THz Local Oscillator Sources: Performance and Capabilities

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ABSTRACT

Frequency multiplier circuits based on planar GaAs Schottky diodes have made significant advances in the last decade. Useful power in the >1 THz range has now been demonstrated from a complete solid-state chain. This paper will review some of the technology responsible for this achievement along with presenting a brief look at future challenges.

1.Introduction

Astrophysical importance of high resolution spectroscopy in the THz range is highlighted by the current build up of the Heterodyne Instrument for Far Infrared (HIFI) on ESA's Herschel Space Observatory [1,2,3]. Traditional 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 local oscillator generation scheme for HIFI and future heterodyne receivers will be drastically different. 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. Better simulation tools along with the ability to make many impedance matching elements on chip have necessitated closer interaction between the RF design engineers and device fabrication engineers. The results have been impressive both in terms of improving circuit efficiencies and in terms of allowing different circuit configurations. Planar multipliers have now been demonstrated up to 2700 GHz [4]. 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. Future challenges especially as applicable to space needs will be discussed.

2.Current status of multiplied sources

Much of the impetus for the recent development has come 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 established it will be possible to design LO sources for other applications. The impressive advancement in multiplier technology has been possible due to a number of factors. At least four major thrusts can be identified without which the current progress would have been impossible. These are, development of GaAs based HEMT MMIC power amplifiers, development of planar GaAs Schottky diodes, availability of better simulation tools, and finally viability of micron level machining.

2.1. Power Amplifier Technology

Given practical limitations on frequency conversion and the high multiplication factor required to implement sources in the THz range one must begin with sufficient drive power. 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 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. Figure 1 shows the progress made during the last two decades in terms of broadband power amplifier modules. The right most data set is obtained from the modules that have been designed and built by a collaborative effort between JPL and TRW [5,6,7]. From a single module (with six MMICs) designed to cover the 92-106 GHz range it is now possible to obtain in excess of 300 mW across the band. To further enhance performance, InP based HEMTs and high frequency HBTs are also being investigated [8]. The task of the multiplier builders is then to harness this power and design planar diode chips that can handle it without burn-out.

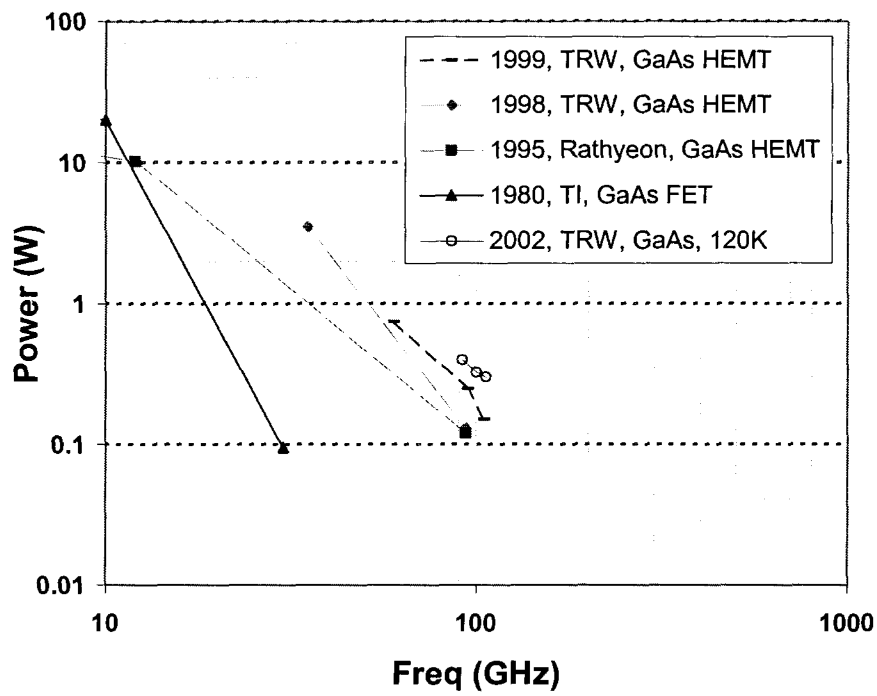


Figure 1: Available output power from GaAs based MMIC power amplifier modules over the years. Early results were based on FET devices but with the advances in HEMT device technology operating frequencies in the W-band become possible.

