Hunt for Molecules
F. Combes, F. Casoli, E. Falgarone, L. Pagani (eds)

THE LONG SUBMILLIMETRIC ROAD: FROM SUPERCONDUCTORS TO SUPERCONDUCTORS VIA THE STARS

Salez, M.[1]

Abstract. New and highly efficient electronic devices based on superconductivity have revolutionized millimeter-wave and submm-wave radioastronomy within the past few decades, allowing us to probe the molecular chemistry of virtually all astrophysical sources, and bringing a wealth of informations on their physical conditions and processes. In particular, one major success has been the discovery of a harldy suspected molecular diversity in the interstellar medium (ISM), using quantum noise-limited and high spectral resolution heterodyne receivers based on superconductive devices. This revolution is far from exhausted, as new devices and instrumentation possibilities continue to emerge from theoretical and experimental research in applied superconductivity. I present some recent and on-going instrumentation developments carried out at LERMA[1], in the light of this general context.

1 Introduction

Since this conference "Hunt for Molecules" is in honor of Pierre Encrenaz, I chose to present some past and on-going developments at LERMA in the field of submillimeter-wave heterodyne detection, the particular angle of superconductivity (SC) - one of his predilection areas, and key to a powerful

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[1] Observatoire de Paris, LERMA, 61 Av. de l'Observatoire, F-75014, Paris

instrumentation artillery for hunting molecules. Hence the title of this paper, the meaning of which will become clear in the last section. Knowing this, the reader may either quantum-tunnel through the rest of this paper, or hold his/her curiosity and read on.

What follows is not an exhaustive review of instrumentation developments in submm-wave radioastronomy worldwide; nor at GEMO (LERMA's instrumentation group): it is a description and personal appreciation of a selection of GEMO's research and development (R&D) activities of which SC is the keystone. LERMA's developments using semiconductor technologies, and contributions to planetary exploration (the MIRO receiver on ROSETTA) or Earth and upper atmosphere remote-sensing studies using heterodyne radiometers, are presented by G. Beaudin and C. Prigent elsewhere in these proceedings. The particular standpoint of SC for presenting some of LERMA's developpements, however, has led me to put these in the wider context of applied superconductivity, in order to show their coherence, complementarity, and pertinence for current and future radioastronomy projects. Also, it had me reflect on 18 years of personal acquaintance with this field: over this period, applied SC has indeed brought tremendous progress to submm-wave (and now "Terahertz") heterodyne instrumentation for astronomy, and also increasingly for numerous new domains, hence fulfilling many of Encrenaz's intuitions and hopes from the "early days".

2 The Ecole Normale Superieure "radio" lab and superconductivity

When in the fall of 1987, I came to Pierre Encrenaz's Radioastronomy - dubbed "Radio" - group, in the Physics Laboratory of Ecole Normale Supérieure (ENS) in Paris, to start a Ph.D. thesis in astronomy, all the buzz in the prestigious institution's corridors and around expresso machines was for superconductors: Müller & Bednorz (1987, later B & M) were just being awarded the Physics Nobel Prize for having discovered the previous year a long-sought Grail: a promising new superconductivity in metal oxides occuring at critical temperatures above what seemed like an asymptotic limit with previous superconductors (the maximum had been $T_c \sim 20$ K with Nb-Ge alloys since 1970). The burden of cryogenic (LHe or below) operation had been a stalling drawback for most applications of superconductivity since its discovery in 1911, despite thriving experimental achievements in the 60's. Yet with this breakthrough of the high-T_c superconductors (HTCS) the future seemed to open up again to the wonderland of ohmic-free electronic transport and quantum properties, bound to revolutionize most fields of science and technology, e.g. power cables, electromagnets for accelerators and tokamaks, magnetically-levitating trains, SQUID medical imagery, "quantum-bit" computers, and highly sensitive photon and particle detectors. B & M's discovery of HTCS using metal oxides resulted from an intuition, and although the so-called BCS (for Bardeen-Cooper-Schrieffer) theoretical framework of 1957 was solid ground for the low-T_c superconductors, the mechanisms responsible for electron-crystal interactions and the SC phase transition in these new compounds were unclear. Renowned physicists who had contributed to the field in the 50's-60's and had somehow retired from it, came back to the battle's front. Nobody could ascertain that the dream of room-temperature SC would never become a reality. In 1987, hundreds of labs in the USA, Europe, Japan or China, were frantically trying to improve B & M's results, changing the cuprate recipes to raise the ultimate T_c. Within the sole year of 1986, the T_c had more than doubled ; in 1987, between january and february with the advent of YBCO, it doubled again!

In the trail of this excitement, the millimetric radioastronomy community was quick to realize the potential advantages from teaming up with a SC research community alive and kicking, that could manufacture high-quality novel sensors and key components for heterodyne receivers - such as superconducting tunnel ("SIS") junctions - using low-T_c materials, as well as provide privileged access to the hip, promising HTCS stuff.

Coherent microwave detection techniques amplify the signal before analyzing its spectral content, allowing very large spectral resolutions. In lab molecular spectroscopy as well as in radioastronomy, these techniques were doubtless heading to shorter and shorter submillimetric wavelengths, where most transitions between the rotational J levels of molecules lie. Certain hydrides and light molecules (e.g. radicals fundamental for the chemistry of the ISM), because of their large dipolar momentum, have their transitions in the submm. The large photon energy generally renders these molecules important through their radiative cooling. Some astrophysical sources such as dense inner cores or bipolar outflows, because of temperature, shocks, or other mechanisms, have their molecules populated in excited high-J states. Also, line strengths usually increase as f^2 or even f^3, making it attractive to study a molecule via its higher J transitions. Yet, to push coherent spectroscopy into the submm-wave range for all these good reasons, one needs to first down-convert the signal frequency to a range where it can be amplified with low-noise amplifiers. This is heterodyne detection; it is achieved by very-low noise mixers as the receiver's first stage, and local oscillators (LOs) to mix the submm-wave signal with. This is where superconducting devices enter the scene.

According to the phenomenologic "two-fluid" model (Ginzburg & Landau 1950), a superconductor below its T_c hosts two kinds of electrical charge carriers: "Cooper pairs" (electrons paired by phonon-mediated interactions and which follow a Bose-Einstein statistics) and "quasiparticles" (unpaired electrons and "holes"). In the early sixties, the discovery that SIS junctions were sensitive microwave detectors via photo-assisted tunneling of either Cooper pairs (Shapiro 1963) or quasiparticles (Dayem & Martin 1962; Tien & Gordon 1963), made them of the utmost interest for both direct detectors and heterodyne mixers in astronomy (Silver 1975; Shen 1981; Phillips & Dolan 1982). SIS "quasiparticle mixers" use the very sharp non-linearity of their dc current-voltage ($I-V$) curve, first observed by Nicol et al. (1960), at the gap voltage ($2\Delta/e$) above this voltage, quasiparticles have enough energy to overcome the superconductor's energy gap 2Δ. However, unlike "classical" diode mixers which act as voltage rectifiers, SIS mixers behave more like photodiodes, where one microwave photon absorbed causes one quasiparticle to tunnel. Much of the work of SIS mixer engineers deals with optimizing the coupling of microwave photons to the junction, so that they can be absorbed in the photo-assisted tunneling process. Extending previous work on noise in tunnel junctions (Rogovin & Scalapino 1974) to SIS mixers, Tucker (1979) developed a theory of quantum mixing in which the SIS junction is treated quantum mechanically and the microwave field, classically[1]. It predicted frequency-conversion *gain*, and mixer noise only limited by the zero-point quantum fluctuations of the rf field. Therefore, SIS mixers are expected to be more sensitive than Schottky-diode and other "classical" mixers by one order of magnitude or more, at least up to the frequency limit imposed by the SC material's energy gap ($2\Delta/e$ = 700 GHz for niobium[2]). Because of this quantum behaviour, SIS mixers also require

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[1] Wengler & Woody (1987) made a full-quantum mechanical treatment of SIS mixers, confirming the noise limitation $T > hf/k_B$ for SSB operation

[2] In fact, properly designed SIS mixers can be used up to $4\Delta/h$, that is 1.5 THz for Nb, if the tuning circuits use a material with low rf loss at these frequencies

much less LO power than Schottky mixers, typically microwatts rather than milliwatts. Simultaneously with Tucker's work, the first successful results with SIS mixers between 30 GHz and 100 GHz were being reported (Dolan, Phillips & Woody 1979, Richards et al. 1979; Rudner & Claeson 1979), and soon after, as high as 400 GHz (Sutton 1983; Wengler et al. 1985).

Other ways of using superconducting tunnel junctions as photon detectors and mm-wave mixers were proposed, however. One should mention the "super-Schottky" mixers, using a SIN junction - a tunnel barrier sandwiched by a SC and a normal metal (McColl et al. 1973). But these do not compare with SIS mixers, and SIN junctions are rather used as sensitive hot-electron microbolometers (Nahum & Martinis 1993). Several teams have also tried to exploit, rather than the non-linear resistance due to quasiparticles, the non-linearity of Cooper pair tunneling, this "supercurrent" flowing between two superconductors (Josephson 1962) with superfluid properties. In principle, both solutions can produce ultra low noise heterodyne systems. In the early 90's, Schoelkopf (1993) developed at Caltech a 100 GHz Josephson mixer with good performance and excellent stability. However, most developpements have focused on SIS mixers, which have made tremendous progress over the past two decades.

By the mid 80's, all major astrophysical research institutes with a mm-wave radioastronomy department started investing budgets, efforts and personnel into SC technology developments, either internally or by setting partnerships with university or private labs, to have quantum noise-limited SIS mixers on their telescopes (Blundell & Tong 1992; Phillips & Keene 1992). It is worth noting that the astronomy community indirectly benefited from the parallel developments of superconducting computers, with new reliable lithographic processes to make SIS junctions of very small size with high-quality $I-V$ curves (e.g. at Bell Labs or Stony Brook), using niobium technology.

There are several reasons why niobium is such a precious superconductor for making tunnel junctions. Refractory and very stable, with a T_c of 9.3 K allowing to make mixers up to about 1.5 THz, niobium gets rapidly coated with a layer of thermal oxide - explaining the well-known fact that it is impossible to solder directly on niobium wires. This allowed the easy making Nb/NbOx/PbIn junctions of high quality. Also, niobium is a type I superconductor, meaning that it repels efficiently any external magnetic field from its volume thanks to a thin shielding layer (London 1935), and that its superconducting phase (Ginzburg & Landau 1950) is quite extended, allowing easy tunneling across insulating barriers.

Nb/Al/AlOx/Nb tunnel junctions (Huggins & Gurvitch 1985) are fabricated after depositing on a quartz or silicon wafer a sandwich of niobium layers separated by a thin layer of aluminum with thermally-grown oxide. This multilayer is patterned into small-size "mesa" junctions by etching the Nb top layer. Before contacting the junctions with another (usually also niobium) top electrode, a layer of dielectric material (e.g. SiO_2) ensures electrical insulation from the base electrode. In the 90's, microwave engineers have made clever use of this stack of electrodes spaced by a dielectric, by turning it into a superconducting stripline-type rf circuit which could tune the junction at submillimetric frequencies, to optimize the SIS mixer sensitivity and bandwidth and to eventually get rid of mechanical tuners (see next chapters).

DEMIRM made a similar early effort to develop and manufacture SIS junctions in-house. P. Feautrier, during his Ph.D thesis, set up DEMIRM's clean-room at ENS and was rapidly able to make high-quality, $\sim 2\ \mu m^2$ size Nb/AlOx/Nb tunnel junctions (Feautrier et al. 1992). Being able to control from end to end - design-fabricate-test - the development of an heterodyne chain's key components, was Pierre Encrenaz's strong push, and proved to be a strategic decision (with long-term implications felt today). Throughout the 90's, all the teams worldwide that have contributed some progress in SIS technology (sensitivity and bandwidth improvement, incursion into the THz range, miniaturization, etc) could do so by heavily relying on well-equiped microtechnology facilities and SC experts (see reviews by Carlstrom & Zmuidzinas 1996; van de Stadt 1996). It is this ENS "radio" lab clean-room equipment which, moved to Paris Observatory in 1995 and somewhat upgraded since, has allowed to make the SIS junctions for PRONAOS-SMH (Beaudin et al. 1994), PIROG 8 (Febvre et al. 1997), and the LERMA devices discussed in the paragraphs below (Boussaha 2003).

The main goal behind setting up the ENS clean-room was to produce SIS junctions to equip mm-wave radiotelescopes like POM-2 at Plateau de Bures, and possibly more ambitious projects, such as the heterodyne instrument SMH being developed by Beaudin's team in Meudon Observatory for the CNES stratospheric balloon PRONAOS, to detect water and oxygen molecular lines in molecular clouds. Schottky-diode technology was still the baseline, but replacing it by SIS technology would decrease receiver noise ten-fold, an option worth the R&D study since this would multiply by 100 the expected spectra harvest of SMH. In the early 90's, the

SMH baseline was indeed switched to using SIS junctions. From the CNES standpoint, PRONAOS was an opportunity to develop and test technologies (dish, pointing, receivers) which might be relevant for the future submm-wave space missions. It was clear then that submm astronomy should sooner or later be lifted off the ground, especially as the frequencies of available heterodyne instruments would increase, due to atmospheric absorption making ground-based observations exceptional above 300 GHz and certainly impossible above 1 THz. Therefore, another buzz at ENS concerned exciting plans for submm-wave space observatories like NASA's Large Deployable Reflector (LDR) or Submillimeter Explorer, in which many european labs like DEMIRM wished to take part.

