

Integrated Front-ends up to 200 GHz

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Abstract—In this paper, we present results of work done in packaging highly integrated circuits based on 100nm mHEMT technology. We present several examples of fully integrated receivers and sources for frequencies bands 90-130 GHz and 160-210 GHz. The circuits are packaged into waveguide blocks, characterized and compared to on-wafer measurements. Waveguide to microstrip transitions based on 50 μm alumina substrate, and including via holes, are used to effectively interface the MMICs to a rectangular waveguide at RF without using tuning structures to resonate wire-inductance. Noise and return loss are characterized on wafer and after packaging. Typical increase of 0.7 dB in the NF is observed at 90-130 GHz after the packaging and 1 dB at 160-210 GHz. We address the issue of MMICs with high level of integration resulting in large cavities in the package causing instabilities for certain biasing conditions. Some of the packaged modules are characterized at both room and cryogenic temperatures.

Index Terms—Millimeter wave circuits, waveguide to microstrip transition, W, F, D, G-band, Millimeter wave receivers, MMIC, frequency multiplier, mHEMT, 118 GHz.

I. INTRODUCTION

Future meteorological and climate observation missions [1] will utilize arrays of receivers to synthesize large apertures and thus provide the required spatial resolution. These instruments are critically dependent on highly integrated, lightweight radiometric front-ends where the incoming signal can be amplified and down-converted into one compact module. Measurement of humidity and temperature profiles of the atmosphere with high resolution requires multi-pixel instruments at geostationary orbit covering atmospheric lines between 60 and 600 GHz. Recent GaAs metamorphic high electron mobility transistor (mHEMT) and InP HEMT technologies made it possible to demonstrate integrated MMIC heterodyne-receivers, incorporating low-noise amplifiers (LNA), mixers and LO-chains at frequencies up to several hundreds of GHz.

For the 118 and 183 GHz atmospheric lines, the existing 100nm mHEMT technology available from the Fraunhofer Institute IAF, described in [2], is a good alternative for

building low noise integrated front-ends. The f_{MAX} of this process is 300 GHz and examples of receivers for frequencies up to 220 GHz using this process can be found in [3], [4], [5].

Lowest equivalent-noise-temperature is of major importance in passive systems and large, highly integrated, MMICs require a separate waveguide to microstrip transitions with minimum loss at RF. In this paper, we present a packaging solution based on low-loss, broad-band waveguide to microstrip transition connected to the MMIC through bond wires. As an example for the 180 GHz water line we present a 150-220 GHz front-end MMIC module consisting of a 5 stage LNA followed by a sub harmonically pumped resistive mixer. For the 90-130 GHz band we demonstrate a four stage LNA and a complete packaged receiver module incorporating a LNA, mixer and a X4 LO chain. A noise budget is presented where the additional RF losses after packaging is estimated to be 0.7 dB at 90-130 GHz and 1 dB for the 150-210 GHz.

II. MODULE DESIGN

One way to couple RF to the MMIC at high frequencies is to integrate an antenna structure, which then is coupled to free space. This solution has the drawback of not so good antenna efficiency and limited bandwidth since most of the broad-side antennas are resonant structures. An alternative solution is to couple the MMIC to a waveguide and thus achieve efficient coupling over broader frequency range.

However, as most highly integrated MMIC circuits are relatively large in size in relation to the wavelength, integration of waveguide-to-line transitions on the MMIC is hardly possible. A separate transition with subcritical dimensions is needed in order to prevent waveguide mode to leak into the circuit cavity.

The drawback of this solution is that it requires a bond-wire interface between the waveguide-transition and the MMIC. Bond wires at these frequencies present considerable inductance and require special measures to provide low return-loss of the interface. Distributed tuning structures are often integrated into the waveguide transition to resonate the wire reactance within the pass band. In our design we avoid tuning structures and focus instead on minimizing the wire inductance.

