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DETECTION OF MILLIMETER AND SUBMILLIMETER WAVES

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Summary

This paper gives an overview of research activities in Europe concerning low noise receivers for millimeter and submillimeter waves. Since radio astronomy is a driving force in this area, most of the information given is related to work done by European radio astronomy groups.

Introduction.

There is a considerable amount of research ongoing in Europe concerning detecting millimeter and submillimeter waves coherently or incoherently. The reason for the relative strength in this field is the large number of millimeter and submillimeter wave radio telescopes around, run by European groups (see Table 1). Of some importance is also an ESA project called FIRST (Far Infrared and submillimeter Space Telescope), which is planned to be operating from about 500 GHz to about 2 THz coherently and to several THz incoherently [1].

There are various ways of detecting millimeter and submillimeter waves. Direct amplification is not yet readily available above about 40 GHz, although maybe within a few years we will see amplifiers or possibly mixers based on HEMT devices for frequencies up to about a hundered GHz. Recent research efforts concerning millimeter wave (f>30 GHz) and certainly submillimeter wave coherent receivers are therefore still focused on mixers. Traditional sytems use either Schottky diodes or indium antimonide crystals as the non-linear element and maximum sensitivity is achieved when the mixer and the first stage IF amplifier are cooled to cryogenic temperatures (typically 1.5 - 15 K, depending on the particular receiver type). More recently the superconducting quasiparticle mixer has been developed for millimeter and submillimeter detection. The performance of the superconducting mixer is likely to surpass other current alternatives, and in fact quantum limited noise performance is, in principle, possible.

Schottky diode mixers

The Schottky diode mixer receiver can still defend its place as number one for submillimeter wave frequencies, but is surpassed by the superconducting mixer for millimeter wave frequencies. Several groups in Europe are active in research and development concerning Schottky mixers. Both waveguide type mixers and open structure mixers have been developed.

Waveguide mixer receivers for frequencies around 100 GHz, have been built with noise temperatures between 200 and 300 K single sideband (SSB) for probably all the telescopes listed in Table 1. An example of such a system is the one recently developed for La Scilla. Maybe more interesting are the mixers developed for higher frequencies. The group at Max Planck Institute for Radio Astronomy (MPIRA) in Bonn has built a receiver for 215 -245 GHz for Pico Veleta (it has been in operation since mid 1985) with a best noise temperature of 270 K double sideband (DSB) [2]. The same group also built one for 460 - 490 GHz with a best DSB noise temperature of < 800 K [2]. In both cases the noise temperatures include noise from the optics, the diode, and the IF amp-

Table 1: EUROPEAN MM-WAVE FACILITIES.

ANTENNA	Altitude (m)	Diameter (m)	$\lambda_{min}^{*)}$ (mm)
(Latitude >20N)			
POM-1 (Bordeaux)	0	2.5	2.5
POM-2 (Plateu de Bure) France	2550	2.5	1.0
COLOGNE (Gornergrat) FRG	3000	3.	0.5
SMT (Mt Graham)**) FRG/USA	3250	10.	0.3
HELSINKI (Mätsehovi) Finland	0	13.7	3.5
YEBES (Guadalajara) Spain		13.7	3.5
JCMT (Hawaii) UK/Netherlands	4300	15.	<0.7
IRAM (Plateau de Bure) France/FRG	2500	3x15	0.8
IRAM (Pico Veleta) FRG/France	3300	30.	1.3
CRIMEA USSR	0	22.	4.5
ONSALA Sweden	0	20.	2.3
(Latitude = 30S)			
SEST (La Silla) Sweden/ESO	2400	15.	0.8

*) λ_{min} is not an absolute wavelength limit but merely indicates to what frequency the telescope is currently used.
**) Not yet finished.

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lifier. A French group at Observatoire de Paris--Meudon has also constructed 100 and 230 GHz mixer receivers with about the same data as those mentioned above [3]. A Dutch group (Radio Observatory, Dwingeloo) has reported excellent results for a cooled (15 K) 350 GHz mixer receiver, which over a 30 GHz band showed a DSB noise temperature of less than 400 K [4].

For short submillimeter waves, the open structure mixer is probably to be preferred to the waveguide one, mainly because it is exceedingly difficult to manufacture a waveguide mixer with an optimum coupling to the diode. Open structure quasioptical mixers, often called **corner cube** mixers, have been designed for frequencies from about 350 GHz to 2.5 THz [5,6]. The mixer mount can be considered as a long wire antenna (the whisker) backed up with the corner cube in order to improve its efficiency [7]. How the dimensions, (i. e. the wire (whisker) length and the distance to the corner cube corner) affect the impedance seen by the diode and the beam direction as referred to the wire has been investigated by Kelly et. al.at the Microelectronics Research Center (MRC), Cork, Ireland [8].

