Development Of Kinetic Inductance Detectors For Far-Infrared Spectroscopy In Astrophysics

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Development Of Kinetic Inductance Detectors For Far-Infrared Spectroscopy In Astrophysics

Abstract
This thesis presents the development of kinetic inductance detectors targeted for applications in far-infrared spectroscopy in astrophysics. The formation and evolution of galaxies across cosmic time is one of the key areas of exploration in modern astrophysics. The star formation rate density peaks at a redshift of around z=2, when the universe was dominated by dusty star-forming galaxies whose optical and ultraviolet radiation are significantly obscured and thermally reprocessed by dust into infrared radiation. A swath of fine-structure lines in the far-infrared serve as tracers of star formation activity in these galaxies, and far-infrared continuum and line emission are unobscured by dust. However, detecting these lines in individual galaxies is difficult and time consuming with currently-available infrared instruments.

The Terahertz Intensity Mapper (TIM) experiment is a balloon-borne telescope spectrometer that will observe these galaxies leading back to the era of peak star formation. TIM will use the intensity mapping technique to create a three-dimensional map, incorporating the spectral dimension as the line-of-sight coordinate. This measurement will survey the aggregate star-formation activity as a function of redshift of the total galaxy population without a flux limit. TIM will incorporate two grating spectrometer modules to observe the 240-420 micron wavelength band with spectral resolution R = 250, each with 1800 low-noise kinetic inductance detectors (KIDs) in its focal plane.

I present the development and testing of prototype KID arrays targeted for use on TIM. KIDs are superconducting microresonators that serve as radiation detectors. They rely on the kinetic inductance effect, which causes a shift in resonant behavior when incident photons are absorbed by Cooper pairs in the superconductor material. I present characterization results from two 45-pixel KID arrays fabricated out of thin-film aluminum on silicon substrates. I demonstrate that their device performance meets the sensitivity and noise requirements for the TIM experiment.

Degree Type
Dissertation

Degree Name
Doctor of Philosophy (PhD)

Graduate Group
Physics & Astronomy

First Advisor
James Aguirre

Keywords
applied superconductivity, far-infrared, intensity mapping, kinetic inductance detectors

This dissertation is available at ScholarlyCommons: https://repository.upenn.edu/edissertations/3286
Dedication

To the women in STEM who have inspired me:

To Kath Schwieger, who taught me to make any problem into one I know how to do.

To Jill Foley, who showed me how exciting building experiments is.

To Joe Hill, who’s never afraid to be herself.

To Alice Cocoros, my partner in physics and dear friend.

To my mom, the original Dr. Barlis.
Acknowledgments

I would first like to sincerely thank my advisor, James Aguirre, who served as a mentor and teacher in many ways during my time as a Penn student. This work was supported by a NASA Space Technology Research Fellowship, and I thank my NSTRF collaborator Thomas Stevenson, along with his NASA GSFC colleagues Ari Brown and Vilem Mikula for sharing their design and fabrication expertise with me. I’m incredibly grateful to Steve Hailey-Dunsheath and Matt Bradford at Caltech for welcoming me into their lab, answering my questions and providing guidance along the way.

I have been so privileged to work alongside (and share office space with) a number of other graduate students: Christina Krawiec, Johanna-Laina Fischer, Saul Kohn, Tashalee Billings, Dillon Brout, Jessie Taylor, Joe Redford, Jon Hunacek, and Howard Hui. I’m thankful for the instructive science conversations, tea parties, Python help, and friendship that we shared at both Penn and Caltech.

Finally, I thank my committee members for their time and patience, and their suggestions on improving my work.
ABSTRACT

DEVELOPMENT OF KINETIC INDUCTANCE DETECTORS FOR FAR-INFRARED SPECTROSCOPY IN ASTROPHYSICS

Alyssa Barlis
James Aguirre

This thesis presents the development of kinetic inductance detectors targeted for applications in far-infrared spectroscopy in astrophysics. The formation and evolution of galaxies across cosmic time is one of the key areas of exploration in modern astrophysics. The star formation rate density peaks at a redshift of around $z = 2$, when the universe was dominated by dusty star-forming galaxies whose optical and ultraviolet radiation are significantly obscured and thermally reprocessed by dust into infrared radiation. A swath of fine-structure lines in the far-infrared serve as tracers of star formation activity in these galaxies, and far-infrared continuum and line emission are unobscured by dust. However, detecting these lines in individual galaxies is difficult and time consuming with currently-available infrared instruments.

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photons are absorbed by Cooper pairs in the superconductor material. I present characteriza-
tion results from two 45-pixel KID arrays fabricated out of thin-film aluminum on silicon substrates. I demonstrate that their device performance meets the sensitivity and noise requirements for the TIM experiment.
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A.2 **Left:** Layer geometry for the SONNET Simulation. The array is patterned on a silicon wafer which is suspended between layers of air (vacuum). **Middle:** Array interdigitated feedline geometry. Pixels sit between fingers, so each pixel connects to both a signal finger and grounded finger. The signal transmission line, with ports 1 and 2, is shown in red at the top, while the bottom half of the feedline is grounded by connecting to the simulation boundary box. **Right:** Simulated forward scattering parameter for the feedline geometry shown. The transmission is smooth and relatively flat compared to the pixel resonances.

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A.4 Images of a GSFC device as fabricated. The full array is 60mm on each side.
This Thesis

The work completed as part of this thesis was all devoted to the development of kinetic inductance detectors (KIDs) suitable for a far-infrared intensity mapping experiment. To that end, I have worked to test and characterize two arrays of aluminum KIDs designed for low-noise, unpolarized measurements in the 240 – 420 µm wavelength band. The devices were designed by C. McKenney, and fabricated by H. LeDuc in the Microdevices Laboratory at NASA JPL. I undertook the bulk of the device testing in the Observational Cosmology/sub-mm Laboratory at Caltech. I packaged the array wafers in their enclosures, and integrated them into the cryostat. I prepared the RF electronics circuits and data acquisition systems. I performed the measurements of both devices over a number of cryostat cooldowns. I wrote the Python-based analysis pipeline for the results described here. The simultaneous fitting algorithm I developed represents a new approach to extracting the quasiparticle lifetime $\tau_{\text{max}}$, crossover quasiparticle density $n^*$, and device optical efficiency $\eta_{\text{opt}}$ from both dark and optical device measurements. Preliminary results of my measurements of the first device, device A, were published in Hailey-Dunsheath et al. (2018), using an analysis pipeline developed by S. Hailey-Dunsheath. I am currently preparing the full analysis results from both devices for publication.

This thesis is organized as follows: in Chapter 1, I briefly present the science of tracing star formation and large-scale structure using far-infrared line and continuum emission, and describe how the intensity mapping is a useful technique to measure that science. In Chapter 2, I present the landscape of existing and future infrared instruments. I also give an overview of the TIM experiment, a new instrument toward which the detector development work I have undertaken has been targeted. In Chapter 3, I explain the basic physics of superconductors. I also give a general overview of the principles of kinetic inductance detectors (KIDs). In Chapter 4, I explain the physics governing KIDs and their expected performance under a range of operating conditions. In Chapter 5, I present the design of prototype KID arrays for the TIM experiment, along with a corresponding optical coupling scheme for their operation. In Chapter 6, I present the results of laboratory testing of the prototype TIM arrays. I give an overview of the experimental system used for the testing, as well as the analysis steps used to characterize the device behavior. In Chapter 7, I offer some concluding remarks about incorporating these devices into the TIM experiment, and the future of far-infrared applications for KIDs.
Chapter 1

Introduction

The primary means of inquiry and experiment in astronomy is observing the cosmos. Though we have now entered the age of multi-messenger astrophysics with the detection of cosmic rays and neutrinos in the mid-20th century and gravitational waves in the last few years, the vast majority of astrophysical knowledge has come through the collection and analysis of photons. As such, astronomers attempt to utilize the full spectrum of electromagnetic radiation in order to better understand our universe. A number of technologies allow us to collect, detect, digitize, and analyze cosmic photons, from gamma rays to radio waves.

The focus of this thesis is on detecting astrophysical radiation in the far-infrared (far-IR) portion of the spectrum, which can be broadly defined as the 30 – 1000 µm wavelength band.

Observing in the far-IR offers access to study a number of astrophysical processes which are invisible at other wavelengths. In particular, continuum emission and absorption from dust grains with equilibrium temperatures between approximately 15 and 100 K fall in the far-IR wavelength range. In addition, there are prominent elemental and molecular emission and absorption lines including those of oxygen, nitrogen, carbon, and hy-
drogen, that serve as diagnostics and tracers for the conditions occurring within a gas cloud (Farrah et al. 2017).

1.1 Star Formation and Galaxy Evolution

One key area of exploration in modern astrophysics is how galaxies (and black holes within them) are born and evolve over cosmic time. The first galaxies began to form at redshift \( z \sim 10 – 15 \), approximately 500 million years after the big bang (Bromm and Yoshida 2011). As galaxies continued to form and evolve following the epoch of reionization at \( z \sim 6 \), the star formation rate density (SFRD) in the universe increased steadily. As Figure 1.1 shows, the SFRD reached a broad peak at around \( z = 2 \), after which it began a decline that continues to the present day. In addition, the spectral characteristics of typical galaxies have evolved over time. Though normal optical galaxies dominate at present, the universe was dominated by luminous infrared galaxies at \( z = 1 \) and ultra-luminous infrared galaxies at \( z = 2 \) (Béthermin et al. 2011).

Understanding the detailed dynamics of the gas, dust, and metals within the interstellar medium (ISM) and intergalactic medium (IGM) that drive this star formation is an important component in filling in the timeline of cosmic history. The most luminous galaxies that existed around the time of peak cosmic star formation were heavily enshrouded with dust. The dust in these galaxies absorbs optical and ultraviolet (UV) radiation from newly-forming stars as well as active galactic nucleus (AGN) activity and thermally reprocesses it into far-IR radiation. As a result, UV and optical observations of these galaxies are highly-obscured. However, a significant population of luminous high-redshift, dust-obscured galaxies have been detected at infrared wavelengths.

Furthermore, far-IR radiation, both continuum and emission, from star-forming regions in early galaxies can penetrate the dust. A number of infrared spectral features exist
Figure 1.1 Star formation rate density $\rho_{SFR}$ as a function of redshift. The data points show SFR densities determined based on infrared measurements (dark red points) and ultraviolet measurements (blue points). The lines and bands show parameterized fits to the data on its own (black dashed line) and in combination with constraints from the Thompson optical depth $\tau$ from Planck (red band, white line) and WMAP (orange band) assuming that the photons from star-forming galaxies drive the process of reionization. Figure from Robertson et al. (2015).

which serve as tracers of the star formation dynamics within galaxies. Figure 1.2 shows a collection of far-IR fine-structure lines as a function of redshift, with rest wavelengths as follows: $[\text{O}^+\text{I}]$ 63 $\mu$m, $[\text{N}^+\text{II}]$ 122 $\mu$m, $[\text{C}^+\text{II}]$ 158 $\mu$m, $[\text{Ne}^+\text{II}]$ 12.8 $\mu$m, $[\text{Ne}^+\text{V}]$ 24.3 $\mu$m, $[\text{Si}^+\text{II}]$ 35 $\mu$m, $\text{H}_2$ rotational lines S(5) 6.9 $\mu$m, S(3) 9.7 $\mu$m, S(1) 17 $\mu$m, and S(0) 28.2 $\mu$m, and polycyclic aromatic hydrocarbon (PAH) molecular lines at 6.2 $\mu$m, 7.7 $\mu$m and 11.3 $\mu$m. Studying these far-IR fine structure lines provides a detailed picture of the kinematics of cooling and energetic feedback processes in the ISM.

The $[\text{C}^+\text{II}]$ fine structure line in particular is one of the brightest far-IR features observed from star-forming regions in early galaxies, and can account for up to 1% of the total far-IR luminosity from a star-forming galaxy. The ionization potential of neutral carbon is 11.3 eV, so $[\text{C}^+\text{II}]$ can be found in neutral atomic, molecular, or ionized regions of the ISM, and it can be excited by collisions with electrons as well as hydrogen atoms.
or molecules. In star-forming regions, UV photons from newly-formed stars heat the
dust and polycyclic aromatic hydrocarbon (PAH) molecules in the surrounding regions
of the ISM via the photoelectric effect. As the gas cools, it emits [CII] photons. [CII]
line intensity therefore serves as a measure of the energy used for star formation activity
(Herrera-Camus et al. 2015). The relationship between the [CII] line intensity $L_{[\text{CII}]}$ and
the far-IR continuum intensity $L_{\text{FIR}}$ is dependent on redshift, but the $L_{[\text{CII}]}/L_{\text{FIR}}$ ratio is
not well-characterized during the era of peak cosmic star formation (Graciá-Carpio et al.,
2011).

