Sensor Technology at Submillimeter Wavelengths for Space Applications

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Abstract

Our universe is most luminous at far-infrared and submillimeter wavelengths (100 GHz – 10 THz) after the Cosmic Microwave Background (CMB) radiation. This region of the electromagnetic spectrum provides critical tracers for the study of a wide range of astrophysical and planetary phenomena. This spectral range contains information on the origin of the planets, stars, galaxies, and clusters; the geometry and matter/energy content of the Universe, atmospheric constituents and dynamics of the planets and comets and tracers for global monitoring and the ultimate health of the Earth. Sensors at far-infrared and submillimeter wavelengths provide unprecedented sensitivity for astrophysical, planetary, and earth observing instruments. Very often, for a spaced based platform where the instruments are not limited by atmospheric losses and absorption, the overall instrument sensitivity is dictated by the sensitivity of the sensors themselves. Moreover, some of the cryogenic sensors at submillimeter wavelengths provide almost quantum-limited sensitivity. This paper provides an overview of the submillimeter-wave sensors and their performance and capabilities for space applications.

Keywords: Submillimeter, terahertz, sensors, mixers, detectors, space applications

1 Introduction

Most of the radiation in the Universe is emitted at wavelengths longer than 10 microns (30 THz), and this peaks at about 100 microns (3 THz), if we exclude contributions from the cosmic microwave background (CMB) [1]. CMB is the cooled radiation (2.7 Kelvin) that permeated the Universe for 15 billion years, which is largely confined to wavelengths between one and five millimeters with peak intensity at two millimetres, and is the earliest electromagnetic relic of our Universe. CMB was emitted about 500,000 years after the big bang, when electrons and protons in the primordial plasma — the hot, dense soup of subatomic particles that filled the early universe — first combined to form hydrogen atoms [2].

Radiation in these wavelengths highlights warm phenomena, processes of change such as star formation, formation of planetary systems, and galaxy evolution; atmospheric constituents and dynamics of the planets and comets and tracers for global monitoring and the ultimate health of the earth. As for the CMB, determining the minute anisotropy in its temperature distributing and its polarization will lead to the knowledge of inflationary gravitational waves and the nature of the Universe after the very first fraction of a second after the Big Bang.

There is a lot of interest to know more about the planets in our solar system, as some of the planets and their moons have characteristics similar to our Earth. Instruments in the submillimeter wavelengths have the capability to unearth a lot of information by studying their atmospheres, surfaces, and subsurface water and ice contents.

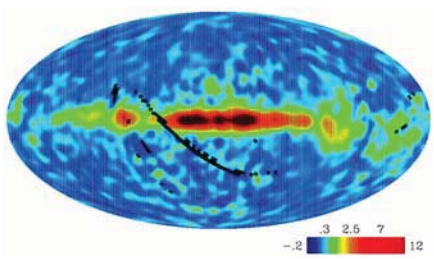
In spite of being the most fascinating part of the electromagnetic spectrum, submillimeter-wave frequency range (loosely defined as 1 mm > λ > 100 μm, corresponds to 300 GHz < ν < 3 THz) remains one of the least explored band. The reason is believed to be the non availability of commercially available sensor components, sub-systems, and instruments. However, with the new emerging applications such as imaging from space platforms [3], stand-off contraband detections and reconnaissance [4], medical imaging [5], and even in the art world – for painting analysis [6]; the far-Infrared and submillimeter-wave band is increasingly playing an important role in pushing the technology frontiers in this electromagnetic band. In this paper we review the current status of submillimeter-wave sensors, instruments, and its applications.

2 Applications

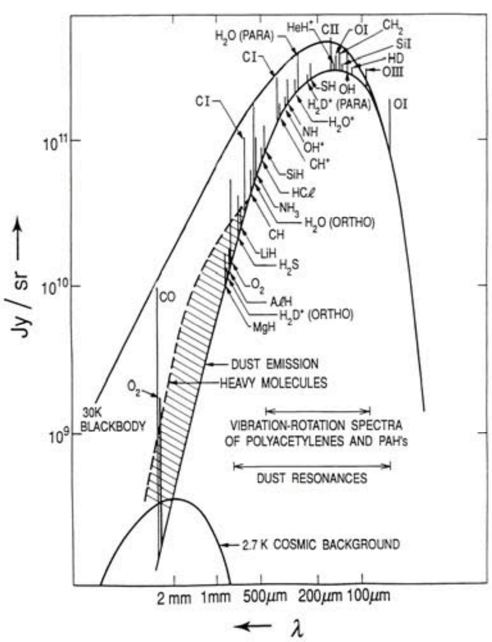
The need for sensitive instruments for astrophysics experiments has primarily pushed the submillimeter-wave sensor development [7]. In astronomy, the challenge is to unearth signals from the distant starts and galaxies embedded in the noise of the interstellar medium and the noise generated by the sensor itself. That led to the development of the highly sensitive sensors and data/image processing techniques which found their way to other fields. In the following sections, we list a couple of important areas which has been the driving force for the development of far-infrared and submillimeter-wave sensors.

