

*(Invited paper)*

# **THz Local Oscillator Technology**

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## **Abstract**

The last decade has seen a number of technological advancements that have now made it possible to implement fully solid state local oscillator chains up to 2 THz. These chains are composed of cascaded planar multiplier stages that are pumped with W-band high power sources. The high power W-band sources are achieved by power combining MMIC amplifiers and can provide in excess of 150 mW with about 10% bandwidth. Planar diode technology has also enabled novel circuit topologies that can take advantage of the high input power and demonstrate significant efficiencies well into the THz range. Cascaded chains to 1.9 THz have now been demonstrated with enough output power to successfully pump hot-electron bolometer mixers in this frequency range. An overview of the current State-of-the-Art of the local oscillator technology will be presented along with highlighting future trends and challenges.

**Keywords:** LO sources, multipliers, THz technology

## **1. INTRODUCTION**

THz spectroscopic remote sensing is a critical tool for answering a wide range of fundamental questions at the forefront of Astrophysics, Cosmology and Galactic Structure [1,2]. High spectral resolution measurements of widely abundant molecular and atomic species with electron transitions that peak at THz frequencies, such as ionized carbon and nitrogen, oxygen, silicon, hydrofluoric acid, etc. provide unparalleled insight into circumstellar processes, galactic structure, stellar and galactic evolution and the cosmology of the early universe. Careful tracing of individual spectral line profiles provides information on molecular or atomic abundance, background temperature, Doppler velocity, local pressure, distribution of matter, intervening dust and age of the source. Due to very severe atmospheric opacity, observations of these and many other chemical species can only be accomplished from high altitude balloons, aircraft or orbiting platforms.

NASA's interest in the submillimeter dates back to the very beginnings of radio astronomy, but it has required enormous technological advances to develop the sensor technology that is just coming on line today. 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. Several existing and proposed instruments are already being hampered by this lack of a reliable low cost THz oscillator technology. The Heterodyne Instrument for Herschel Space Observatory, an ESA cornerstone mission with a significant contribution from NASA, has base lined heterodyne instruments up to 1200 GHz and is hoping to extend its coverage to the critical carbon line at 1.9 THz. Several SOFIA instrument proposals have also been funded for THz spectroscopy measurements, but these instruments are currently science limited by the unavailability of tunable local oscillator sources that can cover significant regions of the submillimeter wave spectrum. In order to enable future submillimeter wave heterodyne instruments and increase the science return of existing instruments, the local oscillator technology must be brought up to par with the existing detector technology.

The most sensitive high spectral resolution detectors in the submillimeter rely on heterodyne downconversion for both optimal signal-to-noise ratio and, almost unlimited frequency resolution, required for profiling spectral lines. Whether employing superconductor or semiconductor detectors, heterodyne receivers in the submillimeter are currently crippled by the lack of available pump sources to serve as local oscillators (LO)-- essential to the downconversion process. 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 radio telescopes that become operational in this Millennium will have a different local oscillator (LO) generation architecture. 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 1 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. A number of technological advances such as direct E-beam patterning and heterostructure material engineering have been utilized to fabricate planar Schottky diode chips well into the THz range. 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 efficiency, bandwidth, and power handling capability of the multipliers. Better and more efficient modeling techniques have also been heavily employed to design these planar circuits with full 3-D wave simulations including detailed chip topologies along with advanced semiconductor models for the diodes. It can be assumed that most of the future multiplier chains will be based on these planar robust 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. Much of the impetus for the recent development came from Herschel Space Observatory and thus the frequencies discussed are unique to the science requirements of Herschel.

## 2. 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 [3]. However, there are some obvious limitations to this technology such as constraints on design and repeatability. Starting in the 1980's the Semiconductor Device Laboratory at the University of Virginia led the effort into making planar Schottky diodes for mixers and multipliers [4]. The first balanced planar Schottky diode varactors in the mm-wave range were demonstrated with great effect in 1993 by Erickson using discrete chips made at the University of Virginia [5]. 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.