Figure 1.2 Infrared spectral lines as a function of redshift, with a reference spectrum
from the Circinus galaxy (a galaxy in our local galaxy group) plotted in its rest frame
at $z = 0$ and redshifted to $z = 12$ when the first galaxies were forming. Lines plotted in
orange are some of the dominant cooling lines in the ISM; lines plotted in blue are key
spectral diagnostics for black hole accretion rate densities; the H$_2$ rotational transitions
plotted in green are tracers of energy dissipation in collapsing gas following reionization;
and plotted in red are the PAHs trace the UV flux emitted in star-forming regions. The
pink shaded region shows the wavelength band accessible from the TIM experiment (see
Section 2.2). Figure adapted from Alato et al. (2016).

Another approach to learning more about the evolution of galaxies over time is to
study large-scale structure using the cosmic infrared background (CIB). The combined relic emission that reaches us from galaxies formed over time appears as a diffuse background of radiation across the sky. The far-IR component of this diffuse background is the CIB, and it contains about half of the total energy of the cosmic background radiation (Dole et al., 2006). Anisotropies in the CIB can be used to measure the SFRD following the epoch of reionization, and can also indirectly trace dark matter distribution. Studies using this technique have relied upon analyses of the power spectra of 2-dimensional mapping surveys like Planck and IRAS (Planck Collaboration et al., 2014).

Cosmological observations in the far-IR therefore allow a connection between the process of star formation in individual early galaxies and the properties of large scale structure evolution. Making this connection, however, requires mapping a large cosmic volume along with large spectroscopic and photometric redshift surveys. Measuring far-IR redshifts of individual galaxies is difficult and slow with instruments and observatories that are currently operating. Another option is to use the technique of intensity mapping to make large spectroscopic maps.

### 1.2 Intensity Mapping

Intensity mapping (also referred to as line intensity mapping, or tomographic mapping) is a spectroscopic observation technique that measures the total integrated spectral luminosity over three-dimensional spatial volumes of the universe. When applied to the study of a specific spectral line, frequency dependence of spectral line emission adds information about position/density of sources along the line-of-sight to a two-dimensional map. Spectroscopic redshift information is therefore contained within the map itself. The power spectrum of the intensity map can then be used to study the evolution of source (galaxy) clustering and large scale structure.
Intensity mapping offers several advantages over traditional imaging for observing the evolution of large-scale structure and galaxy formation. Most importantly, with intensity mapping, every photon emitted within the cosmic volume being observed is measured. While traditional image-based surveys require combining large numbers of individual object measurements in order to probe large-scale structure or galaxy evolution, intensity mapping results in an aggregate, integrated measurement of the spectral emission of all sources within a given cosmic volume, including those too faint to be detected individually. A survey performed using an intensity mapping technique has no flux limit, and includes data from even the faintest sources. In addition, intensity mapping surveys do not require high angular resolution, and can therefore be carried out using telescopes with modestly-sized apertures. They do, however, require spectrometer elements, which adds complexity to the optical system.

Figure 1.3 shows a simulated comparison between an object-based survey and an intensity map for the CO emission lines. The intensity map includes data across the entire survey field, which is extremely useful for studying aggregate properties of the CO line emission. Uzgil et al. (2014) gives a detailed treatment of how a measurement of galaxy clustering would be extracted from an intensity map of [CII] in the far-IR, along with predictions for its power spectrum and detectability.
Figure 1.3 **Left:** A simulated 2.5 deg$^2$ field and **right:** its corresponding CO intensity map, with luminosities drawn from a Schechter function model. The red dots in the left panel represent sources bright enough to detect with 1hr of VLA time, and the right panel assumes resolutions anticipated with the COMAP instrument. Figure from Patrick Breysse as published in [Kovetz et al. (2017)].
Chapter 2

Astrophysical Spectroscopy in the Far-Infrared

2.1 Experimental Landscape

In the mid- to far-IR wavelength range, there are several existing and planned instruments capable of performing spectroscopic surveys. Below, I highlight the architecture of each experiment, along with its prospects for contributing to the science of understanding galaxy evolution. Figure 2.1 shows a comparison of a number of different instruments in terms of their mapping speed to produce a 3-dimensional spatial-spectral map.

- The Atacama Large Millimeter/submillimeter Array (ALMA; Wootten and Thompson, 2009) is a ground-based radio telescope array in the Atacama desert in Chile, at an altitude of 5000 m. It consists of 54 12-m antennas and 12 7-m antennas, which have sensitivity in discrete wavelength bands between 300 µm and 1 cm. The array can be arranged in a variety of configurations depending on the spatial resolution and sensitivity required for a given observation. ALMA is an interferometer, so the signal from the heterodyne antenna detectors is interfered and digitally correlated to
extract the sky signal. ALMA is an extremely powerful instrument for targeted object observations, including followup observations of mapping surveys (e.g. [Weiß et al., 2013]). Producing a large scale map with ALMA, however, would not be feasible for both cost and time reasons. In addition, due to atmospheric opacity, most of the far-IR fine structure lines key to tracing star formation between $0.5 < z < 3$ are not accessible with its detection bands, as shown in Figure 1.2.

- The Far Infrared Field-Imaging Line Spectrometer (FIFI-LS; [Rebell et al., 2014]) is an instrument on the airborne Stratospheric Observatory for Infrared Astronomy (SOFIA) telescope. It contains two integral field spectrometer instruments which span the wavelength band from 50–200 µm with a spectral resolving power of $R \sim 2000$. FIFI-LS has, to date, been used by several groups to do targeted [CII] observations aimed at understanding star formation in individual galaxies ([Klein et al., 2018; Pineda et al., 2018]). FIFI-LS would not be an appropriate instrument for a larger-scale survey, since its mapping speed is quite slow and its band is still limited by atmospheric transmission, even at aircraft altitude ($\sim 12$ km).

- Herschel ([Pilbratt et al., 2010]) was a space observatory launched in 2009 by the European Space Agency that operated at the second Lagrange point (L2) of the Earth-Sun system until 2013. The telescope had a 3.5-m, passively-cooled mirror, and carried three detector instruments. The Photodetector Array Camera and Spectrometer (PACS) contained an imaging photometer covering the wavelength band between 60 and 210 µm and an integral field spectrometer with $1000 < R < 4000$ in the 55–210 µm band. The Heterodyne Instrument for the Far Infrared (HIFI) was a heterodyne spectrometer with wavelength coverage between 157 and 625 µm and $R \sim 10^6$. The Spectral and Photometric Imaging REceiver (SPIRE) contained a three-band imaging photometer at 250 µm, 350 µm and 500 µm, along with an
imaging fourier transform spectrometer operating between 194 and 671 µm with $370 < R < 1300$. SPIRE performed some surveys to characterize galaxies which contribute to the CIB, but they were confusion-limited (see Glenn et al., 2010).

- The **Spitzer Space Telescope** (Werner et al., 2004) is a space observatory launched in 2003 that operates in an Earth-trailing solar orbit. It combines a cooled 85 cm primary mirror with three detector instruments. The Infrared Array Camera (IRAC) is a four-color imaging camera (3.6 µm, 4.5 µm, 5.8 µm and 8 µm), while the Multi-band Imaging Photometer for Spitzer (MIPS) images in three bands at 24 µm, 70 µm and 160 µm. The third instrument is the Infrared Spectrograph (IRS; Houck et al., 2004), which contains four separate slit spectrometers that combine to cover the 5.3 to 38 µm band at $R \sim 90$ and $R \sim 600$. **Spitzer** is capable of performing relatively fast, sensitive surveys, including both the mid-IR continuum luminosities as well as PAH lines back to $z \sim 2.5$. (Smith et al., 2006; Menéndez-Delmestre et al., 2009)

- The **James Webb Space Telescope** (JWST; Gardner et al., 2006) is a space observatory scheduled to launch to L2 in 2021. Its primary mirror is segmented, with a total active area of 6.6 m. The mirror and four science instruments are all cooled to 50 K. The Near InfraRed Camera (NIRCam), Near Infrared Spectrograph (NIRSpec), and Near InfraRed Imager and Slitless Spectrograph (NIRISS) are designed for imaging and spectroscopy in the 0.6 µm to 5 µm wavelength range. The Mid-InfraRed Instrument (MIRI; Wright et al., 2004) contains both an imager and spectrometer ($R \sim 3000$) designed to operate between 5 and 28.3 µm. **JWST** is expected to make groundbreaking observations across astrophysics and cosmology, including infrared luminosity measurements of early dusty galaxies that can be used to extract dust temperature and mass (see Schreiber et al., 2017).

- The **Space Infrared telescope for Cosmology and Astrophysics (SPICA; Swinyard**
is a proposed space telescope that would launch to L₂ in the 2030s. It has a 2.5-m primary mirror cooled to 50 K, and a complement of three scientific instruments. The SPICA Mid-infrared Instrument (SMI) performs low-resolution (HR; $R \sim 100$), mid-resolution (MR; $R \sim 2000$), and high-resolution (HR; $R \sim 28000$) spectroscopy between 12 and 36 µm. The SPICA Far-infrared Instrument (SAFARI) is intended as a successor to Herschel’s HIFI, and covers the 34 µm – 230 µm wavelength band with a LR ($R \sim 300$) diffraction grating spectrometer and an HR ($R \sim 10000$) Martin-Puplett interferometer. POL is a polarization-sensitive camera with bands at 100 µm, 200 µm and 350 µm. One of the primary science drivers for SPICA is the study of gas and dust dynamics within galaxies and star-forming regions, so it will be able to quickly map large areas with very high sensitivity (Roelfsema et al., 2018).

• The Origins Space Telescope (OST; The OST mission concept study team, 2018) is a proposed space telescope that would also launch to L₂ in the 2030s. The mission architecture is still being determined, but it will likely consist of a suite of mid- and far-IR spectrometers and imagers. As the name implies, it is targeted at the study of the formation and growth of the first galaxies, stars, and planetary systems.

2.2 The Terahertz Intensity Mapper

The Terahertz Intensity Mapper (TIM; Viera, 2018), formerly known as the Spectroscopic Terahertz Airborne Receiver for Far-InfraRed Exploration (STARFIRE), is a new balloon-borne far-infrared telescope experiment currently in development. TIM is designed to perform far-IR spectroscopy in order to map a volume spanning 4.5 billion years of cosmic history on spatial scales from 1 – 50 Mpc. It will operate in the 240 – 420 µm wavelength
band, which will allow it to measure $L_{\text{FIR}}$, [C\text{II}], and [N\text{II}] for $0.52 < z < 1.67$, as shown by the pink shaded region in Figure 1.2. TIM fills a gap in terms of currently-operating instruments which are capable of sensitive survey measurements in this wavelength range, and it will serve as a technological and scientific bridge to future far-IR orbital platforms like OST and SPICA. In addition, TIM will be the first experiment to use the technique of intensity mapping in the far-IR.

Figure 2.2 shows a simulated survey volume cone that demonstrates the type of map that TIM will make, including both (blind) individual object detections as well as the full intensity map. TIM creates an intensity data cube $S(\alpha, \delta, \nu)$ with celestial coordinates $(\alpha, \delta)$ and line-of-sight coordinate determined from the spectral dimension, the frequency $\nu$. To map line emission, the smooth continuum contribution is removed so that the frequency axis maps onto the cosmological redshift, from which the line-of-sight distance and corresponding transverse distances for $(\alpha, \delta)$ can be calculated. Thus the measured $S(\alpha, \delta, \nu)$ is transformed to $S(x)$, where $x$ denotes comoving spatial coordinates. The survey volume can be subdivided in redshift such that minimal cosmological evolution occurs within a sub-volume. Within these 3-D sub-volumes we study the fluctuation power in the line emission as a function of spatial wavenumber $|k|$. The power spectrum of $S$ is calculated by combining the linear halo-halo (2-halo) and intra-halo (1-halo) clustering terms:

$$P_i(k) = \bar{S}_i^2 \bar{b}^2 P(k) + P_s$$

$$= \int \left( \frac{dn_i}{dL_i} \right) \left( \frac{y_i D_{\Lambda,co}^2}{4\pi D_L^2} \right) b^2 P(k) \, dL + \int \left( \frac{dn_i}{dL_i} \right)^2 \left( \frac{y_i D_{\Lambda,co}^2}{4\pi D_L^2} \right)^2 dL,$$  \hspace{1cm} (2.1)

where $\bar{S}_i$ is the average line emission signal, $\bar{b}$ is the luminosity weighted average galaxy bias, $P(k)$ is the matter power spectrum, $P_s$ is the Poisson noise term due to the fluctuations of discrete galaxy positioning, $L_i$ is the luminosity of line emission, and $y_i$ is a
The primary science goals of TIM are:

1. Produce deep tomographic maps of the 3D structure of the Universe to measure the power spectrum of [C\textsc{ii}] and [C\textsc{ii}] ×[N\textsc{ii}]. This will be a pioneering demonstration of the technique of intensity mapping, which provides a new method to constrain the cosmic star formation history and measure its relation to the underlying dark matter distribution.

