INVITED PAPER – *in Frequenz, Journal of RF-Engineering and Telecommunications, Issue 5/6 2008, Vol. 62, pp.118-122, May / June 2008.* The layout of this electronic version differs from the printed version in *Frequenz*.

Terahertz Sources Based on Frequency Multiplication and Their Applications*

Alain Maestrini, John Ward, Goutam Chattopadhyay, Erich Schlecht, and Imran Mehdi

Abstract – Compact, robust and broadband sources in the terahertz range are extremely important in diverse applications such as spectroscopy, imaging, communication, and radar. A review of the current state-of-the-art is presented with emphasis on Schottky diode based frequency multiplier technology. Frequency multiplier circuit chips fabricated on few micrometer thick GaAs membranes and packaged in low-loss waveguide circuits have demonstrated tens of microwatts of output power up to 1.9 THz. This breakthrough has enabled sensitive heterodyne receivers in the terahertz range that will be flown on an upcoming ESA mission to answer fundamental questions about our universe.

Index Terms – THz technology, frequency multipliers, sources, Schottky diode, waveguide, GaAs membrane

Introduction

Several recent articles have described the potential and capability of terahertz technology and how developing this technology can lead to exciting scientific discoveries in a variety of fields [1]-[7]. One of the most challenging aspects of terahertz technology is the lack of compact, reliable, efficient sources in the terahertz range. Sources are required for many possible applications, such as transmitters or as local oscillators (LO) for heterodyne detectors. This article will present a brief review of the CW source technologies that are currently available and discuss the recent progress that has been achieved with Schottky diode based frequency multipliers.

1. Terahertz CW sources and their applications

Several competing technologies can generate coherent CW terahertz radiation. While the output power of the source is the single most important criterion for selecting the appropriate technology, from a systems point of view there are secondary criteria such as linewidth, DC-to-RF conversion efficiency, tunable bandwidth, and spectral purity that can dictate the use of any particular technology.

In terms of raw output power, FIR lasers pumped by gas lasers are dominant [8]. These lasers can provide tens of milliwatts in the terahertz range. However, they work at discrete frequencies, are bulky, and require several tens of watts of DC power. They are therefore mainly limited to ground-based applications where size and power are not issues. Other terahertz photonic sources are the fast-improving Quantum Cascade Lasers (QCLs). They are ultra-compact milliwatt-level terahertz solid-state sources able to work in CW mode down to frequencies as low as 1.2 THz [9]. However, QCLs have limited frequency tunability and require cryogenic cooling to approximately 4 K for maximum output power. They can operate in CW mode at higher temperature with reduced output powers and up to 178 K at 3 THz when pulsed [10]. These photonic sources have been successfully employed to build the local oscillator of a cryogenic heterodyne receiver at 2.8 THz [11]. Photomixers are also an attractive solution for terahertz CW generation thanks to their frequency tunability, but their output power in the 1-2 THz range is at least of an order of magnitude lower than the power produced by room-temperature frequency multipliers [12]. From the electronics side there has been considerable progress made in advancing the high frequency performance of InP based HEMT amplifiers [13][14]. Recent results indicate that gain can be achieved at 330 GHz and possibility at even higher frequencies. Transistor-based fundamental oscillators at 346 GHz have also been demonstrated [15]. These advances may open the path to high-speed wireless communication systems with data transmission rates of several tens of gigabytes per second working above 300 GHz.

Another growing application of terahertz sources is in the field of active imaging systems able to see through clothing to detect contraband or weapons [6]. A successful imaging radar has recently been demonstrated at 580 GHz [16]. For such a system, the signal-to-noise ratio and the standoff distance can be improved with higher-power sources. Moreover, spatial resolution is directly proportional to the frequency for a given aperture size.

Despite the broad range of potential applications, technological advances in CW terahertz sources have been mainly driven by the astrophysics community. In astrophysics, heterodyne spectrometers are needed to measure Doppler velocities in the interstellar medium and star forming regions with resolutions typically around 1 km/s. Measurements at frequencies ranging from below 100 GHz to at least 5 THz are needed to identify the spectral signatures of a wide range of molecules, isotopomers, atoms, and ions, as well as to measure such physical properties as the temperature, density, pressure, mass, and dynamics of the systems observed. Terahertz CW sources are needed to use as the local oscillators for the heterodyne receivers.