Not surprisingly, the diode properties are most essential for the mixer performance, i. e. the conversion loss and the noise. An extensive investigation of room temperature corner cube mixers using extremely small diodes (anode diameter less than 1 μm) in the frequency range 350 to 850 GHz has been carried out by Nett et. al. (MPIRA) in cooperation with the group at Univ. of Virginia, Va., USA, who manufactured the diodes [5]. Their results, besides showing that excellent sensitivity can be obtained (SSB noise temperatures for a room-temperature receiver are [5]: 4850 K /693 GHz; 5400 K/803 GHz; 17000 K/2520 GHz), also show how difficult it is to understand in detail the behavior of these small diodes at these very high frequencies. Zirath (CUT) [9] and Jelenski (Inst. El. Tech., Warszawa, Poland) et. al. (CUT) [10] has carefully investigated the sources of exess noise in mixer diodes and in particular described the influence of traps, intervalley scattering and hot electrons.

Superconducting mixers

In recent years very encouraging results have been obtained in various laboratories over the world by using mixing effects associated with the tunnelling of quasi-particles across Superconductor-Insulator-Superconductor (SIS) junctions. In Europe work in this particular area is going on in several places. SIS mixers are used in telescopes for radio astronomy observations in at least two places. At Pico Veleta receivers for the 100 GHz and 150 GHz frequencies ranges, built at IRAM, Grenoble, France are currently in operation. The receiver noise temperature **on the telescope** is typically 150 K SSB for the 100 GHz one [11], and 150 - 250 K DSB for the 150 GHz one [12]. Measurements indicate 125 K DSB for a prototype 230 GHz receiver [13]. Notice that all the measurement quoted are DSB. However, since the intermediate frequency is as high as 4 GHz, it is probable that for one sideband the noise temperature is considerably less than two times the DSB number (compare below).

At Onsala also two SIS receivers are in operation on the telescope, one for 35 to 50 GHz and another for 85 to 116 GHz. The first one typically has a noise temperature of 160 K SSB [14]. For the second one the noise temperature varies between 140 K SSb and a low of 60 K SSB around 105 GHz. In these receivers the **image frequency is rejected** by positioning the backshort where it will create a shortcircuit at the SIS element. At the signal frequency it is still possible to have an almost optimum embedding impedance, since the IF also in this case is 4 GHz. The general outline of this mixer is shown in Fig. 1. Also groups in England (Cavendish Lab., Cambridge and Univ. Kent at Canterbury), Germany (Univ. of Cpositioning the backshort where it will create a shortcircuit at the SIS element. At the signal frequency ipositioning the backshort where it will create a shortcircuit at the SIS element. At the signal frequency it is still possible to have an almost optimum embedding impedance, since the IF also in

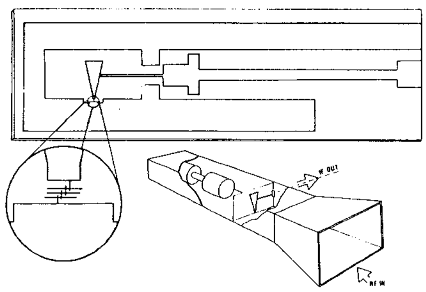

Fig. 1. The SIS-mixer circuit used in the CUT mixers. The amplified part shows how six SIS-elements are coupled in series [14].

this case is 4 GHz. The general outline of this mixer is shown in Fig. 1. Also groups in England (Cavendish Lab., Cambridge and Univ. Kent at Canterbury), Germany (Univ. of Cologne) [15] and France (Ecole Normale Superieure, Paris) [3], are currently working on SIS mixer development but do not yet have systems in operation.

Fundamental work concerning optimization of the embedding circuit has been carried out as a cooperative project between Helsinki Univ. of Tech. and Univ. of California, Berkeley [16]. Extremely low SSB receiver noise temperatures (44 K) and conversion gain have been measured on a labora tory test receiver in the 90 to 100 GHz band [16].

Work is also going on to investigate the possibilities of going to much higher frequencies. In Sweden (CUT) a **750 GHz** SIS mixer [17] and in Holland (Lab. for Space Research, Groningen) a **1000 GHz** Josephson mixer are being developed [18]. The Dutch approach is to use a waveguide mount, while the Swedish group is integrating a slot antenna with the SIS elements on the same substrate (silicon).

Local oscillators

For heterodyne systems local oscillator power is required for pumping the diode. The amount of LO power required for room temperature Schottky diode mixers is about a mW at 100 GHz, 10 mW at 1 THz and 10 times less at 15 K physical temperature. The SIS mixer in this frequency range requires less than one μW of LO power.

