Design of a Balanced Waveguide HEB Mixer for APEX 1.32 THz Receiver

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Abstract

The prototype of a waveguide balanced Hot Electron Bolometer (HEB) Terahertz mixer is designed as a part of development for the APEX Project of Band T2 receiver for 1250-1390 GHz. The proposed mixer employs balanced scheme with two identical HEB devices. These individual mixers would be placed on two separate crystalline quartz substrates with dimensions of 1000μm x67μm x17 μm each with integrated RF choke filters, DC-bias and IF circuitry. A 3 dB quadrature waveguide directional coupler is needed to provide local oscillator (LO) injection and RF signal distribution between the two HEB mixers. We have designed the coupler to achieve the required frequency band, low insertion loss and symmetrical division of the RF and LO power within the band of interest. Initial design of HEB mixer layout is developed based on a previous development for a 345 GHz sideband separation mixer. We present also results of development of microfabrication technology of the waveguide hybrid employing micromachining approach combined with electroplating technique.

I. Introduction

This mixer is being developed for APEX 12m ground based single dish telescope located at Chajnantor, in the Northern Chile at an altitude of 5000 m [1], [2]. This site was selected according to detailed atmospheric transmission measurements [3] showing possibility to make astronomical observations at 0.85, 1.03, 1.30, and 1.50 THz frequencies with useful efficiency. The telescope will have both heterodyne and incoherent instruments covering the frequency range 211-1500 GHz. Presented in this paper mixer prototype is intended for APEX band T2, covering the frequency range 1250-1390 GHz with central frequency of 1320 GHz.

Most millimeter and submillimeter wavelength receivers in radio astronomy use single-ended mixers and LO injection is established using an optical beam splitter or a diplexer (for example, Martin-Pupplet interferometer). Using these schemes and accounting for very low available LO power in this frequency range, the coupling of LO power should be relatively large, e.g., in case of the beam-splitter about −10 dB. This leads to the signal loss and could make a noticeable contribution to the receiver noise temperature due to the thermal noise injected into the receiver input along with LO [4]. The use of balance mixer allows us to suppress LO amplitude modulation noise, provide better LO power handling capabilities, and reject unwanted spurious responses [5]. In addition, the balanced mixer use all available LO power. There is a number of balanced mixer designs has been reported for different frequencies operation, such as 90 GHz [6], 200-300 GHz [7], and 530 GHz [8]. However, no balanced mixers were proposed for frequencies above 1 THz.

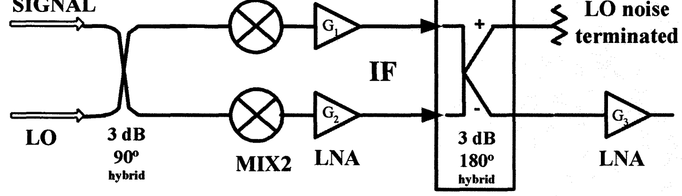

Fig. 1. Block diagram of the balanced mixer.

In the proposed design, waveguide balanced mixer is realized using a quadrature scheme shown in Fig.1. One of the key component is a 3 dB quadrature waveguide hybrid, which couples the signal and LO to the individual mixers. The mixer outputs at intermediate frequency (IF) are connected to cryogenic 2-4 GHz IF low noise amplifiers (LNA). In order to improve system noise temperature, we plan to use 50 Ω-matched inputs LNAs designed at our lab for this project (to be published elsewhere). A 180° IF hybrid combines IF outputs of the two mixers so that the IF signal appears at one output and then amplified by a cryogenic LNA (G_3). The amplitude component of the sideband LO noise is collected at the other port of the IF hybrid and terminated. Use of the LNAs before the IF hybrid improves the system noise performance significantly reducing additional noise due to insertion loss in the IF hybrid but requires 2 gain- and phase- matched amplifiers. The isolation of the balanced mixer depends on the amplitude and phase balance of the components.

II. Waveguide 90° Hybrid Design and Tolerance Requirements

A quadrature hybrid is a four port directional coupler providing LO injection and RF signal distribution between the two mixers with a 90° phase difference. In the ideal case, the incident power at the input ports of the hybrid is divided equally between the two output ports. The quadrature hybrid consists of two parallel waveguides coupled through a series of apertures or branch waveguides usually between the broad walls and approximately quarter of wavelength long. The hybrid design is compatible with the split-block technique with splitting trough the plane of symmetry at the center of broad walls of the waveguides with no surface currents flow across this plane of symmetry[9]. Furthermore, there is just a little concern about imperfect contact between the two halves.

