Kinetic Inductance Detectors for Far-Infrared Spectroscopy

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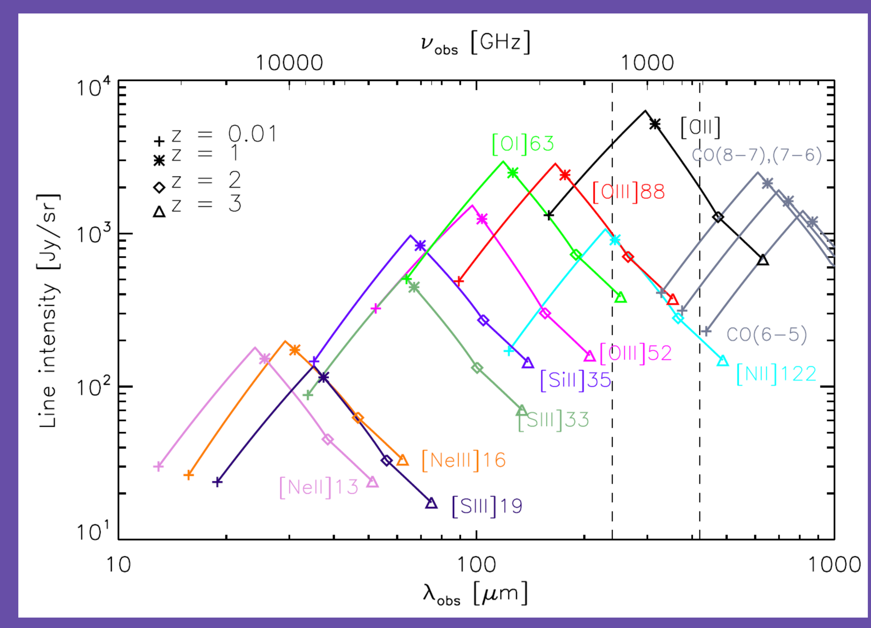
Target Science

The star formation mechanisms at work in the early universe remain one of the major unsolved problems of modern astrophysics. After the big bang, the universe underwent a period of reionization due to the formation of the first stars and galaxies. Following this period, the star formation rate in the early universe increased steadily and reached a peak at a time corresponding to a redshift of approximately 2.5. Many of the luminous galaxies present in the universe at that time were heavily enshrouded in dust, which makes observing their detailed properties difficult. Since they contain the majority of star formation activity in the early universe, however, studying these early galaxies could lead to new insights on star and galaxy formation and evolution. Dust obscures optical observations of these galaxies, but it is possible to observe them at other wavelengths. In particular, a rich variety of spectral lines exist at far-infrared wavelengths that serve as tracers of star formation.

Instrument Concept: STARFIRE



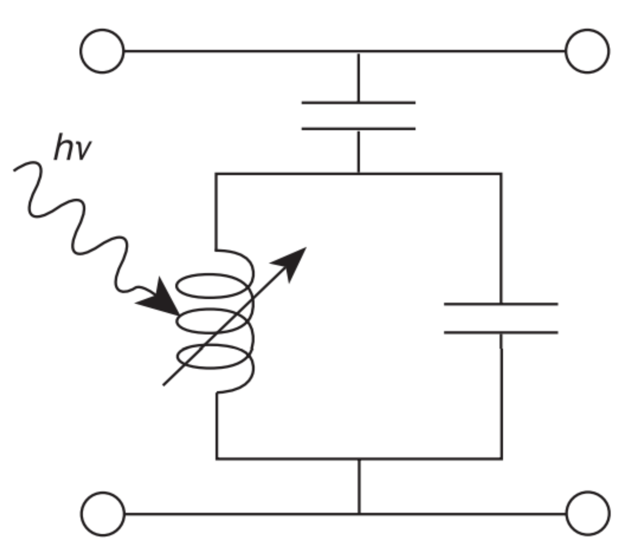
Mean cosmic line intensities of far-IR fine-structure lines based on scaling local-Universe galaxy spectra (Spinoglio et al., 2012) to models of evolving luminosity functions (Bethermin et al. 2011). In the STARFIRE waveband (between dashed vertical lines), [CII] is brightest, so it will dominate the fluctuations.

