Integrated Arrays on Silicon at Terahertz Frequencies

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Abstract—**In this paper we explore various receiver font-end and antenna architecture for use in integrated arrays at terahertz frequencies. Development of wafer-level integrated terahertz receiver front-end by using advanced semiconductor fabrication technologies and use of novel integrated antennas with silicon micromachining are reported. We report novel stacking of micro-machined silicon wafers which allows for the 3-dimensional integration of various terahertz receiver components in extremely small packages which easily leads to the development of 2-dimensioanl multi-pixel receiver front-ends in the terahertz frequency range. We also report an integrated micro-lens antenna that goes with the silicon micro-machined front-end. The micro-lens antenna is fed by a waveguide that excites a silicon lens antenna through a leaky-wave or electromagnetic band gap (EBG) resonant cavity. We utilized advanced semiconductor nanofabrication techniques to design, fabricate, and demonstrate a super-compact, low-mass submillimeter-wave heterodyne front-end. When the micro-lens antenna is integrated with the receiver front-end we will be able to assemble integrated heterodyne array receivers for various applications such as multi-pixel high resolution spectrometer and imaging radar at terahertz frequencies.**

Keywords-silicon micromaching, terahertz, array receivers

I. INTRODUCTION

High resolution spectrometers at terahertz frequencies have been used for radio astronomy applications for years and currently are being proposed as highly sensitive instruments for the remote sensing of planetary atmospheres such as Mars, Venus, Jupiter, Saturn and Titan [1-3]. Heterodyne instruments at terahertz frequencies play a critical role in addressing some of the fundamental questions regarding the evolution of galaxies and interstellar clouds. They also enhance our understanding of the planet Earth by providing remote sensing data on the higher troposphere and lower stratosphere. Moreover, the terahertz frequency range which is also known as the sub-millimeter waves (300 GHz – 3 THz) 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. Sub-millimeter wave 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 [4-6], stand-off contraband detections and reconnaissance [7], [8], medical imaging [9], and even in the art world – for painting analysis [10]. However, the majority of the heterodyne instruments at these frequencies have been single-pixel. Terahertz heterodyne array instruments [11], [12] have not yet been realized because of the cost and complexity of constructing many parallel submillimeter-wave sources and receivers. Moreover, to make these instruments compatible with small space platforms, especially for the study of the outer planets and make them attractive for future planetary missions, 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 report silicon micro-machined front-end components using both two- and three-dimensional arrangement of active and passive components along with novel antenna architecture to accomplish multi-pixel heterodyne arrays at terahertz frequencies.

II. RECEIVER 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

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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. Receivers at submillimeter wavelengths are either waveguide based or quasi-optical, although multi-pixel direct detectors with planar architecture are being used in recent years [13]. 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 to be fabricated using even the best state-of-the-art conventional machining. However, with the development of terahertz waveguide components with silicon micromachining it is now possible to develop integrated terahertz receivers with photolithographic techniques [14]. In the following sections we describe two different array architectures based on silicon micromaching that are being designed for developing terahertz heterodyne array receivers.

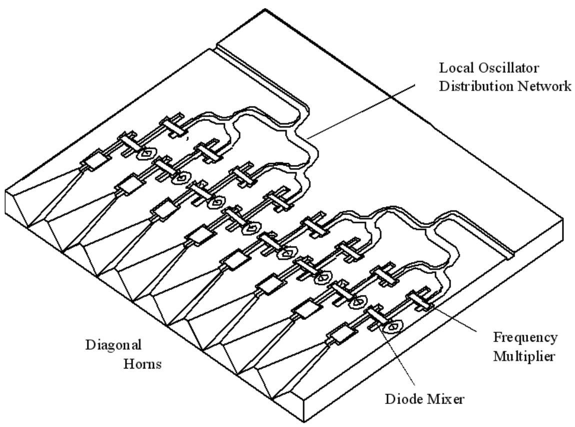

Fig. 1: Schematic of the linear array architecture showing LO coupling and mixer topology (top block not shown). In this configuration, one LO chain pumps four mixers. Two dimensional arrays can be built up by stacking these linear array layers, with an IF layer (not shown) alternated with each RF layer to distribute DC bias and the IF signals.

A. Integration in Two-Dimensional (2-D) Layout

The two-dimensional (2-D) array architecture for the RF front-end includes horn arrays backed by fundamental or sub-harmonically pumped balanced mixers, and is its schematic shown in Fig. 1. 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 and provide added capability of tuning the LO power requirement for each individual mixers. The IF output signal is amplified and filtered on a separate silicon micromachined layer. 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. One of the major advantages for such architecture is that it can be used to design more advanced receiver front-end such as a multi-functional dual-polarized, sideband separating, and balanced receivers. The receivers for space applications, particularly for planetary instruments, require higher sensitivity and image rejection capability. Fig. 2 shows such a single-pixel receiver architecture based on the same silicon micromachining technology which can be stacked to make 2-D array receiver. One key difficulty for such receiver architecture is the beam forming and focusing optics. One has to pay close attention to designing appropriate high efficiency optical coupling elements. Moreover, development of high quality horn antennas with silicon micromachining remains a big challenge.

