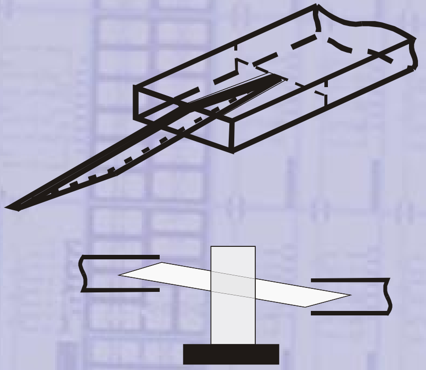
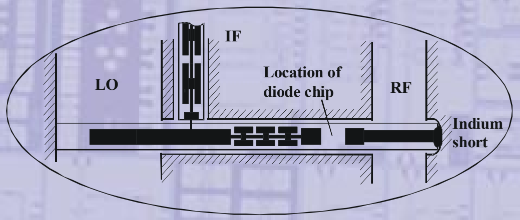
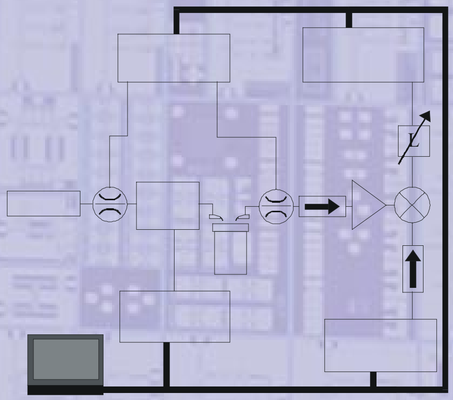
Research Activities of Millilab 1999-2000

MilliLab







Millimetre Wave Laboratory of Finland - Millilab

Joint laboratory between VTT and Helsinki University of Technology

esa

External Laboratory

Research Activities of MilliLab 1999-2000

Editors
Jussi Tuovinen, Juha Mallat

MilliLab

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esa External Laboratory

Contents

1. Introduction

Millimetre Wave Laboratory of Finland - MilliLab is a joint laboratory between Technical Research Centre of Finland (VTT) and Helsinki University of Technology (HUT). MilliLab is also an *European Space Agency (ESA) External Laboratory on Millimetre Wave Technology.* MilliLab was established in 1995.

The main purpose of MilliLab is to support European space industry to meet the demands of future ESA missions. These missions will include several millimetre wave instruments. However, other than space companies and organisations are welcome to use MilliLab's expertise on millimetre wave technology as well. MilliLab offers services at millimetre wave frequencies in the field of device characterisation, device modelling, measurement and testing, and research and development The total research personnel with experience in millimetre waves is over 20.

Key areas of research are:

- On-wafer noise and S-parameter measurements
- Low-noise amplifiers and receivers
- Mm- and sub-mm wave antenna measurements
- Primary power measurements above 110 GHz

MilliLab and its parent organisations, VTT and HUT have a substantial amount of expertise and experience in the field of microwave and millimetre wave technology. Areas of experience are:

- Active devices, circuits, and systems
- Passive transmission line and device mount analyses
- Quasi-optical components and beam waveguides
- Antenna measurements
- Material measurements
- Indoor and satellite radio wave propagation

Main on-going and past space related project are:

- 70 GHz receivers based on InP HEMT MMIC LNAs for the Planck –mission (ESA, 1997–)
- Submillimetre wave antenna testing using a hologram CATR (ESA, 1998–)
- 119 GHz receiver (cooled to 100 K) for the Swedish Odin-satellite, with a planar diode Schottky mixer and a temperature compensated ring-filter (Tekes, 1994–99).
- Hologram compact antenna test range for the tests of the Odin-satellite 1.1 m antenna at 119 GHz (Tekes, 1994–00).
- Study of mm-wave antenna testing techniques (ESA, 1995–96).
- Preparation of millimeter and submillimeter wave technology activities (ESA, 1995),
- Low-noise 60 GHz HEMT MIC amplifier (ESA, 1991–94)
- Design and construction of a low-noise 22 GHz HEMT VLBI-receiver for the Russian Radioastron satellite (Tekes, 1987–93).
- Study of testing and calibration, and test feed horn bread boarding for 2nd generation Meteosat-satellite (ESA, 1989–90).
- Study of submillimeter frequency multipliers in the program "Development of critical detection technologies for space borne submillimetre heterodyne receivers" (ESA, 1988–89).
- Participation in “MM and SubMM Wave Open Structure Integrated Receiver Front-End Technology Development” (ESA, 1996-2000)
- Participation in “Submillimetre integrated SIS imaging receiver technologies (SISIRT)” (ESA, 1996-97)

Especially on the long term for the millimetre waves, important factor is teaching and education. Also in this respect MilliLab, HUT Radio Laboratory has shown unusual commitment and success, which is shown by several awards for high level teaching and education. The recognitions include, e.g., "Centre of Excellence in Academic Education in Finland" in 1995 and in 1996 awards. The courses offered cover widely the field of RF, microwave, and millimetre wave engineering. All together, in 1999-2000, 5 Doctor of Technology, 11 Licentiate of Technology, and 47 Diploma Engineer degrees were awarded to the students of Radio Laboratory. Abstracts of the theses, especially related to millimetre waves are given in Section 7.

2. Personnel

MilliLab has two permanent persons, namely Laboratory Director and MilliLab Senior Scientist. Other personnel is allocated from the existing personnel of VTT and HUT on project basis. Presently, about 20 research persons are working and 14 man-years of work is annually carried out in MilliLab's projects. In general, close to 30 persons are working on mm-waves at MilliLab partners, VTT and HUT.

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3. Facilities and services

Since the beginning of 1996, intensive work has been carried out to develop the capabilities and services of MilliLab. After analysis of the needs in Europe and on the other hand knowing the most suitable technology areas for MilliLab, the following services where chosen to focus the development effort and therefore to be the areas where MilliLab wants to have state-of-the-art capabilities:

Below 110 GHz:

Device and MMIC (Monolithic Microwave Integrated Circuit) on-wafer measurements:

- Noise parameter measurements
- Cryogenic testing
- S-parameter measurements

Above 110 GHz:

- Power measurements
- Antenna testing using a hologram compact antenna test range
- S-parameter measurements

In addition to the state-of-the-art technologies, MilliLab can provide a wide range of other significant mm- and submm-wave measurements as indicated by the table below (for details please look www.vtt.fi/MilliLab). In short, it can be said that MilliLab can offer all the usual electrical measurements at least up to 300 GHz.

