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Schottky diode based terahertz frequency multipliers and mixers

Multiplicateurs de fréquences et mélangeurs THz utilisant des diodes Schottky

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Abstract

This article presents some aspects of the technology of terahertz heterodyne receiver front-ends dedicated to astrophysics, planetary and atmospheric sciences. It focuses on frequency multipliers and on Schottky mixers. Novel architectures of power-combined frequency multipliers at submillimeter-wavelengths, THz planar fundamental mixers, and integrated receivers will be discussed as well as the fabrication of submillimeter-wave planar Schottky diodes in France.
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Résumé

Cet article présente quelques aspects de la technologie des récepteurs d'hétérodynes terahertz consacrés l'astrophysique, la planétologie et aux sciences de l'atmosphère. Il se concentre sur les multiplicateurs de fréquences et sur les mélangeurs Schottky. Des architectures de multiplicateurs de fréquences combinés en puissance fonctionnant aux longueurs d'onde submillimétriques, de mélangeurs fondamentaux planaires THz, et de récepteurs intégrés seront discutées ainsi que la fabrication de diodes Schottky planaires submillimétriques en France.
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Key words: Schottky diode; heterodyne detection; frequency multiplier; mixer; THz, submillimeter

Mots-clés: diode Schottky ; détection hétérodyne, multiplicateur de fréquences ; mélangeur ; THz ; submillimétrique

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1. Introduction

By transferring the spectral information contained in the incoming signal to micro-wave frequencies, heterodyne receivers provide unrivaled sensitivities for observations at high spectral resolutions that are much needed for understanding the physical properties, the dynamics and the chemistry of several astronomical sources like distant galaxies, molecular clouds, the atmospheres of planets or jets emitted by comets. This resolution is also often required to precisely determining the red-shift (i.e. the distance) of distant sources discovered by optical telescopes. Among different technologies available to build THz and sub-THz coherent receivers for radio-astronomy and aeronomy [1], planar Schottky diode technology plays a crucial role. Actually, it is the technology of choice that enables the building of high efficiency frequency multipliers capable of reaching into the THz regions. It is therefore the technology most often used for building compact and robust local oscillators for heterodyne receivers for space observatories like Herschel, successfully launched on May 2009, by the European Space Agency. Schottky diode mixer technology is similarly important for long-term planetary and atmospheric space missions that cannot afford the mass, the power and ultimately the cost of cryocoolers or liquid helium cryostats as it is the sole technology available to build sub-millimeter-wave low-noise mixers working at room temperature.

Planar Schottky technology made tremendous progress in the late 1990's, principally thanks to the astrophysics community that supported the construction of the heterodyne instrument on Herschel [2], [3]. Renewed interest in space-borne arrays of sub-millimeter wave radiometers for improving the modeling of the Earth's atmosphere and ultimately the accuracy of meteorological predictions, or the recent increased interest in concealed weapon detection systems are additional drivers for the development of planar Schottky diode technology.

Abundant literature regarding the modeling of the Schottky junction at THz and Sub-THz frequencies is available [4], [5], [6], [7], [8], [9], [10], [11]. The focus of this paper will be on advanced THz frequency multiplier and mixer circuits utilizing planar Schottky diodes and on recent work on their fabrication.

2. Bridging the microwave to photonics gap with THz frequency multipliers

Frequency multipliers are non-linear devices that generate a specific harmonic of an input sine signal and suppress undesired ones. They require a matching network at the input and output frequencies but also at the undesired (idler) frequencies to optimize the transfer of power from the fundamental frequency to the desired harmonic [12]. The later requirement makes difficult the building of high order frequency multipliers. Typically the order N of multiplication is limited to N=3 and more rarely to N=4 if the frequency multiplier is built with non-symmetrical devices like Schottky diodes, or to N=5 if the frequency multiplier uses symmetrical devices like heterostructure barrier varactors (HBVs) introduced in [13]. At THz frequencies only doublers or triplers are demonstrated with reported powers at room temperature of 100μW at 1.2THz, 15-20μW at 1.5-1.6 THz and 3 μW at 1.9THz [14], [15], [16], [17], [18], [19]. As predicted in [20], these powers improve dramatically upon cooling: the same sources produce respectively, 200μW, 100 μW and 30μW at 120K. Fig. 1 shows the output power of state of the art CW sources from 0.1 THz to about 40 THz.

2.1. *Planar Schottky diodes for THz frequency multipliers*

2.1.1. *Diode topology and associated parasitic elements*

Planar Schottky diodes are the most popular device for building frequency multipliers working above 150 GHz. The reasons are manyfold but all originate from their simplicity. As far as THz frequency operations are concerned, this simplicity translates into the ability to reduce the size of the active area of the diode to a small fraction of a square micron, hence reducing the junction capacitance to a fraction of a femto farad. Parasitic capacitances, series resistances and carrier velocity saturation effects [5], [6], [7] all contribute to reduce the performance of the frequency multiplier. The parasitic capacitances can be partly controlled by reducing the thickness of the dielectric substrate to a few microns and the thickness of passivation layers to a few tens of nanometers. The introduction of airbridges that connect the anodes to the rest of the circuit is a good method to reduce parasitic capacitances, however, the impact of the airbridge on the parasitic capacitance depends on the height of the anode, on its location on the mesa as well as its shape (see Fig. 2a.) The series resistance can be reduced by minimizing the path between the anode and the ohmic contact and by increasing the doping level to $5 \times 10^{17} cm^{-3}$ or more;

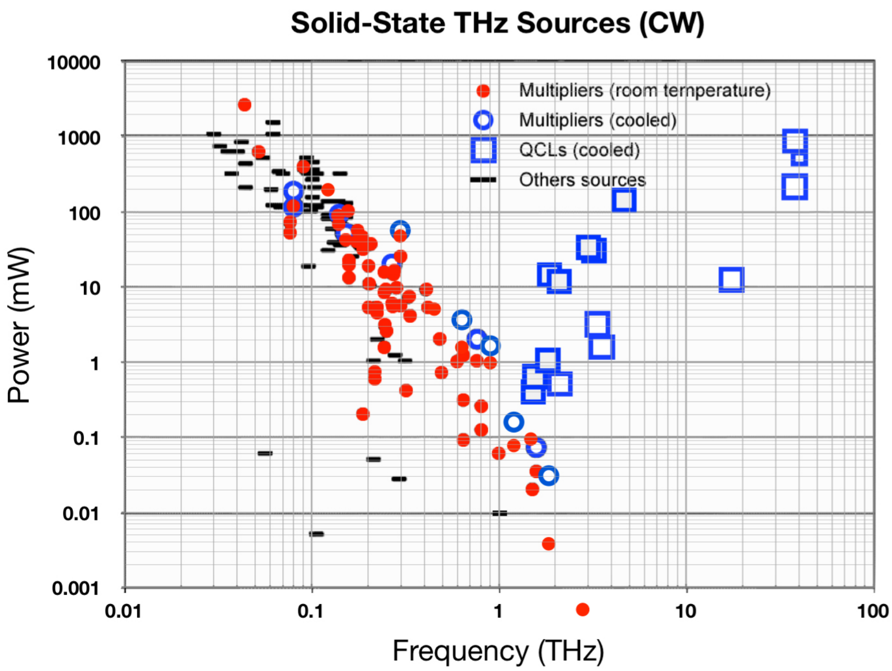

Figure 1. Terahertz gap with respect to source technology. Quantum cascade lasers (□) are progressing downward from higher frequencies, while electronic technology is progressing upward. Frequency multipliers (◯) dominate other electronic devices (-) above about 150 GHz. Cryogenic results are shown as hollow symbols. Adapted from T. Crowe et al., IEEE J. Solid-State Circuits, vol. 40, no. 10, pp. 2104-2110, Oct. 2005. New data added by the author, December 2009

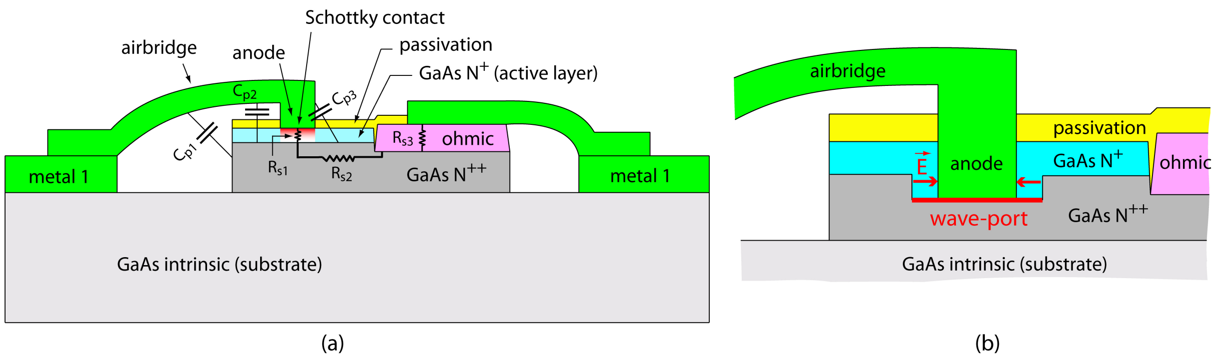

Figure 2. Left view (a): schematic of a planar Schottky diode. C_p stands for parasitic capacitance and R_S for series resistance. Note that R_{S3} is the series resistance introduced by the ohmic contact at DC. At RF the currents flow principally on the surface of the conductors and R_{S3} has a different value. Right view (b): wave port at the location of the Schottky contact as implemented in the electromagnetic field solver. The N^+ layer is modeled as an intrinsic GaAs layer while the N^{++} layer is modeled as a non-perfectly conductive metallic layer. These approximations are made to implement the port that can be seen as an electromagnetic-field probe / emitter.

saturation effects can be mitigated by increasing the doping level but at the expense of other characteristics like the breakdown voltage and the ideality factor of the diode.