2. Perform a blind spectroscopic survey for [C\textsc{ii}] line emitters within an enormous cosmic volume, $10^7$ Mpc$^3$, at $0.52 < z < 1.67$. Approximately 100 galaxy detections are expected, which will provide a powerful observational constraint on models of galaxy evolution.

3. Capture the star formation contribution of galaxies too faint to be detected individually, by measuring the [C\textsc{ii}] luminosity function across the peak of cosmic star formation.

4. Use stellar mass-selected galaxies with spectroscopic redshifts from the GOODS-S field to stack on [C\textsc{ii}] and [N\textsc{ii}], and develop the theory to relate this to the total star formation rate ([C\textsc{ii}]), star formation mode ([C\textsc{ii}]/L$_{FIR}$), metallicity ([N\textsc{ii}]/[C\textsc{ii}]), and specific star formation rate ([C\textsc{ii}]/M$_{\text{star}}$).

5. Cross-correlate the [C\textsc{ii}] data cube (which provides redshift information) with Herschel/SPIRE maps (SFR) to calibrate the [C\textsc{ii}]/SFR relation, and Spitzer/IRAC maps (stellar mass) to measure the specific star formation rate versus redshift.
2.2.1 Instrument Architecture

The balloon-based telescope platform is key to achieving TIM’s science goals. The atmosphere is largely opaque in the far-IR, which makes sensitive measurements difficult or impossible from the ground. With a long-duration balloon (LDB) flight, TIM is expected to reach an observing altitude of around 35–40 km. The telescope optics and detectors should be sensitive enough to be atmosphere-limited at altitude — that is, the photon noise from the atmospheric background should be the dominant source of noise in the system.

As a figure of merit for comparing sources of noise, we can calculate the noise equivalent power (NEP). For a greybody at (physical) temperature $T$ and emissivity $\varepsilon_\nu$, the NEP due to photon shot noise from unpolarized light is:

\[
\text{NEP}_\nu = 2h\nu \sqrt{n(n+1)(\Delta\nu)},
\]

(2.2)

where $h$ is Planck’s constant, $\nu$ is the optical photon frequency, and $\Delta\nu$ is the optical frequency band. The photon occupation number $n_\gamma$ as detected by an optical system with optical efficiency $\eta_{\text{opt}}$ is given by

\[
n_\gamma = \frac{\eta_{\text{opt}} \varepsilon_\nu}{\exp(h\nu/k_BT) - 1},
\]

(2.3)

where $k_B$ is Boltzmann’s constant. Figure 2.3 compares the photon NEP from ground- and balloon-based platforms. Based on $\text{NEP}_\nu$, we can also calculate the line sensitivity for detecting an unresolved line from a point source object with a telescope with effective collecting area $A_{\text{eff}}$:

\[
S_\gamma = \frac{\sqrt{2} \text{NEP}_\nu}{\eta_{\text{opt}} A_{\text{eff}} (1 - \varepsilon_\nu)}.
\]

(2.4)
2.2.1.1 Telescope

To this end, TIM will use a 2-m, segmented, on-axis primary mirror made of carbon fiber reinforced polymer (CFRP) material. A CFRP mirror is both mechanically strong and able to maintain stable performance under varying thermal conditions. In addition, the mirror segments will be gilded in an effort to minimize the thermal emissivity of the mirror itself. The secondary mirror will also be made of gilded CFRP. While the telescope area does not affect intensity mapping speed, it does affect the angular resolution and therefore the maximum wavenumber $k$ that the power spectrum can probe. The 2-m primary is the largest diameter feasible with current fabrication techniques. The total emissivity of the mirrors is expected to be 2.50%.

The architecture of the TIM instrument draws heavily from the BLAST-TNG experiment ([Dober et al., 2014](#)), which is prepared for flight in winter 2019. The TIM gondola, as well as the readout, cryogenics, and pointing systems, will be clones of the BLAST-TNG designs.

2.2.1.2 Spectrometer

The spectrometer design for TIM uses a reflective blazed diffraction grating, with a target spectral resolution of $R = 250$. The grating is fed by a slit, which sets the spatial dimension in the focal plane. Since this approach is dispersive, it results in lower photon noise levels at each detector element; that is, each pixel only sees the photon noise from its own coordinate in the spectral dimension. Furthermore, the grating also allows for instantaneous coverage of a relatively wide spectral band.

Two separate grating modules will be used: a short wavelength (SW) module covering the 240–317 µm range, and a long wavelength (LW) module covering the 317–420 µm range (see Figure 2.4). Both will be configured to operate in first-order. The modules are
very similar in design, with slight adjustments to account for the wavelength difference. The spectrometers will be cooled to 1 K, and contained within separate enclosures in order to minimize stray light.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Telescope</strong></td>
<td>Diameter</td>
<td>2.0 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Illumination</td>
<td>0.93 in diameter (primary mirror is pupil stopped)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temperature, Emissivity</td>
<td>270 K, 0.025 – primarily secondary struts</td>
<td></td>
</tr>
<tr>
<td><strong>Spectrometer</strong></td>
<td>Format</td>
<td>2 modules, each 25 spatial × 72 spectral</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R$</td>
<td>250 (1200 km s$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Optical efficiency</td>
<td>25%, to point source, including horn coupling</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wavelength range</td>
<td>240 – 317</td>
<td>317 – 420</td>
</tr>
<tr>
<td></td>
<td>$\Delta \nu$</td>
<td>4.4</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>Beam FWHM</td>
<td>35</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>1σ median line sensitivity</td>
<td>2.9</td>
<td>2.1</td>
</tr>
</tbody>
</table>

**Observations**

<table>
<thead>
<tr>
<th></th>
<th>[CII] redshift range</th>
<th>0.52–1.0</th>
<th>1.0–1.7</th>
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<tbody>
<tr>
<td></td>
<td>[CII] cosmic epoch</td>
<td>5.9–8.5</td>
<td>3.9–5.9</td>
</tr>
<tr>
<td></td>
<td>5σ [CII] depth, 100h, 0.1 sq deg</td>
<td>1.2</td>
<td>2.75</td>
</tr>
</tbody>
</table>

$5 \sigma$ [CII] depth, $100h$, 0.1 sq deg $\times 10^9 L_\odot$ (in [CII])

2.2.2 Detector Requirements

The primary requirement for the detectors is that their noise performance be background-limited under the conditions expected during the TIM observations. The minimum photon NEP across the TIM band is approximately $1.1 \times 10^{-17}$ W/√Hz, while the median photon loading is anticipated to be 20 fW. We therefore require detectors with NEPs of $1 \times 10^{-17}$ W/√Hz, and target detectors with NEPs of $4 \times 10^{-18}$ W/√Hz.

Each of TIM’s spectrometer modules will contain 1800 kinetic inductance detectors (KIDs) in a 25 (spatial) × 72 (spectral) array format. Each detector is fed by a straight-walled conical feed horn. In the following chapters, I will describe in detail the design and characterization process of prototype KID pixels for the TIM experiment.
Figure 2.1 Comparison of capabilities of existing and future spectroscopic instruments in the mid- to far-IR wavelength band for surveys and spectral line detection. **Top panel:** spatial-spectral mapping speed as a function of wavelength. The survey speed is shown in arcmin²/hr that could be mapped down to a detected RMS intensity of $2 \times 10^{-20}$ W/m², so larger values correspond to faster mapping. **Bottom panel:** spectral line sensitivity $S_γ$ as a function of wavelength, shown in W/m² for a 5σ detection in one hour of observation. Figure adapted from Viera (2018) and Roelfsema et al. (2018).
Figure 2.2 Schematic TIM data volume (without noise), based on a simulated light cone. The aggregate \([\text{CII}]\) emission is shown in blue, and is the result of a power spectrum analysis of the intensity map. Simulated individual object detections in \([\text{CII}]\) are shown in orange. Figure from G. Keating, based on the framework presented in Popping et al. (2019).

Figure 2.3 Noise equivalent power of atmospheric photons from a ground-based site (solid black) and at balloon altitude of 37 km (dashed black). At balloon altitude, the temperature of the atmosphere is 250 K, and it is \(\sim 1\%\) emissive. The variation in the band is due to atmospheric absorption lines, which can be used for frequency calibration. The colored lines give a comparison of different combinations of telescope temperature \(T\) and emissivity \(\varepsilon\).
Figure 2.4 TIM telescope, mirror, and spectrometer designs. The upper left shows a cross-section of the full experiment. The TIM gondola, pointing system, and readout electronics are based on the BLAST-TNG design. The upper right shows the gold-plated CFRP primary mirror, with an individual segment offset to demonstrate the segmentation scheme, along with the gold-plated CFRP secondary mirror, and the CFRP supports to hold the secondary mirror in place. The bottom panel shows a ray tracing simulation of the long wavelength (LW) and short wavelength (SW) spectrometer modules from two different perspectives.
Chapter 3

Background Physics of Superconductors

Kinetic Inductance Detectors (KIDs) are not only made out of superconductors, but the detection principles they use also rely fundamentally on the physics of superconductivity. In this chapter, I will review the historical background and notable effects that characterize superconductors. I will then give an introduction to how KIDs work when incorporated into an astronomical system as optical detectors.

3.1 Historical Background

Superconductivity is a phase that some metals and alloys can take below a threshold temperature, characterized by several distinguishing properties. In 1911, Kamerlingh Onnes discovered the phenomenon of superconductivity by measuring the electrical resistances of metals as he cooled them to very low temperatures [Onnes, 1911]. In normal metals, the voltage-current relationship is given by \( V = IR \), where \( V \) is the voltage across the material, \( I \) is the current running through the circuit formed by the material, and \( R \) is the
material’s electrical resistance. In superconducting materials, however, the effective resistance to a direct current drops precipitously to zero at a low but measurable threshold temperature (known as the critical temperature, or \( T_c \)). Zero resistance corresponds to perfect (infinite) electrical conductivity, since conductivity \( \sigma \) is inversely proportional to resistance. In 1933, Meissner and Ochsenfeld found that another hallmark characteristic of superconductors is perfect diamagnetism; that is, a magnetic field applied to a superconducting material is expelled as the material is cooled through its transition temperature (Meissner and Ochsenfeld, 1933).

### 3.2 BCS Superconductivity

In 1957, Bardeen, Cooper, and Schrieffer laid out the microscopic theory of superconductors which describes a superconducting current as a superfluid of Cooper pairs (Bardeen et al., 1957). Cooper pairs are bound states of two opposite-spin, opposite-angular momentum electrons which form as a result of phonon-electron interactions within the material. As Figure 3.1 shows, free electrons in the superconducting current (“quasiparticles”) combine to form Cooper pairs, releasing energy. Or, Cooper pairs can absorb energy, in the form of photons incident on a superconducting material or phonons from within it, and break into quasiparticles. Quasiparticles themselves can also scatter with each other, interacting with phonons in the process.

The binding energy of a Cooper pair is referred to as \( \Delta \), and its value is related to the superconducting critical temperature. For many superconductors, the relationship between \( \Delta \) and \( T_c \) is given by

\[
2\Delta = 3.5k_B T_c, \tag{3.1}
\]

where \( k_B \) is Boltzmann’s constant.\(^1\) The energy needed to break a single Cooper pair into

\(^1\)In the full microscopic treatment (e.g. Tinkham, 2004), \( \Delta \) is a function of temperature and \( T_c \) is given
two quasiparticles is $2\Delta$.

Figure 3.1 Two quasiparticle-phonon interaction processes within a superconductor. 
(Left) As drawn, a quasiparticle with energy $E_0$ decays into a quasiparticle with energy $E_0 - \Omega$ and emits a phonon with energy $\Omega$. The reverse process also occurs. With the arrows reversed, the diagram represents a quasiparticle with energy $E_0 - \Omega$ absorbing a phonon with energy $\Omega$, leaving a quasiparticle in a higher-energy state with energy $E_0$. (right) As drawn, two quasiparticles with energy $E_1$ and $\Omega + E_2$, respectively, (re-)combine to form a bound state Cooper pair with energy $2\Delta$ and emit a phonon with energy $\Omega$. With the arrows reversed, the diagram represents a phonon pair-breaking process: a Cooper pair absorbs a phonon (with energy $\Omega > 2\Delta$) and breaks into two quasiparticles. (Chang and Scalapino [1977])

Though the DC resistance and conductivity of superconductors are well-understood, their behavior under alternating currents is much more complex. The bulk DC behavior of a superconductor is defined by the Meissner effect, where the resistance, and therefore energy dissipation in the material, are nonexistent at temperatures below $T_c$. When an alternating current is applied, however, a finite dissipation arises as a result of the inertia of the Cooper pair/quasiparticle system. 

by $\Delta(T=0)$. We operate KIDs at temperatures well below $T_c$, so we take $\Delta$ to be a constant as shown in Equation [3.1]. There are also a number of “non-BCS” superconductors which exhibit different scaling relationships between the binding energy and critical temperature.
3.2.1 Kinetic Inductance Effect

When an alternating current is applied to a superconductor, the kinetic inductance effect occurs as a result of the kinetic energy of Cooper pairs “changing direction.” Each time the current changes sign, the kinetic energy must be extracted from the Cooper pairs in order for them to change the direction of effective current flow. This energy extraction in turn results in dissipation in the superconductor, and is known as kinetic inductance.

