Highly Packaged HEB Receivers Using Three-Dimensional Integration

F. Rodriguez-Morales, S. Yngvesson, D. Gu, N. Wadefalk, K. Fu, C. Chan, J. Nicholson, and E. Gerecht

***Abstract*— We report a remarkable progress in the development of highly packaged heterodyne receivers using NbN HEB mixers and MMIC IF amplifiers. We are presenting a record IF noise bandwidth of 8 GHz (measured for a ∼700 GHz LO) using a lumped element matching network for the input of the IF preamplifier. Further, we describe the first three-dimensional (3–D) integration of a sub-millimeter mixer and its pre-amplifier using a simple vertical feed-through structure. Thereby, we achieve a volume shrinkage of at least 20 times, accompanied by a mass reduction of 15:1. These receivers bring promise for the implementation of large-format arrays for heterodyne terahertz sensing applications.**

I. Introduction

HEB type terahertz heterodyne receivers employing NbN devices have been discussed since soon after the first ISSTT symposium. Several such receivers have been operated as ground-based astronomical observation systems and the HIFI instrument that is planned for launch in 2008 includes several HEB mixers [1]. So far no such system has used HEB heterodyne detectors in focal plane arrays, however, whereas arrays of direct detectors are commonly employed. Present HEB mixer receivers are not compact enough to be suitable for packaging in closely spaced arrays, and must be developed further, specifically with arrays in mind. Our group demonstrated the first prototype heterodyne focal plane assembly above 1 THz, a linear array of three elements [2]. Other (non-HEB) work on integrated mixer receivers has been documented in [3]–[5]. The present paper describes development of the HEB integrated receivers into even smaller units, with the final goal being the realization of a compact, multi-element two-dimensional (2–D) array. The immediate objective in the present study has been to develop methods for quantitative design of a receiver consisting of a quasi-optically coupled HEB device directly integrated in the same small block with an MMIC IF amplifier. For this purpose we first performed accurate broadband measurements and modeling of the impedance of the HEB device as a function of IF, and then used the model so obtained, together with CAD models for the MMIC amplifier and other circuit components for the design of several integrated receivers. By improving the broadband matching of the HEB to the MMIC we in one case demonstrated an 8 GHz receiver noise bandwidth. Further, our design methodologies have enabled us to significantly reduce the footprint of the integrated receivers using 2–D and 3–D packaging techniques [6].

This work was supported by NASA through the Langley Research Center under contract NAS1-01058 and CONACyT, Mexico. F. Rodriguez-Morales was with the University of Massachusetts, Amherst, MA 01003 USA. He is now with the Center for Remote Sensing of Ice Sheets (CReSIS), University of Kansas, Lawrence, KS, 66045 USA (e-mail:frodriguez@cresis.ku.edu); S. Yngvesson, J. Nicholson, and K. Fu are with the Dept. of Electrical and Computer Engineering, University of Massachusetts, Amherst, MA 01003 USA; D. Gu was with the Dept. of Electrical and Computer Engineering, University of Massachusetts, Amherst, MA 01003 USA, and is now with the National Institute of Standards and Technology, Boulder, CO 80305 USA; N. Wadefalk was with the RF and Microwave Group, California Institute of Technology, Pasadena, CA 91125 USA. He is now with the Microwave Electronics Laboratory Group, Chalmers University of Technology, SE-412 96 Göteborg, Sweden; C. Chan was with Holyoke Community College, Holyoke, MA 01040 USA. He is now with the Department of Electrical and Computer Engineering, University of Massachusetts, Amherst, MA 01003 USA; E. Gerecht is with the Dept. of Electrical and Computer Engineering, University of Massachusetts, Amherst, MA 01003 USA, and with the National Institute of Standards and Technology, Boulder, CO 80305 USA.

