THz Multiplier Circuits

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***Abstract* — Planar Schottky diode technology has been utilized to fabricate high-power broad-band monolithic multiplier circuits that can produce appreciable power well into the THz range. The chip fabrication technology that has been developed allows for robust circuit designs that can be easily packaged in conventional waveguide blocks. An overview of the capability of GaAs based Schottky diode multipliers will be presented.**

***Index Terms* — THz Technology, LO Sources, Frequency Multipliers, Schottky diodes, heterodyne receivers, varactors.**

I. INTRODUCTION

THz sources are required components for any sucessful spectroscopic study of the Universe in the submillimeter-wave range via radio astronomy. Although significant advances in detector technology have been made over the past ten years, the local oscillator component, required for high-resolution heterodyne detection, has lagged behind. However, recent advances in the design and fabrication of high-power, broad-band sources in the submillimeter-wave range has enabled one to propose flight-borne heterodyne instruments well into the THz range. More recently, THz technology, has also been 'discovered' by a multitude of other applications such as contraband detection, surveillance, urban canyon mapping, DNA identification, and tissue identification. Compact, reliable, and preferably broadband radiation sources are thus in great demand in order to meet mushrooming demands from these applications.

MMIC power amplifiers with impressive gain in the Ka-to-W band have enabled the use of microwave synthesizers that can then be actively multiplied to provide a frequency agile power source beyond 100 GHz. This low power electronically tunable source can then be amplified again with newly available W-band power amps, for efficient pumping of follow-on multiplier stages. If the multiplier can be designed and implemented with a wide bandwidth, then a new class of electronically tuned sources with bandwidth in excess of 10% and frequency coverage beyond 1 THz is possible.

This paper will present an overview of the current capability from fully solid-state sources detailing some of the technologies that have made the recent progress possible.

II. ADVANCES IN PLANAR SCHOTTKY DIODE TECHNOLOGY

Whisker contacted Schottky diodes for frequency multiplication have been used for at least 40 years and have produced useable RF power in the THz range. However, there are some obvious limitations to this technology such as constraints on design and repeatability. Starting in the 1980's, a concerted effort was made to produce planar Schottky diodes [1], resulting in the first demonstration of a successful balanced planar Schottky diode varactor in the mm-wave range [2]. This was a discrete chip that was soldered into the waveguide block and demonstrated superb performance, confirming that planar varactor chips could indeed be practical. This technique works well into the 300 GHz range but beyond that it becomes difficult to implement with any consistency.

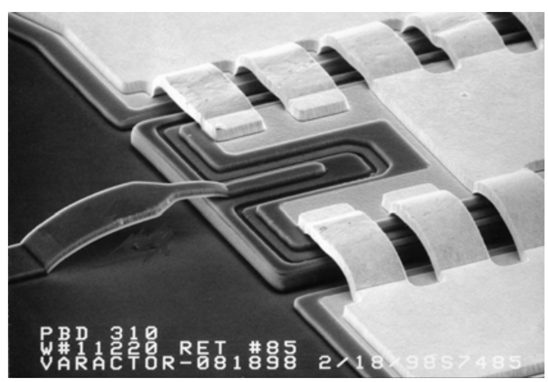

Figure 1: SEM photograph of a bridged T-anode Schottky diode.

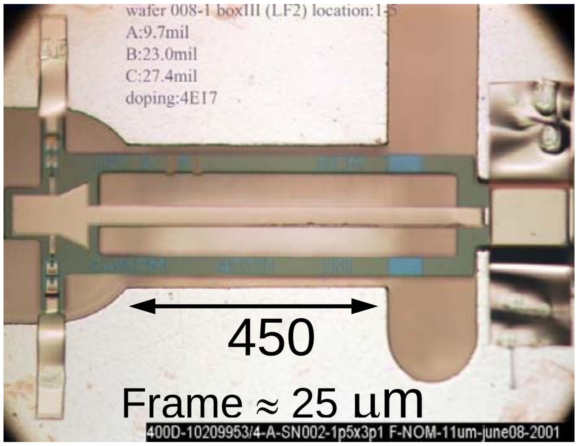

Figure 2: A 400 GHz doubler implemented with the 'substrateless' technology shown placed inside the split waveguide block. The chip consists of 4 anodes placed inside the input waveguide. Most of the GaAs substrate is removed and an on-chip capacitor allows for the bias.