The process that was initiated at JPL in 1992 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 passivating dielectric. Moreover, for submicron dimensions optical lithography becomes difficult to demonstrate. A process was developed that basically uses a anode structure similar to the "T-gates" of high frequency transistors. It utilizes an e-beam direct write procedure and is easy to scale for 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, see *Figure 1*. By making the anode long and thin the access resistance can be reduced by a factor of two [6]. A nominal sub-micron T-anode is shown in *Figure 2*. JPL also developed a technique for making robust airbridges that allowed one to better control the parasitic capacitance associated with the anode. The T-anode process uses a trilevel PMMA procedure that enables one to fabricate mini air-bridges along with the actual anode structure allowing one to make the anodes and fingers in a self-aligned process. *Figure 2* shows the profile used for making these self-aligned air-bridge connections to the anodes.



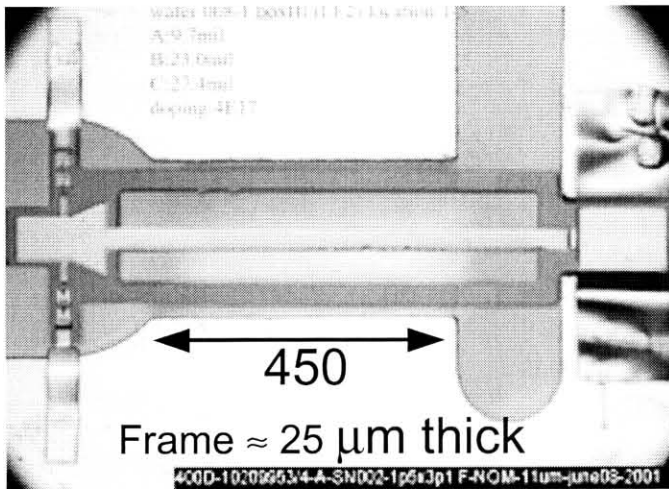


Figure 3: A 400 GHz doubler implemented with the 'substrateless' technology shown placed inside the split waveguide block. The chip consists of 4 anodes placed inside the input waveguide. Most of the GaAs substrate is removed and an on-chip capacitor allows for the bias. Extensive use is made of the beam-leads for biasing as well as RF grounding and physical handling. Similar technology has been used to make chips at 200-800 GHz. For the 800 GHz doubler the frame thickness is reduced to 12 microns. For the 200 GHz doubler there are three diodes per branch while at 800 GHz there is only a single diode per branch.

Finally, to push the devices towards even higher operating frequencies i.e. 1 THz and beyond, “membrane” devices for mixers and multiplier were suggested and fabricated [9,10]. 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 designed to work at 1200 GHz and a doubler designed to work at 1600 GHz are shown in Figure 4. The diode processing details are described in [11].

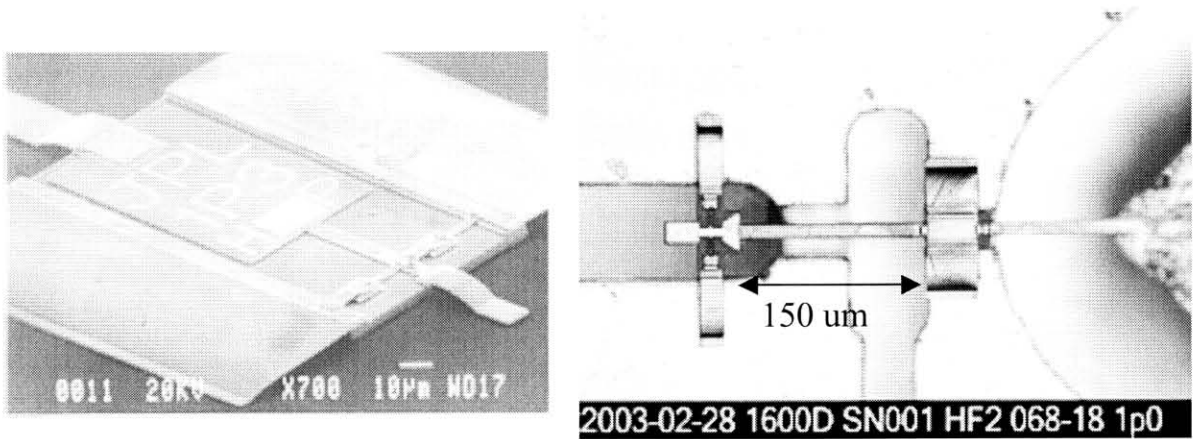


Figure 4: On the left is a SEM picture of the 1200 GHz tripler chip while the right picture shows a 1600 GHz doubler when placed in the split waveguide block. Both of these were fabricated with the membrane process. The GaAs is only 3 microns thick in each case. The beam-leads provide mechanical support as well as electrical contacts.

