Terahertz Array Receivers with Integrated Antennas

Goutam Chattopadhyay*[(1)], Nuria Llombart[(2)], Choonsup Lee[(1)], Cecile Jung[(1)], Robert Lin[(1)], Ken B. Cooper[(1)], Theodore Reck[(1)], Jose Siles[(1)], Erich Schlecht[(1)], Alessandro Peralta[(1)], Bertrand Thomas[(3)], and Imran Mehdi[(1)]

(1) Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA 91109, USA
Email:goutam@jpl.nasa.gov

(2) Universidad Complutense de Madrid, Spain
Email: nuria.llombart@opt.ucm.es

(3) Radiometer Physics GmbH, Meckenheim 53340, Germany
Email: thomas@radiometer-physics.de

ABSTRACT: Highly sensitive terahertz heterodyne receivers have been mostly single-pixel. However, now there is a real need of multi-pixel array receivers at these frequencies driven by the science and instrument requirements. In this paper we explore various receiver font-end and antenna architectures for use in multi-pixel integrated arrays at terahertz frequencies. Development of wafer-level integrated terahertz receiver front-end by using advanced semiconductor fabrication technologies has progressed very well over the past few years. Novel stacking of micro-machined silicon wafers which allows for the 3-dimensional integration of various terahertz receiver components in extremely small packages has made it possible to design multi-pixel heterodyne arrays. One of the critical technologies to achieve fully integrated system is the antenna arrays compatible with the receiver array architecture. In this paper we explore different receiver and antenna architectures for multi-pixel heterodyne and direct detector arrays for various applications such as multi-pixel high resolution spectrometer and imaging radar at terahertz frequencies.

INTRODUCTION

High resolution spectrometers at terahertz frequencies have played a key role in probing the star and galaxy formation process and the interstellar medium [1-3]. Carbon monoxide was first detected in the Orion Nebula in 1970 using a sensitive heterodyne spectrometer in the terahertz frequency [4]. The primary constituents of the molecular clouds where the proto-stars – the precursor to stars – are born is molecular gas (primarily hydrogen), making up to 90% of the cloud's mass. Gas in molecular clouds at prevailing temperatures and densities exhibits spectral line emission in the terahertz spectral region (100 GHz – 3 THz). Therefore, astrophysics instrumentation in exploring the spectral features of the molecular clouds has driven the development of sensitive detectors and spectrometers at these frequencies. High-resolution spectrometry at terahertz frequencies also enhances our understanding of the planet Earth by providing remote sensing data on the higher troposphere and lower stratosphere. Moreover, the terahertz frequency range is rich in emission and absorption lines of various molecular species such as CH_4, CO, H_2O, HCN, and others whose detection and mapping are important to understand the atmospheric circulation of telluric planets such as Venus, Earth, and Mars, the outer planets such as Jupiter and Saturn, and their moons such as Europa and Titan. Terahertz spectrometers with very high spectral resolution have been flown for Earth remote sensing up to 2.5 THz. However, their use in planetary exploration has been severely restricted due to their large mass and power requirements. Only recently heterodyne instruments at terahertz frequencies found its way into the new emerging applications such as imaging from space platforms [5], [6] and stand-off contraband detections and reconnaissance [7], [8].

For important astrophysical target areas as well as for terahertz security imaging application, large focal plane arrays of sensitive heterodyne detectors would be the ideal tool for efficient mapping, imaging, and spectroscopy. Unfortunately, the majority of the heterodyne instruments at these frequencies have been single-pixel. Although the possibility of multi-pixel array detectors at terahertz frequencies was first suggested way back in 1979 [9], it has been a very slow progress in developing such instruments. There has been some progress over the last several years in this area [10-13], but the cost and complexity of building many parallel terahertz sources and receivers has been the hindrance in rapid progress. Moreover, to make these instruments compatible with small space platforms and enable the development of multi-pixel heterodyne arrays for astrophysics and planetary spectroscopy as well as video rate imaging applications on mobile platforms for homeland security applications, it is essential to reduce the mass, power and volume of existing single pixel heterodyne receivers and design multi-pixel heterodyne arrays.

Conventional approach of building single-pixel receivers and stacking them to assemble multi-pixel array receivers is not suited at terahertz frequencies. What one needs are novel ultra-compact receiver architectures which are easy to fabricate, preferably by lithographic techniques, to build multi-pixel heterodyne array receivers where majority of the front-end components along with the antenna element can be integrated in a small form factor. In this paper we explore different multi-pixel receivers with integrated antennas at terahertz frequencies, specifically focusing on silicon micro-machined front-end components.