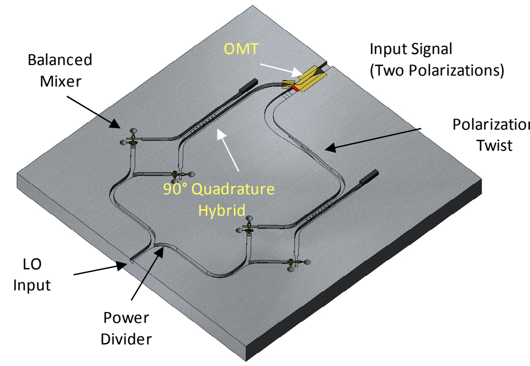

Fig. 2: Schematic of a silicon micromachined dual-polarized, sideband separating balanced receiver which can be stacked to develop two-dimensional terahertz heterodyne arrays.

B. Integration in Three-Dimensional (3-D) Layout

In this 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. 3 shows the schematic of such a architecture 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.

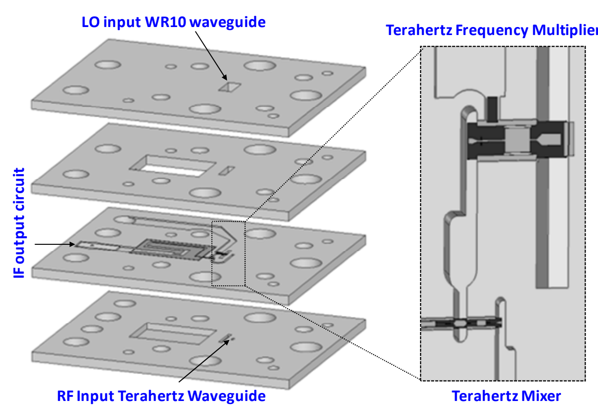

Fig. 3: Thee Dimensional (3-D) receiver architecture where silicon micro-machined wafers are stacked to design the compact receiver front-end. Figure on left shows four micro-machined silicon wafers where active components are assembled. Figure on the right shows the detailed view of the mixers and frequency multiplier circuits assembled in the 3-D stacked 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. 4 shows the photograph of a 600 GHz receiver front-end designed and developed at the Jet Propulsion Laboratory (JPL) using silicon micromachining [15]. 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.

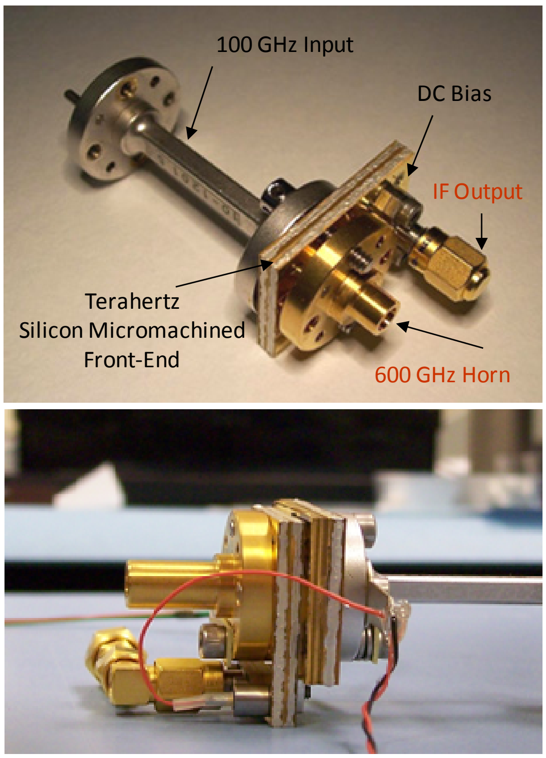

Fig. 4: Photograph of a 600 GHz silicon micromachined front-end developed with 3-D vertical integration of stacked silicon wafers. The circuits include 100 GHz amplifiers, 300 GHz frequency tripler, and 600 GHz sub-harmonic mixer. The top and bottom figures show two different views of the same receiver. The overall dimensions of the silcion micromahcined package are 20x25x3 mm^3.

III. MICRO-LENS ARRAY ANTENNA

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 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 [16]. The antenna geometry consists of a waveguide feed, which excites a silicon lens antenna through a leaky-wave or Electromagnetic Band-Gap (EBG) resonant cavity. This cavity is used to match the waveguide feed with the silicon medium as well as to illuminate the upper part of the lens. One of the key features of this novel antenna is that we do not need to fabricate the full silicon lens. Instead, only a small part of the lens needs to be fabricated, as discussed in [16]. Fig. 5 shows the schematic of such a micro-lens array antenna. This antenna can be developed using photolithographic techniques and can be easily integrated with the silicon micromachined front-end we discussed earlier.

