From Chips to (Space) Ships:
Status of Solid-State LO Sources for THz Receivers

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Abstract

For practical THz applications robust, agile and powerful sources are a must. The last decade has seen an impressive improvement in terms of generating THz signals largely in response to space based needs. MMIC power amplifiers with impressive gains can now provide hundreds of milliwatts around 100 GHz. Similarly, the ability to produce planar GaAs diode chips deep into the THz range, with sub-micron dimensions, 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. LO chains covering the 1.2 to 1.5 THz range have now been demonstrated with sufficient power to pump SIS and HEB mixers respectively. 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

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 design 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. 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. Planar Schottky diode multipliers have now been demonstrated up to 2700 GHz [1] (though it was pumped with a FIR laser) and it can be assumed that most of the future multiplier chains will be based on these 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 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 ~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 [2]. 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.
3. 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 usable RF power in the THz range [3]. 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 with great effect in 1993 by Erickson [4]. This was a discrete chip that was soldered into the waveguide block. This technique works well into the 300 GHz range but beyond that it becomes difficult to implement with any consistency.

To improve the mechanical arrangement and reduce loss the “substrateless” technology was proposed in 1999 [5] and demonstrated by 2000 [6]. 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 200, 400, and 800 GHz is shown in Figure 1. These chips enable the assembly process to become 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 both for handling purposes and for providing the DC and RF return. 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.

Finally, to push the devices towards even higher operating frequencies i.e. 1 THz and beyond, “membrane” devices have been fabricated [7]. 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 [8]. 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 1500 GHz are shown in Figure 2. The diode processing details are described in [9].

Fig. 1: Picture of a nominal 400 GHz doubler chip inside the waveguide block. This chip is made with the substrateless technology. 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. 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.
Figure 2: SEM picture of the 1200 GHz tripler (left) and a 1600 GHz doubler (right) fabricated with the membrane process. The GaAs is only 3 microns thick in each case. The beamleads provide mechanical support as well as electrical contacts.

4. STATE-OF-THE-ART PERFORMANCE

Devices shown in Figure 1 and 2 have been used to build LO chains up to 1500 GHz. Typical results obtained for the first stage doubler at 200 GHz are shown in Fig. 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 400 GHz doubler. The performance of the chain to 400 GHz is shown in Fig. 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 [10]. 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 a tripler to 1200 GHz. 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. Finally, a 800 GHz chain is used to drive a doubler to 1600 GHz. The 1600 GHz doubler is shown in Fig. 2 and is 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. The performance of this device measured at room temperature is shown in Fig. 4. It should be pointed out that the measurement of “absolute” output powers at these frequencies continues to be a significant challenge. Power meters working on the calorimetric principle as well as Golay cells have been used in the laboratory and we find good agreement between the two power meters when measuring the above chain (with 10%). However, realistically one would still expect fairly significant error bars on the order of 2 dB or so on these measurements. The final test for a chain like such is to ascertain that it can successfully pump the HEB mixers. This has now been demonstrated and will be reported shortly [1]. A 1600 GHz doubler was also designed at the University of Massachusetts which was pumped by a 800 GHz source. At room temperature peak powers of 9 microwatts have been measured with this chain. When cooled to 60K this output power improves to a very impressive 45 microwatts [12].

The effect of cooling on these various chains is shown in Figure 5. 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. It should be noted that the observed enhancement in output power with decrease in temperature is highest in the higher frequency chains. Effect of cooling on multipliers is explained further in [13,14,15].

A significant effort has also been made towards improving simulation models along with gaining a better understanding of the diode physics. This can not be discussed in detail presently but the reader is referred to [16] for more details.
Fig. 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.

Figure 4: Measured performance of the 1600 GHz chain at room temperature.
Figure 5: Measured chain output power as a function of ambient temperature. Frequencies listed are the nominal frequencies for each chain. The 1500 GHz chain consists of four cascaded doublers.

5. FUTURE CHALLENGES

The technology described above has matured enough to be base-lined for the Herschel Space Observatory (HSO). A completed chain for HSO to pump the Band 5 mixer is shown in Fig. 6. This chain based on a single power amplifier module can produce >30 microwatts at 120 K from about 1100 to 1220 GHz.

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 probably 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. 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.

6. 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 electronic bandwidth by an impressive margin. The output power in the THz range now seems to be 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 60-120 K can further enhance performance.

7. ACKNOWLEDGEMENTS

I wish to acknowledge the entire team at JPL especially, Frank Maiwald, John Ward, John Pearson, Peter Siegel, Erich Schlecht, Goutam Chattopadhyay, John Gill and others who have made the recent progress possible. I also wish to acknowledge fruitful collaborations with Neal Erickson at University of Massachusetts and Jack East at University of Michigan. This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, under contract with National Aeronautics and Space Administration.
Figure 6: A complete planar device LO chain to 1200 GHz for the Herschel Space Observatory.

REFERENCES

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