Pushing the Limits of Multiplier-Based Local Oscillator Chains

Imran Mehdi[1,*], John Ward[1], Alain Maestrini[2], Goutam Chattopadhyay[1], Erich Schlecht[1] and John Gill[1]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA

[2]University of Paris VI, Paris France

* Contact: Imran.mehdi@jpl.nasa.gov, phone +1-818-354-2001

Abstract—**Generation of coherent terahertz radiation remains a critical technological challenge for applications such as spectroscopy, imaging, communications and radar. A review of the current state-of-the-art for terahertz sources is presented with emphasis on Schottky diode-based frequency multiplier technology. A simple power-combining approach has been demonstrated successfully around 300 GHz. This approach provides a framework for pushing both the output power and the upper frequency range of GaAs Schottky diode based terahertz sources.**

I. INTRODUCTION

Several recent articles have described the potential and capability of terahertz technology and how harnessing this technology can lead to exciting scientific discoveries in various fields [1]-[4]. One of the most challenging aspects of terahertz technology is the lack of compact, reliable, efficient, broadband sources in the terahertz range. Sources are required for all possible applications, either as transmitters or as local oscillators (LO) for heterodyne detectors. This article will present a brief review of the source technologies that are currently available and discuss the recent approach utilizing a power-combining technique that can be used to generate higher output power from GaAs Schottky diode frequency multipliers.

II. TERAHERTZ SOURCES

A number of technologies exist that can provide terahertz radiation. The output power of a source is the dominant figure of merit, however, from a systems point of view there are important secondary criteria such as tunable bandwidth, DC-to-RF conversion efficiency, operating temperature, mass, volume, frequency stability, and spectral purity that can dictate the use of any particular technology.

Much of the recent developmental activity for terahertz sources was driven by the needs of the Heterodyne Instrument for Far Infrared (HIFI) on the Herschel Space Observatory. Multiplied chains that successfully pumped HEB mixers in the 1.6 to 1.9 THz range were developed and delivered. This technology was enabled by the development of high power GaAs power amplifier MMICs in the 100 GHz range. These MMICs allowed one to achieve broadband, electronically tunable sources with >200 mW of power. The approach for HIFI was to use 100-150 mW at around 100 GHz and multiply this with a single string of frequency multipliers. This approach has its limitations and would have to be extremely well optimised to pump multi-pixel receivers or provide useful power beyond 2 THz, especially at room temperature.

In addition to Schottky diode frequency multipliers, there are a number of other technologies that have certain advantages. In terms of raw output power, FIR lasers pumped by gas lasers are dominant [5]. These lasers can provide tens of milliwatts in the terahertz range. However, they are not tunable, generate power only at certain discrete frequencies, are bulky, and are extremely inefficient. Similarly, carcinotrons and other varieties of backward wave oscillators (BWOs) can be useful tools in a laboratory but require huge power supplies and are bulky for space instruments. The quantum cascade lasers (QCLs) have been making immense progress in the last few years and can provide substantial output power in the higher THz frequency range. QCL technology is rapidly advancing; however, there are a number of issues that must be resolved before they can be successfully implemented in flight missions. Current QCL technology is limited to cryogenic operation, is narrow banded, and requires a signal locking scheme before it can be used for applications such as spectroscopy. A recent pertinent review of this technology has been presented in [6].

Considerable advances are also being made in terms of pushing frequency and power performance of three-terminal devices. InP based HEMT amplifiers are now commonly available that operate around 100 GHz and recently gain has been measured at 345 GHz [7][8]. By optimizing material selection and reducing gate widths, it might be possible to extend the frequency coverage to around 500 GHz. Resonant tunnelling diodes (RTDs) [9] and photomixers [10] have also shown that they can work into the terahertz range; however, the low output power from such sources continues to be a limiting factor.

