HETERODYNE ARRAYS AT SUBMILLIMETER WAVELENGTHS

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ABSTRACT

Heterodyne receivers, which down-convert radio frequency (RF) signals to intermediate frequency (IF) signals – preserving the amplitude and phase information of the incoming radiation, are generally the detector of choice for high resolution spectroscopic studies in astrophysics and planetary remote sensing. 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 submillimeter wavelengths are increasingly being used in medical imaging and contraband detection. However, it is clear that the future instruments, specifically the space-based observatories with cold telescopes, will demand heterodyne arrays for higher sensitivity, greater mapping speed, large scale mapping ability, multiple line spectroscopy, and imaging capability. Passive and/or active heterodyne focal plane arrays would have profound impact on medical diagnostics, contraband detections, and astrophysical spectroscopy and 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 for astrophysical studies. In this paper we shall review the challenging issues in the development of heterodyne arrays with state-of-the-art detector sensitivities at submillimeter wavelengths. Such arrays are enabled only by higher levels of component integration with novel array concepts. Front-end architecture, including the choice of mixer elements and local oscillator (LO) injection schemes are critical to the overall design of such instruments, and will be addressed in this paper.

I. INTRODUCTION

Most of the electromagnetic energy in the Universe lies in two thermal components – the cosmic microwave background and the far-infrared background. Indeed the peak of the spectral energy distribution for dusty objects in the distant universe is redshifted entirely to submillimeter wavelengths. This part of the electromagnetic spectrum is primarily used for studying the cool universe – the relic radiation of the Big Bang and the molecular gas and dust that constitute the very building blocks of stars, planetary systems, galaxies, and life itself [1]. This material typically has temperature of 3 K to 100 K, resulting in spectral energy distributions peaking at submillimeter to far-infrared wavelengths. High resolution studies of the earliest, dust-enshrouded phases of star formation are the exclusive regime of submillimeter-wave astronomy. However, unlike other spectral ranges, detector technology in the far-infrared and submillimeter wavelength regime has not reached fundamental limits, with orders of magnitude improvement possible with new technologies and novel approaches [2], [3]. This is especially true for high resolution spectroscopic instruments ($\Delta\lambda/\lambda \approx 10^6$) which rely on coherent detectors and which to date can only be produced in single pixel or very modest focal plane arrays [4 – 6]. Improvements in both the sensitivity and pixel-count of these detectors will dramatically increase the scope and the scientific yield of a wide range of proposed and planned instruments being considered for the next two decades [7].

Ground-based observatories with large interferometric arrays such as the ALMA [8] will provide high angular resolution with excellent sensitivity and high spectral resolution. However, due to high atmospheric attenuation and absorption at these frequencies, ALMA's frequency coverage will be limited to below 1 THz. Therefore, for frequencies above 800 GHz, air-borne and space-based platforms are preferred for far-IR and submillimeter-wave astrophysics [9], [10]. The next generation space-based instruments in the far-infrared and submillimeter wavelengths, such as the NASA's proposed Single Aperture Far-Infrared (SAFIR) observatory [11], will have large (10m-class) cryogenically cooled telescope. The fundamental sensitivity limit for a cold telescope is photon noise from the diffuse astrophysical background; thermally emitting dust in the solar system, the Galaxy, and the aggregate of dusty galaxies at all redshifts. Observations with a cold telescope in the continuum will be limited by source confusion, specifically at the longer wavelengths. Spectroscopy provides a third dimension to distinguish multiple sources in an otherwise confused filed, and thereby allows probing much deeper than in the continuum. For the highest resolving powers necessary for detailed Galactic astrophysics experiments, heterodyne spectrometers will be required. However, heterodyne receivers are inherently handicapped by quantum noise [12]. The quantum noise from heterodyne detectors in THz regime is orders of magnitude higher than the photons noise from the astrophysical backgrounds. So, a cold telescope is not required for optimal heterodyne use. However, heterodyne spectroscopy is the only way to get very high velocity resolution (~ 1 km/s) required for unique galactic astrophysics experiments such as probing dynamics of cloud collapse and star formation. For observatories such as the SAFIR, focal plane arrays of heterodyne receivers will be needed to be developed for higher sensitivity, greater mapping speed, large scale mapping ability, and multiple line spectroscopy [13], [14].