2.1 Astronomy and Astrophysics

The scientific importance of high-resolution spectroscopic observations at submillimeter wavelengths is widely recognized by the international astronomy and astrophysics community. This importance is underscored by the key role of heterodyne spectrometers in the ESA cornerstone Herschel Space Observatory [8] as well as the ground-based Atacama Large Millimeter Array (ALMA) [9] and airborne Stratospheric Observatory for Infrared Astronomy (SOFIA) [10]. Star formation and key phases of galaxy evolution occur in region enshrouded by dust that obscures them at infrared and optical wavelengths, while the temperature range of the interstellar medium of ten to a few thousand Kelvin in these regions excites a wealth of submillimeter-wave spectral lines. Figure 1(a) shows a schematic representation of the spectrum of a typical star-forming region. With high-resolution spectroscopy, resolved line profiles reveal the dynamics of star formation, directly revealing details of turbulence, outflows, and core collapse. Observations of emission from ionized species such as N+ at 1461 GHz (Figure 1(b)), allow one to effectively count ionizing ultraviolet photons from newborn stars still enshrouded in their stellar nurseries. These allow one to understand the energy balance and dynamics of star forming regions and galaxy interactions, and are essential components to understanding the origins of both stars and galaxies.



(a)



(b)

Figure 1: (a) An all-sky view of N+ line emission at 1461 GHz measured with COBE FIRAS at 10° resolution [11], and (b) a schematic representation of the spectrum of a star forming region. Spectral line emission is superimposed on the dust continuum [1].

Submillimeter-wave signals emitted from the stars and galaxies are mostly obscured from most Earth-based observations because of the atmospheric absorptions, they provide strong motivation for a number of existing or upcoming space astrophysics instruments. Most notable are the Submillimeter Wave Astronomy Satellite (SWAS) [12], launched in December 1998, and currently sending back signals. The future missions such as Herschel Space Observatory [8] and Exploratory Submillimeter Space Radio-Interferometric Telescope (ESPRIT) [13] will advance our knowledge about this universe many folds.

2.2 Planetary Sciences

A major space application for submillimeter-wave sensors is in planetary and small-body (asteroids, moons, and comets) observations. Orbital remote sensing or lander-based in-situ observations of gaseous species in the Venutian, Martian, Saturn, and Jovian atmospheres, as well as their moons such as Europa, Ganymede, and Titan have been either proposed or currently in orbit [14]. Submillimeter-wave sensors in the spectroscopic instruments on planetary missions allow a large number of chemical species in the atmospheres of Mars and Titan to be detected at concentrations below a part per billion, and their location to be precisely pinpointed in latitude, longitude, and in altitude. Specific species of interest include water, NO_2, N_2O, NH_3, SO_2, H_2S, CH_4, and HCN, among others. Moreover, the radiometer instruments at submillimeter wavelengths allow determining the nature and composition of cometary and planetary surfaces such as the Mars, Europa, and Titan by measuring the polarization-sensitive thermal emission from the dielectric surfaces.

In March 2004, MIRO (Microwave Instrument for Rosetta) was launched on the Rosetta spacecraft that will rendezvous with Comet 67 P/Churyumov-Gerasimenko [15]. MIRO will measure the near surface temperatures of the comet nucleus (and hopefully of an asteroid), thereby allowing scientists to estimate the thermal and electrical properties of these surfaces. In addition, the spectrometer portion of MIRO will provide measurements of water, carbon monoxide, ammonia, and methanol in the gaseous coma of the comet [16]. These measurements will provide insight as to how the comet nucleus material sublimates (changes from its frozen state, ice, to a gas) in time and distance from the sun. In addition the Doppler shifts of the spectral lines will characterize the velocities of gas outflow from the nucleus. Figure 2 shows the chemistry of the middle atmosphere, cloud layers, lower atmosphere, and surface on the planet Venus which can be detected by submillimeter-wave sensors.

