Performance Improvement of Integrated HEB-MMIC Receivers for Multi-Pixel Terahertz Focal Plane Arrays

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***Abstract*— Phonon-cooled NbN HEB mixers have been successfully integrated with InP MMIC IF amplifiers to produce low-noise HEB-MMIC receivers. Noise temperatures of less than 1,600 K and receiver noise temperature bandwidths of at least 4 GHz (measured at 1.6 THz) have earlier been demonstrated for this type of integrated receivers. Our configuration eliminates the need for isolators which require very large areas on the IF circuit. In this paper, we are presenting recent results from ongoing measurements of these integrated receivers. We propose using different matching schemes for the MMIC LNA that will help reduce the size of the IF circuitry. Small circuit size is a desirable feature for focal plane arrays. Next, we propose a linear terahertz FPA with an increased number of HEB pixels based on the integrated miniaturized design. Lastly, we describe a frequency multiplexing scheme formulated to significantly reduce the number of IF lines required in a large imaging array. The proposed multiplexing scheme utilizes the very broad bandwidth (12 GHz) presently demonstrated for MMIC low-noise IF amplifiers.**

***Index Terms*— HEB mixers, integrated terahertz receivers, MMIC low-noise amplifiers.**

I. INTRODUCTION

IN contrast to the large arrays available for detection in the visible and infrared, the majority of the instrumentation available for terahertz heterodyne detection is still based on single-pixel receivers. Hot electron bolometer (HEB) receivers, in particular, are an excellent choice to achieve near quantum-limited noise performance. The main technological challenges for building array receivers at these frequencies encompass receiver miniaturization, LO power reduction, and minimization of the DC-power consumption in the cryogenic IF circuitry. Complicating the matter, the issue of IF impedance matching needs to be addressed before a practical HEB focal plane array can be constructed. Let us think about the most common and general configuration for an HEB terahertz receiver. This configuration is illustrated in Fig. 1. Typically, the HEB mixer and the IF low-noise amplifier (LNA) are placed in independent blocks connected through a short coaxial cable. The experienced designer knows that if an isolator is not added to the receiver chain, the system will seriously suffer from standing waves between the mixer and the IF LNA. Unfortunately, including an isolator is not an optimal solution for multiple receiver systems. Isolators occupy a significant physical space apart from increasing the thermal load. Moreover, the widest bandwidth that can be achieved with currently available isolators is at most one octave.

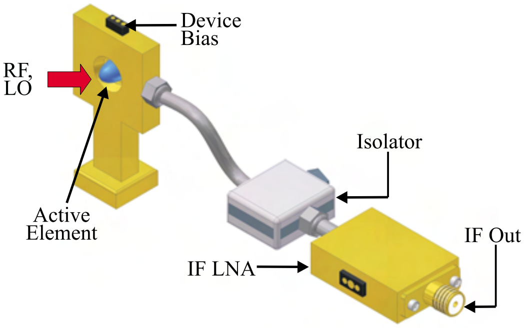

Fig. 1. Typical HEB receiver configuration.

We have developed miniaturized receivers with the HEB mixers integrated in close proximity with InP MMIC amplifiers (Fig. 2). This configuration is compact, broadband and with reasonably low DC-power utilization. The HEB and the MMIC are contained in the same housing, without requiring an isolator. These receivers represent the core of the focal plane array described in [1]. Our recently developed terrestrial terahertz imaging system [2], [3] also makes use of this technology.

In this paper, we are presenting results from ongoing measurements of the current performance of these integrated receivers, as well as their prevailing limitations. Next, we propose a 3x2 terahertz FPA based on a new design, in which the receivers have been further miniaturized. The proposed prototype can be easily extended to a linear array with 10 or more elements, suitable for near-range imaging applications. Lastly, we describe a frequency multiplexing scheme formulated to significantly reduce the number of IF lines required in a large imaging array. The proposed multiplexing scheme utilizes the extremely wide bandwidth attainable with state-of-the-art MMIC LNAs.

