Design and Performance of Planar Schottky Diode Triplers for Radio Astronomy

Alain Maestrini [1], John Ward, John Gill, Hamid Javadi, David Pukala, Frank Maiwald,
and Imran Mehdi

Jet Propulsion Laboratory, California Institute of Technology,
MS 168-314, 4800 Oak Grove Drive, Pasadena, CA 91109

[1] Now at Laboratoire des Instruments et Systèmes d'Ile de France - Université Pierre et Marie Curie,
4 place Jussieu, case 252, 75252 Paris cedex 5

***Abstract* — We report on the design and performance of three split-block waveguide balanced frequency triplers working nominally at 600 GHz, 1200 GHz and 1800 GHz. The circuits utilize GaAs Schottky planar diodes. The 600 GHz tripler is fabricated with JPL substrateless technology that consists of removing the substrate in the center part of the circuit to decrease the dielectric load. At room temperature, it produces 0.8-1.6mW in the band 540-640 GHz when pumped with 22-25mW. The 1200 GHz and 1800 GHz triplers utilize JPL frameless membrane technology. At room temperature, the 1200 GHz tripler produces 25 µW in the band 1130-1260 GHz, while the 1800 GHz tripler produces 3 µW at 1246 GHz. The performance of the triplers improves dramatically upon cooling.**

I. INTRODUCTION

The current importance of astrophysics related, high-resolution spectroscopy in the THz range is highlighted by the current build-up of the Heterodyne Instrument for the Far Infrared (HIFI) on the European Space Agency's Herschel Space Observatory. HIFI will employ high frequency (up to 1.9 THz), high sensitivity heterodyne receivers to discover, measure and map atomic and molecular gases in and around star forming regions, nebulae and galaxies. A critical component of each receiver is the local oscillator (LO) source. Sources in the THz range have been historically extremely difficult to build and deploy. Traditional submillimeter-wave radio telescopes, both space borne and ground based, typically employ local oscillator sources comprised of Gunn diode oscillators followed by whisker contacted Schottky diode multipliers – usually frequency doublers or triplers. This paper will describe the design and development of planar Schottky diode based tripler circuits.

II. DESIGN OF SUBMILLIMETER-WAVE BALANCED TRIPLERS

When designing a frequency tripler, one has to provide the diode(s) proper impedances at each harmonic. Usually, the matching is limited to the first three harmonics (including the fundamental). The matching at the second harmonic is particularly critical. To transfer energy from the fundamental to the third harmonic with the maximum efficiency, the impedance at the second harmonic should be as close as possible to a pure reactance [1]. The best way to meet this requirement is to balance the circuit and to trap the second harmonic in a virtual loop.

Different configurations of balanced triplers can be chosen; for all our designs, the diodes are in a configuration similar to those used at lower frequencies [2]. They are in series at DC but appear to be in an anti-parallel configuration at the RF, due to the symmetry of the excitation and the symmetry of the circuit. In our designs, the virtual loop can only work if the suspended micro-strip line cannot propagate a TE mode at the second harmonic. If the parasitic mode can propagate, then the second harmonic is strongly generated and the circuit does not work as a tripler. Figure 1 shows a block diagram of the triplers: an E-plane probe located in the input rectangular-waveguide couples the signal at the fundamental frequency to a suspended microstrip waveguide that can propagate only a TEM or quasi-TEM mode. In order to keep all other modes cut off, the dimensions of the channel in which the circuit is inserted have to be chosen with care. The diodes are connected to an E-plane probe that couples the third harmonic to the output waveguide. The matching of the diode is performed both by a succession of high and low impedance sections printed on chip and by the input and the output probes with their respective back-shorts. The circuits feature additional matching elements in the input and output waveguides, made with a succession of waveguide sections of different heights and lengths. This configuration makes possible the implementation of more than two diodes. The other advantage is the simplicity of the bias circuit scheme: the diodes are biased in series at DC by means of an on-chip capacitor.

The optimization methodology was described in [3]. It requires intensive 3D electromagnetic simulations that were performed with the finite element method. The non-linear response of the circuit is given by a harmonic balance code. The Schottky diode is described by a simplified model based on [4]. The junction capacitances are calculated with an external program that takes into account the fringing fields.

