Publication P9

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W-band low-noise amplifiers

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Abstract – We report low noise amplifiers for a 94-GHz cloud profiling radar. Four amplifiers were designed using coplanar waveguides and they were manufactured with a 100-nm metamorphic high electron mobility transistor technology. Selected chips were assembled in a split block package having WR-10 waveguide interfaces and alumina microstrip transitions. The scattering parameters and the noise figures of the amplifiers were measured on-wafer and in WR-10 waveguide environment at W-band. At room temperature, the on-wafer measured gain at 94 GHz was between 18 and 23 dB and the measured noise figure ranged from 3.0 to 3.5 dB. Packaged amplifiers exhibit more than 20 dB of gain and noise figures around 3.7 dB. One packaged amplifier was also measured at cryogenic temperature and the results are presented.

Index Terms – Low noise amplifiers, Metamorphic high electron mobility transistors, Microstrip transitions, MMIC amplifiers, packaging, W-band.

I. Introduction

In an effort to increase the accuracy of climate models one has to obtain more information on vertical profile characteristics of clouds. A 94-GHz cloud profiling radar (CPR) is an important element of the joint European-Japanese EarthCARE (Earth Clouds, Aerosols and Radiation Explorer) mission, currently under pre-development for the planned launch in 2012 [1].

The low noise amplifier (LNA) is one of the key components in a millimetre-wave receiver application, such as the cloud profiling radar. Millimetre-wave integrated circuits have traditionally been implemented using technologies, which are based on compound semiconductors such as gallium arsenide (GaAs) or indium phosphide (InP). The metamorphic high electron mobility transistor (MHEMT) has emerged as an attractive, low cost alternative to InP HEMTs. In MHEMT technology, the metamorphic buffer layer is grown on the GaAs, which enables the growth of a channel layer having 30-80 % indium content. This leads to a substantial cost reduction and manufacturability improvement over InP-substrate based devices [2]. Recently, the antimonide-based compound semiconductor (ABCS) InAs/AlSb HEMTs have become interesting because of their low dc-power dissipation.

A performance overview of state-of-the-art millimetre wave integrated amplifiers can be found in [3]. At W-band, GaAs pseudomorphic high electron mobility transistor (PHEMT) amplifiers have achieved noise figures (NF) of 3.6-4.0 dB [4], [5]. Previously, best noise results at W-band have been achieved with InP HEMT amplifiers [6]-[9]. The MHEMT amplifiers have recently shown performances comparable to InP HEMT amplifiers [10]-[12]. The InAs/AlSb HEMT amplifiers have demonstrated noise figures ranging from 3.9 to 5.4 dB at 94 GHz [13], [14].

At millimetre-waves the packaging of the monolithic microwave integrated circuits (MMIC) becomes more demanding than at lower frequencies. Typically, the MMIC can be mounted face-up on a housing and bonded to a transition to couple the MMIC to waveguide [10], [15], [16]. Another approach is the flip-chip technology [17].

The aim of our work was to find out how well the 100-nm metamorphic HEMT technology and an E-plane split-block package assembly suits to low noise amplification at W-band and, particularly, considering the cloud profiling radar operating at 94 GHz. In this paper, we present the design of the waveguide transitions of an E-plane split-block package and the measured results obtained from the packaged amplifiers. Because of the careful design of the mechanical package and the waveguide probes, the packaging degraded the noise figure only by a few tenths of decibels when compared to on-wafer results. In addition, one of the amplifier packages was measured at cryogenic temperatures.

This paper is organized as follows: The fabrication technology is presented in Section II. The detailed design of the MMIC LNAs was reported in [18]. Therefore, only a brief summary and measurement results of these circuits are presented in Section III. The design of the package and waveguide probes are presented in Section IV following the measurement results of the packaged LNAs. In that section, measurement results of one packaged amplifier at cryogenic temperature are also shown. Finally, we present conclusions in Section V.

II. Fabrication technology

The manufacturing process is a 100-nm GaAs based metamorphic HEMT technology from Fraunhofer

Received July 5th, 2007. Revised October 26th, 2007.

