Frequency Multipliers for Local Oscillators at THz Frequencies

Alain Maestrini

Université Pierre et Marie Curie-Paris6, LISIF
4 place Jussieu, case 252, 75252 Paris cedex 5, France
Email: alain.maestrini@lisif.jussieu.fr
and
Observatoire de Paris, LERMA
61 avenue de l'Observatoire, 75014 Paris, France

The author was with the Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, Pasadena, CA 91109, USA

Abstract

Sources at THz frequencies have been the subject of intense research for several decades. From backward-wave oscillators (BWOs) to photo-mixers, a variety of sources have been developed for applications ranging from spectroscopy and radio-astronomy to skin-cancer detection. Among them, sources based on a solid-state millimeter-wave oscillator followed by power amplifiers and a cascade of frequency multipliers can produce several microwatts to several tens of microwatts at frequencies up to 1.9 THz. They offer the advantages of being frequency-agile over 5 to 15% of bandwidth, of working at room-temperature, and of being relatively compact, with typical volumes of a few hundred cubic centimeters. These sources produce sufficient power to pump cryogenically cooled Hot Electron Bolometer (HEB) mixers and are excellent candidates as components in heterodyne receivers dedicated to ground or space-borne radio-astronomy. This paper will focus on the evolution of the technology of frequency multipliers over the past 15 years and will present some key results that led to the construction of all-solid-state frequency-agile THz local oscillators.

Keywords: Frequency multiplier, THz, sub-millimeter-wave, Schottky diode, HBV diode, planar diode, local oscillator.

1. INTRODUCTION

Coherent sources at frequencies ranging from 1 THz to 4 THz are a challenging subject of investigation in electronics since this frequency range is at the heart of the so-called terahertz-gap that for decades researchers have tried to filled-up [1]. During the last five years two technologies, coming from opposite ends of the electromagnetic spectrum, have made such progress that they are now in direct competition for a number of applications and particularly for the building of local oscillators (LOs) of future heterodyne receivers dedicated to astrophysics and planetary sciences. One uses the old concept of frequency multiplication to 'lift' the frequency of a millimeter-wave electronic source, the other, much more recent, uses quantum cascade lasers (QCLs) to emit light at THz frequencies [2].

Coming from photonics, QCLs are able since 2004 to emit continuous-wave (CW) radiation as low as 2.1 THz without the use of a magnetic field [3]. QCLs produce milliwatts of CW power when cryogenically cooled at 4K and can work at liquid-nitrogen temperature or slightly above with reduced performance. They have been used for the first time in 2005 as a LO to pump a 2.8 THz Hot Electron Bolometer (HEB) mixer [4]. HEB mixers are the most sensitive ones above 1.2 THz and require very low level of LO power, in the order of 1μW if optical and coupling losses are considered. The combination QCL+HEB is therefore viewed as very promising for astrophysics: arrays of HEB mixers could be pumped by a single QCL. Unfortunately, the frequency tunability of QCLs is intrinsically limited to a few GHz and is achieved by varying the temperature of the device. For astrophysics, this constitutes a serious limitation since bandwidth is of the essence to detect extragalactic sources. Though, researchers may overcome this drawback by implanting in a single LO unit several QCLs tunable across adjacent frequency bands by taking advantage of the small size of each device. Whatever their limitations, QCLs opened a wide range of applications that astronomers and planetologists will exploit in the near future.

Coming from electronics, planar Schottky diode based frequency multiplier chains pumped at W-band with 100-150 mW have reached 1.9 THz in 2004 [5], [6] with sufficient power to be used as a LO for HEB mixers [7],[8]. These chains produce several microwatts to tens of microwatts at room temperature but, as reported in an earlier work [9], they greatly improve upon cooling at 120-150K. They are electronically and continuously tunable over 10-15% of bandwidth, which makes them the best solution for ground-base or space-borne instruments dedicated to astrophysics like the Heterodyne Instrument for the Far Infrared (HIFI) of the Herschel Space Observatory that will be launched in 2007 by the European Space Agency [10]. In 2005, a ×2×3×3 multiplier chain reached a record 100μW at 1.665 THz [11]: an array of HEB mixers with frequency tunability could be pumped by such a LO.