2.2. Advances in Planar Schottky diode Technology

Whisker contacted Schottky varactor technology has been around for at least 30 years and has produced useable flight-qualified LO sources in the THz range [9]. However, there are some obvious limitations to this technology such as constraints on design and repeatability. The first high power planar Schottky diode varactor in the mm-wave range was demonstrated to great effect in 1993 by Erickson [10]. 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 [11] and demonstrated initially to 400 GHz by 2000 [12] and up to 800 GHz in 2001 [14]. In this approach the diodes are integrated with part of the matching circuit, and most of the GaAs substrate is removed from the chip. Example of a nominal 400 GHz balanced doubler chip mounted in the waveguide block is shown in Figure 2. The 200 GHz chip has three anodes per branch and the design calls for 40 micron thick substrate. For the 800 GHz doubler, the frame thickness is reduced to 12 microns and there is only one anode 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 being developed at the University of Virginia which utilizes a host material substrate. 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 [15].

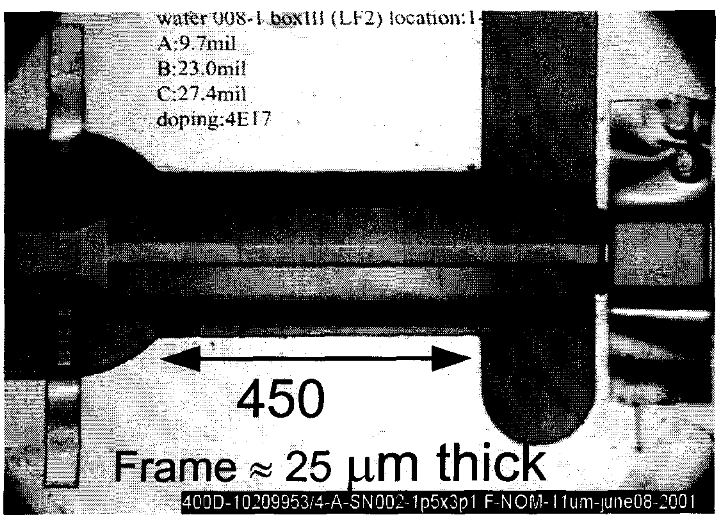


Figure 2: Picture of a 400 GHz doubler chip made with the substrateless technology inside a waveguide block. The diodes are placed in the input guide (left side) while the output guide is shown towards the right side of the picture. An on-chip capacitor is used to block RF power into the bias line. There 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.

The 'substrateless" technology has proven to be fairly robust. A major concern was the sensitivity of the multiplier performance on the substrate thickness. Since the substrates are thinned via a chemical/mechanical process the tolerance on the thickness is hard to keep below +/- 5 microns. For the 200 GHz design the nominal substrate thickness is 40 microns. However, simulations done with substrate thickness ranging from 30 to 50 microns indicate that only the input match is perturbed and this can be rectified to a certain extent by changing the diode capacitance (bias). Obviously, this can only work if the desired capacitance is obtainable without jeopardizing the diode reliability.

Figure 3: A SEM photograph of the anode area for a balanced 1500 GHz doubler chip. Beam-leads provide allow for grounding while a thicker GaAs frame (not shown here) is used to hold and place the chip. Further details of this chip are described by Erickson [22].

