DEVELOPMENT OF MULTI-PIXEL HETERODYNE ARRAY INSTRUMENTS AT SUBMILLIMETER WAVELENGTHS

Goutam Chattopadhyay, Imran Mehdi, John S. Ward, Erich Schlecht,
Anders Skalare, and Peter H. Siegel

California Institute of Technology, Jet Propulsion Laboratory, Pasadena, CA 91125, USA.

ABSTRACT

Heterodyne receivers at submillimeter wavelengths have played a major role in astrophysics as well as earth and planetary remote sensing. For astrophysics, the submillimeter is the primary frequency range for line and continuum radiation from cool gas and dust. It is useful for studying star formation, galaxies, dust and gas chemistry, and cosmology and CMB physics; heterodyne receivers have been the instrument of choice for many of these studies. Although most currently-deployed single-dish heterodyne instruments are based on a single pixel, there is an increasing need for large arrays of high resolution heterodyne receivers for high speed mapping and multiple line spectroscopy. Design and development of multi-pixel heterodyne instruments for both ground and space based platforms are already under way at several different institutes and universities to achieve these goals. In this paper we review the challenging issues in the development of multi-pixel heterodyne receivers with state-of-the-art sensitivity at submillimeter wavelengths. Large heterodyne arrays are possible only by higher levels of component integration with associated packaging and power dissipation issues. Front-end architecture, including the choice of mixer elements and local oscillator (LO) injection techniques are critical to the overall design of the instrument. We present detailed designs of our multi-pixel heterodyne receiver arrays incorporating hot electron bolometer (HEB) and Schottky diode mixers. We also describe the state-of-the-art in LO technology, and present the results of our compact solid-state frequency agile submillimeter sources for use as distributed local oscillators.

I. INTRODUCTION

HETERODYNE receivers are generally the preferred detector for high resolution spectroscopic studies in astrophysics and planetary remote sensing [1]–[3]. Many interesting astronomical objects, such as galaxies, molecular clouds, star-forming regions, proto-stars, and planets have rich submillimeter spectra. Much can be learned from these spectra, including the structure, dynamics, chemistry, energy balance, mass, density and temperature of the sources. High resolution spectroscopy is very often required to avoid line blending and resolve the line shapes. Heterodyne receivers provide both the sensitivity and resolution for such studies. Moreover, heterodyne receivers at terahertz frequencies are increasingly being used in medical imaging and contraband detection [4], [5]. At submillimeter wavelengths, heterodyne detection provides the highest sensitivity of any existing detector technology for instruments operating at or above liquid helium temperatures measuring narrow band signals. It is well known that for a background noise limited instrument, both heterodyne and direct detectors have similar sensitivities [6]. However, when the instrument is detector noise limited, as will be the case with NASA's proposed Single Aperture Far-Infrared (SAFIR) observatory [7], the direct detectors will potentially be more sensitive, as the heterodyne instruments will always be quantum-noise limited. Therefore, it is imperative that large arrays of heterodyne detectors at submillimeter wavelengths are developed for higher sensitivity, greater mapping speed, large scale mapping ability, and video rate imaging capability. Passive and/or active heterodyne large focal plane imaging arrays would have profound impact on medical diagnostics, explosive detections, and astrophysical imaging applications. However, only a handful of heterodyne array instruments at submillimeter wavelengths with a limited number of pixels are currently operational or being developed [8]–[10].

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 mixer configuration, local oscillator (LO) power coupling, the intermediate frequency (IF) layout, and the back-end processing Available LO power is a major concern, and will ultimately decide the type of mixer to use and the pixel count for such an array. In this paper, we describe our plan for building such large format heterodyne arrays at submillimeter wavelengths, and show the recent results of our mixer and local oscillator performance.

II. DESIGN CONSIDERATIONS

A. Mixer Design

There are at least three different mixer technologies one can consider for an array receiver design. The particular choice is mostly dictated by the available local oscillator power, receiver sensitivity criteria, and whether the mixer will operate at room temperature or cryogenic temperatures. Superconductor insulator superconductor (SIS) mixers are the most sensitive mixers available today in the 100–1200 GHz frequency range [11]. These

mixers are less sensitive at frequencies beyond the superconductor bandgap (2Δ for NbTin $\approx$ 1500 GHz) where reverse tunneling becomes a factor and mixer performance is dominated by circuit losses. SIS mixers typically operate at temperatures below 5 K (well below the superconductor critical temperature T_c). Typical state-of-the-art double sideband (DSB) noise temperature for SIS mixers are about 85 K at 500 GHz, have approximately 1 dB of mixer conversion loss, and require approximately 40–100 μW of local oscillator pump power [12]. SIS mixers have wide IF bandwidth, which is an advantage for focal plane arrays. However, for optimal performance, SIS mixers require magnets to suppress Josephson currents. For an array with hundreds of pixels, implementing the magnets and adjusting the field for each individual mixer would be difficult and cumbersome. Moreover, the bias for individual SIS mixers must be adjusted for best noise performance, and that would pose additional challenges for a large array.