Type of capability/service	*Frequency range*	*Comment*
S-parameter measurements		
Waveguide	up to 120 GHz	HP8510c
Waveguide	up to 700 GHz	AB Millimetre. Not full 4-port, narrow sweeps
On-wafer	up to 120 GHz	Temperature range –65 to 200 °C
Cryogenic on-wafer	up to 75 GHz	Temperature range 15 K to 300 K
Noise param./figure meas.		
On-wafer	50 –75 GHz, 79-94 GHz	Temperature range –65 to 200 °C
Waveguide	up to 200 GHz	
Cryogenic testing of components		Continuous adjustment between 20 K and room temperature
Spectrum measurement	at least up to 325 GHz	Can be used also as a narrow band receiver
Measurement of power	at least up to 1000 GHz	Several waveguide power meters and a quasi-optical power meter
Material measurements	100 – 500 GHz	Open resonator. For low-loss materials
	5 – 110 GHz	Free-space trans. and reflection
Antenna measurements		
Anechoic chambers	tested up to 200 GHz	Size (1) 17 m x12 m x12 m , (2) 9 m x 6 m x 5 m
Feed horns	up to 700 GHz	Both phase and amplitude are measured
Reflectors	up to 700 GHz	Note: this depends strongly on the reflector size
Near-field scanning	up to 300 GHz	Planar scanning 1.5 m x 1.5 m
Compact range	around 120 GHz	Maximum reflector diameter 1.1 m
Sources		
HP Synthesisers	up to 110 GHz	HPIB controlled
Phase locked Gunns	75-120 GHz	
BWOs	118-714 GHz	Possible to phase lock in part of the band
Software		
Circuit simulators		Libra, ADS, APLAC, MwSPICE
Electromagnetic simulators		HFSS, XFDTD, IE3D
Antenna simulators		GRASP8, NEC, PSALM, CORHORN

4. Antennas

4.1. Hologram compact antenna test range

Juha Ala-Laurinaho[1], Jussi Säily[1], Janne Häkli[1], Tomi Koskinen[1], Anne Lönnqvist[1], Jussi Tuovinen[2], Arto Lehto[1], Antti V. Räisänen[1]

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Introduction

Measuring high gain millimetre and submillimetre wave antennas is very difficult. At present, there are no available test facilities for accurate measurements of antennas having a diameter of more than 1 m at frequencies higher than 300 GHz. Ideally, the antenna-under-test (AUT) should be tested in a plane wave test field. Conventionally, a quasi-plane wave is obtained with a long enough measurement distance. However, the far-field measurements of large reflector antennas are nearly impossible due to the large far-field distance (several kilometers or more) and very high atmospheric losses and distortions. In the near-field measurement, the field radiated by the AUT is measured on a nearby surface by a probe antenna. The far-field radiation pattern is then calculated from the measured samples. The number of samples is very large resulting in long measurement time. Therefore, the measurement system must be very stable. Also, the probe positioning system has to be efficient and accurate. In a compact antenna test range (CATR), a plane wave is generated by one or more reflectors, a lens, or a hologram. A reflector CATR requires large reflectors with surface errors less than about $\lambda/100$. The surface tolerance requirement can be alleviated by using a lens made of low-ε_r material. However, the thickness of the lens becomes inconveniently large. The hologram is a potential solution to overcome the problems incurred with insufficient surface accuracy of reflectors [1,2].

Hologram CATR

In a hologram CATR, a feed horn radiates a nearly spherical wave, which is transformed into a plane wave by a planar, transmission-type hologram. Figure 1 shows the measurement set-up for testing the quiet-zone field at 310 GHz. Absorbers are used to prevent reflections and direct radiation from the feed to the quiet-zone.

Figure 1. Measurement set-up for testing the quiet-zone at 310 GHz.

In the CATR application, a binary amplitude hologram is used. The binary structure is etched on the copper layer of a copper plated dielectric film. The copper blocks the wave while the slots let the wave go through the hologram structure. The hologram is very large in wavelengths and numerical simulation of the whole hologram CATR is impossible. Measurements have verified that the simulation of only one vertical cut of the hologram gives accurate enough results. Finite difference time domain (FDTD) method is used for simulating the transmission of the electromagnetic wave through the hologram, and physical optics is then used to calculate the quiet-zone field from the aperture field.

Cross-polarisation performance

The simulation of vertical cuts of the hologram does not predict the cross-polarisation produced by the hologram. For calculating the cross-polarisation, transmission of the electromagnetic wave through a narrow slot is studied with the two-dimensional FDTD. The transmissions of the slots are calculated for parallel and perpendicular polarisations respect to the slot direction. These transmissions can be applied to the whole hologram structure and the cross-polarisation, which is due to the curved slots, can be predicted. The experimental results agree well with theoretical calculations and the maximum level of the cross-polarised component is about –20 dB [3].

Feasibility study of a submillimetre wave hologram CATR

The feasibility of the hologram CATR for submillimetre wave antenna measurements has been demonstrated with a 60 cm hologram at 310 GHz [4]. Several 20 cm test hologram have been manufactured and tested at 310 GHz for evaluation of different manufacturing techniques. The minimum slot width for conventional photolithography with photomasks and chemical wet etching is about 100 µm. The minimum slot width is expected to decrease to about 40 µm when a laser is used to write directly the hologram pattern to the photoresist. In the laser-assisted chemical liquid phase deposition (LCLD) method selective metallisation of the substrate is achieved. The overall accuracy of this method is good but the limited thickness of the metallisation is a problem. Also, the 20 cm test holograms are the largest metallisation patterns made so far with this method.

The use of a dual reflector feed system (DRFS) for improving the hologram illumination is also studied. The amplitude taper, which is required for preventing edge diffraction, can be accomplished with shaped illumination instead of narrowed slots. This is expected to ease the hologram manufacturing since very narrow slots are not needed. Other advantages in the use of the DRFS may be the increased size of the quiet-zone compared to the hologram, decreased cross-polarisation produced by the hologram, and the reduced polarisation dependency.

The key issues in the hologram development are related to the manufacturing: making of accurate hologram patterns, and making of large holograms. Several meters wide holograms have to be joined from several pieces, and this will be further studied in future.

Acknowledgements

This work is supported by ESA through ESTEC contract No. 13096/98/NL/SB "Submillimeter Wave Antenna Testing Using a Hologram CATR", by Technology Development Centre, Finland, and by Academy of Finland. CSC – Center for Scientific Computing has offered its computer resources.

