Development of W-Band Dual-Polarization Kinetic Inductance Detectors on Silicon

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***Abstract*— A polarimetric detector in the W-band based on Lumped-Element Kinetic Inductance Detectors (LEKIDs) is presented. Each single optical element consists of two Ti/Al LEKIDs placed in orthogonal configuration on both sides of a Silicon substrate. Room temperature quasi-optical characterization demonstrates the high frequency design and the absorption in the W-band. Cryogenic characterization confirms the high quality factor of the fabricated resonators and polarization sensitivity in the W-band. The design proposed in this work is suitable for the development of polarimetric cameras of large arrays of LEKIDs for future astronomical experiments.**

***Keywords*—Kinetic Inductor Detector, superconducting resonators, millimeter astronomy, polarimeter.**

I. Introduction

Next generation experiments for the study of the Cosmic Microwave Background (CMB) emission require employing state-of-the-art detectors able to distinguish not only the tiny power level of the radiation, but also its polarization. In this sense, the W-band is of particular interest since the foreground contamination reaches minimum values and a great effort is being done in the development of suitable detectors [1]. Superconducting devices have demonstrated significant results in terms of sensitivity and noise equivalent power within millimeter wave bands. Among them, Kinetic Inductance Detectors (KIDs) present the main advantage of being inherently multiplexable in the frequency domain, enabling thousands of detectors to be read-out over a single line. Dual polarization LEKIDs based on the combination of KIDs with an orthomode transducer (OMT) have already been proposed for component separation [2], [3]. Also, dual-polarization KIDs have been discussed as detection technology for CMB observations by using a configuration with detectors spatially distributed [4].

Moreover, the applicability of these detectors expands beyond the astronomical field. For instance, they have recently been proposed as the baseline technology for the detection of dark matter in the W-band [5].

In this work, we present the development of W-band dual-polarization lumped-element kinetic inductance detectors (LEKIDs) to detect and distinguish the radiation of two linearly polarized orthogonal waves. The detectors are designed in an orthogonal configuration at both sides of a high-resistivity Silicon substrate aligned in the same vertical axis and matched to the W-band. Coplanar waveguide (CPW) transmission lines enable the use of both sides of the substrate and Ti/Al bilayers allow detection in the W-band. A first demonstrator is developed demonstrating polarization sensitivity in the W-band.

II. Dual-Polarization LEKID Design and Fabrication

A dual-polarization LEKID for polarimetric measurements in the W-band is proposed. As shown in Fig. 1, each single optical element is composed of two resonators placed on both sides of a Silicon wafer. Orthogonal alignment between resonators provides simultaneous detection of both perpendicular incident waves. Each resonator consists of a common 3 x 3 mm^2 meandered inductor and an interdigital capacitor. The inductor acts as an incident wave absorber and the interdigital capacitor provides the frequency multiplexability. They are inductively coupled to a CPW transmission line for read-out purposes.

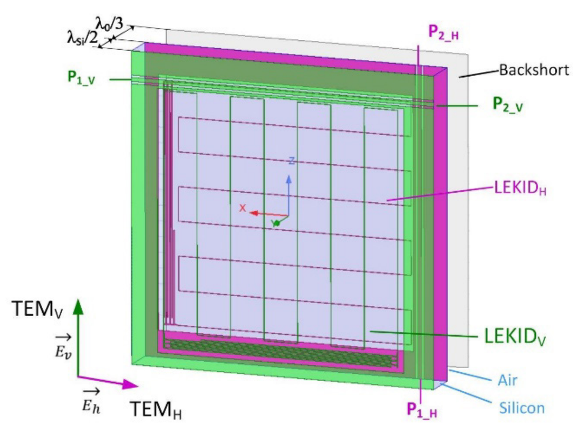

Fig. 1. Schematic of a single detector 3D view. The detector consists of two Al/Ti layers with a resonator in each one and placed orthogonally on a Silicon wafer. The inductors act as the incident wave absorber. The central area of absorption has a diameter of 3 mm.

A. W-band Dual-Polarization Design

Each resonator of the dual-polarization LEKID is designed to be sensitive to one single polarization at a frequency band centered at 90 GHz over a 20 GHz bandwidth. Parallel inductors made of metallic Ti/Al superconducting strips act as the active optical absorber. The sheet resistance, critical for its design, has been determined by cryogenic characterization obtaining 2.16 Ω/sq just before transition. Two LEKIDs, $LEKID_V$ and $LEKID_H$ in Fig. 1, are placed orthogonally aligned on both sides of a Silicon substrate with electrical length λ/2 which together with the backshort, set at a distance of λ/3, allow both LEKIDs to be simultaneously matched to the free space within the frequency band. This design is simulated based on the Floquet theory and the periodic boundary condition with High Frequency Structure Simulator (HFSS) from Ansys, which is a full-wave electromagnetic field solver based on the finite element method.

