Performance of a 1.2 THz Frequency Tripler using a GaAs Frameless Membrane Monolithic Circuit

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Abstract — **A tunerless 1.2 THz waveguide frequency tripler using Schottky planar varactor diodes has been designed, fabricated and tested. The frequency multiplier consists of a 3 micron-thick GaAs frameless-membrane monolithic circuit, mounted in a spilt waveguide-block, which includes a built-in Picket-Potter horn. The 1.2 THz membrane tripler is driven by a 400 GHz solid-state chain composed of HEMT based power amplifiers followed by two tunerless planar diode frequency doublers. At room temperature, output power up to 12 microwatts was measured at 1130 GHz with a peak-efficiency of 0.3% and a 3dB bandwidth of about 1%. The output power of the multiplier chain increased dramatically (up to 25 microwatts) with a decrease of the ambient temperature (175 K). To the best of our knowledge, this is the first demonstration of a fully planar local oscillator (LO) chain at these frequencies.**

I. INTRODUCTION

Several astrophysics and Earth observation space missions, planned for the near future, will require submillimeter-wave heterodyne radiometers for spectral line observations. Hot Electron Bolometers and SIS based junctions are planned to be used as ultra sensitive detectors in the 1.2 THz to 2.4 THz range on those missions. The required LO sources to pump these mixers are critical to the successful implementation of those missions and will be the focus of this paper.

Multiplied sources in the THz regime are essential for compact space instruments since there are no other easily viable alternatives. While the mixer and detector technology has progressed extremely well over the last decade or so, multiplier sources continue to be the bottleneck towards successful instrumentation. To date there have been only a handful of demonstrations of solid-state sources above 1 THz. Moreover, these LO chain utilized whisker contacted Schottky diodes for the last stages of the chain, and therefore they tend to require extremely tedious assembly process without the ability of multiple diode design. In addition, their performances in terms of bandwidth and efficiency are difficult to reproduce when the active device has to be replaced or re-contacted. That is a reason why their use in a space program continues to be a source of concern. The best result reported so far is 17 µW of power at 1395 GHz with an input power of 7 mW [1]. Planar Schottky varactor diodes allow for better reproducibility and have demonstrated considerable efficiency and output power up to the 300 GHz range mostly based on the planar balanced doubler concept proposed and demonstrated by Erickson [2-4]. Discrete planar devices continue to work well into the 300 GHz range but, as the operating frequency is further increased, the limitations of the assembly process soon become formidable. At the Jet Propulsion Laboratory a concerted effort has been made to develop and demonstrate technology that makes the implementation relatively straightforward and more importantly allows for implementation of optimized circuit designs. Within this context, the present paper will discuss the implementation of a solid-state source to 1.2 THz with all planar diode technology. Special emphasis is placed on the final stage tripler (1.2 THz) that demonstrates the viability of planar multiplier devices above the 1 THz range.

II. DESIGN AND FABRICATION PROCESS

The 1.2 THz membrane tripler concept was described previously in [5], whereas the fabrication process of the chip was described with more detail in [6]. It consists of a split-block waveguide tripler using two Schottky planar varactor diodes in a balanced configuration.

The waveguide block also includes a 1.2 THz Picket-Potter dual mode feed-horn that was machined in two symmetrical parts, using custom-made milling tools. The circuit is integrated on a three-micron thick frameless GaAs membrane. It is located between the input waveguide and the output waveguide, inside an 80x80x155 micron channel. The 400 GHz pump signal is coupled to the device by a 175 micron-long E-plane probe, whereas the output signal at 1.2 THz is coupled to the output waveguide by a 35 micron-long E-plane probe (see Figure 1). A matching circuit of only two elements is used in order to reduce the RF losses and the overall length of the chip. Two one-micron-thick gold beam-leads located on the side of the membrane hold the chip on top of the bottom part of the channel. When the two parts of the block are assembled, these beams leads insure a RF and DC ground.