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IAF, Freiburg, Germany. The transistor f_T and f_{max} are 220 and 300 GHz, respectively, and the process features ground via holes through GaAs-substrate as well as backside metallization. The structure of the composite channel of the MHEMT is $In_{0.52}Al_{0.48}As/In_{0.80}Ga_{0.20}As/In_{0.53}Ga_{0.47}As$. A transmission electron microscope (TEM) picture of a cross-section of a 100-nm MHEMT is shown in Fig. 1. This technology achieves a maximum transconductance of 1300 mS/mm and a gate-to-drain breakdown voltage of 4 volts.

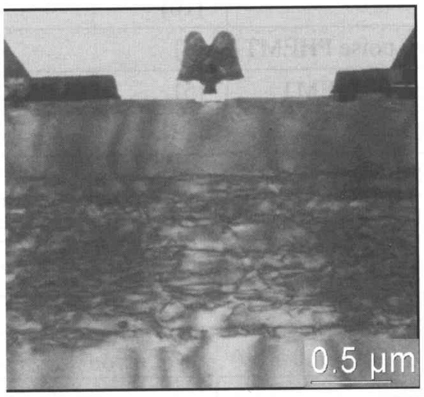

Fig. 1. A TEM cross-section of a 100-nm metamorphic HEMT.

III. MMIC low noise amplifier design

Four low noise amplifiers with different design targets were implemented using grounded coplanar waveguide (GCPW) topology. A 4x15-μm gate width MHEMT was chosen as a suitable low noise device for the amplifiers. The transistor is in a common source configuration. The simulation models were provided by the Fraunhofer IAF. The detailed design of the MMIC LNAs is presented in [18]. The first design (LNA1) is a narrowband three-stage amplifier while the second design (LNA2) is a wideband three-stage amplifier. All the stages are biased to optimum gain. A simplified schematic and a micrograph of the LNA2 is presented in Fig. 2 and 3, respectively.

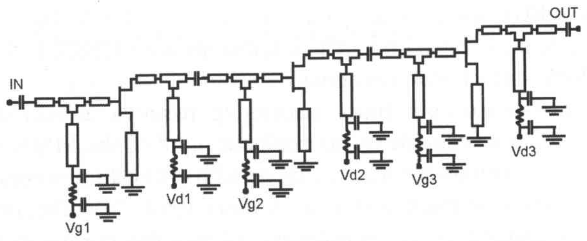

Fig. 2. Simplified schematic of the wideband LNA2.

The third design (LNA3) is also a three-stage amplifier. This design is optimised for low noise performance. The first stage is biased to low noise bias, while second and third stages are biased for peak gain. To increase gain and

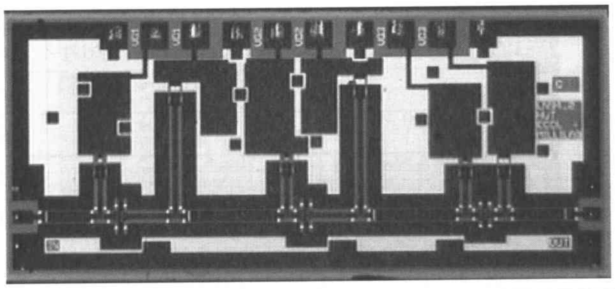

Fig. 3. Micrograph of the LNA2. The chip size is 2.25 mm × 1.00 mm.

bandwidth of the LNA3, a four-stage version (LNA4) was designed.
The on-wafer noise measurement setup is described in [19]. The measured and simulated S-parameters and noise figures of the four amplifiers are presented in Figs. 4-7.

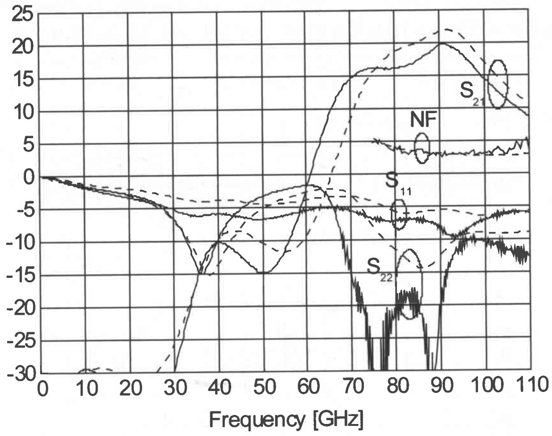

Fig. 4. Measured and simulated (dashed lines) S-parameters and noise figure of the narrowband LNA1. Data from [18]. The measured gain and noise figure are 18 dB and 3.1 dB at 94 GHz, respectively. $V_{supply} = 1.7$ V, $I_d = 54$ mA.

