SEMI- AND SUPER-CONDUCTING TECHNOLOGIES
FOR THE MILLIMETER AND SUBMILLIMETRE WAVE APPLICATIONS

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ABSTRACT

Millimeter and submillimeter-wave observations provide important informations for the studies of atmospheric chemistry and of astrochemistry (molecular clouds, stars formation, galactic study, comets and cosmology). But, these observations depend strongly on instrumentation techniques and on the site quality. New techniques or higher detector performances result in unprecedented observations and sometimes, the observational needs drive developments of new detector technologies, for example, superconducting junctions (SIS mixers) because its high sensitivity in heterodyne detection in the millimeter and submillimeter wave range (100 GHz - 700 GHz), HEB (Hot Electron Bolometer) mixers which are being developed by several groups for application in THz observations. For the sub-millimetre wavelengths heterodyne receivers, the local oscillator (LO) is still a critical element. So far, solid state fundamental sources are not often powerful enough for most of the applications at millimetre or sub-millimetre wavelengths: large efforts using new planar components (HBV) and integrated circuits or new technics (laser mixing) are now in progress in few groups.
The new large projects as SOFIA, ISS, FIRST, ALMA,…for astronomy ; SMILES, EOS-MLS,…for aeronomy and other projects for the planetary science, will profit of the new technologies..

INTRODUCTION

The millimeter and submillimeter wavelength spectral bands, represents one of the least explored yet information rich segments of the electromagnetic spectrum. This frequency span encompasses all of the critical spectral emissions from the key molecules involved in atmospheric chemistry on Earth (and on the planets and comets). These include those molecular transitions which have been identified as crucial to our understanding and monitoring of the global ozone depletion problem. The submillimeter-wave regime also contains spectral line emissions which can further our understanding of interstellar chemistry, new star formation and galactic structures. Due to high atmospheric opacity both astrochemical and stratospheric observations in the millimeter and the submillimeter-wave spectral bands must be made from high altitude sites (Hawai,…Altacama /ALMA) ; aircraft (SOFIA,..) ; balloons: PIROG (SSC-CNES) ; satellites: ISS, FIRST which is designed to have broad spectral coverage beginning at 500 GHz and going up to 2.7THz.

There are two basic ways to analyse electromagnetic radiation at submillimetre and far-infrared wavelengths, either by (super-) heterodyne (coherent detection) or by direct (incoherent) detection techniques. All of the missions requiring high sensitivity and high spectral resolution use the heterodyne detection technic.

HETERODYNE MIXER TECHNOLOGIES

Both Schottky diode and superconducting tunnel junction (Superconducting-Insulator-Superconducting = SIS) mixers could be used on the submillimeter heterodyne receivers. The Earth (or other planets) atmospheric research don't need a so high sensitivity, is the more often using Schottky diode mixers ; the astrophysic research needed the highest sensitivity, currently employe SIS mixers. Waveguide with horn and Quasi-optical mixer technologies are both employed up to 5THz. Arrays have been developped for astronomical focal imagery.

Submillimeter Schottky diode mixers

For more than two decades the best uncooled heterodyne radiometers for use in the 100 GHz - 5 THz frequency range have been composed of waveguide or open structure mixers with whisker-contacted metal-semiconductor Schottky-barrier honeycomb diodes (4.5THz open-structure mixer was developped at MPIFR-DLR for airborne experiment).

In order to reduce the assembly cost and to improve the reliability and reproducibility of heterodyne receivers for the space missions throughout the millimeter and submillimeter wavelength bands, two major changes have been incorporated into current radiometer design. First, the whisker-contact honeycomb diode (used in SWAS, ODIN,…) have been replaced by planar diodes, mainly for subharmonically pumped mixers (SHP), for applications up to (or above) 600 GHz (MHS ; MIRO/ROSETTA ; EOS-MLS, MASTER-SOPRANO,…); second, the diode is integrated with the mixer circuitry (MMIC-like).An added benefit to this latter approach is the all planar photolithographic structure scalable to frequencies well beyond a THz (JPL, SHP mixer for EOS-MLS). A major goal is to advance the state-of-the-art in millimeter-wave with the quasi-planar-diode technology associated with micro-machined mixer structures (RAL ;U.Va) to the point at which it can be used readily at frequencies as high as 2.5 THz (PYRAMID, EOS-MLS…). The Schottky diodes can be cooled to 70 or 20-30 K, increasing the performances, but work even at room temperature which is an advantage for several space applications.