The present paper will outline the evolution of frequency multiplier technology at sub-millimeter wavelengths starting from 1992 when the last complete review of frequency multiplier technology was made by Räisänen [12]. The focus will be put on technological advances rather than device or circuit modeling. Räisänen's review was updated in 2002 by Siegel in [1]. Crowe proposes in [13] a survey of different CW sources from 100 GHz to 10THz that includes several new references for frequency multipliers. A short review of sub-millimeter CW sources that focuses on multipliers can also be found in [14]. Photomixers are not discussed in this paper. They are a potential solution for the building of wideband THz heterodyne receivers dedicated to astrophysics but their output power remains today below 1µW at 1 THz and falls with the increasing frequency [1].

2. FROM WHISKER-CONTACTED DIODES TO PLANAR DISCRETE DIODES

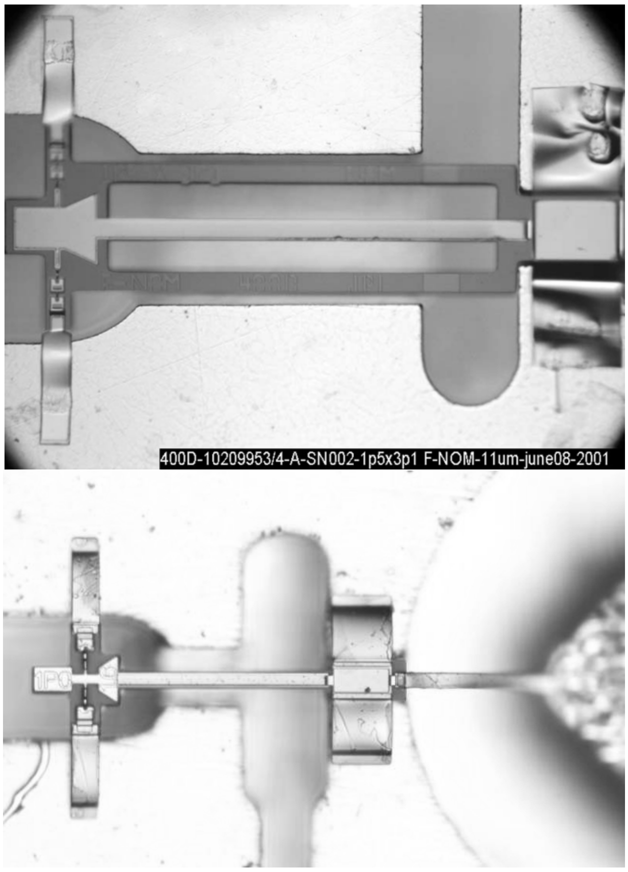
Frequency multipliers using whisker-contacted Schottky diodes played and still play an important role in the development of heterodyne receivers for radio astronomy and planetary sciences. As predicted by Räisänen in 1992, they appeared to be the only available solution for the LOs of space-borne submillimeter-wave heterodyne instruments in the years 1995-2000. Actually, ODIN, launched on February 2001, was the first satellite to embark heterodyne receivers in the 486-580 GHz band using whisker-contacted Schottky multipliers as final stages of the LOs [15]. But in 1992 this already mature technology was still unable to pass the 1 THz mile stone [12]. Progress toward the terahertz region was reported by Crowe and Rüdiger Zimmerman in 1996 [16] before Peter Zimmerman reached 1.135 THz in 1998 with an all-solid-state source that produced 40µW of output power [17]. The Schottky diode was usually mounted in a crossed-waveguide structure featuring several mechanical tuners. The input and output signals were decoupled through a low-pass filter, which was either coaxial (Räisänen / Erickson's design) or a stripline structure (Takada / Archer's design) —see ref. [12]. At submillimeter wavelengths and until the year 2000, whisker-contacted diodes outperformed Schottky planar diodes introduced in the mid-eighties by Cronin and Law [18] at the University of Bath, UK, and shortly later by Bishop and Mattauch [19] at the University of Virginia (UVa), USA, due to their lower parasitic capacitances and lower series resistances. However, at millimeter-wavelengths Schottky planar discrete diodes started to give better performance due to the use of multiple-anodes in balanced configurations. Erickson's balanced doublers, proposed and demonstrated in [20]–[22], have become a standard topology for frequency multiplication due to their good performance. This topology was used recently by Porterfield in a 0.65W-pulsed power 190 GHz balanced doubler featuring no less than 18 anodes [23].