Superconducting tunnel junctions brought another promise for submm-wave heterodyne astronomy, which not only requires submm-wave mixers but also oscillators at submm-wave frequencies to drive them. Josephson junctions were long known to be sources of coherent radiation when voltage or current-biased (Yanson et al. 1965), and in the late 80's they were fashionable candidates for making novel millimeter-wave oscillators, potential LOs in heterodyne systems. Physicists were studying several kinds of junctions for this purpose: phase-locked arrays of small junctions (Wan et al. 1989; Benz & Burroughs 1991), or long junctions in which they could exploit the phenomenon of non-linear waves in the oxide layer such as traveling fluxons (Nagatsuma et al. 1983; Likharev 1986; Pedersen 1986). One attractive goal behind making Josephson-junction LOs was to combine them with SIS mixers, in single on-chip integated heterodyne receivers. This would save tremendously on weight, volume and power consumption (orders of magnitude) compared to more conventional approaches like Gunn oscillators with Schottky-diode frequency-multipliers and separate heterodyne chain components. In 1988 DEMIRM got involved in a european "ESPRIT" research network on the topic of solitons (or "fluxons") in long Josephson junctions. In the following years, specialists from Italy, Denmark, Germany, Sweden, Greece, Russia and France, regularly met and collaborated to investigate numerically and experimentally these devices (Monaco et al. 1988; Zhang & Wu 1990; Holst et al. 1990; Salerno et al. 1990; Fernandez et al. 1991).

Events that have unfolded since 1987 have shown Pierre Encrenaz's vision to be quite accurate. Applied superconductivity has indeed provided modern astronomy with powerful new tools, in particular to detect molecules in this part of the EM spectrum between the millimeter and the near infrared which remains largely unexplored. SIS receivers using Nb/Al/AlOx/Nb tunnel junctions did become the ultimate devices for detecting molecular lines in space up to 1.25 THz, and now equip all submm-wave observatories, from Mauna Kea to the South Pole, covering with unsurpassed sensitivity all atmospheric transmission windows up to nearly 1 THz; SIS receivers freshly installed on the Atacama Pathfinder Experiment (APEX) telescope in Chile, already provide scientific data[3] (Risacher et al. 2005); submm-wave SIS receivers have been flown on airplanes, with DLR's German Falcon (Mees et al. 1994) and soon with SOFIA (Edgar et al. 2000); on a stratospheric balloon with PIROG-8 (Febvre et al. 1997), a collaboration between LERMA and the Swedish Space Corporation; soon on the Japanese Experimental Module of the international space station with SMILES (Superconducting subMillimeter wave Limb Emission Sounder; Fuji et al. 2000); integrated superconducting receivers combining Josephson fluxon-based LOs and SIS mixers were successfully demonstrated (Koshelets & Shitov 2000) and will be used for the SRON-led balloon project TELIS; and twenty years after sketching on table napkins their wildest dreams of submm astronomy satellites, astronomers will witness the launch of Herschel Space Observatory (HSO), formerly FIRST, first ever satellite with cryogenic submm-wave heterodyne instruments and with the largest dish-antenna. It uses a battery of european-made SIS and hot-electron bolometers (HEB) receivers up to 1.6 THz, i.e. superconducting devices on the leading edge of technology, the performances of which contributed to reshape the international state-of-the-art. This list is far from being exhaustive, and to be fair one should add that superconducting sensors have made their way into IR, optical and high-energy astronomical instrumentation (and particle detection) as well. One can find an excellent review of superconducting detectors and mixers for submm astrophysics in Zmuidzinas & Richards (2004), and for other THz spectroscopy applications in Siegel (2002).

3 HIFI Band 1

When the Far-Infrared and Submillimeter Telescope (FIRST) became the fourth "cornerstone" of the European Space Agency (ESA)'s science program in the mid 90's (Ref. 1 1993; Pilbratt 1997), it felt like touching

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[3] In May 2005, the 275-370 GHz SIS receiver developed by V. Belitsky's group at GARD/Chalmers University enabled APEX's "first light" (press release from MPIfR, Sept. 25) with CO(J=3-2) spectra of various sources, and already allows to "do science"

the skin of a much spoken-about and long-chased mythological creature. The concept of the HIFI (ex-HET) instrument in particular, excited the radioastronomy community : it would cover most of the submm-wave spectrum from 480 GHz up to several THz (unfortunately the 7th channel centered at 2.5 THz, allowing to study HD and OH, was dropped since). Many molecules of interest for astronomy have their rotational lines in these bands where Earth's water vapor absorbs, and are therefore unobservable from ground, high-altitude sites, and hardly better from airborne facilities like SOFIA. One molecule of primary interest is of course water itself and its isotopes. Water is a key target for HIFI: it plays a major role in molecular clouds and prestellar cores as radiative coolant, and is a key player in the photochemistry of the ISM and the prebiotic chemistry on planets.

The strength of HIFI results from a combination of instrument features: a wide (4 GHz) bandwidth, speeding up spectral surveys, and required for planetary pressure-broadened lines and extragalactic work; a high spectral resolution (0.5-0.03 km/s with 1 MHz-channels wideband and 140 kHz high-resolution spectrometers); a high sensitivity due to the 3.5-meter collective area combined with cryogenically-cooled superconducting mixers of near quantum noise limited sensitivity. Enough to wait for HIFI like a new astronomical messiah. The FIRST *"Red Book"* (Ref. 1 1993) describing its mission was quite clear: HIFI would do about everything ! High-z and starburst galaxies, galactic nuclei, circumstellar enveloppes, molecular or diffuse clouds, comets, planets...you name it, HIFI will do it! (e.g. see Ref. 2, 2000)

So was claimed in astronomy colloquia and co-I's meetings. Some engineers turned green as they started to realize the technical implications of what was being promised to an eager science community, going wild. To meet the Red Book's scientific goals, HIFI receivers had to meet so-called "state-of-the-art" performance (SOAP) specifications which truly had not been achieved on ground-based observatories, at least not *all together*: near-quantum noise, broad rf and intermediate frequency (IF) bandwidths, with no mechanical tuner, operation range extended above 1 THz, small, lightweight, highly reliable and stable (Whyborn 1996; van de Stadt 1997). Needless to say, they also had to be space-qualified, which nobody could bet on for lack of experience in this matter. To make this even worse, there was little time, a mere couple of years between drawing-board brainstorming and the PDR (not "photo-dissociation region" but "preliminary design review"!) and demonstration model (DM) validation. Yet a large family of crucial, one-point-failure devices was to be specially developed: SIS mixers, HEB mixers, solid-state LOs, IF amplifiers and isolators, digital autocorrelator spectrometers (DACS), and much more. It seemed for a moment that HIFI's ambitious "SOAP" made the project... slippery!

Since the kickoff, a large international consortium has been working together to make HSO a reality. HIFI, with its 7 heterodyne bands, two polarized mixers each, numerous LOs with amplifiers and frequency-multipliers, is probably one of the most complex astronomical space instruments ever built. The highly "political" distribution of workpackages among countries and teams, was helped by the 3-year past experience of an ESA-contracted european R&D effort called STS. The aim of STS was to develop a 1.5 THz receiver using NbN-based SIS technology (Ref. 3 1998); it involved eight european teams specialized in SIS junction fabrication and receiver design (among which LERMA, IRAM, KOSMA, and SRON) and was managed by T. de Graauw - soon to be HIFI's PI. When the HIFI consortium was put together, there was among this network a fairly good knowledge of each other's technical capacities and forces.

LERMA has been in charge of realizing, in collaboration with IRAM, the two SIS mixers (one for each polarization) of HIFI's Band 1 instrument. Their range, 480 GHz-640 GHz, although fine for a Nb-based SIS mixer (Febvre et al. 1995) was a challenge due to the relative bandwidth of 30%, especially in view of the other key specified parameter, sensitivity. In the case of HIFI/Band 1, a double-sideband (DSB) receiver noise temperature better than three times the quantum-noise limit ($T_{rec,DSB} \sim 3hf/k_B$, at a frequency f) was imposed over the whole band.

Until the mid-90's, most SIS mixers used waveguide mounts with mechanical tuners, i.e. backshorts sliding in waveguides to optimize the rf impedance at each frequency (e.g. Ellison et al. 1987; Ogawa et al. 1990; Salez et al. 1994). The optimum impedance for the SIS mixer can be known from the Tucker theory of quantum mixing (Tucker & Feldman, 1985). Meanwhile, people also started to design tunerless waveguide mixers, where the tuning is done by an integrated superconductive rf circuit on the SIS junction chip itself, with no help from any sliding backshort (Winkler et al. 1991; Blundell et al. 1995; Kooi et al. 1995; Honingh et al. 1995). One possible way to increase the bandwidth in tunerless SIS mixers is to make the tunnel barrier thinner[4], or to replace aluminum oxide by aluminum nitride (Barber et al. 1995; Uzawa et al. 1995; Kawamura et al. 2000).

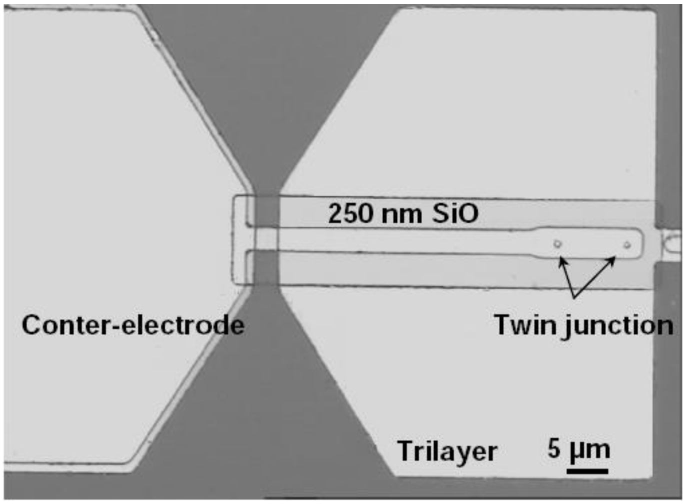

Fig. 1. Twin-junction SIS circuit made at LERMA. The 3 μm wide superconducting Nb/SiO/Nb stripline propagates the rf signal to the junctions from the bow tie antenna. The distance between junctions tunes the SIS mixer for the desired rf bandwidth. This approach was applied to HIFI/Band 1 and ALMA/Band 8

As it turned out, our simulations indicated that a twin-junction mixer with AlOx barriers might suffice to meet the HIFI/Band 1 specifications. Parallel-connected twin junctions as a way of rf tuning the SIS mixer had been proposed earlier by several authors (Belitsky & Tarazov, 1990; Zmuidzinas & LeDuc, 1992), yet on smaller rf bandwidths. Larger coupling bandwidths can be achieved with twin junctions than with single junction circuits, for the same current density. The HIFI/Band 1 rf circuits (see Fig. 1) were optimized using a commercial microwave circuit CAD software[5] in combination with a home-made program taking into account the physics of

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[4] see "multijunctions"

[5] Hewlett-Packard Libra, ADS: CAD software to design microwave circuits

superconductivity of the niobium, via its Meissner effect (Swihart 1961) and its frequency-dependent microwave losses (Mattis & Bardeen 1958). The commercial software allowed to undertake a statistical analysis of the simulation results ; hence we could optimize our circuits, rather than for absolute-best mixer performance, for mixer performance good enough (within specs!) *and* insensitive to design and fabrication parameter tolerances and fluctuations.

We built a submillimetric Fourier Transform Spectrometer (FTS), a very useful instrument to measure the bandwidths of SIS mixers in the lab (Hu et al. 1988). Characterized with this FTS, the very first batches made for HIFI/Band 1 at LERMA and IRAM with single and twin Nb/Al/AlOx/Nb junctions of 1 μm^2 and 10 kA/cm^2, proved right on target in terms of bandwidth, yet the mixer noise could be later improved (Salez et al. 2001). However, a twin-junction circuit with niobium electrodes behaves like a magnetic-field sensitive SQUID (superconductive quantum interference device). The Josephson current modulation by the field looks like the diffraction-pattern in a a two-slit Young experiment (Jacklevic et al. 1964). It is therefore more difficult to cancel parasitic Josephson effects in the SIS device by applying a magnetic field. Providing magnetic shielding to HIFI/Band 1 mixers with a niobium coating was even considered. We designed a small, integrated electromagnet (Fig. 2b), using a cryoperm[6] core concentrating the magnetic field lines efficiently at the junctions (Salez et al. 2002).