TERAHERTZ RECEIVER ARRAY ARCHITECTURE

There are many challenges in developing large arrays of heterodyne detectors at terahertz frequencies. The main design issues relating to the array architecture are the antenna structure, mixer configuration, local oscillator (LO) power coupling, intermediate frequency (IF) layout, and the back-end processing. Available LO power at these frequencies is a major concern and that somewhat drives the type array to use and the pixel count for such an array [14]. Receivers at terahertz frequencies are either waveguide based or quasi-optical, although multi-pixel direct detectors with planar architecture is not far behind with the advent of InP based HEMT amplifiers working at terahertz frequencies [15]. At frequencies beyond a few hundred gigahertz, the feature sizes of all but the simplest waveguide circuits are too small and the required tolerances are too demanding. However, with the development of terahertz waveguide components with silicon micromachining it is now possible to develop integrated terahertz receivers with photolithographic techniques [16]. In the following sections we describe array architectures based on silicon micromaching that are being designed for developing terahertz heterodyne array receivers.

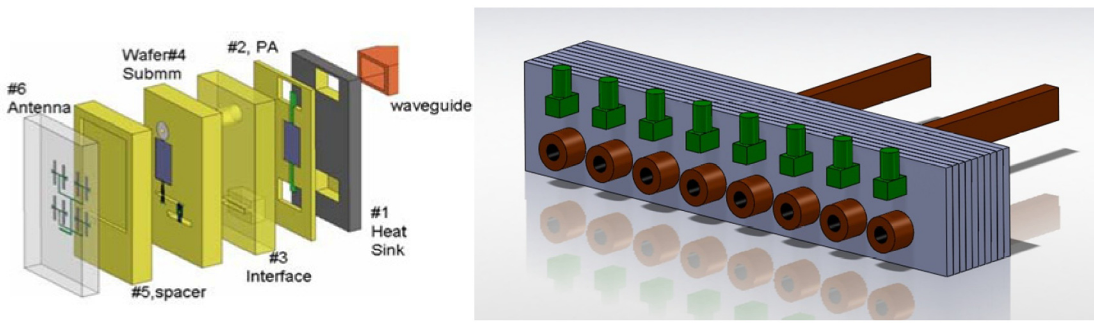

Fig. 1: Schematic of three dimensional array receiver architecture where silicon micro-machined wafers are stacked to design the compact receiver front-end. Figure on left shows four micro-machined silicon wafers where active components are assembled and is fed by a planar antenna array. Figure on the right shows a silicon stacked array with integrated horns as coupling element.

In this silicon micromachined architecture we use a three-dimensional (3-D) arrangement of active and passive components coupled with micromachined waveguides fabricated on silicon wafers in a stacked configuration. Since the integration of the different front-end receiver components are done in a vertical configuration, this leads more naturally to a multi-pixel array architecture. Fig. 1 shows the schematic of such a receiver where the essential heterodyne components such as frequency multipliers and mixers are integrated on a single silicon layer but couples to other components from different layers to form the terahertz receiver front-end.

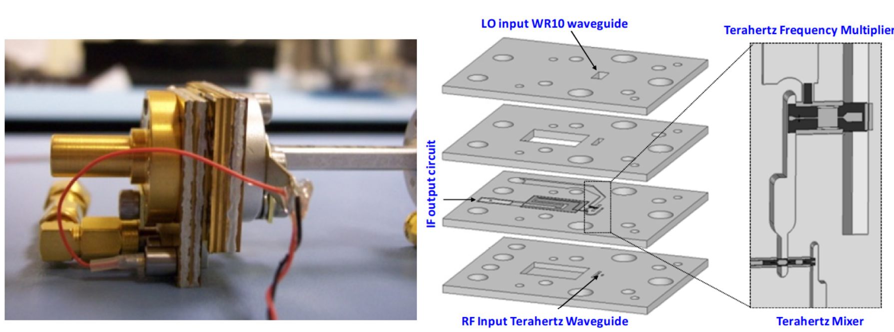

Fig. 2: Photograph of a 600 GHz silicon micromachined front-end developed with 3-D vertical integration of stacked silicon wafers. The circuits include 100 GHz amplifiers, 300 GHz frequency tripler, and 600 GHz sub-harmonic mixer. The top and bottom figures show two different views of the same receiver. The overall dimensions of the silcion micromahcined package are 20x25x3 mm^3. The schematic on the right shows the different layers that were used to fabricate the receiver.