2.1.2. *A practical approach of modeling THz Schottky diodes*

Accurately modeling the behavior of the Schottky diode in a real THz planar frequency multiplier is a delicate task. In addition to the physical modeling of the Schottky barrier, which is in itself an active subject of research [11], it is necessary to take into account the three-dimensional (3D) topology of the full diode structure that features a variety of materials ranging from highly doped semiconductors (N^{++} layer) to poorly conductive metals (ohmic contact). As far as the electromagnetic behavior of the diode is concerned, a classical approach is to represent

the Schottky diode barrier in a non-linear circuit simulator and the 3D-circuit around it in a 3D-electromagnetic field solver using a wave-port at the exact location of the Schottky contact [21], [22]. This wave-port is usually a small section of coaxial waveguide, whose outer conductor is buried in the N^{++} doped layer bellow the anode, and whose inner conductor is connected to the anode. The N^{++} doped layer is assimilated to a metal and it terminates the wave port on one side. From that termination, outgoing electromagnetic waves are generated and incoming waves are received so S-parameters can be calculated. This is the equivalent of a 50 Ω micro coaxial cable used to measure, with a real network analyzer, the impedance of the frequency multiplier at the location of the diode, except that the virtual network analyzer is infinitely small and is accommodated inside the 3D structure itself (see Fig. 2b.) The electromagnetic field solver produces S-parameters of the circuit that take into account the parasitic capacitances of the diode at the exclusion of the intrinsic capacitance of the Schottky contact itself. These parameters are then incorporated into the circuit simulator and connected to the non-linear model of the Schottky barrier to reproduce the behavior of the full structure.
However, thermal effects induced by power dissipation strongly affect the behavior of the Schottky barrier itself as well as the ohmic losses in the interconnecting metals. Only electrothermal models of the full circuit can account for these effects [10]. Given the necessity to implement a diode model in a circuit simulator that allows for fast and converging non-linear simulations, a simplified diode model is often employed. This model was used to design the state of the art frequency multipliers presented later in this article. It consists of a nonlinear junction capacitance C_j in parallel with a nonlinear conductance G_j and in series with a resistance R_S.
- *Junction capacitance C_j:* for varactor Schottky diodes, the junction capacitance is classically modeled as follows [23]:
For $V \leq V_j/2$:

$$C_j(V) = \frac{A\epsilon_s}{t(V)} \text{ where } t(V) = \sqrt{\frac{2\epsilon_s}{qN_d}(V_j - V)} \tag{1}$$

For $V \geq V_j/2$, $C_j(V)$ is defined by a linear extrapolation of equation (1) from V=$V_j/2$, to avoid the singularity of equation (1) at V=V_j. V is the bias voltage, V_j the built-in potential, ϵ_s the semiconductor electric permittivity, A the junction area, $t(V)$ the thickness of the depletion layer, q the charge of the electron, and N_D the doping of the semiconductor epilayer. For GaAs Schottky diodes V_j is in the range 0.7V to 0.9V at room temperature. For small anodes a correction term should be added to $C_j(V)$ to take into account edge effects [7].
- *Nonlinear conductance G_j:* the nonlinear conductance is derived from the classic equations of thermionic emission in Schottky contacts [23]. To improve the speed and the stability of the simulations, saturation effects [5], [6], [7], and breakdown effects are not directly included. However, saturation effects are taken into account by an empirical adjustment of the series resistance (see following paragraph), in addition, time domain simulations are performed to check that the voltage across the diodes never enters breakdown to minimize the risk of damaging the diodes [24].
- *Series resistance R_S:* the presence of a series resistance in the diode impacts negatively the efficiency of the frequency multiplier. Significantly underestimating the value of R_S affects the optimization of the design itself: the optimized junction capacitances would be too big and the bias voltage too far in the reverse regime. With respect to the predictions, the actual frequency multiplier performance would be degraded and shifted down in frequency. To partially compensate for the frequency shift, one would have to use devices with smaller anodes. DC measurements of R_S give an indication of the quality of the diodes, but cannot be directly used in this simplified diode model. Actually, as indicated previously, carrier velocity saturation effects are not taken into account directly but have a similar impact on the conversion efficiency as an increase of the series resistance. To indirectly include these effects in the diode model, one approach relies on the rule introduced in [25] that consists in fixing the product $R_s \times Cj(0)$. This value is derived empirically. For frequency multipliers working at room temperature and for a doping of $1{\times}10^{17} cm^{-3}$, R_s is set according to :

$$R_s \times C_j(0) = 120\ \Omega \times fF \tag{2}$$

For multipliers using diodes with higher doping levels, a lower value of the product $R_S \times Cj(0)$ is used. High doping levels are necessary for THz frequency multipliers to reduce saturation effects. A doping of $1 \times 10^{17} cm^{-3}$ can be used up to 600 GHz but doping of $5 \times 10^{17} cm^{-3}$ are generally employed above 900 GHz. Note that the junction capacitance $C_j(0)$ is the single most important diode parameter that controls the working of the frequency multiplier. A difference of 15% between the actual diode capacitance and the optimized value of that capacitance can lead to important bandwidth shifts, or, if the frequency multiplier is designed for a limited bandwidth, to the total disruption of its working due to impedance mismatches. On the other hand, a difference of 15% between the actual diode series resistance and the calculated value according to equation (2) does not generally impact the bandwidth of the frequency multiplier, only its efficiency. This explains why equation (2) can be used in designing frequency multipliers. A general method of design of THz frequency multiplier circuits can be found in [17], [26].

2.2. *Balanced THz frequency multipliers*

Current-voltage symmetry introduced at the device level like in HBV based frequency multipliers greatly simplifies the circuit topology since only odd harmonics are produced and no bias is required. Although, HBVs are effective devices at millimeter wavelengths [13], [27], [28], [29], [30] they never dethroned Schottky diodes nor were demonstrated at THz frequencies. HBV diodes require a very precise engineering of the epilayer and a precise material etch to define the active area, which is harder to achieve for very small dimensions than to create a metal-semiconductor contact. In addition, once integrated in a MMIC-like circuit, HBVs diodes are designed to work for a specific input power, with little flexibility due to the impossibility of biasing them and consequently adjusting their complex impedance.
Symmetries introduced at the circuit level in Schottky-based frequency multiplier can, however, result in the elimination of even or odd harmonics, hence enabling broad-band operations and high conversion efficiencies with the possibility of biasing the devices for increased bandwidth and operational flexibility. At millimeter wavelengths, an efficient balanced doubler topology was introduced by Erickson in [31] and in [21]. This design became a standard and was scaled later up to THz frequencies [32], [33], [34]. Fig. 6 shows a 1500GHz balanced doubler used for the heterodyne instrument of the Herschel Space Observatory. The circuit features two diodes of about xx fF each fabricated on a 3 μm-thin GaAs membrane and mounted on a split-waveguide block. The diodes are located in the input waveguide cavity and are symmetrical with respect to the central conductor line. The fundamental signal propagates on a TE10 mode while the second harmonic is generated on a quasi-TEM mode that cannot be coupled to the input waveguide due to its reduced dimensions. The output signal is then channeled toward the output waveguide through a short section of suspended micro-strip line and a transition. A bias voltage can be applied evenly to the diodes through the central conductor line thanks to an integrated capacitor located at the end of the output waveguide transition.
Balanced triplers featuring an anti-parallel pair of diodes were demonstrated at sub-millimeter wavelengths by Erickson in [31]. The pair of diodes traps the RF currents at even harmonics in a closed loop so the multiplier can generate only odd harmonics. Opening the loop at DC is, however, necessary for biasing the diodes and optimizing the power handling capabilities as well as the conversion efficiency of the frequency tripler. This can only be achieved by either implanting a DC capacitor on top of one of the mesas to insulate the diodes from each other (see Fig. 3), or by opening a deep trench in the middle of one of the mesas to reach the semi-insulating substrate and bring two independent bias lines to the diodes. Both solutions are difficult to implement at THz frequencies due to processing constraints.
Another topology was adopted for building several THz multipliers used in the local oscillators of HIFI [14], [19], [18], [26]. This type of frequency triplers use two diodes, or an even number of diodes, that are in series at DC but that form a virtual loop at RF (see Fig. 4.) As for the anti-parallel configuration, the virtual loop traps the even harmonics of the fundamental, so the multiplier can produce only odd ones. This configuration has the advantage of enabling the building of balanced frequency triplers with more than a pair of diodes for increased power handling capabilities while keeping good phase balance between the diodes; it facilitates also the implementation of a DC bias circuit. However, this configuration requires that the dimensions of the channel that runs between the input and the output waveguides are set to cutoff the TE mode of the suspended microstrip line [26] at the second harmonic, i.e. only a quasi-TEM mode is allowed to propagate inside this channel at the input frequency and at the idler frequency. This condition is usually extended in frequency up to the third harmonic to avoid any risk of coupling part of the output signal to an undesired mode. This condition translate into very small channel cross-sections, as small as approximately 20×40 μm^2, for a 1.9 THz frequency tripler (see Fig. 7.)

2.3. *Development of the local oscillators of Herschel-HIFI*

The Heterodyne Instrument for the Far Infrared (HIFI) is one of the three instruments of the Herschel Space Observatory launched by the European Space Agency in May 2009. It is a very high resolution spectrometer and the first space instrument using superconductive heterodyne receivers. Covering a frequency range from 480

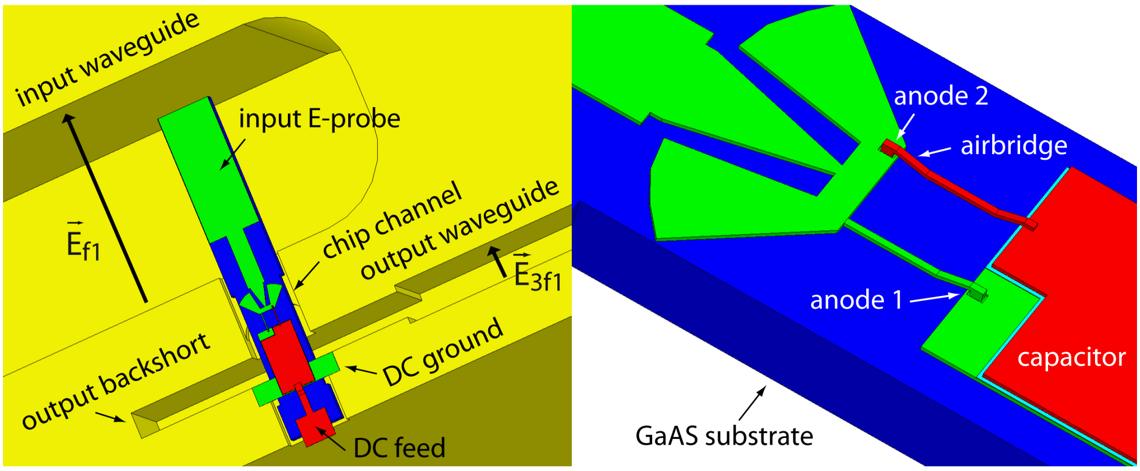

Figure 3. Schematics of a sub-millimeter wave frequency tripler using an anti-parallel pair of diodes. Left : bottom block with the integrated device. Right : detail of the anode area. $\vec{E}_{f1}$ and and $\vec{E}_{3f1}$ stand respectively for the electric field at the fundamental frequency f1 and at the output frequency 3×f1.