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4.2. Instrumentation for submillimeter wave antenna measurements

Jussi Säily[1], Ville Möttönen[1], Juha Ala-Laurinaho[1], Janne Häkli[1], Anne Lönnqvist[1], Tomi Koskinen[1], Jussi Tuovinen[2], Arto Lehto[1], Antti V. Räisänen[1]

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Introduction

Submillimetre wave antenna testing using a hologram CATR needs powerful phase-locked signal sources and sensitive receivers for the frequency range of 300-1000 GHz. The high power is needed for the quiet-zone verification procedure prior to antenna testing. The power level must be lowered when testing large high-gain antennas in order not to saturate the receiver. A high-power phase-locked BWO can be used as the source. We have constructed a fully automatic quiet-zone test system for the hologram CATR. The test system can also be used for near-field antenna measurements up to 300 GHz.

Source system

The source oscillator is phase-locked to a millimetre wave vector network analyzer (MVNA) and both amplitude and phase can be measured [1,2]. Below 500 GHz, a Gunn oscillator followed by a frequency multiplier is used (Figure 1). A more powerful source oscillator for frequencies over 500 GHz is the backward-wave oscillator (BWO). Phase-locking of a BWO is accomplished by controlling the acceleration voltage of the tube. We have constructed a reliable phase-locked BWO source for 180–350 GHz, and locking of a 650 GHz BWO has been demonstrated (Figure 2). A new harmonic mixer is being developed for use with the BWO-PLL at frequencies 500–700 GHz. The estimated conversion losses for the mixer are below 20 dB across the operational band.

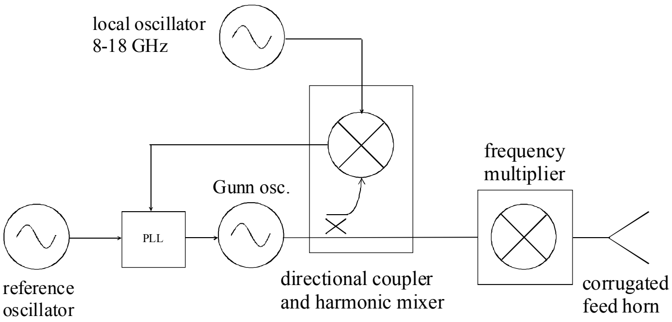

Figure 1. Frequency-multiplied Gunn source (ABmm ESA-1).

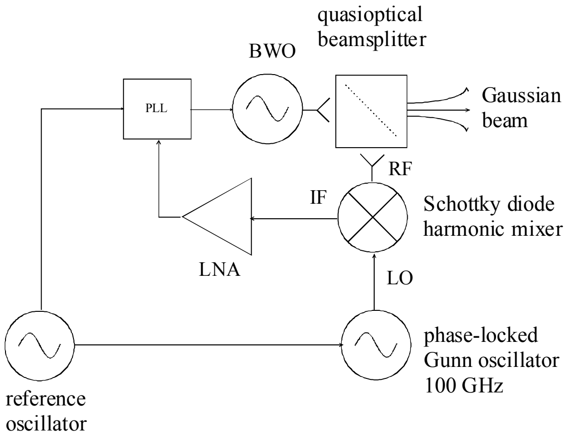

Figure 2. Phase-locked BWO source for >500 GHz.

Receiver

The receiver we have used is a waveguide-type Schottky harmonic mixer pumped by a phase-locked Gunn oscillator [2] (Figure 3). The harmonic number in the mixer is quite small and reasonable conversion losses of about 40 dB at 650 GHz are seen. However, if the newly designed harmonic mixer performs well, it will be used instead.

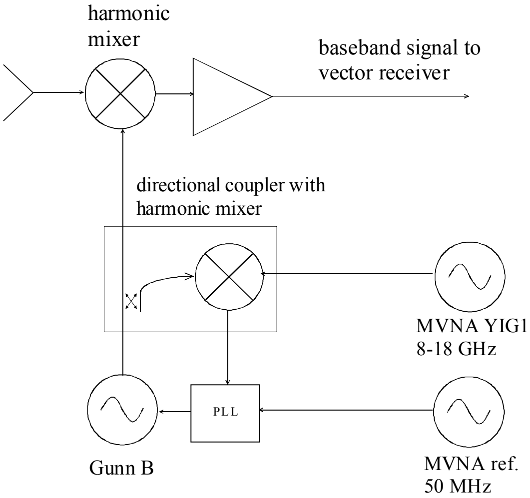

Figure 3. Submillimetre wave receiver (ABmm ESA-2).

Testing of absorber materials

Compact ranges need large amounts of high-quality absorbers in order to suppress reflections. The reflectivities of several commercially available absorbers were tested in the frequency range of 200–600 GHz [3].

Quiet-zone scanning with a near-field scanner

A fully software-controlled quiet-zone field measurement system has been built. It is based on a planar near-field scanner and the MVNA. Triggering and data transfer between the two computers is done through a GPIB instrument control bus. Data acquisition speed depends on the receiver averaging, and can usually be tens of samples per second. The constructed system can also be used for planar near-field measurements for antennas up to 1 meter in diameter with frequencies up to 300 GHz. To further improve the stability of the measurement system, a reference signal source based on an atomic frequency standard with GPS long-time stabilisation is being developed. Also an automatic system for correction of the phase error caused by cable bending is being developed.

Acknowledgements

This work is supported by ESA/ESTEC (contract No. 13096/NL/SB “Submillimeter Wave Antenna Testing Using a Hologram CATR”), TEKES (Finland), and the Academy of Finland. Individual researchers have also received funding from several foundations.

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5. Circuit and component testing

5.1. Automated on-wafer noise parameter testing at 50-75 GHz

Mikko Kantanen, Manu Lahdes, Jussi Tuovinen

MilliLab, VTT Information Technology

Introduction

Noise parameter measurements at mm-wave frequencies are needed in device characterisation as well as in the development and verification of device dependent equivalent circuit models. Especially, noise parameters are essential information during low-noise amplifier (LNA) design process. Wideband on-wafer noise parameter measurements have so far been carried out only up to about 40 GHz. At 50-75 GHz band, measurements with manual input tuner and covering only part of the band has been shown previously [1, 2, 3]. Above 75 GHz, results only on a single frequency and for passive components have been reported [4]. Thus, noise parameters in mm-wave frequencies are usually derived by extrapolation from lower frequencies, using equivalent circuit models. Also, increase in the number of customer measurements in MilliLab creates demand for flexible and faster measurements. Therefore, an unique measurement system has been developed at MilliLab to measure noise parameters of a chip devices over entire 50-75 GHz band relatively fast, with good repeatability and in an automated manner.