One possibility to reduce the wire inductance is to place a pair of additional wires connected to ground near the bond as illustrated in Fig 1. This solution requires a waveguide transition with line widths similar to the ones onto the MMIC. The MMICs fabricated for the 118 GHz and 183 GHz are

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based on microstrip lines on a 50 μm thick GaAs substrate. To keep proportionality between the lines on both sides of the bond we use a 50 μm alumina substrate to fabricate the waveguide transitions. Additional challenge is the need for grounded contact pads where a pair of via-holes to ground provide connection for the extra pair of lines.

The waveguide to microstrip transitions were fabricated by ATC [6] in a test process and include back-side metallization and via holes where the minimum diameter of the via is 100 μm with 120 μm clearance to any other diced edge. The small size of the transition does not allow integration of vias with the required clearance. To get around this issue castellated wrap around vias centered on the edge of the substrate are used. The result after dicing is a recessed wrap of half the original via.

Two types of transitions are fabricated: F-band 90-140 GHz and G-band 140-220 GHz. To verify the quality of this interface, we placed a pair of waveguide-to-microstrip transitions and connected them back-to-back with bond-wires. The return loss was found to be below -15 dB for 90-145 GHz. The insertion loss was measured to be 0.75 dB in the middle of the band. Identical measurement was performed for the 140-220 GHz band and results are shown in Fig. 1.

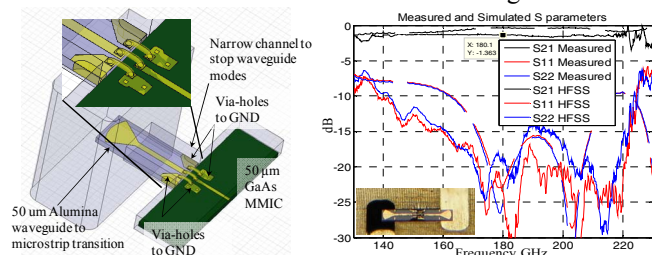


Fig. 1 Illustration of the G-band waveguide to microstrip transition and its bond-wire interface to the MMIC. The insertion loss in the middle of the band is about 1.4 dB and includes losses in 20 mm long waveguide brass section (the block is not gold-plated). The size of the alumina substrate is 350/800 μm .

The MMIC contact pads are placed 50 μm away from the dicing edge, with a practical spacing between the MMIC and the alumina substrate of about 30 μm , the resulting minimum bond wire length is about 140 μm even for wires with low loop. Analysis at G-band show typical inductance of 20 pH for three 25 μm diameter wires with spacing between the signal and the ground wires of 70 μm . The corresponding inductance for only one wire is 37 pH causing additional insertion loss of 0.3-0.4 dB at G-band.

III. 150-220 GHz LNA AND MIXER

A five stage LNA followed by a subharmonically pumped resistive mixer is integrated on a 0.75x2.75 mm MMIC. The LNA includes 2x10 μm common source HEMTs with source degeneration feedback in the first stage. The mixer uses two 30 μm gate fingers driven by out-of-phase LO signals.

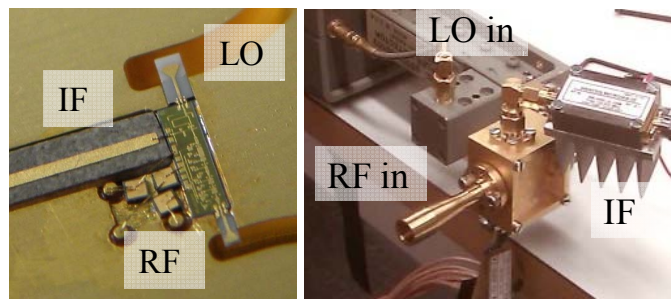


Fig. 2 The 180 GHz front end module. Chip size 0.75x2.75 mm, cavity size is 0.26/2.4/2.8 mm.

Gain and NF are calculated from Hot/Cold load measurements where twenty three LO frequency points are scanned and the IF power is averaged from 50 to 500 MHz.

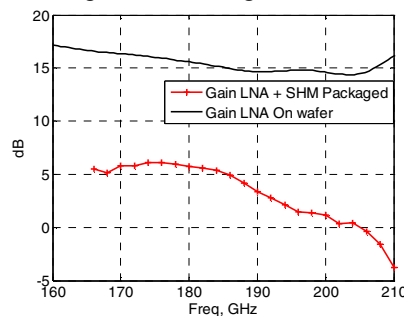


Fig. 3 Gain of the 180 GHz front end including LNA and a SHM – red line. Gain of the LNA only measured on wafer. The difference in the gain indicate a combination of mixer-loss and additional RF losses due to the packaging.