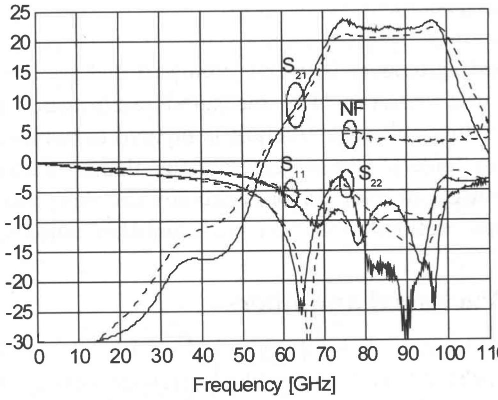

Fig. 5. Measured and simulated (dashed lines) S-parameters and noise figure of the wideband LNA2. Data from [18]. The measured gain and noise figure are 22.5 dB and 3.3 dB at 94 GHz, respectively. $V_{supply} = 1.34$ V, $I_d = 54$ mA.

Frequency [GHz]	Gain [dB]	NF [dB]	Technology	Ref.
95	20	2.5	InP	[6]
94	18	2.9	InP	[7]
94	16	3.2	100-nm InP	[8]
94	12	3.3	100-nm InP	[9]
90	17	2.8	MHEMT	[12]
89	14	4.8	100-nm MHEMT	[20]
80-100	12	2.3	70-nm MHEMT	[11]
70-105	20	2.5	70-nm MHEMT	[10]
94	31	4.0	100-nm GaAs low noise PHEMT	[4]
90-100	10.3	3.6	100-nm GaAs power PHEMT	[5]
94	11	5.4	100-nm InAs/AlSb HEMT	[13]
94	20	3.9	200-nm InAs/AlSb HEMT	[14]
94	18-23	3.0-3.5	100-nm MHEMT	This work, on-wafer

Table 1. Comparison of Published HEMT MMIC Amplifiers for W-band.

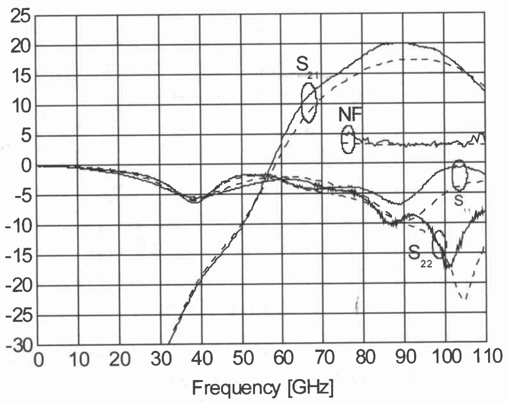

Fig. 6. Measured and simulated (dashed lines) S-parameters and noise figure of the LNA3. Data from [18]. The measured gain and noise figure are 19.5 dB and 3.0 dB at 94 GHz, respectively. $V_{supply} = 0.95$ V, $I_d = 45$ mA.

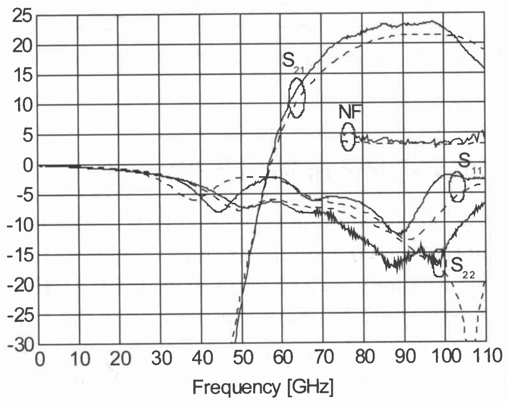

Fig. 7. Measured and simulated (dashed lines) S-parameters and noise figure of the LNA4. Data from [18]. The measured gain and noise figure are 23 dB and 3.5 dB at 94 GHz, respectively. $V_{supply} = 0.94$ V, $I_d = 63$ mA.

A good agreement between simulated and measured results was achieved. The measured performance of the MMIC low noise amplifiers is compared to published results in Table I. The presented results demonstrate excellent noise and gain performance and the designed chips compare well with the previously published amplifiers.