Whereas the fabrication of junctions at IRAM using a new process (Peron et al. 2000) was the baseline source of junctions for the qualification model (QM) and flight model (FM) mixers, a junction development was kept in parallel at LERMA (Boussaha 2003), giving the possibility to investigate new rf tuning circuits (see multijunction arrays), as well as providing a backup source for HIFI/Band 1 devices. The LERMA and IRAM fabrication processes, differed mainly by the dielectric material (SiO vs. SiO$_2$) and the junction patterning lithography, optical at LERMA and by e-beam at IRAM. The choice of e-beam insolation allowed to make highly reproducible micron-size junction areas, yet with a smaller number of devices per wafer.

Another critical issue for HIFI mixers was the required flatness (<2 dB ripple) over a 4-GHz wide IF output. Also, the imposed mechanical and

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[6] high-magnetic permeability material optimized for cryogenic temperatures; Vacuum Schmelze, Germany

electrical interface specifications required innovative solutions. Good new things often arise from challenging situations. For instance, we proposed to press a POGO (spring-bellow) connector onto the IF circuit stripline (Salez et al. 2000a), and to optimize the resulting stripline-coaxial transition by numerical simulations[7]. This technical choice not only works well, but it solves elegantly the problem of mechanical stress on coaxial connectors induced by temperature cycling and by the vibrations of an Ariane V launch. Our choice for orienting the SIS chip inside the waveguide (Fig. 2), totally unlike what was commonly done for waveguide tunerless SIS receivers so far (e.g. Kooi et al. 1994; Blundell et al. 1995), was also driven by the new, highly set mixer specifications. We thought that the mixer rf bandwidth would be more easily achieved if we matched the junctions to a frequency independent, purely real (resistive) impedance. We investigated the impedance of the waveguide mixer using extensive 3D EM simulations. The outcome of this study convinced us to drop conventional mixer mount geometries, and to go for an original solution (see Fig. 2b). The backshort is a simple flat cover, pressed by a springy CuBe fixture which secures the contact despite temperature changes (Salez et al. 2000a). Not only does this solution provide optimal rf coupling: it allows fast and reproducible mixer assemblies, requires no tricky coalignment of waveguides, and is highly reliable in view of space qualification.

Space qualification issues were integrated in the HIFI/Band 1 design from the start (Salez et al. 2002). Rather than focusing on optimum performance first, and then qualify-test the mixer and possibly modify its design to make it space-proof, we chose to focus on reliability and space constraints first, and leave room for mixer performance improvements as new, improved junction designs or batches would be available. For instance, years before the qualification models (QM), a demonstration model (DM) was vibrated at Institut d'Astrophysique Spatiale (IAS) to verify that the POGO contact (a critical choice since it would transmit the mixers output signal) would survive vibrations.

One DM mixer was delivered for early testing of the heterodyne and optical measurement benches at SRON-Groningen, and Chalmers University - in the GARD lab where it was extensively used to optimize the complex system built for characterizing beam patterns of the cold mixer sub-assemblies

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[7] CST-Microwave Studio: 3D EM simulations

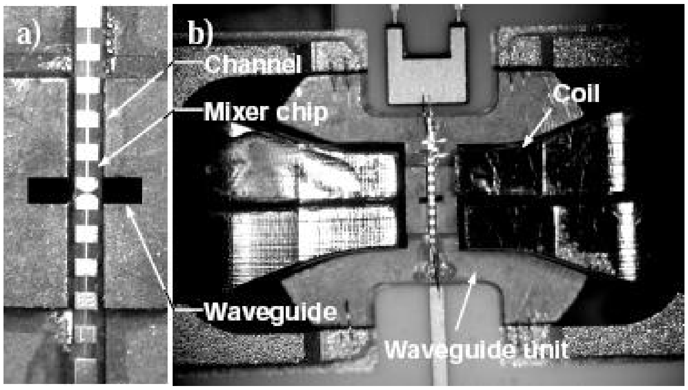

Fig. 2. Pictures of the heart of the HIFI/Band 1 mixer mount. (a) the reduced-height waveguide is 400 μm x 100 μm. The quartz substrate holding the junction circuit, bow-tie antenna and filters, is 110 μm wide and thinned to 50 μm to eliminate substrate modes. It is glued in the substrate channel perpendicular to the input waveguide, that is, the waveguide coming from the feedhorn. (b) zoom out showing the integrated heater (upper) and the IF microstrip circuit, both on alumina boards. The cryoperm core brings the field from a superconducting coil to the junctions. A metallic short (not seen here) closes the waveguide and substrate, between the polar pieces

(MSAs). Space qualification was done on QM mixers in various places : in the Netherlands for EMC/ESD and cold vibration tests, IAS and LERMA for hot and cold thermal cycling, CNRS-Orléans for junction irradiation at room temperature by high energy protons (Peron et al. 2002).

The flight models (FM) have been delivered to SRON in 2005 (Fig. 3). Their performances are better than the initial Band 1 specifications. Figure 4 shows the mixer rf response measured by FTS, quite larger than the targetted 480-640 GHz. Figure 5 shows the DSB receiver noise temperature versus frequency, measured at 2 K, corrected for the rf losses in the diplexer and test-cryostat's front optics, which contribute a large amount of the total receiver noise at these frequencies, with such low-noise mixers. Mixer noise is also significantly improved when measured at 2 K - the physical temperature the mixers will be at in the HSO satellite - relative to 4.2 K measurements, due to a decreased population of quasiparticles (two-fluid

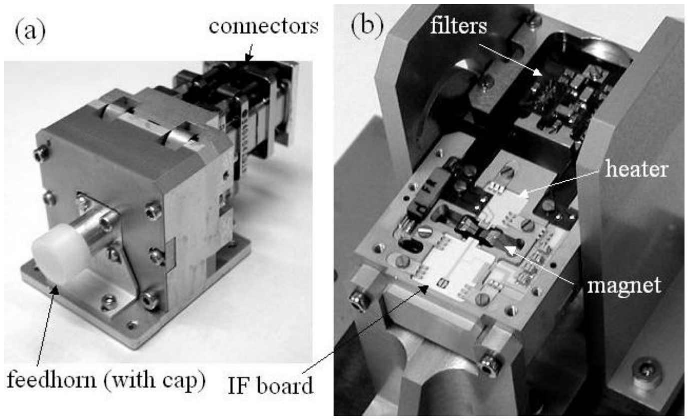

Fig. 3. The HIFI/Band 1 mixer mount (a) closed, with a cap protecting the feedhorn, and connector savers at the rear; (b) open, in a specially designed assembly tool. The upper part contains filters for the dc leads, and is connected to the lower part (hosting the junction, the feedhorn, the IF board) via a wiring printed on kapton-flex foil. To change the frequency band of a mixer, only the inner part (waveguide and SIS chip) needs be changed

model, Ginzburg & Landau 1950).

Each delivered mixer must be extensively characterized and have its "identity card" provided: dc $I-V$ curve, heterodyne mixing performance over the whole band, for various LO powers and bias voltages; dependence of the mixer's dc Josephson current on magnetic field (SQUID-like pattern for twin junctions). The integrated "deflux" heater which can be seen in Fig. 3b allows to warm up the junctions above T_c within a few seconds, in case of trapped flux. Figure 6 shows the receiver's "baseline" measured in the lab, that is, the IF output power and mixer noise across the entire 4-8 GHz IF band.

A mixer prototype covering the ALMA Band 8 channel (380-500 GHz) was built using the same technology as HIFI Band 1, with junctions made at LERMA (Boussaha et al. 2005). In fact, our tunerless waveguide mount design allows to change the mixer rf bandwidth very easily by simply swapping the feedhorn-waveguide pieces which also contain the junction chips. Everything else may remain the same. Preliminary measurement of T_{rec}

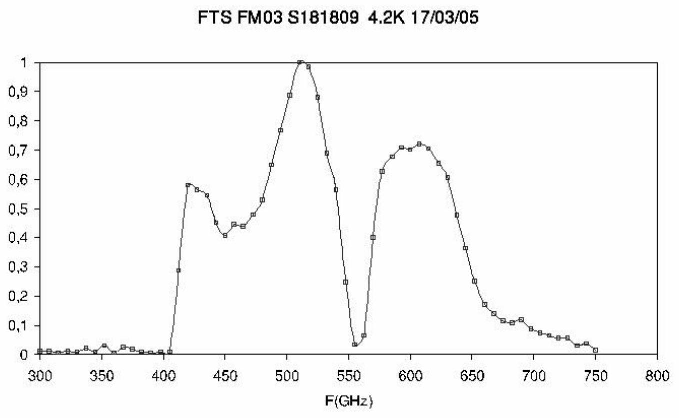

Fig. 4. RF coupling bandwidth of one HIFI/Band 1 flight-model mixer, measured at LERMA by Fourier transform spectrometry (FTS). Clearly visible when the FTS system is not air-evacuated, the absorption line corresponds to the H_2O 557 GHz transition, important for the science objectives of Band 1

DSB, measured in a 4-GHz band, is given in Fig. 7. Although it obviously leaves room for improvement, this result is close to meeting the specs for ALMA band 8. Work is in progress to extend the IF bandwidth to 8 GHz. A report from the asian[8] team working on this band can be found in Shan et al. (2006).

4 Multijunction arrays

The main performance limitation of SIS mixers at submm-wave frequencies comes from the junction's large *RC* product, and therefore various methods have been used to "tune out" the junction's large tunnel barrier capacitance *C* by using integrated rf circuits manufactured at the same time as the junction (Räisänen et al. 1985; Kerr et al. 1992; Kooi et al. 1994; Salez et al. 1994; Blundell et al. 1995; Noguchi et al. 1995).

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[8] a collaboration between Nobeyama Radio Observatory in Japan and Purple Mountain Observatory in China

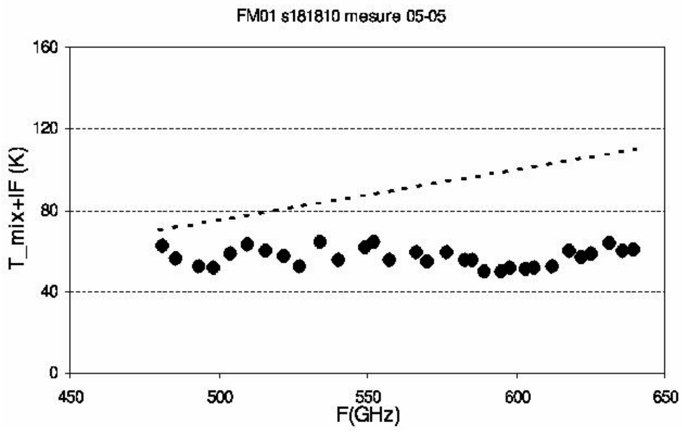

Fig. 5. Double-sideband mixer noise temperature of one HIFI/Band 1 flight model cooled at 2 K, from 480 GHz to 640 GHz, measured at LERMA by the hot-cold load calibration technique, over a 4-GHz wide IF bandwidth. The plotted mixer noise includes the noise contributed by the 4-8 GHz IF amplifier, but excludes the noise added by losses in the coupling optics (diplexer, cryostat window, filters) which shows up in receiver calibrations but will be completely different for the HIFI sub-assembly. The dashed line indicates the 3-photon noise limit, setting HIFI's noise specifications for this band.

As said earlier, going to higher current density is one way to reduce the junction's RC and increase the bandwidth of a SIS mixer, due to a fundamental limit set by resistive mixer theory (Fano 1950; Kerr 1995). However, Nb/AlOx/Nb tunnel junctions at 10 kA/cm^2 are already pretty thin, with barrier thicknesses approaching the atomic scale! Beyond that, inhomogeneities in the barrier and shorting nanobridges rapidly devastate the $I-V$ curve quality and the SIS mixer performance[9]. Hence the quest

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[9] Physicists are pityless: even as the poor tunnel barrier collapsed and mixer performance screamed "halt", they kept kranking up the current density in Nb/AlOx/Nb juntions and could observe new, second-order quasiparticle tunneling processes which show up in the $I-V$ curves as subharmonic energy gap structures (Kleinsasser et al. 1994). These multiple Andreev reflections (MAR) were first studied and observed in superconducting weak links by Klapwijk et al. (1982). These MARs explain beautifully

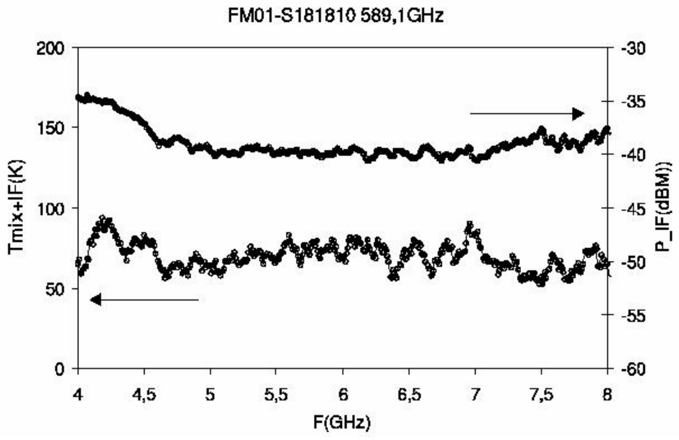

Fig. 6. IF output power and mixer noise, of HIFI/Band 1 FM mixer at 2K, measured at 589 GHz across the IF band from 4 to 8 GHz. The specification on gain fluctuations was < 2 dB

for lower RC barrier materials (AlN) or smarter tuning ways.