One of the major advantages of such architecture is that we can have low frequency circuit elements in one layer which can couple through a vertical waveguide to the next layer where high frequency circuit elements can be assembled. This modular approach is very effective in designing terahertz receivers. Fig. 2 shows the photograph of a 600 GHz receiver front-end designed and developed at the Jet Propulsion Laboratory (JPL) using silicon micromachining [16]. In this design a 100 GHz local oscillator source signal is amplified using InP power amplifiers. The amplifier chips are placed at the lowest layer of the silicon micromachined stack. The amplifier output goes through a vertical waveguide coupling structure to a GaAs Schottky diode based frequency tripler to generate the 300 GHz local oscillator source to pump a 600 GHz subharmonic mixer. The subharmonic mixer and the frequency tripler are integrated on the same layer of the micromachined wafer. This layer also contains the IF matching circuits and DC bias circuits for the mixer and the frequency tripler. The 100 GHz signal is injected to the amplifier layer with an external metal waveguide. The 600 GHz RF signal is input via an external corrugated RF feed-horn. This architecture will easily lead to multi-pixel heterodyne array designs.

ANTENNAS FOR ARRAYS

Antennas will play a pivotal role for the successful development of multi-pixel heterodyne array receivers at terahertz frequencies. Multimode corrugated feed horns have shown very good performance and are the natural choice for multi-pixel arrays. However, their fabrication becomes difficult for very large focal planes at terahertz frequencies. A novel smooth-walled flare angle horn antenna array that can provide very good beam qualities has been developed recently [17]. The antenna array can be fabricated by directly drilling on a metal block with a profiled machined tool. Fig. 4 (left) shows the picture of such an array. Another highly desirable solution would be to fabricate a monolithic array of antennas on a planar substrate. Unfortunately, most planar antenna designs produce broad beam patterns, and therefore require additional elements such a substrate lenses or micromachined horns for efficient coupling. We developed a novel leaky wave antenna with integrated silicon micro lenses which can be easily integrated with silicon micromachined front-end [18], [19]. The advantage of this antenna array is that it can be developed using photolithographic techniques and integration with silicon micromachined array will be easy.

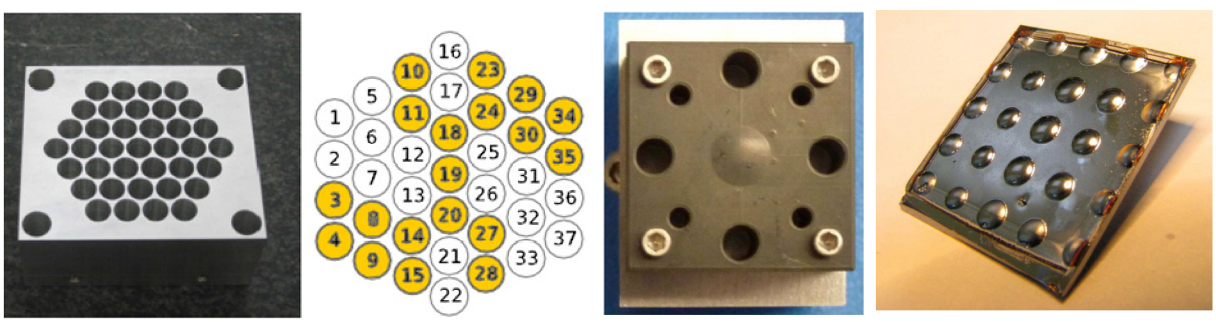

Fig. 3: Left: photograph of a directly drilled smooth-walled flare angle horn array [16]. Right: photograph of a silicon micro-lens array antenna fabricated with photolithographic techniques [17], [18].

SUMMARY

In this paper we described some approaches to develop terahertz heterodyne array receivers with integrated antennas. It is obvious that future generation of high performance receivers will require silicon micromachined receiver architecture with novel integrated antennas to work at terahertz frequencies. We described silicon micromachined front-end receiver components at terahertz frequencies which can be integrated with silicon micro-lens based antennas. The utilization of nanofabrication technologies such as wafer bonding and silicon micromachining allowed us to develop single pixel terahertz receiver components which can be easily integrated with multi-pixel receiver architecture we proposed. These techniques provide the flexibility of building high precision terahertz components and opens up possibilities for large format array receivers, multi-frequency imaging arrays, and beam-steering capabilities for future heterodyne array receivers.

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REFERENCES

[1] P. H. Siegel, “Teraherz Instruments for Space,” *IEEE Trans. on Ant. and Prop.*, vol. 55, pp. 2957–2965, Nov. 2007.

[2] P. H. Siegel, “Terahertz Technology,” *IEEE Trans. on Microwave Theory and Tech.*, vol. 50, no. 3, pp. 910-928, March 2002.

[3] P. Hartogh, et al., "Sub-millimeter Wave Instrument for EJSM", *Proc. EJSM Instrument Workshop*, July 2009, Maryland, USA.K. Elissa, “Title of paper,” unpublished.

