Low Noise Radiometers for Passive Millimeter Wave Imaging

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***Abstract*—W-band passive millimeter wave imaging cameras for concealed weapons detection are being developed and commercialized for security screening and rotorcraft applications. The direct detection chipset from HRL Laboratories has become the standard for the front end because of the low noise of its Sb-based backward tunnel diode detectors and InP HEMT low noise amplifiers. Here we review recent results demonstrating that an NETD<0.5K can be achieved without the use of Dicke switching or optical chopping using a two-MMIC chipset consisting of a low noise amplifier and matched detector. Recent results for an 8x8 imaging array with no RF amplification will also be presented, indicating an NETD of <3K for a 30Hz video rate.**

I. Introduction And Background

HRL Laboratories has developed both preamplified and non-preamplified direct detection radiometer components and modules for passive millimeter wave imaging based on zero-bias Sb-based backward tunnel diode and InP HEMT low noise amplifier technologies. The LNA and detector MMICs provide a "two-chip" imaging solution for commercial millimeter wave cameras and HRL is currently the primary supplier of components to this small but growing market. Traditional cameras have utilized multiple LNA MMICs to overcome noise from biased Schottky detectors. The resulting high 1/f noise necessitates Dicke switches or optical chopping, increasing the cost of the components and assemblies. Measured results of HRL's imaging chipset demonstrate sensitivity levels high enough for indoor security screening applications without the need for Dicke switches. Sensors typically exhibit a noise equivalent temperature difference (NETD) in the range of 0.3K to 0.5K assuming a 3.125 msec integration time and a 10Hz frame rate.

HRL has also developed non-preamplified imaging sensors on the DARPA MIATA† program. The highly sensitive detectors allow for the elimination of LNAs, significantly reducing sensor costs. Two dimensional (staring) arrays allow for longer integration time, achieving close to 2K NETD with a 30Hz frame rate. These focal plane arrays have potential for outdoor imaging applications, such as navigation through rotorcraft brownout.

II. preAmplified Imaging module results

The performance of the detector and LNA MMICs have been presented in previous papers.[1] In this paper we will describe some results for five imaging modules we assembled

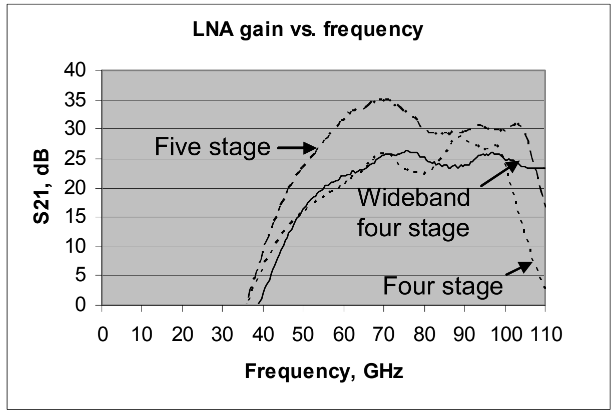

Figure 1—Four and five stage LNA gain vs. frequency.

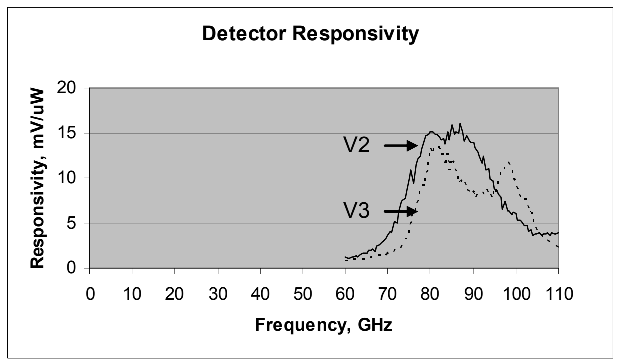

Figure 2—Detector responsivity vs. frequency.

and tested that utilize a variety of component designs and performance parameters. The LNAs were fabricated with HRL's InP HEMT process and both four and five stage amplifiers were tested, with typical gain plots shown in figure 1. The four stage LNA gain is typically 25dB and the five stage 30dB. The gain peak occurs near 70 GHz and can be greater than 35dB for the highest gain MMICs. Various values of LNA gain were selected for module testing in order to evaluate the effect of LNA gain on performance. We note that, on a particular wafer lower gain amplifiers tend to have higher noise figure. The detectors are Sb-heterojunction backward tunnel diodes, also fabricated at HRL. Figure 2 shows typical responsivity plots for two different designs, called V2 and V3. Responsivity is typically above 10mV/uW, and V3 has a wider bandwidth, double-peaked response.