The amplitude and phase imbalance at the outputs of the quadrature hybrid influences also on the LO injection. It is known that in order to ensure 20 dB isolation, the imbalance in the signal path has to be less than 1.7 dB or the phase imbalance should be less then 12° [4]. Part of this work is to design and fabricate a waveguide quadrature hybrid with the worst-case amplitude imbalance ≤0.5 dB and the phase imbalance ≤1° within the band of interest.

Designing a waveguide hybrid coupler for high frequency band involves a number of compromises given by fabricating constrains. To meet the required bandwidth of about 20% the central frequency, fewer sections are needed, e.g., 6 - sections layout was chosen for our coupler design. A larger number of branches would make the hybrid fabrication more difficult because the required dimensions became too small to be produced with sufficient accuracy.

Fig.2 shows drawing of the designed hybrid with 6 sections. The design variables are: the height of the branches (H_n), the spacing between branches (L_n), and the distance (K) between the main waveguides. The limit on the branch

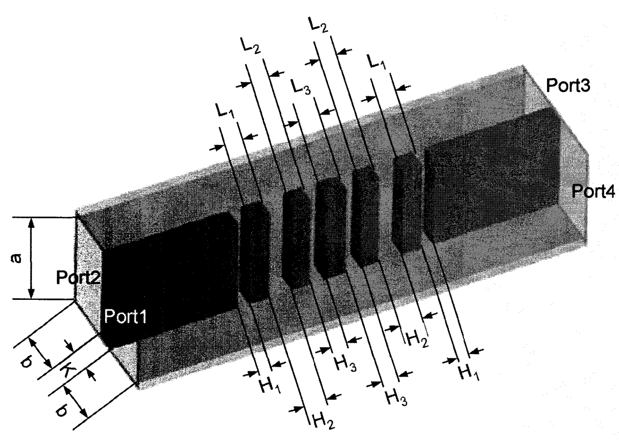

Fig. 2. Design of waveguide hybrid with a 6 branches coupler. The main waveguide height $b = a/2$ is fixed to be $b = 100$ μm.

guide height, H_n, is chosen to be 20 μm. In our design, we have kept the main waveguides at the full height ($b = a/2$) with fixed $b = 100$ μm. Therefore, for each half of split-block, the waveguide channel depth should be 100 μm. Indeed, to simplify the design and fabrication of the hybrid for THz frequencies, we might like to make all the branch lines with the same length and spacing in order to facilitate machining using, e.g., end-mill. However, to achieve maximum possible bandwidth and flat characteristics of the hybrid structure we need to follow classic ripple Chebyschev design, and vary the heights of the branch guides along with spacing between branches from section to section of the coupler.

Initially, the hybrid was simulated as a series of E-plane T-junctions, interconnected by waveguides. We employed a numerical matrix method using matrices based on the circuit theory [10], [11], [12]. For further optimization of the bandwidth, coupling and the return loss, we use High Frequency Structure Simulator (HFSS™) [13]. In Fig.3, the lines without markers show S_{21}, S_{31}, S_{11}, and S_{41} calculated by the numerical matrix analysis mentioned above. The curves of the circles, the squares, the triangles, and the inverted triangles demonstrate the S parameters obtained from HFSS™ simulations. Optimal configuration of the coupler has been achieved with the design variables as follows: K=41 μm, H_1=24 μm, H_2=46 μm, H_3=30 μm, L_1=38 μm, L_2=35 μm, L_3=42 μm. As can be seen from the Fig. 3, the matrix analysis results are well correspond to the data obtained from HFSS™ simulation. As we noted above, the amplitude and phase symmetry is critical to achieve the best possible performance of the balanced mixer. The results of HFSS™ simulations of the amplitude imbalance and the phase differences are shown in Fig.4.

Since the required manufacturing accuracy influences on a choice of a fabricating method, we studied how the manufacturing tolerances would affect the hybrid performance. For that, we varied design parameters around its optimal values and fed the changed geometry in the simulation program to obtain the S-parameters of such a hybrid. According to these simulations, the amplitude imbalance within the band of interest become worse when all structure dimensions are offset from the optimal level even as little as up to 2 microns.