This article will describe the technologies developed to build solid state sources from the 400 GHz to 1900 GHz range for a space-borne radio telescope, the Herschel Space Observatory [17]. Herschel is expected to be launched in 2009 and will address some of the most important questions in cosmology and galaxy evolution.

2. Schottky diode based frequency multipliers

In the last several years, tremendous progress has been made in understanding and realizing diode frequency multipliers that can produce useful amounts of power in the terahertz range. Diode frequency multipliers utilize the reactive and / or resistive nonlinearity of the diode to generate harmonics of an input signal. By providing appropriate embedding impedances at each integer multiple of the input frequency, it is possible to design frequency doublers, triplers, or even quintuplers. While diode structures incorporating heterostructures [18]-[20] have made significant advances, the GaAs Schottky diode continues to be the dominant technology for terahertz frequency multipliers. This article will focus on this technology.

A number of related technological advances have combined to make this progress possible. Firstly, device technology has moved away from discrete chips mounted on hybrid circuits to MMIC-like circuits on thin semiconductor membranes. Secondly, the availability of micrometer-precision CNC milling

---

* This work was supported by the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA and the Observatoire de Paris, Laboratoire d'Etude du Rayonnement et de la Matière en Astrophysique, France.

machines allows the fabrication of high-quality terahertz waveguide blocks in which one or more semiconductor circuits are mounted. Thirdly, the commercialization of accurate full 3-D finite-element-model field simulators and fast harmonic-balance codes have made possible the design of broad-band, fixed-tuned circuits featuring multiple anodes for improved bandwidth and power handing [21]–[25]. Finally, the availability of power amplifiers from 70 to 110 GHz increases available drive power and enables the sources to be driven by electronically-tunable synthesizers followed by W-band active multipliers [26]. These advances together enable the breakthrough of producing frequency multiplier chains electronically tunable over 10-15% of bandwidth with tens of microwatts of power available up to 1.9 THz.