Three of the five modules contain five stage LNAs with various gain levels (low, medium, and high) to assess the sensitivity to LNA gain. Two of the modules utilize two different four stage LNA designs, one of which had a performance roll-off at 100 GHz and the other which extended past 110 GHz ("wideband"). Two different detector designs (V2 and V3) were used that exhibit different response

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TABLE I
MEASURED PERFORMANCE AND EXTRACTED PARAMETERS

LNA	Det	V, mV	dV/dT, uV/K	K (1/f const)	β, V/uW	NF, dB	BW, GHz	NETD, K
4 stg wb	V2	1.4	1.8	3.3	4.5	4.4	28	0.29
5 stg	V3	5.3	7.0	13	14	4.2	35	0.52
5 stg	V2	5.8	6.9	6.1	20	4.6	23	0.41
5 stg	V2	0.6	0.52	10	1.1	5.9	33	0.69
4 stg	V3	3	4.3	5.3	12	3.8	26	0.32

functions. Module performance was measured using a blackbody absorber at room temperature and also submerged in liquid nitrogen. Performance parameters were extracted from low frequency measurements. [2] Table I summarizes the measured results.

The results indicate a spread of NETD values from about 0.3K to 0.7K. The extracted parameters indicate that the best sensitivity (0.29K) is due to the unusually low 1/f noise from a particular LNA. The worst sensitivity (0.69K) was for an LNA purposely chosen for its low gain, which was about 5-7dB lower than typical values found on that wafer, with correspondingly high noise figure. The last module listed in the table contained the four stage LNA with lower frequency roll-off, so it has correspondingly low bandwidth (26 GHz). The third module in the table contained a five stage LNA chosen for its high gain, 38dB at 67 GHz. The reduced bandwidth is likely due to gain peaking around 67 GHz as a result of imperfect LNA input/output isolation. The high sensitivity obtained with the four stage LNAs indicates that the additional gain of the five stage LNAs is not necessary.

The results indicate that reasonable performance (usually taken to be <0.5K) can be obtained using this chipset. 1/f noise performance (K factor) and noise figure of the LNA are the two most important parameters that impact sensitivity. RF bandwidth does not have a significant impact on NETD because the performance is 1/f noise limited.

III. NON-PREAMPLIFIED IMAGE ARRAY RESULTS

An 8x8 imaging array using direct detection without RF amplification has been developed on the DARPA MIATA program.[3] A wideband detector matched to a waveguide horn

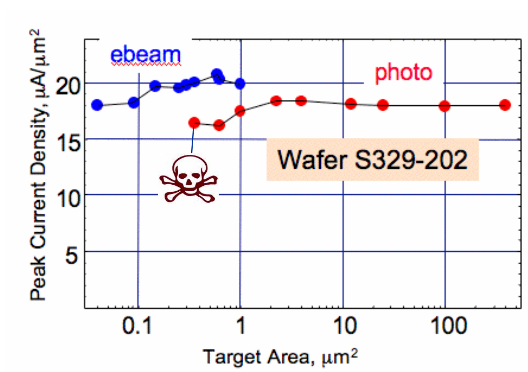

Fig. 3. Plot of peak current density vs. target diode area. Peak current density is ideally flat vs. diode area, and provides a good indication of success in diode scaling.

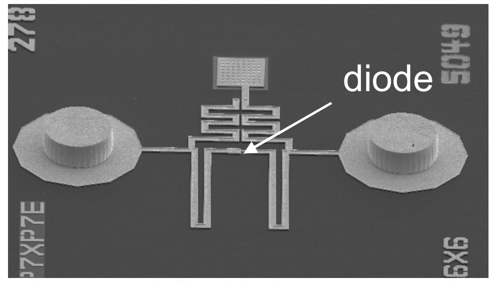

Fig. 4. Photograph of flip chip detector MMIC. The circuitry surrounding the diode is for impedance matching.

