# An 874 GHz fundamental balanced mixer based on MMIC membrane planar Schottky diodes

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*Abstract*— **We present here the design, fabrication and test of a novel 874 GHz Fundamental Balanced Mixer based on MMIC membrane planar Schottky diodes. The device includes an integrated DC bias circuit in order to reduce the amount of LO power required to pump the mixer. The mixer performance are best DSB mixer noise temperature of 2660 K at 865.8 GHz and best DSB mixer conversion losses of 8.02 dB at 862.2 GHz for room temperature operation. When cooled to 120 K ambient temperature, the best DSB mixer noise temperature drops down to 1910 K. Although at least 1 mW of LO power is required to optimally pump the mixer, performance are still acceptable with only 0.5 mW. To the authors' knowledge, these results are state-of-the-art.**

## INTRODUCTION

The remote sensing of stratospheric ice clouds is of key interest in understanding the hydrological cycle of climate systems for life on Earth. Several missions have been proposed that would monitor globally the ice water content of cirrus clouds using passive sub-millimeter radiometer instruments up to 874 GHz [1]. Therefore, highly sensitive heterodyne receivers operating at room temperature in the sub-millimeter wave range are needed for such applications. Development of compact and broadband receivers in this frequency range can also benefit THz imaging applications by providing higher resolution compared to lower frequency systems [2].

Sub-harmonic mixers working up to 874 GHz [3] have already been demonstrated. Previous studies have shown that improved performance can be obtained from fundamental mixers over sub-harmonic types. Recent breakthroughs in power generation from amplifier-multiplier based solid-state sources up to 900 GHz [4] allow for enough LO power to pump a biasable fundamental mixer, as demonstrated here.

We present the design, development and characterization of a fully monolithic 835-900 GHz biasable fundamental balanced mixer (FBM) using GaAs Schottky diode MMIC developed at JPL. The mixer is pumped by a powerful compact LO chain based on solid-state power combined amplifiers and multipliers, resulting in the highest frequency all solid-state compact broad band heterodyne receiver operating at room temperature with state-of-the-art performance. The front-end has been tested at both room and cryogenic temperatures (120 K) using a dedicated cryogenic test system.

## 874 GHz FUNDAMENTAL BALANCED MIXER ARCHITECTURE

The topology of the 835-900 GHz fundamental balanced mixer is based on a cross-bar balanced architecture recently used at higher frequencies [5][6]. For the present design, both diodes are located inside the RF waveguide in a series configuration across the central suspended stripline, as illustrated in Fig. 1&2. Airbridges are used to connect the mesas and Schottky contacts to the central stripline and lateral grounding beamleads. Another beamlead at the end of the circuit is used to connect the MMIC to an IF circuit. A DC bias line and a MIM capacitor are used to bias the diodes in series while providing an efficient IF, LO and RF ground.

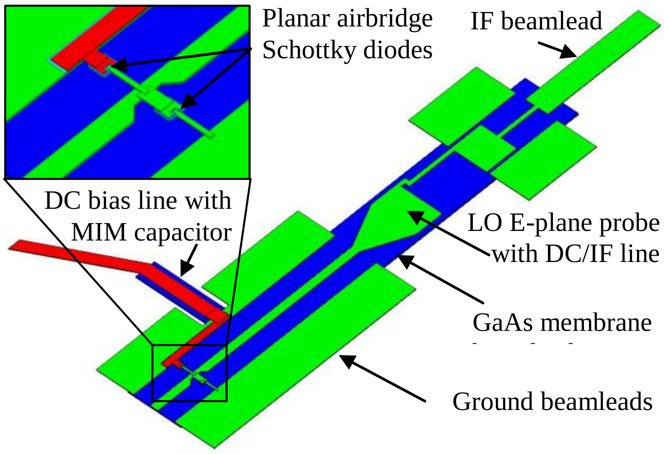


Fig.1. 3-D view of the 874 GHz Fundamental Balanced Mixer MMIC device, featuring a pair of planar Schottky diodes in balanced configuration on a thin GaAs membrane, gold beamleads and DC MIM capacitor.

The LO signal is coupled via a bowtie E-plane probe with integrated DC/IF line to the diode. This transition is adapted from a previous design that uses an integrated DC bias line [8]. The length of the narrow line connecting the bowtie antenna is optimized to prevent any resonance in the desired LO band. The bandwidth of this bowtie-type transition is also improved by adding narrow steps inside the LO waveguide as demonstrated in [9].