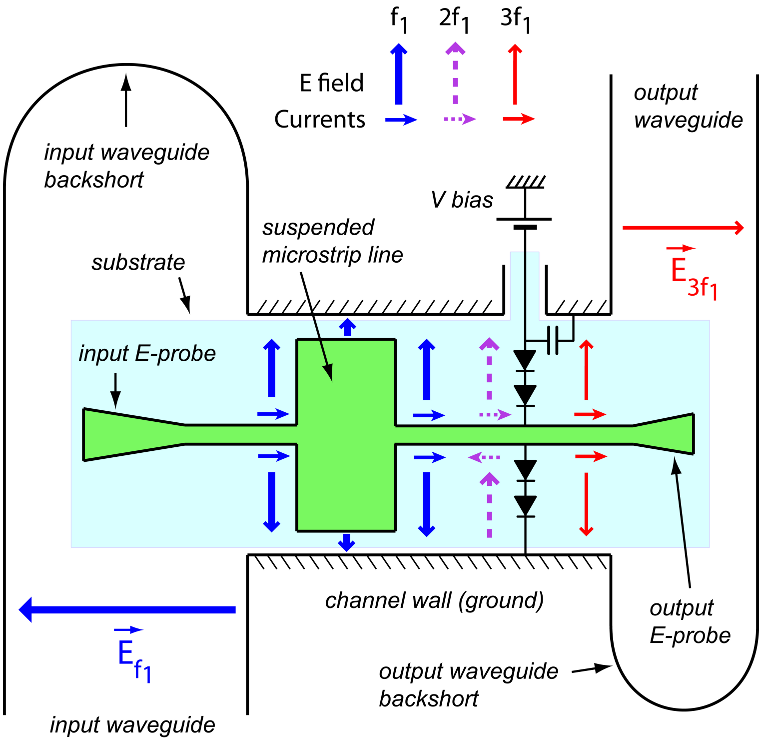

Figure 4. Block diagram of a 4-anode balanced tripler. The tripler uses a split-block waveguide design. The diodes are connected in series at DC and are in a balanced configuration at RF. The chip is inserted between the input and the output rectangular waveguides in a channel. An E-plane probe located in the input waveguide couples the signal at the fundamental frequency to a suspended microstrip line that can propagate only a quasi-TEM mode. This line has several sections of low and high impedances used to match the diodes at the input and output frequency and to prevent the third harmonic from leaking into the input waveguide. The third harmonic produced by the diodes is coupled to the output waveguide by a second E-plane probe. Additional waveguide sections of different impedances and lengths (not shown) are used for the input and output matching. $\vec{E}_{f1}$ and $\vec{E}_{3f1}$ stand respectively for the electric field at the fundamental frequency f1 and at the output frequency 3×f1. The electric fields and the current lines are represented for the fundamental frequency f1 (thick plain lines), the idler frequency 2×f1 (dashed lines) and the output frequency 3×f1 (light plain lines)

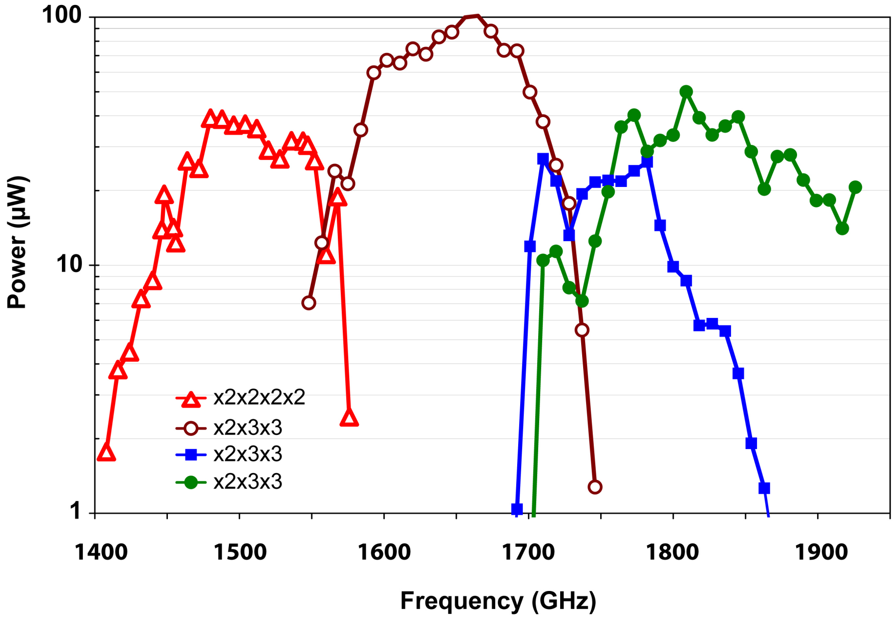

Figure 5. Performance of 1.4-1.6 THz (open triangles), 1.6-1.7THz (open circles) and 1.7-1.9THz (squares and filled circles) local oscillator chains developed for the heterodyne instrument of the Herschel Space Observatory at 120 K

GHz to 1900 GHz and with unprecedented spatial resolution and receiver sensitivities, HIFI has started to probe astrophysical sources via their rotational molecular lines [2].
One of the greatest challenges for HIFI was the building of electronically-tuned local oscillators with sufficient power to pump a pair of Superconductor-Insulator-Superconductor (SIS) mixers in the 480 GHz to 1.3 THz bands and a pair of Hot Electron Bolometer (HEB) mixers in the 1.4-1.9 THz bands (each channel uses two mixers with orthogonal polarizations). A total of 14 local oscillator chains where necessary. For the highest frequency channels, the local oscillators where required to deliver about 2μW of output power over 10% of fractional bandwidth. Starting from a W-band synthesizer module delivering 100 mW to 150 mW at room temperature, the frequency was multiplied three to four times using a $\times2\times2\times2\times2$ scheme for the 1.4-1.6 THz channel or a $\times2\times3\times3$ scheme for the 1.6-1.9 THz channels. Unlike the W-band power modules, the frequency multipliers were passively cooled to 120 K to increase by several fold the output power of the highest frequency local oscillator chains. There is a three-fold reason for this drastic improvement. Firstly, as the device is cooled the GaAs mobility improves thus improving the intrinsic performance of each diode. Secondly, ohmic losses associated with the waveguides and the on-chip matching circuits decrease due to the decrease in phonon scattering. Thirdly, as the drive power increases, the efficiency of the last stage increases significantly since, at room temperature, the last stage is often under-pumped. Fig. 5 shows the performance achieved by Herschel-HIFI local oscillator chains. It must be pointed out that these results far exceeded expectations. Until December 2002, when the first tests of the 1.9THz tripler were performed, it was unclear if the 1.9THz channel would ever be able to provide the required 2μW of power to pump the HEB mixers. Instead, the peak power reached on the 1.6-1.7 THz and 1.7-1.9 THz channels exceeded the needs by a factor 50 and 15 respectively! Unfortunately, as there was no electronic mean to decrease the output power of these local oscillator chains by such a factor, some fixed W-band waveguide attenuators and some fixed THz attenuators had to be implemented in the system to damp down the power and avoid an overdrive of the HEB mixers [36], [37].

2.4. *Power-combined frequency multipliers*

Multi anode frequency multipliers have been introduced at millimeter and submillimeter wavelengths for increased power handling capabilities, which are limited by both the breakdown voltage and the heating of the diodes induced by RF power dissipation. Power combining at the device level is rather limited.. Firstly, only a finite number of diodes can fit on a device due to technological constraints. Secondly, the thickness of the sub-

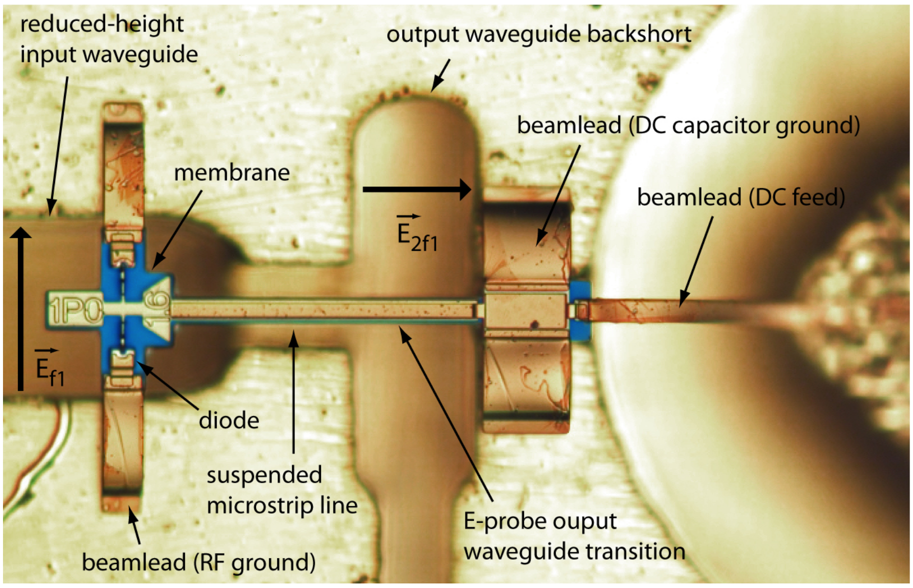

Figure 6. Photograph of JPL 1500GHz doubler used to build the 1.5THz channel of the heterodyne instrument of the Herschel Space Observatory (bottom block with a frame-less 3 μm-thin GaAs membrane device. The chip is approximatively 300 μm long.) $\vec{E}_{f1}$ and and $\vec{E}_{2f1}$ stand respectively for the electric field at the fundamental frequency f1 and at the output frequency 2×f1.

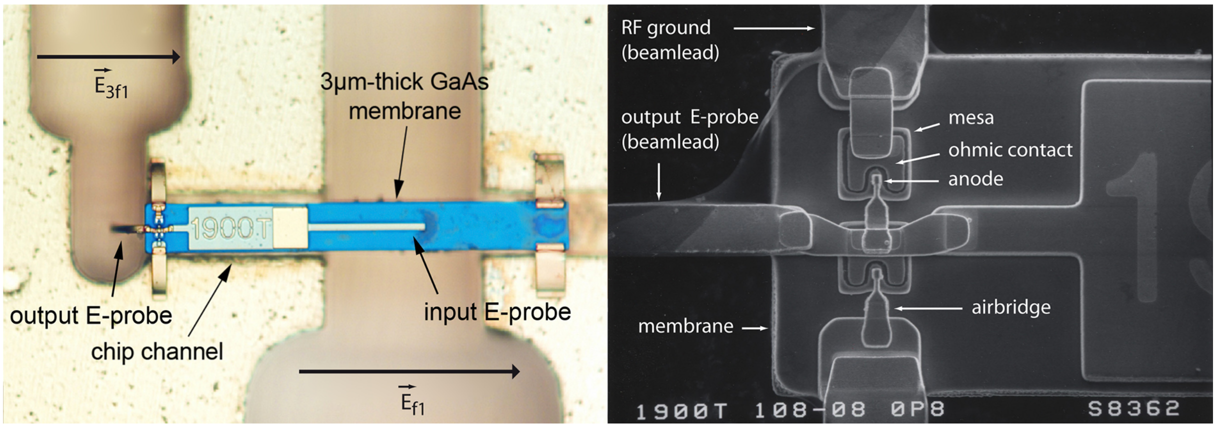

Figure 7. Top view: photograph of JPL 1.9 THz tripler used to build the 1.7-1.9 THz channel of the heterodyne instrument of the Herschel Space Observatory (bottom block with a frame-less 3 μm-thin GaAs membrane device.) $\vec{E}_{f1}$ and and $\vec{E}_{3f1}$ stand respectively for the electric field at the fundamental frequency f1 and at the output frequency 3×f1. The chip is approximatively 290 μm long. Bottom view: SEM picture of a 1.9 THz tripler chip.

strate, which acts as a heat sink, cannot be increased beyond the point where RF performances are significantly degraded, limiting directly the total RF power that can be coupled to the chip. The use of high thermal conductivity substrates such as diamond or aluminum nitride can significantly improve the thermal management, though at the expense of a more complex fabrication process [35]. Thirdly, frequency multipliers with several pairs of anodes are more difficult to balance than those with a single pair, limiting the conversion efficiency of the multiplier for a given input power per anode. A complementary approach is power combing at the circuit level. Several independent devices are integrated in a single (waveguide) circuit using either hybrid couplers or Y-junctions or both. However, RF losses introduced by hybrid couplers at submillimeter wavelengths, as well as fabrication constraints, limit the possibility of power-combining numerous devices efficiently. Y-junctions can allow the power combing of two devices with reduced fabrication constraints with respect to hybrid couplers and virtually no additional losses: the Y-junctions are indeed part of the input and output matching circuits. Recently, an in-phase power combined dual-chip frequency tripler using a compact Y-junction both at the input and output waveguides was