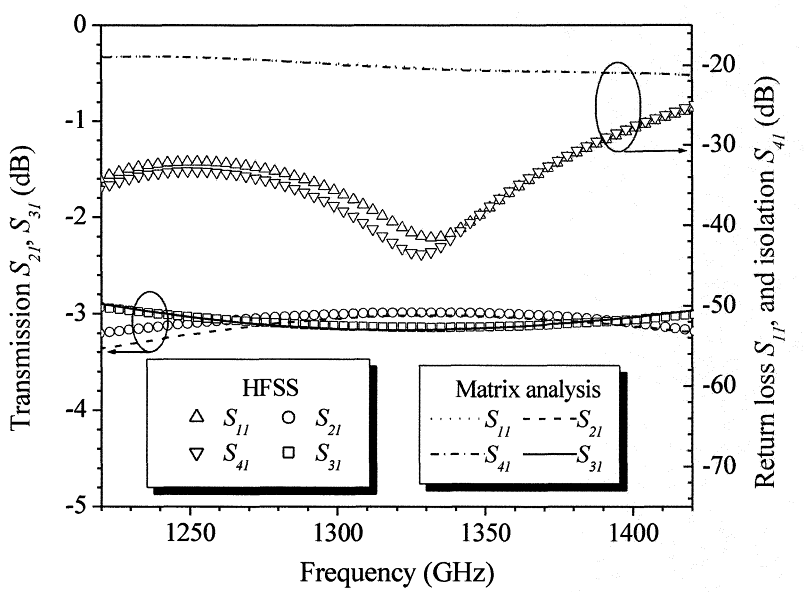

Fig. 3. Comparison of the results for magnitude of the hybrid S-parameters. Results of matrix analysis are shown by lines, results obtaining by HFSS™ simulations are demonstrated by open figures (○ – S_{21}, □ – S_{31}, Δ – S_{11}, ∇ – S_{41}).

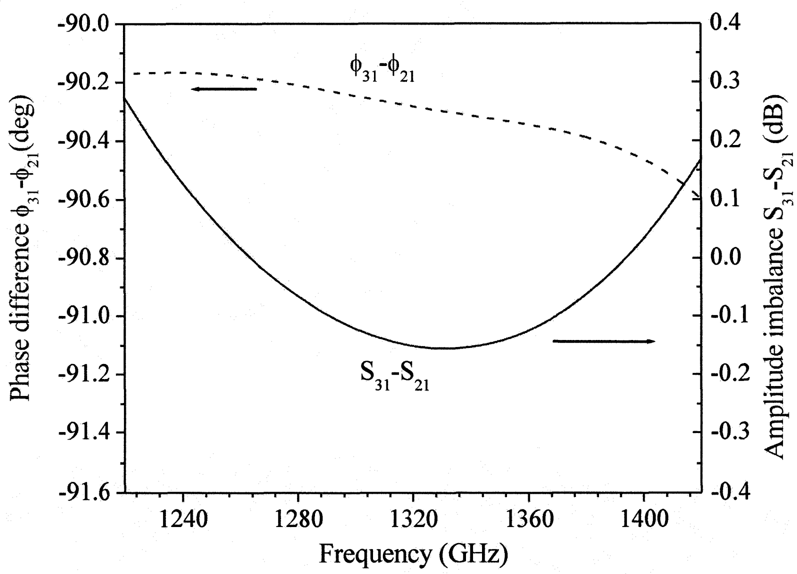

Fig. 4. HFSS™ simulated phase difference *(ϕ_{31}-ϕ_{21})* and amplitude imbalance *(S_{31}-S_{21})* of quadrature hybrid as a function of frequency.

Consequently, the machining of the mixer hybrid structure has to be done with linear dimension error less or about 1 µm in order to meet the required performance. In addition, 1.3 THz frequency operation necessitate very high surface quality in order to minimize the loss due to the waveguide wall roughness because of the skin depth is below 0.1µm at 1.3 THz. Clearly, a fine machining using end mill that was successfully used for longer wavelengths cannot be suitable for reproduction of sub-100 µm dimensions.