## DESIGN METHODOLOGY

This section describes the methodology employed to design the 835-900 GHz fundamental balanced mixer, including the determination and optimization of the diodes geometrical and electrical parameters.

*Linearisation of the ideal mixer*. Non-linear circuit simulation of an ideal pair of Schottky diodes is performed using the Harmonic Balance code of the ADS Software Suite [10]. The goal is to determine the anode size of the diodes in order to get the best mixer conversion losses, lowest RF and LO input return losses. The IF signal is fixed at 5 GHz. With an estimated LO power of 0.5 mW reaching the diodes, the mixer conversion losses are minimized by tuning the bias voltage and ideal embedding impedances. Assuming an epi-layer doping concentration $N_D$ of $5.10^{17}$ $cm^{-3}$, it is found that best conversion losses are obtained for anode area A of approximately 0.4 $\mu m^2$, a bias voltage $V_{DC}$ of 1.3 V, and ideal embedding impedances $Z_{LO}$ of approximately 17 + j.50 for the LO at 870 GHz, $Z_{RF}$ of approximately 90 + j.200 for the RF at 875 GHz, and $Z_{IF}$ of 200 Ω for the IF at 5 GHz. The resulting electrical parameters used at room temperature for the Schottky diode model are a zero voltage capacitance of 1 fF, a saturation current of $2.10^{-13}$ A, barrier height of 0.73 V, ideality factor of 1.4, and series resistance of 30 Ω.

*Synthesis of the mixer circuit*. Three-dimensional electromagnetic (EM) simulations of the different parts of the mixer circuit are simulated separately using HFSS (from Ansys [11]) and exported as S-parameter Touchstone files into ADS. These parts include the RF and LO waveguides-to-stripline transitions, diode cells, high-low suspended stripline transitions and DC/IF transmission lines. Using ADS, a linear simulation bench of the mixer circuit is built which includes the S-parameter files, RF and LO diode's impedance ports obtained previously, electrical transmission lines and the waveguide ports. This bench has two separate sub-circuits: one for the RF signal propagating from the waveguide to the diodes' port with a $TE_{10}$ mode, and the other for the LO signal propagating with a TEM mode. The resulting coupling efficiency from waveguides to both diode ports is predicted to be approximately 80 % between 840 and 910 GHz for the RF, and 40 to 45 % between 850 to 900 GHz for the LO.

*Prediction of the mixer performance*. A set of non-linear simulations is performed to fine tune the circuit and predict the performances of the mixer. For the conversion loss calculation, the standard ADS model of the Schottky diode [11] is used. For the mixer noise temperature calculation, the standard ADS model includes thermal and shot noise sources, but does not include any other sources that account for hot electron noise. As this effect can becomes significant at sub-millimeter wave frequencies for small anode devices, an additional noise source is added in series with the standard ADS Schottky model [12].

Simulations show that the mixer should work with a Local Oscillator power of only 0.5mW and a bias voltage of 1.4V for the two diodes in series. For 1 mW of input LO power and a fixed bias voltage of 1.2 V, DSB mixer conversion losses are 8.5 dB, and DSB mixer noise temperature of 2000 K are predicted between 850 and 910 GHz. This estimation includes additional 0.7 dB of losses for the feed-horn, and 1.2 dB of insertion losses for the IF transformer, connector and cable. Results are shown in Fig. 4 as continuous lines. The predicted RF/LO isolation ranges from 29 dB up to 33 dB between 830 and 900 GHz.

## 874 GHz FBM FABRICATION AND MOUNTING

The circuit is based on a thin GaAs membrane and uses beamleads for connections and handling [7] as shown in Fig. 2. The Schottky contacts, defined using E-beam lithography, are connected to the circuit via air-bridges. The JPL MMIC membrane Schottky process described in [7] is specially suited for the realization of fundamental balanced mixer at these frequencies. Indeed, the thin membrane prevents excessive dielectric loading of the waveguides and channels, the beamleads allow for a precise grounding, centering and DC/IF connection of the MMIC to the block and DC/IF circuits. The on-chip MIM capacitor allows to DC bias the mixer with minimum RF/LO fields disturbance. Finally the MMIC process reduce the uncertainties associated with handling and placing the device inside the block.