Noise parameters are unmeasurable quantities which are determined indirectly by measuring noise figure of a linear two-port with different source impedances connected to the device under test (DUT). At least four noise figure measurements using different source impedances are needed to determine noise parameter set of a minimum noise figure $F_{\min}$, a normalised noise resistance r_n and an optimum source reflection coefficient Γ_{opt}. In order to reduce effect of measurement errors, more than four measurements are usually made and noise parameters are solved using mathematical fitting routines.

Measurement set-up

Figure 1 shows a measurement set-up for a wideband automated noise parameter measurements at 50-75 GHz. Setup can be divided in five functional blocks which are a noise source, a tuner, DUT, a noise receiver and a S-parameter measurement set-up. A solid-state noise source is used as a hot/cold noise reference needed in the noise figure measurement. An automated waveguide tuner is used to change reflection coefficient of the network connected to the input of the DUT. The noise receiver to measure noise power includes a LNA to increase sensitivity and a mixer to down convert the noise power from mm-wave frequencies to microwave frequency region suitable for the standard noise figure meter. The 50-75 GHz band LNA has been obtained through the Planck Surveyor development work [5]. Transition from S-parameter measurements to noise measurements can be made without reconfiguration of the measurement set-up, using the waveguide switches. Measurement system is controlled by computer with in-house written software.

Using the measurement method described by Meierer, *et al.* [6] and Adamian *et al.* [7], only one hot noise power measurement with at least four cold noise power measurements are needed during noise figure measurements. The effect of the receiver to the measurable overall noise figure of the system is taken into account by determining receivers noise parameters during system calibration. Noise parameters are calculated from measured data using noise parameter extraction technique described by Vasilescu, *et al.* [8].

Measurement results

Operation of the measurement system described above has been verified measuring both active and passive chip devices. Excellent agreement between noise parameters determined by measurement system and parameters calculated from measured S-parameters was found for passive devices. DaimlerChrysler InP HEMT was used as an active chip device. The HEMT was set to $V_{ds} = 1.0$ V and $I_{ds} = 10$ mA. The minimum noise figure and the normalised noise resistance measured for HEMT device are presented in Figures 2 and 3, respectively.

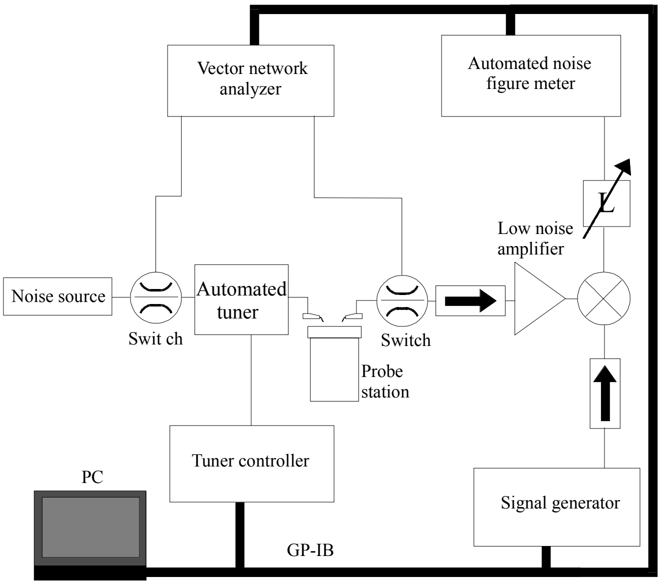

Figure 1: *Measurement set-up for noise parameter measurements at 50-75 GHz.*

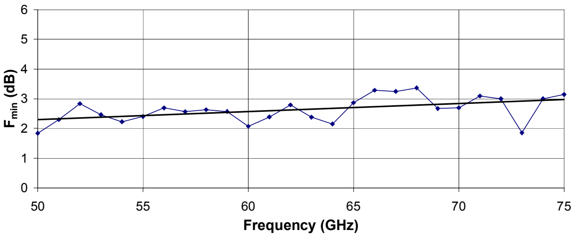

Figure 2: M*inimum noise figure measured for HEMT device.*

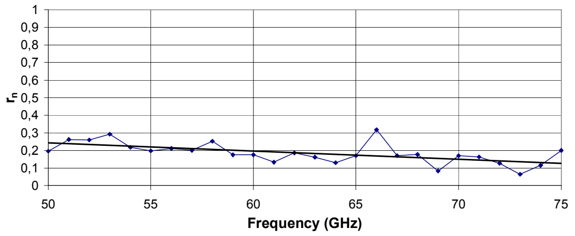

Figure 3: *Normalised noise resistance measured for HEMT device.*

Acknowledgements

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5.2. W-band on-wafer noise parameter measurements

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Introduction

Several current and planned space missions for earth observation and astronomy require very low-noise receivers at W-band. A key component in a W-band low-noise receiver is the low-noise amplifier (LNA). The design of LNAs is greatly dependent on the availability of good noise models for the devices used in the LNAs. To characterise devices in W-band the noise parameters of several In HEMTs in the frequency band 79-94 GHz have been measured. These measurements were based on the cold source method and measurement set-up.

To design an optimum amplifier both noise and scattering parameters are needed. Noise parameters cannot be measured directly. The determination of the noise parameters involves noise figure measurements and data processing. Scattering parameters of a two-port can be measured by using standard commercial vector network analyzers (VNA). However, noise parameter measurements are very challenging. Commercial systems are available only up to 40 GHz. At V-band noise parameter measurement set-up and results have been reported [1]. Measured W-band noise parameters have been presented only for passive devices and at a single frequency [2,3]. This report presents a measurement system which allows simultaneous on-wafer noise and scattering parameter measurements at W-band.

To determine noise parameters, noise figure of the device under test (DUT) with different values of the input reflection coefficients are measured. The noise figure of a two-port as a function of source reflection coefficient Γ_i is given by

$$F = F_{\min} + \frac{4r_n}{1-|\Gamma_i|^2}\left|\frac{\Gamma_i - \Gamma_{opt}}{1+\Gamma_{opt}}\right|^2, \tag{1}$$

where $F_{\min}$ is the minimum noise figure of device, r_n is the normalised noise resistance and the Γ_{opt} is the optimum reflection coefficient. Variables $F_{\min}$, r_n and Γ_{opt} are called noise parameters. Noise parameters are obtained by fitting above equations into the measured data.

Measurement set-up

The measurement system is shown schematically in Figure 1. A photograph of the set-up is shown in Figure 2. The measurement set-up is based on the cold-source method [4]. The improved technique, described in [1], corrects the effects of reflection coefficient changes between cold and hot states of the noise source and takes account losses of the passive network between the DUT and the receiver, is used.

