All Solid-State Receiver Designs at 2 THz for Atmospheric Sounding

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Abstract— **Measurement of the atomic oxygen emission at 2060 GHz has been identified as a key measurement to improve space weather predictions. In this paper we report on an all solid-state 2 THz receiver system. The mixer circuit is based on an anti-parallel pair of diodes in a sub-harmonic bias-able configuration. The design requires no cooling and is tolerant to nominal LO power variations. A compact multiplied source at 1.03 THz with more than 1 mW output power has been demonstrated and mixer chips have been designed.**

I. INTRODUCTION

Thermospheric density and atmospheric motion perturbations from space weather events influence higher atmosphere and upper mesosphere dynamic processes. These processes are involved in the climate evolution and play a major role in the trajectory of low-orbit space vehicles and debris during reentry. It is therefore desirable to build a novel instrument that provides observational data to characterize tropospheric winds at an altitude of 80 to 150 km [1]. One of the identified tracers for the neutral gas winds is the oxygen line (OI) which can be measured via doppler at 2060 GHz. The two main critical goals to develop a state-of-the-art 2 THz radiometer fulfilling the requirements of very small platforms include the development of a mixer and its 1 THz local oscillator source.

This paper describes an on-going effort to build the first ever all-solid-state receiver at 2 THz. While receivers in this frequency range have been demonstrated, see Table I, they have all utilized bulky lasers for the local oscillator. We report on mixer chip designs that are purposely optimized both for performance as well as reduced LO requirements. A mixer chips designed with anti-parallel pair topology provides sensitivity and performance that will enable measurement of the oxygen line. Finally, a compact LO chain that produces more than 1 mW at 1 THz is briefly described.

II. SYSTEM REQUIREMENTS

The implementation requirements for a 2 THz radiometer system compatible with small-sats are 4 kg mass, 10U volume, and power below 15W. This will be addressed by a Schottky based heterodyne spectrometer working at terahertz frequencies and operating at room temperature with large instantaneous bandwidth and high spectral resolution. The two main critical system parameters to fulfill all criteria while keeping state-of-the-art performances include: 1) the configuration of the mixer, its epitaxial layer definition, matching transmission lines and housing, 2) the local oscillator sub-system part and its calibration. Table I provides context for the current design work. Best recorded systems [2] and [3] use fundamental balanced mixers with respectively 5 mW and 10-12 mW of local oscillator power at 2 THz, comfortably provided by a CO2-pumped methanol gas laser. The choice of fundamental mixers is justified by the fact that they can theoretically reach better noise performance over subharmonic mixers [4]. However, the sub-harmonic topology relaxes the local oscillator (LO) source by cutting its operating frequency by a factor of two. This configuration also avoids the requirement to use a bulky CO2 laser that is far from fulfilling the mass/volume/power criteria and doesn't offer spectral tunability easily achievable by Schottky local oscillator sources [5] [6]. The proposed receiver utilized planar Schottky diodes for the mixer and multiplied LO.

III. MIXER DEVELOPMENT

In this part we describe the development of a 2060 THz mixer including the mixer topology, the Schottky junction fabrication parameters, and the circuit matching constraints. We describe comparison between two chips with distinctive topologies that have been fabricated, namely, *Chip-A* originally designed for 1.8 THz and described previously in [7] and *Chip-B which has been designed to optimize performance at 2.06 THz* .

A. Mixer configuration

Recent designs of 1-2 THz MMIC sub-harmonic biasable mixers are based on successful sub-harmonic 1200 GHz

Frequency	Mixer type	Local Oscillator type	Epitaxy (cm^{-3})	Receiver noise temp. DSB (K)	Conversion gain (dB)	Ref.	Flight instrument
2.5 THz	Fundamental	CO2 Laser > 5 mW	1 *10e18	16500 K	- 17 dB	[2]	MLS AURA
2.5 THz	Fundamental	CO2 Laser > 10 mW	1 *10e18	6000 K	- 12.5 dB	[3]	-
1.96 THz	Subharmonic (chip A)	Schottky multipliers – 1 mW	1 *10e18	7000 K (simulated)	- 13 dB (simulated)	This work	-
2.06 THz	Subharmonic (chip B)	Schottky multipliers – 1 mW	1 *10e18	2000 K (simulated)	-10 dB (simulated)	This work	-