The applied LO power is 4 dBm at maximum and it varies with the frequency, the power accessing the mixer is of the order of 2-3 dBm. A negative bias with a typical value of -0.5 V is applied to the gates of the mixer to compensate for the variation of the LO power with the frequency and minimize the conversion loss.

Results of the noise measurements of LNA-on wafer and LNA+SHM-after packaging are shown in Fig. 4.

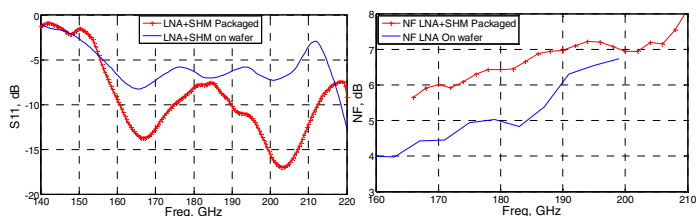


Fig. 4 To the left measured return loss at RF for on wafer – blue and packaged circuit -red. To the right – measured NF of the LNA on wafer and the LNA + Mixer in a module.

The 1.5 dB extra NF in the case of the packaged LNA+SHM is contributed partly by the mixer and the IF amplifier. Conversion loss measurement of the break-out of mixer circuit indicates loss of 12 dB, which together with the IF amplifier contributes with 80 to 170 K along the band (about 0.6 dB in NF). The remaining 1 dB is contributed to the waveguide-to-microstrip transition and the input waveguide and horn.

IV. 165-195 GHz SIGNAL SOURCE

A times six MMIC multiplier chain, described in [9], was designed to be used as a reference source together with a 183 GHz fundamental mixer.

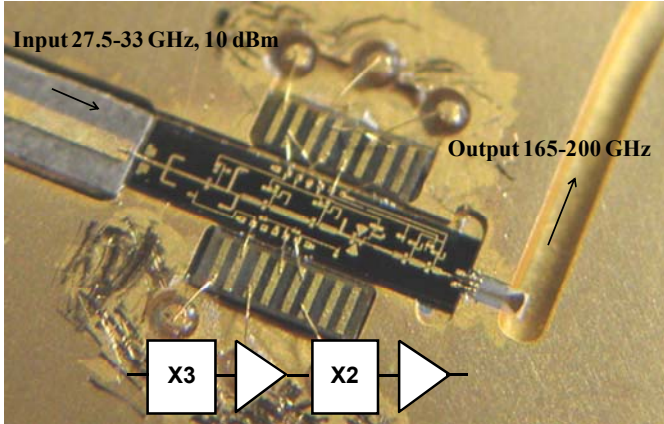


Fig. 5 A close view of the packaged X6 multiplier chain. The input signal is fed through a V-type connector and a microstrip line on a soft substrate. The output is coupled to a G-band 1.29/0.65 mm waveguide.

A split block waveguide module, shown in Fig. 5 and Fig. 6, is fabricated and in addition contains a six channel bias supply with voltage regulators. Fig. 6 shows power measured at the output of the module and on-wafer. The chip mounted in the package is not the same as the one used for on wafer measurements, moreover the input power for both measurements might not be the same as the losses at the input of the module have not been measured.

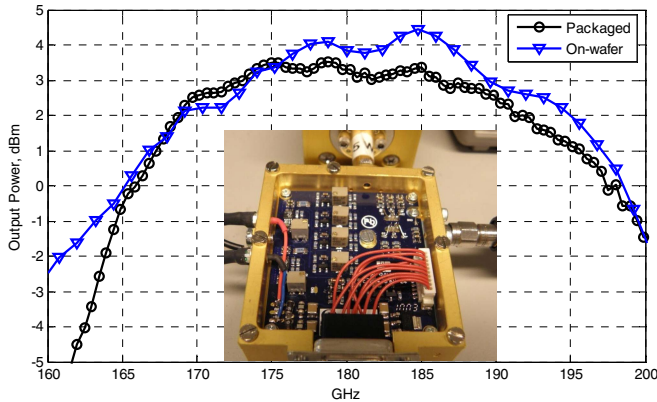


Fig. 6 A picture of the X6 source and the measured output power versus the output frequency. The input power for the on-wafer measurement is 9 dBm, for the module the power at the MMIC input is about 10 dBm but it is not exactly known.