II. Small Signal IF Impedance Characterization

We performed an extensive set of impedance measurements on several mixer devices fabricated from thin NbN film (3.5–4 nm thick[1]) sputtered on a 350 μm thick silicon substrate. The measurements were completed using an automatic network analyzer (ANA). The active NbN area was 0.4–0.5 μm long by 2 μm wide. We used various LO drive frequencies ranging from 694 GHz up to nearly 2 THz, which cover regions of the electromagnetic spectrum below and above the superconducting bandgap frequency of NbN for typical film parameters. The local oscillator source is the same CO_2-pumped far infrared laser system used in previous studies [8], [9]. The HEBs were quasi-optically coupled using monolithic log-periodic antennas in combination with a 4 mm diameter elliptical lens made of silicon. This antenna/lens configuration was designed to operate from 250 GHz to 3 THz. The IF frequency range covered by the ANA was 300 kHz to 8.5 GHz. This frequency range is sufficient to characterize the typical IF bandwidth for all phonon-cooled NbN HEB mixers developed to date. The measurements required an initial one-port short-open-load (SOL) calibration inside the cryostat. The calibration was done by putting each of the standards into the dewar in three consecutive thermal cycles and measuring the corresponding S_{11} using the network analyzer. The power level from the network analyzer was -50 dBm. We designed a customized test vehicle to mount the devices under test (DUTs). This fixture provides the required biasing signals through a broadband resistor network constructed from quartz wire-bondable components. Fig. 1 shows an illustration of the experimental setup used for these measurements, including a picture of the broadband test fixture.

[1]The nominal thickness of the NbN film was given by the manufacturer (Moscow State Pedagogical University, MSPU) as 3.5 to 4 nm. Recent TEM measurements have yielded a thickness of 5–6 nm for similar films [7].

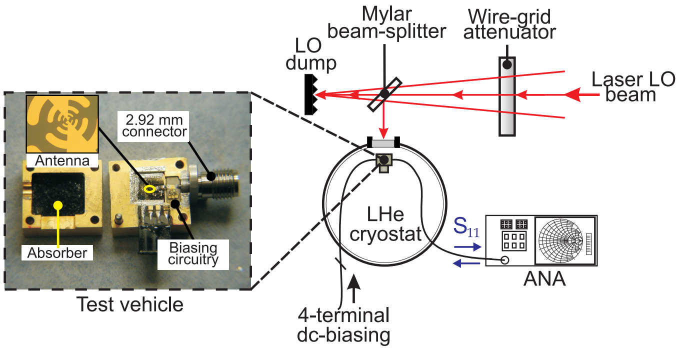

Fig. 1. Experimental setup for small signal IF impedance measurements.

A. Raw Impedance Data

Fig. 2 shows an example of the measured raw reflection coefficient for one specimen as obtained with the network analyzer. This is the actual source impedance seen by the low-noise amplifier at a particular operating point, including parasitic reactances in the circuit derived from the antenna structure, wire-bonds, transmission line transitions, etc. The HEB impedance (controlled by regulating the amount of incoming LO and dc power) determines the main contribution to the total input reflection coefficient of the IF LNA. However, parasitic reactances in the circuit should not be neglected when designing the appropriate input matching network for minimum noise. As will be discussed in the next section, data obtained in this fashion is very useful when designing integrated HEB-based down-converters.

B. De-Embedded Impedance Data

The HEB IF small signal impedance was carefully de-embedded from the the measured reflection coefficient (S_{11}). The preceding SOL cryogenic calibration was used in combination with the S-parameters of two measured known loads (superconducting and normal state of the bolometer, respectively) to obtain a circuit model for the fixture parasitics. We then subtracted the effect of these parasitics from the measured data using standard computer aided design (CAD) tools. Using the de-embedded data we studied the impact of the LO frequency and biasing conditions in the IF impedance for the first time, providing substantially extended information beyond that obtained in previous measurements such as those presented in [7], [9]–[12]. The de-embedded impedance results were compared against two different models, namely the *Standard* model [10] and the Nebosis-Semenov-Gousev-Renk (NSGR) model [13]. These two formulations are convenient since analytical calculations can be performed of important microwave and terahertz parameters. They do not predict parameters such as conversion gain as accurately as the *hot-spot* model [14]–[16], however.