The process that was initiated at JPL incorporated a number of modifications with the primary goal of extending the frequency coverage with planar devices and making them robust enough so that they could be deployed in space. One modification to the traditional planar Schottky diode fabrication process was the use of "T-gate" like structures as the Schottky anodes as compared to circular anodes. Traditionally, circular anodes patterned in a dielectric layer had been used as Schottky anodes. As the frequency of operation is increased it becomes imperative to scale the device accordingly and reduce the parasitics. However, as the anode area is scaled down to micron and submicron dimensions it becomes harder and harder to obtain uniform Schottky contacts since it involves the etching of the passivation dielectric. Moreover, for submicron dimensions optical lithography becomes difficult to demonstrate. A process was developed that basically uses an anode structure similar to the "T-gates" of high frequency transistors. It utilizes an e-beam direct write procedure and is easy to scale to even higher frequencies. While the scaling feasibility of this process is a major advantage this approach also results in lower series resistance of the device. By making the anode long and thin the access resistance can be reduced by a factor of two [3]. JPL has also developed a technique for making robust airbridges that allows one to better control the parasitic capacitance associated with the anode. The T-anode bridge process uses a trilevel PMMA procedure that enables one to fabricate mini air-bridges along with the actual anode structure. Thus one can make the anodes and fingers in a self-aligned process. A nominal sub-micron T-anode is shown in Figure 1.

To push the use of planar technology well beyond 300 GHz and to improve the mechanical arrangement and reduce loss, the "substrateless" technology was proposed in 1999 and demonstrated by 2000 [4]. In this approach the diodes are integrated with the matching circuit and most of the GaAs substrate is removed from the chip. Implementation of this technology at 400 GHz is shown in Figure. Using these chips, the assembly process is straightforward and more repeatable. The assembly of these devices in the waveguide blocks does not require solder or any other high temperature process. The chips are fabricated with ample beam-leads that are used both for handling purposes and for providing the DC and RF return. The devices are also placed anode-side-up in the block making it easy to visually inspect them. The anode sizes and critical dimensions in this technology are limited to about 1.5 microns due to the fact that a stepper is used for most of the masking steps.

Finally, to reach towards even higher operating frequencies i.e. 1 THz and beyond, "membrane" devices for mixers and multipliers were suggested and fabricated

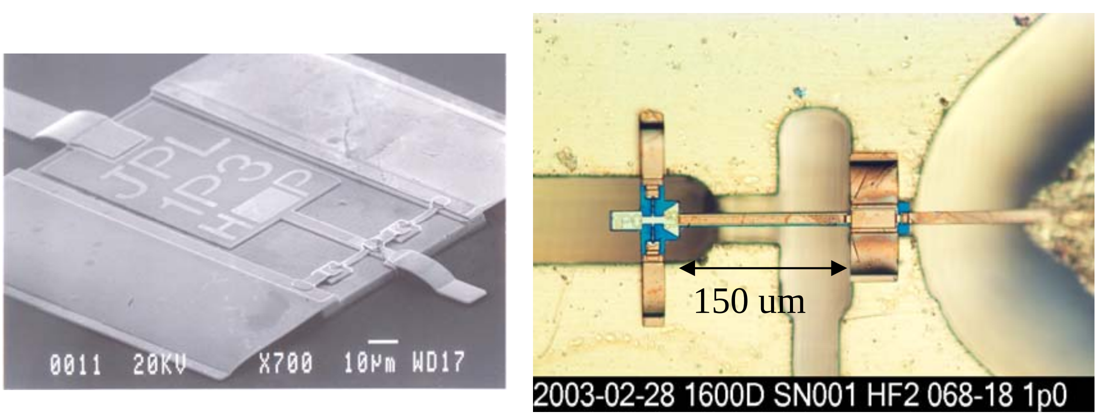

Figure 3: A 1200 GHz balanced tripler and a 1600 GHz balanced doubler chips are shown. Both chips are fabricated on a thin GaAs membrane. The 1200 GHz chip does not require external bias. Beam leads are extensively used for RF as well as DC connections.

[5,6]. The unique feature of these devices is that all of the substrate is removed and the chip is made on a three-micron thick GaAs membrane. The anode sizes and critical dimensions on this technology can be sub-micron since an e-beam is used for direct writing. This technology is more complicated to implement but is necessary given the requirements for high frequency operation. A tripler chip to 1200 GHz and a doubler chip designed to work at 1600 GHz are shown in Figure. The diode processing details are described in [7].