A summary of available output power as a function of operating frequency from the technologies discussed above is shown in Figure 1. For future space applications, the

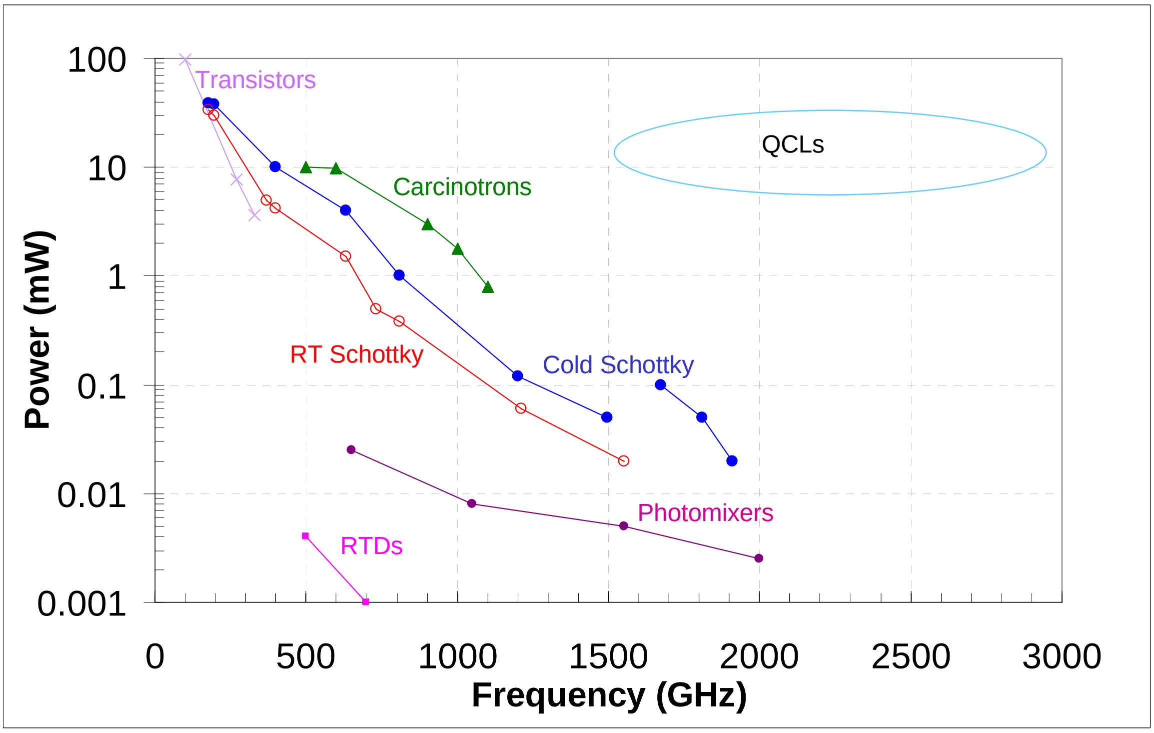

Figure 1: Compilation of available output power from various THz sources as a function of operating frequency. Results from Schottky diode frequency multipliers are shown both for room temperature operation as well as when cryogenically cooled.

required sources can be divided into two categories. For astrophysics, sources are needed that can cover post-HIFI exploration such as the molecular lines in the 2-4 THz range as well as sources that provide sufficient power to pump multi-pixel receivers in the 1-2 THz range [11]. For planetary exploration, sources are needed in the 300-1200 GHz range that are powerful enough to pump Schottky diode mixers [13][14]. Continued advances in frequency multiplier technology will be needed to achieve these goals.

This brief paper will discuss a simple approach of power combining with the help of Y-junctions that can provide a possible solution to increasing input power handling capability of the first and second stage frequency multipliers of a terahertz source. This in turn will greatly increase the output power from the chain by optimally pumping the terahertz frequency multipliers for maximum conversion efficiency.

III. Schottky Diode Frequency Multipliers

A. Limitations of Schottky diode frequency multipliers

In order to understand the potential and capabilities of submillimeter-wave Schottky diode frequency multiplier circuits it is instructive to investigate their limitations. The limitations can generally be divided into two distinct camps. The first set of limitations is related to the intrinsic physics of the Schottky device. These can be understood from the formulation of the Manley-Rowe relationships that in fact hold true for any ideal non-linear reactance or resistance [15]. This limitation bounds the maximum efficiency that can be obtained from an ideal Schottky device.

