Terahertz Multiplier Circuits

I. Mehdi, G. Chattopadhyay, E. Schlecht, J. Ward, J. Gill, F. Maiwald, and A. Maestrini*

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099, USA

*Université Pierre et Marie Curie, 4 place Jussieu, case 252, 75252 Paris cedex 5, France

***Abstract* — Robust radiation sources in the 1-2 THz range have been sorely lacking from the repertoire of terahertz technologists and scientists. This paper will review the progress in chip fabrication technology, based on planar GaAs Schottky diodes, that has enabled the design and fabrication of multiplier circuits working well into the terahertz range. Recent results obtained with multiplied sources in the 1-2 THz range will be summarized.**

***Index Terms* — Terahertz technology, LO sources, frequency multipliers, Schottky diodes, heterodyne receivers, varactors.**

I. Introduction

Recent years have seen an explosion in the use of terahertz technology for a number of applications such as contraband detection, surveillance, terrain mapping, DNA identification, and tissue identification [1]. Though a number of systems have been demonstrated in the 100-600 GHz range there are distinct advantages to operating at even higher frequencies. For certain other applications, such as spectroscopy and radio astronomy, there is need for robust instrumentation in the 1-2 THz range that will allow scientists to explore this mostly uncharted territory with broadband receivers. Thus, there is a major need to develop and demonstrate easy to use, all solid state sources in the 1-2 THz frequency range.

Conventional sources in this range include backward wave oscillators (BWOs) and FIR lasers. Both of these options are bulky and have limitations in terms of signal purity and bandwidth. In the last few years, a number of rapidly developing technologies have converged to enable compact sources in the 1-2 THz range. Advanced EM software tools now allow precise modeling of intricate active and passive circuits with high fidelity and have allowed for desktop optimization, drastically cutting down the time from preliminary design to final build. High rpm milling machines have allowed one to utilize split block waveguide circuits with dimensions approaching tens of micrometers making them a feasible approach for terahertz circuits/packaging. Meanwhile, Ka and W-band power amplifiers have matured to a point where it is now possible to pump initial stage multipliers with hundreds of milliwatts of power in the W-band range. And finally, semiconductor device processing tools have been developed that have allowed us to design and build intricate, highly-functional multiplier chips with sub-micrometer dimensions and substrate sculpturing ideally suited for high frequency applications. The goal of this paper is to highlight the chip fabrication technology that has been developed to realize terahertz MMICs. Recent results in the 1-2 THz band will be summarized.

II. Advances in Planar Schottky Diode Technology

At the heart of every terahertz multiplier chip is the GaAs planar Schottky anode. A schematic of the planar Schottky anode that has been developed for terahertz frequencies is shown in Figure 1 (this schematic is not to scale and certain dimensions are exaggerated for instructional purposes). A number of parasitic elements are identified on this schematic. For high cutoff frequencies it is important to minimize these parasitics. Secondly, it is important to have knowledge of

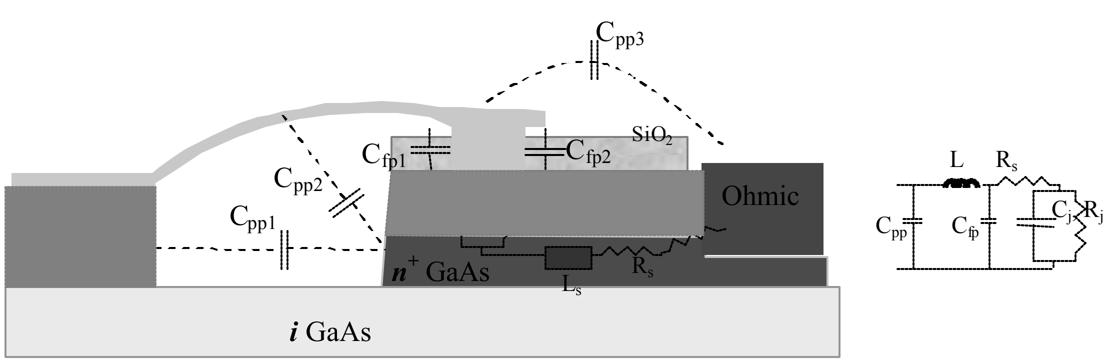

Figure 1: A schematic representation of the planar Schottky anode (not to scale) and its simple equivalent circuit are shown. For terahertz multiplier chips it is important to minimize the parasitics and design the circuit taking the parasitics into consideration.