Hot electron bolometer (HEB) mixers [13] have excellent noise performance from 500 GHz to 5 THz. Both the diffusion cooled and phonon cooled variety use a short superconducting bridge connecting two normal metal pads as the mixing element, and they generally operate at temperatures below 4 K. Typical DSB noise temperatures of HEB mixers are around 600 K at 500 GHz with approximately 10-15 dB of mixer conversion loss. They require approximately 1–2 μW of LO pump power, which is substantially less than SIS mixers. HEB mixers tend to have only a few gigahertz of IF bandwidth, which is a problem for heterodyne imagers where higher IF bandwidth is advantageous. High temperature HEBs, operating in the 100 K range, have shown promise for use as mixers; however, no published results are available.

Schottky diode mixers operate at frequencies up to well beyond 5 THz [14]. One of the major advantages of Schottky mixers compared to SIS and HEB mixers is that they operate at room temperature, although optimum performance is achieved at or below 20 K. Schottky mixers require high local oscillator pump power, approximately in the 1 mW range. Typical DSB noise temperatures for room temperature Schottky mixers are about 1800 K at 500 GHz with approximately 8 dB of conversion loss. However, their noise temperature improves when cooled, e.g., reaching approximately 1200 K (DSB) at 77 K. The main concern in using Schottky mixers in large arrays is the availability of LO power. However, it has been shown that they can be operated with reduced LO power at the expense of marginally higher mixer noise temperature [15].

Another design issue for array receivers is the mixer configuration, namely, single-ended, balanced, or sub-harmonic. Balanced mixers have the advantages that they reject spurious signals, suppress LO AM noise, reject LO thermal noise, use most of the available LO power, and simplify LO injection [16]. However, balanced mixers require a minimum of two diodes and may in some cases need more LO power than a single-ended mixer. On the other hand, sub-harmonic mixers use local oscillators at around half the RF frequency where more LO power is available. However, sub-harmonic mixers require more LO pump power than single-ended mixers. The required LO pump power for a sub-harmonic mixer can be minimized by individually biasing the two anti-parallel diodes.

B. Local Oscillator Design

For our design, we considered only all-solid-state local oscillators because they are compact, tunerless, broadband, and reliable. Tremendous progress has been made in solid-state LO development at submillimeter wavelengths over the last few years [17]. Typically, these solid-state LO sources use cascaded GaAs planar Schottky-barrier varactor diode frequency multipliers driven by a frequency synthesized source [18]. In our frequency multiplier designs, the output from the synthesizer is first multiplied to approximately 100 GHz, and then is amplified by MMIC power amplifier modules to 100–150 mW [19]. Recently one of our multiplier chains has produced 3 μW at 1900 GHz, enough to pump an HEB mixer [20]. Moreover, we have used an 800 GHz solid-state chain [21] to pump an array of 2x2 SIS mixers in the Pole-Star instrument at AST/RO [9].

TABLE I

CURRENT TECHNOLOGY LIMITS WITH SINGLE SOURCE LOCAL OSCILLATORS OPERATED AT 300 K AND 120 K

Output Frequency	Output Power (Published)		Output Power (Possible)		Number of Pixels for Different Mixers					
					Schottky		SIS		HEB	
	300 K	120 K	300 K	120 K	300 K	120 K	300 K	120 K	300 K	120 K
800 GHz	1 mW	2 mW	2 mW	4 mW	2	4	25	50	400	800
1500 GHz	15 μW	40 μW	30 μW	70 μW			1	2	6	14
1800 GHz	3 μW	10 μW	9 μW	20 μW					2	4
2500 GHz			1 μW	2.5 μW						1

Calculations assume 10 W of DC power available for the LO, 1 mW of LO pump power required for the Schottky mixers, 40 μW for the SIS mixers, and 2.5 μW for the HEB mixers. LO coupling loss of 3 dB was assumed for a large array.