The Spectroscopic Terahertz Airborne Receiver for Far-Infrared Exploration (STARFIRE) is a telescope program which aims to demonstrate the key technical milestones necessary for photon-limited, balloon-borne far-infrared spectroscopy. STARFIRE consists of a spectrometer operating from 240 - 420 μm coupled to a 1.8 m telescope, which will obtain spectra of dust-obscured star forming galaxies in the fine structure lines, including [CII] (157 μm; 0.5 < z < 1.54), [OI] (63 μm; 2 < z < 4), and [OIII] (88 μm; 2 < z < 4). Several spectrometer architectures are being considered, including a diffraction grating and waveguide filter bank. Arrays of kinetic inductance detectors (KIDs) will form the instrument's detector system.

Kinetic Inductance Detectors

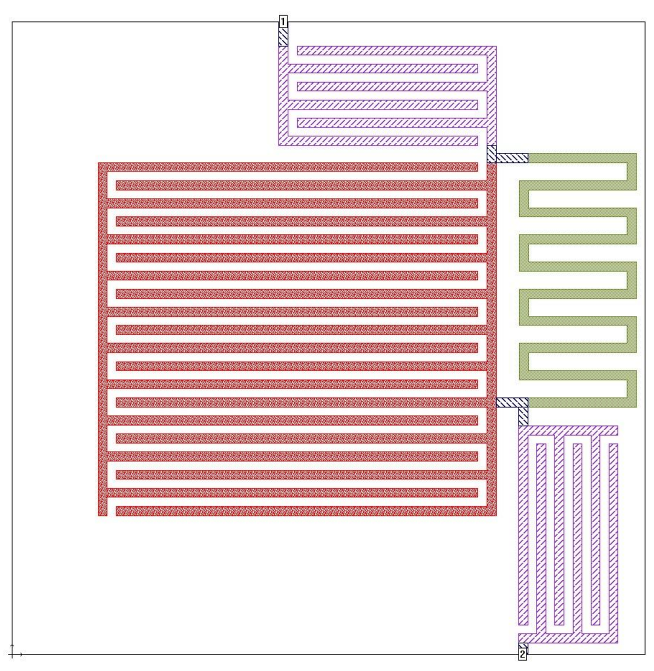
Kinetic inductance detectors (KIDs) are small superconducting resonant circuits patterned out of thin metal films. In superconductors, kinetic inductance arises in addition to geometric inductance as a result of the kinetic energy of Cooper pairs moving through the material. Each detector pixel has an element capable of absorbing incident radiation. Absorbed radiation breaks Cooper pairs into quasiparticles, which changes the resonance frequency and linewidth of the resonator.

Lumped-element KIDs consist of separate capacitive and inductive elements, which can be capacitively coupled to a transmission line. The inductor absorbs and responds to incident radiation.