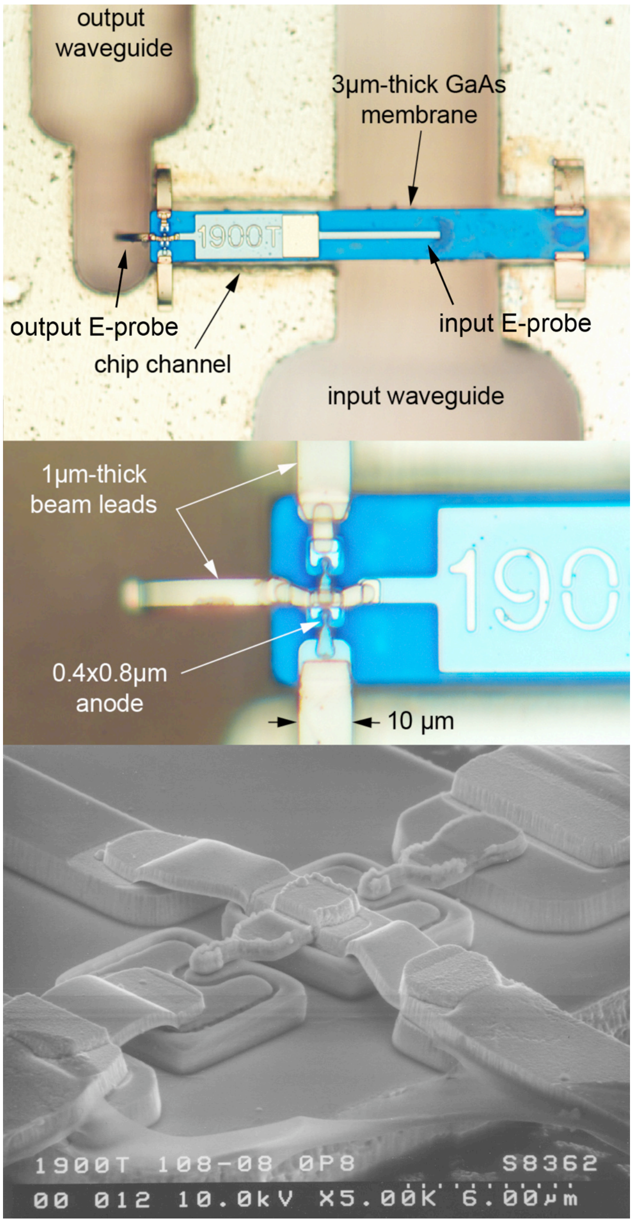

Fig. 1: Last stage frequency tripler used for the 1.6-1.7 THz and 1.7-1.9 THz local oscillator chains of the heterodyne instrument of the Herschel Space Observatory. The top picture shows the chip placed inside the waveguide block. The middle and bottom pictures show close-ups of the chip.

To meet the needs for broadband terahertz sources that could be deployed on the Herschel Space Observatory, GaAs Schottky diodes on membranes a few micrometers thick have been developed. One of the greatest challenges for the Herschel mission was achieving 10% electronically tunable sources in the 1.6 to 1.9 THz range with sufficient power to each pump a pair of Hot Electron Bolometer (HEB) mixers, which translates to being able to produce more than about 2 µW of output power.

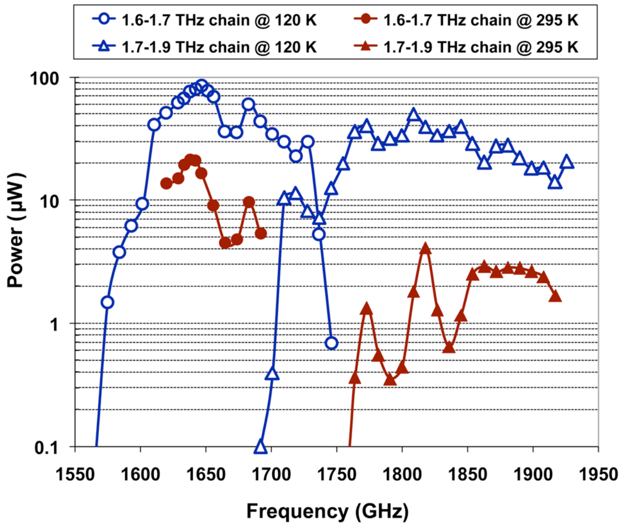

Fig. 2: Performance of 1.6-1.7 THz (circles) and 1.7-1.9 THz (triangles) local oscillator chains developed for the heterodyne instrument of the Herschel Space Observatory at room temperature (filled markers) and at cryogenic temperature (open markers).

A ×2×3×3 multiplication scheme was envisioned to cover the desired band in two sub-bands, 1.6-1.7 THz and 1.7-1.9 THz. Details of these chains have been presented previously [27], [28] and only the last stage multipliers will be discussed here. These multipliers are waveguide biasless balanced frequency triplers featuring two Schottky diodes on a several micrometer thick GaAs membrane (see Fig. 1). They use the same device, except for the size of the anodes (around 0.25 µm^2 of surface area and 1 fF of intrinsic zero bias capacitance per anode). However, the waveguide input and output matching networks are optimized for each sub-band therefore two different waveguide blocks are necessary. On the multiplier circuit, 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 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.

Accurate measurement of power at these frequencies is a difficult challenge and has been discussed in [24], [27]. At room temperature, the power generated by the multiplier chains was either measured with an Erickson meter [29] or with a Thomas Keating quasi-optical power meter placed in a nitrogen-purged Plexiglas enclosure. However, for power measurements at cryogenic temperature a Thomas Keating power meter or a Golay cell calibrated against the Thomas Keating was used.