[4] R. W. Wilson, K. B. Jefferts, and A. A. Penzias, “Carbon Monoxide in the Orion Nebula,” *Astrophys. J.*, vol. 161, no. 1, pt. 2, pp. 143-144, 1970.

[5] P. H. Siegel and R. J. Dengler, “Terahertz Heterodyne Imaging: Instruments,” *Int. Journal of Infrared and Millimeter Waves*, vol.27, no. 5, pp. 631-656, May 2006.

[6] D. Mittleman, “Terahertz imaging”, *in Sensing with Terahertz Radiation*, D. Mittleman Ed., Berlin, Germany: Springer-Verlag, pp. 117-153, 2003.

[7] K. B. Cooper, R. J. Dengler, N. Llombert, B. Thomas, G. Chattopadhyay, and P. H. Siegel, “THz Imaging Radar for Standoff Personnel Screening,” *IEEE Trans. THz Sc. & Tech.*, vol. 1, no. 1, pp. 169-182, September 2011.

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

[9] A. R. Gillespie and T. G. Phillips, “Array Detectors for Millimeter Line Astronomy,” *Astron. Astrophys.*, vol. 73, pp. 14-18, 1979.

[10] C. Groppi, C. Walker, C. Kulesa, D. Golish, J. Kloosterman, S. Weinreb, G. Jones, J. Barden, H. Mani, T. Kuiper, J. Kooi, A. Lichtenberger, T. Cecil, G. Narayanan, P. Putz, and A. Hedden, “SuperCam: A 64 Pixel Heterodyne Array Receiver for the 350 GHz Atmospheric Window”, *Proc. 20th Int. Space Terahertz Tech. Symp.*, Charlottesville, VA., Apr. 2009.

[11] G. Chattopadhyay, “Heterodyne Arrays at Submillimeter Wavelengths”, *Proc. XXVIIIth General Assembly of International Union of Radio Science*, New Delhi, India, Oct. 2005.

[12] G. Narayanan, M. H. Heyer, C. Brunt, P. F. Goldsmith, R. Snell, and D. Li, “The Five College Radio Astronomy Observatory CO Mapping Survey of the Taurus Molecular Cloud,” *Astrophys. J. Suppl. Series*, vol. 177, pp. 341-361, 2008.

[13] G. Chattopadhyay, N. Llombart, C. Lee, B. Thomas, C. Jung, R. Lin, A. Peralta, and I. Mehdi, “Integrated Arrays on Silicon at Terahertz Frequencies,” Proc. IEEE Intl. Symp. Ant. Prop. USNC/URSI National Radio Science Mtg., Spokane, Washington, July 2011.

[14] G. Chattopadhyay, “Technology, Capabilities, and Performance of Low Power Terahertz Sources,” *IEEE Trans. THz Sc. & Tech.*, vol. 1, no. 1, pp. 33-53, September 2011.

[15] W. Deal, X. B. Mei, K. M. K. H. Leong, V. Radisic, S. Sarkozy, and R. Lai, “THz Monolithic Integrated Circuits using InP High Electron Mobility Transistors,” *IEEE Trans. THz Sc. & Tech.*, vol. 1, no. 1, pp. 25-32, September 2011.

[16] C. Jung, B. Thomas, C. Lee, A. Peralta, J. Siles, T. Reck, G. Chattopadhyay, J. Gill, R. Lin, and I. Mehdi, “Compact Submillimeter-Wave Receivers made with Semiconductor Nano-Fabrication Technologies,” *IEEE MTT-S IMS Dig.*, Baltimore, Maryland, June 2011.

[17] J. Leech, B. K. Tan, G. Yassin, P. Kittara, and S. Wangsuya, “The Experimental Demonstration of a Low-Cost 37-Horn Focal-Plane Array Consisting of Smooth-Walled Multiple Flare-Angle Horns Fabricated by Direct Drilling,” *Proc. 22nd Intl. Symp. Space THz Tech.*, Tuscon, Arizona, April 2011.

[18] N. Llombart, G. Chattopadhyay, A. Skalare. I. Mehdi, "Novel Terahertz Antenna Based on a Silicon Lens Fed by a Leaky Wave Enhanced Waveguide,” *IEEE Trans. on Ant. and Prop.*, vol. 59, no. 6, pp. 2160-2168, June 2011.

[19] C. Lee, N. Llombart, C. Jung, G. Chattopadhyay, and I. Mehdi, “Silicon Micromachined Microlens Array for THz Antennas,” *Proc. of the 36th Intl. Conf. on Infrared, Millimeter, and Terahertz Waves*, Houston, Texas, October 2011.