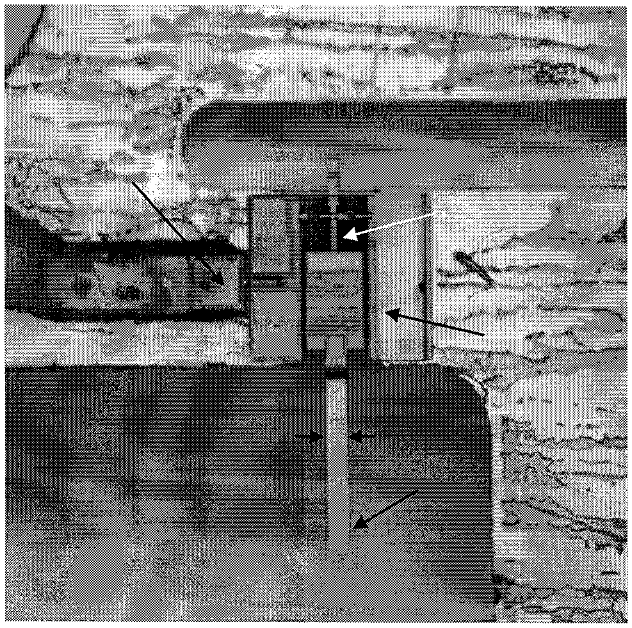

Fig. 1. The frameless membrane circuit in the block. The size of the chip without the input and output probes is about 150x160 μm.

As described in [5], the design philosophy consists in determining first the parameters of the diodes, that can give the best conversion efficiency for a given frequency, a given input power and a given *fabrication process,* and then, to determine a circuit that can best reach that efficiency. The optimization of the diode is made possible by the use of a non-linear model of the planar Schottky diodes fabricated at JPL [7].

In this specific design, we assumed a pump power of 5 mW for each anode (perhaps a bit optimistic in hindsight). In these conditions, we found that the anode size should be around 0.4x1.3 micron for an epitaxial doping of 5×10^{17} cm^{-3}. The circuit itself was constrained dramatically by size and RF losses considerations. In order to achieve a good match at the input and output frequency with very few tuning elements, we had to use the input and output probes as part of the input and output matching circuit. Consequently, they were not optimized separately.

We designed two families of devices: one with an integrated circuit that allows the biasing of the diodes, and one with no bias circuit. Actually, given the relatively low level of pump power at 400 GHz, the simulations show that the optimum bias is fairly close to zero volt and that a bias-less circuit should work. The bias-less approach offers a number of distinct advantages: the devices are easier to fabricate and much easier to mount in the waveguide block. On the other hand, with no bias capability, it is impossible to make any in-block device diagnostics; moreover, as the current on the diodes cannot be monitored, it is impossible to determine the input coupling.

In spite of the very thin membrane, it was not difficult to mount the unbiased devices in the waveguide blocks. The GaAs membrane and the large beam leads turn out to be pretty robust. The beam leads allow one to handle and place the devices as desired.

III. ROOM TEMPERATURE RF MEASUREMENTS

To pump the 1.2 THz membrane tripler, we used a solid-state source at 400 GHz that was described in [8]. The only non solid-state element of the chain is the BWO fundamental source, used for convenience and lab-availability: it could be easily replaced by active multipliers and microwave frequency synthesizers. The power amplifiers that are used to amplify the signal at 100 GHz have been described in [9]. The first doubler at 200 GHz is a discrete planar diode balanced doubler that gives 30 mW at 190 GHz with 20% efficiency [10]. The second stage multiplier at 400 GHz is a "substrate-less" planar circuit [11]. All the multipliers are tunerless. At room temperature, this chain can deliver up to 4mW at 375 GHz.

The output power of the 1.2 THz tripler was measured using a photo-acoustic detector (Thomas Keating) that is considered as a reference in terms of accuracy at sub-millimeter wavelengths. Unfortunately the sensitivity of the detector is not high enough to easily measure signals below a few microwatts. In addition, when the RF power produced by the multiplier chain is below 50 microwatts, optimization is barely possible due to the long integration time necessary to get an acceptable signal-to-noise ratio.

In order to get a calibrated measurement at 1.2 THz, we combined in the same test setup a Thomas Keating detector and a liquid-helium cooled silicon bolometer. The setup is described in Figure 2. Thanks to the sensitivity of the bolometer, the multiplier chain output power can be easily optimized. Then, by increasing the integration time, the power can be measured with the Thomas Keating detector. A noise floor of about ± 0.3 μW can be achieved after 15-20 minutes of integration. The RF losses of the different materials used for the Dewar vacuum window were calibrated using the same setup. Due to the small distance between the detector and the multiplier (about 30 mm), the losses introduced by the water vapor are small, and can be neglected for frequencies not too close to the water absorption lines.