Finally, to push the devices towards even higher operating frequencies i.e. 1 THz and beyond, "membrane" devices were proposed in 1999 [18] and demonstrated by 2001 [19]. 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. Similar technology was successfully demonstrated for the 2.5THz Schottky diode mixer on Earth Observing Station-Microwave Limb Sounder (EOS-MLS) [20]. The anode sizes and critical dimensions on this technology can be sub-micron since an e-beam is used for direct writing. The fabrication technology for these planar devices have been detailed in [21]. Membrane technology is more complicated to implement but necessary, given the requirements for high frequency operation. A close up of the anode area for a balanced doubler to 1500 GHz is shown in Figure 3 [22].

For a successful design at 1200 GHz one of the most critical dimension is the anode size. Anodes are e-beam written so sub-micron precision is possible. However, given the number of difficult fabrication steps preceding the e-beam write and the inherent tolerance on the e-beam writing procedure some variance can be expected. To minimize the effect of this the circuit has been designed to accommodate some variation in the anode size. Moreover, on the actual mask set a plus/minus variation of 15% on the anode size is carried. Simulation results showing the effect of anode size on the multiplier performance is shown in Figure 4. As can be noted the nominal anode size is the optimum, however, the two other anode sizes are also useful.

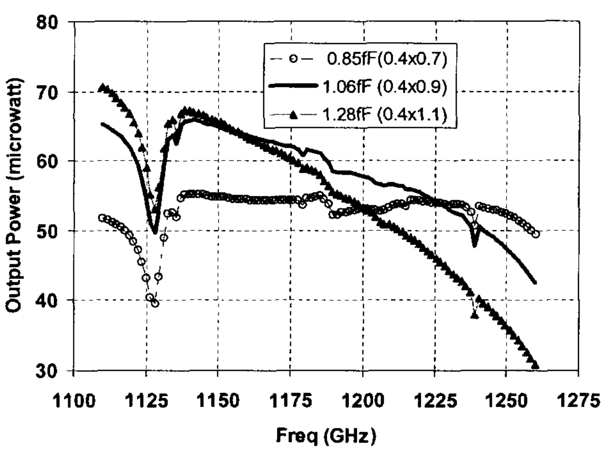


Figure 4: Simulated output power of the 1200 GHz tripler for three different anode sizes at room temperature. Input power of 7 mW is assumed. This is for a self biased chip design thus there is no bias optimization. The nominal anode provides for the optimum coverage, however the robust design allows for slight variation in the anode size. The required specification is to obtain around 30-40 microwatts at 120 K from 1120 to 1250 GHz.

2.3. Performance

Devices shown in Figures 1 and 2 have been used to build LO chains up to 1500 GHz. Most results obtained thus far from work at JPL and the University of Massachusetts have been displayed in Figure 5.

Nominally the first stage doubler is pumped with approximately 150-200 mW. The fix-tuned 3dB bandwidth is approximately 10%. This multiplier is then used to pump the next stage doubler. 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 [14]. 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. Finally, a 800 GHz chain has been used to drive a 4th stage doubler to 1600 GHz. At room temperature peak powers of 9 μW have been measured. When cooled to 70K this output power improves to a very impressive 45 μW [23]. This chain demonstrates that it can be used to successfully pump HEB mixers in this frequency range.

3.Future challenges

In spite of the recent success with this technology there continue to be areas that can be improved. Part of this is mandated by what is required for future missions. However, output power and bandwidth can certainly be improved.

3.1. Cryogenic performance

One relatively simple way of improving performance is to cool the multiplier chain. In order to do this one must take necessary precautions during the assembly/building of these multipliers so that they can tolerate thermal cycling and cryogenic temperatures. The effect of cooling on various chains has been discussed before [24,25,26]. 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 improves providing more input power to the latter stages.