Thomson CSF in France build Carcinotron tubes for frequencies up to 1000 GHz [19]. Although the carcinotrons deliver much more output power than solid state sources, there are obvious advatages with the latter.

Gunn diode oscillators have been developed at Univ. of Cologne and CUT using GaAs diodes [20, 21] and InP diodes [22,23] with enough output power to drive 300 K Schottky mixers. The GaAs oscillators oscillate fundamentally at half the output frequency, and the tuning is made using a tunable fundamental frequency cavity [22] (Fig. 2). Typically frequencies up to 110 GHz has been achieved. The same scheme has been used for a second harmonic InP oscillator for the 150 GHz frequecy range [23].

Multipliers have been constructed at several places, and typically 5 % efficiency for 230 GHz multipliers with a maximum output power of a couple of mW has been reported by Farran Tech. Ltd., Ireland. Of particular interest is a systematic in-

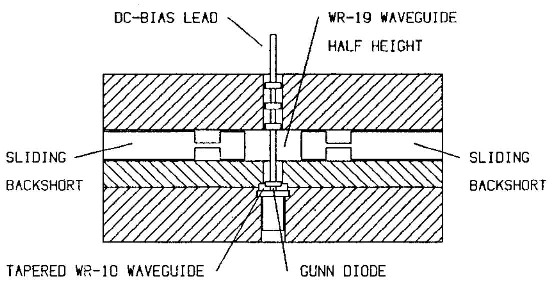

Fig. 2. Outline of the widely tunable Gunn oscillator [20].

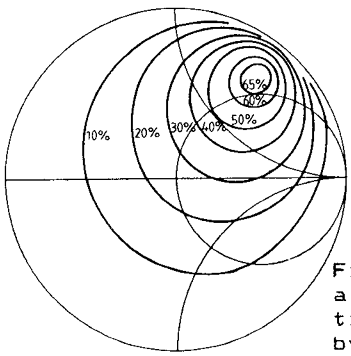

Fig. 3. Efficiency of a doubler as a function of impedance seen by the diode at the 2nd harmonic [24].

vestigation into the optimum embedding impedance of doublers [24] and triplers [25], made in Finland, Helsinki Univ. of Tech. This work included a full nonlinear analysis (see Fig. 3) and experimental confirmation showing that an efficiency of about 44 % for a doubler and about 27 % for a tripler can be obtained for an output frequency of 100 GHz.

Very compact optically pumped lasers as LO sources meant for airborn observations have been developed by Densing et. al. at MPIRA [26]. The dimensions of the whole laser system is 1200x510x-240 mm, and weighs only 70 kg.

Quasi-optical design

Another area of research and development concerns quasioptical design and components.The reason is that a quasioptical approach often is more practical than other means of designing the filters, diplexers etc., neccessary for applying the LO and making the receiver respond only in one sideband (SSB). Coupling the receiver to the outside world (e. g. a telescope) can also be described in terms of quasioptics. Of particulr importance is the loss in components such as interferometers which has been studied at MPIRA [27]. It is shown that the Martin-Puplett interferometer is significantly better than the Mach-Zhender interferometer concerning the loss as well as isolation between the various ports [27].

The design philosophies used in actual receivers are worth studying [5,6,28,29].

Imaging

Recently much attention has been focused on the possibility to construct and use **imaging receivers** in the focal plane of a telescope rather than the conventional single receptor receiver. An imaging receiver with e. g. an array of 4*4 receptors, will speed up observations with a factor of 16 (if the individual receptor elements have the same sensitivity as a single receiver).

A cryogenic test receiver having an array of 3*2 elements has been constructed (Cavendish Lab., Cambridge) in order to investigate practical problems such as the demand for LO power, cooling problems and quasioptical problems [28]. This particular receiver is using InSb hot electron bolometers as nonlinear mixing elements in waveguide mounts.

Investigations have been made concerning using an array of slot-antennas integrated with either Schottky diodes or SIS detector elements [30]. It is shown that these elements can be placed with a spacing to give a beam separation of approximately one Rayleigh distance. These investigations have been made as a cooperative work bet ween CUT and Univ. of Massachusetts, Amherst, Mass

Bolometers

Broad bandwidth measurements require bolometric type detectors. A receiver system for 250 GHz has been constructed by MPIRA for Pico Veleta based on a cooled (0.27 K) NTD-Ge thermoelement bolometer [31]. The NEP of the bolometer is better than $5*10^{-16}$ $W/\sqrt{Hz}$. A 50 GHz band pass filter is used in front of the receiver. The sensitivity of the complete receiver, in a radiometric mode, corresponds to a mixer with a 50 GHz instantaneous bandwidth and a DSB noise temperature of 600 K.

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