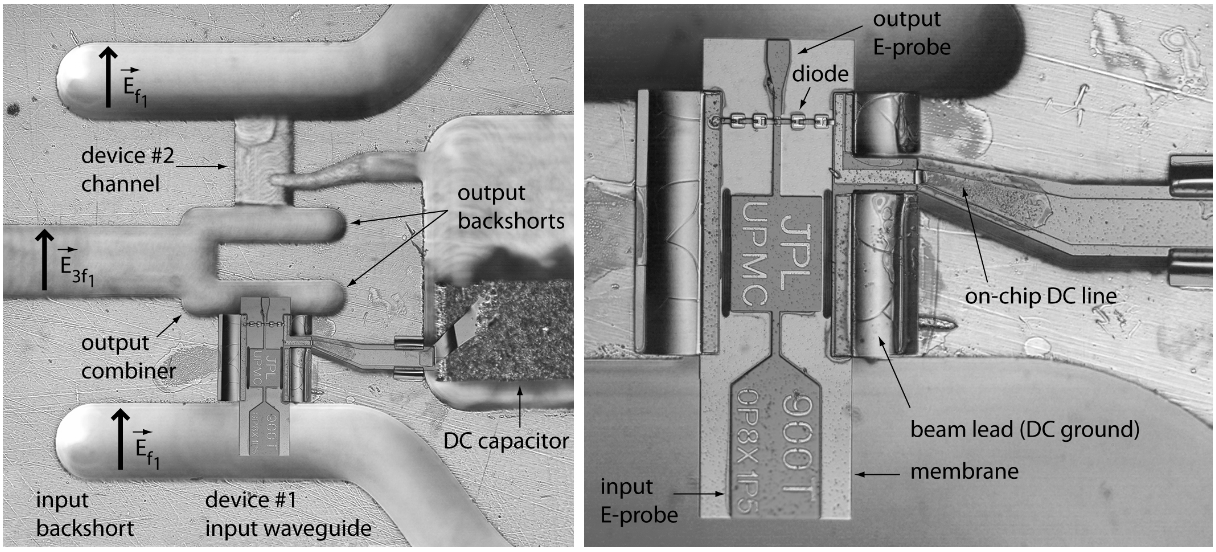

Figure 8. Photograph of the bottom block of a 900 GHz dual chip frequency tripler with one membrane device mounted. The second device is mounted in the top block which is exactly symmetrical. The chip is approximatively 325 μm long and 100 μm wide.

demonstrated at 300 GHz [38]. This frequency tripler produces 26 mW at 318 GHz for a conversion efficiency of 11% and achieves a power combining efficiency of 100%. The same in-phase power combining scheme was later demonstrated at 900 GHz [39] with a dual-chip frequency tripler that produces more than 1 mW in the 840-900 GHz band with a peak power of 1.4 mW at 875 GHz, at room temperature. The driver chain is constituted by a W-band synthesizer followed by a high power W-band amplifier, and a four-chip power-combined 300GHz frequency tripler based on [38] using both integrated hybrid couplers and compact Y-junctions. When pumped with 330-500 mW, the driver chain delivers about 30-50 mW in the 276-321 GHz band. Fig.8 shows a view of the dual-chip 900 GHz frequency tripler.

2.5. *Trends*

A recent study shows that a cascade of Schottky diode-based frequency multipliers have the potential of producing 140 μW at 1600 GHz and 30 μW at 2.4 THz from a 150 mW W-band solid-state source [11], which is significantly higher than the reported state of the art output powers, provided that the anode size, the doping and the thickness of the epilayer of the Schottky diodes are optimized for each individual multiplier. However, the physical dimensions of the mesa, ohmic contact, and airbridge of the Schottky diode as well as RF losses are strong limitations to a proper match of the diode impedance at all the relevant harmonics; as a result only a fraction of that power can, in practice, be produced.

To overcome some of those limitations, diodes for THz frequency multipliers with smaller mesas and interconnecting elements as well as circuits with reduced dielectric load need to be fabricated. But the stronger improvement will likely come from the driver stages at sub-THz frequency. Actually, THz frequency multipliers are currently designed for low input power levels, in the range of 1 mW per anode, and, consequently, feature diodes with small junctions area associated with high series resistances. Improving the drive power to levels in the range of 2 mW to 10 mW per anode for frequency multipliers working in the 1.5-3.0 THz band will dramatically increase the output power since both the conversion efficiency and the input power will be much improved.

To achieve higher power levels from electronic sources at sub-THz frequencies, several paths can be followed simultaneously: one consists in fabricating diodes on gallium nitride (GaN) to increase breakdown voltages to several tens of volts per anode and subsequently to greatly increase the power handling capabilities of frequency multipliers. However, GaN has an electron mobility lower than GaAs, so conversion efficiencies are expected to be lower than those attained with GaAs-based frequency multipliers [40], [41]. The other path is to improve the thermal management of frequency multiplier by transferring the epilayer on high thermal conductivity substrates like CVD diamond [35]. Ultimately, the lower frequency stages of the frequency multiplier chains will be replaced by power amplifiers that are now delivering gain at sub-millimeter wavelengths [42].

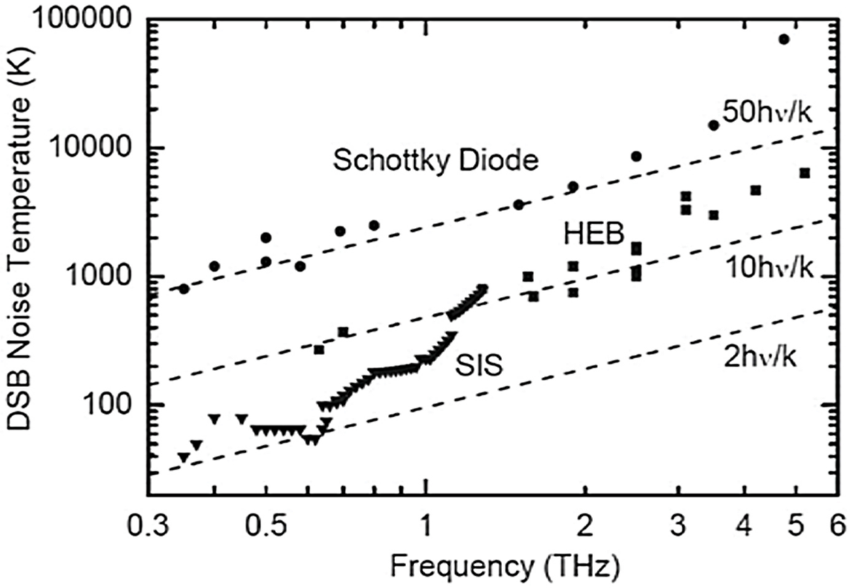

Figure 9. Double sideband (DSB) noise temperature performance of Superconductor Insulator Superconductor (triangles), Hot Electron Bolometer (square), and room-temperature Schottky diode (circle) mixers. The SIS and HEB mixers are cooled between 2 K and 4 K. Also shown are the 2-, 10-, and 50-times quantum noise limit lines for comparison. Reproduced from Chattopadhyay, 2007.

3. Schottky mixers for heterodyne receivers

Despite the progress of submillimeter-wave low noise amplifiers [43], Schottky mixers are still used as the first element of receiver front-ends to down-convert the signal collected by the antenna to microwave frequencies where it can be amplified and analyzed more easily. Schottky mixers have the advantage over other sensor technologies to work at room temperature as well as cryogenic temperatures for improved noise performance, which make them the technology of choice for long term atmospheric and planetary missions. Fig. 9 shows the double side band equivalent mixer noise temperature of mixers depending on the technology and the frequency from 0.3 THz to 6 THz. This graph shows that the sensitivity gap between room temperature Schottky mixers and liquid helium cooled Superconductor Insulator Superconductor (SIS) or Hot Electron Bolometer (HEB) mixers tends to decreases at THz frequencies. This section will first present a practical approach of modeling Schottky mixers before introducing some novel results and trends.

3.1. *Mixer modeling and design*

Mixers can be modeled using a very similar approach as frequency multipliers. The main difference concerns the addition of noise sources in the device model to be able to predict its performance. However, introducing noise sources in the nonlinear simulations during the design of the mixer can prove difficult. Actually, nonlinear simulations with noise analysis are much slower than simulations without noise sources and may present convergence issues. Instead of designing the mixer for best noise performance from the start, the mixer is often designed first for best conversion gain (which is lower than unity for a Schottky mixer) : simulations without noise sources can indeed predict the conversion gain of the mixer. Noise sources are enabled at the end of the process to predict the full performance of the mixer. As explained in details in [44], [45] this approach is possible at the condition that the mixer circuit is designed to maximize the conversion gain while keeping the local oscillator power needed to pump the mixer as low as possible. The later condition ensures that the currents through the diodes are kept close to a minimum, hence ensuring a mixer noise close to a minimum (see following section). This method was employed to design all the mixers presented in the following sessions, in particular a 874 GHz fundamental mixer that exhibits state of the art performance [45]. In practice the local oscillator power can be adjusted to maximize the receiver sensitivity that depends on the noise, the conversion gain of the mixer and the amplifier noise according to the classic Friij formula: for a receiver consisting of a mixer followed by a *matched* low noise amplifier (LNA) connected to the intermediate frequency (IF) port, the equivalent receiver noise temperature is :

$$T_{receiver} = T_{mixer} + \frac{T_{LNA}}{G_{mixer}} \tag{3}$$

where T_{mixer} stands for the mixer equivalent noise temperature, G_{mixer} stands for the mixer gain and T_{LNA} stands for the noise equivalent temperature of the low noise amplifier.

3.2. *Noise sources*

Noise arising from the Schottky barrier is a combination of several sources, some of which are dominating at sub-millimeter wavelengths. At low current levels, the main noise sources are the thermal noise (arising from the random motion of thermally agitated electrons in the epilayer) and the shot noise (arising from the fluctuations of the number of electrons crossing the Schottky barrier)[46]. At high current densities, the electron temperature crossing the barrier is higher than the lattice temperature due to increased kinetic energy, giving rise to excess noise or hot electron noise [47]. This noise source has cyclo-stationary properties and is time varying. In commercial software like the Advanced Design Suite of Agilent, only thermal and shot noises are included in the diode model. In order to take into account the effect of hot electron noise in the total mixer noise predictions, it is important to include an additional noise source in series with the Schottky diode non-linear model [48]. The power spectrum density of this hot electron noise source is proportional to the square of the diode's current. The hot electron noise, as well as the thermal and shot noise, are assumed to be uncorrelated as they arise from different mechanisms. Other types of noises such as intervalley scattering and flicker noise (1/f) are usually negligible at sub-millimeter wavelengths.

3.3. *Schottky mixers for planetology and the sciences of the atmosphere*

Schottky diodes have been used for over a decade to build low-noise mixers for space-borne submillimeter-wave heterodyne instruments. The UARS-MLS, launched in 1991 was one of the first instruments that deployed Schottky diodes for Earth remote sensing. The Submillimeter Wave Astronomy Satellite (SWAS) launched in 1998 by NASA was dedicated to Astrophysics. SWAS featured a 487-493 GHz and 547-557 GHz channels using second harmonic whisker-contacted Schottky diode-based mixers and local oscillators based on an InP Gunn diode followed by a whisker-contacted Schottky diode frequency tripler. The second satellite to employ submillimeter-wave Schottky diode mixers was Odin, launched by the Swedish space agency in 2001. Odin is a mission shared between astrophysics and atmospheric science. It features a sub-millimeter wave channel at 487 GHz based on whisker-contacted Schottky diode, in addition to a millimeter wave channel at 118 GHz employing planar Schottky diodes, to monitor O_2 emission lines in the earth stratosphere. Odin is still operating and delivering important data to the scientific community.