### 3. ADVANCES IN POWER AMPLIFIER TECHNOLOGY

Given practical limitation 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 of  $>100$  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 [12]. Figure 5 shows the output power available from the various power amplifier modules that have recently been demonstrated at 120K. At room temperature the output power drops by 2-3 dB, however, it is still possible to get in excess of 150 mW across the band and even up to 400 mW at some frequency spots. The task of the multiplier builders is then to harness this power and design planar diode chips that can handle this much power without burn-out.

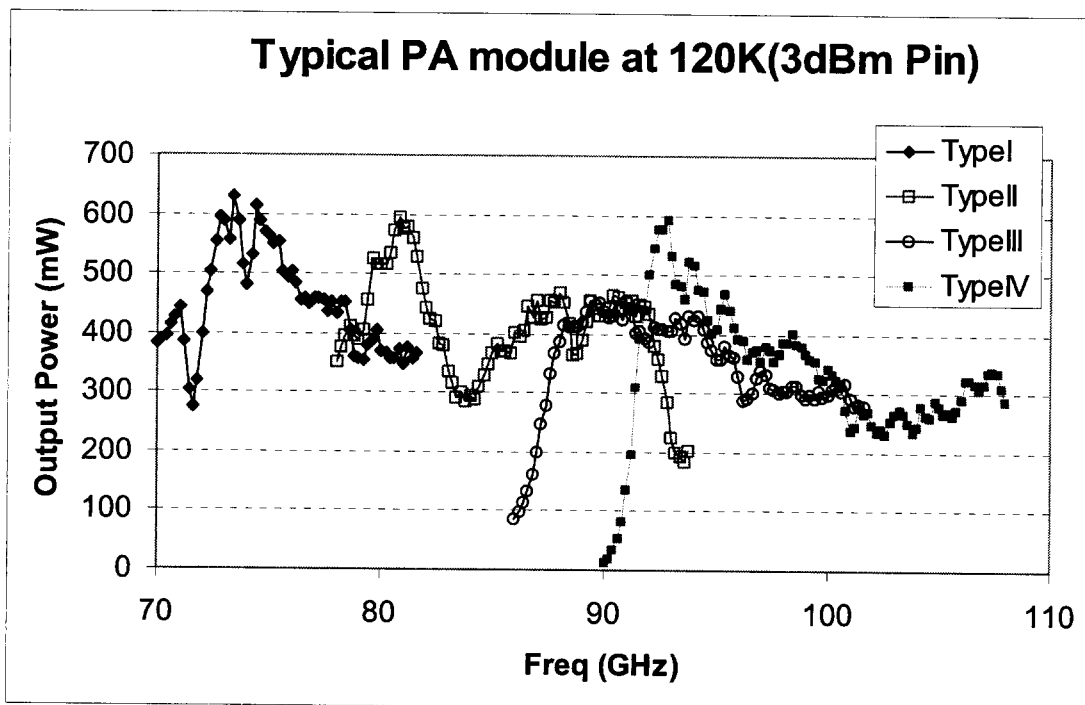


Figure 5: Typical power amplifier module output power at 120K. Nominal bias conditions are used with +3dBm of input power. Total DC power is about 6W for each module.

### 4. 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. Room temperature results from the 190 GHz doubler and the 375 GHz doubler are shown in Figure 6. For this particular design it was important to make it broadband to cover the specified Herschel band. This first stage doubler is pumped with approximately 100 mW. Both doublers are implemented with  $1 \cdot 10^{17}$  cm<sup>-3</sup> 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  $\pm 0.6$  dB [13].