B. Low Frequency Resonators

The design of the resonant circuit for the low frequency read-out was carried out using Sonnet Simulator [6]. Instead of microstrip, a 50 Ω CPW was chosen as transmission line in order to avoid a ground plane between orthogonal LEKIDs and allowing the incidence of both orthogonal waves. The readout frequencies were centered on 600 MHz and a 50 MHz gap between the lower and upper LEKIDs was established for easy distinction between polarization faces. Coupling strength, obtained by an inductive coupling to the CPW and varying distance, was set to reach a coupling quality factor around $6{\cdot}10^4$.

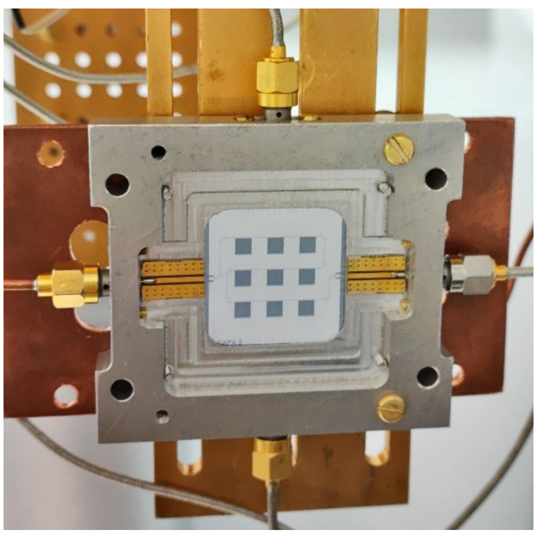

Fig. 2. Dual-polarization LEKIDs array (top face) mounted for testing in the 10 mK stage of the cryogenic hardness.

C. LEKID Fabrication

The devices are fabricated using standard procedure on high-resistivity Silicon. By means of confocal sputtering, a Ti/Al bilayer has been deposited with a critical temperature of 778 mK, suitable for absorption at W-band [7]. The wafer thickness is 485 µm which sets the λ/2 distance at 89.7 GHz between resonators within the same optical element. A maskless laser lithography with backside camera was used to ensure a proper alignment between the upper and lower Silicon faces in the nanofabrication process.

Two double polarization LEKIDs structures have been fabricated for their characterization. One structure consists of a filled array of LEKIDs without readout transmission lines, in order to measure the matching of the designed structure at W-band and to verify the electromagnetic HFSS simulation. A second structure with 9 LEKIDs and CPW readout lines has been fabricated for cryogenic characterization. Aluminum air-bridges were added in each array to suppress the odd mode supported by the CPW geometry, as well as to reduce the crosstalk level. Fig.2 shows the fabricated array mounted for its cryogenic characterization.

III. Experimental Results

The LEKID characterization was made at both room and cryogenic temperatures. Measurements at room temperature demonstrated matching at W-band, absorbing incident waves with the two orthogonal polarizations. Cryogenic characterization allows verifying the low frequency design, the optical responsivity and the cross-polarization between LEKIDs.

A. W-Band Performance at Ambient Temperature

The absorption of the dual-polarization array of LEKIDs was characterized using a W-band quasi-optical test bench at ambient temperature. The 485 µm Silicon substrate with the LEKIDs array without readout, was placed on another 300 µm Silicon substrate (i.e. λ /3) with a backshort. The measurement results compared with the simulations are depicted in Fig. 3. A Load-Reflect-Match (LRM) calibration is used in a set-up composed of two horn antennas, two dielectric lenses and a vector network analyzer (VNA). Two orthogonal and linearly polarized plane waves in the 65–110 GHz frequency band showed a maximum absorption at 83 GHz for both polarizations. The best agreement between measurements and simulation is for a structure with strip lines in the resonator with sheet resistivity of 4 Ω/sq, which agrees with the obtained experimental value of 3.9 Ω/sq. Since the sheet resistance at room temperature is higher than the one at cryogenic temperature, there is an expected shift to lower frequency for the maximum absorption.

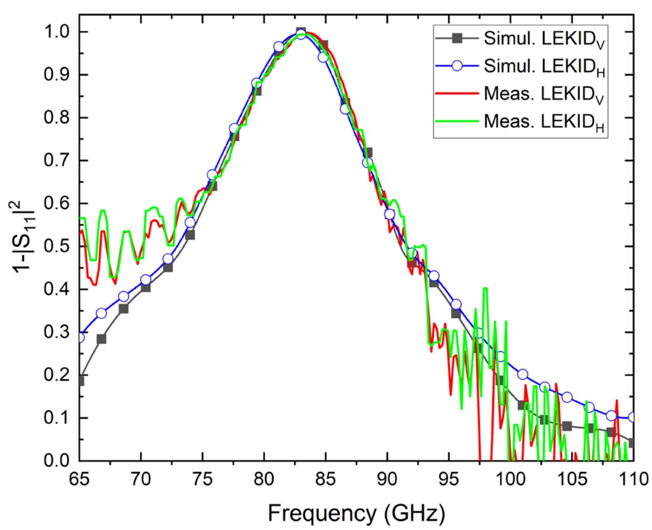

Fig. 3. Room temperature characterization and HFSS simulation of the orthogonal LEKIDs absorption at W-band.