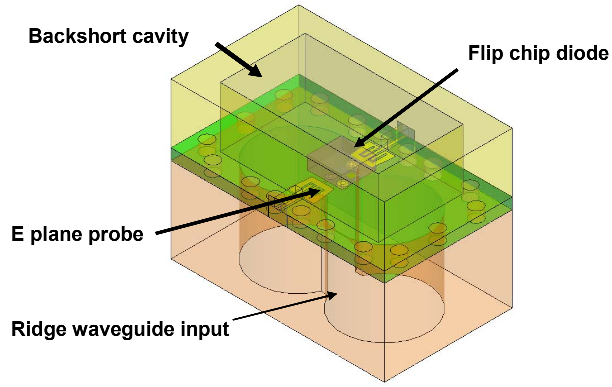

Fig. 5. HFSS model of the detector transition to waveguide. Ridge waveguide extends the bandwidth. The detector is mounted on an RF substrate and connects to E-plane probes. A backshort cavity electrically connects to the waveguide and provides a shielded enclosure.

antenna was developed to achieve a program goal of 2K NETD. To improve detector sensitivity, the backward tunnel diode was scaled down to well below 1x1um^2, as indicated in figure 3. Optical lithography was successfully utilized down to about 0.5x0.5um^2, but yield dropped abruptly for smaller devices. Ebeam lithography produced high yields for devices as small as 0.3x0.3um^2. As the device area is reduced, the diode junction resistance increases inversely to the area and the capacitance decreases proportionally to area, so the device quality factor remains roughly constant‡ The devices have a 3dB responsivity roll-off corner frequency of about 90 GHz.

To maximize sensitivity we developed a wideband matching network and antenna transition to operate over a 70 to 140 GHz band. Figure 4 show a photograph of the detector MMIC with associated matching circuitry. Delay lines in series with the diode compensate for the capacitive reactance of the junction, and a shunt resonator increases the bandwidth by adding additional poles. The balanced differential design helps reject interference.

To minimize losses we developed an efficient transition from a waveguide horn antenna to the detector by flip-chip mounting the MMIC and locating it within a backshort cavity, as shown in figure 5. The single mode frequency of the input was extended using ridge waveguide, realized with circular sections to ease machining. A printed circuit board (PCB) is bonded across the waveguide opening and E-plane probes,

‡ The diode series resistance is difficult to estimate from measurements but seems to increase more slowly than inverse proportion to area, so the quality factor increase somewhat as the device size is scaled down.

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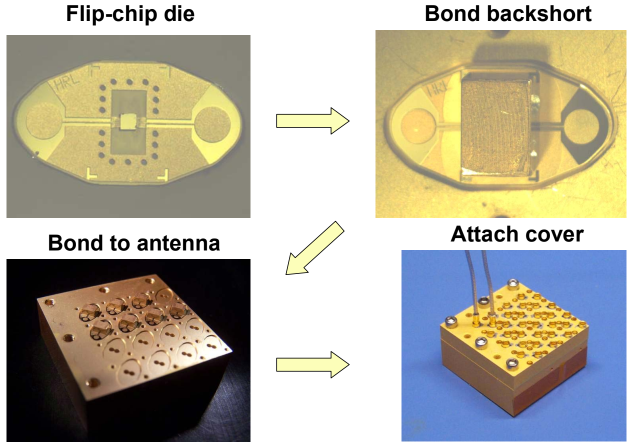

Fig. 6. Array assembly process. A detector is flip-chip attached to an alumina substrate, and then a backshort cavity is bonded over the detector. This assembly is then bonded to the horn array. A cover is attached and cables are connected to the differential outputs.

located on the reverse side of the PCB, couple the diode to the input waveguide. Plated through holes electrically connect the waveguide to the backshort cavity. Locating the detector within the input waveguide minimizes losses between the input and the detector.