Fig. 3 shows and example of the fitting of the Standard and NSGR formulations with respect to the de-embedded experimental data for one of the DUTs (designated #D). The Standard model fits the experimental data quite well specially for 694 GHz, where the LO, dc, and microwave power are absorbed in same central hot-spot region of the device. The

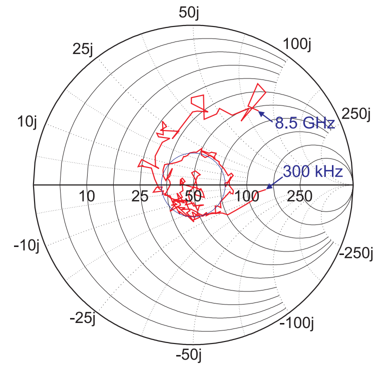

Fig. 2. Typical measured raw impedance data. The blue circle indicates constant standing wave ratio (SWR).

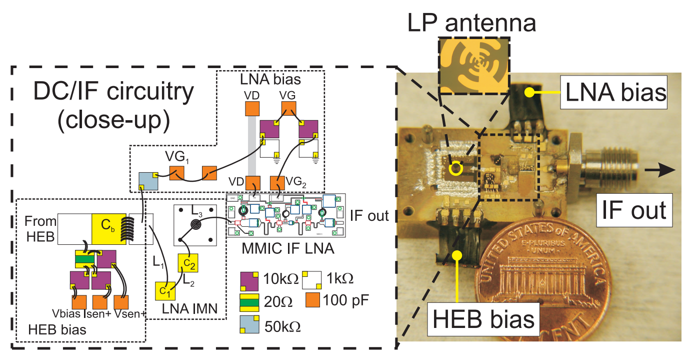

Fig. 5. Integrated receiver module with lumped-element mixer/LNA coupling.

NSGR model does also fit our measured data but requires the use of three time-constant parameters whereas the Standard model only needs one. The NSGR model has advantages in terms of physical interpretation of the time-constants. The interested reader is referred to ref. [17], where further information about our modeling efforts is provided along with additional measured data. We have shown empirically that the IF frequency dependence of the IF impedance, conversion gain, output noise and the receiver noise temperature for at least two devices are well modeled by the Standard model formulation (e.g. Fig. 4). We give experimental evidence of this statement being true for the IF frequency range required for practical integrated receiver design.

III. Integrated Receiver Design

A. Lumped Element Coupling

In order to realize the best trade-off between low-noise figure, wide bandwidth, and size; the coupling between the HEB mixer output and the HEMT IF LNA input needs to be studied. This analysis evidently requires the knowledge of the impedance presented by the HEB and surrounding circuitry, which was the center of our discussion in the previous section. Once this source impedance is known, an appropriate input matching network (IMN) can be designed to transform the HEB IF output impedance into the intended