Fig. 2 shows the output power produced by the two chains at room temperature and at 120 K. Cooling the chain produces an appreciable increase of bandwidth and output power. There is a three-fold reason for this drastic improvement. Firstly, as the device is cooled the GaAs mobility improves thus improving the intrinsic performance of each diode. Secondly, ohmic losses associated with the waveguides and the on-chip matching circuits decrease due to the decrease in phonon scattering. Thirdly, as the drive power increases, the efficiency of the last stage increases significantly since, at room temperature, the last stage is under-pumped. The 1.6-1.7 THz chain produced a record room-temperature output power of 21 µW and an estimated conversion efficiency of 1.5% at 1647 GHz. A record output power of 86 µW with an estimated efficiency of 3% was measured at 1647 GHz at 120 K.

The 1.7-1.9 THz chain produced an output power of 4 µW at room temperature with an estimated efficiency of 0.4% at around 1818 GHz. At 120 K, the measured peak power was 50 µW around 1809 GHz and the estimated efficiency was 1%. These represent the highest power levels at these frequencies from an electronically tunable source. It should also be pointed out that these power levels are more than sufficient to pump the HEB mixers of the heterodyne instrument of Herschel Space Observatory. Both chains also exhibit 3 dB bandwidths of more than 5%, primarily limited by the bandwidth and available power of the drive-stage multipliers.

3. Future Trends

The practical limit of the output power of a frequency multiplier is typically either the power beyond which conversion efficiency drops off due to saturation effects or the device lifetime becoming unacceptably short due to thermal or reverse-breakdown effects [30]. To increase power handling, the device doping can be optimized and the number of anodes per chip can be increased. Additionally, the epilayer can be transferred to a high thermal conductivity substrate [31]. While multi-anode frequency doublers have been widely studied in the past [21]–[24], frequency triplers with more than two anodes have been demonstrated only recently. For example, wideband and high efficiency balanced triplers at 300 GHz and 600 GHz featuring respectively six and four Schottky anodes per chip have been presented by the authors in [32], [25] and unbalanced high-efficiency multi-anode frequency triplers on high-thermal conductivity substrates at 200 and 400 GHz have been presented by Virginia Diodes Inc. in [31]. However, there is a practical limit to the number of anodes based on the chip size, the device impedance, and coupling efficiency. As the number of anodes is increased, compromises must be made between an optimum and even input coupling to the anodes, an optimum matching of each anode at the idler frequencies (second harmonic of the pump frequency for a tripler) and optimum matching at the output frequency.

A complementary approach to increase the power handling of a given source is to power-combine two or more parallel stages. However, for efficient power combining this approach requires increasing care at short wavelengths to keep the parallel paths well-matched despite fabrication and assembly tolerances and to minimize losses in the additional circuits required for dividing and recombining the signal.

We have recently presented results of a 300 GHz frequency tripler that uses two mirror-image circuits power-combined in-phase with a total of twelve Schottky anodes to produce 26 mW at 318 GHz when pumped with 250 mW input power at 106 GHz [33]. This multiplier 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. The complete power-combined tripler was designed using the methodology presented in detail in [25].

Fig. 3 shows the power-combined tripler including the input matching circuit. Fig. 4 shows a photograph (rotated 90° clockwise relative to Fig. 3) of the waveguide area where the chips are mounted including the output waveguide combiner. The tripler uses a split-block waveguide design with two independent DC bias lines. Each sub-circuit is similar to the 1.7-1.9 THz balanced tripler presented in Fig. 1 but with six anodes per chip instead of two. The input waveguide is split by a Y-junction to evenly feed two circuits each featuring six Schottky planar varactor diodes of about 16 fF each. The chips are mounted in two independent channels, running between the input and output waveguides. The two reduced-height output guides are combined by a Y-junction that is seen by each branch of the circuit as a simple waveguide step. Fig. 5 shows the conversion efficiency versus output frequency of the power-combined 300 GHz tripler and of a single-chip 300 GHz tripler when pumped with a flat 100 mW of input power.

This scheme of power combining the first stage to enable a 3 dB increase in power handling 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 2.7 THz tripler. It is expected that we will be able to achieve around 1 µW of output power at this frequency.