B. *Cryogenic Characterization*

Cryogenic measurements were carried out using the BlueFors dilution refrigeration (DR) LD-250 that provides a 10 mK stage, where the detectors were placed. A VNA is used for measuring the forward scattering parameter S_{21} for each readout CPW. A low noise SiGe transistor amplifier is installed at the 4 K stage for read-out.

First, the fabricated prototype was mounted on a closed sealed metal box to be tested in darkness conditions. Following the procedure detailed in [8], internal quality factors greater than $3 \cdot 10^5$ and coupling quality factors around $6 \cdot 10^4$ were obtained, which match reasonably well to the design values. Kinetic inductance is around 3.81 pH/sq which yields to a kinetic inductance fraction of 0.57.

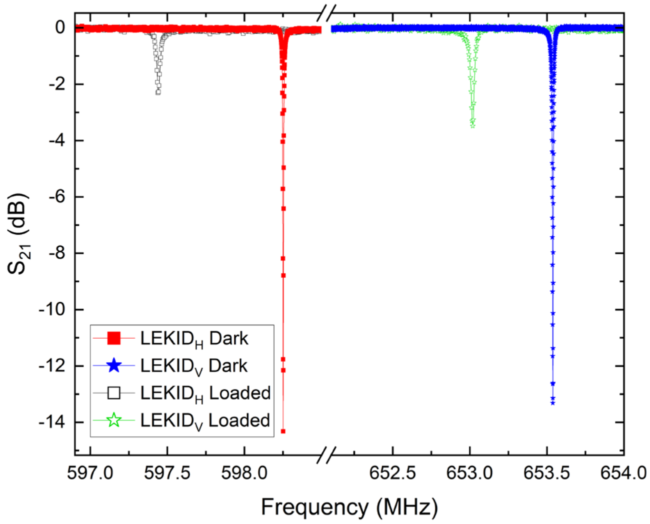

Fig. 4. Transmission response of horizontal (H) and vertical (V) LEKIDs in darkness and optical loaded conditions. Incident radiation is polarized parallel to the horizontal LEKID.

Optical response of the fabricated detector is performed using a 4 K blackbody load with a linear polarizer and a 110 GHz low pass filter. Fig. 4 compares a pair of horizontal/vertical LEKIDs responsivity in dark and optical environments. The shift of the resonance frequency with optical load, as compared with the obtained in darkness conditions, confirms absorption in the W-band.

Regarding polarimetry, the LEKID with the inductor parallel to the incident polarized radiation shifts 809 kHz whereas the perpendicular one shifts 528 kHz. Therefore, an unexpected extra response is observed in the cross polarization. This could be attributed to a possible crosstalk between LEKIDs on both Silicon faces (LEKID$_H$ and LEKID$_V$ in Fig. 1). This effect is analyzed using the pump-probe technique described in [9]. For this, a high power pump tone (black arrow in Fig. 5), is sent to LEKID$_V$, simulating its response to an optical illumination. As shown in Fig. 5, no influence is observed in LEKID$_H$, neglecting the crosstalk contribution. Another possible origin of this extra response may be attributed to straylight radiation from the 1 K environment and further optimization of the optical setup will be performed for the cross-polarization analysis.

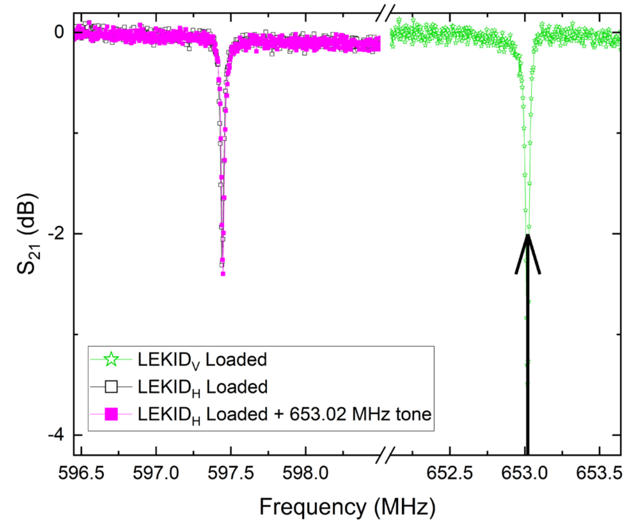

Fig. 5. Pump-probe technique analysis. Black arrow indicates the pump tone frequency. No change is observed in LEKID$_H$, neglecting the crosstalk between faced pixels.

IV. Conclusion

A LEKID based detector for polarimetric measurements in the W-band is presented. Each single optical element consists of two Ti/Al LEKIDs placed in orthogonal configuration on both sides of a Silicon substrate. On one hand, room temperature characterization using a quasi-optical set-up confirms the high frequency design and its response in the W-band. On the other hand, cryogenic characterization is employed for validation of the low frequency design and optical responsivity. Internal quality factors greater than 10^5 are obtained, confirming the good quality of the fabricated devices. Frequency shift under illumination condition confirms responsivity to W-band signal, obtained thanks to the low critical temperature of the Ti/Al superconducting material. Different shifts between horizontal and vertical LEKIDs allow polarimetric characterization; however, an extra cross-polarization is obtained, which may be attributed to straylight radiation.

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