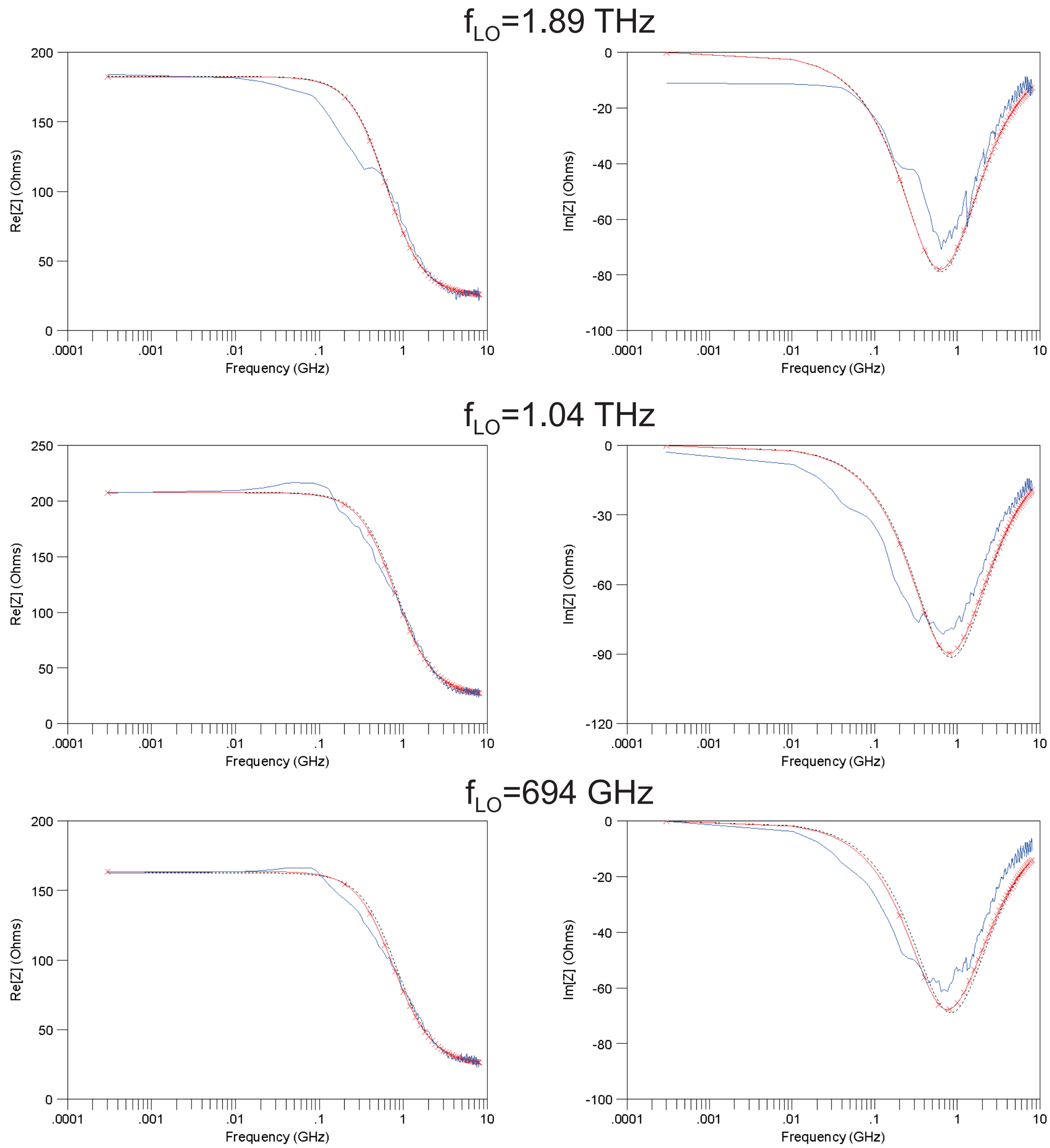

Fig. 3. Comparison of modeled versus de-embedded impedance of device #D measured for a fixed operating point (1 mV, 40 μA) for different LO frequencies: – Measured, -x- Modeled (NSGR), - - Modeled (Standard model).

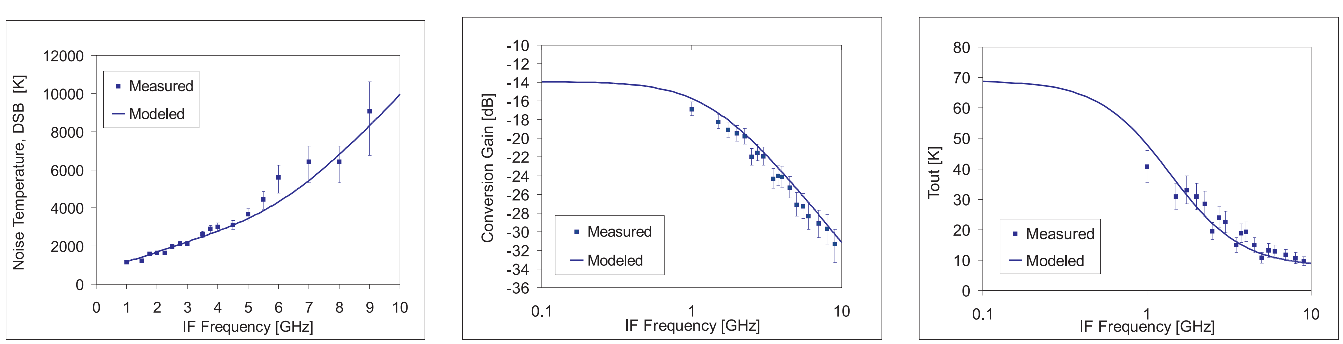

Fig. 4. Modeled versus experimental parameters as a function of IF frequency for a different sample (#C). This data was obtained for f_{LO}= 1.04 THz using an optimized lumped-element coupling circuit between the hot electron mixer and the IF amplifier. The empirical figures for the mixer conversion gain and output noise are estimated from the U-factor and the receiver noise temperature. The modeled curve is obtained using the methodology described in [17].