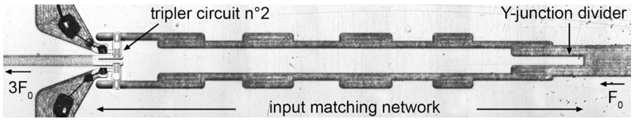

Fig. 3. Horizontal view of the bottom half of the power-combined 260-340 GHz frequency tripler based on two mirror-image integrated circuits. The dual channel input matching network occupies most of the size of the image.

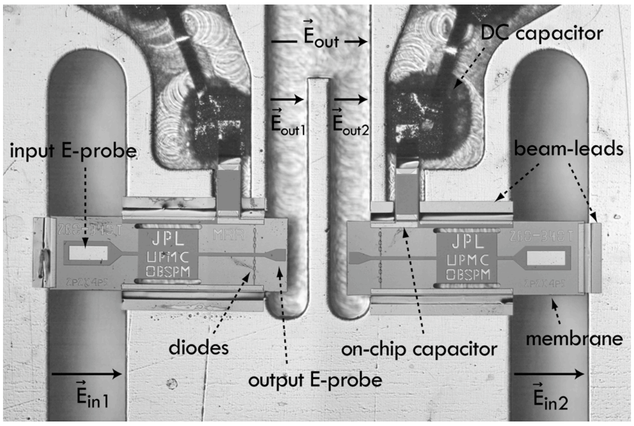

Fig. 4. Close-up vertical view of the power-combined 260-340 GHz frequency tripler showing the two mirror-image GaAs integrated circuits. The E-field vectors in the input and output waveguides are indicated by plain arrows. The E-fields generated by the two sub-circuits are combined in-phase in the output waveguide.

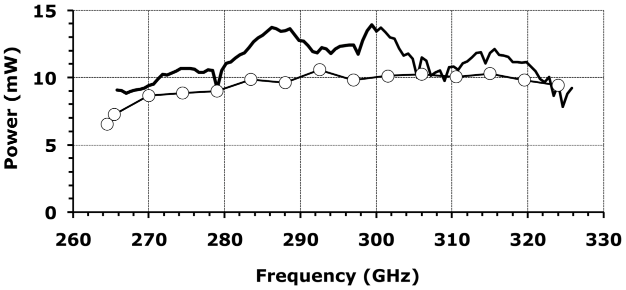

Fig. 5. Comparison of the available output power of the power-combined 300 GHz tripler (top thick curve with no markers) with that of the single-chip 300 GHz tripler when pumped with the same 100 mW input power (bottom curve with open markers.)

4. Conclusion

GaAs Schottky diode technology has advanced substantially in the last few years to enable power generation via frequency multiplication well into the terahertz frequency range. This development has enabled single pixel space borne terahertz receivers for radio astronomy. As the sources become more powerful they will spawn a number of other applications in this frequency range, including multi-pixel imaging.

References

[1] P.H. Siegel, "Terahertz Technology," *IEEE Trans. Microw. Theory Tech.*, Vol. 50, no. 3, March 2002.

[2] P.H. Siegel, "Terahertz Technology in Biology and Medicine," *IEEE Trans. Microw. Theory Tech.*, Vol. 52, no. 10, pp. 2438–2447, Oct. 2004.

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

[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*, Vol. 93, no.10, pp. 1722–1743, Oct. 2005.

[5] Masayoshi Tonouchi, "Cutting-edge terahertz technology," *Nature Photonics*, Vol. 1 , pp. 97–105, Feb. 2007.

[6] R. Appleby and H.B. Wallace, "Standoff Detection of Weapons and Contraband in the 100 GHz to 1 THz Region," *IEEE Trans. on Ant. and Prop.*, Vol. 55, pp. 2944–2956, Nov. 2007.

[7] P.H. Siegel, "Teraherz Instruments for Space," *IEEE Trans. on Ant. and Prop.,* Vol. 55, pp. 2957–2965, Nov. 2007.

[8] D. Hodges, F. Foote, R. Reel, "High-power operation and scaling behavior of CW optically pumped FIR waveguide lasers," *IEEE Journal of Quantum Electronics*, Vol. 13, no. 6, pp. 491–494. June 1977.

[9] B.S. Williams, "Terahertz quantum-cascade lasers," *Nature Photonics*, Vol. 1, pp. 517–525, 2007.