Developing heterodyne arrays at terahertz frequencies pose many challenges, and are enabled only by higher levels of component integration with novel array concepts. Array architecture for such instruments must address mixer configuration, local oscillator (LO) injection, intermediate frequency (IF) layout, and back-end coupling. Available LO power is the major driving force for the ultimate pixel count for such heterodyne array receivers [15]. In this paper we will describe possible heterodyne receivers with component level development for realistic array architectures.

II. DESIGN COSIDERATIONS AND CHALLENGES

Novel array architecture enabling multi-pixel receiver integration is a must for heterodyne arrays at terahertz frequencies. One such receiver configuration, known as the ultimate receiver at submillimeter wavelengths, is shown in Fig. 1, and is being developed at JPL/Caltech. A broadband dual-polarized receiver with image rejection mixers in a balanced configuration will be the ultimate receiver in this frequency range, and arrays of such heterodyne receivers at the focal plane will be very useful for the astrophysics community. One of the critical aspect in developing heteordyne arrays is the LO injection. A balanced sideband-separating architecture with waveguide hybrids will not only reject noise from the image band and eliminate calibration uncertainty from sideband imbalance, it also will reject LO thermal noise and simplify LO injection eliminating the need for diplexers. It has been envisioned to fabricate the receiver components using silicon micromachining techniques, enabling integration of many components on a single wafer, facilitating multi-pixel arrays. The picture on the right side of Fig. 1 shows such a silicon micromachined split-block. These blocks can be stacked to form multiple-pixel heterodyne arrays.

Available LO power is a major concern for the development of heterodyne arrays at submillimeter wavelengths. Tremendous progress has been made in solid-state LO development at these frequencies over the last couple of years [16]. Typically, they use cascaded GaAs planar Schottky-barrier varactor diode frequency multipliers driven by a frequency synthesized source [17]. However, overall efficiency of these frequency multiplied sources is low, producing approximately 5-10 μW of output power at 1.8 THz [18].

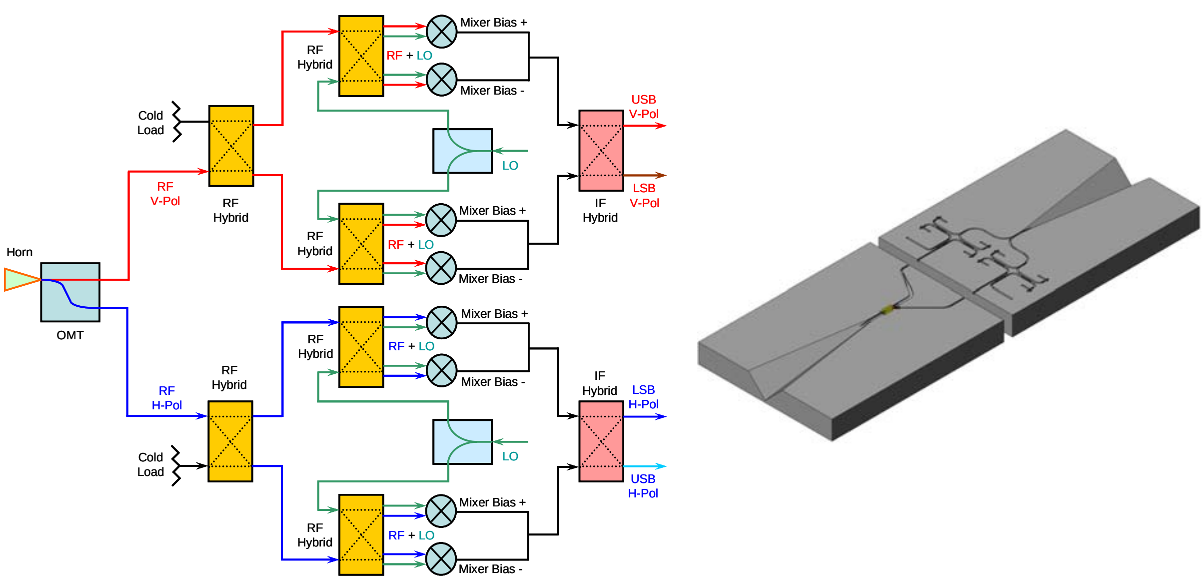
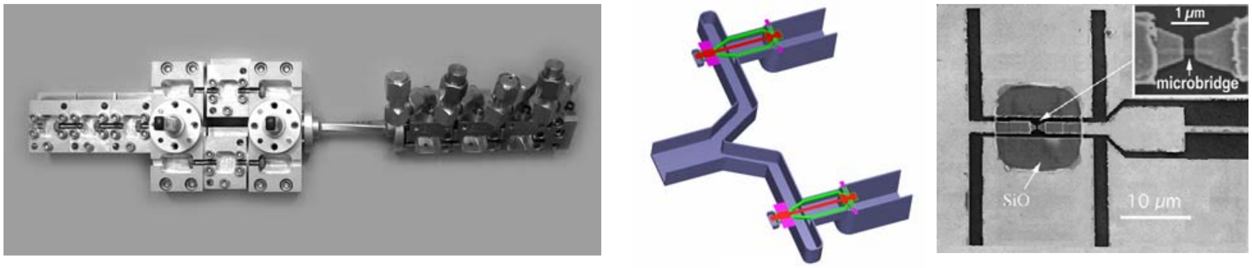