Table 1: State-of-the-art performance of Schottky based 2 THz heterodyne room temperature radiometers.

mixer topology [8] and have been design to give - 15 dB conversion gain with 1.5 mW of LO power [5]. The preferred mixer circuit topology at submillimeter and terahertz frequencies features a minimum of two-anode in order to provide balancing, implemented in a series-balanced [7] or antiparallel-balanced configurations, both featuring antiparallel topology at LO and IF frequencies and named after their anode positioning across the waveguide channel. In both cases a bias favor flexibility in the operative system, especially when the local oscillator source remains a critical sub-system. Indeed, if great LO power (P_{ol}) is usually preferred at THz to relax the mixer efficiency, an optimum in the coupled parameter (P_{ol}, mixer bias voltage) can be found during the optimization of the mixer junction and its matching network so that limited hot-electron noise is added to the mixer conversion noise. In the series-balanced topology the DC biasing is made possible by decoupling the DC path to the RF and LO transmission lines with very compact on-chip capacitors with very well-behaved mode confinement near the diode. The antiparallel configuration is generally used under unbiased operation [9] due to the difficulty to isolate the two anode DC paths. For example, the bias can be applied through the IF port and uses a multilayer transmission line [10]. This solution relies on having a good quality dielectric without pin-hole defects. Recent work has converged lately on a novel mixer configuration [11] that combines both on chip capacitor and a planar transmission line to differentiate the RF, LO and IF port directly at the diode cell level. This alleviates the problem of DC biasing of the anti-parallel configuration mixer in which the extremely secure balance allowing to reach very pure even LO excitation of the anodes for AM noise rejection. In Fig 1. we illustrate two designed chips of seire-balanced and antiparallel configuration that are fabricated at JPL-MDL: *Chip-A* originally designed for 1.8 THz [7]; *Chip-B* [this work].

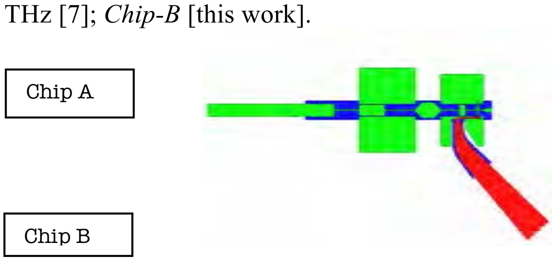


Fig. 1: Top – ***Chip A is a series-balanced mixer configuration that has been described in*** **[7]. Chip B shown in the bottom of the figure is an anti-parallel balanced configuration and provides enhanced performance.**

B. Schottky junction parameters

The doping and epitaxial layer thicknesses of the GaAs-Schottky junction are defined as a trade-off to optimize the junction mixer rectification efficiency for a same anode size. Firstly if we assume equivalent bandgap and electron mobility of the GaAs fabricated material, monte-carlo dedicated studies [12] typical doping initial value range for THz GaAs-based Schottky mixer-operation is located between $3e^{17}$ and $1e^{18}$ cm $^{-3}$, also confirmed by the state-of-the-art heritage listed in Table I. Secondly the thickness of the epitaxial level defines the reverse current excursion, which is maximized in a case of a multiplier operation and minimized in a forward mixer operation in order to reduce series resistance related losses. In this study *Chip-A* [7] and *Chip-B* both feature a thin epilayer thickness and high epitaxial doping suited to mixer operation. The junction parameters used in the harmonic balance electrical simulation are respectively for *Chip-A* [7] and *Chip-B*: a series resistance values of 100 ohms, a junction capacitance of 0.39 and 0.32 fF. Both are simulated with a saturation current I_{sat} = 1.6 pA, an ideality factor η = 1.3, and a built-in potential V_{bi} = 0.718.

