

# **THz LOCAL OSCILLATOR SOURCES**

*(Invited paper)*

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## **Abstract**

Planar GaAs Schottky diode based multiplier chains driven by HEMT power amplifiers have now demonstrated useful power beyond the 1 THz range. This paper will briefly review the state-of-the-art in planar Schottky diode multiplier chains for coherent detection. Future challenges and promising emerging technologies will also be outlined.

## **Introduction**

Most operational submillimeter-wave radio telescopes, both space borne and ground based, employ local oscillator sources based on Gunn diodes followed by whisker contacted Schottky multipliers. Enough progress, however, has been made on a number of fronts to conclude that the next generation of radio telescopes will utilize a drastically different architecture for the generation of the local oscillator (LO) signal. 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, to enable 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 one THz is possible.

This new class of frequency agile sources has been enabled by both advances in W-band power amplifiers and by improvements in the technology for making planar Schottky diodes. The ability to produce planar GaAs diode chips deep into the THz range, with sub-micron dimensions and very little dielectric loading, has opened up a wide range of circuit design space which can be taken advantage of to improve the efficiency, bandwidth, and power handling capability of the multipliers. Planar Schottky diode multipliers have now been demonstrated up to 2700 GHz<sup>(1)</sup>. Though this particular multiplier was pumped with a FIR laser, it does demonstrate that given enough drive power planar diodes can work in this frequency range. It can now be safely assumed that most of the future multiplier chains will be based on robust planar devices rather than the whisker contacted diode of the past.

This paper will present an overview of the current capability from fully solid-state sources that an instrument team can expect for space borne mission concepts. Much of the impetus for the recent development came from the Herschel Space Observatory project; hence, the frequencies discussed are unique to the science requirements of Herschel. However, once the design and fabrication methodology is well understood it will be straightforward to implement the technology for other missions.

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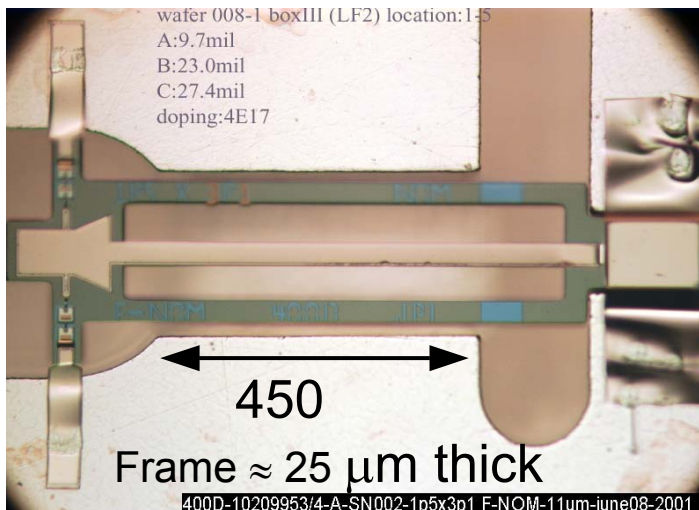
### **Advances in power amplifier technology**

Given the practical limitations on frequency conversion and the high multiplication factor required to make sources in the THz range when starting at  $\sim 100$  GHz, one must have sufficient power at the drive stage. IMPATT and Gunn sources that have been used in previous systems can produce about 50-100 mW at 100 GHz. Power combining these to enhance output power is possible but complicated. The intrinsic bandwidth of these sources is also limited and can only be improved with mechanical tuners. The solution to requirements over 100 mW of broadband power at 100 GHz has been achieved by the use of GaAs-based HEMT power amplifier technology. Tremendous progress has been made in this respect during the last decade. It is now possible to construct modules that have been power combined to produce in excess of 150 mW with a 10% bandwidth at 95 GHz<sup>(2)</sup>. A recent review of this technology can be found by Gaier<sup>(3)</sup>. To further enhance performance, InP based HEMT and high frequency HBTs are also being developed (see for example Samoska<sup>(4)</sup> and Fung<sup>(5)</sup>). The task of the multiplier builders is then to harness this power and design planar diode chips that can handle it without burn-out.