Despite its name, kinetic inductance is not directly related to geometric inductance. They share a name because of the similar energy-current relationships when an element containing either is incorporated into a circuit. That is, if we incorporate a superconductor with kinetic inductance into a circuit, the following derivation can be used to describe its behavior.

The average kinetic energy of the Cooper pairs in the material is given by:

\[ E_k = \frac{1}{2} n m_c v^2, \]  
\[ (3.2) \]

where \( m_c \) is the Cooper pair mass, \( n \) is the density of Cooper pairs (number per unit volume), and \( v \) is their drift velocity in the material. The current that transports the Cooper pairs through the material can be described by

\[ I = n A v q, \]  
\[ (3.3) \]

where \( A \) is the cross-sectional area of the superconducting material, and \( q \) is the Cooper pair charge. Solving this equation for \( v \) and squaring gives

\[ v^2 = \frac{I^2}{n^2 A^2 q^2}. \]  
\[ (3.4) \]
We can then plug this result for $v^2$ back into our equation for $E_k$:

$$E_k = \frac{1}{2}nm_c \left( \frac{I^2}{n^2A^2q^2} \right) = \frac{m_cI^2}{2nA^2q^2} = \frac{1}{2} \left( \frac{m_c}{nA^2q^2} \right) I^2. \quad (3.5)$$

Recall that in a geometric inductor, the relationship between energy and current is given by $E_k = \frac{1}{2}LgI^2$, and the similarity between geometric and kinetic inductance should be evident. We therefore define the kinetic inductance $L_k$ as

$$L_k = \frac{m_c}{nA^2q^2}. \quad (3.6)$$

If we now allow the current and the Cooper pair density within the material to vary, we can continue our analogy to geometric inductance and describe the voltage behavior of the superconducting material by:

$$V_k = -I \frac{dL_k}{dt} - L_k \frac{dI}{dt}, \quad (3.7)$$

or in the complex frequency domain

$$V_k(\omega) = j\omega L_k I(\omega). \quad (3.8)$$

The kinetic inductance $L_k$ depends on the material as well as the geometry of the circuit (the area of the conductor). This is a conceptual overview of the kinetic inductance effect; the full description depends on carefully deriving the complex conductivity of the superconducting material (see Section 4.1).
### 3.2.2 Kinetic Inductance Detectors

KIDs make use of the kinetic inductance effect by incorporating high-kinetic inductance superconducting materials as photon detectors. A KID pixel consists of a high-quality factor microresonator patterned out of thin-film superconducting material. When the superconductor absorbs optical radiation, the resonance of the circuit shifts in both frequency and amplitude.

![Schematic diagram of a single KID pixel.](image)

Figure 3.2 shows a circuit diagram of an individual KID pixel. The parallel capacitor and inductor form a resonant circuit, which is capacitively coupled to a transmission line and to ground. Though there is no (real) resistance, there is energy dissipation in the circuit as a result of kinetic inductance. It has a resonance frequency $f_0$

$$f_0 = \frac{1}{2\pi \sqrt{L_r C_r}}$$  \hspace{1cm} (3.9)

The inductor’s total inductance, $L_r$, includes both the geometric and kinetic inductance. When photons with energy greater than $2\Delta$ are absorbed in the superconductor, they break Cooper pairs and increases the density of quasiparticles. This changes the kinetic inductance, which in turn shifts the resonance frequency of the circuit. The frequency shift is the measured signal corresponding to the incident radiation. It is important to note that $f_0$ is set by the circuit design, and is completely separate from the frequency of optical radiation; in fact, they typically differ by many orders of magnitude.

We measure the frequency shift by setting $V_{in}$ to be a probe tone at frequency $f$, and
comparing the voltage at the input port to the modulated voltage at the output port:

\[
\frac{V_{\text{out}}(f)}{V_{\text{in}}(f)} = S_{21}(f) \equiv I(f) + jQ(f).
\]  \hfill (3.10)

\(S_{21}\) is the scattering parameter for the two-port system which measures transmission through the circuit. \(I\) and \(Q\) are defined to be the real and imaginary parts of \(S_{21}\), respectively. The observed shifts in resonance frequency depend on the optical power levels absorbed in the resonator, but are small compared to the resonance frequency itself \((\delta f/f_0 \sim 10^{-5})\).

Since each individual resonator pixel has its own resonance frequency, KIDs are inherently straightforward to multiplex; that is, we can combine the signals from multiple pixels onto a single transmission line by giving each pixel a different resonance frequency. Figure [3.3] shows an example of a multiplexed KID array circuit.

![Schematic diagram of a number of pixels multiplexed onto a single transmission line. By giving each resonator pixel its own resonance frequency, the signals can be transmitted and read out simultaneously.](image)

### 3.2.3 Quality Factors

For each resonator, the quality factor \(Q_r\) depends on both the superconducting material and the coupling of the resonator circuit to the transmission line. Their contributions add reciprocally:

\[
Q_r^{-1} = Q_c^{-1} + Q_i^{-1}.
\]  \hfill (3.11)
The internal (or intrinsic) quality factor, $Q_i$, is a result of the quasiparticle dissipation loss within the resonator. It is given by

$$Q_i = \frac{2\pi f_0 L_r}{R_{\text{eff}}}$$

(3.12)

for an effective resistance $R_{\text{eff}}$ due to quasiparticle dissipation in the superconductor. For a capacitively-coupled resonator like the one in Figure 3.2, the coupling quality factor $Q_c$ is

$$Q_c = \frac{(C_r + C_C)}{\pi f_0 C_c^2 Z_0},$$

(3.13)

where $Z_0$ is the impedance of the microwave feedline (Mauskopf, 2018).
Chapter 4

Phenomenology of Kinetic Inductance Detectors

In order to describe the behavior of KID devices under a variety of operating conditions including photon loading, we must delve into the electrodynamic properties of superconducting films. In this chapter, I will lay out the relationships between the response of a KID device and the optical photons it absorbs. Incident power falls on the detector, and is absorbed with some efficiency $\eta_{\text{opt}}$. The absorbed power breaks Cooper pairs and increases the quasiparticle density in the superconductor $n_{\text{qp}}$ (Equation 4.31), which in turn shifts the complex conductivity $\sigma$. The conductivity shift causes a change in the surface impedance $Z_s$, which in turn changes the kinetic inductance $L_k$ and effective resistance (dissipation) $R_{\text{eff}}$ in the circuit (Equation 4.13). By measuring the forward scattering parameter $S_{21}$ (Equation 4.23), we calculate the resulting fractional frequency shift $x$ (Equation 4.28) and intrinsic quality factor $Q_i$ (Equation 4.29). The following chapter draws from the derivations laid out in [Gao 2008; Noroozian 2012; Mccarrick 2018].

$$\delta P \Rightarrow \delta n_{\text{qp}} \Rightarrow \delta \sigma \Rightarrow \delta Z_s \Rightarrow \delta L_k \Rightarrow \delta R_{\text{eff}} \Rightarrow \delta x, \delta Q_i$$
4.1 Mattis-Bardeen theory

We start by calculating the number density of quasiparticles in the superconducting film (for temperatures $0 < T < T_c$). Quasiparticles that result from broken Cooper pairs are superposition states of electrons and electron holes, and we can describe them as neutral, spin-$\frac{1}{2}$ fermions (Kivelson and Rokhsar, 1990). This means that when the quasiparticle system is in thermal equilibrium, the energy distribution of quasiparticles is given by the Fermi-Dirac distribution

$$f(E) = \frac{1}{e^{E/k_B T} + 1}. \quad (4.1)$$

From BCS theory, the density of states is given by

$$\rho(E) = \frac{E}{\sqrt{E^2 - \Delta^2}}. \quad (4.2)$$

We can then combine Equations 4.1 and 4.2 to calculate the quasiparticle density per unit volume:

$$n_{qp} = 4N_0 \int_0^\infty f(E)\rho(E) dE, \quad (4.3)$$

where $N_0$ is the single-spin density of electron states at the Fermi energy (for aluminum, $N_0 = 1.72 \times 10^{10}$ $\text{µm}^{-3}\text{eV}^{-1}$). The integral can be evaluated approximately as

$$n_{th}(T) \approx 2N_0 e^{\frac{\Delta}{k_B T}} \sqrt{2\pi k_B T \Delta}. \quad (4.4)$$

(Noroozian, 2012).

We assume that superconductors incorporated into KIDs operate in a regime where a local version of Ohm’s Law applies, such that $\vec{J}(\vec{r}) = \sigma(\omega)\vec{E}(\vec{r})$ for the current density $\vec{J}$, position $\vec{r}$, and conductivity $\sigma$ (Gao, 2008). We consider only (angular) frequencies $\omega = 2\pi f$ below the gap frequency $\omega_g = \frac{4\pi}{h} \Delta$, so that the AC signal cannot itself break
Cooper pairs. The Mattis-Bardeen theory allows us to calculate the complex conductivity of a superconductor, \( \sigma = \sigma_1 - j\sigma_2 \) relative to the normal state conductivity \( \sigma_n = 1/\rho_n \) as:

\[
\frac{\sigma_1(\omega)}{\sigma_n} = \frac{2}{\hbar \omega} \int_{\Delta}^{\infty} dE \frac{E^2 + \Delta^2 + \hbar \omega E}{\sqrt{(E^2 - \Delta^2)(E + \hbar \omega)^2 - \Delta^2}} [f(E) - f(E + \hbar \omega)] \tag{4.5}
\]

and

\[
\frac{\sigma_2(\omega)}{\sigma_n} = \frac{1}{\hbar \omega} \int_{\Delta}^{\Delta + h \omega} dE \frac{E^2 + \Delta^2 - \hbar \omega E}{\sqrt{(E^2 - \Delta^2)(E - \hbar \omega)^2}} [1 - 2f(E)]. \tag{4.6}
\]

Since we are operating in the limit where \( \hbar \omega \ll \Delta \) and \( k_B T \ll \Delta \), these integrals can be solved as:

\[
\frac{\sigma_1}{\sigma_n} = \frac{4\Delta}{\hbar \omega} e^{-\Delta/k_B T} \sinh (\xi_0) K_0(\xi_0) \tag{4.7}
\]

and

\[
\frac{\sigma_2}{\sigma_n} = \frac{\pi \Delta}{\hbar \omega} \left[ 1 - 2e^{-\Delta/k_B T} e^{-\xi_0} I_0(\xi_0) \right], \tag{4.8}
\]

where \( K_0 \) and \( I_0 \) are the zeroth-order modified Bessel functions of the first and second kind, respectively. \( \xi_0 = \hbar \omega / 2k_B T \) is the coherence length of the superconductor, which we can think of as the minimum size of a Cooper pair according to the Heisenberg uncertainty principle (Gao, 2008). Using Equation 4.4, we can rewrite the complex conductivity expressions in terms of \( n_{qp} \) as:

\[
\frac{\sigma_1}{\sigma_n} = \frac{n_{qp}}{N_0 \hbar \omega} \sqrt{\frac{2\Delta}{\pi k_B T}} \sinh (\xi_0) K_0(\xi_0) \tag{4.9}
\]

and

\[
\frac{\sigma_2}{\sigma_n} = \frac{\pi \Delta}{\hbar \omega} \left[ 1 - \frac{n_{qp}}{2N_0 \Delta} \left( 1 + \sqrt{\frac{2\Delta}{\pi k_B T}} e^{-\xi_0} I_0(\xi_0) \right) \right]. \tag{4.10}
\]

We now consider small perturbations in \( \sigma_1 \) and \( \sigma_2 \), assuming that a perturbation in the quasiparticle energy distribution function, \( \delta f(E) \), has the same shape as \( f(E) \). Combin-
ing this assumption with Equations 4.9 and 4.10, we can write:

\[
\frac{\delta \sigma_1}{\sigma_1} = \frac{\delta n_{qp}}{n_{qp}} \tag{4.11}
\]

and

\[
\frac{\delta \sigma_2}{\sigma_2 - \sigma_2(n_{qp} = 0)} = \frac{\delta n_{qp}}{n_{qp}} \tag{4.12}
\]


These equations are fundamental to explaining the detection principles of kinetic inductance detectors, because they demonstrate the fact that a fractional shift in the quasiparticle number density results in a proportional shift in the complex conductivity.