IV. Packaged amplifiers

Selected chips of the designs LNA1, LNA2, and LNA4 were assembled in a split block package having WR-10 waveguide interfaces.

A) Mechanical package and waveguide probes

The design of the package is based on an E-plane split-block [16]. The block has a space for a 5-pin micro connector and a small PCB for installing a bias network (low pass RC), and a small space adjacent to the LNA-chip for single layer capacitors. All components are attached to the block with conductive epoxy.

The E-plane split block packaging requires transitions from the waveguide to the coplanar input of the MMICs. The transitions are manufactured with a thin-film process on 100 μm thick polished alumina (99.6 %). The design method of the transitions follows the outline presented in [21]. By using Ansoft HFSS electromagnetic simulations, the transitions were designed by determining the length, metallization width and backshort distance of the waveguide probe to achieve nearly constant impedance over a wide bandwidth. A short inductive line and a quarter-wave transformer were then added as matching elements to bring this impedance to 50 Ω. As shown in simulations in Fig. 8., the transition provides better than 20 dB return loss to the microstrip over almost 30-GHz bandwidth.

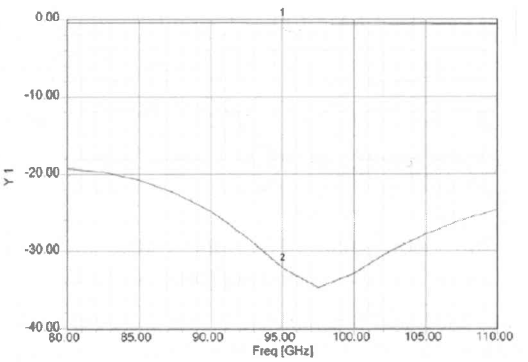

Fig. 8. Simulated transmission (1) and return loss (2) of the WR-10-to-microstrip transition.

Since the MMIC has a coplanar waveguide input, a transition from microstrip to CPW was added to the probe. The ground pads are connected to the backside metal by plated-through vias as shown in Fig. 9. In simulations, the effect of this transition is negligible on the overall performance of the waveguide probe.

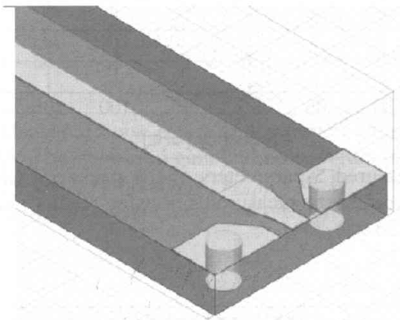

Fig. 9. Microstrip to CPW transition.

A micrograph of a low noise amplifier chip assembled in a housing is presented in Fig. 10 and a photograph of the package is shown in Fig. 11.

B) Measurement systems for LNA packages

The packaged amplifiers were measured in WR-10 waveguide environment. The s-parameters were measured using an HP8510C vector network analyser with the Agilent W85104A extension modules for W-band. Correction coefficients for the analyser were obtained through the TRL-calibration method [22]. An external attenuator was needed to reduce input power from port one to avoid compression of the LNAs. The attenuator reduces the dynamic range of the analyser and, thus, the quality of S11 calibration will deteriorate. However, despite the approximate 15 dB of additional attenuation, a successful calibration was achieved.

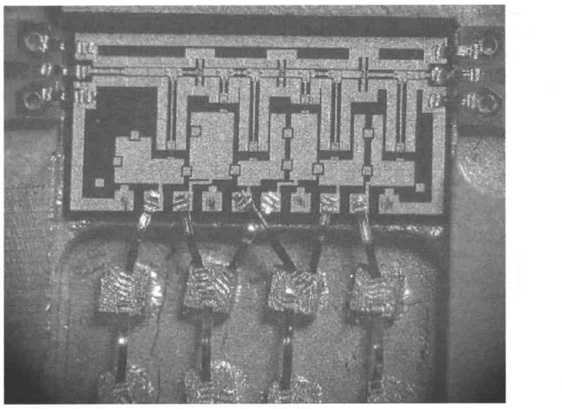

Fig. 10. A 94-GHz MMIC low noise amplifier assembled in the lower half of the split block package.