The noise source is used here only due the calibration of the receiver. Also, only a simple 1-port tuner is needed. The 1-port tuner is consists of an adjustable waveguide short and attenuator. The system characterization and S-parameter measurements of the DUT are done by using standard VNA. System characterization is consisted of the S-parameter measurements of the passive networks A-B, C-E and D-E (A-B and C-E are non-insertable) and reflection coefficients of the receiver Γ_{rcv} and the noise source Γ_C, Γ_H (both cold and hot states). Meaning of these reference planes and reflection coefficients are shown in Figure 1. By including two waveguide switches both noise- and S-parameter measurements and the receiver calibration can be done without breaking any connections. The reflection coefficient of the tuner Γ_{tuner} is set and then is measured using the VNA. This is possible due the switch 1. After this tuner is switched to the DUT and the corresponding noise power is measured using the noise receiver which is encircled by dashed line in Figure 1. The LNA is used to increase the sensitivity of the noise receiver. The LNA was obtained through the Planck Surveyor development work [5]. The mixer is used to downconvert the noise power from W-band to the measurement region of the standard noise figure meter.

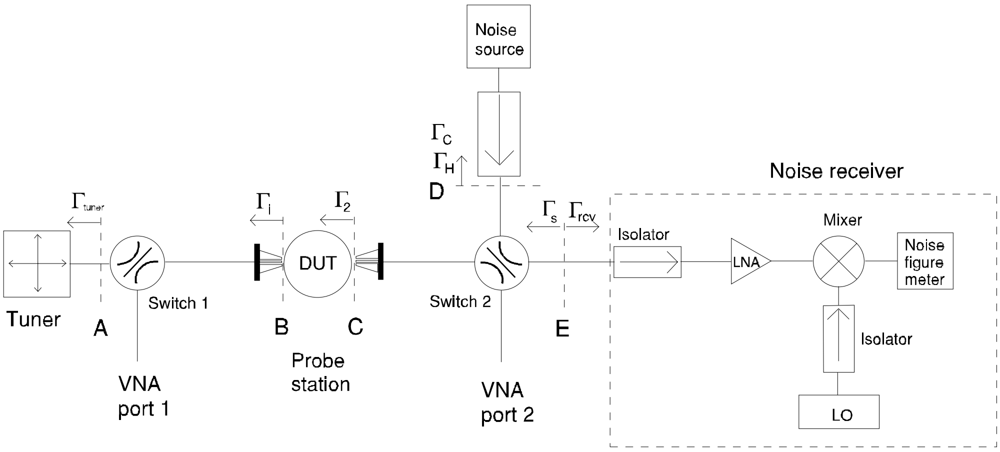
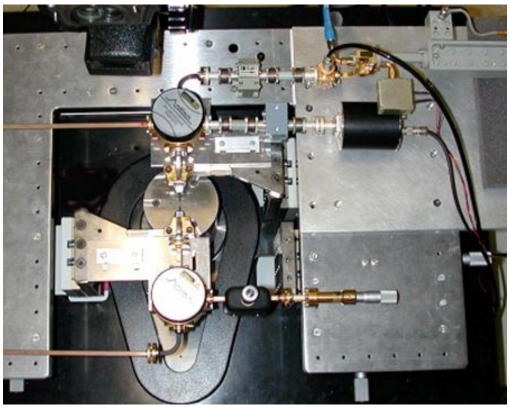


Figure 1. Set-up for noise parameter measurements at 79-94 GHz.

Results

As a DUT a DaimlerChrysler InP HEMT is used which has 0.18 µm gate length and 2 x 40 µm gate width. During the measurements the HEMT was set to the operating point: a drain voltage V_{ds} of 1.0 V and a drain current I_{ds} of 10 mA. The noise parameters are calculated from measurements by using Lane's method [6]. The mean value of the noise parameter were: $F_{\min =}$ 2.9 dB, $r_n = 0.30$, $|\Gamma_{opt}| = 0.46$, and $\angle\Gamma_{opt} = -140$ degrees. The minimum noise figure of the HEMT is shown in Figure 3. To show repeatability three different measurements are presented.



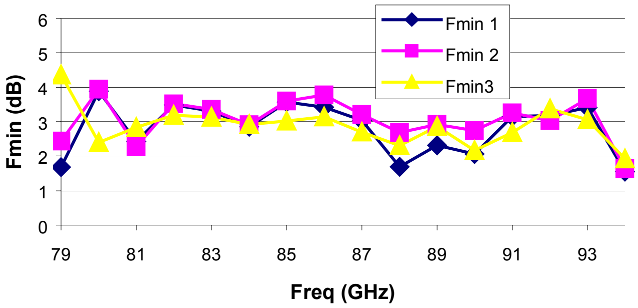


Figure 2. Photograph of the measurement set-up. *Figure 3. Measured minimum noise figure of an InP HEMT.*

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5.3. Cryogenic on-wafer measurements

Jussi Varis, Jussi Tuovinen, Manu Lahdes, Timo Karttaavi, Hannu Hakojärvi

MilliLab, VTT Information Technology

Introduction

In order to achieve a very low noise performance, the millimeter wave receivers are often cooled to cryogenic temperatures. As an example, in the Planck Low Frequency Instrument (LFI) the MMIC low noise amplifiers (LNA) and phase shifters will be cooled down to 20 K to improve the performance of the receivers. For this reason, it is also necessary to characterise the MMIC performance at cryogenic temperatures. The on-wafer tests performed at MilliLab include DC testing, S-parameter measurements up to 110 GHz, 1/f noise measurements, and noise figure measurements up to 75 GHz.

During 1999-2000, the functionality of the measurement set-up has been further enhanced by adding a video microscope and a 1-D translation stage for the cold plate. These improvements enable larger operating area on a wafer. In the experiments, the major emphasis has been on the development of cryogenic noise figure measurement. This report describes the measurement set-up for cryogenic on-wafer tests used at MilliLab, and gives results of tests performed on MMICs at 20 K.

Cryogenic measurement set-up

The measurement set-up [1] shown in Fig. 1 consists of a vacuum chamber and a closed cycle helium refridgerator capable of cooling MMICs down to 15 K. The MMICs under testing are placed inside the vacuum chamber on a cold plate (diameter 50 mm). This plate is connected to the cooling system via flexible cold fingers. The temperature of the cold plate can be adjusted continuously between 15 and 300 K with temperature stability of ±0.2 K. The cooling time is approximately 100 minutes. The millimetre wave signal is connected to the device under test using coplanar measurement probes and waveguides consisting of copper and stainless steel. An additional probe is used for delivering DC bias. The probes are connected to the cooling system with cold fingers. The stainless steel in the waveguides is used for temperature isolation and for enabling probe movement. In addition, the cold plate can be moved in one direction. The loss due to the waveguide and the measurement probe is about 3 dB. The probes are connected to x-y-z positioners outside the vacuum chamber with steel rods.

