Balanced Waveguide HEB Mixer for APEX 1.3 THz receiver

Denis Meledin, Miroslav Pantaleev, Alexey Pavolotsky, Christophe Risacher, Victor A. Perez Robles, Victor Belitsky, Vladimir Drakinskiy and Sergey Cherednichenko

Abstract— **We present results on the design and construction of a waveguide balanced Hot Electron Bolometer (HEB) Terahertz mixer for Atacama Pathfinder EXperiment (APEX), band T2 covering 1250-1390 GHz frequency range. In the proposed design, a waveguide balanced mixer is realized using a quadrature scheme. The two identical HEB elements are integrated with RF choke filters, DC-bias, IF circuitry, and fabricated from 4 nm thick NbN film deposited on a crystalline quartz substrate with dimensions of 1100 µm×70 µm×17 µm. We have designed and fabricated an input 3 dB quadrature waveguide hybrid. For its fabrication, we use micromachining approach to achieve low insertion loss and symmetrical division of the RF and local oscillator (LO) power within the band of interest. We plan to use two HEB mixer configurations with different probe impedance values of 55, 70 Ohm within 1250-1390 GHz frequency range.**

***Index Terms*—balanced mixer, terahertz radio astronomy, hot-electron bolometer mixer.**

I. Introduction

THE APEX 12 single dish telescope located at Chajnantor Plato, in Northern Chile will be equipped with heterodyne and bolometric receivers for radio astronomical observations at the frequency range 211 – 1500 GHz [1]. According to recent atmospheric measurements, the three windows centered at 1.03, 1.35 and 1.5 THz show transmission as high as 40% under favorable conditions on this site [2]. Currently, there is only one ground-based submillimeter telescope successfully operating at frequencies above 1 THz [3].

In this paper, we present progress of our development of the waveguide balanced HEB mixer intended for APEX band T2 covering 1250 - 1390 GHz frequency range with a central frequency of 1320 GHz.

The balanced scheme of HEB mixer has a number of benefits over a single-ended mixer. Among them, for instance, are good rejection of LO amplitude modulation noise and better LO power handling capabilities [4]. On the other hand, the high operating frequencies, above 1 THz, introduce significant difficulties for manufacturing waveguide components, and make balanced design less attractive.

The prototype's design of waveguide balanced HEB mixer for APEX 1.3 THz receiver proposed in [9] is revised significantly. In the current paper, we present important improvement in mixer components design and fabrication. Figure 1 shows the quadrature scheme of our balanced HEB mixer. The 3 dB quadrature waveguide hybrid couples the RF signal and LO to the individual identical HEB mixers. The outputs from the HEB mixers at intermediate frequency (IF) are connected to cryogenic IF low noise amplifiers (LNA). These LNAs 2-4 GHz designed at GARD use 50 Ω-matched inputs in order to improve system noise temperature by avoiding circulators [5]. A commercial 180° IF hybrid combines IF outputs from the both mixers. The resulting IF signal is collected at one of the IF hybrid outputs, and the amplitude component of the sideband LO noise is terminated at the other output. Placing the LNAs before the IF hybrid should improve the system noise performance by the reduction of the additional noise caused by the IF hybrid insertion loss. In contradistinction to the previous mixer design [9], we do not use an additional cryogenic LNA following the IF hybrid. Moreover, the isolation of the balanced mixer depends on the amplitude and phase imbalance of the two IF amplifiers.

II. Waveguide 90° Hybrid

The input waveguide 3dB hybrid providing LO injection and RF signal distribution between two HEB mixers with 90° phase shift, is designed compatible with the split-block technique. The splitting takes place through the plane of symmetry in the middle of the waveguide's broad walls. Therefore, possible imperfect contact between two halves will not affect the

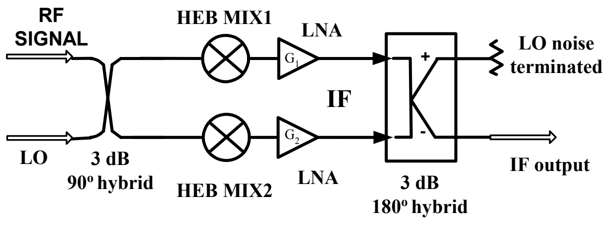

Fig.1. Scheme of the balanced HEB mixer

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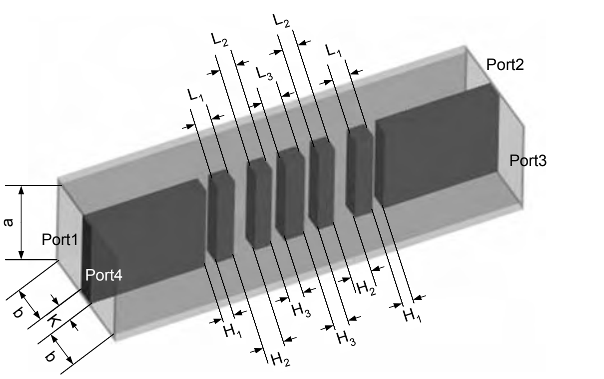


Fig.2. The waveguide hybrid with six branches. The main waveguide size is 180 μm (dimension *a*) by 90 μm (dimension *b*). Values of *K*, L_n, H_n were varied to achieve the optimal configuration of the coupler at *K*=50 μm, H_1=21 μm, H_2=35 μm, H_3=25 μm, L_1=44 μm, L_2=41 μm, L_3=45 μm.

hybrid's performances.