### 4.1.1 Surface Impedance

In typical lab measurements, we are not able to directly measure the complex conductivity. Instead, we probe the complex surface impedance \( Z_s \), which is related to the complex conductivity as:

\[
Z_s = R_s + jX_s = \frac{1}{\sigma t}, \tag{4.13}
\]

where \( R_s \) is the surface resistance resulting from the quasiparticle dissipation, and \( X_s = \omega L_k \) is the reactance resulting from the kinetic inductance of the Cooper pairs. The right side of the equation assumes that we operate in the thin-film limit, in which the superconducting film thickness \( t \) is much smaller than the London penetration depth \( \lambda_L = \sqrt{\frac{m_e c^2}{4\pi n_{qp} q^2}} \).

If we consider a small change in the surface impedance \( \delta Z_s = Z_s - Z_s(T = 0) = Z_s - jX_s \), we find

\[
\frac{\delta Z_s}{Z_s} = -\frac{\delta \sigma}{\sigma}. \tag{4.14}
\]
Near zero temperature, we can separate the real and imaginary contributions to the surface impedance as follows, since at $T = 0 \sigma(0) = -j\sigma_2(0)$:

$$\frac{\delta R_s}{X_s(T = 0)} = \frac{\delta \sigma_1}{\sigma_2(T = 0)} \quad (4.15)$$

$$\frac{\delta X_s}{X_s(T = 0)} = -\frac{\delta \sigma_2}{\sigma_2(T = 0)} \quad (4.16)$$

We can then combine this with the expressions for $\sigma$ (Equations 4.9 and 4.10 and $\delta \sigma$ (Equations 4.11 and 4.12) to find the relationship between quasiparticle density fluctuations and the surface impedance:

$$\frac{\delta R_s}{X_s(0)} = \frac{S_1}{2\Delta N_0} \delta n_{qp} \quad (4.17)$$

$$\frac{\delta X_s}{X_s(0)} = \frac{S_2}{2\Delta N_0} \delta n_{qp}. \quad (4.18)$$

Following convention in the literature, $S_1$ and $S_2$ are defined as:

$$S_1 = \frac{2}{\pi} \sqrt{\frac{2\Delta}{\pi k_B T}} \sinh \xi_0 K_0(\xi_0) \quad (4.19)$$

$$S_2 = 1 + \sqrt{\frac{2\Delta}{\pi k_B T}} e^{-\xi_0} I_0(\xi_0). \quad (4.20)$$

### 4.2 Forward Scattering Parameter

As introduced in Section 3.2.2, the forward scattering parameter $S_{21}$ is the directly-measurable quantity when operating a KID. For an ideal resonator,

$$S_{21}(f) = 1 - \frac{Q_r}{Q_c} \frac{1}{1 + 2jQ_r x}, \quad (4.21)$$
where we have introduced the resonator detuning, or fractional frequency shift relative to the resonance at zero temperature and zero optical loading:

\[ x = \frac{\delta f}{f} = \frac{f(T, n_{qp}) - f(0, 0)}{f(0, 0)} \]  

(4.22)

(for a complete circuit-model derivation of the expression for \( S_{21} \), see Noroozian, 2012).

With this idealized model, \( |S_{21}| = (I^2 + Q^2)^{1/2} \) has a Lorentzian line profile, while the complex \( S_{21} \) function traces out a circle in the \( IQ \) plane.

Since of course our resonators are not perfect, we introduce some correction factors in order to model the scattering parameters of our resonators. In particular, the fact that the output signal from KID resonators is fed into an amplifier (while the input is not amplified) introduces some asymmetry between the input and output impedance. Following the approach used by Khalil et al. (2012), we introduce an additional parameter \( \chi \) to account for this asymmetry, along with an overall complex amplitude prefactor \( A \):

\[ S_{21} = A \left[ 1 - \left( \frac{Q_r}{Q_c} \right) \frac{1 + j\chi}{1 + 2jQ_r x} \right]. \]  

(4.23)

4.2.1 Nonlinear Behavior

The microwave power of the probe tone, \( P_g \) (also sometimes referred to as the generator power), can effect the resonant behavior of a pixel. One reason for this is that the kinetic inductance effect itself is fundamentally nonlinear. As probe tone power increases, the nonlinearity becomes more pronounced, eventually causing a bifurcation in the resonance line profile. This phenomenon is described in detail in Swenson et al. (2013), and we follow their approach in modeling the nonlinearity. While Equation 4.22 describes the detuning of a resonator behaving linearly, we define \( x \) for nonlinear resonators to be the
solution to the cubic equation

\[ y = y_0 + \frac{a_{nl}}{1 + 4y^2}, \]  

(4.24)

where \( a_{nl} \) is the nonlinearity parameter defined in Swenson et al. (2013). For values of \( a_{nl} > 0.77 \), \( y \) becomes nonmonotonic in \( y_0 \), which gives rise to the bifurcation between states.

Another way the microwave power can impact the resonance is by inducing a nonequilibrium quasiparticle energy distribution in the superconductor. Even though the microwave photons have energies below the superconducting gap energy \( \Delta \) and therefore cannot break Cooper pairs, they can be absorbed into the quasiparticle system and shift the density of states equation used to calculate \( \sigma \) in Equations 4.5 and 4.6 (De Visser et al., 2014). At high operating temperatures or high incident optical power levels, this effect can be significant, and even reverse the sign of the frequency and dissipation responses described in the next section. In our model of the resonance line profile, we allow \( a_{nl} \) to be negative in an attempt to approximate the nonlinearity that results from microwave photon absorption.

### 4.3 Resonator Response

#### 4.3.1 Quasiparticle Lifetime

When Cooper pairs are broken into quasiparticles, these quasiparticles travel in the superconducting material for a time before recombining into Cooper pairs. The total quasiparticle population is calculated by balancing the generation of quasiparticles from various sources with their recombination. The quasiparticle lifetime \( \tau_{qp} \) is related to the total
quasiparticle density by the experimentally-determined relation:

\[ \tau_{qp} = \frac{\tau_{\text{max}}}{1 + \frac{n_{qp}}{n^*}} \]  \hspace{1cm} (4.25)

(Zmuidzinas, 2012). The maximum quasiparticle lifetime \( \tau_{\text{max}} \) and the crossover density \( n^* \) are experimentally-determined and assumed to be constant for a given device configuration.

For a resonator with absorber volume \( V \), the generation rate of quasiparticles from thermal excitations, \( \Gamma_{\text{th}} \) is given by:

\[ \Gamma_{\text{th}} = \frac{n_{\text{th}} V}{2} \left( \frac{1}{\tau_{\text{max}}} + \frac{1}{\tau_{qp}} \right), \]  \hspace{1cm} (4.26)

while the total rate of quasiparticle recombination from all sources is given by

\[ \Gamma_r = \left( \frac{n_{qp} V}{2} \right) \left( \frac{1}{\tau_{\text{max}}} + \frac{1}{\tau_{qp}} \right). \]  \hspace{1cm} (4.27)

### 4.3.2 Frequency and Dissipation Response

By solving the quasiparticle dynamics equation, the Mattis-Bardeen response in both the frequency \( (x_{MB}) \) and dissipation \( (Q_{i,MB}) \) directions can be calculated (see Noroozian, 2012):

\[ x_{MB} = \frac{f(T, P_{abs}) - f_0(T = 0, P_{abs} = 0)}{f_0(T = 0, P_{abs} = 0)} = -\frac{1}{4N_0 \Delta} \alpha S_2(T) n_{qp}(T, P_{abs}) \]  \hspace{1cm} (4.28)

\[ Q_{i,MB}^{-1} = \frac{1}{2N_0 \Delta} \alpha S_1(T) n_{qp}(T, P_{abs}) \]  \hspace{1cm} (4.29)

where \( \alpha = L_k/L_r \) is the kinetic inductance fraction of the circuit.

The source of quasiparticle generation in which we are most interested is optical pho-
tons. The generation rate of optical quasiparticles depends on the power absorbed in the superconductor, \( P_{\text{abs}} = \eta_{\text{opt}} P_{\text{inc}} \), where \( P_{\text{inc}} \) is the power incident on the surface of the superconductor, and \( \eta_{\text{opt}} \) is the optical efficiency of the device. The rate of optical quasiparticle generation, \( \Gamma_{\text{opt}} \), also depends on the pair-breaking efficiency of the incident photons, which we take to be \( \eta_{\text{pb}} = 0.57 \) (Guruswamy et al., 2014):

\[
\Gamma_{\text{opt}} = \frac{\eta_{\text{pb}} P_{\text{abs}}}{\Delta}.
\]  

(4.30)

When optical photons are present, the total quasiparticle number density is given by:

\[
n_{\text{qp}} = -n^* + \sqrt{(n^* + n_{\text{th}})^2 + \frac{2n^* \eta_{\text{pb}} P_{\text{abs}} \tau_{\text{max}}}{\Delta V}}.
\]  

(4.31)

In calculating the optically-loaded frequency and dissipation shifts, we plug this expression into Equations 4.28 and 4.29. Instead of the physical temperature of the device, we use the effective electron temperature in the superconductor to calculate \( S_1 \) and \( S_2 \), which is obtained by inverting \( n_{\text{th}}(T) \) to solve for \( n_{\text{qp}} \).

The frequency response, \( \delta x / \delta P_{\text{inc}} \), is the product of the device responsivity \( R \) and optical efficiency:

\[
\frac{\delta x}{\delta P_{\text{inc}}} = \eta_{\text{opt}} R = \eta_{\text{opt}} \left( \frac{\alpha S_2}{4N_0\Delta} \right) \left( \frac{\eta_{\text{pb}} \tau_{\text{qp}}}{\Delta V} \right)
\]  

(4.32)

When a KID pixel is illuminated by radiation at frequency \( \nu_{\text{opt}} \) from a blackbody source at temperature \( T_{BB} \), the photon occupation number in the detector is given by

\[
n_\gamma = \left( \exp \left( \frac{-h\nu_{\text{opt}}}{k_B T_{BB}} \right) - 1 \right)^{-1}.
\]  

(4.33)

The general noise model we use combines photon generation noise, thermal genera-
tion noise, and noise from recombination from quasiparticles from all sources:

\[
S_{xx,\text{tot}} = \left( \frac{1}{4N_0} \frac{\alpha}{\Delta} S_2(T) \right)^2 \left[ 2h\nu P_{\text{abs}} (1 + n_\gamma) \left( \frac{n_{\text{pb}} \tau_{\text{qp}} (T, P_{\text{abs}})}{\Delta V} \right) \right.
\]
\[
+ \left( \frac{2\tau_{\text{qp}} (T, P_{\text{abs}})}{V} \right)^2 \left( \Gamma_{\text{th}} (T, P_{\text{abs}}) + \Gamma_{\text{r}} (T, P_{\text{abs}}) \right) \right].
\] (4.34)

The sensitivity of a KID pixel can be quantified with the noise equivalent power (NEP), which is defined as the amount of power the device can detect in 0.5 seconds with a signal-to-noise ratio of 1. We combine Equations 4.32 and 4.34 to calculate the NEP of the detector:

\[
NEP_{\text{meas}} = \sqrt{\frac{S_{xx,\text{tot}}}{\Delta x / \delta P_{\text{inc}}}}.
\] (4.35)
Chapter 5

Device Design

This chapter describes the design considerations and constraints for the KID devices tested as prototypes for the TIM experiment. I tested two KID arrays, both of which used identical pixel geometries. The first, Device A, was fabricated from sputtered aluminum on a flat silicon wafer. The second, Device B, was fabricated from evaporated aluminum and includes optical backshorts.

5.1 Resonator Type

There are several approaches to designing the superconducting microresonators that make up KID pixels. The basic elements of a KID pixel are: an absorber, which absorbs incident radiation; a resonator, which responds to and generates a signal based on the absorbed radiation; and a transmission feedline, which allows the signal to be read out from the device. While it is possible to use a KID in a configuration where the full pixel is illuminated by optical radiation, only photons whose energy is absorbed in the superconducting material will lead to signal generation. Therefore, many pixel designs also include another element that couples radiation onto the absorber.
The first KID devices used distributed quarter-wave and half-wave resonators coupled to coplanar waveguide (CPW) transmission lines (Day et al., 2003; Mazin, 2004). This implementation typically requires that a pixel be coupled to an antenna which is physically separate from the resonator to serve as an absorber of incident radiation.

An alternative to the distributed resonator design is a lumped-element approach. A lumped-element resonator contains discrete circuit elements (inductors and capacitors) whose physical dimensions are much smaller than the wavelength of the microwave signal. In a lumped-element KID pixel, the inductor itself typically serves as the radiation absorber.

![Figure 5.1 Illustration of two overall pixel design approaches used for KID pixels. The blue shading represents the areas covered by superconducting film, while the white represents areas where the film has been etched away to reveal the bare dielectric substrate. Both examples are single-layer designs consisting of only a superconducting film atop a dielectric substrate. (a): Distributed \( \lambda/4 \) (quarter-wave) resonator, shunt-coupled to a coplanar waveguide (CPW) transmission line. (b): Lumped-element resonator including a meandered inductor and an interdigitated capacitor, which directly couples to a CPW transmission line. Figure adapted from Zmuidzinas (2012).](image_url)

The approach we take for the prototype TIM KID pixels is a lumped-element design that uses microstrip-based transmission lines. We use a single layer of superconducting...
film on a dielectric substrate to make both the resonator and the transmission line structures. While a traditional microstrip conductor would include a continuous ground plane layer on the opposite side of the substrate from the patterned layer, we use the gold plating of the device package as a ground plane.