III. Micromachining of the Hybrid

Following the considerations above, we employed photolithography of thick photoresist combined with electroplating for fabricating of the waveguide hybrid structure. The scheme of the hybrid fabricating process is shown in Fig.5. In the processing, a 2" silicon wafer was used as a substrate. Release layer of PiRL-III [14] has been applied first at 3000 rpm spin and baked at 200°C for 5 minutes (Fig. 5a). Thick photoresist, SU8-2035 [15] has been applied afterwards. We found the subsequent spinning of the two layers at 2000 rpm with intermediate baking at 65°C for 20 minutes provides the best resist uniformity. After spinning of the second layer we applied soft baking at 65°C for 20 minutes followed by 95°C for 20 minutes. A pattern has been exposed with a contact mode i-line mask aligner with wavelengths shorter than 350 nm filtered out. Post - exposure baking at 65°C for 5 minutes and subsequently 95°C 10 minutes followed by developing in XP-SU8 developer for about 10 minutes have been carried out (Fig. 3b).

In order to get higher conductivity of the waveguide walls and to provide conductive seeding layer for the following electroplating, a 0.5 µm layer of Au, Pd or Al/Pd has been deposited by magnetron sputtering (Fig. 5c). Copper electroplating has been carried out with a *dc* power feed in proprietary solutions [16]. We have plated in two steps, first at a slow plating rate for fine gap filling, 20 µm at 0.5 A/cm^2, followed by thick plating of 500 µm at 2 A/cm^2 (Fig. 5d). After completion of the electroplating, we detached the silicon substrate by dissolving of the release layer at 60°C in an ultrasonic bath of alkaline developer (Fig. 5e).

To strip SU8 resist (Fig. 5f) we have tried Piranha (sulfuric acid + 2% of hydrogen peroxide) wet etching at 60°C and microwave plasma ashing in oxygen at 1 mbar with temperature kept below 120°C. Both methods provided reasonable results, but Piranha etching better removed resist from the narrowest gaps. Test pattern after copper plating and etching of SU8 resist is demonstrated in Fig.6.

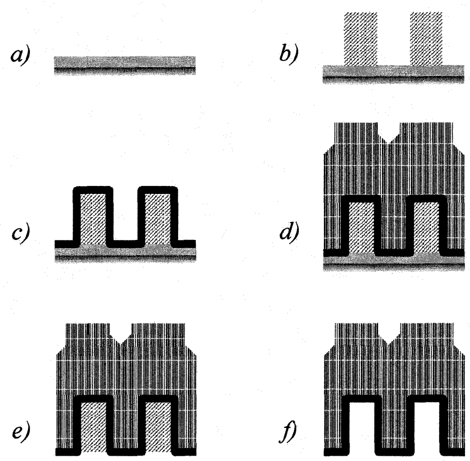

Fig. 5. Fabricating scheme of waveguide structure.

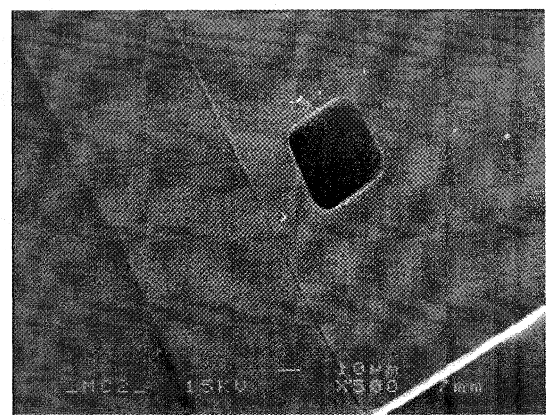

Fig. 6. SEM micrograph of produced test pattern after copper plating and stripping of SU8 resist.

Summarizing, the test pattern with characteristic dimension of 30 μm proved that the suggested technology meets the requirements on the precision for the patterned geometry and the surface quality.

IV. Initial HEB mixers layout

The heart of our balanced receiver is two phonon-cooled HEB mixers based on an thin NbN film and which are placed on separated substrates. In ideal case, the mixers has to be identical for complete rejection of LO noise contribution. Practically, DC and noise characteristic of them are wanted to be as close as possible, which can be producible by modern HEB technology.

Each of the HEB elements are planned to be integrated with RF choke filters and DC-bias and IF circuitry on individual chips of a crystalline quartz substrate of dimensions 1000 μm x67 μm x17 μm fit into suspended microstrip channel across full height waveguide of dimensions 200 μm x 100 μm. The mixer layout design is based on a previous development done for a 345 GHz sideband separation mixer [17]. The chosen "one-side" configuration of probe suspended in a full height waveguide achieves good match over a wide frequency band without reducing of waveguide height, which normally would increase resistive loss in the waveguide wall.