Figure 1. Cryogenic on-wafer measurement set-up at Millilab, VTT Information technology.

Measurement results

Figures 2 and 3 show examples of S-parameter and noise figure measurements carried out at the cryogenic on-wafer measurement set-up at 20 K. In Figure 2, S-parameters of an InP PIN diode phase shifter measured with bias voltages 0.8 V and -0.8 V are shown. The results indicate a 180 degree phase difference with a power consumption less than 1 mW. The transmission loss is well balanced between the two states as well. In figure 3, the gain and noise figure of a 4-stage InP LNA was measured in bias point V_{ds}=1 V, I_{ds}=20 mA. The obtained insertion gain was in excess of 30 dB. The measured noise figure was about 1 dB. However, the noise figure result sufferes from high ripple lowering the confidence of the estimate.

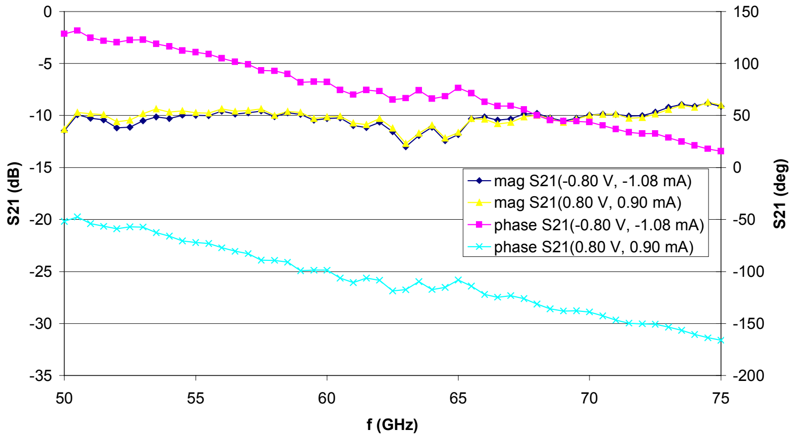

Figure 2. Measured on-wafer S-parameters of an InP PIN diode phase shifter at 20 K.

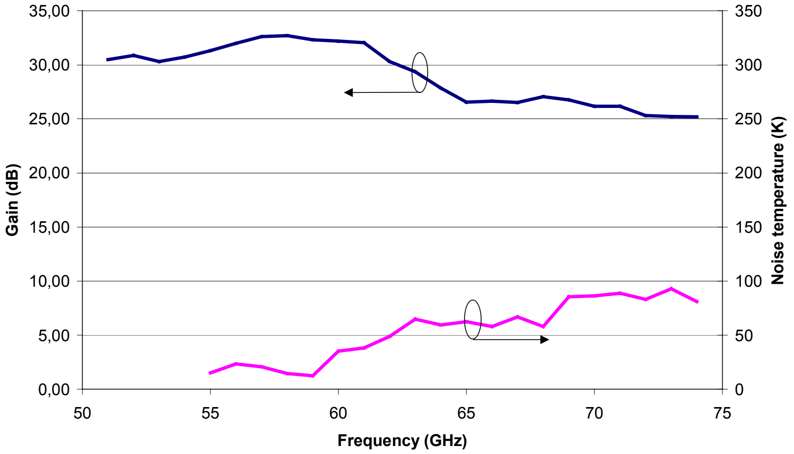

Figure 3. *Preliminary on-wafer gain and noise temperature results of an InP HEMT 4-stage LNA at 20 K (V_{ds}= 1V and I_{ds}=20 mA).*

Future plans

The noise figure measurements suffer from large ripple and low sensitivity of the noise receiver used. Especially, the calibration of the noise measurement setup is particularly demanding at cryogenic temperatures. Future efforts are concentrated on improving the sensitivity of the receiver and the quality of the calibration, which will require to place the noise source inside the cryo dewar.

Acknowledgments

This work has been supported by ESA contracts and funding from Technology Development Centre, Finland.

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5.4. Development of a primary power measurement standard

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Introduction

This activity is related to MilliLab's strategy of developing millimetre wave power measurement and power standard capabilities at frequencies above 110 GHz. At these frequencies, waveguide power standard services are not available generally although the technology in telecommunications, radar, space technology etc. will be increasingly requiring accurate power measurements or calibrations. Thus, a need for a supply of such services is seen, and MilliLab - as an ESA External Laboratory - is developing this area as one of its near future technology spear heads. The first project "Initial development work for a primary power measurement standard for D-band" is continuing. It is accompanied by the next stage, called “Development work for a primary power measurement standard for D-band, second phase”, now also under progress. MilliLab's power standard development is supported by research in dielectric materials and especially in their application to dielectric waveguides. These are needed for replacing relatively lossy metal waveguides. Low losses are required for high sensitivity and especially for high accuracy which is the main requirement in any power standard device. A primary power standard possibly to be used also as a national power standard will have stringent requirements as a calibration reference.

Activities in 1999-2000

During 1999-2000, MilliLab continued establishing contacts in the field of millimetre wave power measurement. Contacts in Europe resulted in a cooperation on designing and manufacturing power standard devices and a total system. Thus, with the conclusion of the two first projects, MilliLab will have a working power standard system available up to 170 GHz. Manufacturing is to take place in company Elmika, Lithuania. In MilliLab, a dielectric waveguide in the input section has been estimated as a major new possibility for improving the power standard design for high millimetre wave frequencies. Due to this, dielectric waveguide materials and designs have been investigated in MilliLab with a focus on high-epsilon materials, such as sapphire and semiconductors. Several important activity subareas were under progress, covering material aspects, theory, computer simulations and even very practical measurement set-up development. A new very stable resonator system was procured and received. This system is to be set up for most accurate dielectric material characterisation (for determination of permittivity and loss tangent).

As a companion activity, in year 2000 MilliLab started to pursue another quite a different way of developing power sensors. Besides millimetre wave engineering skills, this new sensor approach is based on using modern microelectronic processing knowledge and capability in order to manufacture a small integrated sensor. Processing expertise is well available in MilliLab’s parent organisations. Computer simulations and sensitivity estimations were found to be promising and thus first practical experimental designs are now in target for near future.