Unfortunately, in reality a purely varactor or varistor device does not exist. The diode has both a capacitive and a resistive nonlinearity. Consider a uniformly doped semiconductor structure with an ohmic contact on one end and a metal-semiconductor contact on the other end. The semiconductor will have a depletion layer with a width w, with the remaining portion of the structure undepleted. The depletion layer can be represented as a capacitor and the undepleted portion can be represented as a resistor. The depletion layer will act as a parallel plate capacitor where the capacitance can be modulated with an applied electric field by modulating the depletion width. This inverse square root dependent capacitance is the starting point for analytic varactor frequency multiplier analysis. Similarly, under forward bias, the device current will be an exponential function of the applied voltage giving rise to the non-linear resistance. Submillimeter-wave frequency multipliers often work in a mode that is not purely varactor or varistor in nature but a combination of both. There are also parasitic elements that must be considered in any analytical model, however, the simple diode model with nonlinear resistor and nonlinear capacitance can be used to look at the limitations of the device.

The undepleted region of the device and various contact and package resistances will appear in series with the nonlinear junction. Although the undepleted region width is voltage dependent, this series resistance is usually modeled with a constant value. However, at very high frequencies the current through the undepleted region can crowd to the outside edge of the material due to the skin effect, increasing the resistance [16]. This frequency dependent resistance should be included in any simulation and must be considered to obtain realistic performance predictions.

The early simulation tools and simple device model did a reasonable job in predicting device performance; however, the output powers and efficiencies predicted were always higher than the experimental results. There are several possible reasons. Circuit loss increases with frequency, so the loss between the diode and the external connection should be higher. Measurements are less accurate at these frequencies, so the differences between the desired designed circuit embedding impedances and the actual values may be larger. Parasitic effects are also more important, degrading the performance. However, even when all these effects were taken into account, the experimental powers and efficiencies were still lower than expected especially as the operating frequency was increased. This led researchers to further investigate device physics in the presence of a time varying field.

A first order view of the problem can be described by rewriting the width of the depletion layer as a function of a time dependent applied voltage. The time derivative of this equation is the velocity of the edge of the depletion layer. When this velocity, which depends on a combination of the frequency, RF and DC voltages across the device, and the doping, is larger than the saturated velocity imposed by the semiconductor physics the voltage dependent description of the calculated capacitance is no longer correct [17]. The velocity of the edge of the depletion layer is just the velocity of the electrons in the undepleted portion of the structure. The time rate of change of the nonlinear capacitance is limited by the saturated velocity of the semiconductor material. Driving the device beyond this saturation point will increase the voltage drop and resistance of the undepleted region and reduce the conversion efficiency of the frequency multiplier.A detailed discussion of the current saturation effect is presented in [18].

A third limitation related to the intrinsic device is the onset of plasma resonances that can effectively increase the resistance of the device [19]. However, most likely this phenomenon becomes dominant at above a few terahertz and can be neglected for the current discussion.

Thus, a careful design of the device is required that provides maximum non-linearity but avoids current saturation effects based on the frequency of operation and available pump power. However, this is only half of the story. A second set of limitations must also be considered.

The second set of limitations can broadly be categorized as 'practical' limitations related to the way a particular frequency multiplier circuit will be physically implemented and used. An important criterion of any successful design is the input and output coupling property of the device. The Manley-Rowe and current saturation theories provide no guidance on this and in reality at these frequencies it is difficult to provide a purely reactive match to the device for maximum coupling efficiency.

Another important consideration is the bias conditions for the frequency multiplier circuit. Current saturation theory suggests increasing the doping of the semiconductor; however, this decreases the breakdown voltage of the device and can result in limiting output power from the device. While some general guidelines can be provided to determine safe operating conditions for a given frequency multiplier a quantitative analysis requires extensively testing the frequency multiplier in question.