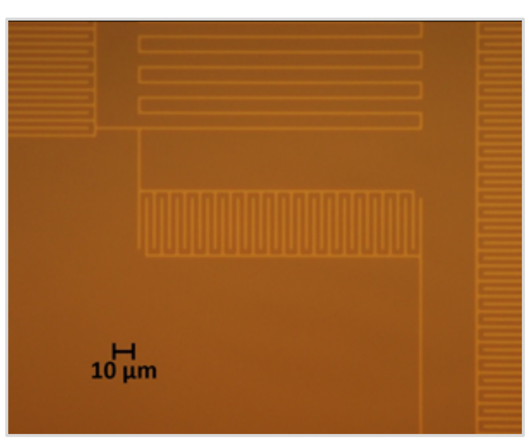


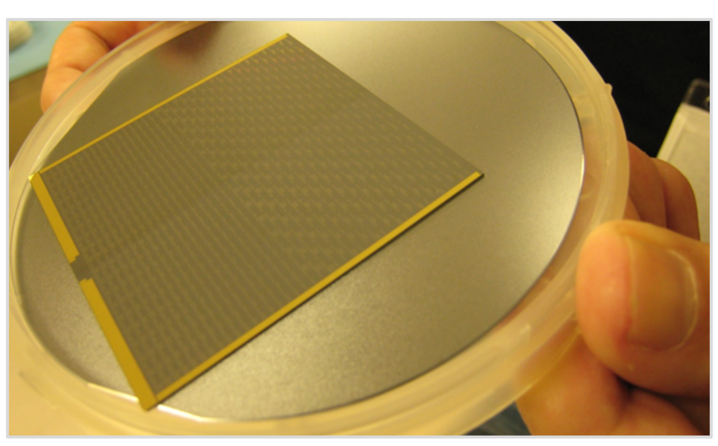
Left: Schematic circuit diagram of a lumped-element KID capacitively coupled to a feedline. (Day et al. 2003)

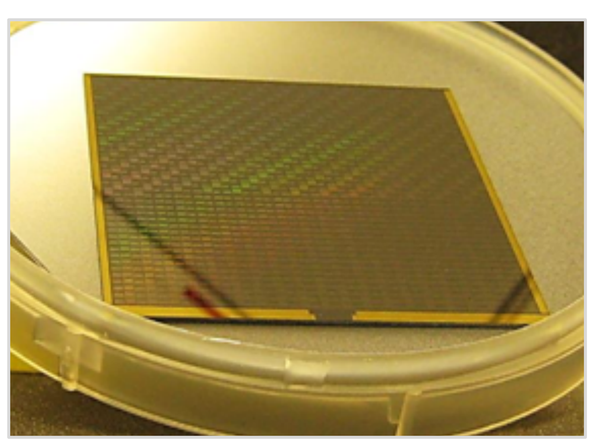
Right: Schematic layout of a lumped-element KID pixel, including an interdigitated capacitor (red), meandered inductor (green), and two coupling capacitors (purple).

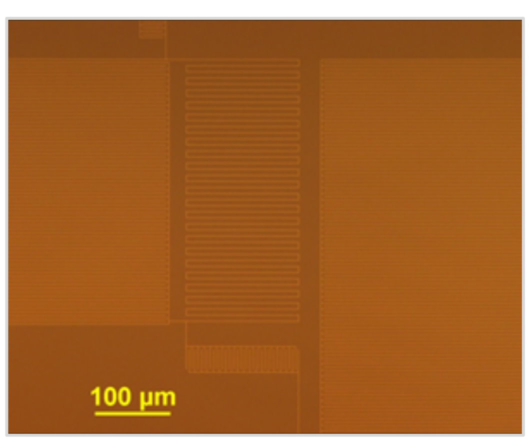


Fabrication









Four identical prototype KID arrays were fabricated at NASA GSFC using a photolithography process. The trilayer TiN/Ti/TiN material was deposited according to a recipe developed at NASA GSFC, then patterned with a photolithography mask of the resonator design.

Left: Micrograph images of the completed KID arrays.

Detector Design Considerations

The following considerations were used in the design of prototype detector arrays for the STARFIRE experiment:

- **Approach**: Lumped-element KID
- **Number of pixels**: 1600/array × 4 arrays
- **Pixel dimensions**: 1.4 mm × 1.4 mm
- **KID Resonant frequencies**: 100-250 MHz
- **Incident optical wavelengths**: 240-420 μm
- **Material**: thin-film TiN/Ti/TiN trilayer (3 nm/10 nm/3 nm) on crystalline Si wafer
- **Linewidth**: 2 μm for pixel features, 5 μm for feedline
- **Feedline structure**: interdigitated capacitor with pixels between fingers
- **Target detector NEP**: 9×10^{-19} W/√Hz

Readout Scheme

Each resonator is coupled to a feedline in order to measure the resonance changes. To form an array, each pixel can be tuned to have its own resonance frequency. It is therefore possible to distinguish the signals of many KIDs coupled onto the same transmission line. The signal path includes a low-noise cryogenic amplifier.

The detectors are read out using the FPGA-based Reconfigurable Open Architecture Computing Hardware (ROACH) platform developed by the CASPER collaboration.