The program goal was to demonstrate an 8x8 array of imaging sensors, so care was taken to ensure a simple assembly process, which is shown in Figure 6. First, a detector MMIC is flip-chip mounted on an alumina PCB. Note that the PCB has two rectangular cutouts, removed via laser, that prevent unwanted resonances within the structure due to the high permittivity of the material. Next, a backshort cavity is bonded over the detector using silver epoxy. The result is a millimeter wave direct detection receiver assembly that is then silver-epoxy bonded to the waveguide side of the horn antenna housing. Finally, a back cover is attached to the assembly, containing fuzz button[4] contacts for the output connectors. The entire assembly process was completed by hand at HRL due to the relatively small number of sensors produced for the program, but the process is amenable to mass production. Four 4x4 subarrays were assembled and combined together to form an 8x8 array, shown in figure 7.

The sensors were tested by directing them at an RF blackbody absorber (a corner reflector with radar absorbing material on its interior walls) submerged in liquid nitrogen. An optical chopper and lock-in amplifier provided a reading

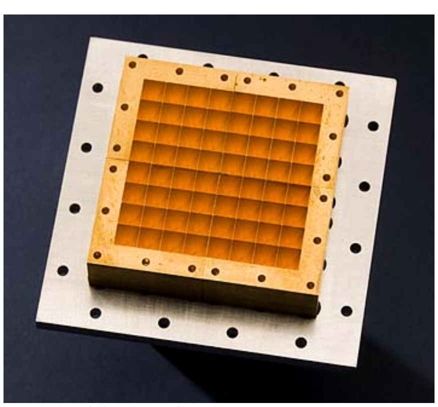

Fig. 7. Photograph of the completed 8x8 array.

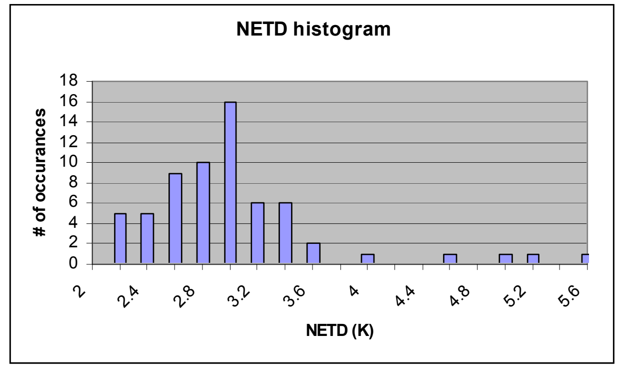

Fig. 8. Histogram of NETD values for the 8x8 array elements. The average value was 2.92K with a 0.65K standard deviation.

proportional to the output voltage difference between the room temperature and liquid nitrogen blackbodies providing the thermal sensitivity (nV/K) of the sensors. Output noise was measured by directing the sensor at a room temperature blackbody and measuring the output voltage on a spectrum analyzer from 5 to 55Hz. This frequency range allowed us to estimate the voltage noise while avoiding 60Hz interference. Because the detector is non-preamplified and unbiased it does not generate appreciable 1/f noise. The measured power spectral density was multiplied by 15Hz, corresponding to a 30Hz frame rate, to obtain the mean square voltage noise.

The ratio of the RMS voltage noise to the thermal sensitivity gives the NETD for the sensor. This measurement process was performed on all 64 elements of the array, and the results are shown in figure 8 as a histogram. The average value was 2.9K and the standard deviation was 0.65K. The performance variation is largely due to hand assembly and could be improved with automated assembly processes.

SUMMARY

HRL has developed a W band imaging chipset based on an Sb-heterojunction backward tunnel diode. The LNA and detector MMICs provide NETD less than 0.5K without the use of Dicke switches or optical choppers, with a 3.125 msec integration time and 10 Hz frame rate. An 8x8 imaging array without the use of RF LNAs was demonstrated with NETD less then 3K for a 30 Hz frame rate.

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[3] James H. Schaffner, Jonathan J. Lynch, Keith Guinn, Joel N. Schulman, Harris P. Moyer, Ross L. Bowen, Marcel M. Musni, "A Wideband, Scalable Radiometer Module for an Unamplified Direct Detection W-Band Imaging Array," Proc. SPIE 6948, 2008.

[4] Fuzz buttons are available from Technit® Interconnect Products, 1505 W. Third Ave., Denver, CO, www.fuzzbuttons.com.

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