II. RECEIVER CHARACTERIZATION

A. Overview of the HEB/MMIC Integrated Receivers

The integrated receiver configuration has been put together in a mixer block unit, as shown in Fig. 3. The mixer elements

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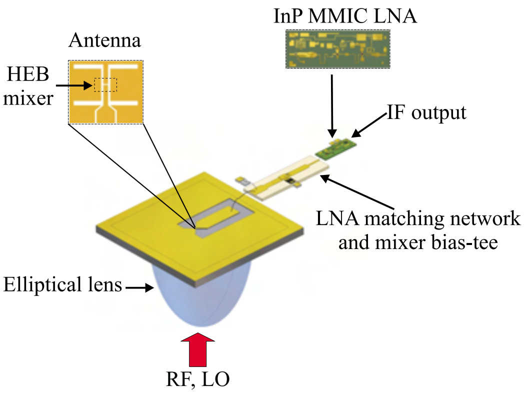

Fig. 2. Integrated HEB receiver configuration.

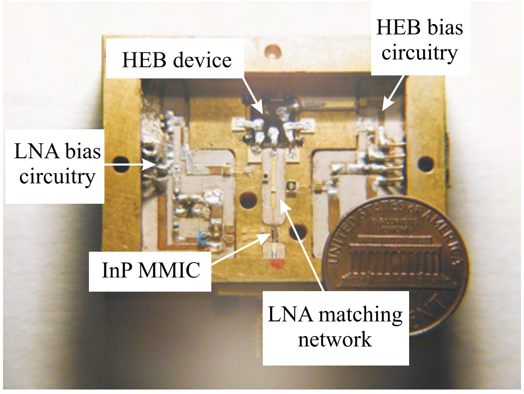

Fig. 3. Inside view of the integrated quasi-optical receiver.

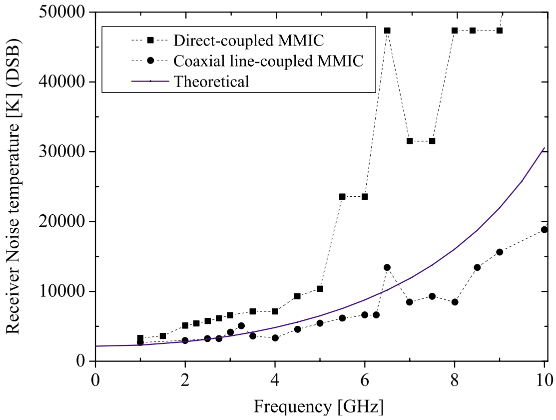

Fig. 4. Comparison between performance of the different receiver configurations. The response of the integrated configuration is before optimization.

are phonon-cooled NbN HEBs integrated with planar twin-slot antennas. The PHEBs have been fabricated on silicon substrates. The IF amplifiers are 3-stage InP MMIC chips. These chips (denoted WBA-13) have been developed by Weinreb and Wadefalk [4] at JPL/Caltech. The MMICs require an input matching network for optimum noise performance. In our circuit, the matching network is a multi-stage microstip transformer. All the bias and IF circuitry is included in the same housing, resulting in a very compact design. Relevant details on the construction of these receivers can be found in [5].

B. Measurement Setup

The main objective of the measurements described here is to show how the performance of these integrated receivers has been improved in comparison with previously presented results. The two parameters of interest for this analysis are the double-sideband noise temperature , T_{sys}, and the receiver bandwidth.

We measured T_{sys} as a function of IF frequency, using the standard Y-factor method. We have a broadband IF back-end that allows us to perform noise measurements over a very wide frequency range. The LO source was a CO_2-pumped far infrared (FIR) laser system. We used a 6 μm thick mylar beam splitter as the diplexer between the LO and the signal beam. The measurements were performed using a 1.63 THz laser line, which runs on difluoromethane gas.

III. MEASUREMENT RESULTS

A. Noise Performance

Fig. 4 shows the noise performance of a test HEB device measured at 1.6 THz using two different configurations. The solid line represents the prediction for the simple receiver configuration (Fig. 1) obtained using the standard model. In the first measurement the standard receiver configuration was used with no isolator in the IF chain. This curve presents two sharp peaks at 3.25 GHz and 6.5 GHz, respectively. Calculations showed that the location of the peaks was associated with the length (approximately 15 cms) of the stainless steel coax cable that connected the MMIC LNA module with the HEB mixer block. The presence of these peaks is not unexpected and is consistent with similar measurements performed by other groups [6]. The second measurement was completed using the integrated receiver configuration (Fig. 2) with the MMIC and the HEB located in the same plane. The difference between the two measurements at the low IF frequencies is mostly due to a slight degradation suffered in the critical current of the NbN film. This parameter changed about 10% between measurements. The differences in performance at the upper end of the band were first attributed exclusively to mismatch between the MMIC LNA and the HEB. However, impedance mismatch is only a partial justification. It was later found that the bias resistor for the first stage's gate of the MMIC (in the integrated configuration), exhibited poor performance beyond 5 GHz. This had a strong impact on the MMIC noise temperature. The abrupt increase in the noise for frequencies larger than the noise bandwidth was aggravated by the low self-resonant frequency (SRF) of other components in the IF circuitry, in particular the spiral inductor used for the HEB mixer bias-tee.