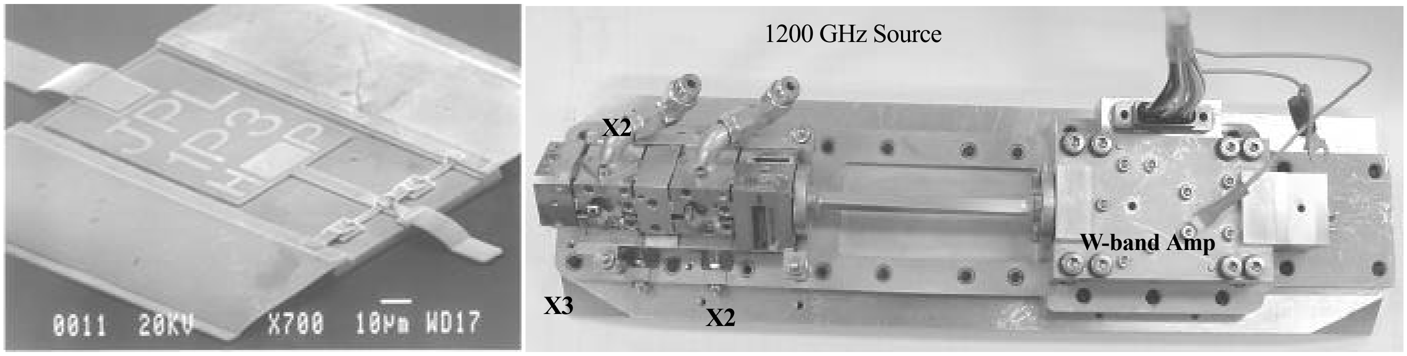

Figure 3: A 1200 GHz tripler chip is shown on the left. This chip is packaged in a waveguide block and tested as the last stage on the LO chain shown on the right. The chain on the right is driven by a 1-2 mW signal at W-band. Results from this chain are shown in Figure 4.

the waveguide blocks does not require solder or any other high temperature process. Instead, 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 placed anode-side-up in the block, making it easy to visually inspect them. The diode processing details are described in [3].

III. State-of-the-art performance

To test the terahertz multiplier circuits, it is important to have relatively high power sources at the input frequencies. A number of sources have been developed for this purpose and they have been detailed in previous publications [4-6]. In summary, we have sources that produce 30 mW at 200 GHz with 3dB bandwidths of 12%. Around 400 GHz we have sources that produce 5 mW with 10% bandwidths. We have sources at 600 GHz that produce over 1 mW across 15% bandwidths, and sources that produce several hundred microwatts up to 950 GHz. These sources are used to drive the terahertz multiplier circuits.

A 1200 GHz tripler chip is shown in Figure 3 (left). The chip is based on a balanced design with two anodes. The input E-plane probe is shown on the left of the chip while the output probe is shown on the right. The chip is based on a few micrometers thick GaAs membrane and sits in a waveguide channel that is only 50 µm deep. The assembled LO chain to 1200 GHz is shown in Figure 3 (right). The amplifier module puts out about 100 mW across the 92-105 GHz band. This is followed by two doublers which are then used to drive the final stage tripler. At room temperature this multiplier chain can produce about 100 µW.

A 1.6 THz source was constructed from four cascaded frequency doublers. The 1.6 THz doubler was also fabricated on a few micrometer-thick GaAs membrane without a support frame. At these frequencies, mounting the device inside the waveguide block is complicated by the fragility of the device and the required high precision alignment. Similarly, the tolerance on the machined blocks now becomes extremely important. Results obtained with chains consisting of four cascaded doublers have been presented in [7]. More recently, successful demonstrations of x2x3x3 cascaded chains to 1.9 THz have been made [8]. For cascaded chains, as has been shown before [8], 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. A summary of the achieved cryogenic performance is shown in Figure 4. Room temperature results with detailed descriptions from these sources have been presented previously [8,9,10].

IV. Future Challenges

The next challenge is to develop sources in the 2-3 THz range. This frequency range is of great importance to astrophysics. Devices working in this frequency range will push the fabrication technology to its limit, but they can be fabricated with existing technology. Quantum cascade lasers have shown significant improvement over a short period of time but they require cryogenic cooling and are inherently narrow-band sources. Finally, the next heterodyne space mission will probably utilize array detectors and thus it will be important to investigate LO sources that can be used to pump array mixers. Sources will also be needed for a variety of terahertz imaging applications. Power combining techniques will be needed to pump large-format array receivers as well as to provide high input power for stages working in the 2-3 THz range.

V. Conclusion

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

these parasitics in order to design the circuit around the Schottky diode. Some of these parasitic capacitances are much less than 1 fF and thus are difficult to measure precisely. However, modern EM wave solvers allow one to model the chip topology with great precision and can allow one to get a feel for these parasitics by cleverly defining simulation ports. The bandwidth of a circuit can be severely limited if these parasitics are not taken into consideration.