Development views

The first power standard system to be available in MilliLab will still mostly be relying on present conventional and approved features used in waveguide power standards. However, one of the devices is targeted to include a low-loss and highly thermally isolating dielectric waveguide input section designed in MilliLab. Backed up by some smaller enhancements, this is the first step of a main new development which also opens way to new designs of power standards applicable at increasingly high millimetre and submillimetre wave frequencies. It is obvious that obtaining and maintaining very high accuracy and reliability for standards at these frequencies is quite a challenge. This is best possible by taking suitable steps in adapting new technology into the designs. Continuous comparison and verification with previously existing standard devices (in common overlapping frequency bands) is important and also this practice will be possible in MilliLab.

Conclusions

MilliLab is progressing towards having in near future a D-band (110-170 GHz) power standard system possibly to be used also as a national standard. Further development of power standard devices with properties scalable even for usage at still higher millimetre and submillimetre frequency has been studied and initiated. Application of low-loss dielectric waveguides and benefitting from modern microelectronic processing capabilities are seen to offer great potential.

Acknowledgments

This work is supported by ESA contract No 11655/95/NL/MV in CO8 of WO01 "Initial development work for a primary power measurement standard for D-band" and in CO10 of WO01 "Development work for a primary power measurement standard for D-band, second phase" and funding from Academy of Finland.

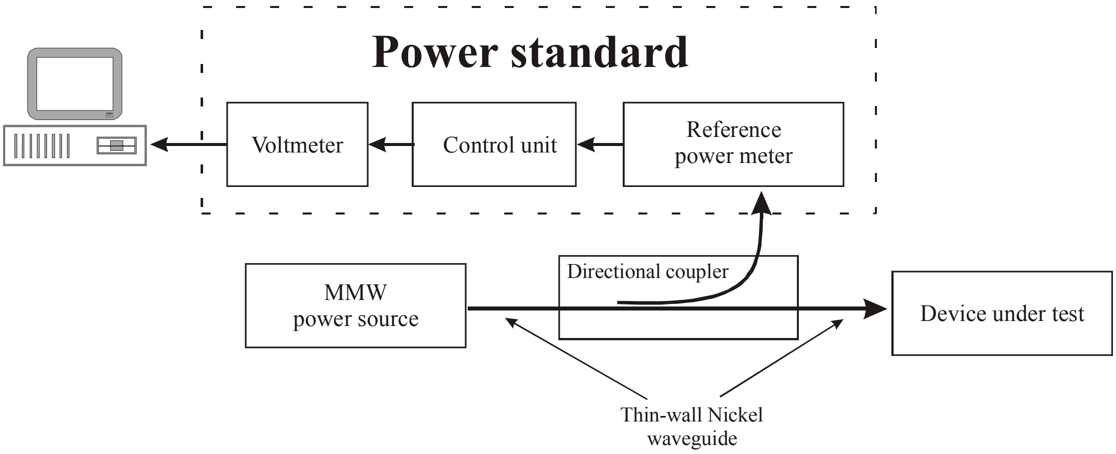

Figure 1. Simplified block diagram of a power measurement device calibration set-up.

6. Systems, components, and circuits

6.1. Receiver for the Planck Surveyor Low Frequency Instrument (LFI)

Jussi Tuovinen[1], Timo Karttaavi[1], Manu Lahdes[1], Jussi Varis[1], Nicholas Hughes[2], Pekka Kangaslahti[2], Petri Jukkala[2], Tho LeCong[2], Pekka Sjöman[3], Olli Koistinen[3] , Seppo Urpo[3]

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Introduction

The aim of the European Space Agency (ESA) Planck mission, to be launched in February 2007, is to measure the Cosmic Microwave Background (CMB) anisotropy with a great angular resolution (10' at 100 GHz) and radiometric sensitivity ($\Delta T / T = 4.3\times10^{-6}$) [1,2]. The Planck spacecraft will have two instruments on-board: Low Frequency Instrument (LFI) and High Frequency Instrument (HFI). Both instruments will utilise a common 1.5 m aperture offset reflector antenna. LFI will have channels at 30, 44, 70, and 100 GHz. The number of receivers at each frequency is 4, 6, 12, and 34 respectively. Both polarisations will be measured at all LFI frequencies. Each corrugated horn on the focal surface will be followed by an orthomode transducer (OMT) to separate the two polarisations. Therefore, the number of feed horns is half of the number of receivers. HFI, based on bolometer technology, will have channels at 100, 143, 217, 353, 545, and 857 GHz and 4, 12, 12, 6, 6, and 6 detectors at each frequency, respectively. The LFI receivers will make use of Monolithic Microwave Integrated Circuits (MMIC) and the key components will be the Low-Noise Amplifiers (LNA). Because of the very low-noise performance requirements, the MMIC chips will be made using an Indium Phosphide (InP) High Electron Mobility Transistor (HEMT) technology. At the two lower frequencies 30 and 44 GHz, instead of MMICs discreet HEMTs on a substrate (MIC technology) will be used.

Program for 70 GHz receivers

The 70 GHz receivers, excluding the horns and OMTs, will be built by the Finnish team lead by MilliLab [3]. So called Front-End (FEM) and Back-End Modules (BEM) will be delivered. The whole 70 GHz instrumentation project is divided in to eight phases. The first three phases to develop proper MMIC chips and to breadboard the receiver technology are:

- Phase 00: This will provide a selection of MMIC building blocks developed using a European foundry.
- Phase 0: The activity should enable the integration of the building blocks provided by Phase 00 and the demonstration of a feasible radiometric receiver.
- Phase Ia: TRW Evaluation. This activity is necessary for the advanced evaluation of the TRW MMIC process and selection of the most suitable MMIC source.

These phases have been mostly completed and are part of the Pre-Phase B activity of the mission. In year 2000, the Phase B of the mission has stared, which includes the development work prior the qualification model. The first two ongoing steps in Phase B of the mission at 70 GHz are:

- Phase Ib: EBB (Elegant Breadboard Model). This continues the work of Phase 0. The Elegant Breadboard is foreseen as a receiver which is representative in shape, size, and interfaces and uses representative circuit components with respect to the real flight hardware.
- Phase III: Cryogenic Microwave Test Subsystem. A test subsystem to support EBB, QM, FM, and FS test campaigns is provided. Among other thing, this includes a large dewar, about 1.6 m x 1.2 m x 0.5 m in size, and coolers for 4 K and 20 K stages.

Next Phases will be Phase Ic: Main Batch MMIC Manufacture, starting year 2001; Phase II: MMIC Qualification, 2001; Phase IV: QM (Qualification Model), 2001; Phase V: FM (Flight Model), 2003; Phase VI: FS (Flight Spare), 2004.