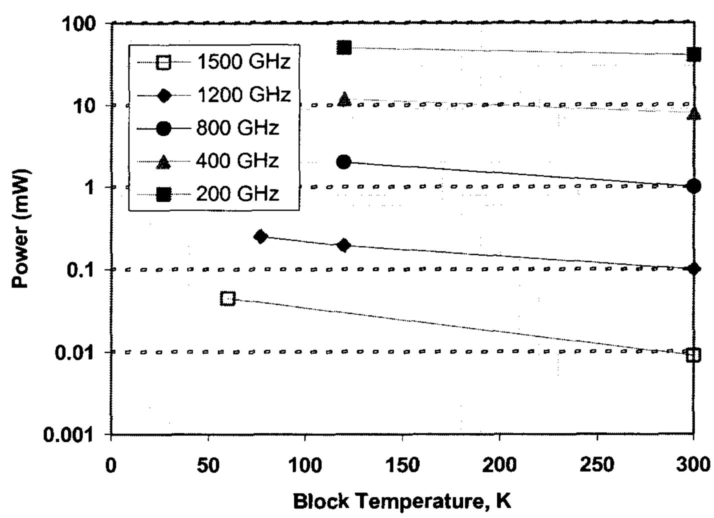
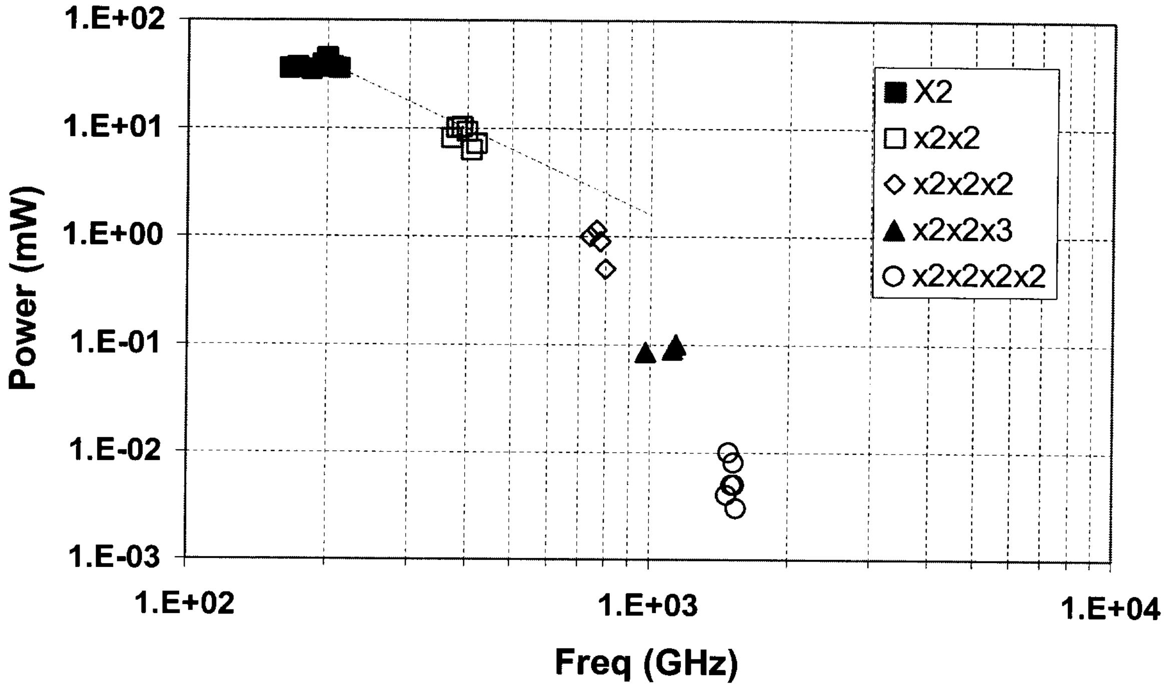


Figure 5: Effect of block cooling on the output power of various LO chains. Note that for the (x2x2x2x2) chain to 1500 GHz more than 3 DB improvement can be made by cooling the multiplier chain to 77K.