Fig. 5 shows the measured noise response of five different detectors, all measured at 1.6 THz. The noise temperatures are clearly different for each detector. Since the HEB specimens were all fabricated from different film, these differences are not unexpected. What is more important in this set of measurements is the difference in the smoothness of noise

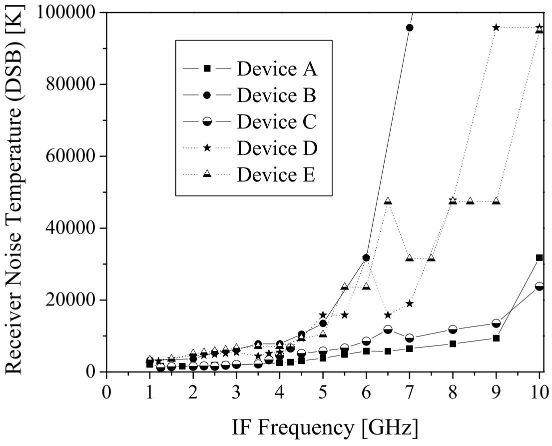

Fig. 5. Measured performance of different devices using the integrated configuration.

performance. The dotted lines (devices D and E) indicate the use of IF circuitry with poor performance. Devices A, B, and C show the improved performance of the integrated configuration after optimization. From these results, we may conclude that the microwave properties of the components used in the IF circuitry plays a very important role in the performance of the integrated receiver.

B. Receiver Bandwidth

An important figure of merit used to describe quantitatively the bandwidth performance of any HEB receiver, is the the noise bandwidth, N_B. This parameter is defined as the frequency at which the noise temperature doubles with respect to the zero IF value. N_B can be obtained by inspection from the experimental noise data. A different figure of merit is introduced in this paper for the same purpose, the effective bandwidth, B_{eff}. This parameter can be obtained by integrating the expression for the inverse of ΔT_{rms}^2 in the well-known radiometer equation,

$$\frac{1}{\Delta T_{rms}^2} = \int_{f_o}^{\infty} \frac{1}{T_{sys}^2(f)}\, df \cdot \tau = \frac{B_{eff} \cdot \tau}{T_{sys}^2(f = f_o)} \tag{1}$$

$$B_{eff} = T_{sys}^2(f = f_o) \cdot \int_{f_o}^{\infty} \frac{1}{T_{sys}^2(f)}\, df \tag{2}$$

where τ is the integration time, f_o is the lowest frequency of operation of the MMIC IF amplifier (close to 0.5 GHz for the WBA-13), and $T_{sys}(f)$ is obtained by fitting the measured noise temperature response to a polynomial in f.

Table I presents a summary of important results obtained for the five devices measured in the integrated mixer block. The widest effective bandwidth obtained corresponds to 5 GHz for device A, which also had a very competitive noise temperature. The best trade-off between sufficiently low noise and wide bandwidth will be achieved when the interaction between the LNA and the HEB is better understood and modeled.

TABLE I

NOISE AND BANDWIDTH PERFORMANCE OF DIFFERENT DEVICES TESTED USING THE INTEGRATED HEB/MMIC CONFIGURATION.

Device #	NT (at 1 GHz)	N_B GHz	B_{eff} GHz
A	1600 K	4.5	5.0
B	3200 K	3.5	3.0
C	1200 K	3.4	2.9
D	3000 K	4.2	3.8
E	3500 K	3.0	2.2