An ongoing challenge in the exploration of the outer solar system is how to determine the prospects for life and how life might have evolved on Earth. The larger moons of Jupiter and Saturn are among the most interesting bodies in the solar system because their composition includes a large amount of water ice. In the case of Europa there is strong evidence that there is at least some liquid water under the surface and the tantalizing possibility of a biosphere. The products of high-resolution submillimeter-wave remote sensing, such as composition, temperature, pressure, and gas velocity (winds) offer the planetologist a wealth of information on a global scale. It is not unreasonable to suppose that the first detection of planets containing atmospheric conditions (temperature, pressure, composition) suitable for extraterrestrial life forms will be confirmed by submillimeter-wave spectroscopy. An excellent overview of these applications for space can be found in [17].

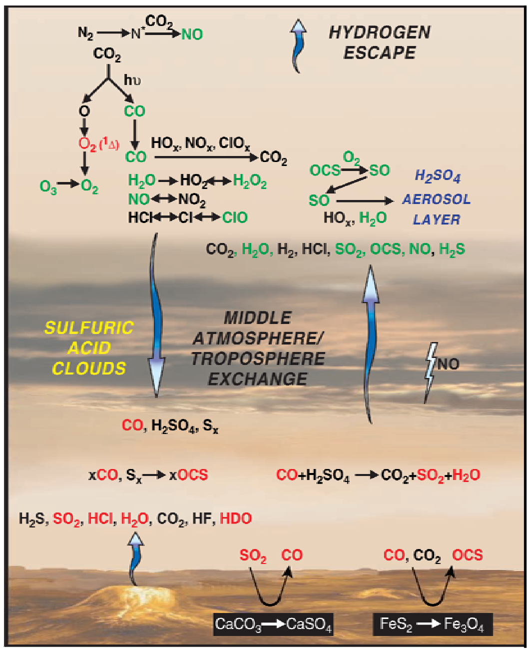


Figure 2: The chemistry of the middle atmosphere, cloud layers, lower atmosphere, and surface on the planet Venus which can be detected by submillimeter-wave sensors.

2.3 Earth Observations

Many of the same spectral signatures that are so abundant in interstellar and intragalactic space are also present in planetary atmospheres where background temperatures range from tens of Kelvin to several hundred Kelvin. Particularly important are thermal emission lines from gases that appear in the Earth's stratosphere and upper troposphere that serve as pointers to the abundances, distributions, and reaction rates of species involved in ozone destruction, global warming, total radiation balance, and pollution monitoring. Many key species either have thermal emission line peaks or their first rotational or vibrational line emissions in the submillimeter, especially between 300–2500 GHz. Again, these emission lines are best observed from platforms above the Earth's atmosphere.

It is now well established that human activity has begin to affect the health of our planet [18]. A prime example is anthropogenic effects on stratospheric chemistry that lead to global depletion of the protective ozone layer and the Antarctic ozone hole [19]. Tropospheric ozone and related trace gases have also been perturbed significantly and are likely to have modified the atmospheric oxidizing capacity and contributed to climate change [20], [21]. Remote sensing of Earth's atmosphere at submillimeter wavelengths is an important method of obtaining global observations needed for atmospheric chemistry and climate [22]. Submillimeter-wave measurements are obtained from observations of atmospheric spectral line thermal emission, allowing daily global coverage from a satellite-based instrument. Additional important features include the ability to (a) make chemical measurements in the presence of dense volcanic aerosol, smoke, and ice cloud, and (b) measure signals from weak spectral lines in the presence of nearby very strong ones. These features are due to the relatively long wavelengths – compared to infrared, visible, and ultraviolet spectral regions; and the excellent spectral resolution available with heterodyne techniques at submillimeter-wave frequencies [23].