In the mid-90's, the Nobeyama group proposed a novel way to tune SIS mixers (Shi et al. 1998). By making an array of parallel-connected SIS junctions, the bandwidth limit imposed by RC could be circumvented. Multijunction arrays extend the concept of using junctions themselves to provide the rf tuning (Belitsky & Tarazov 1990; Zmuidzinas & LeDuc 1994), one step farther. In a twin-junction mixer, the small stripline between the junctions provides the right inductance. As seen above, this is the solution which was retained for HIFI/Band 1. A "cousin" approach for designing self-tuned SIS mixers, declined in two variations, was proposed by Tong et al. (1995) and Belitsky & Kollberg (1996), using a long SIS tunnel junction (i.e. of size comparable to the rf wavelength) as a non-linear transmission line, in which quasiparticle mixing is distributed along the device and tuning

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the "excess shot noise" in SIS mixers, a discrepancy between theory and experiments which for a long time remained unexplained (Dieleman & Klapwijk 1998). They are also more prominent in $I-V$ curves of NbN/MgO/NbN junctions, explaining why NbN-based mixers have always been noisier than their Nb-based counterparts

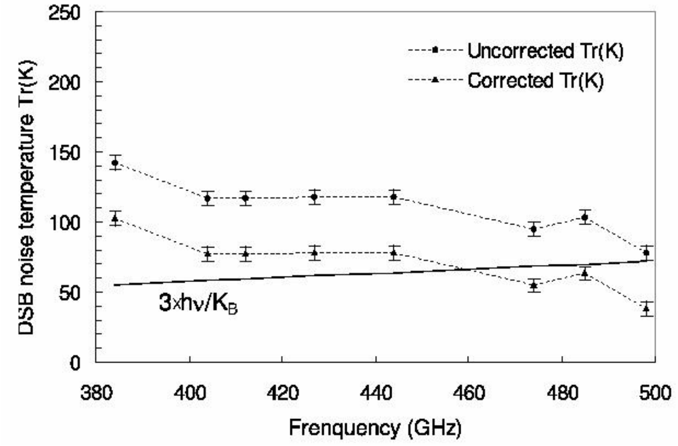

Fig. 7. DSB noise temperature at 4.2 K of a tunerless mixer made for ALMA Band 8, using the same design and technology as HIFI/Band 1 and twin Nb/AlOx/Nb junctions made at LERMA. The corrected curve corresponds to the noise of the mixer plus 4-8 GHz IF chain

is provided by the junction inductance.

The development of multijunctions at LERMA started at the beginning of the HIFI project. Then the sensitivity-bandwidth specs were a real challenge. We pursued the array-mixer development alongside our baseline solution, as both a technological (fabrication at LERMA) and design (should the twin-junction solution fail) backup.

In the first publications by the Nobeyama group, simulations and experimental results showed an unusually wide bandwidth, but also unwanted large oscillations on the resulting mixer's gain and noise temperature (Shi et al. 1997). To solve this drawback we proposed non-uniformly distributed arrays (Fig. 8): by placing the N junctions in the stripline according to an optimized pattern, we could customize the rf tuning bandwidth in a similar way as a multipole bandpass filter's frequency response can be made to fit the desired bandwidth and ripple, by adjusting its poles (Salez et al. 2000b). A similar approach has also been used by the Japanese group since (Takeda & Noguchi 2002), to make wideband mixers but also direct detectors (Ariyoshi et al. 2002). A submm-wave camera using non-uniform

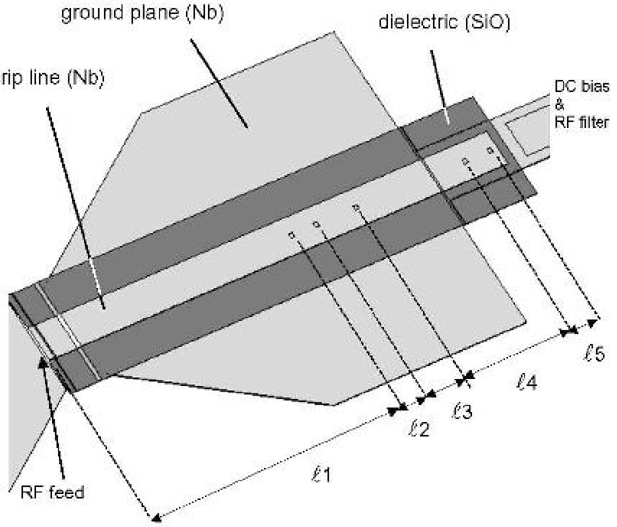

Fig. 8. A non-uniform parallel array with 5 junctions, made at LERMA. The stripline is Nb/SiO/Nb. The junctions are 1 μm^2 in size, and their distribution optimized for a wideband rf coupling and low mixer noise around 400-700 GHz

SIS array detectors has been developed in recent years for the Atacama Submillimeter Telescope Experiment (ASTE) in Chile.

SIS array mixers required to develop new simulation tools, in particular a numerical model to compute mixer performance based on Tucker theory and taking into account N junctions distributed along a microstrip line (Salez et al. 2000b). The whole circuit must be considered to compute the impedance provided at any LO frequency. We have used a harmonic balance method (Withington & Kollberg 1989) in the three-frequency approximation (signal, LO, IF) but also in the five-frequency approximation, that is, taking into account the first LO harmonics (Chung & Salez 1999). We adapted the model developed by Tong et al. (1997) for analyzing the long SIS junction mixers mentioned above.

We used our numerical code to simulate stripline circuits loaded with any numbers of tunnel junctions, with any distribution. Because non-uniform arrays have many degrees of freedom and an infinite number of possible choices for their design, we used the optimization routine of HP Libra to select the correct geometries. More exactly, since HP Libra deals only with normal metal circuits and not superconductive ones, its outputs were the sets of impedances and electrical lengths providing the right tuning. These were then converted into actual physical parameters and dimensions using a home-made program. The latter is the the same program used for optimizing the HIFI Band 1 junctions, taking into account superconductivity in the niobium, rf losses in the stripline, and fringing field effects. By using the same softwares and design philosophy for the twin- and multi-junctions, we ensured a coherent development and backup strategy.

In the course of this study, simulations of heterodyne performances showed that certain array geometries could provide, at some frequencies, sideband rejection ratios larger than 10 dB. The possibility to exploit this property in view of integrated single-sideband (SSB) mixers should be considered. The image band rejection in SSB mixers is usually achieved either by quasioptical filtering or by integrated circuits doing the chore. The latter was done by Kerr & Pan (1996) at NRAO on millimeter-wave SIS mixers, but is harder at high submm-wave frequencies. The mixers for ALMA are required to be SSB mixers, which renders their design and fabrication more complex, requiring micromachined waveguide hybrid couplers (for example Vassilev et al. 2000; Lazareff et al. 2002; Risacher et al. 2005). The junctions distribution can be used for new integrated sideband rejection circuits. It also has an influence on the array mixer's IF output impedance was also investigated by simulations : it is an important issue from the perspective of very wideband IF receivers required for planetology or uncertain-redshift extragalactic work (4 GHz for HIFI, 8 GHz for ALMA, and still more GHz in future projects).

An obvious application of multijunction array mixers is superconducting integrated receivers (SIR) - a topic discussed more later. Flux-flow based oscillators are tunable over very wide ranges, and so far the operating bandwidth of SIRs has been limited by the mixing junctions. By employing very wideband multijunction mixers, the potential of SIRs as wideband spectral scanning devices (instead of batteries of adjacent bulky receivers for the same purpose, as in HIFI and ALMA) becomes very attractive. Another unexpected (well, not quite!) property of multijunction arrays makes them hot for SIRs. This will be explained later.

Several batches of junction arrays have been processed at Observatoire de Paris, as part of F. Boussaha's Ph.D. thesis. Particular care was taken to achieve reproducible results and high yields with small (1 μm^2) Nb/AlOx/Nb junctions of high current density (10 kA/cm^2). Since this development was a possible last-minute backup for HIFI, space qualification tests were done of these arrays, such as bake-out, temperature cycles, ESD. Several non-uniform arrays of 5 junctions optimized for 450-650 GHz and beyond, were tested in FTS and heterodyne measurements, showing a good though not fully understood behaviour. These results can be found in Boussaha et al. (2003), and more work is being done.

It is important, in particular, to understand the Josephson effect in these circuits, both statically (dc) and dynamically (ac). LO-induced "Shapiro" steps generate excess noise and instabilities in a SIS mixer, when they are in the vicinity of the optimum bias voltage (Winkler & Claeson 1987, Leridon 1997). Also, the possibility of having "fluxons" (see next section) was anticipated, as a potential source of rf noise. The average supercurrent is what we see on $I - V$ curves. Quenching it by an applied magnetic field may not only be difficult in arrays, but irrelevant should such fluxons propagate.

Figure 9 shows the zero-voltage current I versus magnetic field H of one 5-junction array. This curve is clearly the signature of a SQUIG (G for "grating") i.e. a parallel array of SQUIDs. Feynman et al. (1965) predicted that such SQUIGs could be useful as sensitive magnetometers. Yet our data reflect for the first time a non-uniform junction distribution : so far all SQUIGs reported in the literature (Miller et al. 1991) have dealt with periodical arrays, with qualitatively different curves. The measured $I - H$ curves are all very well fitted by numerical simulations of our circuits using an original model developed by Caputo & Loukitch (2006), and this will be published soon (Salez et al. 2006a). The nature of the curves means that an external magnetic field enters the array as flux quanta, i.e. fluxons. This is important to acknowledge and control for mixer noise issues, but also for using multijunction arrays in other applications, in magnetometry[10], RSFQ electronics, submm-wave direct detection, or as a new type of submm-wave oscillators as we shall see.

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[10] SQIFs (superconducting quantum interference filters) developed these past few years for ultrasensitive magnetometry are indeed very close to the circuits described here, and make use of their peculiar $I - H$ curves

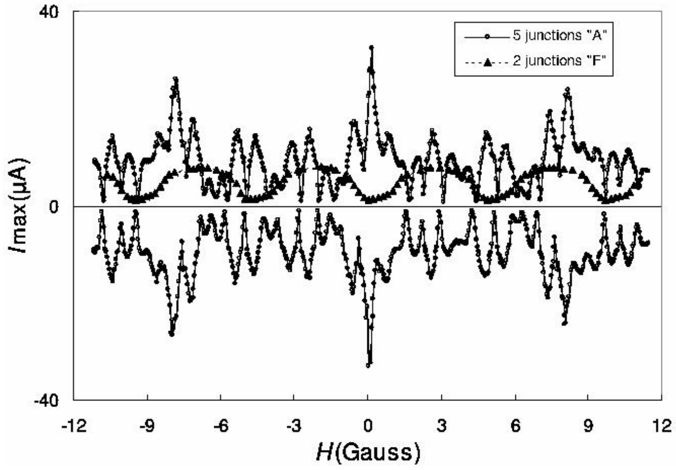

Fig. 9. Zero-voltage current measured in the dc $I - V$ curves of a 5-junction non-uniform array and of 2-junction circuit, with the same materials and from the same batch, as a function of an applied magnetic field. The array displays a peculiar interference pattern, reminding of periodic arrays or discrete Josephson transmission lines, yet more complex, which is perfectly fitted by numerical simulations (Salez et al. 2006b). Used as calibrator, the same measurement for the 2-junction circuit shows a canonical "SQUID" pattern

5 Superconducting integrated receivers

5.1 Long junction oscillators

Today, nearly all SIS receivers on telescopes use mm-wave Gunn sources with cascaded Schottky-diode frequency-multipliers as LOs (Räisänen 1992). This solution has made tremendous progress recently (Chattopadhyay et al. 2004), by the use of substrate-less planar Schottky-varactor diodes, and MMIC (Microwave Monolithic Integrated Circuits) amplifying the signal at their input. Still, producing enough LO power to pump SIS or HEB mixers near or above 1 THz, and in the not-too distant future, 2D arrays of numerous mixers in the submm (Rabanus et al. 2002), remains today a challenge. The difficulty increases as receiver frequency goes up, and for wide-bandwidth tunerless instruments.

Other LOs usable to drive submm-wave heterodyne systems, such as backward-wave oscillators, carcinotrons, CO_2-pumped far-infrared gas lasers, resonant-tunnelling diodes (Brown et al. 1991), or laser-diode frequency down-conversion by photomixing with low-temperature-GaAs photoconductors (Brown et al. 1995), are either too bulky and power-consuming, or not mature enough at this time to credibly postulate for practical heterodyne operation in most projects, especially future space missions. A possible exception may be quantum-cascade lasers, which, despite a narrow range of tunability, progress rapidly and were recently demonstrated on an astronomical receiver (Gao et al. 2005).