Available LO power at submillimeter wavelengths is a major concern for using these sources in heterodyne array receivers and imagers. One rather straightforward approach to address this is to power-combine a number of multiplier chains to produce sufficient power to drive the mixer arrays. However, distributing LO from a power-combined, high-power single source to potentially hundreds of mixes would require a novel low-loss distribution

scheme. For the SMART instrument at KOSMA [22], Fourier gratings along with grid-polarizers and diplexers are used for LO coupling. However, Fourier grating components are generally narrow band, and distribution through long waveguide sections or quasi-optical techniques become lossy. Another approach is to use individual LO sources for each mixer. In this method, each mixer block is pumped with an independent LO source. Phase error at different mixers is a potential concern in this technique. Therefore, we decided to adopt a combination of the above two methods where one LO source is used for pumping several of the mixers. This alleviates the phase-error problem to some extent, and makes the LO distribution simpler. Table I shows the currently available LO power from a single multiplier chain at different frequencies. Also listed is the LO power that can be obtained from the multiplier chains at submillimeter wavelengths and the number of different mixers they will be able to pump. It is clear that in principle, with the available LO chains cooled to 120 K, approximately 800 HEB mixers could be pumped at 800 GHz and 14 mixers pumped at 1500 GHz. Fig. 1 shows our 1500 GHz multiplier chain and the Schottky and HEB mixers we have developed which could be used for the array receiver.
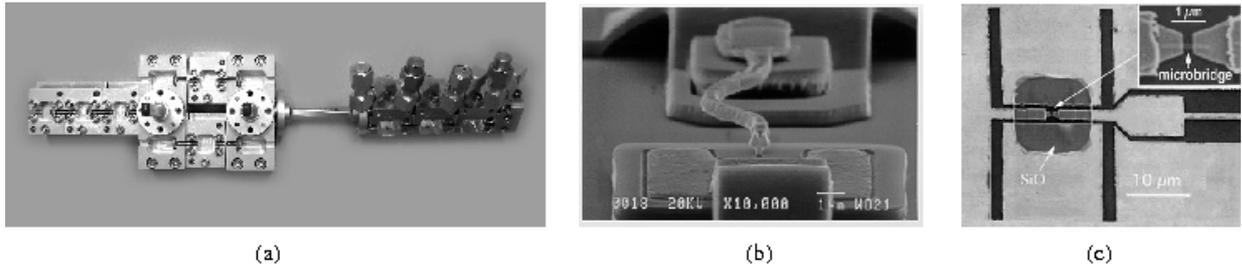

Fig. 1. Pictures of the LO and mixers: (a) 1500 GHz four-stage frequency multiplier chain; on the left are the MMIC power amplifier modules and on the right are the four cascaded doublers, (b) 2500 GHz Schottky diode mixer, (c) HEB mixer with twin-slot antennas.
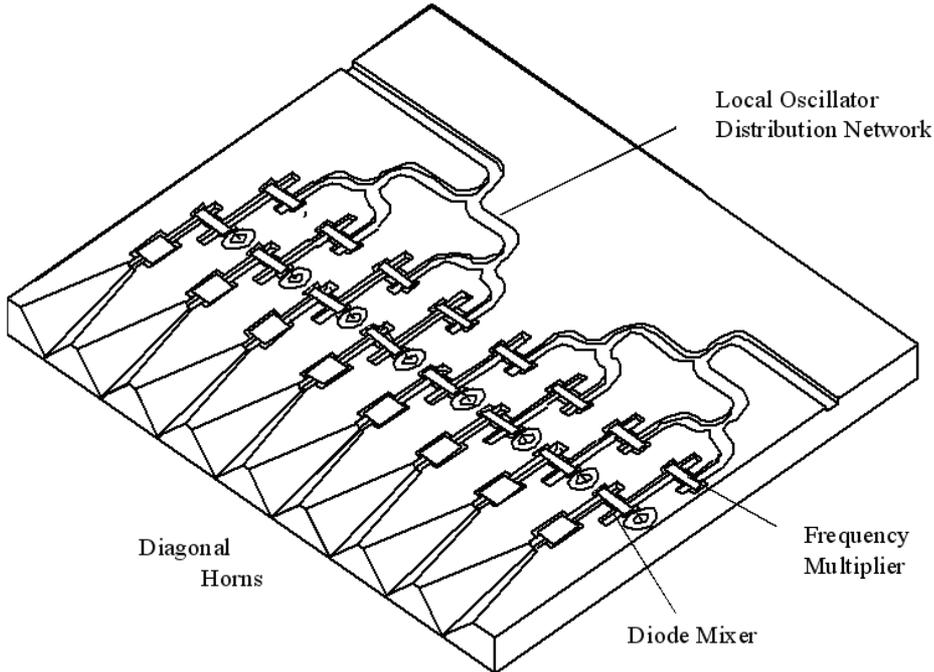

Fig. 2. Schematic of the linear array architecture showing LO coupling and mixer topology (top block not shown). In this configuration, one LO chain pumps four mixers. Two dimensional arrays can be built up by stacking these linear array layers, with an IF layer (not shown) alternated with each RF layer to distribute DC bias and the IF signals.