These techniques have already been developed and applied to stratospheric chemistry measurements from space. The Microwave Limb Sounder (MLS) experiments [24] on the Upper Atmosphere Research Satellite (UARS), launched in 2004, have stratospheric chemistry measurements as primary goal. High-resolution heterodyne receivers at 118, 190, 240, 640, and 2520 GHz were designed for this mission to take advantage of the information content available through high-resolution spectroscopic measurements of these gases at submillimeter-wave frequencies. Unlike the astrophysical sources, even modest diameter collecting surfaces are fully filled by the signal beam in atmospheric observations. Resolution requirements are set by the orbital path and speed or by the atmospheric processes themselves. In both limb sounding (scanning through the atmospheric limb) or nadir sounding (looking straight down through the atmosphere), precise

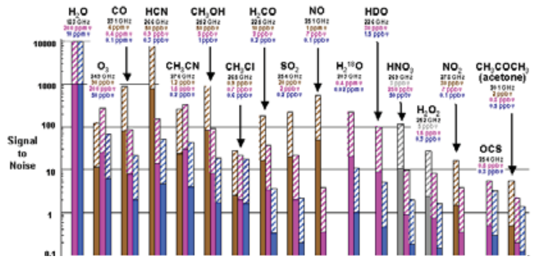


Figure 3: Mid-upper tropospheric chemistry measurements achievable by a future satellite-based sensor with sensitive (T_{sys} = 100 K) submillimeter-wave sensors. Many molecules have strong spectral emissions at frequencies between 180 and 280 GHz, detectable with short integration times.

spectral line-shape information is required to separate out the effects of pressure and Doppler broadening at each altitude along the emission path. Spectral resolution of better than one part in a million is typically needed for line widths that range from tens of kilohertz in the upper stratosphere to 10 MHz or more lower down. Figure 3 shows the capability of submillimeter-wave sensors for tropospheric chemistry measurements.

2.4 Security Imaging and Other Applications

Recent progress in submillimeter-wave and terahertz (THz) technology, as well as the demand for new surveillance capabilities, has led to the development of prototype submillimeter imagers capable of detecting weapons concealed within clothing or packages [25-29]. Imaging in the submillimeter wavelengths is attractive because wavelengths in the range 100 μm < λ < 1 mm are short enough to provide high resolution with modest apertures and long enough to penetrate materials such as cloth or cardboard. However, current approaches to submillimeter-wave imaging do not yet meet all of the real-world and often conflicting requirements of standoff range, portability, high speed, penetrability, and target identification amongst clutter.

For example, while active submillimeter-wave imaging systems using high-power coherent illumination and ultra-low-noise heterodyne detection show great promise, they often face operational drawbacks such as requiring cryogenic detectors or bulky laser sources. A more fundamental difficulty with coherent active imaging is that by relying on a single frequency, target recognition is reliant on an object's contrast and brightness which, in turn, are highly sensitive to incidence angle of radiation, clutter signal from the foreground or background, and interference and speckle effects.

Imaging radar at these frequencies is believed to solve many of the problems listed above. A room temperature active submillimeter imager can be used in the swept-frequency frequency modulated continuous wave (FMCW) radar mode to map a target in three dimensions. Figure 4 shows images using such a radar which can distinguish targets with centimeter-scale resolution in both range and cross-range. The images clearly indicate that radar capability may emerge as a key component of active submillimeter-wave imagers.

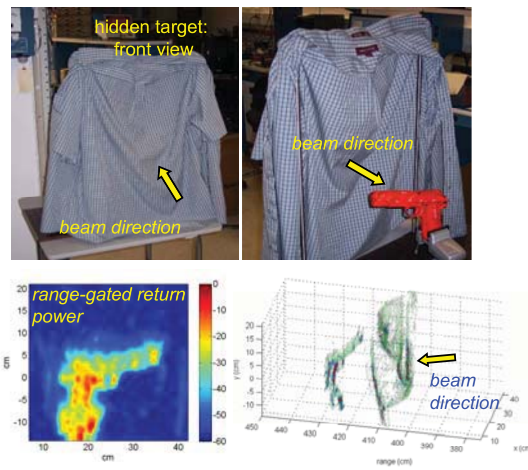


Figure 4: A 580 GHz radar image of a concealed gun behind a shirt at 4m stand-off distance with 2 cm range and sub-centimeter spatial resolution. Radar imaging allows 3-D reconstruction of images of concealed objects [4].

Submillimeter-wave imaging techniques are also showing a lot of promise in biological systems, from imaging of tooth cavity to cancerous cells. A detailed review of this subject is available in [5]. Another application of submillimeter-wave sensors has been in the areas of plasma fusion diagnostics and gas spectroscopy. An excellent review of submillimeter-wave techniques in the fusion field can be found in the paper by Luhmann and Peebles [30].