TABLE I

PERFORMANCE OF TWO MIXER SAMPLES MEASURED USING THE LUMPED-ELEMENT INTEGRATED RECEIVER MODULE

Sample	LO [THz]	$T_{\mathrm{R,DSB}}$ [K]	B_{eff} [GHz]	B_{N} [GHz]
#C	0.694	825	6	3.5
	1.04	1160	3.25	2.4
	1.89	3300	4.5	3.2
	2.50	4450	5	3.3
#D	0.694	1100	8	5.5
	1.04	1600	6	3.8
	1.89	2700	3.2	2.0

optimum source impedance Z_{opt} required by the LNA.

Since the input impedance of a HEMT-based amplifier is mainly dominated by the gate-to-source capacitive reactance of the first transistor stage, the IMN should behave as a series inductor. One such IMN has already been successfully implemented by our group in the form of a multi-section microstrip transformer [18]. The use of a lumped-element matching network with wire-bonds as inductive elements to further reduce the down-converter size was proposed in previous editions of the ISSTT proceedings [8], [9]. As shown in Fig. 5, we have recently been able to successfully implement such a coupling circuit. The design methodology employed as well as the measured performance of this receiver implementation are discussed in great detail in [17]. In the proposed design methodology, we used the Standard model formulation for the mixer with parameters extracted from the impedance measurements, in combination with CAD models for the IF and dc circuitry to find theoretical estimates of the down-converter performance (e.g. Fig. 4). The estimations are self-consistent in the sense that they account for the noise produced by an MMIC LNA when an HEB is connected at its input, including fixture parasitics. Fig. 6 shows the variation of the double sideband receiver noise temperature, $T_{\mathrm{R,DSB}}$, as a function of IF frequency for two different operating points measured on sample #D. The biasing points were the optimum (1.5 mV, 35 μA) and (1.0 mV, 35 μA) using an LO frequency of 694 GHz. This plot shows a remarkable noise bandwidth of 8 GHz for the lowest-noise quiescent point. The narrower bandwidth observed at a slightly lower operating voltage agrees with the expected lower electron temperature, θ, caused by a lower dc-power dissipated at bias point 2. We have also measured $T_{\mathrm{R,DSB}}$ for other LO frequencies (1.04 THz, 1.89 THz, and 2.5 THz) and other devices installed on the same down-converter block. As shown in Table I[2], the demonstrated noise and bandwidth[3] figures obtained are very competitive, in agreement with theoretical predictions.

[2]A different mixer sample (designated #C) was used for this comparative assessment.

[3]The receiver bandwidth performance was quantified in terms of the IF noise bandwidth, B_{N}, and the effective IF bandwidth, B_{eff}. B_{N} is the frequency at which $T_{\mathrm{R,DSB}}$ increases by a factor of two with respect to its lowest frequency value. B_{eff}, is the bandwidth of an ideal receiver with perfectly sharp passband that yields the same output noise as the system being characterized [18].

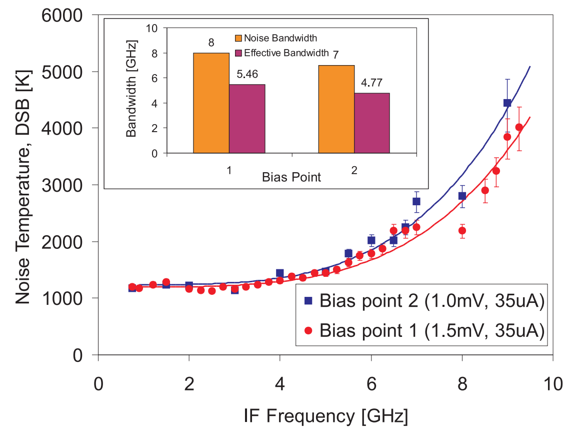

Fig. 6. Double-sideband receiver noise temperature measured at f_{LO}= 0.694 THz (sample #D) for two different bias points: i) 1.5 mV, 35 μA, and ii) 1.0 mV, 35 μA.