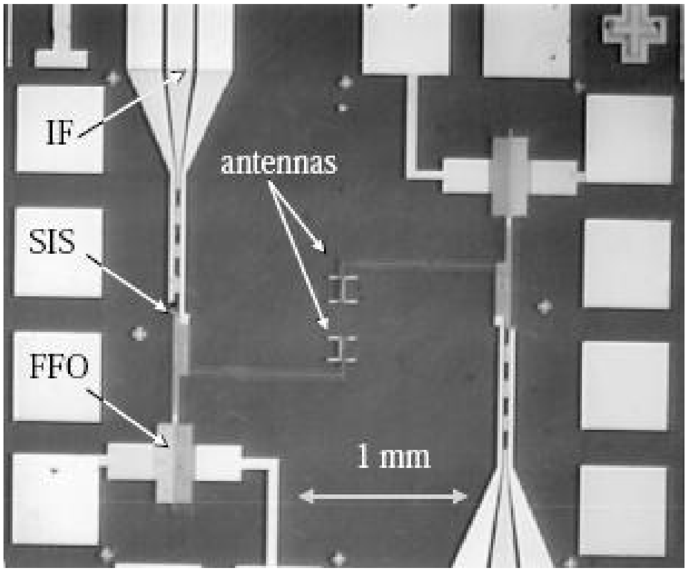

Fig. 10. Two superconducting integrated receivers (SIR) on the same 4 mm x 4 mm quartz chip (Chung 2000). Each SIR contains a double-dipole antenna, a SIS twin-junction mixer, a long-Josephson line FFO oscillator, and an IF coplanar output line. The rf signal is diplexed with the LO radiation and coupled to the mixer via a hybrid coupler.

A very promising alternative mentioned in the introduction is the Superconducting Integrated Receiver (SIR) (Koshelets & Shitov 2000). Both the mixer and the LO use low-T_c SC technology and are fabricated on the same chip - typically a few square-millimeters in size - along with passive receiver components: printed submm-wave antenna, integrated rf tuning, filters and transmission lines. Figure 10 shows a SIR (in fact, two SIRs side by side to study "crosstalk" interferences) designed and fabricated at LERMA (Chung 2000). In a near future, engineers will push this integration even further by including cryogenic first-stage amplifiers - as has been done already with a regular SIS and HEMT (Padin et al. 1995) or SQUID amplifier (Tarasov et al. 1991) - early digitization and processing of the IF signal, including autocorrelation. Several of these integrated functions could make massive use of rapid single-flux quantum (RSFQ) digital electronics (Likharev & Semenov 1991; Koshelets et al. 1991) and other volume- and power-saving superconducting technology.

In this all-superconductive receiver solution, foreseen early by some (Silver 1975), the LO makes use of the ac tunneling supercurrent (borne by Cooper pairs). This so-called "ac Josephson effect" (Josephson 1962) exists in any superconducting tunnel junction, and can be used for microwave detection (Shapiro 1963) and for microwave generation: the latter was first experimentally observed indirectly by Giaever (1965) and directly by Yanson et al. (1965). In SIS quasiparticle mixers, the ac Josephson effect becomes a parasitic, strongly non-linear response to microwave radiation that engineers have to get rid off (see HIFI).

For Josephson physicists, this non-linear tunneling is however a blessing. The second Josephson equation tells that ac Josephson currents in a junction biased at a voltage V, oscillate at $2eV/h = 484$ GHz per mV. This relation arising from quantum mechanics is so accurate that it is used in metrology, for dc and ac voltage standards (Niemeyer 2000). Therefore, an all-Nb junction (with a gap voltage of 2.8 mV) can in principle produce microwave photons up to $4\Delta/h \sim 1.5$ THz, with very small dc power input (microwatts) and very large oscillator efficiency.

People have attempted to make microwave oscillators using various types of junctions, for example arrays of small [11] (Wan et al. 1989; Bi et al. 1993; Benz et al. 1992; Kawakami & Wang 1998) or long Josephson junctions (LJJs). A junction is dubbed "long" when one of its dimensions is larger

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[11] Oscillators based on phase-locked arrays - and Josephson mixers - generally use resistively shunted Josephson junctions. The junctions are then non-hysteretic and described by a so-called "RSJ" model

than the Josephson length λ_J, a penetration depth for magnetic fields in the tunnel barrier (Lehwohl & Stephen 1967), and also the size of supercurrent vortices which can enter the junction or be nucleated thermally. Each vortex imprisons exactly one quantum, $\Phi_o = h/2e$, of magnetic flux in the tunnel barrier's plane, hence the name "fluxon". Their first mention in theoretical and experimental papers goes back to the early 70's (Chen et al. 1971; Fulton & Dynes 1973). Fluxons can equivalently be viewed as polarized, charged particles, or as soliton waves in the supercurrent; their electrodynamics is well described by perturbation theory (McLaughlin & Scott 1978; Kivshar & Malomed 1989), or by solving a sine-Gordon equation describing in the time-domain the evolution of the superconducting phase difference anywhere along the junction (Pedersen 1986; Likharev 1986; Ustinov 1998), in good agreement with experiments (Dueholm et al. 1981). Unlike small junctions, LJJs do not rely on a voltage bias to emit the radiation, but on the longitudinal travel time of fluxons. With typical values of λ_J and light velocity in tunnel barriers, the radiation frequency of fluxon-based oscillators easily falls in the submm. From the 80's on, there have been various attempts at making submm-wave oscillators based on LJJs, either in the resonant mode or in the unidirectional "flux-flow" mode.

The interest for Josephson LOs at LERMA goes back to the days of the ESPRIT european network on fluxon electrodynamics in LJJs. Then, most researchers in Europe (mostly Denmark and Italy) were focusing their studies on the resonant-mode (Monaco et al. 1988; Holst et al. 1990; Salerno et al. 1990; Fernandez et al. 1991; Gronbech-Jensen et al. 1992; Ustinov et al. 1993), where fluxons travel back and forth and sustain non-linear cavity modes in the LJJ. Yet these oscillators have several drawbacks: lack of tunability, small output coupling, criticality of the geometrical and process tolerances.

The flux-flow mode, proposed early by Nagatsuma et al. (1983), is more suited to high coupling efficiency and widely tunable oscillators. In flux-flow oscillators (FFOs), both frequency and output power can be continuously adjusted via the bias current and the magnetic field. Nagatsuma et al. demonstrated the FFO radiation by direct detection in a small junction. Dag Winkler and Y-M. Zhang at Chalmers were the first to measure the radiation linewidth from a FFO around 300 GHz by mixing two of them, and used a SIS mixer to measure the output power (Zhang et al. 1993). Within a few years, much progress was made by the team led by Valery Koshelets of IREE-Moscow in collaboration with SRON-Groningen

(Koshelets et al. 1994; 1999), in its attempt at building fully functional superconducting receivers between 200 and 600 GHz, with Nb/AlOx/Nb barriers. The technology is still complex, but mature enough to do science: it was demonstrated that a FFO can be phase-locked and has a very narrow linewidth (Koshelets et al. 2002); that the sensitivity of a SIR using a FFO competes with that of a conventional SIS receiver with a conventional LO; one instrument on the TELIS balloon will be a SIR at 630 GHz to study atmospheric ClO and HCl by limb-sounding. One can capture from Baryshev (2005) a good overview of the state of the start of this technology. Its potential developments and applications will be discussed later.

Let us also mention here that Japanese teams have recently proposed to use a fluxon motion in hight-T_c superconductors (see section 7) similar to flux-flow modes in low-T_c LJJs to generate continuous THz radiation (Tachiki et al. 2005; Bae & Lee 2006).

Figure 10 shows one typical SIR chip designed by M.H. Chung for his Ph.D. thesis at LERMA (Chung 2000) and processed by F. Boussaha in 2005. It uses a double-dipole antenna and a twin-junction mixer designed for 400-440 GHz. The dc characterization of these chips show the good quality of the LJJ FFO and the twin-junction SIS mixer. The next steps are the FTS validation of the receiver bandwidth, and the heterodyne characterization, with an external LO and with the integrated FFO. Already, the $I-V$ curve of the FFO displays the typical branches of flux-flow motion (see Fig. 11), unseen in other types of single junctions, LJJs or arrays that we have manufactured so far. Confirming the flux flow radiation, the SIS mixer could be pumped by the FFO at 430 GHz.

5.2 Junction array oscillators

As soon as we started at LERMA investigating parallel SIS junction arrays for wideband mixing (see previous section), we anticipated that these multijunction devices could also be interesting for submm-wave signal generation. This expectation came from the fact that, as said above, a 1D SIS junction array is not different from a SQUIG (parallel array of SQUIDs) or DJTL (digitized Josephson transmission line) studied in physics for their Josephson properties and applications in magnetometry, phase-mode logic, RSFQ applications. This was verified by our static measurement of Fig. 9.

From the standpoint of their equivalent circuit, a DJTL is fundamentally indistinguishable from a continuous LJJ (Peyrard & Kruskal 1984; Naka-

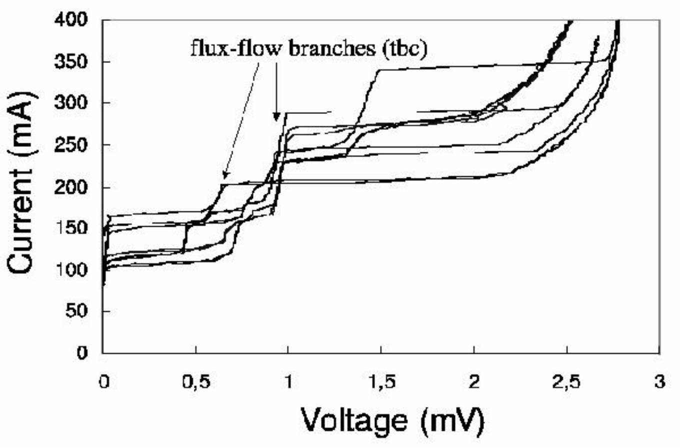

Fig. 11. $I-V$ curve of a LJJ-based FFO measured at 4.2 K at LERMA, showing typical flux-flow branches, indicating microwave radiation by traveling fluxons. FFO radiation frequency is adjusted by controlling the current and the magnetic field. 1 mV corresponds to 484 GHz.

jima et al. 1990)[12] , save for the fact that the circuit elements are either lumped or continuously distributed. Both devices are described by the same mathematics, a sine-Gordon equation with driving and dissipation terms. Therefore Josephson junction arrays should host the same fluxons, at rest or in motion, as LJJs (van der Zant et al. 1993). Fluxon propagation is the basic principle of RSFQ devices, using other types of Josephson junction arrays (Hohenwarter et al. 1989; Likharev & Semenov 1991).

However, DJTLs have been far less studied than LJJs for their potential as microwave oscillators, experimentally and theoretically (Ustinov et al. 1993; Duwell et al. 1997; Ustinov et al. 1998). Constant-voltage steps were reported in the $I-V$ curves of DJTLs containing typically 10 to 20 junctions

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[12] ... or from the distributed SIS quasiparticle mixer (Tong et al. 1995). But there Josephson currents are neglected. The SIS community looks at the Josephson effect as parasitics to eradicate; the Josephson community looks at quasiparticle tunneling as a dissipation mechanism, a mere loss term in the Josephson electrodynamics! For years, it was difficult to have these two sit at the same table...

by several authors (van der Zant et al. 1993; van der Zant et al. 1994; Ustinov et al. 1995), but their attribution to either fluxon resonances ("zero-field steps") or linear cavity resonances (Fiske 1963) remains ambiguous.

One parameter of much importance in discrete 1D arrays, is the so-called "discreteness" parameter Λ_J. It measures the ratio of Josephson potential energy in a junction to the magnetic energy stored in a cell between two junctions; it also determines whether fluxons are pinned at junction sites because of an energy barrier, or free to propagate (van der Zant et al. 1993). For $\Lambda_J < 1$, fluxons are well localized in the array and need energy to hop from cell to cell, which is perfect for RSFQ applications. For $\Lambda_J > 1$, array fluxons behave almost like in the continuous LJJ case, and can propagate smoothly. Exotic phenomena, however, are expected in 1D arrays which do not occur in LJJs, like "superfluxons" (big jumps of the superconducting phase difference amounting to $nh/2e$), propagation cutoff when the wavelength becomes smaller than the array lattice (Ustinov et al. 1993), small-amplitude oscillations ("phonons")[13] radiated by moving fluxons (Currie et al. 1977); fluxon-bunching (Barbara et al. 1996; Ustinov et al. 1998). Our case is very particular, however, because non-uniformely distributed SIS arrays do not have a unique lattice parameter. No theoretical framework exists to analyse fluxons in non-periodic DJTLs yet. Experiment-wise, this is also entirely new.