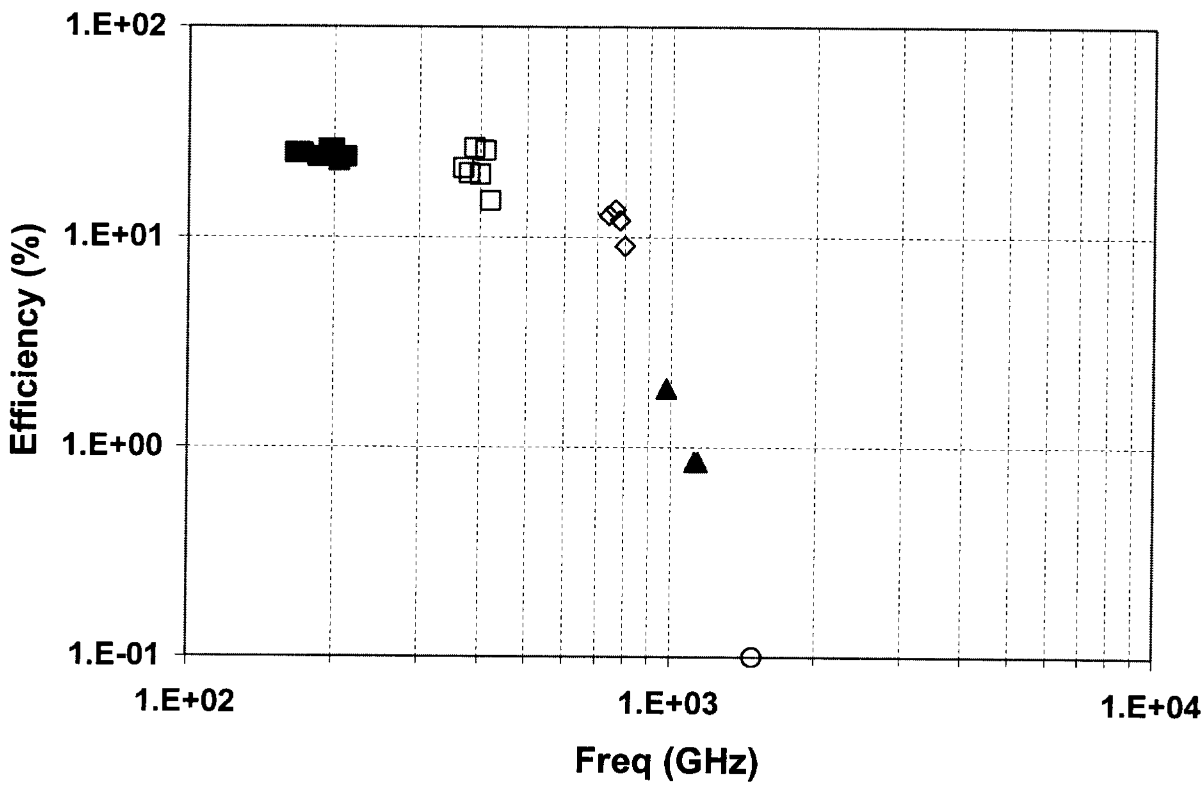


Figure 5: Recent performance from all solid state sources has been compounded. This includes results from discrete chips as well as 'substrateless' designs. All of the results reported here were measured either at JPL or at the University of Massachusetts.