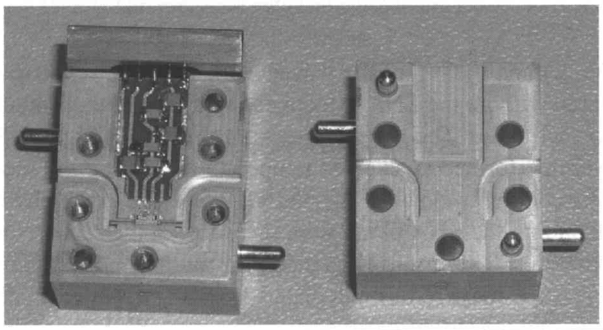

Fig. 11. A photograph of the split-block package. The dimensions of the package are 16 mm × 19 mm × 19 mm.

The noise figure and the insertion gain were measured using the Y-factor method. The block diagram of the room temperature measurement setup is shown in Fig. 12(a). The measurement system utilizes an Agilent N8973A Noise Figure Analyzer and a noise diode from ELVA-1 having an excess noise ratio (ENR) of about 15 dB. An in-house assembled noise downconverter, consisting of a mixer and a LO-multiplier, transforms the noise signal from the 75-110 GHz range to a 50-MHz signal, which is a suitable input frequency for the noise figure analyser. At frequencies above 105 GHz the noise figure of the downconverter increases rapidly, which leads to a higher measurement uncertainty.

The same setup was also used for noise figure (NF) and the insertion gain (G_{ins}) measurements at cryogenic temperatures. The setup is shown in Fig. 12(b). In this case, a cryogenic test chamber is connected between the noise diode and the noise downconverter. The input and output waveguide assemblies, which both consist of a stainless steel waveguide for thermal isolation and a short section of standard waveguide, are located inside the test chamber. The LNA block is connected between these assemblies. The entire assembly is presented in Fig. 13. A thermally conductive wire connects the LNA block to a cold finger of the cryogenic cooler. Temperature sensors are placed on the LNA block and on the waveguides to monitor cooling. At first, during the first cooling cycle, the insertion gain

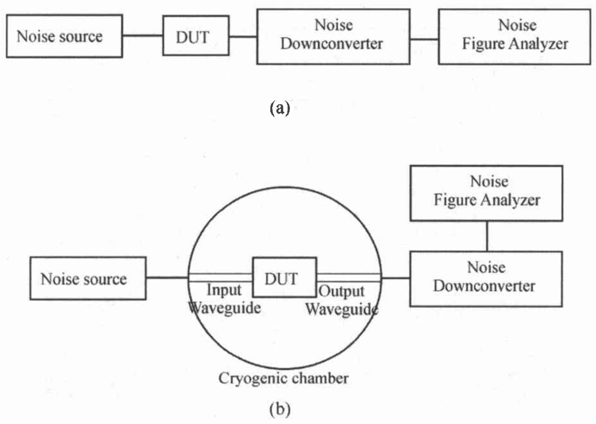

Fig. 12. Block diagrams of noise figure measurement setups. (a) Room temperature setup. (b) Cryogenic temperatures setup.

(G_{ins}) and the NF of the waveguide assembly were measured without the LNA by connecting the input and output to each other. The measurements of the G_{ins} and the NF were performed at selected temperatures. During the second cooling cycle the G_{ins} and the NF of the entire chain including the LNA block were measured at the same temperatures. The insertion gain G_{LNA} and the noise figure F_{LNA} of the LNA is calculated from the total insertion gain and noise figure using

$$F_{LNA} = \frac{F_{tot} - F_{in}}{L_{in}} + \frac{F_{out} - 1}{G_{LNA}} + 1, \quad (1)$$

where F_{tot} is the total noise figure of cascaded waveguides and the LNA, F_{in} and F_{out} are noise figures of the input and output waveguides, respectively, and L_{in} is the loss of the input waveguide.