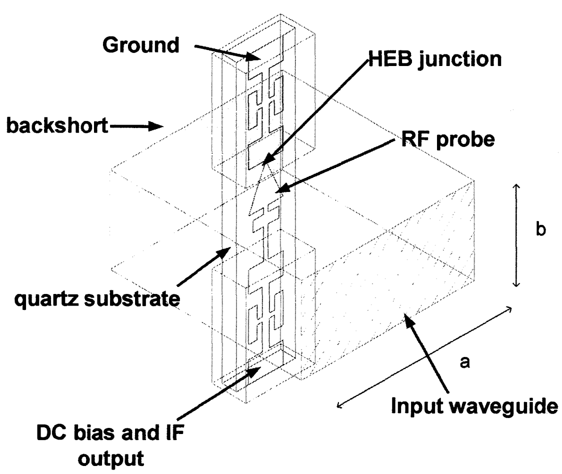

Fig. 7. Layout of the individual HEB mixer.

The central part of the individual HEB mixer layout is shown in Fig.7. It allows coupling of the input waveguide signal to the HEB junction via a radial E-type probe while having an isolated port at the opposite side of the substrate where the IF signal can be extracted and DC bias applied. The RF probe

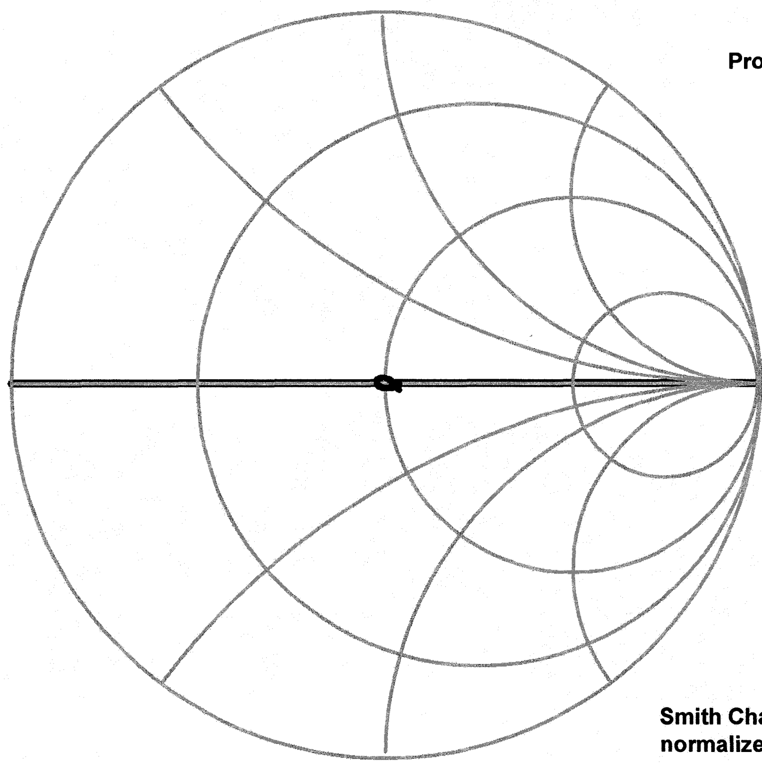

Fig. 8. The RF probe impedance at the HEB input is almost purely real of value about 80 Ohm between 1250 and 1390 GHz.

impedance at the HEB input is almost purely real according to our simulation and has a value of about 80 Ohm between 1250 and 1390 GHz as shown on the Smith chart, Fig.8. The length of the backshort section of the waveguide was chosen to provide good input match over the entire signal frequency band.

V. Summary

We have presented design for 3 dB waveguide hybrid along with initial design of individual HEB mixer layout. These results are based on detailed HFSS™ simulations. Required value of the amplitude and phase imbalance for the hybrid of 0.3 dB and 1 deg respectively have been achieved. We have successfully demonstrated processing technology suitable for the waveguide hybrid fabricating for 1.32 THz balanced heterodyne receiver.

VI. Acknowledgements

Authors would like to acknowledge Galvanord and Dr.B. Okholm for providing excellent possibilities for electroplating. Authors are thankful to Dr. A. Bogdanov for his idea of using SU8 thick photoresist for micromachining of the hybrid. This work is part of APEX Project and is supported by Swedish Research Council and Wallenberg Foundation by their respective grants.

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