Figure 12 shows the $I - V$ curve measured at 4.2. K of a 5-junction non-uniform array. Three resonant steps looking strikingly and behaving like zero-field steps (ZFS) typical of resonant fluxons in LJJs (Chen et al. 1971; Pedersen 1986), are seen at reproducible voltages in the absence of a magnetic field (Boussaha et al. 2005; Salez et al. 2006). We explain these steps as respectively $n = 1$, 2 and 3 fluxons traveling one way and synchronized with the array cavity natural frequency: the maximum number of observed steps ($n = 4$) is also consistent with this model. Fluxon oscillations at such high submm-wave frequencies ($n = 3$ corresponds to $>$ 600 GHz) is new, and good news. This is only possible because the average of the discreteness parameter LJ in our arrays is slightly larger than unity. These results are being published elsewhere (Salez et al. 2006).

One can play with the stripline design and with the number, current den-

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[13] analog of Cherenkov radiation. This radiation of fluxons moving in the discrete array is a source of energy dissipation, and also induces the bunching of fluxons. This does not happen in a long junction

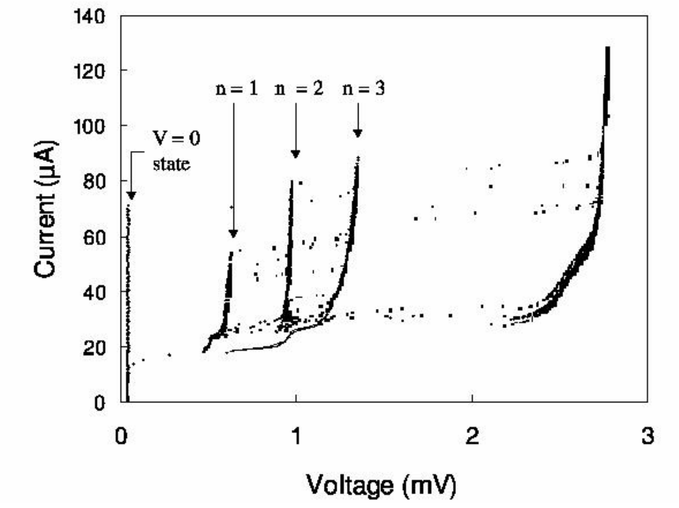

Fig. 12. $I - V$ curve at 4.2 K of a non-uniform 5-junction array. Three constant-voltage steps (and up to 4 in certain devices) are seen, which remind of and behave like the so-called "zero-field steps" seen in long Josephson junctions. These resonances are observed for the first time in non-uniform arrays, and might correspond to "Fiske" oscillation modes, where fluxons travel one way, synchronized by the stripline resonant cavity (Salez et al. 2006)

sity and size of junctions, to adjust the array's parameters. In particular its quasiparticle losses and electrode surface losses - the normalized parameters α and β found in sine-Gordon equations - must be well controlled. It was shown that they jointly determine the oscillator mode (resonant vs. flux-flow) (Zhang 1993; Zhang & Wu 1990).

Interestingly, submm-wave oscillators based on arrays of Josephson junctions connected by superconducting striplines already exist (Kawakami & Wang 1998). But here the junctions are resistively shunted, weakly coupled to the striplines; such an array operates as a sum of phase-locked lumped Josephson oscillators, with little tunability, not at all as a non-linear Josephson transmission line.

We believe that multijunction-based FFOs will offer advantages over LJJ-based FFOs on at least three things. First, the speed of light and therefore the fluxons velocities are much higher in discrete arrays than in continuous LJJs. Array-based oscillators will potentially generate more available power at the same frequency, for lower junction current densities.

Second, let us recall that the non-uniform junction distribution was determined to optimally match the SIS-array mixer over a broad rf bandwidth, somewhat like a passband filter: therefore by symmetry, this distribution is also optimized for output coupling over this bandwidth, if the array can be used as an emitter. This solves the long-standing difficulty of impedance-matching the ultra-small impedance (<1 ohm) LJJ oscillators to SIS mixers (Erné & Parmentier 1981; Pagano et al. 1991). The ease with which a 5-junction array could be phase-locked to an external LO source at 600 GHz on the $n = 3$ step reinforces this hypothesis (Salez et al. 2006b).

Third, rf design of FFOs would be more flexible because stripline design parameters and junction design parameters are disentangled, allowing for instance, to separately adjust the α and β loss parameters which together dictate the oscillating mode. This would allow, for instance, to raise FFO's frequencies above 700 GHz with Nb/AlOx/Nb tunnel junctions, by using stripline electrodes made out of a higher-T_c superconductor (NbN, NbCN or NbTiN) - in a similar way as SIS mixers are designed for frequencies up to 1.5 THz with all-Nb junctions and higher-T_c tuning circuits (Kooi et al. 1998; Jackson 2005).

6 Perspectives for superconducting heterodyne receivers

The advantages of SIRs over classical receivers are numerous, particularly for space-based instruments: (a) much smaller size and weight; (b) LO's higher efficiency and lower power consumption (compared to most other submm-wave LO technologies); (c) possibility to squeeze many heterodyne pixels within the focal plane of a single instrument - each pixel-receiver is then electronically optimized by adjusting the LO power coupled from the FFO to the SIS mixer, according to its needs at each frequency, and allowing to compensate for junction parameters scattering across a wafer. The latter point seems especially relevant for high frequencies and large pixel numbers, for two combined reasons: (1) the scattering of junction parameters and hence of optimum LO requirements may become large enough to affect an array's performance; (2) submm-wave LO power is a scarce resource, and its uniform delivery to a 2D array of N pixels makes the challenge of having sufficient LO power at each mixer even harder. Available power from LO chains is really what limits the number of pixels in a THz heterodyne array so far (even more so than backend processing capacities). For instance, using state-of-the-art Schottky-varactor diode frequency-multipliers cooled at 120 K, a maximum of 14 HEB mixers could be pumped at 1.5 THz, and only 4 at 1.8 THz (Chattoopadhyay et al. 2005). In addition, efficient LO coupling is a critical issue with quasioptical array designs. In the SMART array developed at KOSMA (Graf et al. 2002), Fourier gratings and grid-polarizers are used; however such gratings are narrow band.

Therefore for large THz arrays, the relative complexity of N SIRs electronically controlled in real-time is justified and rewarded by the inflated scientific harvest when sources can be mapped by a single heterodyne instrument, with a fully sampled field-of-view (FOV), wide rf bandwidth (several 100 GHz), huge flexibility (e.g. several sub-arrays of pixels tuned on different molecules simultaneously), hardware compactity and receiver-on-wafer fabrication low cost. Mid-90's developments of SIR (Koshelets et al. 1999) had in mind heterodyne imaging capabilities. A "fly's eye" array of 9 quasi-optically coupled SIRs was demonstrated in the framework of an ESA-funded R&D program[14].

Because SIR-pixel LOs are all phase-locked but are not mutually phase-correlated, it should be possible to use these pixels in interferometry mode. This would be useful to recover certain forbidden regions of the (u,v) plane and circumvent the shadowing effect from nearby dishes, in very large interferometers like ALMA (Viallefond 2002).

Integrated heterodyne arrays for submillimetric-THz frequencies are a much needed technology development, for fast mapping in future astronomical observations (Goldsmith et al. 1993; Phillips 2002). It is also important for Earth-observing and upper atmosphere remote sensing at these wavelengths (Waters 1992), and for THz image acquisition at video rates in medicine and contraband detection (Siegel 2004), or plasma fusion research (discussed later). However very few developments have been done in this direction as of today, with few operational arrays and moderate numbers of pixels (Rutledge et al. 1982 ; Rebeiz et al. 1990 ; Rabanus et al. 2002; Groppi et al. 2003).

Some of these needs for integrated 2D heterodyne-imaging arrays have guided SHAHIRA, a R&D study managed by ESA and carried out jointly

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[14] SISIRT - ESA TRP Contract No11653/95/NL/PB/SC

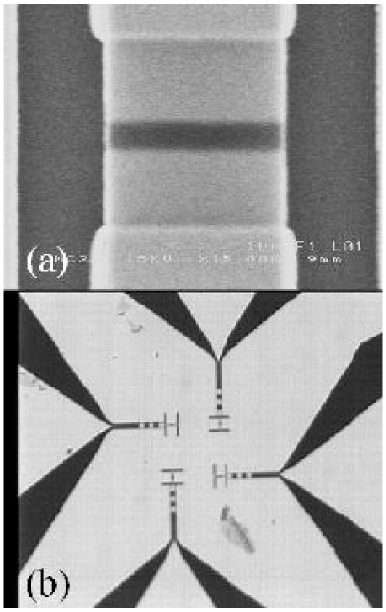

Fig. 13. (a) A hot-electron bolometer (HEB) is a thin (few nm) superconducting film (here NbN), making a short (sub-micron) bridge between two normal metal conductors (Au) ; (b) four 2.5 THz NbN HEB mixers coupled to double-slot antennas, made by J. Baubert (2005) in a collaboration between LERMA, Chalmers University and LAAS-Toulouse (SHAHIRA). Adjacent pixels use orthogonal polarizations to minimize cross-talk.

by Chalmers University, LERMA, LAAS-Toulouse, DLR-Berlin (Baubert et al. 2005a). SHAHIRA's goal is to provide a design for monolithic THz heterodyne cameras, suited for large pixel numbers. The prototypes, 4 x 4 arrays at 2.5 THz and 4.7 THz (Figs. 13b, 14b), were designed to be compatible with the telescope beam of SOFIA to enable the detection of OH, HD, and OI lines. In our case, each pixel is a NbN hot-electron bolometer (HEB) mixer (see Fig. 13a), using a new quasioptical coupling design. In this project, the focus was on array design, and the LO is not integrated.

Phonon-cooled NbN HEBs have been developed for more than a decade

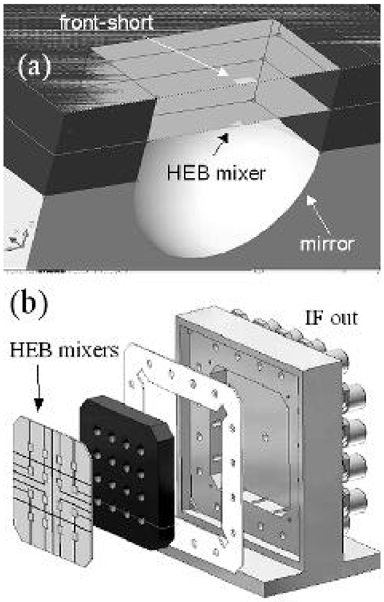

Fig. 14. A new quasioptical coupling scheme proposed for THz heterodyne arrays (SHAHIRA). (a) The HEB mixer and its planar antenna are on a thin dielectric membrane. The Gaussian beam from the telescope is coupled to the pixel antenna by a spherical mirror. An additional membrane supports a metallic plane (subreflector) in front of the HEB device to tune the antenna directivity and double its gain. (b) A prototype for testing 16 pixels is built at LERMA. Two wafers with membranes are stacked in front of the array of focusing mirrors, made either by printing or by lithographic techniques

for submm-wave heterodyne mixing and have provided good results up to several THz, beating cooled Schottky mixers in sensitivity by an order of magnitude (Gershenzon et al. 1990; Karasik et al. 1999; Cherednichenko et al. 2002). NbN HEB mixers using a waveguide mount have been used for atronomical observations up to 1.26 THz at the Heinrich Herz Telescope telescope on Mont Graham, AZ (Kawamura et al. 2002). Yet at several THz where waveguides are difficult to machine, most HEB mixers are quasioptically coupled to the rf signal by means of a planar antenna (made by lithography) and a hyperhemispherical silicon lens. Heterodyne instruments at 1.6 THz on HIFI (Cherednichenko et al. 2002) and from 1.2 to 2 THz on SOFIA (Hüebers et al. 2000) use quasioptical HEB receivers. It has been shown, however, that a substantial fraction of the receiver noise at several THz should be attributed not to the HEB mixing device itself but to poor rf coupling and rf losses. Indeed, despite much progress in quasioptical receiver design (Filipovic et al. 1993; Zmuidzinas et al. 1995), coupling efficiently the planar antenna to a gaussian mode remains difficult.

The original quasi-optical design proposed by LERMA (see Fig. 14a) uses two thin dielectric membranes. One membrane holds the HEB at the apex of a planar antenna, and the dc and IF leads. Another provides an rf reflecting "front-short" located in front of the HEB and at a subwavelength distance, to enhance its antenna directivity and gain. The whole system is backed by a parabolic or spherical reflector - like a minaturized telescope dish - focusing the rf beam to the mixer element (Baubert et al. 2005b). Prototypes of such focusing mirrors were made at LERMA using an imprint in soft copper, but they can also be micromachined as 2D arrays by lithographic techniques, such as the Si laser-micromaching process developed at University of Arizona by Walker et al. (1997). We have used a broadband twin-slot planar antenna design (Zmuidzinas & LeDuc 1992) but double-dipole or other planar antenna types could be employed.

