Superconducting Direct Detectors

New Concepts

- A variety of new concepts are under development
  - Will enable new instrument architectures
- Superconducting components
  - Low-loss transmission lines
  - Narrow-beam planar antennas
  - High performance lithographic filters
- TES bolometers
  - Antenna coupled (NEP and optical coupling)
  - Absorber coupled (electrical NEP)
  - Leg-isolated and electron-phonon decoupled
  - Broadband “absorber-antenna” concept
- Kinetic inductance detectors
  - Powerful new approach for arrays (multiplexing)
  - Easily fabricated
  - Can substitute for bolometers

Discuss with P. Day or H. G. LeDuc
Superconducting Direct Detectors
Low-loss Superconducting Microstrip Lines

Test chip with 10 mm stub

- Loss is quite low
- 20 cm attenuation length (100 GHz)
- Loss continues to be low to at least 500 GHz (0.5% per wavelength)

A. Vayonakis et al.

October 11, 2003

Cornell/Caltech
Large Submillimeter Telescope Workshop

- Characteristic impedance (Ohm) 10.7 ± 0.6
- phase velocity at 4.2 K 0.3414 ± 0.0001
- phase velocity at 1.5 K 0.3424 ± 0.0001
- power loss per wavelength at 4.2 K (1.95 ± 0.14) %
- power loss per wavelength at 1.5 K (0.55 ± 0.12) %
Superconducting Direct Detectors

How to Build a Bigger Focal Plane?

- Corrugated feeds
- 4K filters & lenses
- Thermal gap
- 250mK filt & lens
- Vespel legs

Get rid of discrete feeds and filters!
Use antenna-coupled planar arrays

Bolometers from JPL

Source: J. Bock
Superconducting Direct Detectors

Demonstration of Antenna-Coupled TES

- Dual slot antennas
- Microstrip lines
- Normal metal absorber
- TES (Al/Ti/Au)
- SiN legs
- Shunt resistor

Twin slot antenna: Zmuidzinas & LeDuc 1992
500 GHz SIS

Optical time const.
$\tau = 400 \ \mu$s

NEP = 1.8 e-17 W/$\sqrt{\text{Hz}}$

$\tau = 400 \ \mu$s

NEP $\sqrt{\tau} = 4 \ e^{-19} \ J$

$T_0 = 300 \ mK$

High optical efficiency

C. Hunt et al. (2003)

NOTE: twin-slot needs substrate lens

Cornell/Caltech
Large Submillimeter Telescope Workshop

Current Noise (A/$\sqrt{\text{Hz}}$)

$10^{-12} \ \text{to} \ 10^{-10}$

$10^{-11}$

$10^{-10}$

$10^{-9}$

$10^{-8}$

$10^{-7}$

$10^{-6}$

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$10^0$

$10^1$

$10^2$

$10^3$

$10^4$

$10^5$

$10^6$

$10^7$

$10^8$

$10^9$

$10^{10}$

Frequency (Hz)

- Total
- Johnson
- Phonon
- Amplifier

October 11, 2003
Superconducting Direct Detectors

Narrow-beam planar antennas

- Multi-band, single pol
  \[ \sim F_\lambda \]

- Single band, dual pol

- Long slot antennas
- Tapered Nb microstrip

- Niobium ground plane
- Filterbank
- C1, C2, C3

- F \sim 3 \text{ feasible!} (since microstrip loss is low)

October 11, 2003

Cornell/Caltech
Large Submillimeter Telescope Workshop
Superconducting Direct Detectors
Measured antenna pattern

- use SIS direct detector
- 4 K testing
- silicon substrate
- quartz AR plate
- 19° FWHM
- 95% main beam efficiency

Goldin et al. (2003)
Superconducting Direct Detectors

Lumped-Element MM-wave Filters

Calculated Transmittance

- 3-pole lumped-element filter
- calculation using Supermix and Sonnet
- designed for multichannel applications
A broadband superconducting detector suitable for use in large arrays

Peter K. Day¹, Henry G. LeDuc¹, Benjamin A. Mazin¹,
Anastasios Vayonakis² & Jonas Zmuidzinas²

¹Jet Propulsion Laboratory, Pasadena, California 91107, USA
²California Institute of Technology, 320-47, Pasadena, California 91125, USA

Cryogenic detectors are extremely sensitive and have a wide variety of applications¹–³ (particularly in astronomy⁴–⁸), but are difficult to integrate into large arrays like a modern CCD (charge-coupled device) camera. As current detectors of the cosmic microwave background (CMB) already have sensitivities comparable to the noise arising from the random arrival of CMB photons, the further gains in sensitivity needed to probe the very early Universe will have to arise from large arrays. A similar situation is encountered at other wavelengths. Single-pixel X-ray detectors now have a resolving power of ΔE < 5 eV for single 6-keV photons, and future X-ray astronomy missions⁹ anticipate the need for 1,000-pixel arrays. Here we report the demonstration of a superconducting detector that is easily fabricated and can readily be incorporated into such an array. Its sensitivity is already within an order of magnitude of that needed for CMB observations, and its energy resolution is similarly close to the targets required for future X-ray astronomy missions.