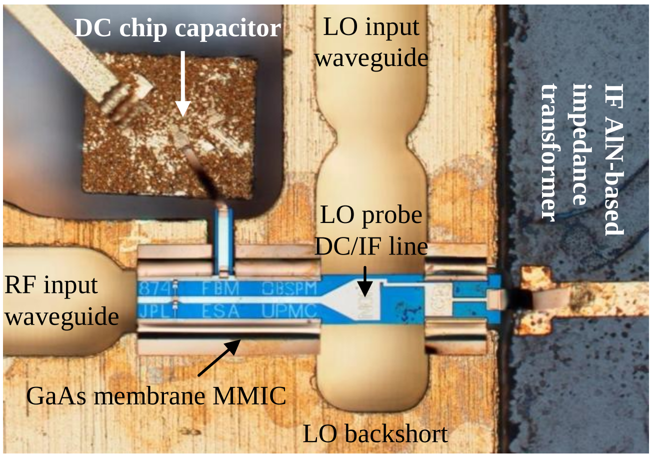


Fig.2: View of the 835-900 GHz fundamental mixer circuit mounted inside the lower half of the mechanical block, including a MMIC mixer device (center) mounted with DC chip capacitor (top) and IF transformer (right), DC bias, ground and IF gold beam-leads.

External chip capacitors are used for the DC bias and further filtering of any unwanted IF residue. The IF signal is output through an IF impedance transformer to the K-type connector. The IF transformer circuit is designed to improve the Voltage Standing Wave Ratio between the mixer and the external first low noise Amplifier in the 2-11 GHz range. A view of the IF transformer mounted inside the lower half of the mechanical block is shown in Fig. 3. It consists of a meandering line to match from 200 Ω to 50 Ω in 4-sections impedance steps. The circuit is based on gold microstrip lines deposited on a 1.27 mm thick Aluminum Nitride substrate. This enables to keep return losses above 10 dB and insertion losses below 1 dB over a relatively broad bandwidth 2-11 GHz. The DC bias chip capacitors are connected with thermo-compressed bond wires to a SMA-type glass bead.

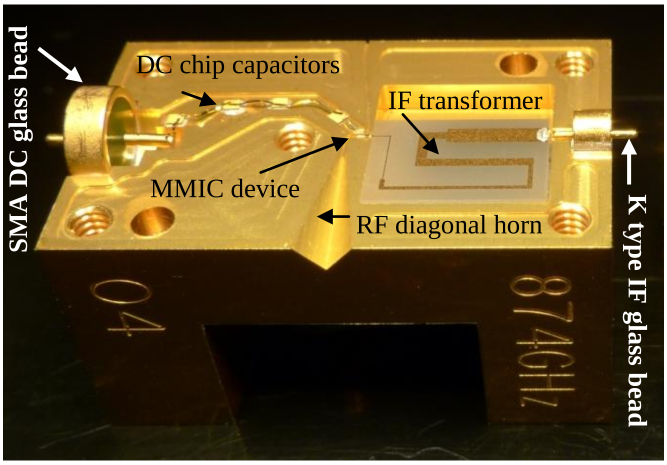


Fig.3: View of the lower half of the mechanical split-block, showing from left to right the SMA-type DC glass bead, DC chip capacitors, the IF impedance transformer and the K-type IF glass bead.

SMA flange launcher connector is mounted afterwards to the block. The IF circuit is connected to a K-type glass bead via a stripline stress relief contact inserted on the tip of the glass bead and silver-epoxy glued on the ending of the microstrip line section.

## 874 GHz FBM TESTING

The 874 GHz Fundamental Balanced Mixer has been tested at room temperature and at cryogenic temperatures using the test set-up described in [12]. The mixer is pumped by a W-band Agilent source linked to an Agilent E8257D synthesizer. The LO signal is then amplified outside the cryogenic test chamber using a series of power combined W-band power amplifiers. The 2-4 GHz IF amplification and filtering chain is described in [13]. The output power of the IF chain was measured using an Agilent total power sensor N8482A linked to a N1912A power meter.

The first multiplier chains used inside the test chamber to generate the 830-900 GHz LO signal is a medium power multiplier chain featuring a dual-chip power combined 300 GHz tripler and single-chip 900 GHz tripler. The characteristics of this LO chain is described in [14][4]. It outputs an LO power ranging from 0.3 to 0.6 mW at ambient temperature from 840 to 930 GHz. The complete multipliers/mixer front-end receiver is very compact and is shown in Fig. 4. Measured performance are shown in Fig.5. As illustrated in Fig.5, a DSB mixer noise temperature of 3000-4000 K and DSB mixer conversion losses of 10.5 to 11 dB in the range 847-885 GHz are measured at room temperature.