5.2 Material choice

The prototype KID arrays tested for TIM are both fabricated out of thin-film aluminum. As an elemental superconductor, Al is well-described theoretically by the Mattis-Bardeen picture of superconductors as described in the previous two chapters. It also allows for a simple, single-deposition fabrication step for the active pixels.

For pure Al, \( T_c = 1.2 \text{ K} \) \cite{McMillan}, which by equation 3.1 corresponds to a superconducting gap energy \( \Delta = 182 \mu\text{eV} \). This in turn implies that photons with energies above \( 2\Delta = 364 \mu\text{eV} \) (or wavelengths less than 3.4 mm), can break Cooper pairs in an Al superconductor. A photon with a wavelength of 350 µm (in the middle of the TIM spectral band), would in theory have enough energy to break as many as nine Cooper pairs if all its energy were to be absorbed in the Al film.

The aluminum films we use for the TIM prototype devices have sheet resistances of \( R_s = 1.8 \Omega/\square \), according to measurements by the JPL Microdevices Laboratory (P. Day, private communication). For thin films, we can rearrange the equation for the imaginary part of the conductivity from the Mattis-Bardeen relation to give the kinetic inductance of the film:

\[
L_{k\square} = \frac{\hbar}{\pi\Delta} R_s, \quad (5.1)
\]

which gives \( L_{k\square} \approx 2 \text{pH/\square} \).

The devices were fabricated photolithographically in the Microdevices Laboratory at
NASA’s JPL. As mentioned above, Device A was fabricated using a sputtered aluminum deposition, while Device B was fabricated using an evaporated aluminum deposition. The entire KID array circuit is a single layer of aluminum. Both devices also include gold rectangular patches around the edges of the array, which we use for heat-sinking the silicon wafers. For alignment with the packaging, both devices have a mechanical pin-hole and slot etched through the wafer.

Device A is patterned on a 600-nm thick (1,0,0) crystalline silicon wafer. Device B, which includes the backshort, is patterned on a silicon-on-insulator (SOI) wafer with the following layers: 600 µm handle layer (Si), 1 µm oxide, 25 µm device layer.

SEM measurements of the devices show that the aluminum film on Device A was 31±3 nm thick. Device B measured 39±3 nm thick. The traces in Device B also appeared to be over-etched in trace width by approximately 20%, which would reduce the inductor active volume proportionally.

![SEM images of aluminum film on TIM devices](image)

Figure 5.2 SEM measurements of the aluminum film on the prototype TIM devices. Both images show the inductor meander mesh, which nominally consists of traces which are 0.4 µm wide, separated by 0.3 µm. Device A, on the left, was measured to be around 31 nm thick, with measurements at different points on the array measuring between 28 and 34 nm. Device B, shown on the right, was measured to be 39 nm, with measurements around the array between 36 and 42 nm.
5.3 Resonance Frequencies

KID pixel resonance frequencies are constrained by both pixel area and readout electronics considerations. The lower the desired resonance frequency, the larger the pixel area must be. In our case with lumped-element pixels, all resonator pixels have identical inductors to ensure that detector response is as uniform as possible across the detector array. The resonator design we use is based on the devices used for the MAKO camera, which operated at the Caltech Submillimeter Observatory (McKenney et al., 2012). MAKO was limited to resonance frequencies below 250 MHz as a result of its readout electronics. The prototype TIM resonators were designed such that 20 nm Al films would have resonance frequencies below 250 MHz. Since $\frac{1}{Z}$ scales inversely with film thickness, the resonance frequencies increase as the film gets thicker.

The inductor is meandered, but rather than a traditional rectangular meander area (like the one shown in Figure 5.1b), we use a circular meander area in order to more effectively couple to feedhorns (see Section 5.5). In addition, the traces are meandered in a square mesh pattern so that both polarizations of optical radiation are equally well-absorbed in the material. The corners of the mesh do not intersect, but are separated by 300 nm. Since the gap between adjacent mesh traces is significantly smaller than the wavelength of photons in the TIM band, the mesh appears as a sheet to the incident radiation. We use SONNET, an electromagnetic simulation program, to simulate the inductance of the absorber. The absorber geometry is shown in Figure 5.3. The SONNET simulations give a total inductance value of $L_{\text{tot}} = 29 \text{nH}$ in our operating frequency range. Since the inductor meander active volume includes 11300 squares at $2 \text{pH/□}$, the kinetic inductance $L_k$ should be about $22 \text{pH}$. This gives us an estimate for the kinetic inductance fraction $\alpha = L_k/L_{\text{tot}} \approx 0.8$.

The resonance frequencies are then set by the interdigitated capacitors. We can use an
Figure 5.3 Drawing of the meandered mesh absorber geometry. In all panels, the green trace width is 400 nm. The left panel shows the full inductor geometry, with the simulated signal ports 1 and 2 on top, which in the full device connect to the interdigitated capacitor. The middle panel shows a single mesh element, with a filling fraction of 1.3%. The right panel shows a close-up of the corners between adjacent mesh elements. The traces do not actually touch, although the inductor appears as a solid mesh to incident photons in the TIM band. All pixels across the arrays tested have identical absorbers.

Analytical formula to determine the expected capacitance of an interdigitated capacitor:

\[
C = \varepsilon_0 (1 + \varepsilon_r) N_{cap} S_{cap},
\]  

(5.2)

where \( \varepsilon_0 \) is the permittivity of free space, \( \varepsilon_r \) is the relative dielectric constant of the substrate material, \( N_{cap} \) is the number of finger pairs, and \( S_{cap} \) is the length of each finger, and we assume that the trace width is equal to the spacing between traces (Noroozian, 2012). In our case, the number of finger (pairs) is the variable element between resonator pixels that sets the capacitance. Capacitors for a few pixels were simulated in SONNET to verify that the geometry would produce the expected capacitance.

5.4 Array design

The prototype TIM arrays each have 45 pixels on a single transmission line. The transmission line itself is interdigitated, with one half connected to ports for signal input and
output, and the other half connected via aluminum wirebonds to the package which serves as ground. Each pixel occupies an equal area on the wafer. The resonators are not placed sequentially along the feedline; rather, they are interspersed so as to minimize cross-talk between adjacent pixels.

The array layout contains 45 pixels with resonance frequencies originally designed to be below 250 MHz for 20-nm thick aluminum films with lower sheet resistances. For the devices tested in this thesis using thicker films, the resonance frequencies were: 230 – 280 MHz for Device A, and 325 – 365 MHz for Device B.

While the TIM prototype devices are intended to be relatively simple to fabricate in that the array itself requires only one layer of deposition and patterning, there are nonetheless limitations on the process. The inductors are designed to have very narrow gaps 300 nm between adjacent meanders. As a result of an issue with the photolithography process, some of those gaps were shorted together on Device B. This caused the yield for that device to be substantially reduced. Device A had a yield of 40/45 pixels, or 88%, but only 16/45, or 30% of the pixels on Device B were usable.

5.5 Optical Coupling

In order to extract as much signal as possible from the lumped-element KID pixel, we need to maximize the number of optical photons that are absorbed in the inductor, while minimizing the number that are absorbed either into other device components, or the substrate material itself. We use several techniques to achieve this: tuning the filling fraction of the inductor meander to match its effective impedance to free space, backshorts so that incident power is not absorbed in the dielectric, feedhorns to serve as waveguides for the incident radiation, and chokes patterned around the inductor.

Each “square” in the inductor mesh is defined by Al traces which are 0.4 µm wide and
30 µm long on each side. This corresponds to a filling fraction $\phi$ of 1.3%. For meandered absorbers, the filling fraction is related to the effective sheet impedance in the material:

$$R_{s,eff} = \frac{\eta_0}{\sqrt{\varepsilon_r}} = \frac{\rho N}{\phi t} \approx 377 \, \Omega,$$

where $\eta_0 = 377 \, \Omega$ is the impedance of free space, and $\varepsilon_r = 1$ is the relative dielectric constant of the medium the photons travel through (in this case, free space). For a given coupling scheme and film thickness, tuning the filling fraction allows for better matching to the effective sheet impedance and therefore increased optical power absorbed in the inductor.

Device B incorporates backshorts behind the absorbers for each pixel (shown in Figure 5.5). The handle layer of the silicon wafer is etched away in a circle directly beneath the absorber area, leaving only 25 µm of silicon. Incident photons which are not absorbed when they encounter the absorber initially can reflect off the back side of the backshort and then be absorbed in the superconductor. HFSS simulations (and test results) show that the backshorts allow for as much as four times as much power to be absorbed in the inductors compared to leaving the back of the wafer unpatterned.

Since the inductor accounts for less than 10% of the total pixel area, we use straight-walled, conical feedhorns to couple incident radiation onto the array (see Figure 5.6). Each pixel is coupled to a single feedhorn, with the horn aperture sitting directly above the absorber area. The horns are held in place mechanically on the package by a pin and slot pairing mechanism. We also use electrical chokes patterned out of the same aluminum material as the rest of the device. These three circular ring chokes are designed to constrain incident power to the absorber at their center and discourage any propagation outwards into the substrate. HFSS simulations with and without the chokes show that they increase absorbed power by as much as 20% in the TIM optical band.
Figure 5.4 HFSS simulation of the optical coupling scheme. The top shows a CAD drawing of the pixel optical structure, including the feedhorn (actually vacuum, but drawn for illustration purposes), circular choke structure, wafer, and patterned absorber. The plot shows the simulation results for power absorbed in the device as a function of optical frequency.
Figure 5.5 Photograph of the back of the fabricated Device B array, showing the backshort patterning. The SOI handle wafer is etched away underneath the absorber area to form a 25
Figure 5.6 The KID devices tested as prototypes for the TIM experiment.  

A: Diagram of the pixel geometry for a fiducial resonator pixel. The interdigitated capacitor is shown in red, while the meandered inductor/absorber is shown in green, and the coupling capacitors are shown in yellow. The signal transmission lines are at the top and bottom. The circular chokes are shown in blue.  

B: Micrograph image of a fabricated pixel. All elements shown are patterned from a single layer of thin-film aluminum superconductor deposited on a crystalline silicon substrate.  

C: Full 45-pixel array as fabricated. The feedline structure is interdigitated, with the signal in and out ports connected to the fingers attached on the left side, and the fingers attached to the right side grounded. Each pixel is then capacitively coupled to both a signal finger and a grounded finger.  

D: Fabricated array seated in its package. The package itself is machined from gold-plated aluminum. The beryllium-copper spring clips at the four corners hold the array in place while allowing for shifting between the aluminum package and silicon substrate during thermal cycling. The array is wirebonded with aluminum bonds to the signal circuit board on top, and the package gold-plating as ground on the bottom. There are also gold wirebonds for heat sinking connecting the gold rectangular patches around the edges of the wafer.  

E: Cross sectional view from a CAD model of a feedhorn and backshort, with the device wafer sandwiched between them. The detector geometry and air gap shown are not to scale.  

F: The packaged array with feedhorns attached. Two SMA connectors serve as the signal input and output for all 45 pixels in the array.
Chapter 6

Device Testing and Results

In this chapter, I will describe the test setup and data acquisition systems we use for laboratory characterization of the prototype TIM KID arrays described in the previous chapter. I will then explain the data processing steps we take to extract the resonator characteristics under each set of measurement conditions. Finally, I present the analysis methods used to determine the device properties by incorporating measurements under a variety of different temperature and optical loading conditions. Preliminary analysis of Device A was published in Hailey-Dunsheath et al. (2018), and the full analysis of both devices is currently in preparation for publication.

6.1 Cryostat & cooling

Since KIDs rely fundamentally on their superconducting properties, they must be cooled below $T_c$ for operation. Our aluminum devices have critical temperatures around 1.4 K, so they need to be cooled to sub-Kelvin temperatures. For lab testing, we use a cryostat testbed that was originally developed for the Multicolor Submillimeter kinetic Inductance Camera (MUSIC) experiment. The cryomechanical design for the fridge is described in
The testbed is cooled by a closed-cycle fridge that combines pulse tube cooling with adsorption refrigeration. There are four cold stages in the cryostat, at temperatures of 50 K, 4 K, 1 K, and a cold stage which reaches a base temperature of 210 mK (see Figure 6.1). The pulse tube, a Cryomech PT415, provides the cooling for the 50 K and 4 K stages. Then, a \( ^3\text{He}/^3\text{He}/^4\text{He} \) adsorption fridge cools the remaining stages (Devlin et al., 2004). The \(^3\text{He} \) fridge has a hold time of approximately 24 hours, and can be cycled in approximately four hours using Labview software.