Moreover, the anode structure should be formulated to reduce these parasitics as much as possible. 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 micrometer and sub-micrometer dimensions it becomes harder and harder to obtain uniform Schottky contacts since it involves the etching of the passivation dielectric. An e-beam based 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 can pattern sub-micrometer structures. 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 [2].

A critical dimension that needs to be optimized for each anode is the distance between the anode and the edge of the ohmic contact. This needs to be reduced to decrease the series resistance, however, reducing this distance results in an increase of the fringing finger-to-pad capacitance. This distance is optimized based on the circuit impedance and the patterning is done via e-beam. Mesas smaller than 15x15 μm^2 have been successfully fabricated. Due to the small dimensions at these frequencies, the finger (bridge) and the anode are fabricated together to eliminate alignment concerns, resulting in self-aligned anodes. It is also critical for successful anode definition to correct for proximity effects on the e-beam since close location of the ohmic metal can have significant effect on the electron dose requirements. A close-up of a tripler chip at 1.9 THz is shown in Figure 2 (left). This is based on a balanced design and requires that both of the anodes are electrically identical. The input power is coupled via an integrated E-plane probe. The right side of Figure 2 shows a slightly different approach used for a 1.6 THz doubler. The figure shows the doubler when placed in one half of the split waveguide block. This doubler is also a balanced design, but in this particular case the anodes actually sit inside the input waveguide. Again, care must be taken to make sure that both anodes are electrically identical. Naïvely, this implies that anode sizes must be identical. However, sometimes it becomes necessary to utilize non-identical mechanical features in order to get electrically identical anodes.

Unlike their lower frequency counterparts, the terahertz chips need to be based on very thin and uniform GaAs substrates. This is important to eliminate substrate modes in the chip. The appropriate epilayers are grown by molecular beam epitaxy and an etch stop layer is grown to allow the substrate to be etched away. The completed chip is thus only a few micrometers thick (<10 µm). Such a delicate chip becomes difficult to handle and requires special precautions including placement of handling structures on the chip.

Finally, it is extremely important to design features on these chips that will allow one to package them in the appropriate circuit. All of the chips that have been described are made for split-block waveguide circuits, although the chip technology could easily lend it self to making quasi-optical structures with some minor modifications. The assembly of these devices in

Figure 2: A close-up of a 1.9 THz tripler chip is shown in the left. The mesa is less than 15 µm long. The anodes are smaller than a square micrometer. A 1.6 THz doubler placed in the waveguide mount is shown on the right. The chip is only a few micrometers thick. Note the machined feature size of the output waveguide which is less than 50 µm.

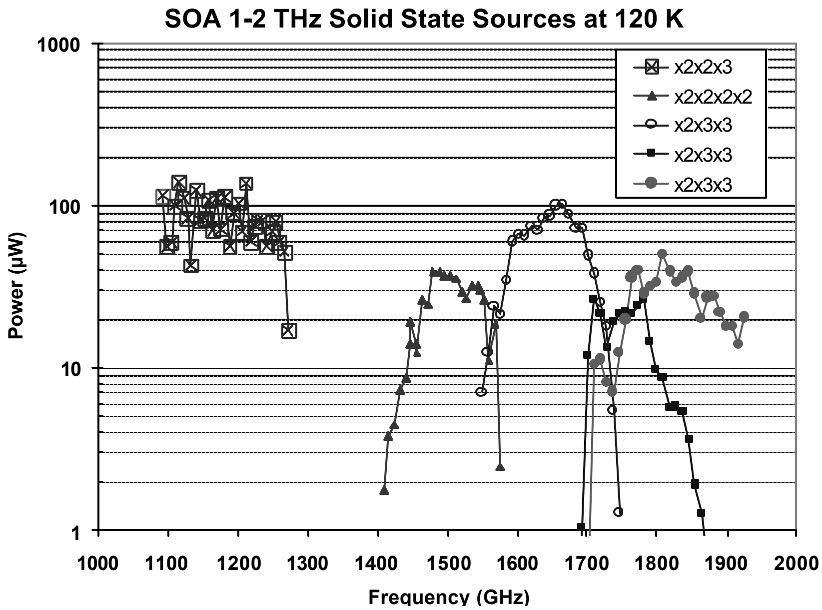

Figure 4: State-of-the-art (SOA) performance from available multiplied sources in the 1-2 THz range is shown. These data were obtained at 120 K. Power measurements at these frequencies require careful calibration and very specifically designed power meters.

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