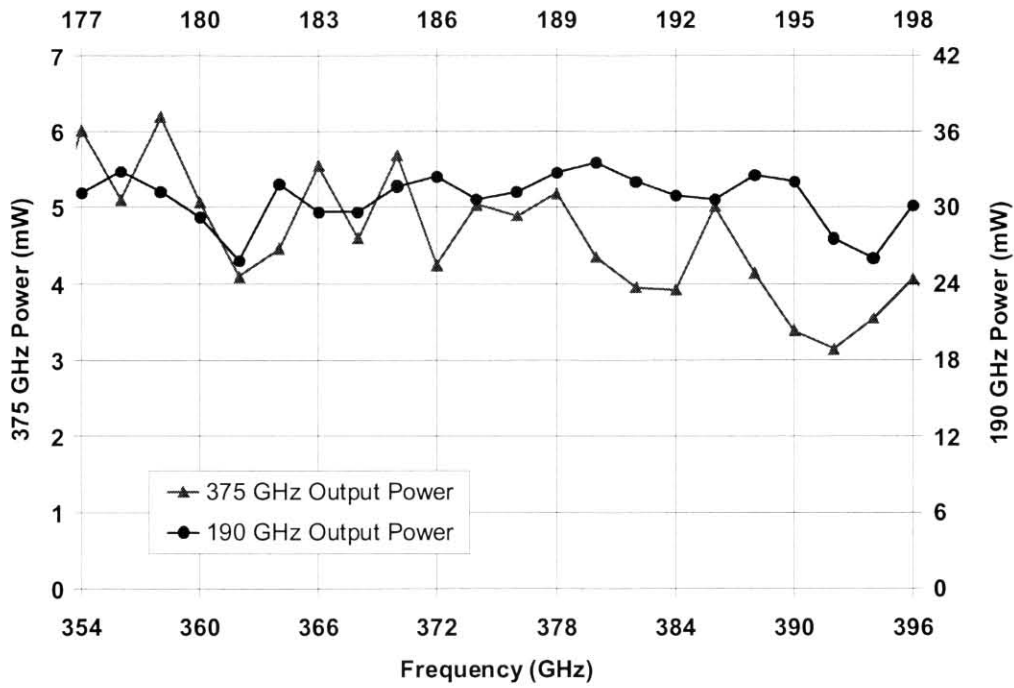


Figure 6: Measured room temperature performance of 190 and 375 GHz balanced doublers as a function of frequency. A constant input power of 100 mW was used.

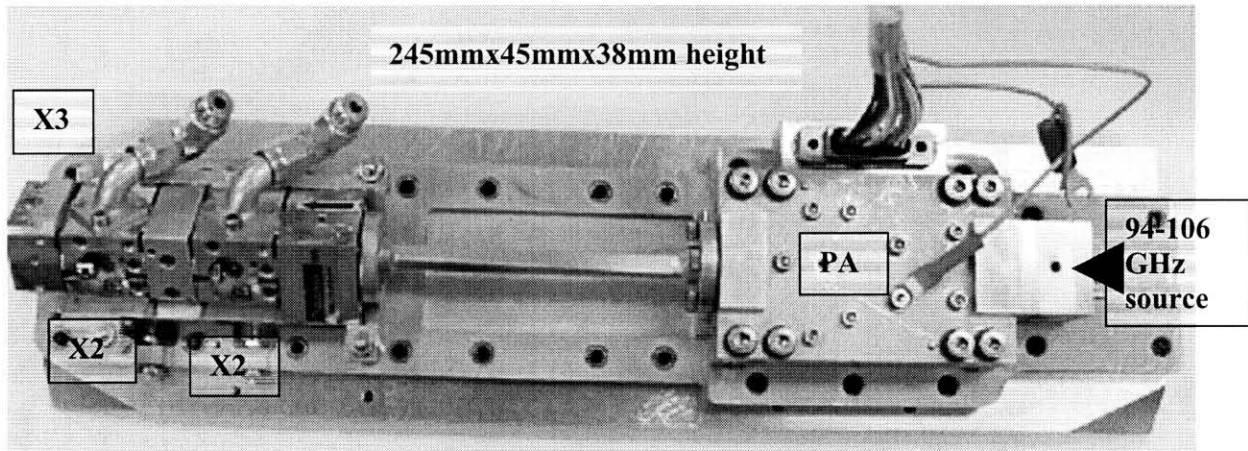


Figure 7: A complete Herschel chain for 1200 GHz. The chain consists of three cascaded chains, x2x2x3. The last multiplier block has built in diagonal horn. The multipliers are placed on the 'flexure' saddle that allows one to fine tune position of the output beam. More details on this implementation can be found in [10].

Similar designs also exist that cover the 184-212 GHz and 368-424 bands [14]. 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 [15]. The 400 GHz chain is also used to drive a tripler to 1200 GHz. The tripler chip is made with membrane technology and is shown in Figure 4. The chain to 1200 GHz has produced about a peak of 100 microwatts at room temperature with about 6% 3dB bandwidth. The peak power improves to about 200 microwatts when the whole chain is cooled to 120 K [16]. A picture of the 1200 GHz chain is shown in Figure 7.