C. Transmission line

The mixer sensitivity and conversion loss are related to the diode parasitics at RF and LO frequencies and to how well the RF and LO signals are coupled from the feed-horn and waveguide input ports to the anodes. Diode topology including mesa-to-mesa and finger-to-finger distances are optimized to limit diode parasitic coupling and harmonic trapping. *Chip-B* features a photolithographic backside process in the diode cell vicinity used in order to reduce the substrate parasitic loss by avoiding mode confinement in the substrate. For both chips, the transmission lines are designed to minimize loss while providing effective impedance matching. *Chip-A* [7] uses a very thin 3-µm thick GaAs membrane to support the diode devices while reducing the dielectric loading of the chip. The sections of the transmission lines are suspended by gold beam leads on both sides of the chip. The anti-parallel pair configuration *Chip-B* provides wider channel dimensions not affordable by *Chip-A* [7] configuration and thus introduces a larger range of low loss transmission lines for matching the RF and LO signals to the anodes. Its transmission lines are defined by a suspended central gold line so that the signal propagates on the edge of the gold only and the membrane underneath the gold does not significantly affect the mixer performance. *Chip B* features two different channel sections. The channel dimensions are defined to ensure that the RF and LO signals are propagated with the quasi-TEM mode of the central channel line, and that no unwanted transmission mode coupling occurs. The first matching section is designed so that the RF signal is confined as close as possible and coupled efficiently to the diode anodes. The second section supports the LO signal only, therefore its dimensions can be relaxed to minimize the losses coming from the LO source. The transmission sections feature two low (60 ohms) and medium (100 ohms) impedance lines with respectively 140, 160 dB/m loss at RF frequency, and around 110 and 100 dB/m losses at LO frequency.

D. Mixer performance comparison

Some key features of the two mixer chips (A and B) are compared in Table II. RF and LO signal coupling in percent is defined as the percentage of the input RF and LO signals from the waveguide input ports coupled to both Schottky anodes. These are distinct from the *RF and LO return losses* simulated at RF and LO waveguide input port as they also depend on the transmission line losses. The *RF and LO lost signal* indicates how efficient the coupling is and illustrates the possible differentiation in the two designs. *Chip-B* features a higher RF return loss compared to *Chip-A*. However, its RF coupling signal is higher by 25 % and lost RF signal lower by more than 20% thanks to its reduced RF transmission line losses.

The expected mixer performance as a function of design frequency for the two chips is shown in Fig. 2. The improved sensitivity expected from Chip B makes it the baseline design. *Chip-B* features a LO return loss that is higher compared to *Chip-A* and its LO signal coupling it higher by more than 30%. This has an impact on the operation mode of the junction requiring lower DC bias voltage level, and where *Chip-A* requires 1 V of DC voltage, *Chip-B* requires only 0.4 V. Both conversion loss and sensitivity of Chip B are drastically improved. These results are for room temperature and further improvement can be expected if the mixers can be cooled even to 120 K.

Table 2 : ***Comparison performance of the two mixer chips (A and B) shows the expected enhancement of the new topology.***

	Chip-A [7]	*Chip-B*
RF Return loss	**< -15 dB**	**< -12 dB**
RF signal coupling	**50 %**	**75%**
Lost RF signal	**47 %**	**19 %**
LO Return loss	**< -12 dB**	**< -15 dB**
LO signal coupling	**40 %**	**75 %**
Lost LO signal	**50 %**	**22 %**
Pol Bias Per 2 anodes	**1 mW 1 V**	**1 mW 0,4 V**