In order to ensure fractional bandwidth of about 20%, we intend to use a six-section hybrid. Drawing of the proposed hybrid design is shown in Fig.2. The increased number of branches makes the fabrication difficult because the required dimensions become too small to be produced with sufficient accuracy using conventional machining techniques.

The design variables are the heights of the branches (H_n), the spacing between branches (L_n), and the distance between the main waveguides (K). The main waveguide dimensions a=180 μm and b=90 μm are fixed. Thus, for each half of the split-block the waveguide depth channel has to be 90 μm. The limit of branch guide height H_n is chosen to be as low as 20 μm.

To analyze the hybrid performance, the hybrid was represented as a series of E-plane T-junctions interconnected by waveguides. On the initial stage of the design, we applied a numerical matrix method based on circuit theory [6], [7]. Then final optimization of the hybrid performance was carried out by using HFSS™[8]. The optimal configuration of the hybrid is achieved with the following values of the design variables: K=50 μm, H_1=21 μm, H_2=35 μm, H_3=25 μm, L_1=44 μm, L_2=41 μm, L_3=45 μm. In Figure 3, the lines show S_{21}, S_{31}, S_{11}, and S_{41} values obtained from HFSS simulations. As we mentioned above, the amplitude and phase symmetry at the two ports of the hybrid is crucial for good isolation between the mixers. For the optimal design parameters, amplitude imbalance, $S_{31} - S_{21}$, and phase difference, ϕ_{31}-ϕ_{21}, at the outputs of the hybrid are better then 0.5 dB and 0.5°, correspondingly, within the 1250-1390 GHz band.

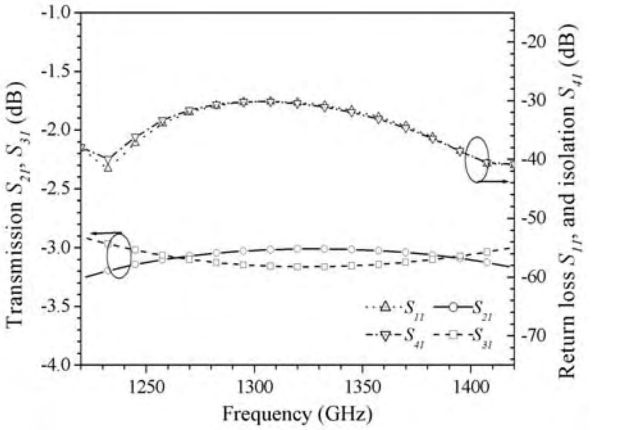


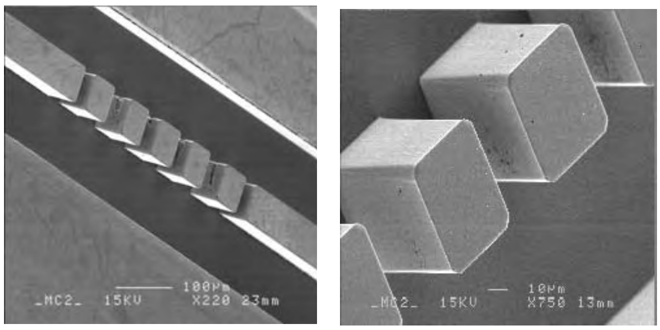
Fig.3. Results of HFSS simulations of the hybrid S-parameters at the optimal design variables.

In our previous paper [9], we found that the amplitude imbalance between port 2 and 3 of the hybrid over the required band became not acceptable if all structure dimensions has been produced with a linear error as small as 2 μm. Therefore, the required dimension tolerances along with high quality of the waveguide walls surface (better than 0.1 μm at 1.3 THz) prompts to use a micromachining method for fabrication the hybrid. In order to achieve the required machining precision, we use photolithography of thick SU-8 [10] photoresist combined with the copper electroplating. This fabrication method was discussed in a greater detail in [11], and has shown good dimension reproducibility with accuracy of better than 2 μm. The hybrid made using this technology is shown in Fig. 4a, b.