Since these two precursor missions, important technological advances have been made in Schottky diode technology. Remarkably, the The Earth Observing System (EOS) Microwave Limb Sounder (MLS) heterodyne instrument [51], developed at the Jet Propulsion Laboratory, onboard AURA launched in 2004 by NASA, introduced new Schottky diode technologies that were used for building low noise mixers up to THz frequencies. In particular, the EOS-MLS instrument featured a GaAs membrane-based Schottky planar fundamental mixer working at 2.5 THz and pumped by a far infrared laser [52]. The technology developed for building this mixer was later reused and adapted for the THz frequency multipliers employed in the Heterodyne Instrument for the Far Infrared (HIFI) onboard the Herschel Space Observatory. In addition to the 2.5 THz channel, the EOS-MLS instrument features channels at 118 GHz, 190 GHz, 240 GHz, 640 GHz for O_2, H_2O, N_2O, O_2, HCl and OH lines retrieval.

In parallel to the development of EOS-MLS, the Microwave Instrument for the Rosetta Orbiter (MIRO) onboard Rosetta [53], a European Space Agency cornerstone mission for cometary science launched in 2004, was developed by the Jet Propulsion Laboratory with a participation of the Observatoire de Paris. MIRO features two Schottky receiver channels at 190 GHz and 557 GHz to observe H_2O, CO, NH_3 and CH_3OH lines. MIRO is expected to observe the Comet 67P/Churyumov-Gerasimenko in 2014 after a 10 year journey in space. MIRO has already observed successfully the atmosphere of Mars during the several flybys needed by the Rosetta spacecraft to reach its final target.

Future planetary or atmospheric missions employing submillimeter-wave Schottky mixers, are, however, still in the proposal stage. For missions dedicated to the remote sensing of planetary atmospheres like those of Venus, Mars, Jupiter, Ganymede, Saturn and Titan, passive heterodyne instruments employing un-cooled or passively cooled Schottky mixers are envisioned with channels operating in various bands up to 1.2 THz [49]. Due to mass and power constraints, planetary missions do not currently allow more than one or two independent channels being accommodated in the spacecraft. Atmospheric missions, however, do have less power and mass limitations and could embark multi-channel and multi-beam heterodyne instruments. More complex mixers with the capability to separate the lower side and the upper side of the detection band could be also implemented in heterodyne receivers in order to avoid the confusion that may arise at the intermediate frequency when observing the lowest and intermediate layers of the Earth atmosphere where emission or absorption lines are broadend by the pressure. We present in the following sections some recent developments made in the field of sub-millimeter wave Schottky mixers in the anticipation of future space borne instruments.

3.4. *Fundamental vs sub-harmonic Schottky mixers*

Sub-millimeter wave Schottky mixers are of two kinds: fundamental type where the difference between the LO and RF frequencies is only the IF frequency, typically a few GHz, or sub-harmonic type that uses a local oscillator (LO) signal at $1/N$ times the signal radio frequency (RF), with the integer $N \geq 2$. In the later case, the mixing occurs between the N^{th} harmonic of the LO signal and the RF signal. Both types of mixers have historically been developed first using honeycomb whisker-contacted Schottky diodes, and later with planar Schottky diodes that exhibit better mechanical reliability and reproducibility and enable the integration of several diodes in balanced or anti-parallel configurations.

3.4.1. *Fundamental planar Schottky diode mixers*

Fundamental mixers can exhibit better noise performances than sub-harmonic types [50]. However, they require an LO signal at about twice the frequency of their subharmonic type counterparts (for $N = 2$). As seen earlier in this article, the output power of THz electronic sources decreases sharply with the increasing frequency so fundamental mixer pumped by a solid-state source have been only demonstrated up to about 900 GHz [45] due to lack of power. Higher frequency fundamental mixers have been built in the past but were pumped with far infrared gas lasers [52]. To decrease the power needed to pump the fundamental mixer, a bias voltage can be applied to the diodes. For single-ended fundamental mixer, the bias circuit can be easily implemented contrary to fundamental balanced mixers that require on-chip capacitors located near the diodes, which can be a delicate task at THz frequencies. However, single-ended mixers have a single port for coupling both the RF signal and the LO signal requiring a duplexer between the antenna and the mixer input that can be either a beam splitter, a Martin Puplett interferometer or a waveguide coupler, and that inevitably attenuates both the RF signal and the LO signal. Fundamental balanced mixers require two diodes and provide two independent ports for the RF signal and the LO signal removing the need of any duplexer and avoiding the loss of LO power. Fundamental balanced mixers cancel the AM noise injected by the local oscillator but are inherently noisier than single ended mixers since they feature twice the number of diodes. However, the diodes are in a parallel configuration at IF, decreasing the impedance (by a factor two if the diodes are operated at exactly the same bias voltage and pumped with the same LO power), which greatly facilitate the matching of the IF signal with a LNA, specially for THz mixers that exhibit IF impedances much higher than 50 Ω. This lower IF impedance translates in wider IF bandwidth and better effective conversion losses for balanced fundamental mixers than for single-ended mixers. An example of fundamental balanced mixer working in the 840-900 GHz band is shown in Fig. 10. This mixer exhibits state-of-the-art performance with a DSB mixer noise temperature of 2700 K and DSB conversion losses of 9 dB at 850 GHz. It uses approximately 1 mW to 1.5 mW of LO power. The instantaneous RF bandwidth extends from 840 to 900 GHz [45].

3.4.2. *Sub-harmonically pumped planar Schottky diode mixers*

Sub-harmonically pumped mixers are more common than fundamental mixers at frequencies above 150 GHz due to the difficulty, or the cost, of providing a higher frequency local oscillator. The two most common topologies employ a pair of planar Schottky diodes, either in an anti-parallel configuration or in an open loop configuration. These configurations resemble those of the triplers presented in previous sections. The RF signal is mixed with the second harmonic of the LO signal trapped in the diode loop. Subharmonic mixers have many of the advantages of fundamental balanced mixers, in particular independent LO and RF ports, lower IF impedances than single-ended

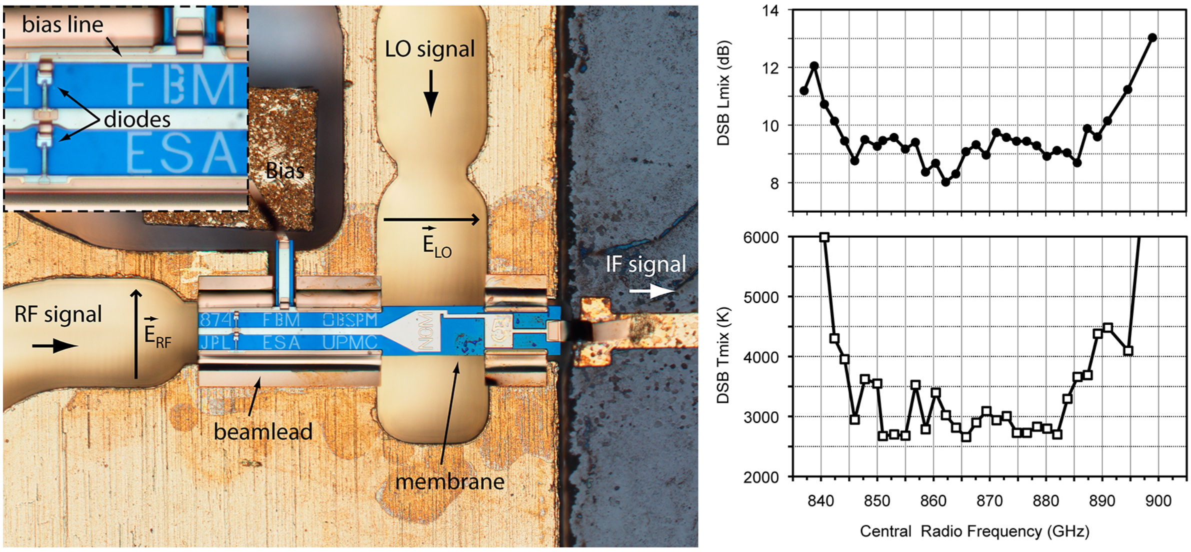

Figure 10. Photograph of a 840-900 GHz fundamental balanced mixer circuit mounted on the lower half of the mechanical block featuring MMIC Schottky diodes device from JPL (left) and associated performance (right). The top-right curve (plain circles) shows the mixer DSB conversion losses Lmix for a radio frequency ranging from 840 GHz to 900 GHz. The bottom-right curve (open squares) shows the corresponding DSB mixer equivalent noise temperature Tmix. $\vec{E}_{RF}$, $\vec{E}_{LO}$ stand respectively for the electric field at RF and LO frequency. The chip is approximatively 530 μm long.

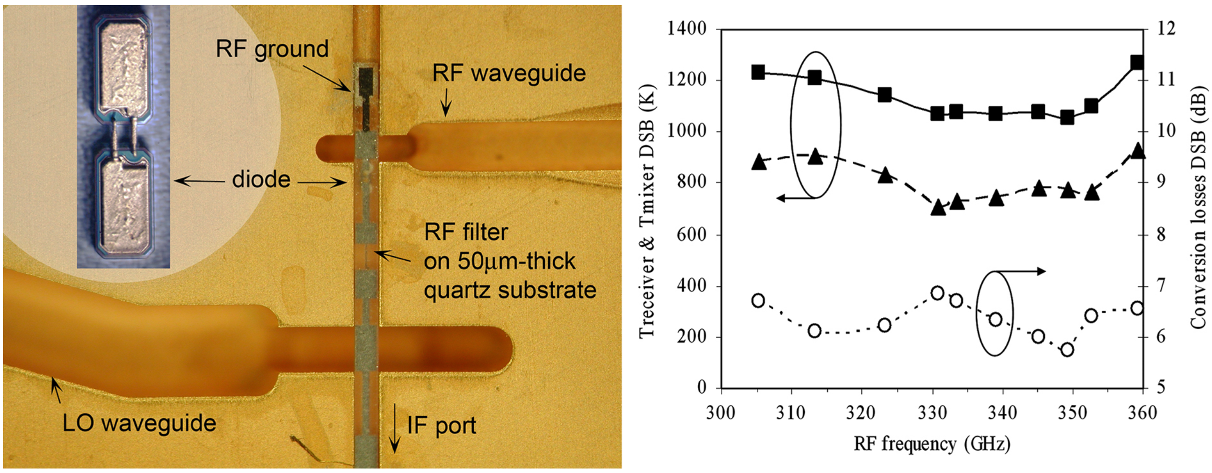

Figure 11. Photo of a 300-360 GHz sub-harmonic mixer circuit mounted on the lower half of the mechanical block featuring a discrete anti-parallel pair of planar Schottky diodes from the University of Virginia (left) and associated performance (right). The discrete chip from the University of Virginia is 70 μm-wide by 200 μm-long and is mounted onto a 50 μm-thick quartz substrate. The mixer was designed and fabricated at the Observatoire de Paris and show state-of-the-art performances in this band