### **Advances in Planar Schottky diode Technology**

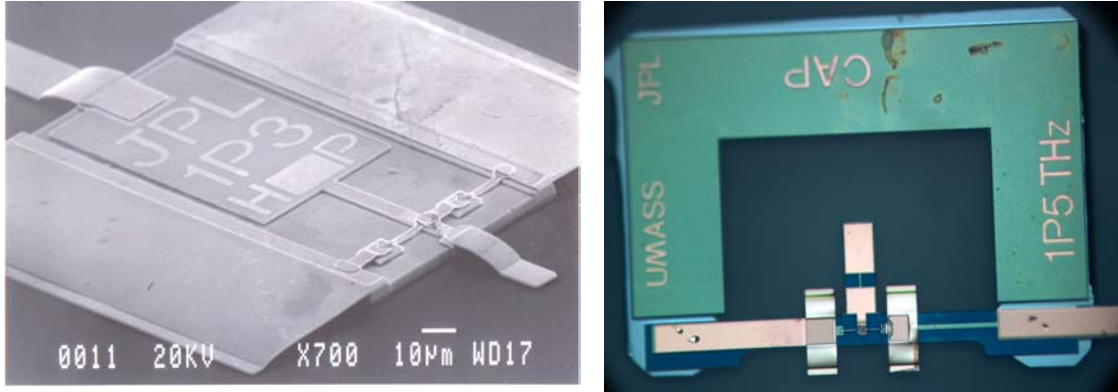
Most current heterodyne receivers utilize whisker contacted Schottky diodes for frequency multiplication. This technology has been around for at least 30 years and has produced useable RF power in the THz range<sup>(6)</sup>. However, there are some obvious limitations to this technology such as constraints on design and repeatability. The first planar Schottky diode varactor in the mm-wave range was demonstrated to great effect in 1993 by Erickson<sup>(7)</sup>. This was a discrete chip that was soldered into a waveguide block. This technique works well into the 300 GHz range but beyond that it becomes difficult to implement consistently.

To improve the mechanical arrangement and reduce loss, the "substrateless" technology was proposed in 1999<sup>(8)</sup> and demonstrated by 2000<sup>(9)</sup>. In this approach the diodes are integrated with part of the matching circuit, and most of the GaAs substrate is removed from the chip. Implementation of this technology at 200, 400, and 800 GHz has been accomplished, and an example is shown in Figure 1. For the 800 GHz doubler, the frame thickness is reduced to 12 microns, and for the 200 GHz it is 40 microns. The 200 GHz doubler has three diodes per branch while the 800 GHz has a single diode per branch. These chips make the assembly process quite straightforward and more importantly, 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 for handling purposes and for providing the DC and RF return, as well as a path to remove heat from the diodes. The devices are also placed up-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. It should also be pointed out that a separate technology is utilized at the University of Virginia that relies on putting the Schottky diodes on a host material. This technology has also been demonstrated up to a few hundred GHz for mixer diodes and work is continuing to extend it further with multiplier diodes<sup>(10)</sup>.



*Figure 1: Picture of a 400 GHz doubler chip made with the substrateless technology inside a waveguide block. The diodes are placed in the input guide (left side) while the output guide is shown towards the right side of the picture. An on-chip capacitor is used to block RF power into the bias line. There is no GaAs under the matching circuit. Beam leads are used to place the chip and provide electrical contacts. Similar technology has been used to make chips at 200-800 GHz.*

Finally, to push the devices towards even higher operating frequencies i.e. 1 THz and beyond, “membrane” devices have been fabricated. 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. This technology was successfully demonstrated for the 2.5THz Schottky diode mixer on EOS-MLS <sup>(11)</sup>. 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 necessary, given the requirements for high frequency operation. A tripler designed to work at 1200 GHz <sup>(12)</sup> and a doubler designed to work at 1500 GHz <sup>(13)</sup> are shown in Figure 2.



*Figure 2: SEM picture of the 1200 GHz tripler (left) and 1600 GHz doubler (right) fabricated with the membrane process.*