3 Submillimeter-Wave Sensors

There are two distinct regimes in which submillimeter-wave sensors are used in an instrument. In the first case, they are used to make images by detecting the thermal emission from the objects. In the second case, spectroscopic studies are carried out either in absorption or in emission. In spectroscopy, there are two generic approaches. Measurements with low spectrum resolution λ/Δλ of 3-10 are called photometry. They are used to characterize broad spectrum sources such as electron synchrotron and thermal bremstrahlung emission, and thermal emission from interstellar dust grains (for astrophysics applications). Measurements with higher resolution (10^6 or higher) are generally different from photometry, and are typically used to characterize molecular and atomic spectral lines [31].

The sensors at submillimeter wavelengths can be broadly categorized into two distinct sets: coherent detectors and incoherent (direct) detectors [32]. For coherent detection the signal received at submillimeter wavelengths is down converted to the gigahertz (GHz) band over a limited bandwidth. The frequency conversion relies on a nonlinear element – the mixer – and a local oscillator (LO). The output or intermediate-frequency (IF) signal can then be further processed using additional electronics, usually a spectrometer, correlator, or total power detector. On the other hand, for incoherent detection the submillimeter-wave photons are directly absorbed by some material, creating either electronic excitations or thermal energy (heat). In the later case, the sensor is called a bolometer.

The primary distinction between coherent and incoherent (or direct) detection is the presence or absence of quantum noise. Coherent receivers preserve information about both the amplitude and phase of the electromagnetic field while providing large photon number gain. As a result, coherent receivers are subject to quantum noise, which can be expressed as a minimum noise temperature of $T_n = h\nu/k_B$, or 48 K/THz. Quantum noise is equivalent to the shot noise produced by a background radiation flux of one photon per second per Hertz of detection bandwidth. At radio wavelengths, the background is significantly larger than this value and in any case never falls below the 2.7 K cosmic microwave background (CMB), and so the use of coherent receivers at radio wavelengths need not lead to a loss of sensitivity. In contrast, at optical or infrared wavelengths the quantum noise of coherent receivers is intolerably large, far larger than the typical backgrounds, and so direct detection is strongly preferred.

3.1 Coherent (Heterodyne) Sensors

Since low-noise amplifiers are not available in the submillimeter band, the first operation that a coherent receiver must perform is frequency down-conversion, or heterodyning, from submillimeter-wave frequencies to GHz frequencies. This is accomplished in the usual way, using a mixer and a local oscillator; however the mixer noise sets the system sensitivity and should be as low as possible. Figure 5 shows the typical schematic block diagram of a submillimeter-wave heterodyne receiver.

There are at least three different mixer technologies for submillimeter-wave heterodyne detection. The particular choice is mostly dictated by the available local oscillator power, receiver sensitivity criteria, and whether the mixer will operate at room temperature or cryogenic temperatures. In the following section we evaluate the Superconductor insulator superconductor (SIS) mixers, Hot Electron Bolometer (HEB) mixers, and Schottky mixers for their usage at submillimeter wavelengths.

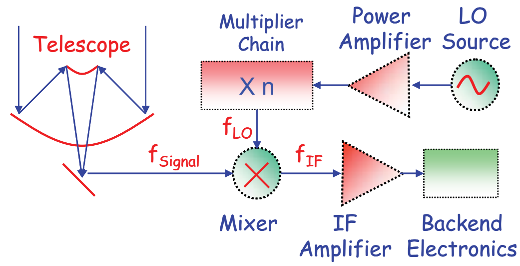


Figure 5: Typical schematic block diagram of a submillimeter-wave heterodyne receiver.

SIS mixers are the most sensitive mixers available today in the 100–1200 GHz frequency range [33]. These mixers are less sensitive at frequencies beyond the superconductor bandgap (2Δ for NbTin ≈ 1500 GHz) where reverse tunnelling becomes a factor and mixer performance is dominated by circuit losses. SIS mixers typically operate at temperatures below 5 K (well below the superconductor critical temperature T_c). Typical state-of-the-art double sideband (DSB) noise temperature for SIS mixers are about 85 K at 500 GHz, have approximately 1 dB of mixer conversion loss, and require approximately 40–100 μW of local oscillator pump power [34]. For optimal performance, SIS mixers require magnets to suppress Josephson currents. Figure 6 shows the operating principle, energy band diagram, and photo of a SIS mixer device along with the mixer in a receiver configuration.