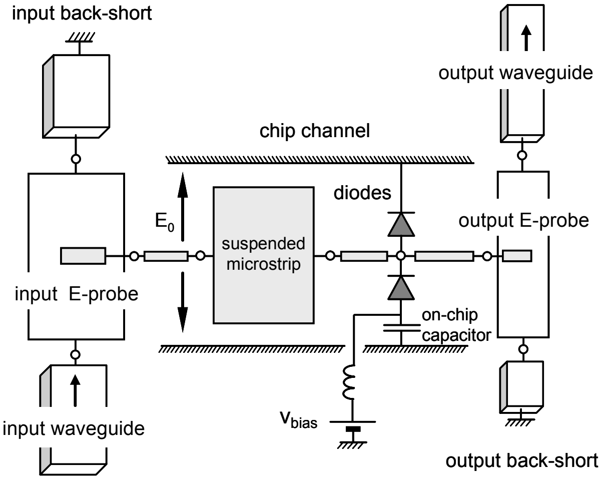

Figure 1: block diagram of the balanced triplers. The 600 GHz balanced tripler features two groups of two anodes in series each. The 1.2 THz and 1.8 THz triplers feature two anodes, but the bias circuit is removed.

III. TECHNOLOGY

All the triplers are split-block waveguide designs. The 600 GHz balanced tripler was made with JPL substrateless technology introduced in [5], [6], [7]; it consists of removing the substrate in most of the parts to decrease the dielectric load. The circuit is 1100 µm x 950 µm x 12 µm thin. The chip is suspended above the bottom half of the block by several beam-leads. The chip features 4 anodes of 1.7 x 2.8µm each; the doping is 10^{17} cm^{-3}. The corresponding junction capacitance is approximately 5.7 fF. The series resistance is about 15 Ω per anode.

The 1.2 THz and 1.8 THz balanced tripler were made with JPL membrane technology [7], [8]. Both designs features two anodes and are biasless. For the 1.2 THz tripler, each anode is nominally 0.4 x 0.9 µm, epilayer doping is $5x10^{17}cm^{-3}$ and Cj(0)=1.1 fF; the series resistance is about 45 Ω per anode. More details can be found in [9]. For the 1.8 THz tripler, the anodes are approximately 0.4 x 0.8 µm, epilayer doping is $5x10^{17}cm^{-3}$ and Cj(0)= 0.9 fF; the series resistance is about 70 Ω per anode. More details about this tripler can be found in [3].

The waveguide block includes respectively a 1.2 THz and a 1.8 THz diagonal feed-horn machined in two symmetrical parts. The circuits are integrated on a 3 µm thick frameless GaAs membrane located between the input waveguide and the output waveguide, inside a channel. One-micron thick gold beam-leads, located on either side of the membrane, suspend the chips above the bottom half of the channel. For the 1.2 THz tripler, the beam leads run the full length of the channel; for the 1.8 THz tripler, two beam leads provide the required DC and RF connections for the diodes and two others are used only to support the chip (see Figure2).

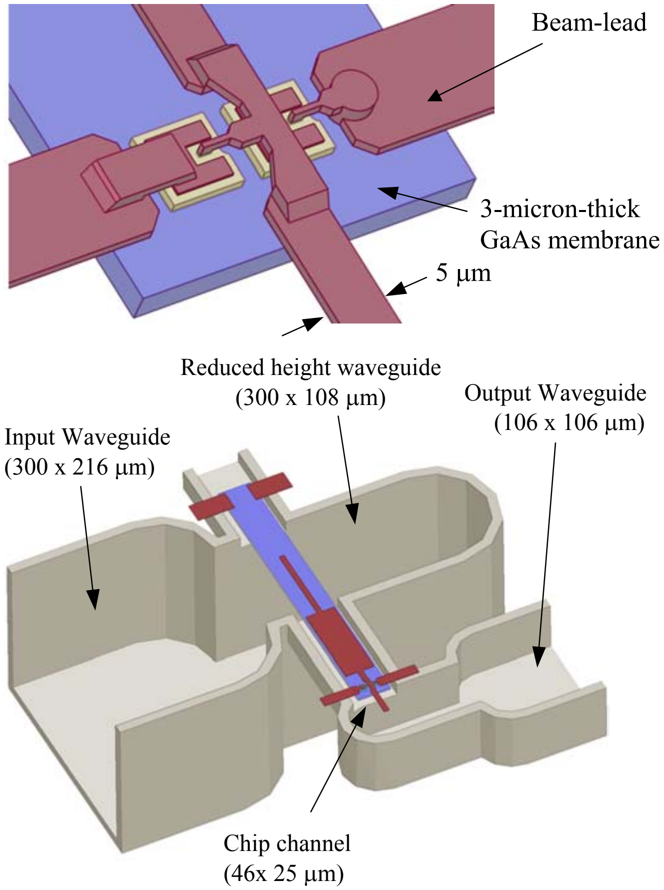

Figure 2: 1.8 THz balanced tripler. The top view shows a detail of the anode area. The chip is suspended in the middle of the channel by beam-leads. This circuit cannot be externally biased.