The 1600 GHz doubler shown in Figure 7 was also fabricated on 3 micron thick GaAs membrane without a support frame. Even at these frequencies it is relatively straight-forward to mount the device inside the waveguide block. However, the tolerance on the machined blocks now becomes extremely important. It should be pointed out that the measurement of “absolute” output powers at these frequencies continues to be a significant challenge. We utilize calorimeters, Thomas-Keating meters, Golay cells, and cryogenic bolometers to measure power depending on the frequency and signal strength. Generally, we cross calibrate between these meters to within 10% accuracy wherever possible. However, realistically one would still expect fairly significant error bars on the order of 2 dB or so on the measurements especially beyond 1400 GHz. Results obtained with the chains consisting of four cascaded doublers have been presented elsewhere [17,18]. The final test for a chain like such is to ascertain that it can successfully pump the HEB mixers. This has now been demonstrated [19] and 1 microwatt has been reported to be sufficient to pump HEB mixers given good receiver design. More recently, we have also successfully demonstrated  $x2x3x3$  chains to 1900 GHz. Detailed results from these chains are presented in [13,20].

A number of cascaded chains have now been made at JPL specifically for the Herschel Space Observatory. The output peak power from representative chains has been plotted in Figure 8. The lower set of data shows the output power at room temperature. Effect of cooling the multipliers results in improvements which have been discussed previously [21,22,23]. The measured 120K data for each corresponding chain is plotted where available. For single stages the improvement with cooling is not significant. However, for cascaded chains cooling can provide a significant increase in output power. 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. As can be seen, the data can be approximated with an exponentially decaying function. This has been further explored in [24] and better fitting parameters are provided depending on the multiplier type as well as desired bandwidth.

## 5. ARRAY SOURCES

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, the next heterodyne mission will probably utilize array detectors and thus it would 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 straight-forward approach would be to power combine a number of the chains discussed in the paper to produce sufficient power to pump multi-pixel HEB mixers. Preliminary calculations indicate that by power combining 4 multiplier chains to 318 GHz and then pumping two triplers which 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 could then sufficiently pump a 2-4 pixel array at 1.9 THz for the important CII survey.

However, for 100's of pixel a better approach would be desirable. A proposed 'tray' concept is shown in Figure 9. A 100 GHz input signal is divided to pump two first stage multipliers. The output at 200 GHz is further divided into two. Finally, a single 400 GHz doubler pumps a single 800 GHz doubler providing for four 800 GHz sources. A serious concern that needs to be addressed for array receivers would be the rather large DC power requirement.