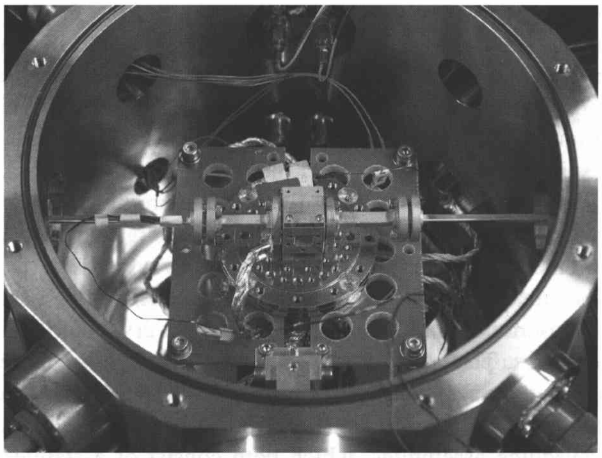

Fig. 13. Photograph of the cryogenic measurement setup.

C) Room temperature measurement results of the packaged LNAs

The measured S-parameters of the packaged LNA1, LNA2 and LNA4 are presented in Fig. 14, Fig. 15. and Fig. 16, respectively.

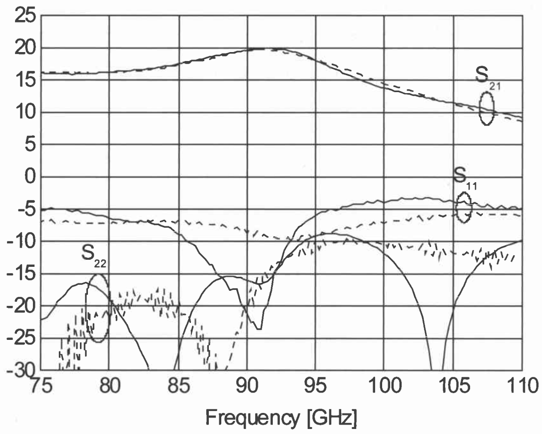

Fig. 14. Measured S-parameters of the packaged LNA1. The dashed lines represent measured on-wafer results. $V_{supply} = 1.7$ V, $I_d = 54$ mA.

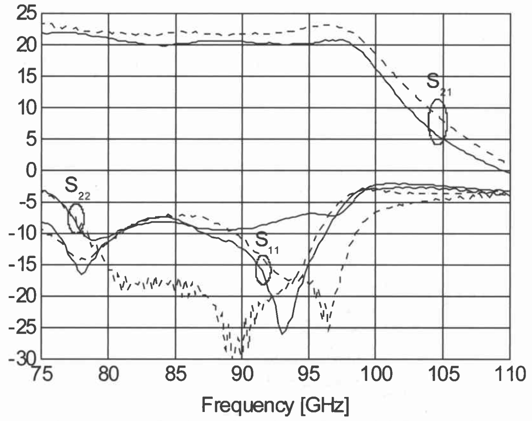

Fig. 15. Measured S-parameters of the packaged LNA2. The dashed lines represent measured on-wafer results. V_{supply} = 1.34 V, $I_d = 54$ mA.

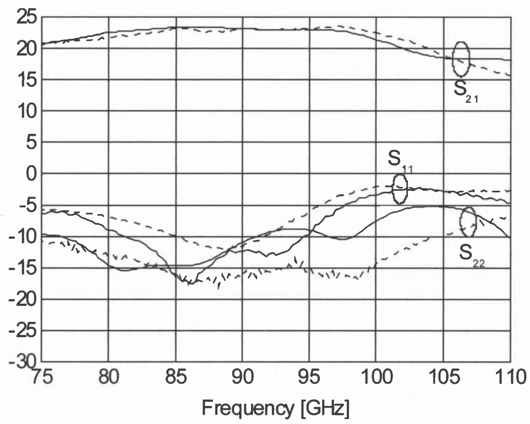

Fig. 16. Measured S-parameters of the packaged LNA4. The dashed lines represent measured on-wafer results. V_{supply} = 0.94 V, $I_d = 63$ mA.

The noise performances of the packaged amplifiers are shown in Fig. 17, Fig. 18. and Fig. 19. The measured on-wafer results are included in these figures for comparison. Although, the gain response of the packaged LNA1 has slightly shifted downwards in frequency, the measured gain and noise figure are 15 dB and 4.2 dB at 94 GHz, respectively. The packaged LNA2 exhibits a gain better than 18.5 dB from 75 to 100 GHz. It achieves a 3.7 dB noise figure at 94 GHz. The packaged LNA4 has more than 15 dB gain over the entire W-band. At 94 GHz, the measured noise figure is 3.7 dB.