(fundamental) mixers and local oscillator AM noise cancelation. Fig. 11 shows a sub-harmonic mixer working in the 300-360 GHz band designed and fabricated at the Observatoire de Paris with an anti-parallel pair of diodes from the University of Virginia. The diodes are flip-chip mounted onto a 50 μm-thick quartz substrate and glued with a conductive silver epoxy. This mixer exhibits a state of the art Double Side Band (DSB) mixer noise temperature of approximately 700 K and conversion losses of 6.5 dB at 330 GHz [44]. Fig. 12 shows a picture of 183 GHz sub-harmonic mixer featuring integrated planar diodes on a 50 μm-thick GaAs substrate. The devices were fabricated by the industrial and space-qualified French-German foundry United Monolithic Semiconductors (UMS), while the mixer was designed at the Observatoire de Paris. The use of integrated planar devices facilitates the mounting, improves its accuracy, and subsequently improves the repeatability of RF performances. Working on substrates with high effective dielectric constants like GaAs, however, does increase the losses at RF and increases

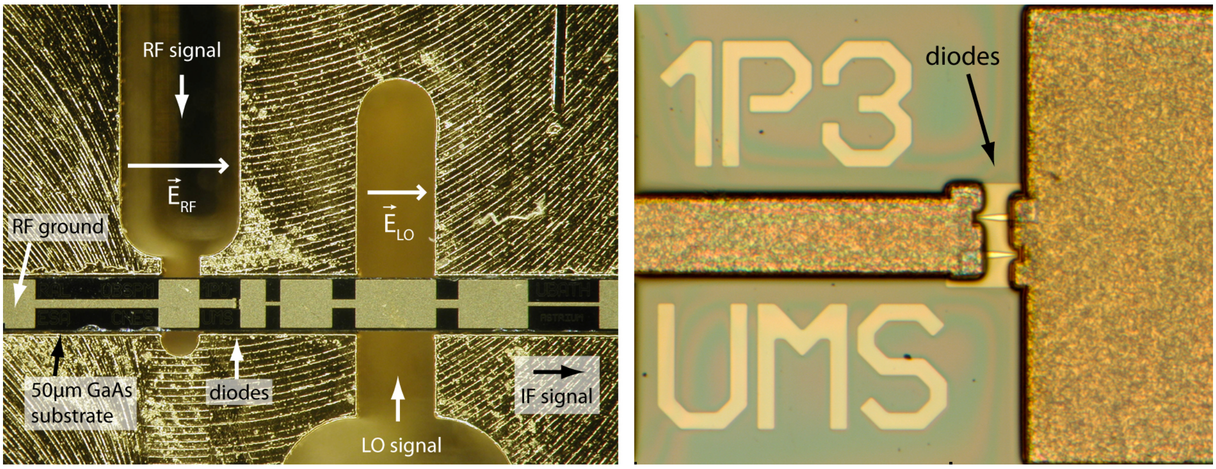

Figure 12. Photo of a 183 GHz sub-harmonic mixer circuit mounted on the lower half of the mechanical block featuring a 4 mm-long MMIC device on a 50 μm-thick GaAs substrate from United Monolithic Semiconductors (left). For the final assembly, the device is actually flipped at 180° and connected to the block using a silver-epoxy conductive glue (so only the back of the device can be seen). The right view shows a closeup of the diode region. This mixer was designed at the Observatoire de Paris.

dispersions which tends to reduce the RF bandwidth. The DSB mixer equivalent noise temperature achieved with integrated UMS Schottky diodes at 183 GHs is in the range of 700-900 K, which is higher than noise temperatures achieved with diodes mounted on a quartz substrate (around 500 K); the difference can also be related to other parameter like the series resistance.

3.5. *Image rejection mixers*

Mixers are inherently double sideband, i.e. they down-convert RF signals at an intermediate frequency F_{IF} equal to $\|F_{RF} \pm F_{LO}\|$ which implies that two signals of different frequencies are down-converted at the same IF frequency causing a superposition of their spectrum. To overcome this problem, a widely employed approach at microwave frequencies is to build sideband separating mixers, also called image rejection mixers, that use two DSB mixers put in quadrature at RF and/or at the LO frequency, and whose IF signals are re-combined at the output ports of an hybrid coupler. Submillimeter-wave image rejection mixers have been developed first for ground-based radio-telescopes using Superconductor-Insulator-Superconductor (SIS) junctions cooled at 4 K or bellow. The extra-circuitry needed to build such mixers makes great use of both the extremely-low RF losses associated with superconducting propagating lines and of the improvement of the conductivity of normal metals when cooling. For instance, the Atacama Large Millimeter Array (ALMA) uses such mixers as baseline for all its channels from 100 GHz to 900 GHz. Submillimeter-wave Schottky image rejection mixers, however, are much less common. They suffer from the difficulty to fabricate low-loss hybrid couplers, dividers and combiners that work at room temperature. One recent example of a 330 GHz sub-harmonicaly pumped image rejection mixer is presented in [54].

3.6. *Trend : integrated mixer-multiplier devices for arrays*

Regardless of the device technology employed, arrays of heterodyne receivers are the subject of intense research. Heterodyne arrays are indeed needed by astronomers to map more rapidly extended astrophysical sources and to decrease the gap with existing direct detector arrays that provide a much larger field of view for the same telescopes. Arrays are equally needed for acquiring near-real time images of the Earth's atmosphere from a geo-stationary satellite. Dealing extensively with such a vast subject would require a dedicated article. This section will only present recent works that focus on reducing the size of single elements of a Schottky diode-based heterodyne arrays.

In order to build linear or two-dimensional arrays of heterodyne receivers using Schottky devices, it is highly desirable to integrate the mixer with the last stage of the local oscillator, which at submillimeter wavelengths is either a frequency doubler or a frequency tripler. Such an integration can lead to significant reduction in size and mass of single pixel front-end elements, at the potential benefit of the pixel density of the array. Integrating a frequency multiplier and a mixer in a compact architecture also reduces waveguide losses, improves coupling efficiencies between devices, and reduces overall power consumption. There are two levels of mixer-frequency multiplier integration.

The first one consists in using independent chips for the mixer stage and the frequency multiplier stage. The circuits resemble those presented previously but are linked by a common waveguide whose length can be reduced to a minimum since no interface is required between the mixer and the frequency multiplier. A more advanced technique consists in optimizing together the output matching network of the frequency multiplier with the local oscillator input matching network of the mixer. It is equally possible to pump several mixers with a single frequency multipliers using compact Y-junction dividers [55]. These approaches are similar and present the advantage of allowing a two-step optimization procedure where each sub-circuits are optimized independently before the coupling between them is optimized. The other significant advantage is the presence of a rectangular waveguide between the frequency multiplier and the mixer that insulate them at DC allowing an easy implantation of two independent bias circuits, and, very importantly, that cutoff any leakage of the input signal of the frequency multiplier stage, so the mixer is pumped by a pure LO signal.

The second level of integration consists in implanting both the frequency multiplier and the mixer on the same substrate to further reduce the size of the overall structure. In that case, both sub-circuits need to be designed together from the beginning since they share a common matching and filtering network. This approach is indeed much more complex than the previous one and suffers from the absence of natural isolation between the two stages. A high-pass filter needs therefore to be inserted between the two sub-circuits which is not easily feasible at sub-millimeter wavelengths due to the RF losses that this filter introduces. In addition, if a monolithic process is used to fabricate the circuit, a compromise needs to be found between the noise performance of the mixer sub-circuit and the conversion efficiency of the frequency multiplier sub-circuit, since they share the same epilayer structure. This type of circuit was first introduced at submillimeter wavelengths in [56] by integrating a 190 GHz frequency doubler and a 380 GHz sub-harmonic mixer on a single chip, using discrete Schottky planar diodes flip-chip mounted on a quartz substrate. Similarly, an ongoing study at the Observatoire de Paris is aimed at integrating a 165 GHz frequency tripler with a 330 GHz subharmonic mixer for building a compact bi-dimensional heterodyne array dedicated to observe the Earth atmosphere. Fig. 13 shows a 3D view of this circuit as currently modeled in the 3D-electromagnetic field solver. It uses two discrete planar chips fabricated at the Rutherford Appleton Laboratory and flip-chip mounted on a quartz substrate featuring a T-shape and gold-beam-leads for an accurate RF-grounding [57].

4. Planar Schottky diode processes in the USA and in Europe

While planar Schottky diodes were first introduced at the University of Bath, UK [59], they were essentially developed and brought to a great degree of maturity in the USA during the 1990's, first at the University of Virginia (which spun-off Virginia Diodes Inc. that is now commercializing diodes), and later at the Jet Propulsion Laboratory (JPL), whose state of the art Schottky diode process is presented extensively in [52], [60], [17]. In Europe, several ongoing programs sponsored by the European Space Agency and the European Union are aimed to produce high quality devices for sub-millimeter wave applications. Several groups or companies like the University of Chalmers, the Advanced Compound Semiconductor Technologies (ACST) GmbH in Darmstadt, the Rutherford Appleton laboratory in UK are now fabricating high quality Schottky diode-based circuits working at sub-THz frequencies. In addition, the French-German commercial foundry United Monolithic Semiconductors can be used up to frequencies around 200 GHz [58].

Recently, the Observatoire de Paris - LERMA and CNRS, Laboratoire de Photonique et de Nanostructure, with the support of CNES and EADS-ASTRIUM, initiated the development of a Schottky diode process entirely based on e-beam lithography to fabricate devices for THz mixers or frequency multipliers. The starting material is a semi-insulating $500\mu m$ GaAs substrate with epitaxial layers grown at LPN by Metal-Organic Chemical Vapor Deposition (MOCVD) or Molecular Beam Epitaxy (MBE). Several AlGaAs etch-stop layers are inserted in the epilayer structure to allow the fabrication, with the same wafer, of membrane-based circuits of different thicknesses. The first step of the processing is a selective AlGaAs/GaAs wet etching used to define the device mesas. Then the ohmic contacts are formed: the N^+ GaAs layer is recessed, Ni/Ge/Au metal films are successively evaporated and a rapid thermal annealing is performed. For the formation of the air-bridges and the anodes/connection pads, the process consists first in exposing and reflowing a square of resist to form the support for the air-bridges.

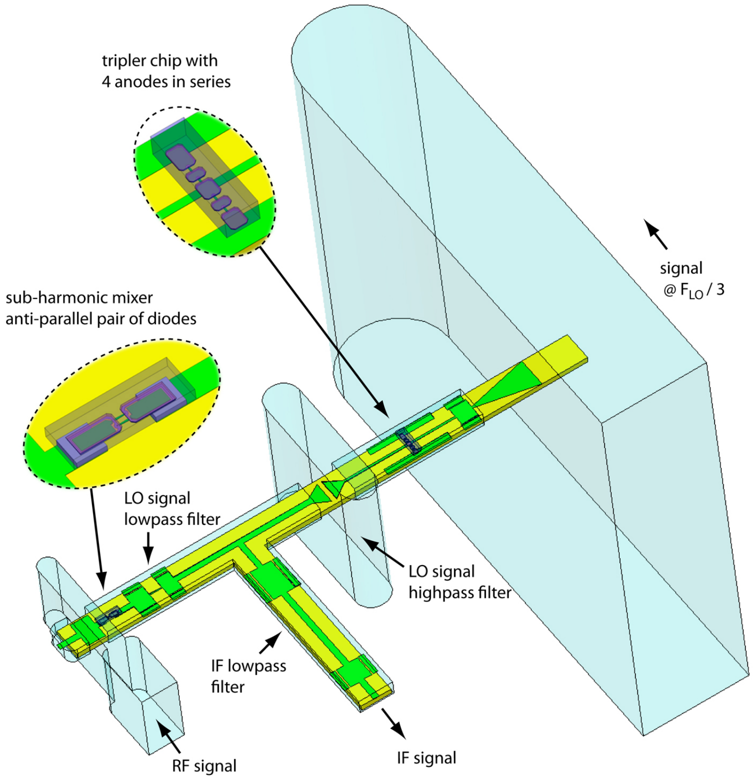

Figure 13. 3D view of the circuit as modeled in the 3D-electromagnetic field solver. In this model, the RF waveguide, the IF channel and the LO input waveguide are all coming from the same side since it does not have any impact on the simulations. For the fabrication of the circuit, however, one of the waveguides or the IF channel has to be rotated by 180° or bent at 90°.