In the nineties, GaAs-based Heterostructure barrier varactors (HBV) were introduced by Kollberg and Rydberg at the University of Chalmers [24], Sweden, as alternate diodes. They were initially made to be whisker-contacted before being made planar. HBV diodes produce only odd harmonics of an incident signal due to their internal symmetry. Thus, they are attractive devices to design high order odd harmonic multipliers such as triplers [25],[26] or quintuplers that can reach conversion efficiencies up to 5% at 210 GHz [27] or 11% at 100 GHz [28]. HBV technology took a significant turn in the late nineties when Lippens and Mélique at IEMN, France, introduced InP-based multiple-barrier devices [25]. The results obtained on a 250 GHz waveguide tripler (11% efficiency and 9.5mW of output power) demonstrated that HBV technology was a serious challenger to the classic and simpler Schottky technology. However, despite further efforts by IEMN, Chalmers and UVa, HBV multipliers did not reach the level of performance of Schottky multipliers. Another technique to build devices that exhibit internal symmetries was recently explored by Krach in [29]. It gave a state-of-the-art conversion efficiency of 22% for a 230 GHz planar diode tripler.

3. SEMI-MONOLITHIC FREQUENCY MULTIPLIERS AT THZ FREQUENCIES

In the mid-nineties the release of powerful commercial three-dimensional (3D) field-solvers (Ansoft HFSS) and non-linear circuit simulators (HP-now-Agilent MDS-now-ADS) transformed the way frequency multipliers were designed and built. These codes greatly increased the accuracy and the speed of the calculations necessary to optimize frequency multipliers. Erickson and Tiovunen pioneered the way by designing a 4-anode balanced doubler at 170 GHz entirely with HFSS and MDS [30]. In this article, they gave rationale to justify the use of 3D field-solvers instead of traditional RF measurements performed on scaled-models: *"Conventional scale model measurements, because of the wide range of sizes (>1000:1), are difficult when one considers the smallest important features on the diode relative to the size of a waveguide mount. Another major problem is providing the small coaxial probes to the diode locations…The advantages of numerical analysis are that one may easily study dielectric thickness effects, optimum inductances in the diode package, power balance between the diodes, and the origin of the parasitic effects.*" Erickson's and Tiovunen's design methodology was rapidly adopted by other researchers and opened the way, several years later, to the design of highly integrated fixed-tuned waveguide multipliers working well above 1THz.

Within the years 1995-2000, it became clear that discrete planar diodes were limited in frequency due to their size and the difficulty to connect them to the circuit with sufficient precision. Their integration on a circuit featuring several matching elements and providing precise connections to the waveguide block was necessary. However, MMIC-like submillimeter-wave circuits on GaAs substrate presented the inconvenient of being lossy and dispersive due to the high dielectric constant of GaAs (or InP for IEMN HBV diodes). To solve this difficulty several device fabrication technologies were proposed. One consists of transferring the epilayer on quartz (or some other application-optimized substrate) to decrease the losses and dispersion [29],[31], or on high thermal conductivity substrates to address heat dissipation issues [23],[32]. An alternative approach introduced by Mehdi and Smith at the Jet Propulsion Laboratory (JPL), USA, is to decrease dielectric loading by removing most of the substrate from the chip [14],[33]-[35] or by using GaAs membrane technology [5],[6],[11],[35]-[38]. The first solution, called *substrateless* technology is used at JPL for sub-THz circuits with substrate thickness ranging from 12 µm to 50 µm depending on the frequency (see Fig.1 top left picture). For THz circuits, only the membrane process combined with e-beam lithography is used. JPL membranes are 3 µm thick and can be made with no supporting frame (see Fig.1 bottom left and top-and bottom right images). The introduction of beam leads to facilitate chip handling and placement and provide more precise RF and DC grounding brought significant further improvement to this technology [5],[6],[11],[14],[33]-[38]. It is important to mention that the precision of the machining of the waveguide blocks plays a fundamental role in the working of THz frequency multipliers. For instance, JPL 1.9 THz tripler chips are inserted in a channel which width and depth are respectively 38 µm and 12 µm. The required precision for the alignment of the chip in the channel or the alignment of the two halves of the block is 2-to-3 µm.