As a conclusion, the measured results indicate that the packaging and the design of waveguide probes were realized successfully. The packaging has a minimal effect on the frequency responses of the LNA MMICs. Moreover, the packaging degraded the noise figure only by a few tenths of decibels when compared to the on-wafer results.

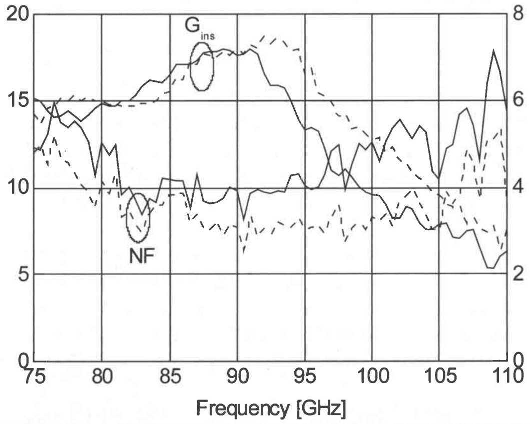

Fig. 17. Measured noise figure and insertion gain of the packaged LNA1. The measured gain and noise figure are 15 dB and 4.2 dB at 94 GHz, respectively. V_{supply} = 1.7 V, I_d = 54 mA. The dashed lines represent measured on-wafer results.

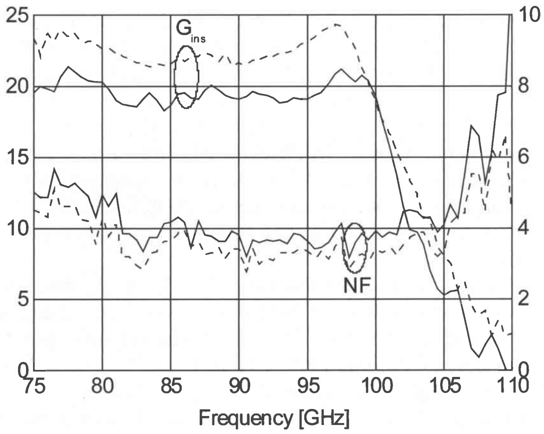

Fig. 18. Measured noise figure and insertion gain of the packaged LNA2. The measured gain and noise figure are 19 dB and 3.7 dB at 94 GHz, respectively. V_{supply} = 1.34 V, I_d = 54 mA. The dashed lines represent measured on-wafer results.

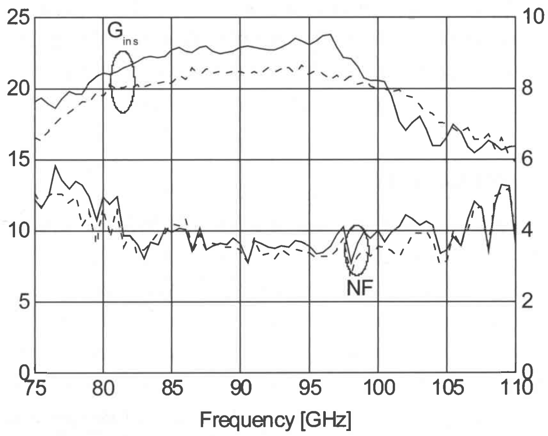

Fig. 19. Measured noise figure and insertion gain of the packaged LNA4. The measured gain and noise figure are 23.5 dB and 3.7 dB at 94 GHz, respectively. V_{supply} = 0.94 V, I_d =63 mA. The dashed lines represent measured on-wafer results.

D) Test results at cryogenic temperatures

Measured noise figure and insertion gain of the packaged LNA2 for various physical temperatures in cryogenic measurement setup are presented in Fig. 20. and Fig. 21, respectively.

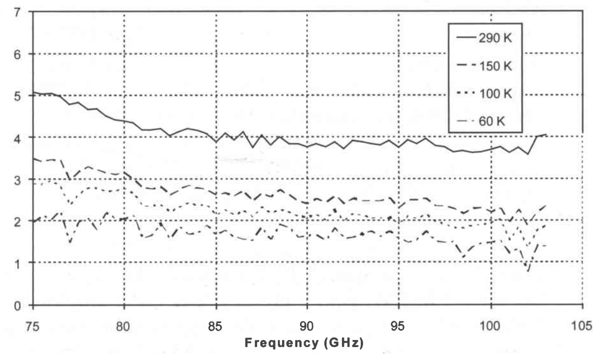

Fig. 20. Measured noise figure of the packaged LNA2 at various physical temperatures. V_{supply} = 1.1 V, V_g =0.1 V, I_d = 38, 32, 30, 28 mA.