Superconducting tunnel junctions and HEB mixers

In the push to obtain ever higher sensitivity, shorter observation times and the use of smaller collecting surfaces, the submillimeter-wave astrophysics community has devoted much of their ressources towards the developpement of heterodyne radiometer front-ends based on superconducting mixers. The small area superconductor-insulator-superconductor (SIS) Nb tunnel junction offers the potential of near quantum limited sensitivity throughout the millimeter-wave bands up to 700 GHz and possibly at frequencies as high as 1.1 THz with normal metal tuning stub circuits (Al) or up to 1.4 THz by using NbTiN superconducting new material. The Supra-THz domain is recently achievable by using Hot Electron Bolometers heterodyne (HEB) mixers. The SIS and HEB mixers must be physically cooled to temperatures well below the superconduction transition temperature, (4 K or less). However, the requirement for a liquid helium ambient environment poses a significant limitation for remote, long lifetime space operation.

Superconducting mixer developments at DEMIRM :

SIS mixers : For the **PIROG 8 ballon borne** experiment (SSC-CNES), DEMIRM has developped an heterodyne front-end receiver at 420-440 GHz using SIS Nb junction with a classical tuning circuit {1}. Pirog 8 was devoted to detect interstellar and atmospheric CO and O2 lines ; it has flown from Air sur l'Adour (France) in september 1997 .

DEMIRM is now in charge of the design and realization (with IRAM) of the **FIRST-HIFI channel 1** in the 480-640 GHz band. Today, an important part of the research in this field aims at developing receivers combining ultra wide bandwidths (around 30% relative or more) with ultra low-noise capabilities (a few times the quantum limit), with no mechanical tuning. This goal has been an insentive to explore either new tunnel barrier materials or new types of circuits. The classical approach, using Nb integrated tuning stubs with E-beam lithography for the junctions, is under developpement jointly with IRAM {2,3}. But, the results on discrete version (NRO) of the distributed non-linear quasiparticle SIS mixer proposed by Tong et al, offering high sensitivity over wide bandwidths, have triggered our interest in these circuits as potential solutions for wideband tunerless DSB mixers, such as those needed for FIRST/HIFI…This approach is now under development at Paris Observatory {4}, it is supported by a CNES contract.

Integrated SIS front-end : The purpose of superconducting integrated receiver is to integrate FFO (Flux-Flow Oscillator) in SIS mixer chip and make use of FFO as LO (Local Oscillator) of SIS mixer. FFO is one kind of superconducting oscillator. There were many research works about Josephson junction oscillator in searching for alternative of the other LO, like solid state, because the difficulty to make LO at millimeter and submillimeter wavelengths. Our activity at DEMIRM was intrigued by such results and directly related to a development of prototype superconducting integrated SIS receiver. An SIS mixer chip including FFO, double-dipole antenna and diverse super-conducting RF passive circuits have also been designed and the realization is now in progress at Paris Observatory {5}.

HEB mixers : Superconducting Hot Electron Bolometers becomes very promising mixing element for THz observations {6} and it also shows good performances even below the gap frequency of Nb. Super-conducting HEB may go competitive with SIS junction at millimeter and submillimeter wavelengths since it provides several advantages compared to SIS mixers: smaller LO power, no need of external magnetic field to suppress Josephson current noise, relatively ease to match into the antenna impedance due to its nearly resistive impedance, and no upper frequency limit. But there are some problems to be resolved for radioastronomical applications like relatively narrow IF bandwidth and elaboration of mixing theory on superconducting HEB.

The research about superconducting HEB has become active at DEMIRM from last years:

HEB NbN on SiO_2 membrane in wave-guide mixer is under development with the cooperation of the University of Moscow and the LAAS in Toulouse (this work is starting to be supported by an INTAS –ESA contract).

HEB/SHTc (YBCO) quasi-optical mixer is in progress at Paris 6 University/Supelec with the Paris Observatory and the Moscow University (this work is now supported by an INTAS-CNES contract).

LOCAL OSCILLATOR GENERATION TECHNOLOGIES

For millimetre and sub-millimetre wavelengths heterodyne receivers, the local oscillator (LO) is still a critical element. So far, solid state fundamental sources are not often powerful enough for most of the applications at millimetre or sub-millimetre wavelengths. The L.O. power needed for Schottky diodes or SIS junctions, is currently obtained by Gunn oscillators cascaded with frequency multipliers using whiskered varactor diodes {7}. This technology is now able to provide enough power up to 1 THz for SIS mixers. New planars devices and circuits are under development (up to and above 1 THz). HEMT oscillators, Quantum well oscillators are able to provide enough power up to 300-400 GHz ; long Josephson junctions and flux-flow oscillators arrays are also opportunities to drive the SIS mixers up to 600-700 GHz (see the integrated SIS mixers section). Microwave tube oscillators or CO_2 lasers pumping submillimeter masers are used as LO sources in the range 300 GHz and up to several THz, but they need high electrical power consumption. Heterodyned lasers diodes (laser mixing) usign LTG-GaAs technology to drive HEB mixers above 1THz, is in now progress in few laboratories {8}.