III. STATE-OF-THE-ART PERFORMANCE

The substrateless technology discussed above was utilized to design and fabricate a set of planar multiplier chips that were both broadband as well as reasonably efficient. Thermal modeling was used to ensure that the chips could also accommodate the relatively large input power. For this particular design it was important to make it broadband to cover the specified 178-198 GHz band. This first stage doubler is pumped with approximately 100 mW. Both doublers are implemented with $1\cdot10^{17}$ cm^{-3} doped GaAs in the substrateless technology, with six anodes in the first stage and four anodes in the second stage. The efficiency of the first stage is flat to better than ±0.6 dB [8].

Similar designs also exist that cover the 184-212 GHz and 368-424 bands [9]. This two-stage chain can then be used to drive higher frequency multipliers. A doubler driven with this chain at 800 GHz has produced in excess of 1 mW at room temperature [10]. The 400 GHz chain is also used to drive a tripler to 1200 GHz. The peak power improves to about 180 microwatts when the whole chain is cooled to 120 K [9]. The 1600 GHz doubler was also fabricated on a 3-micron thick GaAs membrane without a support frame. Even at these frequencies it is relatively straightforward to mount the device inside the waveguide block. However, the tolerance on the machined blocks now becomes extremely important. Results obtained with the chains consisting of four cascaded doublers have been presented elsewhere [11,12]. More recently, successful demonstrations of x2x3x3 cascaded chains to 1900 GHz have been made. Detailed results from these chains are presented in [8]. A summary of the achieved performance is indicated in Table 1.

Config	Freq GHz	Pout(peak) mW	Effi (peak) %	BW (3dB) %
x2	190	33	33.5	>12
x2x2	357	6.2	20	>11
x2x3	602	1.8	9	14
x2x2x2	775	1.1	13.5	8
x2x2x3	1200	0.1	1.9	6
x2x2x2x2	1504	0.015	3.5	6
x2x3x3	1640	0.021	0.2	4

Table 1: Table providing summary performance of various sources that have been tested. The last column indicates the 3dB bandwidth of the source. The reported efficiency relates to the efficiency of the last stage multiplier.

For cascaded chains cooling can provide a significant increase in output power since both the drive power and the diode efficiency are increased. In most cases the input power at W-band was limited to 100 mW except for the 1400-1900 GHz chains where a higher input power of 150 mW was nominally used. The measured data can be approximated with an exponentially decaying function. This has been further explored in [8] and better fitting parameters are provided depending on the multiplier type as well as desired bandwidth.

IV. FUTURE CHALLENGES

Devices reaching even higher frequencies will truly be pushing the fabrication technology but they must be fabricated and tested since there are not many other viable technologies to meet this task. A better diode model that can accurately predict performance given input power, temperature and matching circuit is being developed. Finally, the next heterodyne mission will probably utilize array detectors and thus it will be important to investigate LO sources that can be used to pump array mixers. Array sources will also be needed for applications requiring THz imaging. One rather straightforward approach would be to power-combine a number of the chains discussed in this paper to produce sufficient power to pump multi-pixel HEB mixers. Preliminary calculations indicate that by power combining 4 multiplier chains to 318 GHz, which pump two triplers that are then further combined to pump a doubler at 1.9 THz, it would be possible to obtain around 5 microwatts of output power. This would be sufficient to pump a 2-4 pixel array at 1.9 THz for the important CII survey. However, for an array with hundreds of pixels, a better approach is desirable. A serious concern that needs to be addressed for array receivers would be the rather large DC power requirement for generating sufficient LO power.

V. Conclusion

Planar Schottky diode based monolithic chips have been designed, fabricated and tested, that provide a robust, compact and broad-band solution for THz radiation. Though the primary application has been space based astrophysics missions, this technology can readily be adopted for multi-pixel imaging, both active as well as radiometric based, for earth based applications.

Acknowledgement

The authors wish to acknowledge significant contributions of past and present members of the Submillimeter-wave Advanced Technology Team at JPL. This work would not have been possible without the exceptionally high precision machining of P. Bruneau and J. Crosby of the JPL Space Instruments Shop. Finally, we wish to thank N. Erickson of the University of Massachusetts and P. Siegel of JPL for helpful technical discussions and suggestions.

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