![Schematic diagram of the circuit and temperature stages within the laboratory cryostat.](image)

Figure 6.1 Schematic diagram of the circuit and temperature stages within the laboratory cryostat. The signal is transmitted by coaxial cables, which are heat sunk to each cold plate.

Thermometry for the cryostat and cryogenic blackbody source are connected with DC wiring that feeds through the 300 K plate. The thermometry wires are heat sunk with feed-through connectors at each cold plate on their way to their destinations in the cryostat. We also have a DC connection to a resistor on the cold stage that allows it to be...
heated incrementally. The blackbody source is attached to the inside of the 4 K shield, and can be heated via DC wiring. The cold stage and blackbody heaters, are controlled from within the same Labview program that runs the fridge thermometry.

The KID array is mounted in an enclosure that is thermally attached to the cold stage (see Figure [6.2]). A tunable cryogenic blackbody source sits inside the cryostat facing the array feedhorns. The enclosure contains a window so that optical radiation can be directed onto the array. We use a bandpass filter (see Figure [6.3]) to set the band of optical radiation allowed through the window.

The electronics within the cryostat are designed to transmit the input signal to the detectors while attenuating radiation from the warm electronics, and then to preserve the signal from the detectors and return it at the cryostat output. Coaxial cables carry the input and output RF signal from outside the cryostat to the cold stage. The cables are heat-sunk to each stage of the fridge in order to prevent extra heat dissipation on the cold stage. Between 300 K and 4 K, we use stainless steel coaxial cables, in order to reduce the thermal loading from the warm cables. On the input line, we use a fixed 30 dB attenuator at the 4 K stage to dissipate power coming down the line from 300 K radiation. We use superconducting NbTi coaxial cables between 4 K and the cold stage. There is also a fixed 10 dB attenuator at the 1 K stage. The coaxial cable leading from the 0.4 K stage to the cold stage terminates in an SMA connector on the array package. The SMA connector is soldered to a microstrip transition board (shown in Figure [5.6D]), which is in turn wirebonded to the detector array using aluminum wirebonds. The transition board is made of TMM10 laminate[2](which has a dielectric constant of $\varepsilon_r = 9.2$), and patterned with bare copper traces.

The output signal from the devices is amplified by a low-noise amplifier, which is heat sunk at 4 K. We use a SiGe LF-3 amplifier designed and produced at Caltech [Weinreb].

---

et al., 2007), which has a noise temperature of 6 K and gain of +35 dB in the signal frequency band for our devices.

Figure 6.2 Two views of the laboratory test cryostat. The array enclosure, at the top, is mounted to the cold stage which reaches a base temperature of 210 mK. The cryogenic blackbody source is mounted to the 4 K jacket enclosure, so that with the cryostat closed, the blackbody radiation is directed at the KID array. To operate the fridge, the entire cryostat is flipped upside down for operation of the pulse tube cold head.

6.2 RF Signal Processing

Outside the cryostat, we can use two separate warm electronics setups for signal readout. The multitone setup uses the readout firmware developed for the MAKO camera, and is limited to operation below 250 MHz. It allows for proper signal multiplexing and is capable of reading out hundreds of devices simultaneously. The single-tone setup uses analog hardware, and collects data for one pixel at a time. It is, however, more flexible
and can operate over a much wider frequency band. The data presented here for Device A were collected with the multitone system, while the data presented for Device B were collected using the single tone system.

### 6.2.1 Multitone Setup

The multitone system we use is the same system developed for and fielded by the MAKO camera ([Zmuidzinas et al., 2013](#) see Figure 6.4). The multitone readout setup is powered by a field-programmable gate array (FPGA) card integrated into the Reconfigurable Open Architecture Computing Hardware (ROACH) platform created by the Collaboration for Astronomy Signal Processing (CASPER) group at UC Berkeley. The ROACH(1) board that we use contains a Xilinx Virtex5 FPGA. The FPGA is programmed with firmware that generates the probe tone signal, which is a superposition of the tones for each resonator on the array. A digital-to-analog converter (DAC) generates the analog signal, and connects to the coaxial line leading into the cryostat. The probe tone signal enters the cryostat and is modulated by the KID devices and sent back out. An analog-to-digital converter (ADC) digitizes the signal coming from the cryostat for digital analysis.
The keystone of the ROACH analysis firmware is its use of polyphase filter banks in place of traditional discrete Fourier transform methods to produce an output spectrum in frequency-space. The multitone data taken as part of this thesis used the software package makosoft, also developed for MAKO, which provides an interface to control the ROACH and take measurements with a variety of readout parameters.

Figure 6.4 Schematic diagram of the circuit used for multitone device testing.

6.2.2 Single Tone Setup

The single tone circuit uses a complement of traditional RF components to measure an individual resonator (see Figure 6.5). A signal generator outputs an analog tone at a single frequency. The signal is split, and one of the signal lines is connected to the cryostat to excite the resonator. The modulated cryostat output signal and the duplicated input signal are both fed into an IQ mixer. The mixer compares the signals and outputs the complex $S_{21}$. The single tone setup relies on a suite of LabView software to automatically carry out frequency sweeps and noise scans, and save the data.
6.3 Resonator Characterization

To characterize a pixel under a given set of operating conditions (probe tone power, cold stage temperature, incident power from the blackbody source), we make a series of measurements. We first take frequency sweeps to trace out the full resonance line profile. We take a low resolution frequency sweep (gain scan) to measure the baseline behavior of $S_{21}$ near resonance. Amplifier gain variations and the frequency dependence of the signal delay as it travels the length of the coaxial cable mean that this must be done for each resonator. We also take fine resolution scans to pinpoint the resonance frequency itself. Using the fine scan data, both setups described in the previous section use software to determine the resonance frequency by finding the point where $\delta S_{21}/\delta f$ is maximized. This is the frequency at which we measure noise timestreams. For noise timestreams, the resonator is probed by a single tone frequency for a set period of time, which allows us to
measure the resonator noise levels under varying conditions.

### 6.4 Calibration and Resonance Fitting

The signal data from the readout electronics is saved in the form of \((I(f), Q(f))\) ordered pairs, where, (restating Equation 3.10):

\[
S_{21}(f) = I(f) + jQ(f)
\]

\[
|S_{21}| = \sqrt{I^2 + Q^2}
\]

\[
\arg(S_{21}) = \phi = \arctan\left(\frac{Q}{I}\right).
\]

To analyze the data and characterize the resonators, we begin by using the gain scan to calibrate out the amplifier gain variations and cable delay terms in \(S_{21}\). Then, we fit the corrected \(S_{21}\) data to Equation 4.23 to extract the resonance frequency and quality factors. We also use the corrected \(S_{21}\) to determine \(\theta(f)\), the relationship between the phase angle and frequency. We apply the calibrations calculated from the frequency sweeps to the noise timestreams \(S_{21}(t)\). Finally, we calculate the power spectral density (PSD) of the noise data, which gives \(S_{xx}\) as a function of (audio) frequency.

Below, I describe the calibration and analysis steps we take for resonator characterization. This approach is similar to the one described in [Gao, 2008]. We can consider these steps in terms of \(|S_{21}|\) and \(\phi\), or in terms of \(I\) and \(Q\); since \(S_{21}\) is complex, they are equivalent.

1. **Divide out gain variations.** If our electronics were perfect, we would measure the resonance dips against a flat off-resonance spectrum (at \(|S_{21}| = 1\), since the resonators do not dissipate any microwave power off-resonance). Our electronics are not perfect, however, so we must account for systematic effects in the measure-
ment circuits that shift $S_{21}$. These include frequency-dependent variations in the gain/attenuation of the low-noise cryogenic amplifier, the warm amplifier, or the programmable attenuators. To mitigate any gain variations in the system, we fit the off-resonance parts of the spectrum to a low-order polynomial $P(f) = \sum a_n f^n$, then divide the transmission data by $P(f)$. This normalizes the $S_{21}$ spectrum to have an approximately flat baseline, and shifts the on-resonance edge of the IQ loop to lie on the unit circle.

2. *Divide out the cable delay.* The length of the coaxial cable used to transmit signal to and from the resonators introduces a phase delay because it represents a different fractional path length for each frequency in our readout band. To correct for this, fit the complex phase $\phi$ as a function of frequency to a line (again only including the off-resonance parts of the spectrum). The slope of the line is the cable delay $\tau$. Multiply $S_{21}$ by $\exp(-i\tau f)$ to correct for the cable delay. This collapses the tails of the IQ loop to lie on the off-resonance part of the unit circle.

3. *Correct for impedance mismatch.* At this point, the resonance frequency lies on the unit circle in the IQ plane but at an arbitrary rotation angle from the $+I$ axis. This rotation is the result of impedance mismatches going from the signal line onto or off of the device. We correct for this by finding the angle $\phi_0$ between the $+I$ axis and the resonance point, and multiplying the $S_{21}$ data by $\exp(-j\phi_0)$. This places the resonance point along the $+I$ axis.

4. *Frequency-phase calibration.* With the corrections above applied, our frequency sweeps form a loop centered on the real axis in the IQ plane (an “IQ loop”), internally tangent to the unit circle. Since the calibration data are sweeps in frequency, we can now use them parametrically to convert a given point on the IQ loop to a frequency.
(a) We first fit the IQ data to a circle, and use the fit to translate the IQ loop to be centered at the origin.

(b) Then, we calculate the phase angle relative to the resonance frequency \( \theta(f) = \arctan\left(\frac{Q_{cal}(f)}{I_{cal}(f)}\right) \) of each point in the IQ loop using the \( S_{21} \) frequency sweeps with the previous calibration steps applied (see Figure 6.6). We then numerically invert \( \theta(f) \) using a cubic spline approach, to find a function for \( f(\theta) \).

5. *Fit the frequency sweeps to extract the resonator parameters.* We now fit the calibrated fine scan to fit \( S_{21}(f) \) to the resonance model function given in Equation 4.23. This fit includes as free parameters \( f_0, Q_r, Q_c, \chi \), and \( a_{nl} \). Figure 6.6 shows an example of the resonator parameter fitting.

6. *Calibrate the noise timestream.* We apply the calibration steps above to the noise data, correcting it for the gain variations and cable delay. Since the timestream points \((I(t), Q(t))\) were taken on-resonance, they form a “noise ball” surrounding the resonance frequency in the IQ plane. We calculate the relative phase \( \theta(t) \) for each point, then apply the function \( f(\theta) \). Although the timestream data were all taken at a single frequency per each resonator, \( f(\theta) \) transforms them into an equivalent frequency shift \( x(t) = (f(t) - f_0) / f_0 \) relative to the resonance frequency.

7. *Calculate PSDs using the noise timestream.* We take the PSDs of \( I(t) \) and \( Q(t) \), which as calibrated correspond to the directions perpendicular and parallel to the IQ loop, respectively. The device noise should be limited to the parallel direction, so we use the perpendicular direction as a gauge of the relative contribution of amplifier or other electronic noise in the system.\(^3\) Finally, we calculate the PSD of

\[ \text{PSD}(\delta S_{21}) \] can be calculated as \( \frac{G_k T_N}{P_g} \), where \( G = 35 \text{ dB} \) is the amplifier gain, \( T_N = 6 \text{ K} \) is the amplifier noise temperature, and \( P_g \) is the microwave tone power. We find that this matches reasonably well with, though slightly underestimates, the perpendicular direction PSD white noise level.

\(^3\)The contribution of the cryogenic low-noise amplifier to PSD(\( \delta S_{21} \)) can be calculated as \( \frac{G_k T_N}{P_g} \), where \( G = 35 \text{ dB} \) is the amplifier gain, \( T_N = 6 \text{ K} \) is the amplifier noise temperature, and \( P_g \) is the microwave tone power. We find that this matches reasonably well with, though slightly underestimates, the perpendicular direction PSD white noise level.
which is known as $S_{xx}$. We use the fractional difference between the parallel and perpendicular PSDs to subtract off an approximate amplifier contribution to the $S_{xx}$ spectrum. For the analysis described below, we are mainly concerned with the white noise levels of the PSDs. We choose a range over which the spectra are reasonably white, and average the PSD values in this range in order to calculate a white noise value.

6.5 Dark Tests

To characterize the KIDs on a given array, we first block off the feedhorns so that no optical radiation reaches the detectors, then cool them in the cryostat. We use a metal tape to block the horns and seal the edges of the package, in order to minimize stray radiation. These dark tests allow us to measure the device response to thermal radiation in the absence of optical radiation. We first make a wide frequency sweep with a VNA in order to locate the resonance frequencies and assess device yield. We take characterization measurement sets as described above, sweeping the cold stage temperature from its base temperature at 210 mK up to $\sim$400 mK. For each operating temperature, we use the programmable variable attenuators to increment the tone power to determine the readout tone power level at which bifurcation occurs for each resonator. We typically choose to operate the devices approximately 3 dB below the onset of bifurcation to maximize the separation between the parallel and perpendicular noise levels.