Determining the safe operating zone for a given frequency multiplier boils down to biasing the frequency multiplier in a range where no significant reverse current is present. This safe operating zone can be determined by extensively testing the multiplier in question as a function of different bias conditions, power levels and across the frequency range of interest. One has to determine the bias and power conditions for each frequency point to determine the onset of reverse current. Based on this information the limit on the reverse bias voltage of the multiplier can be established. In the forward direction the envelope is determined by the maximum current that can be sustained by the diode without damage (approximately 0.5 $mA/\mu m^2$) as discussed in [20]. Thus, between these two boundary conditions lies the safe operating zone of this particular frequency multiplier. As can be seen from this example, this safe zone will be unique for each design and is strongly coupled to the implementation of the frequency multiplier circuit.

Another important practical consideration that has become increasingly important due to the availability of high input power levels is the thermal design of the frequency multiplier circuit. GaAs thermal conductivity decreases with increasing temperatures resulting in thermal runaway and failures. A number of approaches can be employed to improve the thermal performance of frequency multiplier circuits.

IV. Membrane-Based Schottky Diodes

In the last several years considerable progress has been made in understanding and more importantly being able to realize terahertz frequency multiplier chips that can produce useful amount of power in the terahertz range. A number of different technologies have colluded to make this progress possible. Powerful 3-D electromagnetic simulations have enabled accurate modelling of the devices and circuits. Application of advanced semiconductor processing tools have resulted in low-parasitic GaAs planar Schottky diodes on ultra-thin membranes. The membrane devices have allowed implementation of increased functionality at the chip level while also making possible a simplified integration process. Precise metal machining has enabled high quality waveguide blocks with micron level precision. Finally, availability of high power GaAs power amplifiers in the w-band range allowed one to design frequency multiplier based LO chains with large multiplication factors and still obtain useful amounts of power.

Broadband terahertz sources for the Herschel Space Observatory were built based on the technologies outlined above. The tall pole for the mission was achieving 10% electronically tunable sources in the 1.6 to 1.9 THz range with sufficient power to pump a pair of Hot Electron Mixers (HEB) mixers. Results for the HIFI LO chains have been presented elsewhere in detail [21][22][23]. Simulations for first stage frequency multipliers as well as multipliers in the 1.6 to 1.9 THz range have shown good agreement with measured results. Based on these simulations we believe that Schottky diode frequency multipliers can be fabricated and implemented that work in the 2-3 THz range. However, to accomplish this one must construct a driver chain that ensures that the last stage multiplier will be sufficiently pumped. To accomplish this goal one must have first and second stage frequency multipliers that can handle large amounts of pump power without sacrificing device lifetime.

A number of approaches have been demonstrated to this effect. Increasing the number of anodes per chip, mounting chips on higher thermal conductivity substrates have shown to work very well [24]. However, there is a practical limit to the number of anodes based on chip size dictated by the RF design. .A new approach, where the input signal is first split, then multiplied and finally recombined has recently been demonstrated. This allows one to optimize each chip and then essentially package two chips in a single waveguide block and get a 3 dB increase in input power handling capability without sacrificing conversion efficiency.

A. In-phase power combining of frequency multiplier chips

A single chip 260-340 GHz balanced tripler with six-anodes has been successfully implemented with a membrane based device [25]. This design works well and provides ~10% efficiency across much of the band. However, the efficiency starts to saturate once pumped with more than 100 mW of input power. Since input power in the 200-250 mW is now readily available it would be useful to re-design this circuit for increased input power. The small size of the channel dictated by the onset of unwanted parasitic modes does not allow further increase in the anodes per chip. Thus, a simple approach involving Y-junction power-combining was implemented.

The power-combined version is based on two mirror-image tripler chips that are power-combined in-phase in a single waveguide block using a compact Y-junction divider at the input waveguide and a Y-junction combiner at the output waveguide. Fig. 2 shows a schematic of the bottom half of the waveguide block. A close up of the area where the chips are mounted is shown in Fig. 3. The two chips are of identical design and are a mirror image of each other. The tripler uses a split-block waveguide design with two independent DC bias lines. The input waveguide is split in two by a Y-junction to evenly feed two chips each featuring six anodes. The chips are mounted in two independent channels that run between their respective input and the output waveguides. The two reduced-height output waveguides are combined by a Y-junction that is seen by each branch of the circuit as a simple waveguide step.