A second high power LO chain featuring a quad-chip 300 GHz power combined tripler and dual-chip 900 GHz power combined tripler outputting over 1 mW of power at room temperature in the 840-900 GHz range and up to 2 mW when cooled at 120 K has been used. Details concerning the LO chain can be found in [15]. Measured mixer performance for 295 K and 120 K ambient temperature operation is shown in Fig.6.

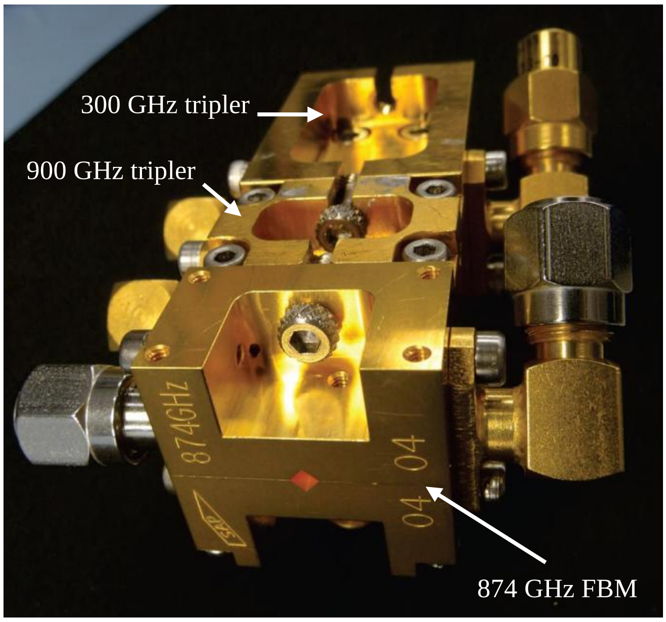


Fig.4: Photo of an entire 874 GHz receiver front-end including the 874 GHz Fundamental Balanced Mixer (foreground), a 900 GHz single-chip tripler (middle), and a dual-chip 300 GHz power combined tripler (background).

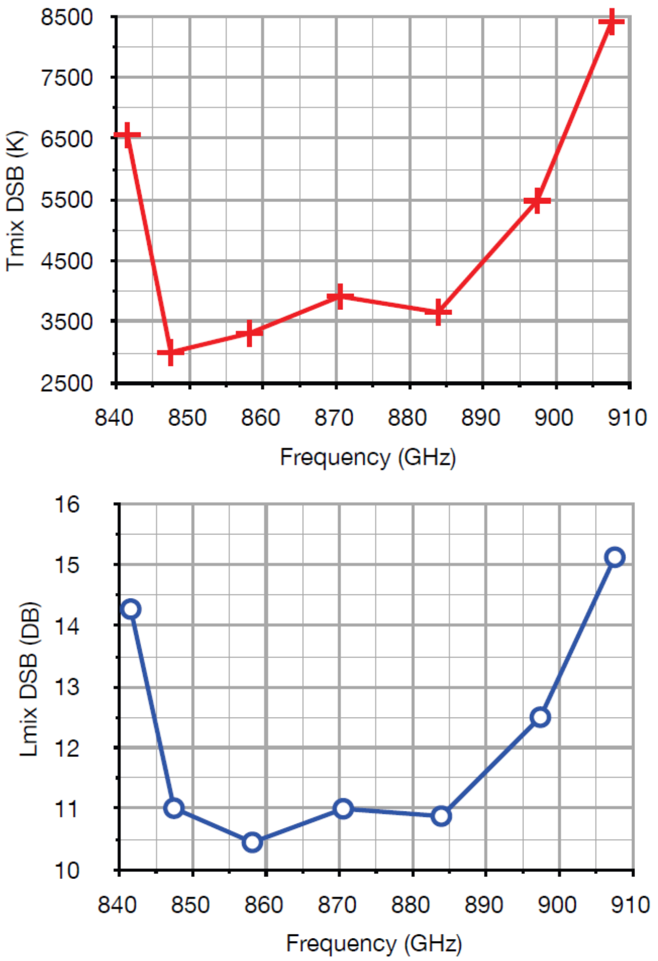


Fig.5: 874 GHz FBM mixer performance at room temperature using a medium power LO chain in the range 840-930 GHz. Top curve shows the DSB mixer noise temperature, lower curve shows the DSB mixer conversion losses *VS* center RF frequency.

