculated and measured optical performance) requires either Ta devices with Ta bridges or Al devices with Ta or Al bridges, and this planned for next batches. However, this device can still be used for fabrication validation, while the radiation coupling is only through the antenna so can be used to characterize the antenna and optical test setup via beam pattern measurements. The introduction of the air bridges led to good radiation patterns at 670 GHz. These patterns are shown in Fig.6 where they are also compared with the simulated patterns.

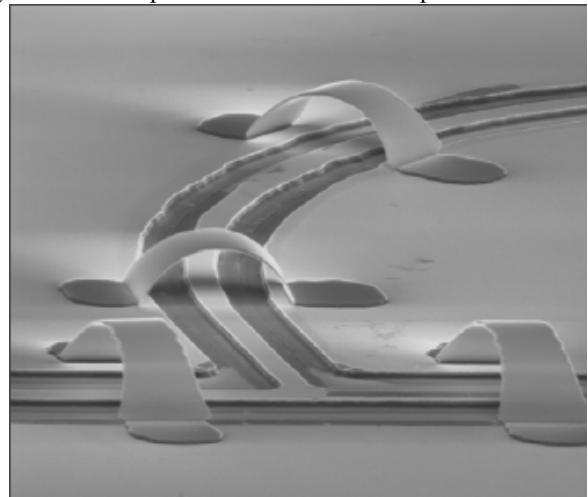


Fig. 5 Details of the air bridges realized in order to suppress the even electric field mode in the CPW lines.

Cross polarized levels are in the order of -10 dB with respect to polarized signal. At the present time it is thought that this might be due to the fact that the summation of the two signals arising from the two slots is only partially coherent due to the fact that significant losses occur in the two different CPW connecting to each slot before the in phase summing point is reached. These losses are actually associated to the actual excitation of the Cooper pairs which is the cause of the alteration of the resonator impedance and equivalent electric length.

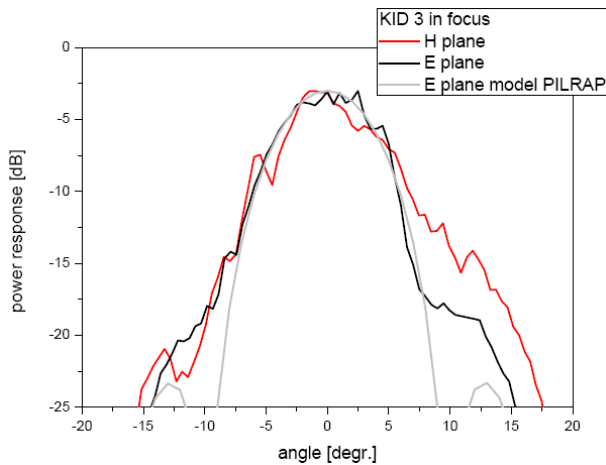


Fig. 6 E and H plane radiation patterns and comparison with expected results.

The co-polarized and cross polarized fields are shown in the contour plots in Fig.7 and 8, respectively.

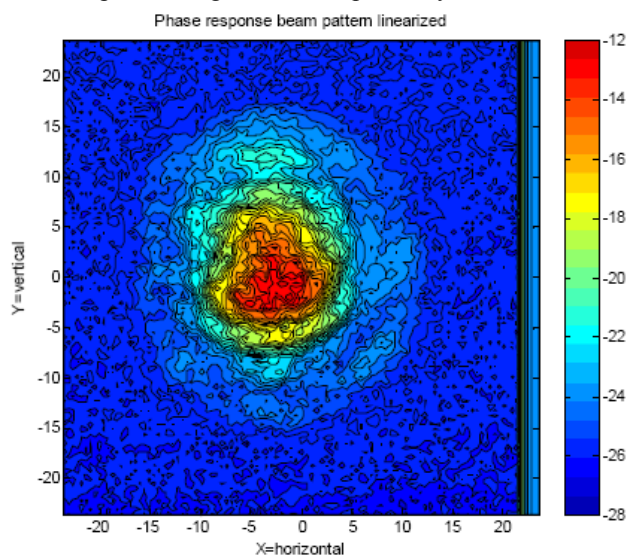


Fig. 7 Co-polar planar measured distribution

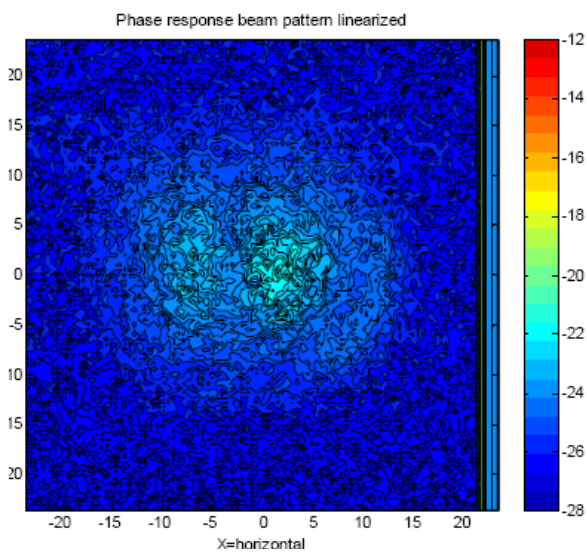


Fig. 8 Cross polar planar measured distribution.

III. FUTURE WORK

This demonstrates that the concept of integrated antenna with an Kinetic Inductance Detector can be used to measure THz radiation. Future work will proceed by building on these measurements using new devices to obtain optical performance, optical efficiency and frequency response of detectors giving a fully characterized device. Very sensitive devices and a very low optical load setup will need to be developed to demonstrate the optical sensitivity required by SPICA. However, the technology used so far is entirely scalable up to 3 THz with high sensitivity[3],[4] without significant changes. In the short term the activity of team will now focus on first demonstrating that similar performances can be obtained with broader band antennas, that can be realized with uniplanar technology as close as possible to the present one even at the cost of non-optimal cross polarized patterns (cross polarization is not an issue at this time for SPICA since the polarization purity is guaranteed by filters at the input). Moreover the team will proceed as soon as possible to the demonstration of the described system in an array configuration given that this is one of the main SPICA requirements and that it is also one of the main advantages of using Kinetic Inductance Detectors. The properties of the UWB leaky lenses will be investigated and exploited at a later moment when the access to the SPICA mission via the design of the SAFARI receiver will be earned.

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