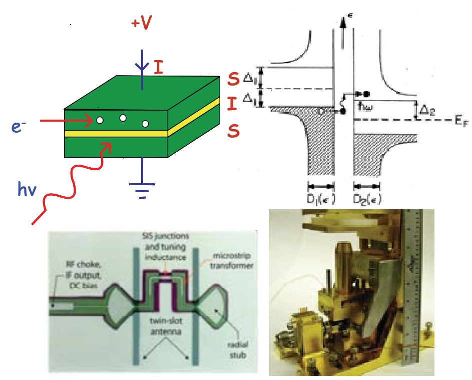


Figure 6: Operating principle and energy band diagram for SIS mixers (top). Bottom: Quasi-optical SIS mixer device (left) and receiver system (right).

Hot electron bolometer (HEB) mixers [35] have excellent noise performance from 500 GHz to 5 THz. Both the diffusion cooled and phonon cooled variety use a short superconducting bridge connecting two normal metal pads as the mixing element, and they generally operate at temperatures below 4 K. Typical DSB noise temperatures of HEB mixers are around 600 K at 500 GHz with approximately 10-15 dB of mixer conversion loss. They require approximately 1–2 μW of LO pump power, which is substantially less than SIS mixers. HEB mixers tend to have only a few

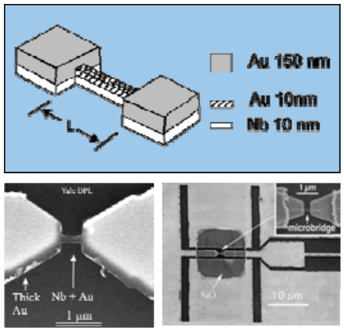


Figure 7: Schematic drawing and device photo of HEB mixers. Bottom left shows the photo of a 1.6 THz quasi-optical HEB mixer.

gigahertz of IF bandwidth, which is a problem for heterodyne imagers where higher IF bandwidth is advantageous. High temperature HEBs, operating in the 100 K range, have shown promise for use as mixers; however, no published results are available. Figure 7 shows the schematic drawing and close-up photo of a HEB mixer device along with the photo of a 1.6 THz quasi-optical HEB mixer.

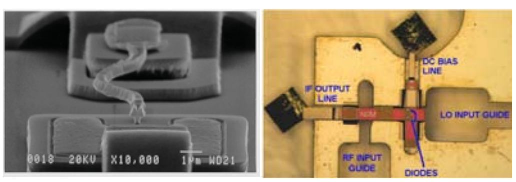


Figure 8: SEM photo of a 2.5 THz GaAs Schottky diode mixer (left) and a photo of a 560 GHz fundamental balanced mixer inside a waveguide block.

Schottky diode mixers operate at frequencies up to well beyond 5 THz [36]. One of the major advantages of Schottky mixers compared to SIS and HEB mixers is that they operate at room temperature, although optimum performance is achieved at or below 20 K. Schottky mixers require high local oscillator pump power, approximately in the 1 mW range. Typical DSB noise temperatures for room temperature Schottky mixers are about 1800 K at 500 GHz with approximately 8 dB of conversion loss. However, their noise temperature improves when cooled, e.g., reaching approximately 1200 K (DSB) at 77 K. It has also been shown that the Schottky mixers can be operated with reduced LO power at the expense of marginally higher mixer noise temperature [37]. Figure 8 shows photos of GaAs Schottky diode mixers operating at submillimeter wavelengths. Figure 9 shows the performance of different coherent sensors (heterodyne mixers) at submillimeter wavelengths.

3.2 Incoherent (Direct) Detectors

Direct detectors function by absorbing photons in a material and sensing the resulting change in a physical property of that material. In semiconductor

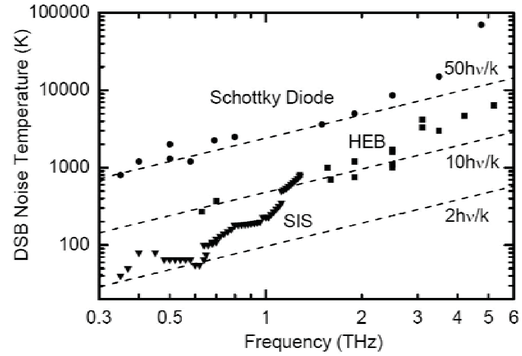


Figure 9: Double sideband (DSB) noise temperature performance of SIS (triangles), HEB (square), and Schottky diode (circle) mixers. Also shown are the 2-, 10-, and 50-times quantum noise limit lines for comparison.

photo-detectors, the mobile charge carriers created by photons are sensed by measuring the current flow in response to an applied electric field. The minimum photon energy required to create an excitation sets a long-wavelength cut-off.