The concept behind this novel design is an offspring from a development at LERMA for "STS" (Salez et al. 1998), where we designed a NbN SIS mixer - later a NbN HEB mixer - on a membrane substrate with a reflecting plane a quarter-wavelength away from it. A similar quasioptical coupling approach had been investigated earlier at the University of Michigan (Rebeiz et al. 1990). The stressless membrane technology that we chose has been developed in the microsystems group at LAAS, for low-loss microwave circuits in K band for telecom satellites (Pons et al. 2001): a 1.4 μm thick bilayer of Si_3N_4/SiO_2 is deposited on a silicon wafer which is then etched from the rear side by wet-etching (in a KOH solution) or by plasma etching (RIE). The thicknesses of the Si-nitride and Si-oxyde films are optimized to achieve a composite membrane with minimum stress and deformation, typically a few mm^2 in size.

Making HEB mixers on thin membranes may improve their heterodyne performance in the supra-THz range and makes chip handling easier. It avoids rf power being wasted into substrate modes. This solution also makes large-scale manufacturing of 2D-arrays much easier and lower cost than conventional techniques, especially for large numbers of pixels or arrays to be made, by extensive use of lithographic processing. This is relevant for nearly all future heterodyne-imaging applications.

Several teams investigated SIS or Schottky mixers on dielectric membranes, implemented either in waveguide blocks (Siegel et al. 1999; Kooi et al. 1995; Walker et al. 2001) or quasioptically (Rutledge & Muha 1982; Rebeiz et al. 1990; deLange et al. 1995) often with the goal of making multi-pixel THz heterodyne systems. Yet, HEB membrane-mixers developments have been modest so far. In 2000, we made[15] NbN HEB devices on membranes with excellent $I-V$ curves and we could pump them with a solid-state LO at 500 GHz.

The feasibility of this should not be taken for granted. HEB mixers use the ultrafast bolometric response of "hot" electrons in a thin (few nm) superconducting bridge coupled to microwaves via an antenna. Therefore they can operate well beyond the gap frequency of the SC material, unlike SIS mixers. At T $<< T_c$, a time-varying "hot-spot" (region of the film where the electronic temperature exceeds T_c) modulates the bridge resistance at the IF frequency (Merkel et al. 1999; Wilms Floet et al. 1999). Therefore the IF frequency cutoff (how fast the HEB mixer can respond to microwaves) is determined by the thermal relaxation (or cooling) time in the bridge. An IF bandwidth around 4-5 GHz has been measured in most NbN HEB mixers, depending on substrate material, film T_c, and on the acoustic mismatch between film and substrate. Usually the substrate is bulk silicon, in which phonons endorse most of the cooling.

With membrane-based HEBs, it is important to study the potential affect of membranes on HEB's $I-V$ quality, rf sensitivity, and IF bandwidth. Numerical simulations (Baubert et al. 2003, 2005b) show that a 1 μm membrane does not affect rf performance in critical ways, but that we may be on the verge of witnessing so far unencountered, membrane-induced phenomena, such as "hot" phonons, electron-heating enhancement (a feedback from "hot" phonons), and phonon diffusion. The latter cooling channel is a novelty, and corresponds to an intermediate case between phonon-cooling (Gershenzon et al. 1990) and electron-diffusion cooling (Prober 1993; Wilms Floet et al. 1998), the only two situations that have been theoretically stud-

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[15] at LERMA, in collaboration with the team of G. Goltsman of Moscow State Pedagogical University who processed the NbN films, and with P. Pons of LAAS who made the membranes. Though probably a "first", this result was not published

ied so far. Measurements indicate that the IF bandwidth is reduced to 0.6-1 GHz with our NbN HEB mixers on membranes (Baubert 2005a; Drakinskiy et al. 2006). However, it may be a Si_3N_4/SiO_2 bilayer's material and acoustic mismatch issue and not a consequence of the membrane per say (that is, of having a thin substrate). This IF bandwidth - which still allows the comfortable observation of molecular lines in many sources - can probably be increased again by adding a proper buffer layer (such as MgO) between the membrane and the NbN film during fabrication.

SHAHIRA's new quasioptical pixel design can be applied to 2D-arrays of Schottky or SIS mixers, solid-state LOs, or SIRs. A membrane is ideal to integrate a FFO and convey its generated radiation to "its" SIS mixer. 2D-arrays of SIRs on membranes would be more compact, better coupled, and easier to assemble than in the fly's eye solution. In particular, there is no critical coalignement of lenses with respect to the planar antennas (a problem so far): stacked wafers can be co-aligned with the precision of lithography, that is, better than 1 μm.

Extensive integration of other superconducting electronics for IF signal processing at cryogenic temperatures, e.g. amplification, analog-to-digital conversion, diplexing, digital correlation (Koshelets et al. 1991), currently in a research phase, will downplay by orders of magnitude the size and power consumption of backend spectrometers required for heterodyne arrays.

Can superconducting FFOs ever be used for pumping HEB mixers in arrays, at typically several THz? That question remains unanswered at this time. A few teams have tried to make LJJ-based FFOs using a superconductor of higher T_c than Nb, such as NbN, NbCN, and NbTiN (Kohjiro et al. 2002). There is a convergence between the quest for high-frequency SIS mixers and high-frequency FFOs using new materials: in either case one needs to increase the Cooper-pair breaking energy (Shoji et al. 1985; LeDuc et al. 1991). But rf surface losses in electrodes may be too important for materials like NbN or NbCN in polycrystalline form (Kohjiro et al. 1993). Hence efforts were made to deposit these superconductors epitaxially[16], to make FFOs and SIS rf tuning circuits above 700 GHz (Kohjiro et al. 2002). Fully epitaxial NbN/MgO/NbN junction array oscillators for 1.1 THz have been developed by Kawakami et al. (1999). Also, it must be emphasized

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[16] epitaxial growth : crystal layer by crystal layer, so that its structure is maintained throughout the deposition

that FFOs based on junction *arrays* can have junctions and superconducting striplines out of different materials (of different T_c), to combine the best of both worlds.

In addition, we suggest another research direction. Since all FFOs are by nature submm-wave pulse generators, they generate a rich comb-like spectrum. Only the energy in the FFO's fundamental has been exploited today. By designing the SIR differently, one could enhance and couple out the higher harmonics of the FFO, and pump mixers above the THz-ish limit of niobium technology. To our knowledge, this possibility has not been studied so far, neither theoretically nor experimentally.

We have discussed why SIRs would be an important step forward for future submm-wave and THz radioastronomy projects, in particular for heterodyne imaging arrays. This technology, already proven in the lab, will soon be seen at the focal plane of several telescopes. Yet one can foresee many other applications, in various domains.

In plasma research, for instance, mm-wave/terahertz heterodyne imagers with scanned LOs or wide IF bandwidths are needed to probe the electron density and temperature profiles in tokamaks in real time, via the electron cyclotron emission (ECE) (Baumel et al. 2000; Deng et al. 2001). The fundamental ECE modes are usually around 100 GHz, but their harmonics provide useful informations on the stronger magnetic fields regions. In addition, temperature fluctuations in the plasma core can be obtained by interferometric techniques. Heterodyne receivers are being developed in several places, for instance at the Institute for Plasma Research, Ahmedabad, for this purpose (Kaur 2005).

As far as hunting for molecules?... The submm range is the richest region of the EM spectrum to search for, monitor and make diagnostics of molecules, regardless of their size and complexity. The submm is where retinas of all molecular physicists, chemists, and increasingly biologists, ought to be sensitive. The romance of biology with submm-wave techniques is new, but promising (Siegel 2002). Many interactions between submm-wave THz radiation and macromolecules of biological interest, viruses, living cells, are only now being studied and discovered[17]. It has been shown for example that DNA and RNA molecules have specific THz phonon-modes, and sub-

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[17] In the early 2000's, the literature on this topic is abundant : for instance, the THz spectral signature of freshly incised human tissues was studied by Fitszgerald et al. (2003). Any volunteer? Come on, it's for Science!

sequently absorption “fingerprints” in the submm-wave-THz range (Globus et al. 2003). Instruments detecting DNA’s THz spectral signatures will be used in biomedicine - cancers early detection, gene therapy - but also in biological warfare (Woolard et al. 1999). Since the THz spectra of molecules reflect their inner vibration and rotation modes, it also reflects their 3D conformation. THz spectroscopy can therefore be a powerful investigation tool, in complement to X-ray diffraction and other methods, for the fast-growth research field of protein crystallography, or to study viruses outer structures.

Non-invasive $in-situ$ spectral imaging in the terahertz of biological tissues already finds an exploding niche of biomedical applications (Arnone et al. 1999). One type of now commercially available instruments is the “T-ray” imager, where a sample is analyzed via the transmitted or reflected EM transients (in the 0.5-2 THz range) generated by an intense, femtosecond optical pulse (Hu & Nuss 1995). These tomographical systems using optical pulses are versatile, can have their targets reconstructed in 3D, however do not have a very high spectral resolution. Heterodyne imaging systems will permit a much finer analysis of molecular content, especially at the trace level.

SIRs make ideally compact and multipurpose molecule detectors, with either one or several pixels, to scan broad portions of the submm-wave spectrum as well as to carry out deep integrations of few lines. Room-temperature semiconductor-based receivers will find it hard to compete with superconducting receivers, in many of these emerging applications for which the speed of detection or mapping is crucial. In addition, the cryogenic requirements will be alleviated, the weight of a SIR frontend being enormously smaller than currently existing heterodyne receivers.

Coupled to a planar (possibly active, beam synthesizing) antenna, SIRs could be used for remote detection, in particular for sensitive submm-wave targeted molecule radars (Gopalsami & Raptis 1998); no doubt that key components of such radars will be technological spinoffs from THz-range ultra-wideband telecom developments, for space-based systems and optical-fiber networks in particular.

Coupled to gas-cells “sniffing” the surrounding gaseous environment, SIRs could be used for $in-situ$ molecule detection. These self-calibrated, high-sensitivity molecular detectors (tapping from a line databank for real-time species identification) would be an attractive complement to existing instrumentation like chromatogaz mass spectrometry (CGMS), employed on space probes (e.g. Huyghens) and rovers for planetary exploration (Buch et al. 2003; Niemann et al. 2005); but also in planes, balloons, and ground-station networks for global climatology and atmosphere-biosphere interaction studies. Mass spectrometers and IR spectroscopy used in this field often require relative calibrations of instruments (Ciais 2003) and are in some case limited by ambiguities, low resolution, or pre-targetted search. In toxic gas detection, biomedicine, or exobiology, one should not miss a molecule because it was not anticipated to be searched for! In the latter research domain, THz spectroscopy will allow the identification of prebiotic and so-called "predisposed" molecules (Kasting & Brown 1998), and will no doubt be used at some stage in combination with near-IR spectroscopy from space-based interferometers in the search for life in extrasolar planets. Back on Earth, this technology might be employed for pollution surveillance, chemical/energy plant safety, and many industrial quality controls, e.g. detection of foreign bodies or unwanted chemical elements in water, processed foods, materials... In material science, semiconductors can be better characterized using THz spectroscopy. Could some of these materials also be... superconductors?

7 Josephson plasma resonance

One summer day of 2004, discussing casually with my neighbour C.J. van der Beek, who works at Laboratoire des Solides Irradiés (LSI) of Ecole Polytechnique, about our respective research activities, it dawned on us that we could merge our fields of expertise into a new and unique experiment. An expert of high-T_c cuprates, van der Beek has been investigating the Josephson plasma resonance (JPR) in various hight-T_c superconductors (HTCS) to study their structure and properties, in particular anisotropy, arrays of 2D vortices and magnetic flux-pinning (Colson et al. 2003). The JPR frequency f_p depends on material, doping and temperature, and often falls in the millimeter-wave range.