V. 90-130 GHz LNA

A four stage LNA based on $2 \times 20 \mu\text{m}$ common source HEMTs, with inductive source feedback in the first two stages, was packaged into an F-band waveguide split-block using the waveguide transitions described above. The S-parameters were measured using a combination of W and G-band VNA extension modules and comparison between on-wafer and packaged gain/return loss is presented in Fig. 7. The loss in gain is about 1-2 dB in the case of the packaged LNA indicating loss of 0.5-1 dB loss per transition. This

conclusion should be taken with caution since the on-wafer measurement and the packaged LNA measurements are not from the same circuit. However 0.5-1 dB loss per transition was also measured with back-to-back transitions and is also consistent with the increase of the NF presented in Fig. 8.

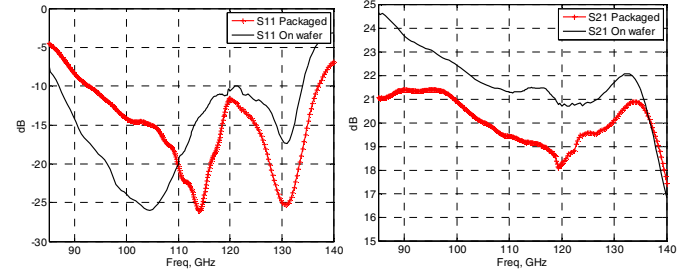


Fig. 7 Input return loss and gain before and after the packaging. Due to the lack of measurement equipment for the 90-130 GHz band, we divide the measurement in two steps and use W-band (75-110 GHz) up to 120 GHz and G-band (140-220 GHz) for frequencies above 120 GHz. The discontinuity in the gain curves are due to lack of dynamic range of the VNA extension modules around 120 GHz.

The LNA noise was characterized on-wafer using a combination of W and D-band noise diodes. A typical NF of about 2.5-3 dB was measured and is shown in Fig. 8. The packaged LNA was measured using Hot/Cold loads and shows NF of about 3.5-4 dB indicating 0.5-1 dB extra loss at the input of the LNA after the packaging. This contribution is consistent with the expected loss in the transition and the bond-wires.

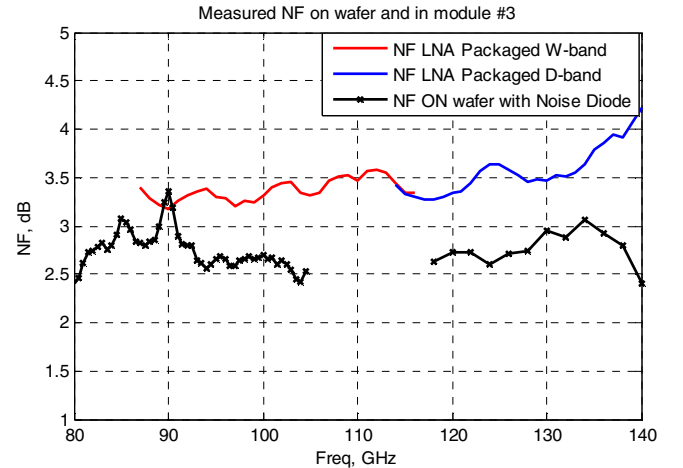


Fig. 8 Noise figure measured on-wafer with noise diodes and after packaging measured with Hot/Cold loads.

To test the performance of the LNA at cryogenic temperatures, the block was integrated into a two-stage closed cycle cryostat providing temperature of about 20 K. The measured noise temperature varies between 60 and 80 K (0.8-1dB NF) over 90-110 GHz [7], which is approximately six times less than the corresponding noise-temperature at 300 K.