Fig. 1. Schematic diagram of the ultimate heterodyne receiver at submillimeter wavelengths with compact architecture which will enable array integration. This dual-polarized, sideband-separating, balanced receiver can be fabricated using silicon micromachining techniques. The figure on right shows a potential silicon micromachined split-block.



(a) (b) (c)

Fig. 2. 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 [17], (b) proposed frequency multiplier and power combiner module, and (c) HEB mixer with twin-slot antennas [21].

Fig. 2(a) shows JPL's 1500 GHz multiplier chain using four cascaded frequency doublers driven by power amplifier modules, and produces approximately 15-20 μW output when pumped with 100 mW of drive power at 100 GHz [17]. One approach to increase power output from these multipliers is to power combine a number of multiplier chains, as shown in Fig. 2(b). However, distributing LO from a power-combined high-power source to potentially a large number of mixers in an array would require a novel low-loss distribution scheme. To mitigate this, we propose to use a distribution scheme where the LO is power combined to a moderate output power level and drive a number of mixers simultaneously, and thus, forming a modular LO-mixer combination unit. All the LO modules is this scheme would be phase locked to a common reference, providing phased LO distribution to all the mixer modules.

The choice of mixers for use in array receiver designs is dictated by the available local oscillator power, receiver sensitivity requirement, and the operating temperature of the mixer. Superconductor insulator superconductor (SIS) mixers are the most sensitive mixers available today. However, they are less sensitive at frequencies beyond the superconductor bandgap (2Δ for NbTin ≈ 1500 GHz) where reverse tunneling becomes a factor and mixer performance is dominated by circuit losses. SIS mixers typically require approximately 40–100 μW of local oscillator pump power. On the other hand, hot electron bolometer (HEB) mixers [20], [21] have excellent noise performance from 500 GHz to 5 THz, and require approximately 1–2 μW of LO pump power, which is substantially less than SIS mixers. HEB mixers tend to have only a few GHz of IF bandwidth, which is a concern. Both SIS and HEB mixers typically operate at temperatures below 4 K. Schottky diode mixers can operate at room temperatures, and have moderate noise temperature performance at frequencies up to 5 THz. However, they require approximately 1 mW of pump power.

Current technology limits for a single source solid-state LO output power and the number pixels of different variety of mixers they can drive are listed in Table I. It is obvious that with the current technology, a single source LO at room temperature can drive approximately 10-20 HEB mixers at 1.5 THz. However, the pixel count can be increased significantly with power combining a number of solid-state LO chains.

III. CONCLUSION

Heterodyne arrays at submillimeter wavelengths are at their infancy – only a handful of arrays with limited number of pixels are currently operational or being planned. Future space missions will require heterodyne arrays at these wavelengths to accomplish major scientific initiatives which require very high resolution spectroscopy. New

TABLE I

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

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 μW for the HEB mixers. LO coupling loss of 3 dB was assumed for a reasonable size array.

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	40 μW	80 μW			1	2	20	40
1800 GHz	3 μW	20 μW	10 μW	50 μW					5	25
2400 GHz			2 μW	5 μW					1	2

receiver array architectures with novel integration techniques will be required to make progress in this area. The ultimate receiver concept with silicon micromachining fabrication techniques appears to be a promising choice. Available power from solid-state local oscillator sources is one of the major areas where focused research will be required. With the current technology limits, only a modest number of pixels in an array can be pumped. Backend electronics is another area of concern. Potentially large number of IF outputs from an array receiver will need to be processed, and that will require substantial research and development in this area.

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