C. Array Architecture

Our proposed front-end architecture includes diagonal horn arrays backed by fundamental, sub-harmonically pumped, or balanced mixers, and is shown in Fig. 2. The LO power for the array is produced by a sequence of power amplifiers and multipliers, and is distributed and coupled to the mixers by a low loss waveguide distribution network. The final stage of the multiplier chain and the mixer elements are put in the same block, simplifying LO coupling. The IF output signal is amplified and filtered on a separate layer that also distributes DC bias. Waveguide parts are precision-machined as split blocks, and the linear array "trays" are alternated with IF trays in a stack to complete the two dimensional array receiver. This design is primarily intended for a cryogenically cooled HEB-

based focal plane instrument. For space-borne applications where cryogenic cooling is not available, Schottky diode sub-harmonic mixers will be used. However, Schottky mixers require more LO drive power, which puts more burden on the DC power budget. As shown in Table I, the number of pixels one can have for a particular array depends strongly on the availability of LO and DC power. Beam forming and focusing optics are the issues for the heterodyne array instrument. For using the array as an imager, we are also considering mechanically scanning a linear array to form a 2-D image.

III. CONCLUSION

We have developed various components, such as the mixers and local oscillators, suitable for use in a multi-pixel heterodyne array receiver at submillimeter wavelengths. Compact, robust, and broadband planar Schottky diode multipliers have been demonstrated up to 1.9 THz with sufficient power to pump arrays of sensitive HEB mixers. Planar Schottky diode mixers and HEB mixers have been developed for integration in array instruments. These arrays will use a novel LO distribution scheme where one source pumps several mixers, simplifying LO coupling. We are currently optimizing array designs for use with HEB and Schottky mixers, and are also developing a new generation of power-combined frequency multipliers to produce more LO power for the mixers.