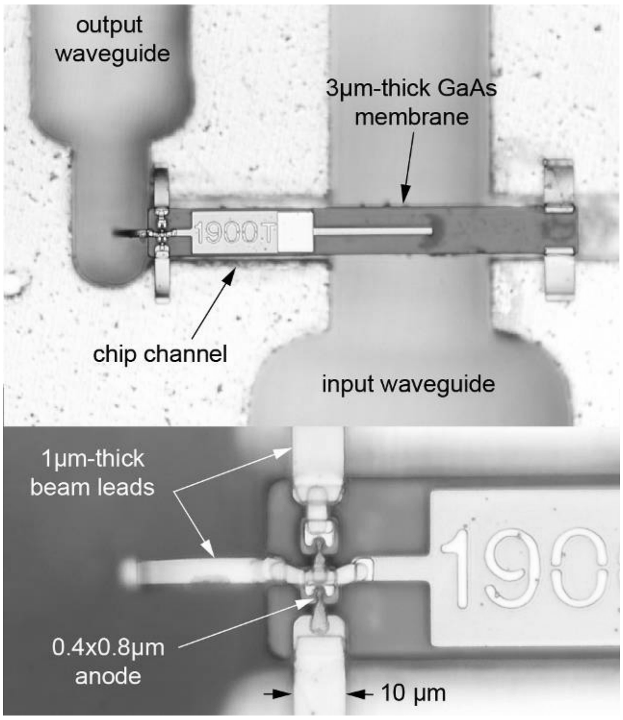


Fig. 1: JPL 400 GHz 4-anode doubler with substrate-less technology (top left). JPL 1500 GHz doubler with JPL frame-less membrane technology (bottom left). JPL 1900 GHz tripler with frame-less membrane technology (top and bottom right).

4. BUIDING LOCAL OSCILLATORS FOR SPACE-BORNE THZ HETERODYNE INSTRUMENTS

THz frequency multipliers rely on drivers which performance is critical. It is therefore important to consider the LO chain as a whole, starting from the fundamental source. Millimeter and submillimeter-wave heterodyne receivers dedicated to astrophysics or planetary sciences essentially use mechanically-tunable Gunn oscillators which output power varies from about 40 mW to 100 mW at W-band. However, in the late nineties, progress in transistor technology allowed the construction of powerful and wideband MMIC amplifiers working at W-band. By using power combining techniques, more than 200 mW fully solid-state became available at 100 GHz [39]. This was an important turning point in the development of LOs at THz frequencies: it created a solid foundation for the building of three-to-four-stage multiplier chains. These power amplifiers were initially developed for HIFI, but they will certainly be used in future ground-base or space-borne instruments. For HIFI multiplier chains, two main architectures were proposed: one based exclusively on balanced doublers, the other based on a combination of doublers and triplers [6]. In both cases the first stage was a 6-anode balanced doubler. Frequency triplers share the same technology as the doublers but their performance has been somewhat overshadowed by the success of balanced doublers. Recently, they have been demonstrated to work with record output power and bandwidth at submillimeter-wavelengths [5],[11], [14],[36]. Fig. 2 shows results obtained with flight multiplier chains for NASA EOS-MLS and for HIFI at room temperature. They were compiled by Siegel in 2003 [40] and updated in 2005. It is important to point-out that unlike multipliers developed for laboratory use, flight multipliers need to be operated significantly below their limits in terms of maximum input power, maximum reverse bias voltage and maximum forward dc current to guarantee the reliability of the hardware during the entire mission. Actually, as shown by Maiwald in [41], a degradation of the Schottky barrier can occur at relatively low levels of input power. The degradation of the barrier does not impact immediately the rf performance but can be detected by reverse IV curve measurements. This explains why the flight LO chains of HIFI can be pumped with only 100-120mW of input power at W-band while 200-to-250mW were commonly used for early prototypes.