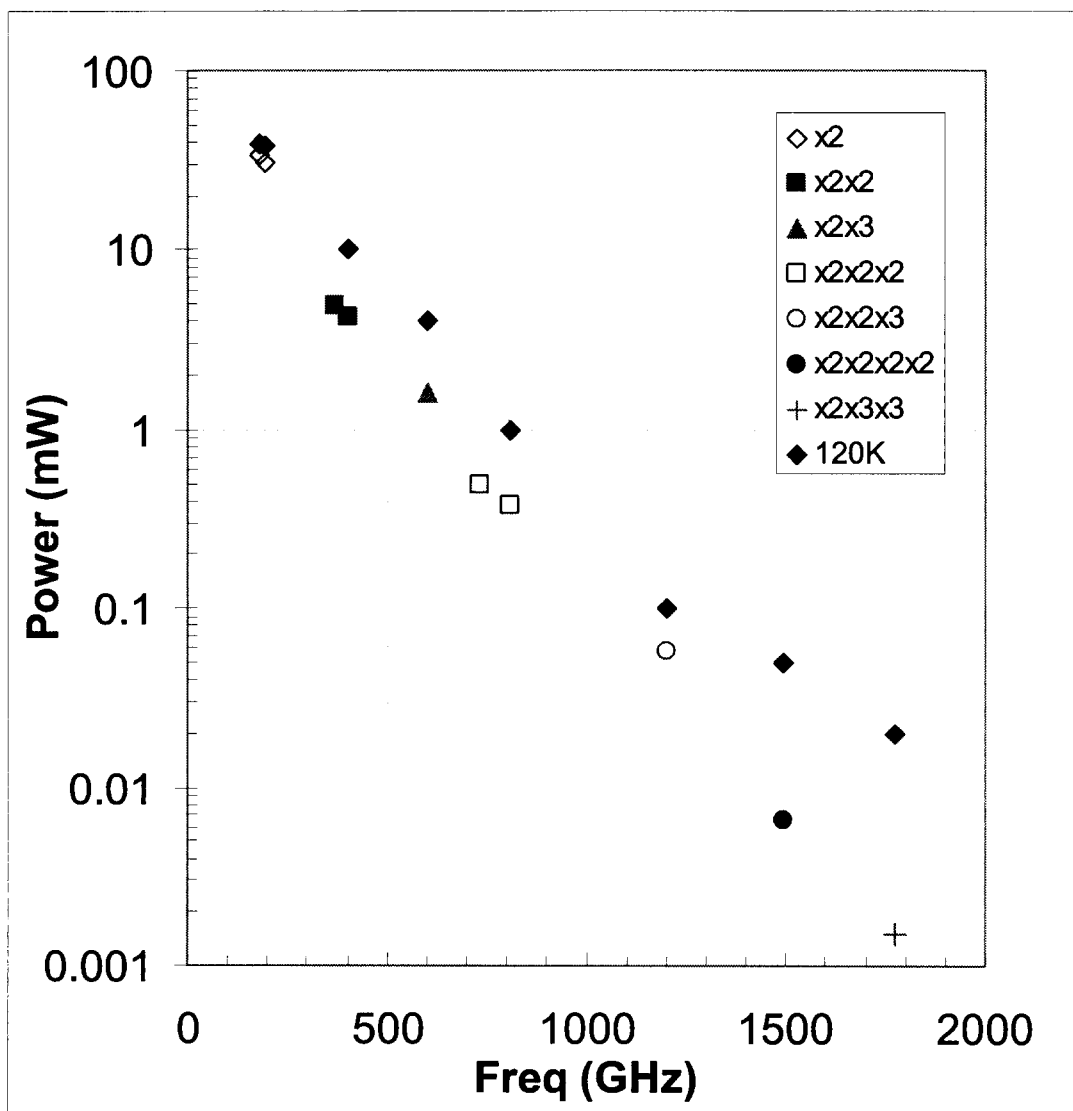


Figure 8: Room temperature as well as 120K results from various LO chains that have been built at JPL. Input power at w-band was 100-150 mW in all cases.



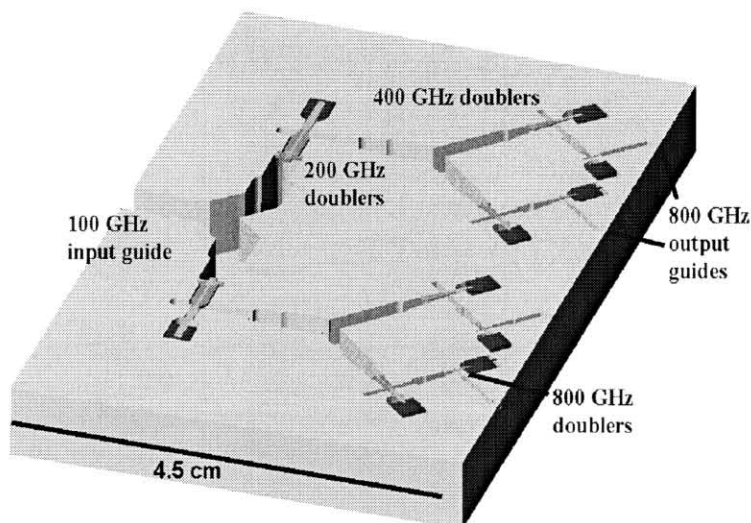


Figure 9: A proposed scheme for a 800 GHz source to pump array mixers.

## 6. CONCLUSION

Compact, robust, and broadband planar Schottky diode multipliers have now been demonstrated to 1.9 THz with sufficient output powers to pump very sensitive detectors. This technology can now be deployed to build the next generation of radio telescopes and instrumentation. Work is under progress to extend the frequency range of multiplied sources by power combining lower stages to obtain sufficient drive power. Also, the design and manufacturing of these sources is being optimized for future array receivers.

## 7. ACKNOWLEDGEMENTS

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