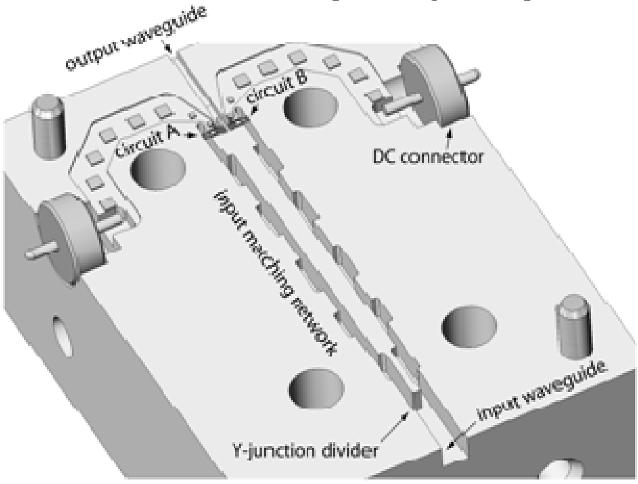

Figure 2: Bottom half of the waveguide block for the in-phase power-combined tripler at 300 GHz.

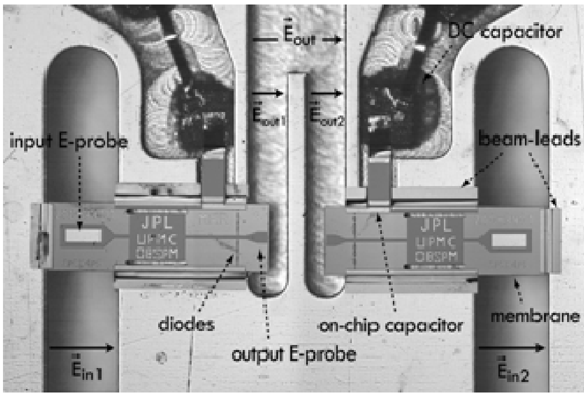

Figure 3: Close up view of a power-combined 300 GHz frequency tripler showing the two GaAs integrated circuit chips.

On each chip, an E-plane probe located in the input waveguide couples the signal at the input frequency to a suspended microstrip line. This line has several sections of low and high impedance used to match the diodes at the input and output frequencies and to prevent the third harmonic from leaking into the input waveguide. The third harmonic produced by the diodes is coupled to the output waveguide by a second E-plane probe. In order to balance the circuit, the

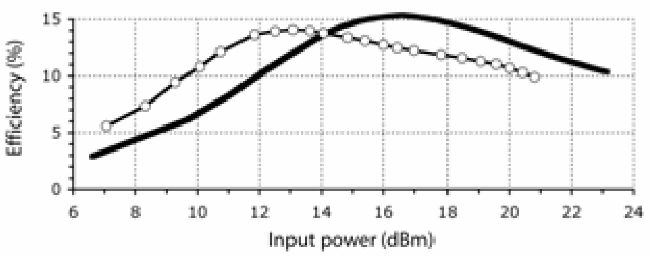

Figure 4: Power sweep of the single-chip tripler at 292.2 GHz (light curve with open markers) and of the power-combined tripler at 286.2 GHz (heavy curve with no markers). It can be seen that the power-combined tripler begins to compress at an input power which is 3 dB above that of the single-circuit tripler, as expected.

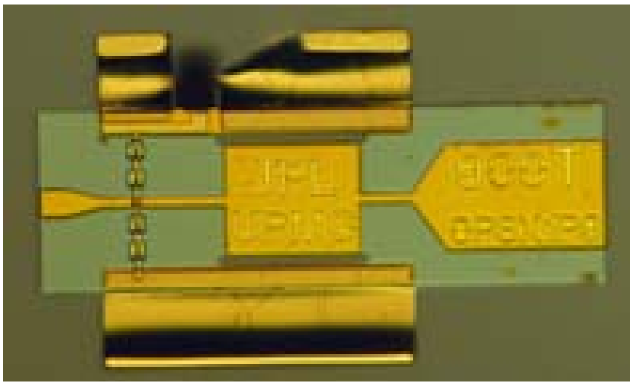

Figure 5: Picture of a 4-anode 900 GHz tripler chip fabricated on a thin GaAs membrane.

dimensions of both the channel and the circuit are chosen to cut off the TE-mode at the second (idler) frequency. The dimensions of the output waveguide ensure that the second harmonic is cut off at all frequencies measured, and the balanced geometry of the chips ensures that power at the fourth harmonic of the input is strongly suppressed.