IV. PERFORMANCE

The 600 GHz tripler requires a 200 GHz driver, and the 1.2 THz tripler requires a 400 GHz driver. These drivers are based on balanced doublers described in [6]. The fundamental source is a commercial 75-110 GHz synthesizer followed by power amplifiers that can deliver up to 300 mW [10], [11]. The 1.8 THz tripler is driven by the 600 GHz tripler.

Power measurements at submillimeter wavelength are difficult due to a variety of factors including the lack of accurate submillimeter-wave calibration standards and the increasing importance of losses such as ohmic losses and water vapor absorption. Depending on the frequency and the power level to be measured, different sensors can be used. The 600 GHz tripler output power was measured at room temperature with an Erickson Instruments calorimeter [12]; at cryogenic temperature, however, it was measured with a photo-acoustic power meter from Keating LTD. To couple the output signal to the power-meter, the multiplier had to be fed with an external horn. At 1.2 THz the signals were weaker, in the range of 10-150µW. The Thomas Keating meter was still used, but with much longer integration time (up to 10 minutes). To be able to tune the bias of the lower-stage multipliers (the drivers), an ultra-sensitive but un-calibrated bolometer working at 4K was used. Figure 3 shows the complete set-up.

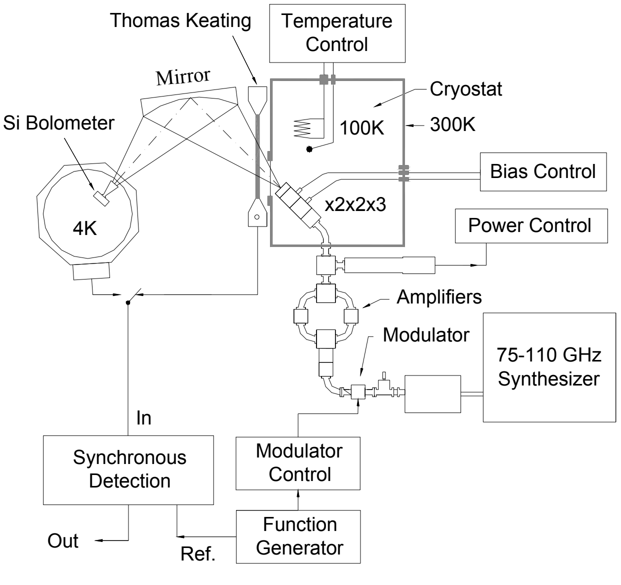

Figure 3: Block diagram of a cryogenic test bench used to measure the output power of the 1.2THz tripler.

At 1.8 THz, the output signal was in the range 0.5-30µW. As it is barely feasible to measure signals below 4 µW with the Thomas Keating meter, a Golay cell with a diamond window was used for its sensitivity and flat frequency response. Unfortunately, the Golay cell saturates with power above 10 µW and can be destroyed with power in the range of several tens of microwatts. Therefore, a calibrated attenuation was introduced in the test procedure to avoid any damage to the sensor. The Golay cell responsivity was calibrated against the Thomas Keating meter with power of about 7 µW.

Preliminary results of the 600 GHz balanced tripler show an efficiency of about 4-8% from 545 GHz to 640 GHz at room temperature. The corresponding output power is in the range of 0.8 to 1.6 mW. When the chain is cooled to 120 K, the drive power can be increased; the efficiency then jumps to 7-13% in the same band with an output power of about 2.5-4 mW.

At room temperature, the 1.2 THz tripler provides more than 25 µW of output power in the band 1130-1250 GHz and 100 µW at 1180 GHz. When cooled to 120 K, the chain delivers 50 µW in the band 1120-1260 GHz and 200 µW at 1190 GHz. The efficiency is about 1% at room temperature and 2% at 120K.