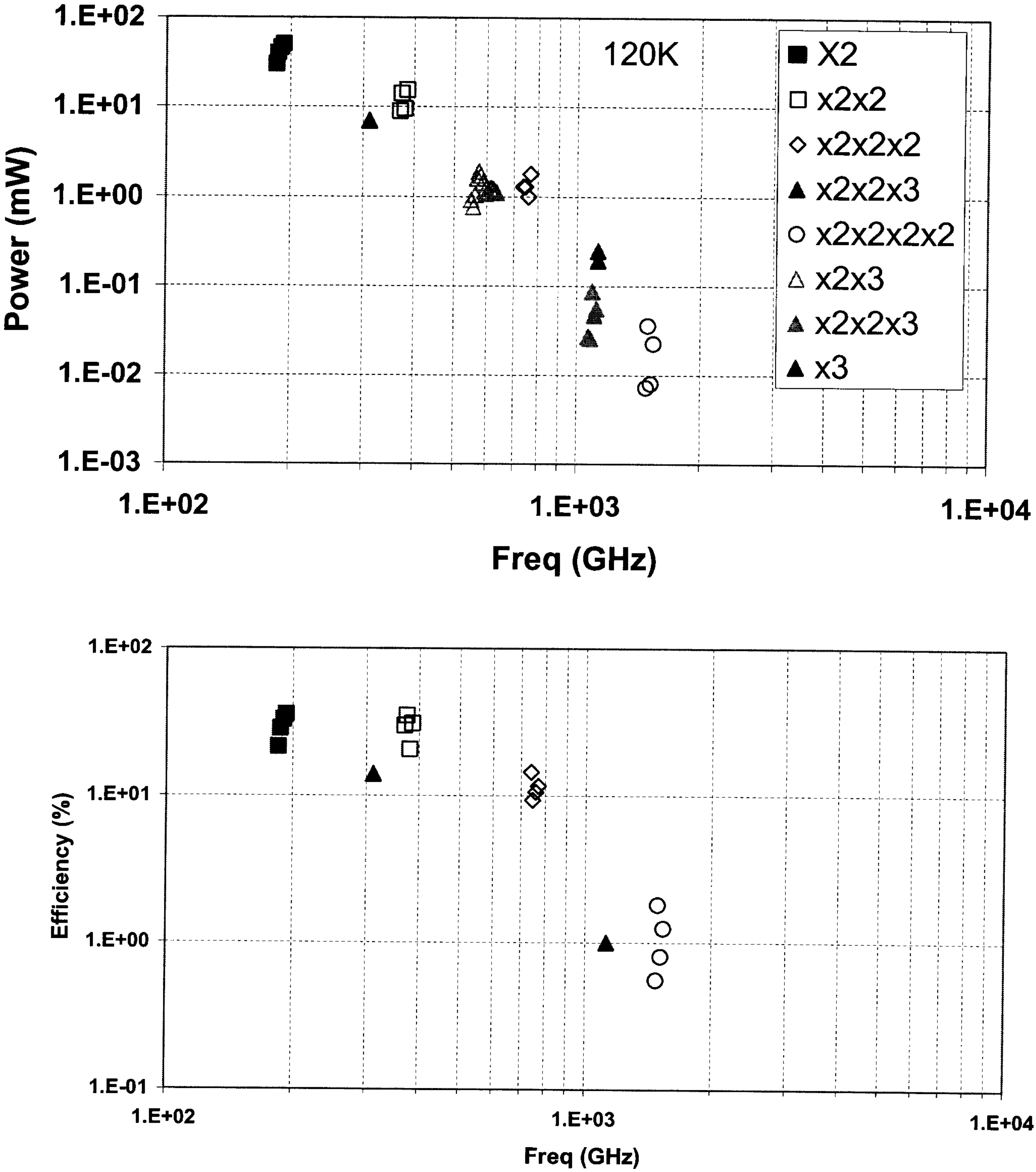


Figure 7: Recent performance from all solid state sources has been compounded. This includes results from discrete chips as well as 'substrateless' designs. All of the results reported here were measured either at JPL or at the University of Massachusetts.

3.2. Modeling

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. Designs that push the upper frequency band to 1900 GHz have already been developed and are currently in fabrication [27,28]. A better diode model that can accurately predict performance given input power, temperature and matching circuit has also been developed [22]. The usefulness of this model can be demonstrated via Figure 8 that shows the measured and simulated performance of the 800 GHz balanced doubler. The agreement is very impressive. However, to point out some of the deficiencies that still exist the performance of the 200 GHz circuit as a function of input power is plotted in Figure 9. The model overestimates the circuit efficiency. This could be due to an underestimation of the anode temperature or could be due to some other physical effects related to high power levels that need to be further explored.