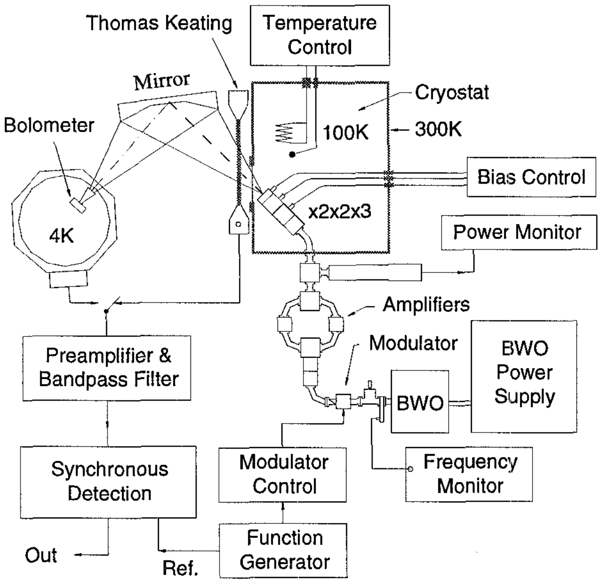

Fig. 2. Schematics of the cryogenic test bench.

When using a biasless circuit with 2 anodes of 0.4 by 0.9 micron, signals up to 12 microwatts at 300K were measured, which gives an efficiency of 0.3% for the 1.2 THz tripler. The instantaneous bandwidth was found to be about 1%.

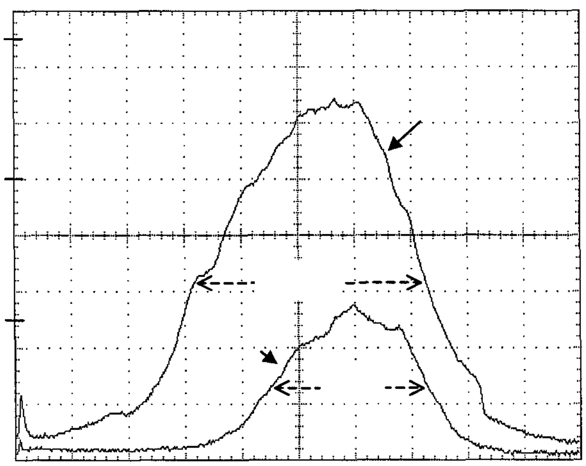

Fig. 3. Output power measured at 297K and 175K of the 1.2 THz multiplier chain. Biases on the 200 GHZ and 400 GHz multipliers are fixed and optimized for center frequency.

IV. CRYOGENIC RF MEASUREMENTS

As apparent in Figure 2, the multiplier chain is mounted inside of a cryostat for enabling cryogenic measurements. Lower operating temperatures have shown to drastically improve varactor performance especially when a number of multiplier stages are cascaded together [8], [11]. In this particular setup, only the multiplier stages are cooled though there is the possibility of cooling the amplifiers to further increase the input power.

Detailed performance investigation of the multiplier chain to 400 GHz has been presented previously [8]. The present chain to 1200 GHz was cooled down to 175 K. Further cooling to even lower temperatures is possible and will be done in the near future. At 175 K the maximum input power to the 1200 GHz tripler is about 6.5 mW.

Figure 3 shows the output power of the 1.2 THz chain when cooled at 175K. We can estimate that the efficiency of the 1.2 THz tripler is about 0.4% over 1% instantaneous bandwidth. It is remarkable to see the increase of the bandwidth and the strong increase of power when cooling the chain. A gain of more that 3dB is observed at the center frequency and much more at the edges of the band. That clearly indicates that the 1.2 THz tripler is underpumped and that its intrinsic bandwidth is wider. No isolators were used between the different multiplier stages.

V. CONCLUSION

A complete solid state multiplier chain to 1200 GHz has been demonstrated. Output power of 12 microwatts at room temperature with 1% bandwidth has been measured. This chain is based on planar Schottky diode varactors and results in output power levels that are consistent with the best ever multiplier chains with whisker contacted diodes. The planar diode technology enables optimized circuit topologies along with simplifying implementation and reproducibility.

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