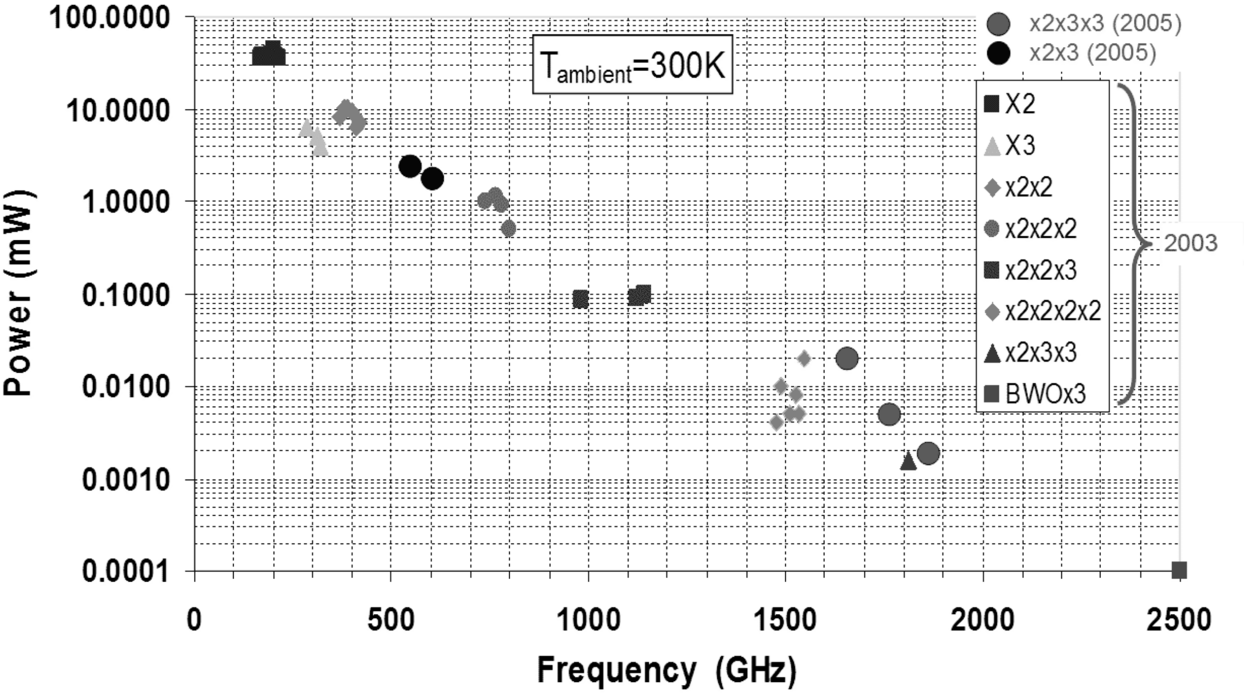


Fig. 2: Output power of flight frequency multiplier chains for HIFI and EOS-MLS at room temperature.

4. CONCLUSION

HIFI has been for more than 15 years one of the main drivers of the development of solid-state local oscillators at THz frequencies. Results obtained recently with JPL frequency multiplier chains greatly exceed the specifications of the instrument in terms of output power, but for future needs more bandwidth is desirable. To increase the bandwidth of THz multiplier chains, several solutions are being studied. One of them consists in combining the power after the first or even the second stage of the chain to ease power-handling management while providing higher input power to the last stages which are currently LO-starved. An interesting way of doing this is to include the power-combiner as a common part of the matching circuit of the multipliers. The other and complementary approach would consist in further reducing the size of the mesas and air-bridges of THz diodes to better control the impedance matching (fixed-size mesas acts as big pads at THz frequencies) or in the case of frequency triplers to improve the balance of the diodes, especially at the idler frequency.

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