The input power of the triplers was adjusted by varying the drain voltage of the power amplifiers and was monitored using a directional coupler. For all the measurements, the input power of the triplers was kept below 250 mW. The reverse voltage of each circuit was kept above -14 V (for 6 anodes in series) and the rectified direct current was kept below 3 mA. The two bias voltages were optimized independently at each frequency to maximize the output power. Performance gains by independently optimizing the two bias voltages were small; for most applications, the two bias lines could be tied to a single bias voltage for simplified operation. The typical power-combined frequency tripler has efficiency in the range from 5% to 13% across the frequency band for 50 mW to 250 mW of input pump power. Maximum power obtained to date is a record 26 mW at 318 GHz with 11% conversion efficiency.

Detailed measurements of the power combined tripler have been presented in [26]. Despite the high frequencies involved and large fractional bandwidth, the power combining is nearly ideal, with the power-combined version performing with almost identical bandwidth and conversion efficiency as the single-circuit version except with twice the power handling. The conversion efficiency of the power-combined tripler exceeds 10% for input powers ranging from 1.4 mW to 17 mW per anode or 17 mW to 206 mW of total power. The peak efficiency reaches a record 15.3% at 286.2 GHz and is obtained with an input power of 3.5 mW per anode or 41.5 mW of total power. This large dynamic range makes the power-combined tripler very versatile. Fig. 4 shows the conversion efficiency versus input power of the power-combined 300 GHz tripler and of a single-chip 300 GHz tripler. Each tripler was tuned to a frequency where the conversion efficiency was near the maximum and where at least 200 mW and 100 mW of drive power were available for the power-combined tripler and the single-chip tripler, respectively. As can be noted similar efficiency is obtained with the two-chip tripler but with a 3-dB increase in the input power. It should be pointed out that the current version of the power combining is done in waveguide but in future the same functionality could be accomplished by on-chip components. Moreover, it is also simple to conceptualize four or even more chips to further increase input power handling capability.

The power combined tripler can now be used to drive higher frequency multipliers. A 900 GHz tripler chip based on four-anodes is shown in Figure 5. To further improve the performance of the chain, the frequency multipliers were cooled to 77K. The output power from the two stage chain is shown in Fig. 6. None of the available amplifier modules were able to cover the full band of the frequency multiplier chain thus two different amplifier modules were used to generate the data in Fig. 6. The higher power drive stage allows us to obtain these power levels without risking device lifetime of the first stage tripler. To the best of our knowledge, this chain represents the highest output power from electronics-based sources at this frequency. This data, if included on Figure 1, would indicate that by power combining one can further increase the output power producing capability of Schottky diode based multiplier chains. An input power vs output power characterization of the 900 GHz tripler indicates that the chip is getting saturated around 20 mW of input power. Thus, it can be expected that better performance can be obtained if a two-chip circuit is also built for the 900 GHz tripler.

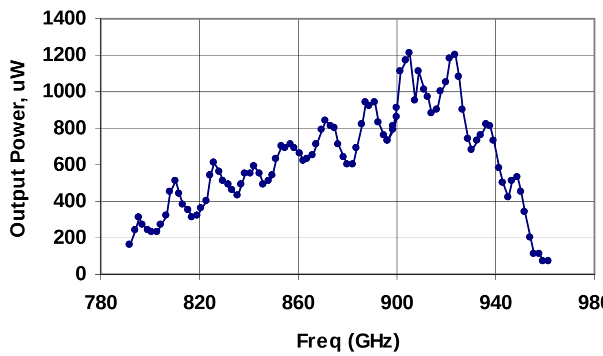

Figure 6: Measured performance of a two-stage x3x3 chain. The first stage tripler is the two-chip power-combined version discussed in this paper. The second stage tripler is a single chip design. All of the multipliers were at 77K ambient temperature.