[10] Mikhail A. Belkin, Jonathan A. Fan, Sahand Hormoz, Federico Capasso, Suraj P. Khanna, Mohamed Lachab, A. Giles Davies, and Edmund H. Linfield, "Terahertz quantum cascade lasers with copper metal-metal waveguides operating up to 178 K," *Optics Express*, Vol. 16, n°5, pp. 3242–3248, March 2008.

[11] J.R. Gao , J.N. Hovenier, Z.Q. Yang, J.J.A. Baselmans, A. Baryshev, M. Hajenius, T.M. Klapwijk, A.J.L. Adam, T.O. Klaassen, B.S. Williams, S. Kumar, Q. Hu, and J.L. Reno "Terahertz heterodyne receiver based on a quantum cascade laser and a superconducting bolometer," *Applied Physics Letters*, 86, 244104, 2005.

[12] H. Ito, F. Nakajima, T. Furuta, T. Ishibashi, "Continuous THz-wave generation using antenna-integrated uni-travelling-carrier photodiodes." *Semicond. Sci. Technol. 20*, S192-S198, 2005.

[13] 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 Trans. Microw. Theory Tech.*, Vol. 55, no. 12, Part 2, pp. 2719–2726. Dec. 2007.

[14] 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, R. Lai, "Submillimeter-Wave InP MMIC Amplifiers From 300–345 GHz," *IEEE Microw. Wireless Compon. Lett.*, Vol. 18, no. 1, pp. 61–63. Jan. 2008.

[15] V. Radisic, X.B. Mei, W.R. Deal, W. Yoshida, P.H. Liu, J. Uyeda, M. Barsky, L. Samoska, A. Fung, T. Gaier, R. Lai, "Demonstration of Sub-Millimeter Wave Fundamental Oscillators Using 35-nm InP HEMT Technology," *IEEE Microw. Wireless Compon. Lett.*, Vol. 17, no. 3, pp. 223–225, March 2007.

[16] K. B. Cooper, R. J. Dengler, G. Chattopadhyay, E. Schlecht, J. Gill, A. Skalare, I. Mehdi, and P. H. Siegel, "A High-Resolution Imaging Radar at 580 GHz", *IEEE Microw. Wireless Compon. Lett.*, Vol. 18, no. 1, pp. 64–66, Jan. 2008.

[17] G.L. Pilbratt, "The Herschel mission, scientific objectives, and this meeting," *in Proc. Eur. Space Agency Symp.*, ESA paper SP-460, pp. 13–20, Dec. 2000.

[18] X. Mélique, A. Maestrini, P. Mounaix, M. Favreau, G. Beaudin, G. Goutoule, T. Närhi and D. Lippens, "Fabrication and performance of InP-based Heterostructure Barrier Varactors in a 250 GHz Waveguide Tripler," *IEEE Trans. Microw. Theory Tech.*, Vol. 48, no. 6, pp. 1000–1006, June 2000.

[19] M. Sağlam, B. Schumann, K. Duwe, C. Domoto, A. Megej, M. Rodríguez-Gironés, J. Müller, R. Judaschke, and H. L. Hartnagel, "High-performance 450-GHz GaAs-based heterostructure barrier varactor tripler," *IEEE Electron Device Letters*, Vol. 24, no. 3, pp. 138–140, March 2003.

[20] Q. Xiao, Y. Duan, J.L. Hesler, T.W. Crowe, R.M. Weikle II, "A 5 mW and 5% efficiency 210 GHz InP-based heterostructure barrier varactor quintupler", *IEEE Microw. Wireless Compon. Lett.*, Vol. 14, no. 4 , pp. 159–161, April 2004.

[21] J. Tuovinen, N.R. Erickson, "Analysis of a 170 GHz frequency doubler with an array of planar diodes," *IEEE Trans. Microwave Theory Tech.*, Vol. 43, no. 4, pp. 962–968, April 1995.

[22] D.W. Porterfield, T.W. Crowe, R.F. Bradley, N.R. Erickson, "A high-power fixed-tuned millimeter-wave balanced frequency doubler," *IEEE Trans. Microwave Theory Tech.*, Vol. 47, no. 4, pp. 419–425, April 1999.