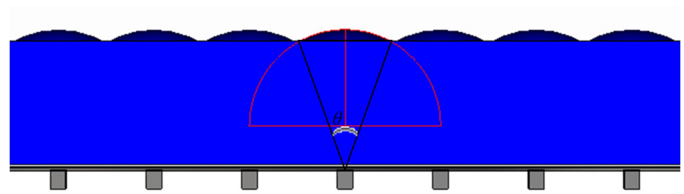

Fig. 5: Schematic of the silicon micro-lens antenna array. The antenna requires only a small fraction of the hemispherical silicon lens to be fabricated which can be easily accomplished using lithographic techniques.

We fabricated an array of silicon lenses on a couple of hundred micron thick silicon substrate by reflowing a photo-resist material and then etching the silicon. To illuminate such thin lenses, a directivity primary feed is required. We used an air cavity, as discussed in [16], to obtain such feed which has a well matched transition. Fig. 6 shows such a silicon lens array fabricated at JPL. We are in the process of integrating the micro-lens array antenna with the silicon micromachined front-end to have a multi-pixel terahertz heterodyne array receiver.

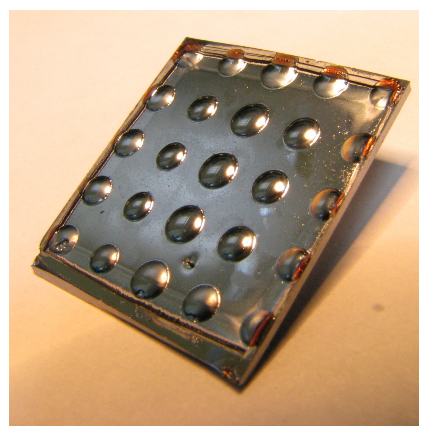

Fig. 6: Photograph of a silicon micro-lens array antenna fabricated with photolithographic techniques.

IV. SILICON MICROMACHINING FABRICATION

We developed silicon micromaching fabrication capability in our laboratory to develop the terahertz heterodyne array receiver. Micromaching of silicon at terahertz frequencies places a number of important constraints on the structures. First, the terahertz frequency waveguides and device channels need very smooth sidewalls and bottom surfaces in order to minimize Ohmic losses. The cross sections of the waveguide walls also have to be precisely rectangular in order to minimize scattering from geometric inhomogeneities and integrate terahertz active components successfully. Finally, a robust and accurate alignment scheme is needed to assure good impedance matching across vertical wafer-to-wafer waveguide transitions.

In our laboratory, silicon wafers are processed with conventional UV lithography, and deep reactive ion etching (DRIE) techniques using thick AZ9260 resist as etching mask. The DRIE process used here is the well-known Bosch process [17] based on the use of alternative exposures to SF_6 and C_4F_8. With optimized plasma power and etching gas ratios, we can achieve a selectivity of 50:1 for etching at low rates (2 μm/min) and up to 75:1 for long and deep etches (4 μm/min). Fig. 7 shows the SEM picture of the one of the silicon layers of the terahertz front-end we fabricated using DRIE.

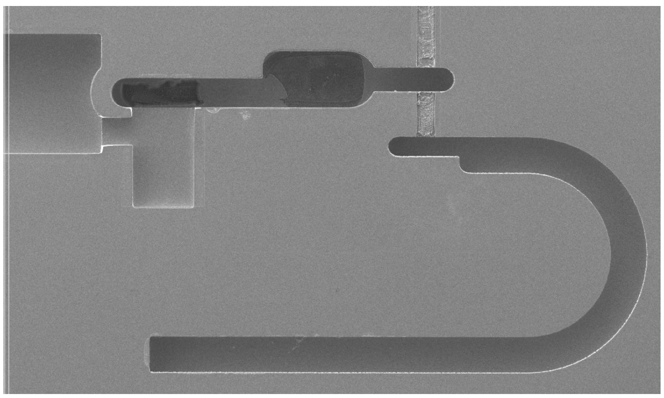

Fig. 7: SEM picture of silicon micromachined waveguide components fabricated for the 600 GHz heterodyne receiver front-ends. The smallest dimensions in the fabricated part are the 75 μm by 75 μm waveguide section.

One critical area of concern for silicon micromachined components is the alignment of different silicon layers. We developed a technique using circular etched pockets and silicon donuts-shaped dowel pins to align two wafers together. The donut shape was selected to prevent trapped air under the silicon pin during the assembly and to make it easier to handle with tweezers. With this technique, we can achieve better than 5 μm alignment. We believe that with this capability we will be able to fabricate and assemble micromachined components well over one terahertz.

V. CONCLUSION

In this paper we explored various architectures to develop an integrated heterodyne array at terahertz frequencies. 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 designed, developed, and fabricated 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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