LO multipliers chains: The local oscillator signal is generated by a low frequency (<150 GHz) fundamental source, followed by one frequency multiplier at least. Whisker-contacted Schottky barrier varactor diodes are still the most efficient devices for LO generation at sub-millimetre wavelengths. Nevertheless, for space-borne radio-telescopes such as the Far Infrared Space Telescope or for arrays with a large number of antennas such as the Large Southern Array, the use of much more reliable and reproducible components like planar varactor diodes is highly desirable {9}. Thanks to the possibility of power combining, planar diodes have already compete the whisker-contacted diodes in the millimetre region; but at higher frequencies, planar diodes are limited by their parasitic capacitances and their series resistance and must be integrated to the circuitry (MMIC-like: JPL,..).

Multiplier developpements at DEMIRM / IEMN / MMS-F

Schottky varactor planar diode doubler: A Neal Erickson-like balanced doubler at 260 GHz has been designed and tested at DEMIRM. The devices are Schottky planar varactors SC3T2 fabricated at the University of Virginia. The multiplier operates in the range 210 - 270 GHz with 10% efficiency when adjusting the mechanical tuners. Its 12.5 mW maximum output power was obtained at 265 GHz. The 3dB instantaneous bandwidth at 260 GHz is about 4%. For RF characterisation, DEMIRM used both a photo-acoustic absolute power sensor fabricated by Thomas Keating LTD, and a vector sub-millimetre network analyser from ABmm. The combination of both devices offers unique possibilities in terms of sensitivity and accuracy.

Heterostructure planar diode tripler developments: due to the natural symmetry of their C(V) curve, Heterostructure Barrier Varactors (HBV) generate odd harmonics only. This characteristic makes them the appropriate device for wide-band and high efficiency frequency tripler or quintupler. InGaAs/InAlAs/AlAs HBV have been designed, fabricated and tested by IEMN. Devices with two barriers stacked on the same epitaxy and several anodes in series (up to four) are planar integrated. They exhibit state-of-the-art DC characteristics with a zero-bias capacitance C_{j0} of $1fF/\mu m^2$, a capacitance ratio of 6:1, and an overall breakdown voltage of 12 V per anode, with an extremely low leakage current. Several components from IEMN have been RF tested on the test bench developed at DEMIRM in a 250 GHz waveguide tripler designed by MMS-Toulouse and DEMIRM{10}. State-of-the-art performances are obtained at 246 GHz with a conversion efficiency up to 12% ; 9.5 mW max. output power was obtained with 90 mW input power {11}.

CONCLUSION

For most observations in the Earth's, planets and comets atmospheres, sensitivity is not nearly as critical an issue as it is for stellar astrophysics. A large number of key molecular transitions can be observed with the sensitivity available from current room-temperature of passively cooled semiconductor-diode radiometers. For the most part, the emphasis for millimeter and submillimeter-wave, Earth remote sensing applications has been on pushing to higher frequencies (up to 3 THz), increasing the instantaneous bandwidth, improving device reliability and reducing radiometer complexity and cost.

For astrophysic, very sensitive and very high spectral resolution heterodyne spectroscopy ($R > 10^6$) are requiered. SIS mixers up to 1250 GHz, HEB mixers above 1 THz have made significant progress in performances and reliability the last years. It seems no doubt that superconducting heterodyne submillimetric receivers will fly in space in the very near future…

The local-oscillators did not yet the same progress comparing the mixers did..this is certainly due to so not enough effort have been made in the past in this field… The technology is now ready to improve that part of the heterodyne receiver (MMIC technology, new components : «HBV »,..) : we now have to push the work on that field.
The focal plane heterodyne array receiver which simultaneously provides 3D data (2D spatial and 1D frequency informations), will make enormous impacts on radioastronomical observations. And, there are also various application of focal plane array heterodyne receiver in the other domains like remote sensing, plasma diagnostics etc. We can believe that multi-element array will be the next generation of heterodyne receivers in the near future.

AKNOWLEDGMENTS

The author thanks very much the colleagues at Lille University (IEMN : D.Lippens, X.Mélique and al), at LAAS (D.Pons), at MMS-F (J.M.Goutoule, M.Trier and al), at Paris University (Supelec : A.Kreisler, A.Gaugue and al) as well as Pr Golt'sman and al (Russian team), at Paris Observatory DEMIRM : M.Salez, Y.Delorme, A.Maestrini, M.H.Chung, F.Boussaha,.. the FIRST-HIFI channel 1 project team and the LMO & Technology Pole supports. We express our aknowledgements to the Paris-Observatory Scientific Concil, the CNRS-INSU, the CNES, ESA, INTAS, for supporting and funding our millimeter and submillimeter developments.

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