V. FUTURE TRENDS

This scheme of power combining the first stage to get a 3-dB increase in output power is very effective and can be adopted for higher frequencies. Currently, we plan to design and build a 900 GHz two-chip tripler which will then be able to sufficiently pump a 2700 GHz tripler. It is expected that we will be able to achieve around 1 microwatts of output power at this frequency. Introduction of GaN based power amplifiers in the 100 GHz range will provide impetus for a re-think of how first stage frequency multipliers are designed and implemented. With the availability of one-watt power levels it would be important to optimize designs that can handle this much power.

CONCLUSIONS

Two submillimeter-wave tripler chips have been successfully power combined in a single waveguide block. The power combined tripler produces approximately twice as much power without sacrificing efficiency or bandwidth compared with a single chip implementation. This approach represents an important step towards building more powerful sources in the submillimeter-wave range which can then successfully drive sources beyond 1 THz.

ACKNOWLEDGMENT

We are greatly indebted to the JPL machine shop for the superb fabrication of the precision waveguide blocks. We also acknowledge help from Robert Lin and Hamid Javadi for assembly and testing of the sources. The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with National Astronomical and Space Administration.

REFERENCES

[1] P.H. Siegel, "Terahertz Technology in Biology and Medicine," IEEE Trans. Microwave Theory Tech., vol. 52, no. 10, pp. 2438–2447, Oct. 2004.

[2] T. W. Crowe, W. L. Bishop, D. W. Porterfield, J. L. Hesler, and R. M. Weikle, "Opening the THz window with integrated diode circuits," *IEEE Journal of Solid-State Circuits*, vol. 40, no.10, October 2005.

[3] D. Mittleman, "Terahertz imaging," in Sensing With Terahertz Radiation, D. Mittleman Ed. Berlin, Germany: Springer-Verlag, 2003, pp. 117–153.

[4] D. L. Woolard, E. Brown, M. Pepper, M.Kemp, "Terahertz Frequency Sensing and Imaging: A Time of Reckoning Future Applications?" , Proceedings of the IEEE, Volume 93, Issue 10, Oct. 2005, pp. 1722 – 1743.

[5] D. Hodges, F. Foote, R. Reel, "High-power operation and scaling behavior of CW optically pumped FIR waveguide lasers," IEEE Journal of Quantum Electronics, Volume 13, Issue 6, Jun 1977, Page(s):491 – 494.

[6] B.S. Williams, "Terahertz quantum-cascade lasers," Nature Photonics, volume 1, pp. 517-525, 2007.

[7] W. R. Deal, X. B. Mei, V. Radisic, M. D. Lange, W. Yoshida, P. –H. Liu, J. Uyeda, M. E. Barsky, A. Fung, T. Gaier, R. Lai, "Development of Sub-Millimeter-Wave Power Amplifiers," IEEE Transactions on Microwave Theory and Techniques, Volume 55, Issue 12, Part 2, Dec. 2007 Page(s):2719 – 2726.

[8] D. Pukala, L. Samoska, T. Gaier, A. Fung, X. B. Mei, W. Yoshida, J. Lee, J. Uyeda, P.H Liu, W. R. Deal, V. Radisic, and R. Lai, "Submillimeter-Wave InP MMIC Amplifiers From 300–345 GHz," IEEE Microwave and Wireless Components Letters,Volume 18, Issue 1, Jan. 2008 Page(s):61 – 63.

[9] Masahiro Asada, Safumi Suzuki, and Naomichi Kishimoto, "Resonant Tunneling Diodes for Sub-Terahertz and Terahertz Oscillators," Jpn. J. Appl. Phys. 47 (2008), pp. 4375-4384.

[10] Hiroshi Ito, Fumito Nakajima, Tomofumi furuta and Tadao Ishibashi, "Continuous THz-wave generation using antenna-integrated uni-travelling-carrier photodiodes," Semicond. Sci. Technol, Vol. 20, S191-8.

[11] B. Drouin, F. Maiwald & J. Pearson, "Application of Cascaded Frequency Multiplication to Microwave Spectroscopy," Rev. Sci. Instrum. 76, 093113, 2005.