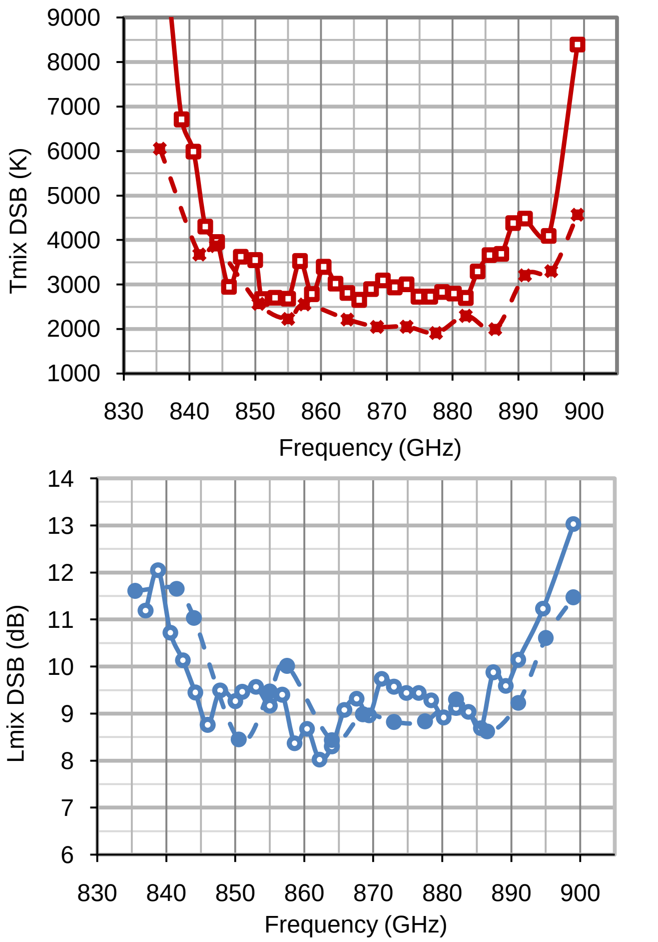


Fig.6: 874 GHz FBM mixer performance at 295 K (empty dotted curves) and 120 K (full dotted curves) ambient temperature operation using a high power LO chain in the range 840-930 GHz. Top curves show the DSB mixer noise temperature, lower curves show the DSB mixer conversion losses *VS* center RF frequency.

As shown in Fig.6, The best mixer noise temperature measured at room temperature is 2660 at 865.8 GHz, with DSB mixer conversion losses of 9.08 dB. The best DSB mixer conversion losses measured at room temperature is 8.02 dB at 862.2 GHz, with corresponding DSB mixer noise temperature of 3021 K. If the mixer performances are corrected for IF external cable losses (0.64 dB), DSB mixer noise temperature and conversion losses drops to 2330 K at 865.8 GHz, and 7.38 dB at 862.2 GHz respectively. DSB mixer noise temperature and conversion losses are below 4000 K and 10.5 dB resp. from 845 GHz to 888 GHz. At 120 K of operating temperature, the best DSB mixer noise temperature measured is 1910 K at 877.5 GHz, with DSB mixer conversion losses of 8.84 dB. The best DSB mixer conversion losses observed is 8.44 dB at 864 GHz, with corresponding DSB mixer noise temperature of 2213 K. DSB mixer noise temperature and conversion losses are below 3000 K and 10 dB resp. from 847 GHz to 890 GHz.

It is interesting to notice that, for room temperature operation, the mixer still works relatively well with only 0.5 mW of LO power in average, and a bias voltage increased to 1.4 V, as shown in Fig.5. A maximum of 2 dB degradation of the DSB conversion losses is measured by going from 1 mW to 0.5 mW of LO power.

## Conclusions

The design, fabrication and test of a 874 GHz fundamental balanced mixer based on MMIC membrane planar Schottky diodes has been presented. It exhibits state-of-the-art performance at room temperature and cooled to 120 K. Although at least 1 mW is required to optimally pump this mixer, performance degrades nicely with only 0.5 mW.

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