Superconducting bolometers are the most sensitive incoherent detectors, their sensitivity increases when the operating temperature of the detector is reduced. Superconducting transition edge sensors (TES) thermistors are the most popular direct detectors which promise to have unprecedented sensitivity [38]. A TES bolometer for millimeter and submillimeter wavelengths consists of a radiation absorbing element attached to a thin superconducting film with a transition temperature T_c, which is weakly coupled to a heat sink at temperature $T_0 \sim T_c/2$, as shown in Figure 10. Also shown in Figure 10 is the resistance of the TES as a function of temperature, showing the sharp transition at T_c.

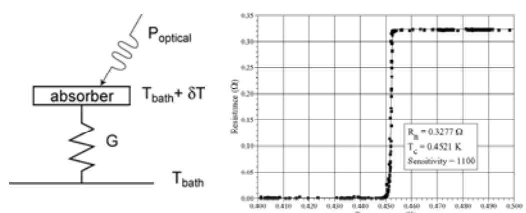


Figure 10: Operating principle of a transition edge sensor (TES). On the right is a typical resistance vs. temperature plot for such sensors showing the transition temperature between normal metal to superconductor [31].

An alternative approach to photon detection using superconductivity is to operate far below the transition temperature T_c. In this situation, most of the electrons are bound together into Cooper pairs [39]. Photons absorbed in the superconductor may break Cooper pairs to produce single electron quasi-particles, similar to electron-hole pair creation in semiconductors. However, it is difficult to separate the quasi-particles from Cooper pairs in this method.

In superconducting tunnel junction detectors (STJ), incoming photons break the Cooper pairs and are filtered out through the tunnel junction [40]. Multiplexed readout of these detectors can be accomplished using RF single-electron transistors.

The quasi-particles produced by photons when they break the Cooper pairs may also be detected by measuring the complex ac surface impedance of the superconductor. At finite frequencies, the surface impedance is nonzero and is in fact largely inductive; this is known as the kinetic inductance effect. This effect can be used to make very simple detectors where the resonance frequency of a superconducting resonator will change when a photon is detected, and can be monitored with microwave readout circuits [41]. Figure 11 shows the operation of kinetic inductance detectors.

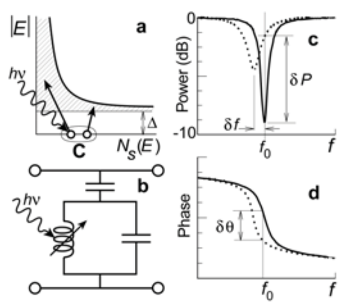


Figure 11: Operation of a microwave kinetic inductance detector when the change of resonance of a superconducting resonator is detected when a photon is absorbed.

There are also a few other direct detectors which provide very good sensitivity for detecting photons at submillimeter wavelengths such as the SIS photon detectors where superconducting tunnel junctions directly convert submillimeter photons to electrical current through the process of photon assisted tunneling. There is also another kind of detector known as superconductor insulator normal metal (SIN) sensors which is similar to SIS detectors except one of the metals is a normal metal [42]. There are also room temperature direct detectors which have limited applications because of their poor sensitivity compared to superconducting detectors. However, for applications where cryogenic detectors are not feasible, they play an active role. Small area GaAs Schottky diodes, composite bolometers with bismuth or tellurium, and Golay cells are all used for room temperature direct detectors. Reference [7] has a good review on these detectors.

4 Summary

Sensors at submillimeter wavelengths have a wide range of applications, from astrophysics, planetary, Earth-observing, plasma diagnostics to medical imaging and homeland security. Due to severe atmospheric attenuation at these frequencies except for a handful available of windows, most of the sensors at these frequencies are used for space-borne applications. Sensors at these wavelengths provide unprecedented sensitivity. Coherent detectors are reaching quantum-noise limit, and the sensitivity direct detector instruments are not limited by the background noise. This is an exciting time for submillimeter-wave sensors.

5 Acknowledgements

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