[12] Chris Walker, "The Stratospheric TeraHertz Observatory (STO)," 19th International Symposium on Space THz Technology, Groningen, Netherlands, April 28-30, 2008.

[13] E. Lellouch et al, "Science case for a sub-millimeter sounder on the TSSM mission ",poster presentation at the OPFM Instrument Workshop, June 2008, Monrovia (http://opfm.jpl.nasa.gov/InstrumentWorkshop/).

[14] Mark Allen, et al, "Ultrahigh spectral resolution submillimeter spectrometry for plannetary observations" poster presentation at the OPFM Instrument Workshop, June 2008, Monrovia (http://opfm.jpl.nasa.gov/InstrumentWorkshop/).

[15] J. M. Manley and H. E. Rowe, "Some general properties of nonlinear elements—part I, general energy relations," Proceeding of IRE, vol. 44, pp.904-914: July, 1956.

[16] L. E. Dickens, "Spreading Resistance as a Function of Frequency," IEEE Trans. Microwave Theory Tech., vol. MTT-15, no. 2, pp. 101-109, Feb. 1967.

[17] E.L. Kollberg, T.J. Tolmunen, M.A. Frerking and J.R. East, "Current Saturation in Submillimeter Wave Varactors," IEEE Transactions on Microwave Theory and Techniques, Volume MTT-40, No. 5, 831-838, May,1992.

[18] Jack East and Imran Mehdi, "Schottky Diode Frequency Multipliers", in RF and Microwave Passive and Active Technologies, M. Golio Editor, CRC Press 2008.

[19] K.S. Champlin and G. Eisenstein, "Cutoff Frequency of Submillimeter Schottky-Barrier Diodes," IEEE Trans. Microwave Theory Tech., Vol. M'IT-26, No. 1, pp. 31-34, 1978.

[20] F. Maiwald, E. Schlecht, J. Ward, R. Lin, R. Leon, J. Pearson, and I. Mehdi, "Design and operational considerations for robust planar GaAs varactors: A reliability study," in Proc. 14th International Symposium on Space Terahertz Technology, Tucson, AZ, April 2003.

[21] John Ward, Erich Schlecht, Goutam Chattopadhyay, Hamid Javadi, John Gill, and Imran Mehdi, Local Oscillators from 1.4 to 1.9 THz, Proceedings, Sixteenth International Symposium on Space Terahertz Technology, Göteborg, Sweden, May 2005.

[22] Alain Maestrini, John S. Ward, Hamid Javadi, Charlotte Tripon-Canseliet, John Gill, Goutam Chattopadhyay, Erich Schlecht, and Imran Mehdi, Local Oscillator Chain for 1.55 to 1.75 THz with 100 µW Peak Power, Microwave and Wireless Components Letters, Volume 15, Issue 12, Pages 871 - 873, December 2005.

[23] G. Chattopadhyay, E. Schlecht, J. Ward, J. Gill, H. Javadi, F. Maiwald, and I. Mehdi, "An all solid-state broadband frequency multiplier chain at 1500 GHz," IEEE Trans. Microwave Theory Tech., Vol. 52, no. 5, pp. 1538-1547, May 2004.

[24] D. Porterfield, "High-Efficiency Terahertz Frequency Triplers", in *Proc. of IEEE MTT-S International,* pp. 337-340, Honolulu, Hawaii, 3-8 June, 2007.

[25] A. Maestrini, C. Tripon-Canseliet, J.S. Ward, J.J. Gill and I. Mehdi, "A High Efficiency Multiple-Anode 260-340 GHz Frequency Tripler," *Proc. of the 17th International Symp. on Space Terahertz Technology*, pp. 233-236, Paris, France, 10-12 May 2006.

[26] Alain Maestrini, John S. Ward, Charlotte Tripon-Canseliet, John J. Gill, Choonsup Lee, Hamid Javadi, Goutam Chattopadhyay, and Imran Mehdi, "In-Phase Power-Combined Frequency Triplers at 300 GHz," IEEE Microwave and Wireless Components Letters, March 2008.