B. Three-Dimensional Integration

We have mentioned that efficient receiver packaging techniques are essential to the development of close-fitting arrays. By far, the most efficient packaging scheme developed to date is three-dimensional integration. The benefits of 3-D packing have been thoroughly described in the literature (e.g. [19], [20]). We have recently explored the use of such techniques to realize an ultra-compact module with an HEB mixer and its corresponding IF amplifier stacked across the z-direction. A straightforward vertical microwave transition has been developed to convey dc and IF signals from the HEB mixer chip to the IF/DC circuitry, both of which are located on different planes. The transition provides impedance matched coupling between the coplanar waveguide (CPW) structure on the HEB chip and the microstrip-based MMIC IF LNA. The three-terminal vertical transition was designed based on ideas proposed within the electronic packaging community (e.g. [20]–[22]). We used full wave electromagnetic CAD tools (CST Microwave Studio) to simulate and optimize the performance of the IF/DC interconnect. The concept of the packaged down-converter is illustrated on the left inset of Fig. 7. Aside from the vertical feedthrough itself, the package consists of three multi-level blocks:

- The device block, where the quasi-optically coupled HEB mixer chip is mounted.
- The IF/DC block, where all the IF circuitry (MMIC IF LNA included) as well as dc-biasing networks and connectors are installed.
- The top lid, which is used to provide environmental, mechanical, and electromagnetic shielding for the components inside the package.

A photograph of the assembled module without cover is shown in the right inset of Fig. 7. The stacked module technique provides a volume reduction of 20 times with a corresponding mass reduction of 15x. The wide bandwidth performance is preserved at the expense of slightly lower sensitivity in this prototype version. A comparison of performance between the 2–D and 3–D down-converter implementations is

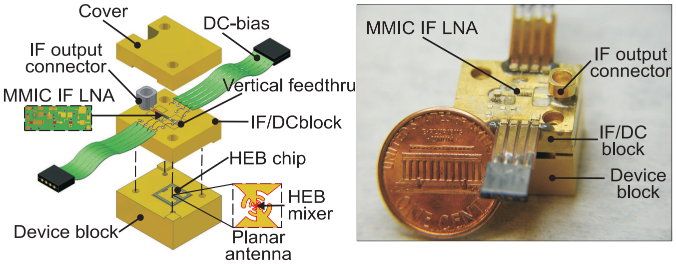

Fig. 7. Integrated receiver module with vertical IF interconnets: (left) concept and (right) photograph.

shown in Table II. For more details on the design considerations for this packaging approach the reader is referred to [6].

IV. Conclusion

Following a series of previous papers by the authors, we have presented our most recent progress in the development of highly-packaged down-converters. We briefly describe how we have been able to accurately measure and model the small signal IF impedance of phonon-cooled HEB mixers over a wide IF frequency range and for more than one LO frequency. We have used parameters extracted from these measurements in combination with circuit models for the MMIC IF LNA to achieve the close and direct integration of the mixer/LNA combination. For this purpose, a compact, lumped-element matching circuit is proposed and implemented. We have accomplished a high degree of convergence between measurements and modeled performance as per our design methodology. Several integrated receivers for terahertz frequencies have been designed using this modeling approach and have been successfully tested, including what is believed to be the first 3-D terahertz receiver. The stacked module technique provides an outstanding volume and mass reduction while maintaining good electrical performance. The ultimate goal of this investigation was to make a large array a feasible architecture. We believe that a medium size array is now within reach.

Acknowledgment

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TABLE II
Performance comparison between the 2-D and 3-D integration receiver implementations using mixer sample #C

LO [THz]	Configuration	$T_{\mathrm{R,DSB}}$ [K]	B_{eff} [GHz]	B_{N} [GHz]
0.694	2-D	825	5.6	3.2
	3-D	975	5.5	3.15
1.89	2-D	3300	4.5	3.2
	3-D	4200	4.6	3.0

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