The anodes are then fabricated using two layers of resists. Finally, Ti/Au metal film is evaporated to make the Schottky contacts and connection pads. The diodes are then passivated using Si_3N_4 deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD). The last step consists in separating the circuits by a deep dry etching using Inductive Coupled Plasma (ICP)- Reactive Ion Etching (RIE) up to a depth of $50\mu m$ depending on the membrane thickness. This process, which is still being optimized, was used for fabricating a 300-360 GHz mixer that exhibits a DSB equivalent noise temperature of 1800 K at room temperature. These are the first planar Schottky diodes successfully tested at RF in France. Details on the process can be found in [61]. Fig.14 shows a picture of an antiparallel pair of Schottky diodes fabricated at LPN and employed in that mixer.

5. Conclusion

GaAs Schottky diode technology has advanced dramatically in the last few years to enable power generation via frequency multiplication well into the terahertz frequency range. To further increase power levels above 1THz, the priority is currently set on improving the power handling capabilities of the driver stages at millimeter wavelengths, firstly by using advanced power combining schemes, secondly by improving the thermal management at the chip level and finally by exploring new materials. In parallel, these advances in Schottky diode technology have enabled the building of low-noise frequency mixers up to 2.5 THz for planetary and atmospheric sciences. The focus is now put on the construction of arrays of heterodyne receivers, which will require a high level of integration between the various components of the receiver.

References

[1] P.H. Siegel, Terahertz Technology, IEEE Trans. Microw. Theory and Tech., Vol. 50, no. 3, March 2002.

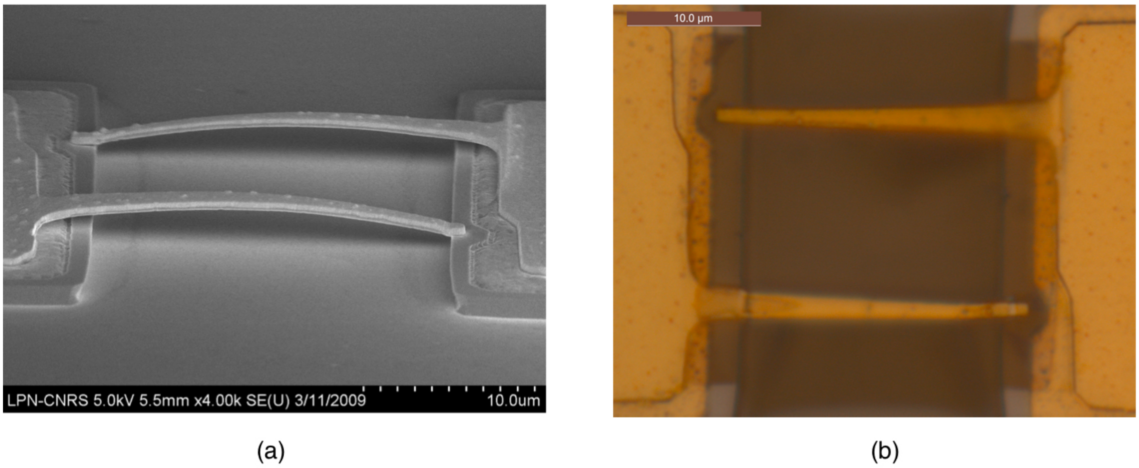

Figure 14. SEM picture of an antiparallel pair of Schottky diodes fabricated at LPN for a 300-360GHz sub-harmonic mixer (a) and optical picture of a similar diode.

[2] H. van de Stadt, Detectors for the Heterodyne Spectrometer of FIRST, Proceedings of the ESA Symposium “The Far Infrared and Submm Universe”, P. 457, Grenoble, April 15-17, 1997.

[3] G.L. Pilbratt, The Herschel mission, scientific objectives, and this meeting, in Proc. Eur. Space Agency Symp., ESA paper SP-460, pp. 1320, Dec. 2000.

[4] I. Mehdi, P. H. Siegel, J. East, Improved millimeter-wave mixer performance analysis using a drift diffusion capacitance model, Microwave Symposium Digest, 1991, IEEE MTT-S International, vol. 2, pp. 887-890, 1991.

[5] E. L. Kollberg, T. J. Tolmunen, M. A. Frerking, and J. R. East, Current saturation in submillimeter wave varactors, IEEE Trans. Microw. Theory Tech., vol. 40, no. 5, pp. 831-838, May 1992.

[6] T. W. Crowe, W. C. B. Peatman, R. Zimmermann, and R. Zimmermann, Consideration of velocity saturation in the design of GaAs varactor diodes, IEEE Microw. Guided Wave Lett., vol. 3, no. 6, pp. 161-163, Jun. 1993.

[7] J. T. Louhi and A. V. Räisänen, On the modeling and optimization of Schottky varactor frequency multipliers at submillimeter wavelengths, IEEE Trans. Microw. Theory and Tech., vol. 43, no. 4, pp. 922-926, Apr. 1995.

[8] J. T. Louhi and A. V. Räisänen, Dynamic shape of the depletion layer of a submillimeter-wave Schottky varactor, IEEE Trans. Microw. Theory Tech., vol. 44, no. 12, pp. 2159-2165, Dec. 1996.

[9] J. Grajal, V. Krozer, E. Gonzalez, F. Maldonado, and J. Gismero, Modeling and design aspects of millimeter-wave and submillimeter-wave schottky diode varactor frequency multipliers, IEEE Trans. Microw. Theory and Tech., vol. 48, no. 4, pp. 700-712, Apr. 2000.

[10] E. Schlecht, G. Chattopadhyay, A. Maestrini, D. Pukala, J. Gill, and I. Mehdi, Harmonic balance optimization of terahertz Schottky diode multipliers using an advanced device model, in Proc. 13th Int. Symp. Space Terahertz Technology, Cambridge, MA, Mar. 2002, pp. 187-196.

[11] José V. Siles, and Jesús Grajal, Physics-based design and optimization of Schottky diode frequency multipliers for THz applications, to appear in IEEE Trans. Microw. Theory and Tech., Special Issue on “THz Technology: Bridging the Microwave-to-Photonics Gap”, July 2010.

[12] P. Penfield, R.P. Rafuse, Varactor Applications, Chapter 8: Harmonic Multipliers, MIT Press, 1962.

[13] A. Rydberg, H. Grönqvist and E. Kollberg, Milllimeter and Submillimeter-Wave Multipliers using Quantum Barrier-Varactor (QBV) Diodes, IEEE Electron Device Letters, Vol. 11, pp. 373-375, September 1990.

[14] J. Bruston, A. Maestrini, D. Pukala, S. Martin, B. Nakamura and I. Mehdi, A 1.2 THz planar tripler using GaAs membrane based chips, in Proc. 12th International Symposium on Space Terahertz Technology, pp 310-319, San Diego, February 14-16, 2001.

[15] A. Maestrini, J. Bruston, D. Pukala, S. Martin and I. Mehdi, Performance of a 1.2 THz Frequency Tripler using a GaAs Frameless Membrane Monolithic Circuit, Microwave Symposium Digest, 2001, IEEE MTT-S International, Vol. 3, pp. 1657-1660, Phoenix, Arizona, May 20-25, 2001.

[16] F. Maiwald, E. Schlecht, A. Maestrini, G. Chattopadhyay, J. C. Pear-son, D. Pukala, and I. Mehdi, THz Frequency Multiplier Chains Based on Planar Schottky Diodes, Proceedings of SPIE: International Conference on Astronomical Telescopes and Instrumentation, Vol. 4855, pp. 447-458, Waikoloa, Hawaii, August 22-28, 2002.

[17] G. Chattopadhyay, E. Schlecht, J. Ward, J. Gill, H. Javadi, F. Maiwald, and I. Mehdi, An all solid-state broadband frequency multi-plier chain at 1500 GHz, IEEE Trans. Microw. Theory and Tech., Vol. 52, no. 5, pp. 1538-1547, May 2004.

[18] A. Maestrini, J. S. Ward, H. Javadi, C. Tripon-Canseliet, J. Gill, G. Chattopadhyay, E. Schlecht, and I. Mehdi, Local Oscillator Chain for 1.55 to 1.75 THz with 100 μW Peak Power, IEEE Microw. Wireless Compon. Lett., Vol. 15, no. 12, pp. 871-873, Dec. 2005.

[19] A. Maestrini, J. Ward, J. Gill, H. Javadi, E. Schlecht, G. Chattopadhyay, F. Maiwald, N.R. Erickson, and I. Mehdi, A 1.7 to 1.9 THz Local Oscillator Source, IEEE Microw. Wireless Compon. Letters, Vol. 14, no. 6, pp. 253-255, June 2004.

[20] J. T. Louhi, A. V. Raisanen, and N. R. Erickson, Cooled Schottky varactor frequency multipliers at submillimeter wavelengths, IEEE Trans. Microw. Theory and Tech., Vol. 41, no. 4, pp. 565-571, Apr. 1993.

[21] J. Tuovinen, N.R. Erickson, Analysis of a 170 GHz frequency doubler with an array of planar diodes, IEEE Trans. Microwave Theory Tech., Vol. 43, no. 4, pp. 962-968, April 1995.

[22] J. L. Hesler, Planar Schottky diodes in submillimeter-wavelength wave-guide receivers, Ph.D. dissertation, Univ. Virginia, Charlottesville, Jan. 1996.

[23] G. Massobrio and P. Antognetti, Semiconductor device modeling with SPICE, New York: McGraw-Hill, Second Edition 1993.

[24] F. Maiwald, E. Schlecht, J. Ward, R. Lin, R. Leon, J. Pearson, and I. Mehdi, Design and operational considerations for robust planar GaAs varactors: A reliability study, in Proc. 14th International Symposium on Space Terahertz Technology, Tucson, AZ, April 2003.

[25] N.R. Erickson, Diode frequency multipliers for terahertz local-oscillator applications, in Proc. SPIE: Advanced Technology MMW, Radio, and Terahertz Telescopes, Vol. 3357, Kona, HI, pp. 75-84, March 1998.

[26] A. Maestrini, J. Ward, J. Gill, H. Javadi, E. Schlecht, C. Tripon-Canseliet, G. Chattopadhyay and I. Mehdi, A 540-640 GHz High Efficiency Four Anode Frequency Tripler, IEEE Trans. Microwave Theory and Tech., Vol. 53, pp. 2835-2843, Sept. 2005.

[27] X. Mélique, A. Maestrini, P. Mounaix, M. Favreau, G. Beaudin, G. Goutoule, T. Närhi and D. Lippens, Fabrication and performance of InP-based Heterostructure Barrier Varactors in a 250 GHz Waveguide Tripler, IEEE Trans. Microwave Theory Tech., Vol. 48, no. 6, pp 1000-1006, June 2000.