Advantage: quasiparticle G-R noise scales as

\[
\frac{n_{qp}}{t_{qp}}^{1/2} \sim \exp\left(-\frac{\Delta}{kT}\right)
\]
Superconducting Direct Detectors

Quarter-wavelength resonator

CPW - 200 nm Al on sapphire
$L = 3$ mm; $V = 2000 \, \mu m^3$
$f_0 = 10$ GHz; $Q = 55,000$
$\alpha = 0.04$

Expect position-dependent response, $\sim \cos^2(\pi x/2L)$

October 11, 2003
Cornell/Caltech
Large Submillimeter Telescope
Superconducting Direct Detectors

IQ readout of amplitude and phase

\[ V \cos(\omega t - \phi) = V \cos \phi \cos \omega t + V \sin \phi \sin \omega t \]
Superconducting Direct Detectors

It works !!!

- Rise time: resonator bandwidth
- Fall time: quasiparticle decay
- Nyquist sampled readout
- High pulse SNR:
  - $\Delta E \sim 11 \text{ eV}$
- Output noise spectrum measured
  - Appears to be dominated by resonator noise
  - Origin not yet determined
  - Readout NEP contribution $\sim 10 \text{ dB lower}$
  - NEP $\sim 10^{-16} \text{ W} / \text{Hz}^{1/2}$
  - NEP consistent with observed pulse $\Delta E$

Graph showing x-ray pulse for Aluminum, 1/4-wave detector.

Fe-55, 6 KeV
Superconducting Direct Detectors

Antenna-coupled kinetic inductance detector

- Niobium - ground plane (green) and top microstrip conductor (black)
- Aluminum – center conductor of CPW KID resonator (blue)
- Simple to fabricate!
- KID is easy to couple to antenna
- Ultimate NEP limit < $10^{-19}$ W/Hz$^{1/2}$
- Demonstrated NEP already useful for ground-based submm imaging
- Single-pixel or small array lab demo at $\lambda=850$ $\mu$m expected in 2004
- Prototype instrument on CSO by end of 2005?
Superconducting Direct Detectors
Example of a UV/Optical Array

- 64 resonators
- 20 x 32 Optical/UV Array
- $Q \sim 10^6$ (design; previously demonstrated)
- 50 $\mu$m square pixels
- 96% fill factor
Superconducting Direct Detectors
Measurements – 30 resonators; Q ~ 200,000
Superconducting Direct Detectors
Frequency-domain Multiplexing
Superconducting Direct Detectors

Wireless Technology for Readouts

- Many readout channels can be condensed onto a single circuit board using cell phone ICs (at 1-2 GHz, plus block upconversion if necessary)
Superconducting Direct Detectors
Demonstration of Frequency Multiplexing

- demonstrates qp trapping (Ta-Al) and frequency mux
- $\Delta E$ is limited by low Q, around $10^4$
Summary and Conclusions

- **New elements for direct detection instruments**
  - Low-loss transmission lines
  - Narrow-beam planar antennas
  - Planar lithographed filters
  - Microstrip-coupled bolometers

- **Kinetic Inductance Detectors**
  - Already interesting for ground-based submm
  - Must develop prototype arrays and readout electronics
  - Continue study of device physics, noise, materials
## Personnel

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Research Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jamie Bock</td>
<td>JPL/Caltech</td>
<td>Bolometers, TES, Antennas…</td>
</tr>
<tr>
<td>Peter Day</td>
<td>JPL</td>
<td>KIDs, TES</td>
</tr>
<tr>
<td>Brian Dougherty</td>
<td>Caltech</td>
<td>KIDs for dark matter</td>
</tr>
<tr>
<td>Darren Dowell</td>
<td>JPL</td>
<td>Instruments, polarimetry, …</td>
</tr>
<tr>
<td>Megan Eckart</td>
<td>Ph.D. student</td>
<td>KIDs for X-rays</td>
</tr>
<tr>
<td>Jiansong Gao</td>
<td>Ph.D. student</td>
<td>KID device physics</td>
</tr>
<tr>
<td>Alexey Goldin</td>
<td>JPL</td>
<td>Array antennas, filters</td>
</tr>
<tr>
<td>Sunil Golwala</td>
<td>Professor</td>
<td>KIDs for dark matter</td>
</tr>
<tr>
<td>Fiona Harrison</td>
<td>Professor</td>
<td>KIDs for X-rays</td>
</tr>
<tr>
<td>Cynthia Hunt</td>
<td>Ph.D. ’03</td>
<td>Twin-slot TES</td>
</tr>
<tr>
<td>Andrew Lange</td>
<td>Professor</td>
<td>CMB applications</td>
</tr>
<tr>
<td>Rick LeDuc</td>
<td>JPL</td>
<td>Low-Tc Lead</td>
</tr>
<tr>
<td>Chris Martin</td>
<td>Professor</td>
<td>UV/optical applications for KIDs</td>
</tr>
<tr>
<td>Ben Mazin</td>
<td>Ph.D. student</td>
<td>KIDs, UV/optical applications</td>
</tr>
<tr>
<td>Tasos Vayonakis</td>
<td>Ph.D. student</td>
<td>Microstrips, antennas, KIDs</td>
</tr>
<tr>
<td>Minhee Yun</td>
<td>JPL</td>
<td>Antenna-coupled TES</td>
</tr>
<tr>
<td>Jonas Zmuidzinas</td>
<td>Professor</td>
<td>KIDs, antennas, etc.</td>
</tr>
</tbody>
</table>

October 11, 2003  
Cornell/Caltech  
Large Submillimeter Telescope Workshop