III. HEB MIXER DESIGN

The key and extremely important part of our heterodyne receiver is a pair of phonon-cooled HEB waveguide mixers based on NbN film deposited on 150 μm thick crystalline quartz substrate. For these films, the typical critical temperature is about 9.5 K with transition widths of 0.6-0.7 K. The film is patterned using e-beam lithography to form the bolometer elements of 0.1-0.2 μm long and 1-2 μm wide. With those dimensions, the measured mixer's room-temperature resistance is within a range of 100-130 Ω. The normal-state resistance, R_N, is about 15% higher than the room-temperature value. Critical current value is close to 140 μA at 4.2 K bath temperature.

For a balanced mixer, each HEB should have very similar DC and noise characteristics to guaranty better balance and the LO noise rejection. The HEB element is integrated with the "hammer" type RF filters, DC-bias circuitry, and IF leads on an individual crystalline quartz substrate with dimensions of



a). b).

Fig.4a, b. SEM pictures of the hybrid's halves fabricated from copper, and split through the plane of symmetry at the middle of the main waveguides broad walls.

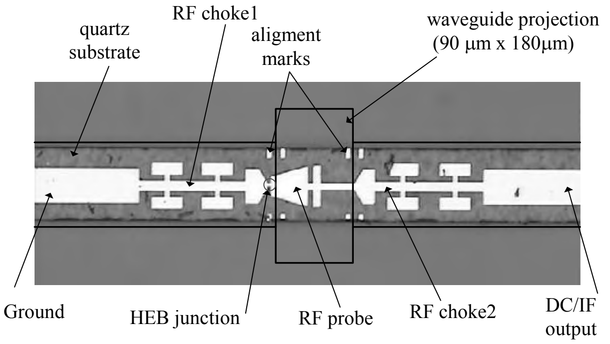


Fig.5. The layout of the individual HEB mixers integrated with RF filters, DC-bias, and IF circuitry on an individual crystalline quartz substrate with dimensions of 1000 μm x70 μm x17 μm

1000 μm x70 μm x17 μm. Both substrates will fit into a suspended microstrip channel across the broad wall of full height 180 μm x 90 μm waveguide inside a copper mixer block with fixed 70 μm backshort. The individual HEB mixer layout is shown in Fig.5. In the probe design, the input RF signal coming from waveguide port is coupled to the HEB junction by E-type probe, and appeared to be isolated from DC bias/IF output port using RF choke [12]. Good match over wide frequency band with no needs to reduce the waveguide height makes the "one side" probe's configuration attractive especially for THz frequencies. The 17 μm thickness of quartz substrate is chosen to prevent propagation of waveguide mode to the IF port.

We have two designs of the RF probe providing different embedding impedance to the HEB elements of about 55 Ohm (type A), 70 Ohm (type B) within the receiver frequency band, as shown on the Smith chart in Fig. 6. The HFSS simulation results show that RF probe impedance is purely real in

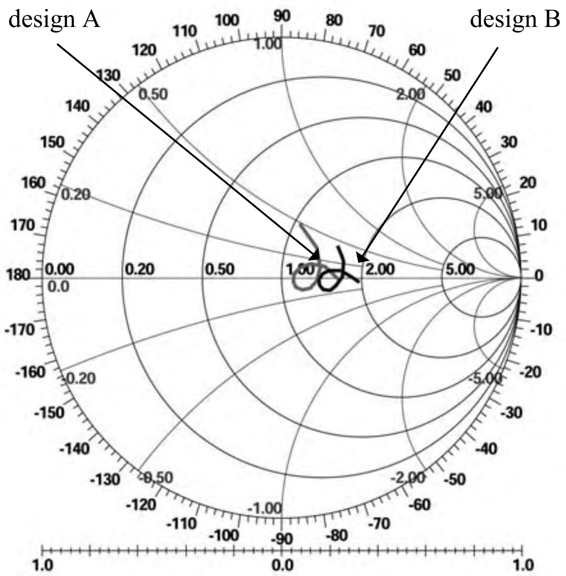


Fig.7. Smith chart normalized to 50 Ohm with RF probe impedance values at the HEB junction input for two probe designs: type A (gray curve) and type B (black curve). The frequency range is from 1220 to 1420 GHz.

frequency range from 1248 to 1392 GHz for the both proposed designs.

The mixer block is under machining at our workshop, and we expect that the first measurements results of the 1.3 THz mixers will be reported soon.

IV. Conclusion

We have achieved a final stage of the development of a waveguide balanced HEB 1.3 THz receiver for APEX Band T2. We have successfully designed and fabricated 1.32 THz waveguide 3 dB 90°-hybrid. According to the detailed HFSS simulations, the required values of the amplitude and phase imbalance at the coupler's outputs have been achieved.

We have designed two types of RF probe with different embedding impedance to the HEB elements of about 55 and 70 Ohm in 1250-1390 GHz frequency range. The first batch of NbN HEB mixers with the two types of RF probe has been fabricated and prepared for further measurements.

V. Acknowledgment

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