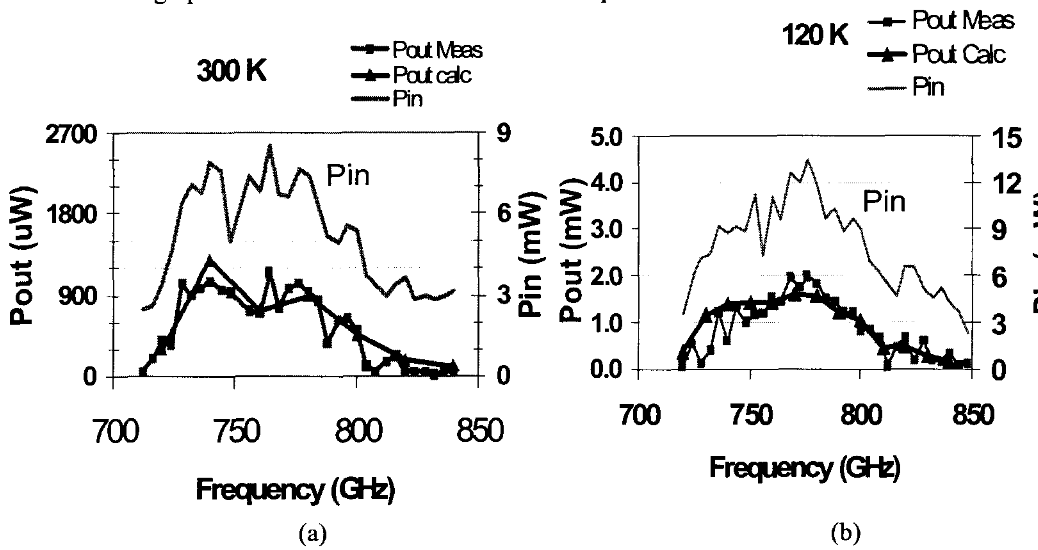


Figure 8: Plots of measured and simulated 800 GHz doubler efficiency. The doping is $3x10^{17}$ cm^{-3}. Anodes are 1x1.2 micros. Square symbols mark the measurements, triangles mark the simulations. (a) 300 K block temperature (b) 120 K block temperature.

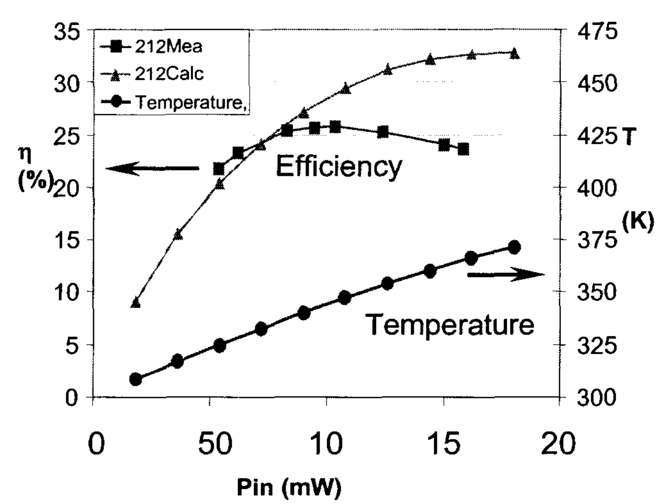


Figure9: Performance of the 200 GHz multiplier as a function of input power per anode. Nominally the design is optimized for 25-30 mW of input power at room temperature. The hottest temperature on the chip (anode) is also simulated as a function of input power.