### **State-of-the-art performance**

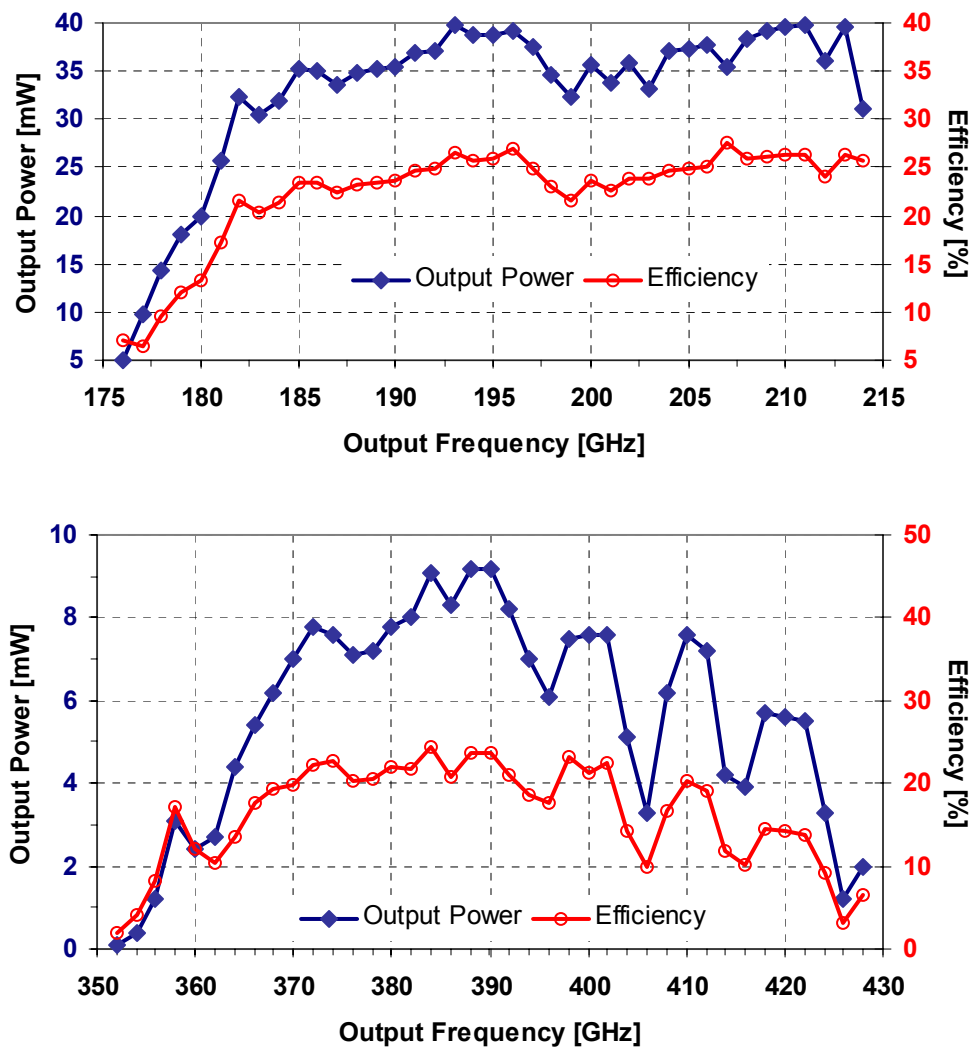
Devices shown in Figures 1 and 2 have been used to build LO chains up to 1500 GHz. Results obtained for the first stage doubler at 200 GHz are shown in Figure 3 (top plot). This doubler is pumped with approximately 150 mW. The fix-tuned 3dB bandwidth is approximately 10%. This multiplier is then used to pump the next stage doubler. The performance of the chain to 400 GHz is shown in Figure 3 (bottom). A fix-tuned 3dB bandwidth of 10% is still achievable. 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 <sup>(13,14)</sup>. The peak output power improves to 2 mW when the whole chain is cooled to 120 K. The 400 GHz chain is also used to drive the tripler to 1200 GHz. The chain to 1200 GHz has produced about 70-100 μW at room temperature with about 5% 3dB bandwidth. The peak power improves to about 200 μW when the whole chain is cooled to 120 K. Finally, the 800 GHz chain mentioned above is used to drive a 4<sup>th</sup> stage doubler to 1600 GHz. At room temperature peak powers of 9 μW have been measured. When cooled to 60K this output power improves to a very impressive 45 μW <sup>(13)</sup>. This chain demonstrates that it can be used to successfully pump HEB mixers in this frequency range. The “spikiness” in the output power is probably due to the fact that no isolators are used in this chain and more significantly, the last two multipliers are coupled via a diagonal horn.

The effect of cooling on various chains has been discussed by Maestrini <sup>(15)</sup> and for the chains discussed above is shown in Figure 4. The mobility in GaAs increases monotonically with decreasing temperature and exhibits a peak around 77K. This enhancement in mobility is directly correlated to increased efficiency in the multipliers. A peak in the performance is not observed since the anode tends to be hotter than the ambient temperature of the chip. It should be noted that the observed enhancement in output power with decrease in temperature is highest in the higher frequency chains. This is due to the fact that with decreasing temperatures the efficiency of the earlier stages also improve providing more input power to the latter stages.

