# Design of Waveguide Coupled MKID Detectors

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***Abstract*—We investigate the sensitivity and the noise of Microwave Kinetic Inductance Detector (MKID) devices that are coupled to a waveguide utilizing a proven waveguide probe antenna. The RF signal is split into two coplanar waveguide (CPW) absorber lines with a 40 nm thick aluminum centerline as the absorbing part and Niobium ground planes. The CPW centerline forms the inductive section of a 2.5 GHz superconducting resonator, which is capacitively coupled to the readout line. Since the deposition of the centerline is a separate lithography step, the design also enables us to exchange the aluminum and use the circuit as a testbed for kinetic inductance and loss measurements of other absorber materials. This design will be compared to an quarter wave transmission line resonator with identical resonance frequency fabricated on the same wafer. The simulated signal input reflection of both designs is below -15 dB over a frequency band of 100 GHz centered at 350 GHz.**

## I. Introduction

MICROWAVE Kinetic Inductance Detectors (MKID, [1]) are direct detectors which utilize the change of the kinetic inductance of superconducting material caused by the breaking of Cooper pairs by incoming radiation for detection. The material is usually part of a resonator with a resonance frequency in the GHz range and changes in the impedance cause a change of the resonance frequency. MKID can be read out using frequency multiplexing by attaching many resonators with different resonance frequencies to a single readout line. This facilitates the construction of cameras [2] or filter bank spectrometers with many channels [3]. MKID can operate over a wide frequency band ranging from the pair breaking energy of the superconductor, approximately given by $2\Delta = 73$ GHz $\cdot T_c/1\text{K}$[4] for many superconductors, up to the X-ray regime for applications in nuclear physics [5], [6], [7].

We plan to study the sensitivity and noise performance of a single MKID resonator with a well known signal coupling consisting of a horn antenna and a waveguide probe which have proven to give quantum limited sensitivity in 350 GHz SIS mixer measurements [8]. This paper will present the design of a 350 GHz MKID detector coupled to the waveguide.

## II. Design

From free space, the 350 GHz radiation is coupled into a rectangular waveguide using a spline profile horn antenna. The waveguide dimensions are 630 $\mu$m by 320 $\mu$m . A waveguide to microstrip transition [9] extracts the fundamental mode and guides it to a coplanar waveguide (CPW) transmission line on a 9 $\mu$m silicon membrane substrate. Superconducting bridges using 400 nm $SiO_2$ as support dielectric are used to ensure a proper CPW mode. The radiation is then coupled to the aluminum absorber section of the MKID for which two different design approaches were taken. The ground and readout connections are made using 3 $\mu$m thick electroplated gold beamleads.

### A. Transmission line resonator KID

A transmission line resonator KID is a proven design, as similar resonators were already fabricated and tested [10]. The design is shown in Fig. 1. The impedance of the line behind the antenna is set to 50Ω which results in a CPW line which are reliable to fabricate. To couple a 2.5 GHz transmission line resonator to the readout line capacitively, the open end of the resonator has to be at the coupling capacity and the shorted end at the antenna. Since waveguide probe is an open circuit at the readout frequency, two 1/8 wave tuning stubs are used to provide the short circuit to the readout signal. These stubs transform their short at the end to an open at 350 GHz and thus do not obstruct the propagation of the 350 GHz signal on the CPW transmission line. Due to the large frequency difference between 350 GHz and the 2.5 GHz readout, the stubs are just short circuits at the readout frequency. Two stubs are used to maintain the symmetry of the circuit. The stubs are made of superconducting niobium, since no absorption is intended here.

The resonator consists of the absorber line section which is 740 $\mu$m long that consists of a CPW with an aluminum center conductor and niobium ground planes. The width of the center conductor is 2 $\mu$m and the gaps are 1 $\mu$m , while the aluminum thickness is 40 nm. Since the 350 GHz input signal is above the pair breaking energy, the signal is absorbed and cooper pairs are broken. The readout signal is far below the gap energy, therefore absorption is much smaller but can still happen due to heating or multi photon events at high readout signal powers [11]. The absorber line ensures an estimated absorption of about 30 dB of the signal before the second section of the resonator starts which is made of niobium only. Since the total resonator length is about 1.8 cm, only the front part is intended for absorption of radiation and thus made of thin and narrow aluminum. Most of the length has uncritical dimensions of the center conductor and the gaps. For coupling the resonator to the readout line, a line is branched off the main readout line that goes parallel to the open end of the resonator as shown in Fig. 1 c). The coupling strength can be set by the length of the section and the gap width and is designed for coupling quality factors of 10000 or 100000.