3.3. Waveguide block fabrication

With the commercialization of high RPM spindles it has now become possible to machine blocks with tolerances within +/- 5 microns. Admittedly, this process requires extensive tooling and an extraordinary effort. Blocks with feature sizes of 25 microns have been successfully made at JPL. For blocks up to 2-3 THz feature sizes on the order of 20-25 microns will be required.

It can be predicted that in the next 1-2 years if sustained funding is available a complete solid state source chain to 2400 GHz with the technology outlined in the this paper is quite possible. However, it looks like a further push to 3-4 THz will require some 'outside the box' thinking. Techniques based on MEMS technology or Silicon Micromaching based on laser sources [29] become very attractive at these frequency ranges.

3.4. Diode reliability concerns

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. Accurate thermal models need to be iteratively solved along with device electronic models to successfully predict reliability concerns. Similarly, it is well known that reverse current tends to degrade ideal diode behavior, however, a detailed understanding of this mechanism along with possible solutions needs investigation. Based on long term RF stress we have concluded that with 150 mW of input power to the first stage multipliers we are operating in a safe regime. However, extensive lifetime and stress testing needs to be accomplished to further define the safe operating conditions.

3.5. Multiplier Arrays

Another possible future direction for this technology would be towards the development of multiplier array sources. Multiplier arrays could be required to (a) further increase output power, (b) pump an array of mixers at a single frequency, or (c) pump an array of mixers at multiple frequencies. Some work on mixer arrays is already in progress [30,31] though it is not clear what architecture will be preferable for space borne applications. The current technology could lend itself to array but it would also be worthwhile to re-visit quasi optically pumped multipliers as demonstrated in [32]. An example of a balanced doubler to 600 GHz is shown in Figure 9.

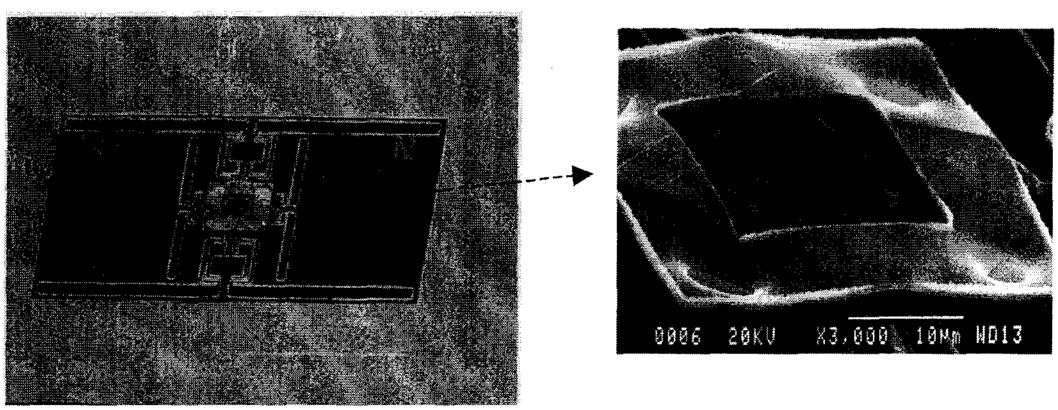


Figure 10: Example of a quasi-optical quad-diode doubler for 600 GHz. The chip is mounted on a dielectric filled parabola for coupling [32].

4.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 [33].

Pushing the limit on InP based HEMT and HBT structures can complement the Schottky varactor work. By implementing amplifiers in the higher frequency range, power combining can be used to produce sufficient power to drive higher stage multipliers. Moreover, by improving transistor structures it is also possible to design and implement active multipliers, which might provide better conversion gain at least for the lower frequency range.

Miniaturization of vacuum tube technology seems promising, once the cathode technology has been developed sufficiently. 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 a major breakthrough [35,36].

Rapid progress has also been made in photonic based sources [37,38]. 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 [39]. 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.

5.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. All solid state chains to 2-3 THz now seem possible given sustained resource allocation. However, to achieve useable power beyond this will require investigations into new technologies and techniques.

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