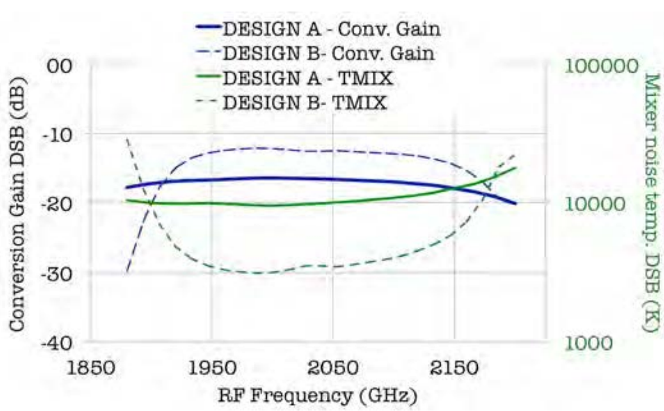
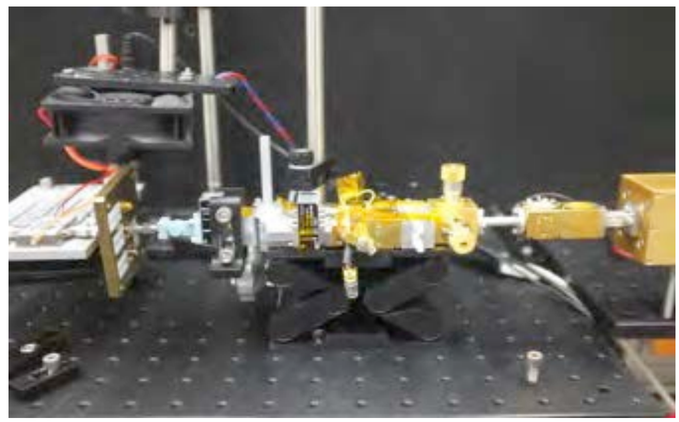


Fig. 2 Simulated performance of the two mixer chips as a function of frequency is shown. Identical anode parameters are selected for both designs.

IV. Local Oscillator Development

Another key hurdle towards developing an all-solid-state 2 THz receiver system is the associated local oscillator source. For implementation on small satellites it is important that the LO source is compact and highly efficient. The local oscillator consists of a synthesized signal at 38 GHz which is amplified with power amplifiers to >1.5 Watt of power at Ka-band. The signal is then fed into two separated branches each featuring one dual chip tripler at 114 GHz based on [14] that are recombined [15] to produce > 300 mW at the input of the 350 GHz stage. This allows us to generate a 350 GHz spectrally pure signal of > 35 mW which is then used to pump the last stage tripler. The mixer is subharmonically pumped and thus requires the LO to be at 1.03 THz. The LO schematic is consolidated and secured with an E-H tuner to allow mismatch correction over frequency, and thermally secured to operate the 110 GHz at their maximum input power. The LO chain is shown in Fig. 3. The output power was recorded with an Erickson-VDI PM5 meter. The measurement plot demonstrates a record power of 1.75 mW at 1.02 THz (Fig. 3). Two LO chains were assembled and their performance is found to be fairly comparable, see Fig. 3. This LO chain has already demonstrated that it is capable of pumping the mixer as reported in [13].



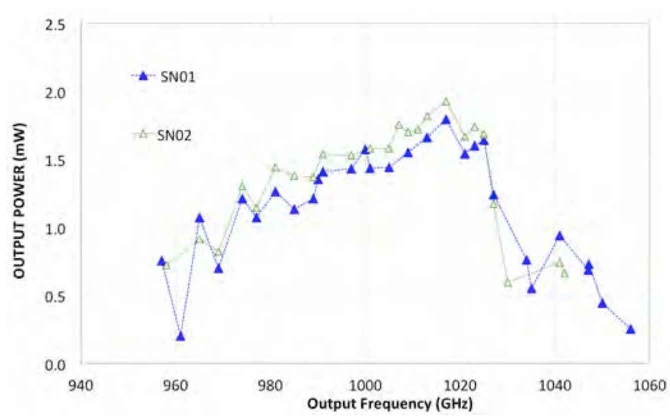


Fig. 3: A compact 1 THz LO chain has been built and demonstrated. The measured power should be sufficient to pump Schottky diode mixers in the 2 THz range.

V. Conclusion and Perspectives

All-solid-state receivers capable of making spectroscopic measurements in the 2 THz range are being developed to observe the neutral oxygen line in the troposphere and measure wind velocities. Winds at higher altitudes are directly linked to understanding key heliophysics questions such as energy balance. A solid state LO chain that provides more than 1 mW of output power at 1.03 THz has been demonstrated. A novel mixer chip has been designed and simulated to show enhancement in performance from existing state of the art. The chip is currently being fabricated and will be packaged and characterized in the future.

VI. Acknowledgment

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