A cuprate-based superconductor is basically a stack of CuO_2 layers (ab-planes) where most of the superconductivity, carried by Cooper pairs as in low-T_c SC, occurs (see Fig. 15a). Along the c-axis, coherence length is smaller than the thickness of the interplane layers (1.2 nm); these therefore are semiconducting and also act as electron reservoirs thanks to doping atoms; yet the superconducting CuO_2 layers are mutually strongly cou-

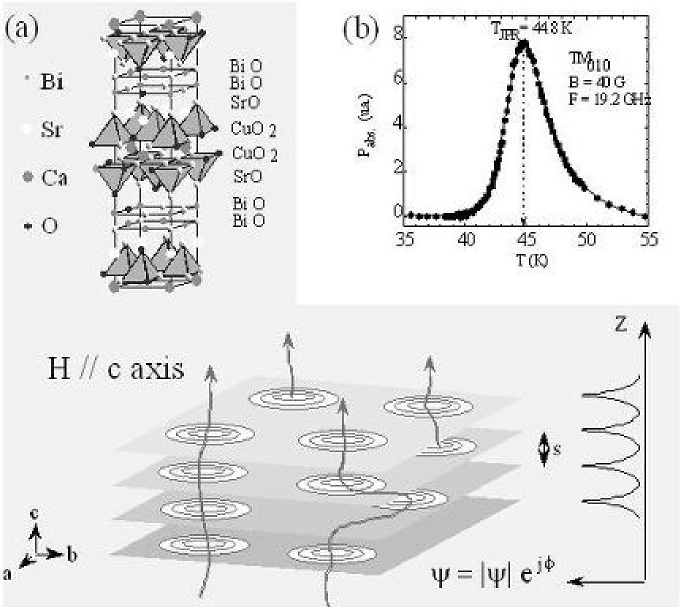

Fig. 15. (a) A lamellar high-T_c superconductor (HTCS) is a stack of superconducting layers (the CuO_2 planes) separated by insulating layers yet strongly coupled by Josephson coupling. Arrays of 2D vortices can undergo transitions from the solid to the liquid phase depending on temperature and magnetic field. (b) The Josephson plasma resonance (JPR), measured using a cavity. The JPR allows to study the anisotropy, Josephson coupling, and vortex matter in HTCS materials. It can be detected as a microwave absorption line due to quasiparticle dissipation at the resonance (Colson et al. 2002)

pled, and although not yet fully understood[18], this coupling is believed to be Josephson tunneling (Kleiner & Müller 1994; Yurgens et al. 1996). Therefore a lamellar HTCS has a formal similarity with a superstack of SIS junctions (Ustinov & Sakai 1998). The HTCS material's anisotropy (mea-

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[18] Certain theoreticians even suspect the coupling between superconducting layers of being at the origin of high- T superconductivity : hence the fundamental importance of studying experimentally with new tools the c-axis electrodynamics!

sured by the ratio of London depths in the c-axis and ab plane) varies from several hundreds to more than 10^3.

The JPR is the natural resonance associated with the Josephson interplane coupling energy. Its frequency is therefore a direct measurement of this coupling, or superfluid density, and a good probe of the HTCS anisotropy ratio. When a magnetic field stronger than the critical field H_{c1} is applied along the c-axis of a HTCS cuprate, it enters it as an array of "pancake" 2D-vortices (van der Beek et al. 1995). The disordering of this "vortex matter" by thermal excitation can also be studied by JPR measurements.

Therefore in recent years, several groups have tried to detect the JPR in HTCS, at various wavelengths and with various methods. One is a microwave (around 50 GHz) absorption measurement using a bolometer (Matsuda et al. 1995); another is IR reflectometry along the c-axis (Motohashi et al. 2000). At LSI, van der Beek et al. have also used microwave cavities from to 20 to 40 GHz (Colson 2002), to study HTCS materials with particular doping rates bringing their plasma frequency at 77 K within a cavity frequency range - for instance, strongly underdoped $Bi_2Sr_2CaCu_2O_{8+d}$ (BSCCO) of $T_c = 69.4$ K. The JPR frequency is scanned by changing the sample's physical temperature (Fig. 15b) or the magnetic field. It would be of extreme interest, however, to explore the JPR phenomenon for optimally doped materials, and at 4.2 K where f_p reaches its maximum (around 100 GHz for BSCCO, higher and up to 1 THz for other compounds like $Tl_2Ba_2CuO_6$ or $La_{2-x}Sr_xCuO_4$). Yet reliable microwave cavity measurements at 100 GHz and above are extremely difficult.

The JPR is detectable as a microwave absorption peak in the material, because quasiparticles, excited at the plasma resonance, induce dissipation (Gaifullin et al. 1999). In addition, one expects the JPR to be potentially very narrow - as narrow as 10^{-5}. This was never demonstrated probably because of resonance-spreading due to sample inhomogeneity, combined with poor spectral resolution of most methods. Resolving the JPR linewidth would provide a direct measurement of the quasiparticle conductivity along the c-axis in the material. Trying to extract a weak absorption feature from a noise background with high spectral resolution "ringed a bell". Why not treat the elusive JPR as a weak interstellar absorption line? Why not use the heterodyne detection method with its unbeatable sensitivity and spectral resolution, not only to detect but also fully resolve the JPR profile? This experiment can be attempted around 100 GHz with optimally doped

BSCCO and around 450-500 GHz with BiPbSnCuO.

A collaboration between LERMA and LSI is on-going at the time of writing, around this new experiment. An absorber radiates a submm-wave continuum background, diplexed with LO and injected into a millimeter-wave transmission line at 4.2 K where the HTCS sample is inserted, in a way to produce as little rf mismatch as possible. The sample is then connected by a thermally-decoupling waveguide to a broadband SIS mixer. The amplified IF output is sent to a spectrum analyzer, or if need be, a spectrometer optimized for weak line detections (AOS, DACS, fast-Fourier spectrometer). A 4-GHz IF bandwidth like HIFI's is ideal, since even the wider JPR lines detected so far are a few GHz. The phased-locked LO will scan the target bandwidth by ~2 GHz intervals, and the obtained spectra will be calibrated via $frequency - switching$: this calibration method will minimize total integration time and circumvent the drawback of having our wideband source and LO radiation diplexed prior to reaching the sample. The JPR frequency is tuned by temperature changes up to several degrees, and by the magnetic field B from an integrated electromagnet. This is important not only to verify the dependence of f_p on T and B, but also because at a given temperature, several 10 Gauss will have the vortex matter undergo a first-order transition from the solid to a liquid phase (Colson et al. 2003). The $I - V$ curve of the sample is also monitored to confirm the JPR frequency by a change in the qualitative appearance of the Shapiro steps induced by the LO below and above the plasma resonance.

In a preliminary test we have mounted a BiPbSnCuO sample ($T_c = 74$ K, from the University of Tokyo) in the substrate channel next to the SIS junction in an ALMA mixer block ideal for the range 450-500 GHz where the JPR is expected (Fig. 16). The sample is glued on the rf choke filter: it will not perturb the SIS mixer rf response significantly, save for the JPR frequency, where the large change of sample's impedance will detune the SIS mixer and change its gain and sensitivity. DC current-voltage and FTS measurements have shown that the SIS mixer is indeed unaffected by the sample over the whole band, but also that the FTS data have too poor a S/N ratio to allow seeing the JPR: heterodyne mode must be used. It is worth noting that the JPR is of interest and has been studied in low-T_c tunnel junctions (Dahm et al. 1968). In Macroscopic Quantum Tunnelling (MQT) experiments, for instance, where the rate of escape Γ from the zero-voltage state is monitored, the JPR is seen as an enhancement of Γ when a microwave resonator is tuned to f_p (Turlot et al. 1989). At low enough

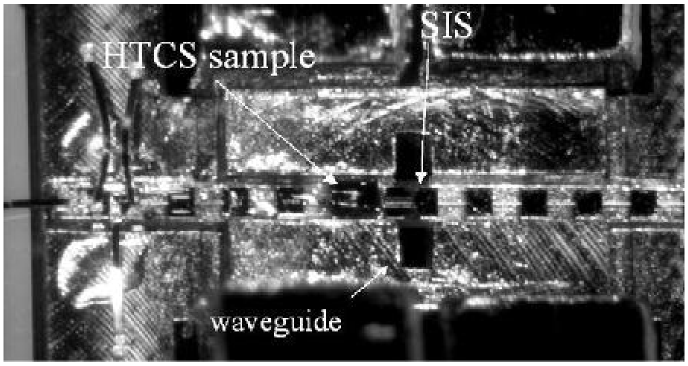

Fig. 16. Photograph of a PbBiSnCuO sample ($T_c = 74$ K) inserted in the ALMA Band 8 SIS mixer block, to study its JPR around 450-500 GHz

temperatures, when $k_B T << hf_p$, the JPR curve is observed to split into a series of narrow spikes, corresponding to the junction's Josephson coupling potential oscillator levels predicted by quantum theory. This transition from classical regime to the quantum regime was seen below 100 mK with Pb-based junctions ($f_p < 10$ GHz).

Therefore, there is an exciting possibility, if we can measure the JPR in the submm and at 4.2 K with a high enough spectral resolution, to observe this phenomenon in ultrasmall HTCS monocrystal samples. With sufficient microwave filtering, one should observe the quantum regime as a hyperfine structure in the resolved JPR lineshape. To our knowledge, this possibility has not been published anywhere. Recently, Krasnov et al. (2005) have confirmed the Josephson nature of the HTCS interplane coupling, in thermal activation experiments with BSCCO samples trimmed by focused ion beam into mesas of submicronic dimensions; they report seeing the HTCS intrinsic Josephson junctions, and escape from the zero-voltage state, just as with low-T_c junctions in the MQT experiments mentioned above.

The JPR heterodyne detection technique proposed here will be much more accurate than the indirect extrapolation from optical measurements. It could become a useful laboratory tool for studying the physics, chemistry and quality of many HTCS - and possibly other - materials. Most cuprates happen to have their JPR within the submm-wave domain and below 1 THz, making SIS receivers ideal instruments. In the future, ultra-compact and wideband SIRs would be very adequate for specialized JPR-detection systems. After much development and progress during decades aiming at the study of the most remote objects of our universe, heterodyne systems based on superconductivity may now be applied to study...superconductivity. A fair return. And closing a long - indeed, very long - loop.

8 Conclusion

Since early civilizations, astronomy has always been a primary driver for new technologies, and often an excuse to venture into unbeaten sidepaths. So it was for the focusing optical lenses first turned to the planets, now enabling many of us with blurred eyesight to decipher the footnotes of this paper and enjoy this month's ApJ. The same is true for the current exploration of the submm-wave-THz spectrum with new devices, freshly baked from the ovens of solid-state physics. Carried on radioastronomy's shoulders during the last decades, this technology is now meeting new interest and users in medicine, biology, chemistry, materials, nuclear fusion, atmospheric science, environment, security, defense, and most certainly things we cannot dream about yet. By developing powerful ways to hunt for molecules as far as millions of light-years away, submillimetric astronomy probably has - unknowingly - triggered a revolution in our daily world; because this living planet and ourselves are obviously thriving with molecules, and all processes in ecology and human activities need be analyzed, understood, and controlled at least at the molecular level. Molecular spectroscopists have been pioneers, the founding- and god-fathers of high-spectral resolution spectroscopy, from the millimeter to the terahertz. These techniques, pushed hard and validated on the most extreme case by radioastronomy, are now entering adulthood, and about to democratize molecular spectroscopy. Therefore there is no doubt that identification of molecules via their submm-wave and THz signatures will invade our everyday life. With the progress in the fields of high-T_c SC, compact cryogenics, RSFQ fast-signal digital processing, I predict that SC will be a top-brass leader of this invasion. Twenty years ago, Pierre Encrenaz anticipated the importance of superconductive devices for submillimeter-wave astronomy, at a time when these were mostly toys for condensed-matter physicists: as we can see today, he was right.

This paper focused on what superconductivity brought to heterodyne detection, therefore I remained discreet on the fact that it has also done much for astronomy at other wavelengths (NIR, visible, UV, gamma and X-ray), in modes other than coherent detection (bolometry, photon-counting) and in "big science" astronomy (high-energy particle and gravitational wave detection). We can distil from this bloom and boom of instrumental techniques at least one major lesson - or is it a reminder? It is that, in the area of instrumentation, a lively and constant dialogue between engineers and physicists is an important key to success. Physicists working on advanced topics in their labs are often eager to collaborate with instrumentalists, on exciting applications and projects granting their fundamental research work a second life and purpose of another nature. Equally important, in particular for astronomy, is the need for partnership between engineers building the instrumentation and its future users. The instrumentation level can be the creative and mediating node interfacing the scientific community with specific needs, and basic research's possibilities and offer. Ideally, the three (physicists, engineers, astronomers) should be mated in a triangle of close, active and fruitful two-way relationships[19]. It is regrettable when research is highly compartmentalized and when even communities working on similar or related topics, having much to share, are fragmented, with little access to each other[20]. In countries where strong, sometimes audacious transdisciplinary bridges have been set at national or institute level, a collective, synthetic vision of goals and means was allowed to emerge, and impressive technological achievements were made. This can be encouraged by proper programming and funding by research agencies, and most of all, I believe, through an evolution in many places of the scientific culture. Dialogue means more than being able to speak, it means being able to listen. Dialogue requires the development of common language and common thinking. One language barrier to overcome, in particular, is that which, in certain scientific cultures, unduly separates engineers from physicists, and from astrophysicists. Unless they are made highly porous, the

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[19] Superconductivity has also contributed directly to astrophysics, by providing new theoretical concepts and mathematical frameworks useful to describe, for instance, phase transitions in the Standard Model, black holes, neutron stars

[20] In certain countries research in applied superconductivity is strong and well organized at the national level, and this coherence is obvious in international conferences like ASC or EUCAS. To help break a certain lack of mutual communication of french groups working in this domain, two workshops on superconductive devices were organized at Paris Observatory in 2004 and 2005, and a network of a dozen french teams has been created, in order to share goals, problems and solutions, and initiate collaborations. See http://sefira.univ-savoie.fr

numerous walls between disciplines are obstacles to progress, prevent scientific cross-fertilization from which stem many new ideas. Several examples of these potentially powerful alliances have been suggested in this article. The nearly half-century long history of the superconductivity-astronomy relationship tells us much about this. And it is far from over, with a vast horizon of technological possibilities, challenges, and scientific quests ahead of us.

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