### **Future challenges**

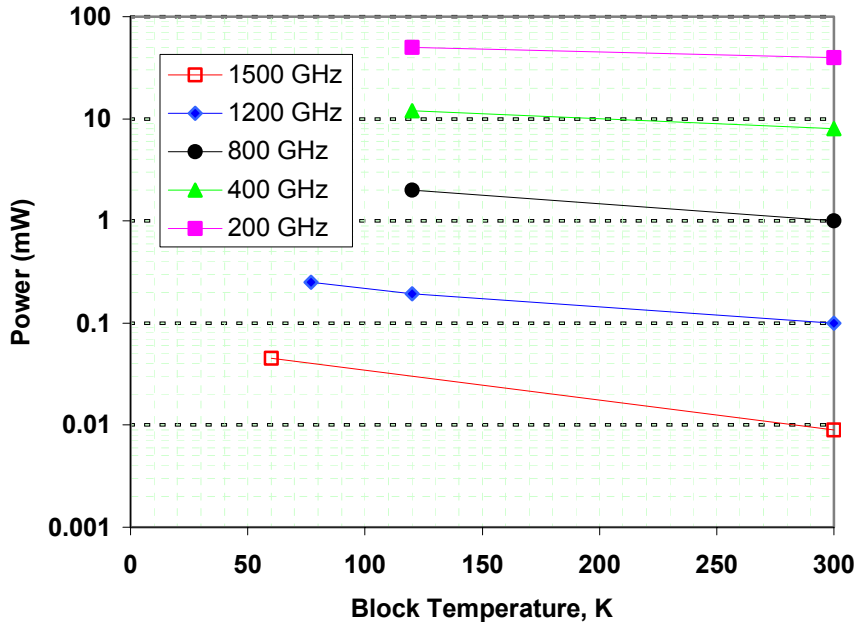
Recent performance of planar multiplier chains in combination with high power amplifiers has made these the obvious choice for any future heterodyne mission. However, this is the first time that so much input power has been available to pump the multiplier diodes and thus a number of issues need to be resolved

before this technology can truly be claimed as mature. Diode reliability in the presence of so much input power must be investigated in accordance with an accurate thermal model of the chip for any given frequency and operating conditions. The availability of planar diodes also remains a major concern for the Heterodyne Community as there are only two laboratories (Jet Propulsion Laboratory and The University of Virginia) currently that can produce planar chips with any success.



*Figure 3: Performance of the 200 (top) and 400 GHz (bottom) balanced doubler at room temperature. The input power for the 200 GHz doubler was a constant 150 mW across the band.*

The diodes for pushing towards even higher frequencies will truly be pushing the fabrication technology limit, but they must be fabricated and tested to learn more about the limitations. A better diode model that can accurately predict performance given input power, temperature and matching circuit is being developed. Finally, most probably the next heterodyne mission will utilize array detectors and thus it would be important to investigate LO sources that can be arrayed conveniently. Array sources will also be needed for applications requiring THz imaging.



*Figure 4: Multiplier chain performance as a function of ambient temperature. Peak power point is represented for each chain.*

### Emerging Technologies

Space constraints do not leave room for an extensive discussion of the emerging technologies that can compete or complement Schottky diode multipliers. The reader is referred to the recent review paper by Siegel <sup>(16)</sup>.

However, of the lower frequency various competing technologies, a number of approaches seem reasonable. Miniaturization of vacuum tube technology seems promising, once the cathode technology has been developed sufficiently. A number of competing options were presented at the 12<sup>th</sup> International Space Terahertz Symposium and the JPL option is discussed by Manohara <sup>(17)</sup>. The idea is to use micro-fabrication technologies such as high density MEMS and carbon nano-tubes for the cathodes to make monolithic vacuum tube klystrons. The possibility of direct mW oscillators and amplifiers above 1 THz would be a major breakthrough.

Rapid progress has also been made in photonic based sources as outlined by P. Chen <sup>(18)</sup>. The most promising approach involves using photomixers to generate power. A number of research groups are working on implementing these sources and new material systems promise operation at 1.55 micron in fiber. A major advantage of this approach is the ability to leverage off the commercial photonics community. System stability has been a major hurdle, making it difficult to achieve low phase noise. However, methods have been demonstrated that can obtain acceptable line-widths. Currently, it is possible to achieve approximately 1 mW at 100 GHz and 1 microwatt at 1 THz. System complexity, noise and stability must be studied in more detail to develop these technologies for future instruments.

Cascade lasers based on super-lattice semiconductor material have also shown promise at shorter wavelengths <sup>(19)</sup>. Progress is continuing on this front to increase both the wavelength and operating temperature. A single device will intrinsically have a narrow bandwidth but conceptually it is possible to array a number of these devices together in order to achieve broad frequency coverage.

### **Conclusion**

This review paper has attempted to present the state-of-the-art for planar Schottky diode multiplier chains that are now being developed for ground-based and space-borne applications. Recent technology advances have increased frequency, power and bandwidth by almost an order of magnitude over the past 5 years. The output power in the THz range is now sufficient to pump SIS mixers in the 1200 GHz range and HEB mixers in the 1500 GHz range at room temperature. Cooling the multiplier chain to 60-100K can further enhance performance.

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