IV. FURTHER INTEGRATED RECEIVER IMPROVEMENTS

A. Matching Network Design

It has been mentioned that the MMIC LNA used in our receivers requires an external input matching network (IMN) for best noise performance. In particular, this IMN should be designed to provide a conjugate match over the bandwidth of interest. Since the input impedance of the LNA is mainly dominated by the gate-to-source capacitive reactance of the first HEMT transistor, the IMN should behave as a series inductor. It is thus reasonable to think of substituting the microstrip transformer by a lumped-element matching network in order to further reduce the size of the prototype. The difficulty that arises from this approach is finding (or making) chip inductors that can cover the entire frequency range of interest. Large inductors typically have low SRF, while small inductors do not present enough reactance at low frequencies. A set of circuit simulations has been performed using models for the best inductors available in the market [7], [8]. Thus far, this analysis appears to indicate that the incorporation of such inductors in the LNA circuitry has a negative impact on the performance of the MMIC, causing the noise temperature to rise rapidly with frequency. Concurrently, Wadefalk has performed microwave measurements on these inductors [9], finding that the models provided by the manufacturers correspond to a best case approximation. The measured performance appears to be below the manufacturer's specifications. The satisfactory performance of the inductors used for matching purposes is more critical than that of the RF-choke in the mixer bias-tee. Substituting the IMN with a circuit based on these inductors would therefore produce a serious deterioration in the overall receiver performance. We are currently investigating other design possibilities to overcome the lack of commercially available broadband inductors.

In the first place, if one can make the IF impedance of the HEB high enough (100-200 Ω) at the operating point, our simulations indicate that the requirements for the external IMN become relaxed. Accurate measurements need to be performed in order to determine exactly how the HEB impedance of an actual receiver mixer can be made high enough. Another possibility is to use wire-bonds as inductive elements, as is often done in microwave and mm-wave circuit design. Fig. 6 shows the simulated performance of the WBA-13 LNA for different input matching conditions. The solid curve represents the original response, using the microstrip matching transformer. The dotted line was obtained by using a 800 μm long wire-bond

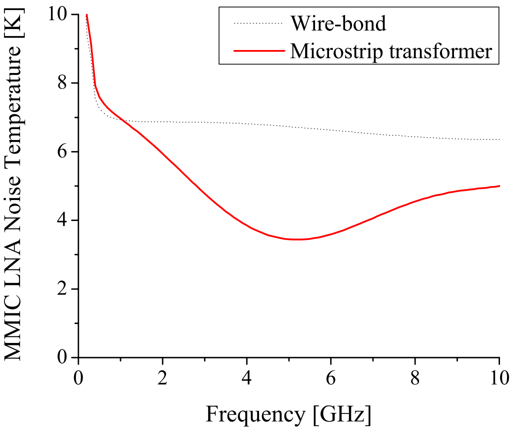

Fig. 6. Simulated noise performance of the LNA using bond wires as inductive elements for input conjugate match. The solid line indicates the original response using the microstrip transformer.

(25 μm diameter) as a series inductor for the input, in place of the microstrip circuit. Although the noise temperature obtained in the second case is higher, it is still low enough to not affect the performance of the integrated receiver in a significant way. An extra increase in the LNA noise temperature is expected after the effect of the integrated mixed bias-tee is accounted for in the simulation. This increase, however, is roughly 1K throughout the band. This holds provided that the resistors used in the 4-wire HEB biasing scheme present a high SRF. High quality microwave resistors are readily available from a variety of vendors, so this does not represent a major pitfall. Further measurements will demonstrate the adequateness of this approach. The preliminary simulation results obtained for this part are certainly promising.

B. New Prototype FPA

After finding the most appropriate substitute for the microstrip transformer, a new focal plane array prototype will be constructed. The concept of this 3x2 element FPA is illustrated in Fig. 7. This array will be useful to test the functionality of a number of new design features and can be easily extended to a larger number of elements. The DC-bias circuitry is on the opposite side from the MMICs. The connections between the two sides are made with glass beads. One side of the bead is soldered to the printed circuit board underneath the chips, while the other side is wire-bonded to the gate and drain pads of the MMICs. The HEB device is biased on a similar fashion. This technique has been sucessful in producing multichip modules with up to 20 MMICs [9]. We will continue to use 4-mm diameter elliptical lenses. The spacing between radiating elements will be set to the minimum possible, which has been found to be close to the diameter of the lens [1]. This FPA will be optimized for near-range scanning applications, relevant to security and and medical imaging.