The 1800 GHz tripler works best at the low end of the design band and provides more than 3 µW of output power around 1785 GHz at room temperature. The performance of this chain improves dramatically when cooled to 120 K. Power above 1.5 µW was measured from 1730 to 1875 GHz with a peak power of 15 µW at 1746 GHz.

CONCLUSION

Utilizing powerful circuit simulation tools along with advanced planar diode technology a class of robust triplers has been demonstrated from 600 GHz to 1800 GHz. These triplers provide record output powers and enable the deployment of ultra-high sensitivity heterodyne receivers for a better understanding of the universe.

ACKNOWLEDGEMENTS

The authors are grateful to Peter Bruneau and the JPL Space Instruments Shop for the superb fabrication of the waveguide blocks. The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

[1] P. Penfield, R.P. Rafuse, “Varactor Applications,” M.I.T Press, 1962.

[2] C.P. Hu, "Millimeter wave frequency multipliers employing semiconductor diodes in a balanced configuration," *Proc. 16th European Microwave Conf.*, Dublin 1986, 247-251.

[3] A. Maestrini, J. Ward, John Gill, G. Chattopadhyay, F. Maiwald, K. Ellis, H. Javadi, and I. Mehdi, "A Planar-Diode Frequency Tripler at 1.9 THz," Proceedings of the IEEE MTT-S, Philadelphia, Pennsylvania, June 8-13, 2003.

[4] N.R. Erickson, "Diode Frequency Multipliers for Terahertz Local Oscillator Applications," *Proc. SPIE*, vol. 3357, pp. 75-84, *Advanced Technology MMW, Radio, and Terahertz Telescopes*, T.G. Phillips, Ed., July 1998.

[5] G. Chattopadhyay, E. Schlecht, J. Gill, S. Martin, A. Maestrini, D. Pukala, F. Maiwald, and I. Mehdi, "A Broadband 800 GHz Schottky Balanced Doubler," *IEEE Microwave Guided Wave Lett.*, vol. 12 no. 4, pp. 117-118, April 2002.

[6] E. Schlecht, G. Chattopadhyay, A. Maestrini, A. Fung, S. Martin, D. Pukala, J. Bruston and I. Mehdi, "200, 400 and 800 GHz Schottky Diode `Substrateless' Multipliers: Design and Results," *IEEE Int. Microwave Symp. Digest,* pp. 1649-1652, Phoenix, AZ, May 2001.

[7] Suzanne Martin, Barbara Nakamura, Andy Fung, Peter Smith, Jean Bruston, Alain Maestrini, Frank Maiwald, Peter Siegel, Erich Schlecht and Imran Mehdi, "Fabrication of 200GHz to 2700GHz Multiplier Devices using GaAs and Metal Membranes," *IEEE MTT-S International Microwave Symposium,* Phoenix, Arizona, May 20-25, 2001.

[8] J. Bruston, S. Martin, A. Maestrini, E. Schlecht, P. Smith, and I. Mehdi, "The Frameless Membrane: a Novel Technology for THz Circuits", *Proceedings of the 11th International Symposium on Space Terahertz Technology, Ann Arbor*, June 2000.

[9] A Maestrini, J. Bruston, D. Pukala, S. Martin and I. Mehdi, "Performance of a 1.2 THz Frequency Tripler using a GaAs Frameless Membrane Monolithic Circuit," Proceedings of the IEEE MTT-S, Vol. 3, pp. 1657-1660, Phoenix, Arizona, May 20-25, 2001.

[10] L. Samoska, T. Gaier, A. Peralta, S. Weinreb, J. Bruston, I. Mehdi, Y.C. Chen, H.H. Liao, M. Nishimoto, R. Lai, H. Wang, Y.C. Leong, "MMIC Power Amplifiers as Local Oscillators for FIRST," *Proc. SPIE UV, Optical, and IR Space Telescopes and Instruments*, SPIE 4013, Munich, Germany, March 2000.

[11] H. Wang, et al., "Power-Amplifier Modules Covering 70-113 GHz using MMICs," IEEE Trans. Microwave Theory and Techniques, vol. 49, pp. 9-16, 2001.

[12] N. R. Erickson., "A Fast and Sensitive Submillimeter Waveguide Power Sensor," Tenth Int'l Conference on Space THz Tech., pp. 501-507, Charlottesville, VA, 1999. Available from Erickson^2 Instruments LLC, Amherst, MA.