The RF side of the circuit is simulated using CST$^{\text{TM}}$microwave studio. The input port is located at the waveguide entrance, so the horn antenna is not included

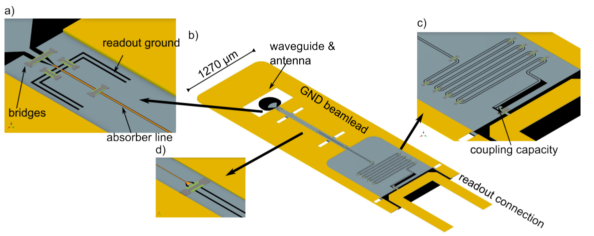


Fig. 1. CAD rendering of the transmission line resonator design. a) Waveguide antenna and choke. b) Overview of the chip. Dimensions are 1.2 by 3.6 mm. c) Meandered resonator line and coupling to the readout. d) Transision from aluminum absorber to the niobium resonator line.

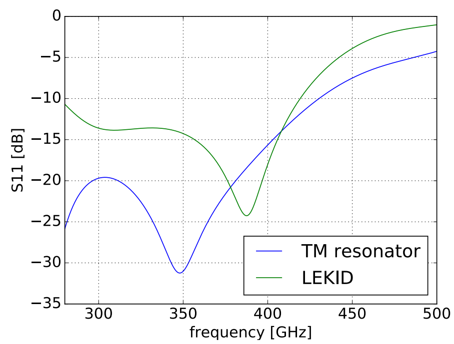


Fig. 2. CST$^{\mathrm{TM}}$microwave studio simulation results of the input reflection (S11) seen from the waveguide for the high frequency signal input for the transmission line resonator design (TM) and the lumped element design.

in the simulation. The frequency dependent impedance calculated from the operating temperature and the measured resistivity of 40 nm aluminum films for absorber line were included into the simulation to estimate the absorption. For measured Lift-Off films the resisitivity at 4.2 K is 1.35 $\mu\Omega$ cm. The simulated performance of the antenna and choke section is shown in Fig. 2 and shows a good input coupling up to at least 400 GHz.

### B. Lumped Element resonator KID

The alternative design for the KID part of the detector follows the lumped-element kinetic inductor design [12]. In this design, the resonator is made of an inductor and capacitor as circuit elements instead of a traveling wave on a transmission line. The advantage of this design is that the L/C ratio can be specifically designed and that the current distribution on the inductor (the absorber) is uniform. This design is shown in Fig. 3. The waveguide probe is the same as in the design mentioned above except that the CPW line impedance of the attached line is about 35 Ohm. Behind the probe the signal is split onto two absorber lines which each have a line impedance of 70 Ohm to maintain a good match. Those impedances are chosen to be still managable in fabrication for the 35 $\Omega$ line and still keep the CPW fundamental mode for the 70 $\Omega$ line. The width of the absorber lines is 1.6 $\mu$m and the gaps are 2 $\mu$m . Bridges across the line are necessary again to keep a proper ground potential on the part between the absorber lines. Splitting the CPW line is necessary to form a loop out of the

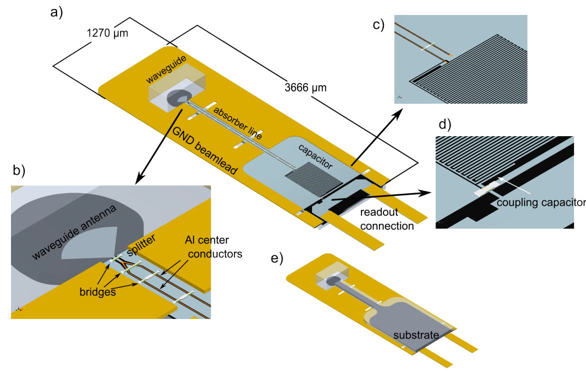


Fig. 3. CAD rendering of the lumped element resonator design. a) Overview b) Waveguide probe section with splitter. c) Transition from absorber line to capacitor. d) Couplig to the readout line.

absorber line which acts as the inductor of an LC resonator. At the end of the inductor which has a length of about 1700 $\mu$m , an interdigital capacitor is attached. The capacitor is again capacitively coupled to the readout line and is designed to coupling Q factors of 10000 or 100000.

The signal part of this circuit was also simulated using CST$^{\mathrm{TM}}$microwave studio as shown in Fig. 2. The simulation is done the same way as for the TM resonator design mentioned above. The input bandwidth if this design goes up to 400 GHz.

## III. Summary

We designed two single pixel waveguide coupled MKID detectors for 350 GHz with about 100 GHz of bandwidth. Those detectors can be used to examine the absorption efficiency and act as a testbed for investigation of different active materials since the deposition of the absorber lines is designed as a seperate lithography step. Since the absorber lines will be written using electron beam lithography, they can be adapted to an absorber material with different resistivity.

The devices will be measured in an ADR cryostat at a base temperature below 100 mK with an blackbody load as radiation source. Measurements of the detector response and noise at different radiation levels will allow determination of an optical noise equivalent power (NEP) in dependence of the optical loading level for a relevent characterization of the performance.

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