V. FREQUENCY MULTIPLEXING

Another important concern in the design of FPAs comes to play as we desire to increase the number of elements in the array. A primary difficulty resides in how to multiplex the IF outputs for individual pixels. Having one coaxial line per active element becomes impractical in a large multiple receiver system. We are developing a frequency division multiplexing scheme in which each detector's output, IF$_n$, is mixed with a microwave signal F$_{LOn}$ (Fig. 8). The microwave LO signals can be produced by means of inexpensive voltage controlled oscillators (VCOs) operating at room temperature. These signals are combined and injected into the cryostat through a single coax line. The F$_{LO}$ signals are then separated inside the dewar by using a filter bank and connected to their corresponding mixer. The mixing of the FPA IF outputs is performed in order to assign a narrow bandwidth channel to each detector. Each channel is centered at a different frequency in order to make a distinction between different elements. All the mixer outputs are fed to a power combining network, and further amplified by a broadband MMIC amplifier. A single coaxial line is required for the signal containing all the FPA outputs. Individual pixel IF outputs can be recovered outside the cryostat by means of filtering.

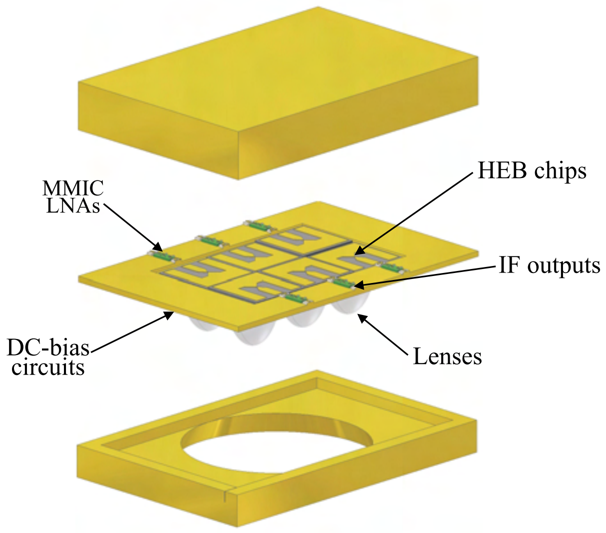

Fig. 7. Prototype 3x2 HEB focal plane array.

This scheme is advantageous over other alternatives, specially since the multiplexer is not required to operate at 4K. The mixers can be based on inexpensive Schottky diodes and fabricated on a special purpose MMIC. This would make the entire multiplexer compact, based in a multi-chip module configuration. Future developments are expected to further increase the bandwidth of the MMIC amplifiers, which will make the multiplexing scheme even more effective.

VI. CONCLUSION

An extensive set of measurements has been performed on the integrated HEB-MMIC receiver configuration we have developed. A significant improvement in the receiver bandwidth has been achieved compared to the results presented in last year's symposium. Effective receiver bandwidths up

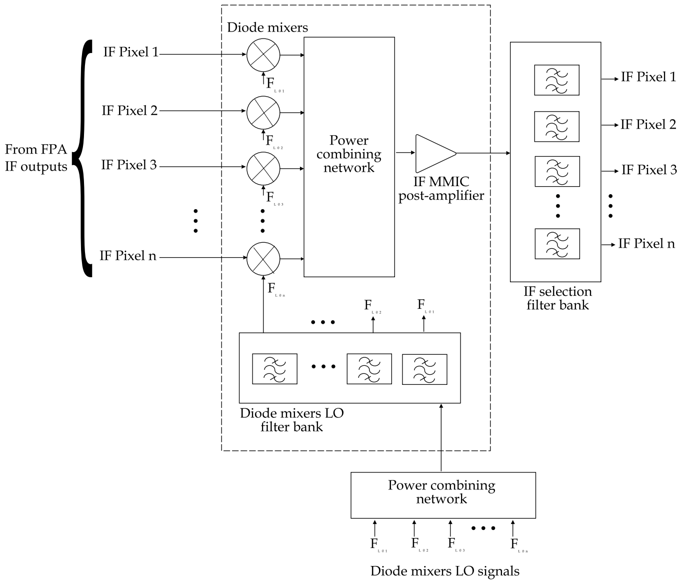

Fig. 8. Block diagram of the proposed frequency multiplexing scheme.

to 5 GHz can now be achieved using this configuration. The integrated quasi-optical detectors provide an important advantage for multi-pixel focal plane arrays. The incorporation of a different input matching scheme for the MMIC LNA is being investigated. This change will result in the further miniaturization of the receivers. A new 3x2 element FPA has been proposed. This system will incorporate the new matching mechanism and a variety of other features. The proposed array will be used for THz imaging and can be easily extended to a larger size array.

A frequency multiplexing scheme has been proposed to reduce the number of IF lines required for an array with a large number of quasi-optical detectors.

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