[23] 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 MTT-S Int. Dig.*, pp. 1649–1652, Phoenix, AZ, May 2001.

[24] 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. Microw. Theory Tech.*, Vol. 52, no. 5, pp. 1538–1547, May 2004.

[25] A. Maestrini, J. Ward, J. Gill, H. Javadi, E. Schlecht, C. Tripon-Canseliet, G. Chattopadhyay and I. Mehdi, "A 540-640 GHz High Efficiency Four Anode Frequency Tripler," *IEEE Trans. Microwave Theory Tech.*, Vol. 53, pp. 2835–2843, Sept. 2005.

[26] L.A. Samoska, T.C. Gaier, A. Peralta, S. Weinreb, J. Bruston, I. Mehdi, Y. Chen, H. H. Liao, M. Nishimoto, R. Lai, Huei Wang, and Y.C. Leong, "MMIC power amplifiers as local oscillator drivers for FIRST," *in Proc. SPIE: UV, Optical, and IR Space Telescopes and Instruments*, Vol. 4013, San Diego, CA, pp. 275–284, Aug. 2000.

[27] A. Maestrini, J. Ward, J. Gill, H. Javadi, E. Schlecht, G. Chattopadhyay, F. Maiwald, N.R. Erickson, and I. Mehdi, "A 1.7 to 1.9 THz Local Oscillator Source," *IEEE Microw. Wireless Compon. Lett.*, Vol. 14, no. 6, pp. 253–255, June 2004.

[28] A. Maestrini, J. S. Ward, H. Javadi, C. Tripon-Canseliet, J. Gill, G. Chattopadhyay, E. Schlecht, and I. Mehdi, "Local Oscillator Chain for 1.55 to 1.75 THz with 100 µW Peak Power," *IEEE Microw. Wireless Compon. Lett.*, Vol. 15, no. 12, pp. 871–873, Dec. 2005.

[29] N.R. Erickson, "A Fast and Sensitive Submillimeter Waveguide Power Sensor," *in Proc. 10th International Symposium on Space Terahertz Technology*, pp. 501–507, Charlottesville, VA, 1999. Available from Erickson Instruments LLC, Amherst, MA.

[30] 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, pp. 488–491. 22–24 April 2003.

[31] D.W. Porterfield, "High-Efficiency Terahertz Frequency Triplers," *IEEE MTT-S Int. Dig.*, pp. 337–340, Honolulu, Hawaii, 3-8 June, 2007.

[32] A. Maestrini, C. Tripon-Canseliet, J.S. Ward, J.J. Gill, and I. Mehdi, "A High efficiency Multiple-Anode 260-340 GHz Frequency Tripler," *proceedings of the 17th International Conference on Space Terahertz Technology*, Paris, paper P2-05, pp. 233–236, 10–12 May 2006.

[33] A. Maestrini, J.S. Ward, C. Tripon-Canseliet, J.J. Gill, C. Lee, H. Javadi, G. Chattopadhyay and I. Mehdi, "In-Phase Power-Combined Frequency Triplers at 300 GHz," *IEEE Microw. Wireless Compon. Lett.*, Vol. 18, no. 3, pp. 218–220, March 2008.

We are greatly indebted to the JPL machine shop for the exceptionally high precision of the waveguide blocks as well as to our colleagues who fabricated the integrated circuits, assembled the frequency multipliers, and tested them in the laboratory.

Alain Maestrini,
Observatoire de Paris , LERMA,
61, avenue de l'Observatoire,
75014 Paris, France
E-mail: alain.maestrini@obspm.fr

John Ward
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109, USA
E-mail: john.ward@jpl.nasa.gov

Goutam Chattopadhyay
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109, USA
E-mail: goutam.chattopadhyay@jpl.nasa.gov

Erich Schlecht
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109, USA
E-mail: erich.schlecht@jpl.nasa.gov

Imran Mehdi
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109, USA
E-mail: Imran.mehdi@jpl.nasa.gov