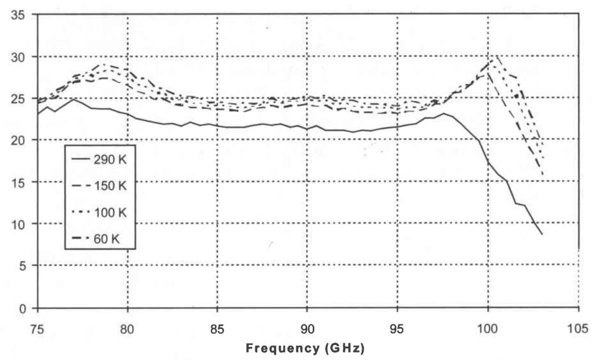

Fig. 21. Measured insertion gain of the packaged LNA2 at various physical temperatures. V_{supply} =1.1 V, V_g =0.1 V, I_d = 38, 32, 30, 28 mA.

The supply voltage and gate-to-source voltages were kept constant at different temperatures. About 3 dB improvement in insertion gain and 2.5 dB in noise figure can be observed over the tested temperature range.

V. Conclusions

This paper describes the design of MMIC amplifiers and their successful integration into waveguide packages. Measurement results of both LNA MMICs and packaged amplifiers are presented and the results are discussed. The presented results demonstrate excellent noise and gain performance and the designed chips compare well with the previously published amplifiers. Because of the careful design of the mechanical package and the waveguide probes, the packaging has a minimal effect on the frequency responses of the LNA MMICs. Moreover, the packaging degraded the noise figure only by a few tenths of decibels when compared to the on-wafer results. These design methods and the chosen manufacturing technologies look promising when considering the intended cloud radar application.

VI. Acknowledgment

This work was done under Contract 13521/99/NL/PB to the European Space Agency and was supported by the Academy of Finland under the Millimono Project. Ylinen Electronics (Finland, email: info@ylinen.fi) was the prime contractor of the work while Fraunhofer Institute for Applied Solid-State Physics and Millimetre Wave Laboratory of Finland-MilliLab acted as subcontractors.
The authors would like to thank Petri Jukkala from Elektrobit Ltd., Espoo, Finland, for advice.

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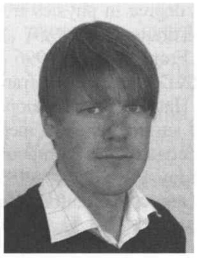

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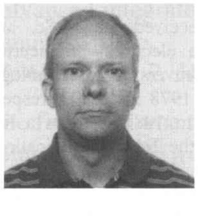

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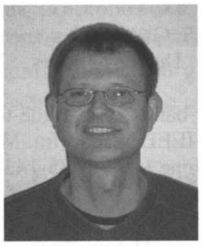

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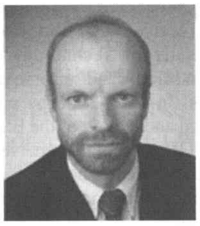
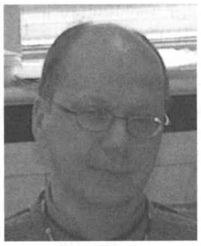


Matthias Seelmann-Eggebert received his Diploma and Ph.D. degree in physics from the University of Tübingen in 1980 and 1986, respectively. From 1980 to 1996 he was involved in R&D related to infrared detectors based on HgCdTe and developed electrochemical and surface physical methods for the characterization of compound semiconductor surfaces. From 1990 to 1991 he was a visiting scientist at Stanford University. From 1997 to 2000 he was engaged in the growth of CVD diamond. Since 2001 he is a member of the department of high frequency electronics of the IAF in Freiburg,Germany, and is concerned with the preparation and development of simulation models for active and passive III-V devices.



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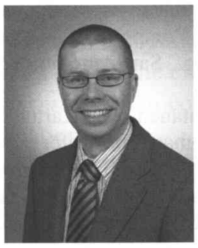

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