VI. 90-130 GHz RECEIVER

A 118 GHz receiver MMIC was developed for an oxygen profiling multi-pixel radiometer system. The receiver, shown in Fig. 9, includes the LNA described in the previous section,

a mixer, and a X4 LO chain, all integrated onto a single MMIC. The mixer is a scaled version of the resistive mixer described in [5] and provides a conversion loss of 8-10 dB for LO power of 4 dBm. The LO chain consists of two doublers followed by a two stage power amplifier [8]. The amplifier delivers about 5dBm of LO signal to the mixer with an input power of 9 dBm at 29.5 GHz. More detail on the LO-chain design and measurements of the break-out circuit can be found in [9].

A mechanical block was designed where the circuit is mounted and interfaced to RF through the same transition as the ones used for the LNA. The LO and IF are interfaced through bond wires to a microstrip line on a soft substrate.

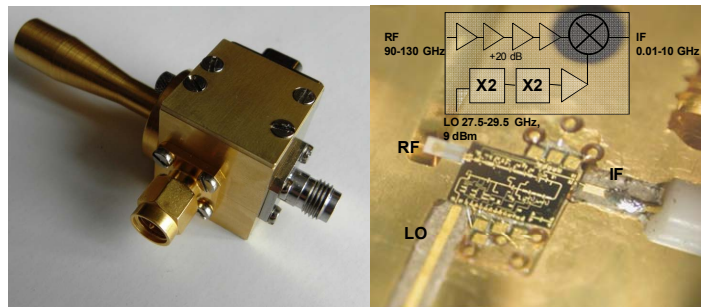


Fig. 9 A picture and a block diagram of the receiver module. The MMIC size is 0.05/2.25/3.25 mm whereas the main cavity comprising the filter capacitors and feed-thrus is 0.36/3.4/4.3 mm

Because of the large MMIC size and the large number of DC bias lines required to bias the circuit, the cavity cut-off frequency for the lowest TE 101 mode is about 56 GHz, which is well within the band where the MMIC is active. Possibly because of this, the performance of the receiver was found to be unstable for some LO frequencies below 112GHz. The instability is believed to originate from the power amplifier following the second doubler and occurs only for certain bias points. No such instability was observed when the MMIC was measured on-wafer. As a measure to suppress the occurrence of the cavity modes, the lid of the block was upgraded with corrugations quarter of wavelength deep creating open circuit boundary over certain frequency band [10].

The receiver is designed for a fixed LO of 118 GHz. Gain and NF vs. IF frequency are constant up to at least 10 GHz. The packaged receiver shows extra 1 dB NF and 2 dB less gain, relative to the corresponding on-wafer measurement.

VII. CONCLUSION

A packaging solution based on 50 μ m alumina waveguide-to-microstrip transitions is presented. The transitions include back-side metallization and via holes to include additional bond wires to ground. The extra wires reduce the inductance of the wire from 37 pH to 20 pH for a typical wire length of 140 μ m and 25 μ m diameter. At G-band this improves the return loss of the transition and results in improvement in the insertion loss with about 0.3-0.4 dB. With three wires, the insertion loss at F-band is improved by less than 0.1 dB compared to one wire. The transitions do not use tuning structures and after measurements of several packaged circuits

we found them insensitive to variation in the bond wire geometry. The drawback of this solution is that there is no available commercial process for 50 μ m alumina substrates that include via-holes.

The performance of the MMIC front end components is characterized both on-wafer and after packaging. It was found difficult to measure a circuit on-wafer and then to package the same circuit in a module. The contact pads are scratched by the on-wafer probes making it very difficult to bond afterwards. Since the NF varies less than the gain between the circuits, the increase in the NF after packaging is more indicative to evaluate the additional loss introduced by the transition, the input waveguide and the horn. It was found that the additional RF loss after packaging is about 1 dB between 150 and 200 GHz and about 0.5-1 dB from 90 to 130 GHz.

The use of MMICs with high level of integration resulting in large cavities and can produce instabilities for certain biasing conditions. An attempt to terminate (suppress) reactively cavity modes by introducing corrugations in the lid of the block was made. This work is ongoing and hopefully at the conference further results can be available.

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