Snowmass2021 - Letter of Interest

Kinetic Inductance Detectors for long-wavelength photon detection

Thematic Areas:
■ (IF2) Photon detectors (primary)
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before

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Abstract:
The kinetic inductance detector (KID) is a novel and promising detector for photons and particles covering a wide range of energies and applications.. These pair-breaking superconducting detectors offer significant advantages: simple and robust fabrication, intrinsic multiplexing that will allow thousands of detectors to be read out with a single microwave line, and simple and low cost room temperature electronics. After years of development, KIDs are now mature enough to allow for near-future instrument proposals. Arrays of thousands of pixels have returned on-sky science observations, readout techniques and ancillary hardware are capable of accommodating multi-megapixel arrays, and laboratory noise measurements have demonstrated sensitivity appropriate for any ground-based experiment and are quickly approaching the requirements of extremely low background applications.

Introduction

In recent years, the field of observational cosmology has revealed a startling picture of the Universe: we live in a world dominated by a combination of non-baryonic dark matter and dark energy whose fundamental properties we're just beginning to explore. The global properties of the Universe are consistent with a model containing only a few free parameters (now measured with percent level accuracy) in combination with locally measured physical laws. All evidence suggests the very early Universe underwent a period of exponential expansion during the first 10^{-34} of its existence, driven by new physics at the GUT scale.[1]

Much of the rapid progress in observational cosmology has been driven by new instrumentation, particularly in measurements of the Cosmic Microwave Background (CMB.) CMB detectors reached the background limit, the sensitivity at which photon arrival statistics dominate measurement error, decades ago. Since then it has been impossible to build a more sensitive detector; to build a more sensitive instrument, one must pack more detectors into each focal plane. The transition from individual hand-assembled semiconductor detectors to monolithic arrays containing tens of thousands of lithographically-defined bolometers has allowed us increase the depth of our CMB maps by three orders of magnitude in less than two decades. These advances, combined with theoretical discoveries and late-universe observations at other wavelengths, have ushered in the era of precision cosmology.

The next step in understanding the early Universe will require many hundreds of thousands of detectors. These focal planes will enable observations at high frequencies where far larger number of pixels are required, as well as millimeter and sub-millimeter wavelength spectroscopy which will probe large scale structure in the early universe, the epoch of reionization and the first stars, and the line emission from the decay of axion and photon-like dark matter candidates. The Kinetic Inductance Detector (KID) is a compelling candidate for these near-future instruments

Technology

The basic principle of KID operation is shown in fig. 1. Pair-breaking photons cause a change in the resonant frequency of a superconducting microwave resonator. The frequency (or, in practice, phase of a single microwave probe tone) serves as a power detector. Because each microwave resonator operates at a specific frequency, this allows for natural multiplexing of up to many thousands of detectors on a single microwave readout line. These devices are manufactures using lithographic, thin-film techniques, which make possible the production of very large monolithic arrays.[2,3].

The state of the art

Recent years have seen a number of KID instruments which are either on-sky or are preparing to deploy at submm wavelengths, in addition to a number of devices for high energy photons and particle detection which are discussed in other LOIs. Notable examples include the NIKA and NIKA-2 mm-wave facility instruments, the deployed MUSIC and MAKO cameras, several ready-to-deploy cameras including MUSCAT and TolTEC, which will provide background limited observations with kilopixel-scale focal planes, and the balloon-borne BLAST-TNG instrument[4–9]. Spectroscopic instruments include the recently deployed DESHIMA, the deployment ready SuperSpec, and the MicroSpec instrument optimized for future space telescopes[10,11]. Low loading applications include the EU/UK SpaceKids Programme demonstration, the TIM intensity mapping balloon instrument, and recently funded pilot projects for axion-like dark matter decay observations and devices for future low background cold space telescopes.[12] Currently deployed readout is largely based on the CASPER-ROACH FPGA readout hardware and is limited to approximately 2000 channels per board; however, a number of groups including FNAL and SLAC have much more efficient prototype hardware that make use of contemporary technology to increase that number significantly.

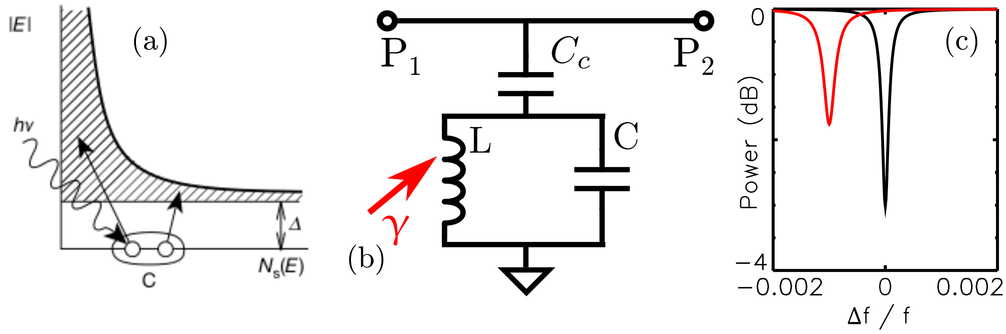

Figure 1: KID operation: (a) mm-wave photons break cooper pairs in a superconductor, generating quasiparticles (b) The increased quasiparticle density modifies the kinetic inductance, and thus the frequency of an LC resonator made from superconducting thin films. (c) The microwave resonance moves from the black to the red curve as optical power increases. This change in frequency (and the smaller change in resonance depth) can be read out by measuring the phase of a single microwave tone located on-resonance.

Post-testing resonator modification to prevent resonator collision has been successfully demonstrated by NIST and U. Chicago, which will enable significant increases in channel density. A number of ongoing projects at both DOE labs and US Universities are currently working on the design and fabrication of large, uniform arrays, suitable for both high-frequency submm cameras and spectroscopic instruments.

Opportunities

Current mm-wavelength readout technology, based on TESes and SQUIDs, will make possible CMB-S4 and other next-generation CMB instruments. However, the readout density required for densely packed submm and THz focal planes is a significant challenge. For spectroscopy, especially the large focal planes required for future Line Intensity Mapping projects that will reveal the structure of the early Universe, the challenge is even harder. KIDs are a promising and well demonstrated technology capable of meeting these challenges. In the near future, improvements in both fabrication and readout technology will make possible a new frontier in massivly multiplexed, dense, background-limited focal planes from the mm-wavelength through THz, providing a unique window on the early Universe.

In addition to the mm/submm wavelength science discussed here, superconducting resonators have applications in the detection of higher energy photons and particles and as magnetic field and current sensors. The technology is also closely related to superconducting experiments in quantum information and has lead to many research collaborations with groups designing superconducting Qubits.

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