Based on the data collected with the dark measurements, we fit the frequency and dissipation response in order to extract the superconducting critical temperature, $T_c$, and kinetic inductance fraction, $\alpha$. $x$ is calculated relative to the lowest-temperature resonance frequency. We use the Mattis-Bardeen expressions for $x(T)$ and $Q_i(T)$ (Equations 4.28).
and respectively), and add offset parameters:

\[
x_{\text{meas}} = x_{MB} + x_{\text{offset}}
\]

\[
Q^{-1}_{\text{meas}} = Q^{-1}_{MB} + Q^{-1}_{\text{loss}},
\]

where \(x_{\text{offset}}\) is an overall shift that accounts for the fact that we cannot measure at zero temperature, and \(Q_{\text{loss}}\) is a fixed term that accounts for the limiting internal quality factor of the material. McCarrick et al. We calculate \(x_{MB}\) and \(Q_{MB}\) assuming that the incident optical power is zero. Free parameters in the fit are: \(\alpha\), \(T_c\), \(x_{\text{offset}}\), and \(Q^{-1}_{\text{loss}}\).

We use the curve_fit algorithm from the scipy Python package to fit the data to the models. We use a simultaneous fit of the \(x\) and \(Q_i\) data, so that they must agree on values for \(\alpha\) and \(T_c\). We find that for both devices A and B, \(\alpha \sim 0.7\) and \(T_c \sim 1.4\), which matches our design predictions well. Figure 6.7 shows a plot of the fitting for a Device A resonator.

### 6.6 Optical Tests

For optical testing, we leave the horns open above the devices, and use the cryogenic blackbody source to vary the optical power incident on the devices. We sweep the blackbody temperature, \(T_{BB}\), between its base temperature just below 6 K and about 12 K. Again, we choose the tone power level to be about 3 dB below the onset of bifurcation under each loading condition. The stage temperature is held constant at 215 m K, slightly elevated from the base stage temperature.

Using the optical measurements of \(x\) and \(S_{xx}\) as a function of incident power, in combination with dark measurements of \(S_{xx}\) as a function of stage temperature, we perform
simultaneous fits of the data to extract the film parameters \( n^* \) and \( \tau_{\text{max}} \) as well as the optical efficiency of the devices. In calculating \( x \), we again use the resonant frequency at the lowest optical loading level \( f_0 \), which introduces a shift \( \delta x = f_0 \right.df \) relative to the model, which describes the fractional frequency shift from the resonance at zero temperature and optical loading. Since part of the excess noise term \( S_{xx,0} \) could be due to stray radiation reaching the devices, we use separate parameters for this term for the dark and optical noise models: \( S_{xx,0,\text{dark}} \) and \( S_{xx,0,\text{opt}} \), respectively. We again make use of the \texttt{curve_fit} algorithm from the \texttt{scipy} package to carry out the fits. The models are given in equations 4.28 and 4.34. For the noise measurements, we add a fixed noise floor term, \( S_{xx,0} \), to account for additional sources of noise, such that

\[
S_{xx,\text{meas}} = S_{xx,\text{tot}} + S_{xx,0} \quad (6.2)
\]

Fit parameters for the simultaneous fits are: \( n^* \), \( \tau_{\text{max}} \), \( \eta_{\text{opt}} \), \( df \), \( S_{xx,0,\text{dark}} \), and \( S_{xx,0,\text{opt}} \). We use the covariance matrices returned by \texttt{curve_fit} to calculate the standard error on the fit parameters.

Figure 6.8 shows the data and fit results for Device A. The simultaneous fit gives a quasiparticle lifetime \( \tau_{\text{max}} = 19 \pm 2 \) µs, which is much lower than expected for thin aluminum films. Nonetheless, the device is photon-noise-limited above \( \sim 0.2 \) pW. The fit value for \( \eta_{\text{opt}} \) is \( 22 \pm 2\% \), which matches well with the expected absorption as simulated in HFSS for the device without backshorts.

In testing Device B, we performed a separate cooldown with an additional absorptive optical filter in place between the blackbody and the feedhorns. Since Device B included backshorts and was therefore absorbing more optical power, we used the filter to probe the device response at lower incident power levels. While the mask is designed to be 3% transmissive in the far-IR wavelength range, its transmission is not known exactly and we
include it as an additional fit parameter, \( T_{\text{mask}} \). The data taken with the mask in place are modeled separately, and included in the simultaneous fitting procedure.

Figure 6.9 shows the data and fit results for Device B, with the data taken with the mask ("CD012") separated from the data taken without it ("CD010+13"). The fits to these data give \( \tau_{\text{max}} = 37 \pm 4 \) µs, nearly double the value for Device A. While this difference could be due to the difference in aluminum film deposition methods, 37 µs is still approximately an order of magnitude lower than other groups have measured for aluminum (McCarrick et al., 2014). We find \( \eta_{\text{opt}} \) to be 59 ± 2%, which is \( \sim 10 - 15\% \) lower than expected based on HFSS simulations for the device with backshorts. One reason for this could be that the traces in Device B were over-etched and therefore thinner than designed. This would decrease the filling fraction and cause a slight impedance mismatch for the incident radiation. Even so, Device B is photon noise-limited for optical loading levels above 0.02 pW.

To calculate the device NEP at a given optical loading, we can plug the values for \( n^* \), \( \tau_{\text{max}} \), \( \eta_{\text{opt}} \) into Equation 4.32 to calculate the response, and combine with the \( S_{xx} \) noise level based on the model or data. For a fiducial optical loading of 0.2 pW, we find that the response of Device A is \( 2.0 \times 10^8 \) W\(^{-1}\) and the detector NEP is \( 2.4 \times 10^{-17} \) W/Hz\(^{1/2}\), while for Device B the response is \( 7.3 \times 10^8 \) W\(^{-1}\) and the detector NEP is \( 9.1 \times 10^{-18} \) W/Hz\(^{1/2}\).
Figure 6.6 Steps in the calibration process for two measurements of Device B. **Top:** frequency-phase calibration, including the fine scan and noise timestream data, as well as a fit to the $\theta(f)$ data which we use as priors for the full $S_{21}$ model fit. **Middle:** plots of $|S_{21}|$ of both the fine and medium scans, the model fit based on this data (Equation 4.23), along with the fit residuals. For the top two panels, the x axis is in terms of fractional frequency shift $\delta f/f$ relative to the value of $f_0$ given by the model fit. **Bottom:** PSDs of the noise timestream data in the perpendicular and parallel directions, as well as the fractional frequency noise $S_{xx}$. 

$T_{\text{stage}} = 215$ mK
$P_{\text{inc}} = 0$ (dark test)
$P_{\text{tone}} \sim 15$ dB below bifurcation

$T_{\text{stage}} = 215$ mK
$P_{\text{inc}} = 0.41$ pW
$P_{\text{tone}} \sim 3$ dB below bifurcation
Figure 6.7 Fractional frequency shift $x$ and $Q_l$ vs. $T_{\text{stage}}$ for a dark measurement of a representative resonator on Device A, along with fits for $\alpha$ and $T_c$. Green dashed curves show fits to the Mattis-Bardeen equations only; red dashed curves add in the $x_{\text{offset}}$ and $Q_{\text{loss}}$ parameters. The black curves show a simultaneous fit to the two functions.
Figure 6.8 Simultaneous fit of dark noise data with optical frequency response and noise data for Device A. Error bars are fractional estimates. All optical data with Device A were taken with the bandpass filter only in the optical path between the cryogenic black-body and the devices.
Figure 6.9 Simultaneous fit of dark noise data with optical frequency response and noise data for Device B. Error bars represent \( s/\sqrt{n_{\text{scans}}} \) (where \( s \) is the standard deviation) for repeated measurements under the same conditions. The yellow points and shaded regions correspond to the optical power levels probed with the bandpass filter only, while the white points and region with white background correspond to incident power levels measured with the additional absorptive mask in place.
Chapter 7

Conclusion

I have described the design and testing of two prototype KID arrays targeted for application to the TIM experiment. The results in Chapter 6 imply that both devices are photon limited for the range of optical loadings expected for TIM, and have high enough sensitivity and low enough noise to be used in the TIM spectrometer focal plane. As expected, device B, which contains backshorts, showed much higher photon absorption efficiency than device A without the backshorts, but the optical absorption could be further optimized. The next step in the TIM detector development process is to scale up the number of devices on the array to fill the TIM focal plane.

In concluding, I would like to point out that device characterization is essentially the opposite process from how the devices will be used in the field for the TIM experiment. To characterize the detectors, we expose them to a known optical loading and measure their frequency, dissipation, and noise response. In operation, we will use the known device response in order to measure the optical loading for a given telescope pointing configuration. Laboratory testing to fully characterize the devices is a crucial step in maximizing the utility of our detector system.

While the devices described here meet the TIM detector requirements, future far-
infrared instruments (like OST) will require even more sensitive detectors. Fielding sensitive KIDs on a balloon-borne platform like TIM serves as a technology demonstration for space-based missions.
Appendices
Appendix A

GSFC Devices

In this section, I describe the design and fabrication of another set of prototype KID arrays for the TIM experiment. While the devices described in Chapters 5 and 6 were designed and fabricated by collaborators at Caltech/JPL, I designed and fabricated this set of devices at NASA’s Goddard Space Flight Center.

A.1 Design

The design of these devices is straightforward: each pixel contains a meandered inductor with a rectangular profile area, an interdigitated capacitor to set the resonance frequency, and two coupling capacitors to couple to signal and ground transmission lines. The circuit is identical to the one shown in Figure 3.2. The resonance frequencies were designed to fall between 100 and 250 MHz, within the ROACH1 baseband of operation. The feedline structure is again interdigitated, with one side connecting to both signal in and out, and the other connecting to ground.

The arrays each contain 1600 pixels with an pixel pitch of 1.4 mm × 1.4 mm. Rather than using the same inductance value for every inductor across the array, I used three...
inductances corresponding to three absorber volumes in an effort to verify that device performance scaled as expected with absorber volume. In addition, I used three different coupling capacitor capacitance values, since the expected values for $Q_i$ for the materials I used were not well-known prior to fabrication.

Once the general device design was set, I used SONNET to simulate several of the pixels to ensure that they had the resonance frequencies expected. Figure A.1 shows a SONNET simulation of an individual pixel. I also simulated the feedline structure, to ensure that it wouldn’t itself introduce resonant features within our signal frequency band of interest (see Figure A.2).

![SONNET Simulation of an Individual Pixel](image)

Figure A.1 **Left:** Layer geometry for the SONNET Simulation. The pixels are patterned on a silicon wafer which is suspended between layers of air (vacuum). **Middle:** Pixel geometry. The red shaded area is the meandered inductor, while the large blue element is the resonator capacitor. The signal transmission line, with ports 1 and 2, is shown in red at the top. **Right:** Simulated forward scattering parameter for the pixel shown.

### A.2 Fabrication

I fabricated several versions of this array design at GSFC’s Detector Development Lab using photolithography techniques. I used several different materials for the fabrication.
Figure A.2 **Left:** Layer geometry for the SONNET Simulation. The array is patterned on a silicon wafer which is suspended between layers of air (vacuum). **Middle:** Array interdigitated feedline geometry. Pixels sit between fingers, so each pixel connects to both a signal finger and grounded finger. The signal transmission line, with ports 1 and 2, is shown in red at the top, while the bottom half of the feedline is grounded by connecting to the simulation boundary box. **Right:** Simulated forward scattering parameter for the feedline geometry shown. The transmission is smooth and relatively flat compared to the pixel resonances.

For the first version, the entire array, both resonators and feedlines, was patterned out of a trilayer TiN/Ti/TiN film. For the second version, the resonators were patterned out of the trilayer material, while the feedlines were Nb, in an effort to reduce parasitic inductance. For the third version, the resonators were thin-film Al, while the feedlines were Nb. All versions also used Ti/Au for rectangular patches around the outside of the arrays for heatsinking. Figure A.3 shows the photolithographic mask layout, while Figure A.4 shows a fabricated array.

Unfortunately, I was not able to test the GSFC devices. The first version was hampered by contamination which prevented the film from superconducting. The second and third versions, which used different materials for the resonators and feedlines, required precise alignment between the material layers. The alignment necessary proved to be beyond the capabilities of the microscope optics, so the coupling capacitor fingers were
Figure A.3 Mask layout for the GSFC devices. The right panel shows the full mask design, including all 1600 pixels and the feedline structure, as well as bond pads at the top and heat sinking patches around the edges. The middle and left panels show individual pixels. The resonator material is shown in cyan, while the feedline material is shown in red. Some arrays used the same material for both resonators and feedlines.

shorted to each other, which effectively shorted out the resonators to ground. This prevented any signal from being modulated by the resonators.
Figure A.4 Images of a GSFC device as fabricated. The full array is 60mm on each side.
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