[28] M. Saglam, B. Schumann, K. Duwe, C. Domoto, A. Megej, M. Rodríguez-Gironés, J. Müller, R. Judaschke, and H. L. Hartnagel, High-performance 450-GHz GaAs-based heterostructure barrier varactor tripler, IEEE Electron Device Letters, Vol.24, no. 3, pp. 138-140, March 2003.

[29] Q. Xiao, Y. Duan, J.L. Hesler, T.W. Crowe, R.M. Weikle II, A 5mW and 5% efficiency 210 GHz InP-based heterostructure barrier varactor quintupler, IEEE Microwave and Wireless Components Letters, Vol.14,no. 4 , pp. 159-161,April 2004.

[30] T. Bryllert, A. Olsen, J. Vukusic, T.A. Emadi, M. Ingvarson, J. Stake, D. Lippens, 11% efficiency 100 GHz InP-based heterostructure barrier varactor quintupler, Electronics Letters, Vol. 41, no. 3, pp. 131132, February 2005.

[31] N.R. Erickson, High efficiency submillimeter frequency multipliers, in Proc. IEEE MTT-S International, pp.1301-1304, 1990.

[32] D.W. Porterfield, T. W. Crowe, R. F. Bradley, N. R. Erickson, A high-power fixed-tuned millimeter-wave balanced frequency doubler, IEEE Trans. Microwave Theory and Tech., Vol.47, no 4, pp. 419-425, 1999.

[33] E. Schlecht, G. Chattopadhyay, A. Maestrini, A. Fung, S. Martin, J. Bruston, and I. Mehdi, 200, 400, and 800 GHz Schottky Diode Substrateless Multipliers: Design and Results, 2001 IEEE MTT-S International Microwave Symposium Digest, Phoenix, AZ, pp. 1649-1652, May 2001.

[34] G. Chattopadhyay, E. Schlecht, J. Gill, S. Martin, A. Maestrini, D. Pukala, F. Maiwald, and I. Mehdi, A Broadband 800 GHz Schottky Balanced Doubler, IEEE Microwave and Wireless Components Letters, vol.12, no.4, pp.117-118, April 2002.

[35] C. Lee, J. Ward, R. Lin, E. Schlecht, G. Chattopadhyay, J. Gill, B. Thomas, A. Maestrini, I. Mehdi, and P. Siegel, A Wafer-Level Diamond Bonding Process To Improve Power Handling Capability of Submillimeter-wave Schottky Diode Multipliers, in Microwave Symposium Digest, 2009 IEEE MTT-S International, pp. 957-960, Boston, 7-12 June, 2009.

[36] J. W. Kooi, J. J. A. Baselmans, A. Baryshev, R. Schieder, M. Hajenius, J. R. Gao, T. M. Klapwijk, B. Voronov,G. Gol'tsman, Stability of heterodyne terahertz receivers, Journal of Applied Physics, Vol. 100, no 6, 2006.

[37] J. W. Kooi, V. Ossenkopf, M. Olberg, R. Shipman, R. Schieder, and D. Teyssier, HIFI Stability as Measured During ILT Phase, proceedings of the 19th International Symposium on Space Terahertz Technology, Groningen, 28-30 April, 2008.

[38] A. Maestrini, J.S. Ward, C. Tripon-Canseliet, J.J. Gill, C. Lee, H. Javadi, G. Chattopadhyay and I. Mehdi, In-Phase Power-Combined Frequency Triplers at 300 GHz, IEEE Microw. Wireless Compon. Lett., Vol. 18, no. 3, pp. 218220, March 2008.

[39] A. Maestrini, J.S. Ward, J.J. Gill, C. Lee, B. Thomas, R.H. Lin, G. Chattopadhyay, and Imran Mehdi, A Frequency-Multiplied Source with more than 1 mW of Power across the 840-900GHz Band, to be published in IEEE-MTT Special Issue on "THz Technology: Bridging the Microwave-to-Photonics Gap", 2010.

[40] F. Schwierz, An electron mobility model for wurtzite GaN, Solid-State Electronics, vol. 48, no. 6, pp. 889-895, June 2005.

[41] J. V. Siles and J. Grajal, Capabilities of GaN Schottky multipliers for LO Power Generation at Millimeter-Wave Bands, 19th International Symposium on Space Terahertz Technology, pp. 504-507, April 2008.

[42] R. Lai, W. R. Deal, V. Radisic, K. Leong, X. B. Mei, S. Sarkozy, T. Gaier, L. Samoska, A. Fung, Sub-MMW active integrated circuits based on 35 nm InP HEMT technology, IEEE International Conference on Indium Phosphide & Related Materials, IPRM '09, 2009.

[43] T. Gaier, L. Samoska, A. Fung, W. R. Deal, V. Radisic, X. B. Mei, W. Yoshida, P. H. Liu, J. Uyeda, M. Barsky, and R. Lai, Measurement of a 270 GHz low noise amplifier with 7.5 dB noise figure, IEEE Microw. Wireless Compon. Lett., Vol. 17, no. 7, 2007.

[44] B. Thomas, A. Maestrini, and G. Beaudin, A Low-Noise Fixed-Tuned 300-360 GHz Sub-Harmonic Mixer using Planar Schottky Diodes, IEEE Microwave and Wireless Component Letters, Vol. 15, no. 12, pp. 865-867, December 2005.

[45] B. Thomas, A. Maestrini, J. Gill, C. Lee, R. Lin, I. Mehdi, and P. de Maagt, A Broadband 835-900 GHz Fundamental Balanced Mixer Based on Monolithic GaAs Membrane Schottky Diodes, to appear on IEEE-MTT Special Issue on "THz Technology: Bridging the Microwave-to-Photonics Gap", 2010.

[46] M.T. Faber, J. Chramiec and M. E. Adamski, Microwave and Millimeter-Wave Diode Frequency Multipliers, Edition: Artech House Microwave Library, pp. 46-62, 1995.

[47] T.W. Crowe and R.J. Mattauch, Analysis and Optimization of Millimeter - and Submillimeter-Wavelength Mixer Diodes, IEEE Trans. on Microw. Theory and Tech., Vol. MTT-35, no. 2, pp.159-168, Feb. 1987.

[48] B. Thomas, A. Maestrini, J. C. Orlhac, J. M. Goutoule and G. Beaudin, Numerical analysis of a 330 GHz sub-harmonic mixer with planar Schottky diodes, proceedings of the 3rd ESA workshop on millimetre-wave technology and techniques, Espoo, Finland, May 21-23, 2003.

[49] P. Hartogh, et al., Submillimeter Wave Instrument for EJSM, presented at the Europa Jupiter System Mission Instrument Workshop, July 15-17, 2009, Maryland, USA (http://opfm.jpl.nasa.gov).

[50] A.R. Kerr, Low-Noise Room-Temperature and Cryogenic Mixers for 80-120 GHz, IEEE Trans. on Microw. Theory and Tech., Vol. 23, No. 10, pp. 781-787, October 1975.

[51] J. W. Waters, L. Froidevaux, R. S. Harwood, R. F. Jarnot, H. M. Pickett, W. G. Read, P. H. Siegel, R. E. Cofield, M. J. Filipiak, D. A. Flower, J. R. Holden, G. K. Lau, N. J. Livesey, G. L. Manney, H. C. Pumphrey, M. L. Santee, D. L. Wu, D. T. Cuddy, R. R. Lay, M. S. Loo, V. S. Perun, M. J. Schwartz, P. C. Stek, R. P. Thurstans, M. A. Boyles, K. M. Chandra, M. C. Chavez, G.-S. Chen, B. V. Chudasama, R. Dodge, R. A. Fuller, M. A. Girard, J. H. Jiang, Y. Jiang, B. W. Knosp, R. C. LaBelle, J. C. Lam, K. A. Lee, D. Miller, J. E. Oswald, N. C. Patel, D. M. Pukala, O. Quintero, D. M. Scaff, W. Van Snyder, M. C. Tope, P. A. Wagner, and M. J. Walch, The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura Satellite, IEEE Tran. Geoscience and Remote Sensing, Vol. 44, no. 5, pp. 1075-1092, 2006.

[52] P. H. Siegel, R. P. Smith, M. C. Gaidis, and S. C. Martin, 2.5-THz GaAs Monolithic Membrane-Diode Mixer, IEEE Trans. Microwave Theory and Tech., Vol. 47, no. 5, pp. 596-604, 1999.

[53] S. Gulkis, M. Frerking, J. Crovisier, G. Beaudin, P. Hartogh, P. Encrenaz, T. Koch, C. Kahn, Y. Salinas, R. Nowicki, R. Irigoyen, M. Janssen, P. Stek, M. Hofstadter, M. Allen, C. Backus, L. Kamp, C. Jarchow, E. Steinmetz, A. Deschamps, J.M. Krieg, M. Gheudin, D. Bockelée-Morvan, N. Biver, T. Encrenaz, D. Despois, W. Ip, E. Lellouch, I. Mann, D. Muhleman, H. Rauer, P. Schloerb and T. Spilker, MIRO: Microwave Instrument for Rosetta Orbiter, Space Science Reviews, Vol. 128, no 1-4, pp. 561-597, 2007.

[54] B. Thomas, S. Rea, B. Moyna, B. Alderman and D. Matheson, A 320-360 GHz Sub-Harmonically Pumped Image Rejection Mixer Using Planar Schottky Diodes, IEEE Microw. Wireless Compon. Lett., Vol. 19, no. 2, pp-101-103, 2009.

[55] H. Wang, A. Maestrini, B. Thomas, B. Alderman, and G. Beaudin, Development of a two-pixel integratedheterodyne Schottky diode receiver at 183 GHz, proceedings of the 19th Int. Symp. on Space THz Technology, Poster P6.5, pp. 490-493, Groningen, the Netherlands, April 28-30, 2008.

[56] B. Thomas, B. Alderman, D. Matheson and P. de Maagt, A Combined 380 GHz Mixer/Doubler Circuit based on Planar Schottky Diodes, IEEE Microw. Wireless Compon. Lett., Vol.18, no.5, pp. 353-355, 2008.

[57] J. Treuttel, A. Maestrini, B. Alderman, H. Wang, D. Matheson, P. De Maagt, Design of a combined tripler-subharmonic mixer at 330 GHz for multipixel application using European Schottky diodes, to appear in Proc. 21^{th} International Symposium on Space Terahertz Technology, Oxford, UK, 23-25 March, 2010.

[58] B. Alderman, H. Sanghera, B. Thomas, D. Matheson, A. Maestrini, H. Wang, J. Treuttel, J. V. Siles, S. Davies & T. Närhi, Integrated Schottky Structures for Applications Above 100 GHz, proceedings of the 38th European Microwave Conf., European Microwave Week, Amsterdam, October 27-31, 2008

[59] N. J. Cronin and V. J. Law, Planar millimeter-wave diode mixer , IEEE Trans. Microwave Theory and Tech., Vol. 33, no.9, pp. 827-830, 1985.

[60] S. Martin, B. Nakamura, A. Fung, P. Smith, J. Bruston, A. Maestrini, F. Maiwald, P. Siegel, E. Schlecht and I. Mehdi, Fabrication of 200GHz to 2700GHz Multiplier Devices using GaAs and Metal Membranes, in Proc. IEEE MTT-S International, Phoenix, Arizona, May 20-25, 2001.

[61] C. Jung, H. Wang, A. Maestrini & Y. Jin, Fabrication of GaAs Schottky nano-diodes with T-Anodes for Submillimeter Wave mixers, in Proc. 19th International Symposium on Space Terahertz Technology, Groningen, the Nederlands, April 28-30, 2008