ACKNOWLEDGMENT

REFERENCES

[1] T. G. Phillips, "The Role of Heterodyne Detection in Future Space Missions," In *Proc. Far-IR, Sub-MM, and MM Detector Technology Workshop,* J. Wolf, J. Farhoomand and C. Crelght, eds., Montery, CA, April 2002, pp. 31-37.
[2] T. G. Blaney, "Radiation detection at submillimeter wavelengths," *J. Phys. E: Sci. Instrum.,* vol. 11, pp. 856-881, 1978.
[3] P. H. Siegel, "Terahertz Technology," *IEEE Trans. Microwave Theory Tech.,* vol. 50, no. 3, pp. 910-928, March 2002.
[4] P. H. Siegel, "Terahertz Technology in Biology and Medicine," *2004 IEEE MTT-S Intl. Microwave Symp. Digest,* Fort Worth, TX, pp. 1575-1578, June 2004.
[5] P. H. Siegel and R. J. Dengler, "Terahertz Heterodyne Imaging for Biological Applications," NASA/*NCI Fundamental Technologies for Biomolecular Sensors,* Chicago, IL, July 2003.
[6] J. Zmuidzinas, "Coherent Detection and SIS Mixers," In *Proc. Far-IR, Sub-MM, and MM Detector Technology Workshop,* J. Wolf, J. Farhoomand, and C. Crelght, eds., Montery, CA, April 2002, pp. 149-154.
[7] M. J. Amato, D. J. Benford, S. H. Moseley, and J. A. Roman, "An Engineering Concept and Enabling Technologies for a Large Single Aperture Far-Infrared Observatory (SAFIR/FAIR)," In *Proc. SPIE,* vo. 4850, 2002, pp. 1120-1131.
[8] G. Narayanan, N. R. Erickson, and A. W. Lichtenberger, "Integrated Terahertz Heterodyne Focal Plane Array Receivers," In *Proc. Far-IR, Sub-MM, and MM Detector Technology Workshop,* J. Wolf, J. Farhoomand and C. Crelght, eds., Montery, CA, April 2002, pp. 203-206.
[9] C. Groppi, C. Walker, C. Kulesa, G. Narayanan, K. Jacobs, U. Graf, R. Schieder, and J. Kooi, "Heterodyne Array Development at the University of Arizona," In *Proc. 14th. Intl. Symp. Space THz Tech.,* Tucson, AZ, April 2003, pp. 189-203.
[10] D. Rabanus, U. U. Graf, S. Heyminck, S. Stanko, and J. Stutzki, "Techniques for Heterodyne Array Receivers," In *Proc. Far-IR, Sub-MM, and MM Detector Technology Workshop,* J. Wolf, J. Farhoomand and C. Crelght, eds., Montery, CA, April 2002, pp. 179-182.
[11] J. Zmuidzinas, J. W. Kooi, J. Kawamura, G. Chattopadhyay, J. A. Stern, B. Bumble, and H. G. LeDuc, "Development of SIS Mixers for 1 THz," In *Proc. SPIE,* T. G. Phillips, ed., vol. 3357, Kona, HI, March 1998, pp. 53-61.
[12] G. Chattopadhyay, D. Miller, H. G. LeDuc, and J. Zmuidzinas, "A Dual-Polarized Quasi-Optical SIS Mixer at 550 GHz," *IEEE Trans. Microwave Theory and Tech.,* vol. 48, no. 10, pp. 1680-1686, October 2000.
[13] E. M. Gershenzon, G. N. Gol'tsman, I. G. Gogidze, Y. P. Gusev, A. I. Elant'ev, B. S. Karasik, and A. D. Semenov, "Millimeter and Submillimeter Range Mixer Based on Electronic Heating of Superconducting Films in Resistive State," *Sov. Phys. Superconductivity,* vol. 3, 1582, 1990.
[14] M. C. Gaidis, H. M. Pickett, C. D. Smith, S. C. Martin, R. P. Smith, and P. H. Siegel, "A 2.5 THz Receiver Front End for Space Borne Applications," *IEEE Trans. Microwave Theory and Tech.,* vol. 48, no. 4, pp. 733-739, April 2000.
[15] J. L. Hesler, W. R. Hall, T. W. Crowe, R. M. Weikle, B. S. Deaver, R. F. Bradley, and S-K Pan, "Fixed-Tuned Submillimeter Wavelength Waveguide Mixers Using Planar Schottky-Barrier Diodes," *IEEE Trans. Microwave Theory and Tech.,* vol. 45, no. 5, pp. 653-658, May 1997.
[16] G. Chattopadhyay, F. Rice, D. Miller, H. G. LeDuc, and J. Zmuidzinas, "A 530-GHz Balanced Mixer," *IEEE Microwave Guided Wave Lett.,* vol. 9, no. 11, pp. 467-469, November 1999.
[17] I. Mehdi, E. Schlecht, G. Chattopadhyay, and P. H. Siegel, "THz Local Oscillator Sources," In *Proc. SPIE,* T. G. Phillips, J. Zmuidzinas, eds., vol. 4855, Waikoloa, HI, August 2002, pp. 435-446.
[18] G. Chattopadhyay, E. Schlecht, J. Ward, J. Gill, H. Javadi, F. Maiwald, and I. Mehdi, "An All-Solid-State Broad-Band Frequency Multiplier Chain at 1500 GHz," *IEEE Trans. Microwave Theory and Tech.,* vol. 52, no. 5, pp. 1538-1547, May 2004.
[19] L. A. Samoska, T. C. Gaier, A. Peralta, S. Weinreb, J. Bruston, I. Medí, Y. Chen, H. H. Liao, M. Nishimoto, R. Lai, H. Wang, and Y. C. Leong, "MMIC Power Amplifiers as Local Oscillator Drivers for FIRST," In *Proc. SPIE,* vol. 4013, San Diego, CA, August 2000, pp. 275-284.
[20] A. Maestrini, J. Ward, J. Gill, H. Javadi, E. Schlecht, G. Chattopadhyay, F. Maiwald, N. R. Erickson, and I. Mehdi, "A 1.7-1.9 THz Local Oscillator Source," *IEEE Microwave Wireless Comp. Lett.,* vol. 14, no. 6, pp. 253-255, June 2004.
[21] 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 Wireless Comp. Lett.,* vol. 12, no. 4, pp. 117-118, April 2002.
[22] U. U. Graf, S. Heyminck, E. A. Michael, S. Stanko, C. E. Honingh, K. Jacobs, R. T. Schieder, J. Stutzki, and B. Vowinkel, "SMART: the KOSMA submillimeter array receiver for two frequencies," In *Proc. SPIE,* T. G. Phillips, J. Zmuidzinas, eds., vol. 4855, pp. 322-329, Waikoloa, HI, August 2002.