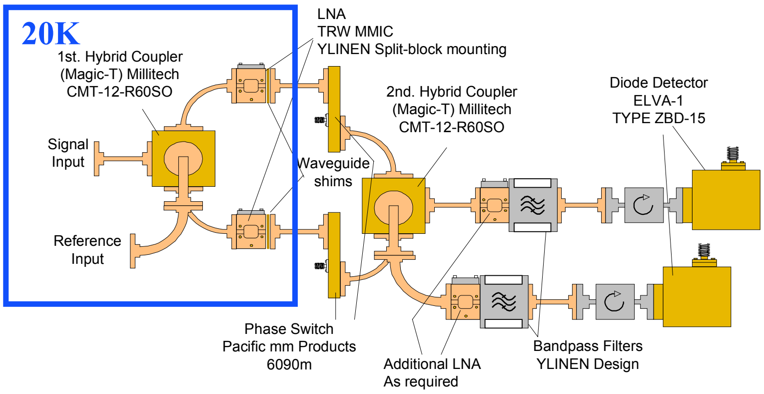

Figure 1. Planck LFI prototype receive at 70 GHz. In the final version of the receiver, the phase shifters and the second hybrid, which are also part of the Front-End Module (FEM), will be at 20 K.

Receiver architecture

The prototype receiver is shown in Figure 1. The LFI receivers with front-ends cooled to 20 K are direct detection radiometers where signal is first amplified sufficiently, approximately 65 dB, and then detected with a diode. The time scale of the stability of the receiver is driven by the 1 rpm rotation speed of the spacecraft, which leads to a very low 1/f noise or gain variation of the LNAs (and other components). The extreme stability is obtained by this continuous comparison, where the difference between the reference and source is measured simultaneously. The effect of the gain variation (or 1/f noise) of the front-end LNAs between the two hybrids is significantly reduced, because both the signal and reference are amplified by the common two lines of amplifiers. The second hybrid is used to reseparate the signal and reference. The effect of the 1/f noise of the LNAs and detector diodes after the second hybrid is reduced by switching the output ports of the signal and reference channels of the second hybrid using a phase shifter(s) between the hybrides. A magic-T is used as the hybrid. A compact Front-End Module (FEM) design in shown in Figure 2.

Development and testing of MMICs is of crucial importance. To develop LNA and phase shifters, several InP MMIC HEMT and PIN diode runs using TRW, DaimlerChrysler, and HRL have been completed. State-of-the-art low-noise results have been obtained for the LNAs using the TRW process. Both, the MMIC development and testing are described separately in more detail in this report.

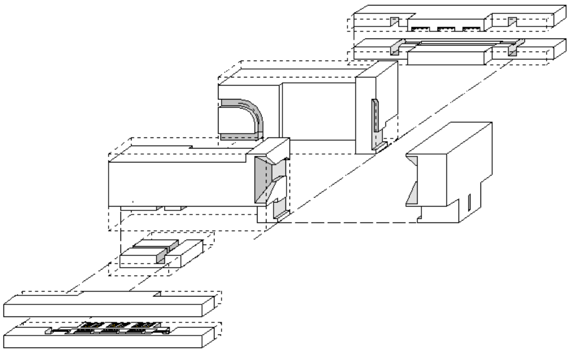

Figure 2.One half of a Front-End Module (FEM) for Planck LFI 70 GHz receiver. This compact unit with six MMIC chips is about the size of a matchbox.

Acknowledgements

This work is supported by ESA contracts No 12681/97/NL/NB "MMICs for Receiver Array" and No 12851/98/NL/NB "Critical Technology for Millimetre Wave Radiometers" and funding from the National Technology Agency TEKES, Finland.

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6.2. MMIC Low-Noise Amplifiers for 70 GHz

Timo Karttaavi[1], Pekka Kangaslahti[2], Manu Lahdes[1], Olli Koistinen[3], Jussi Tuovinen[1]

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Introduction

European Space Agency's Planck-mission aims to use cryogenically cooled monolithic low-noise amplifiers in the Low Frequency Instrument (see previous chapter). The application requires amplifiers with a 30K noise temperature at 70 GHz. This is expected to be achievable with cryogenically cooled Indium-Phosphide (InP) HEMT (high electron mobility transistor) technology. InP-based transistors have shown the lowest noise combined with very high cut-off frequencies. To evaluate the performance of this technology, several foundry runs using different suppliers have been carried out. Two of these runs were at DaimlerChrysler Research Center in Ulm, Germany, Two at TRW and one at HRL laboratories, both in the United States..

Amplifiers

A total of over 20 amplifier designs for the Planck frequency band have been submitted in the different processing runs. In addition to this, the wafers have included some W-band amplifiers (94 GHz), phase shifters, hybrid couplers, power detectors, as well as test and calibration structures.

Because all the used processes are more or less experimental we have invested considerable effort in modeling the small-signal and noise properties of the transistors for the design process. This has been done by characterising the devices with noise parameter measurements at V-band and scattering parameter measurements up to 110 GHz.

The DaimlerChrysler process does not have via holes which makes coplanar construction the only choice. The transistor gate length is 0.15 µm whereas TRW and HRL achieve nominally a 0.1 µm gate length. They also process via-holes and backside metallization which enables the use of microstrip transmission lines. The measured minimum noise figure of these devices at 70 GHz is normally below 3 dB.

As an example of the amplifiers Figure 1 shows a photograph of a 4-stage microstrip design from a TRW wafer.

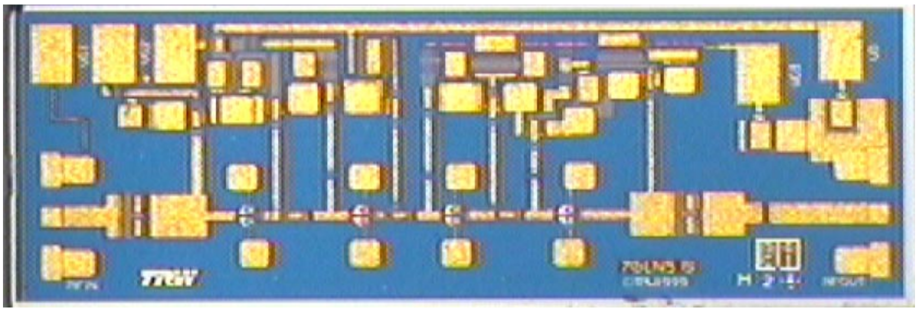
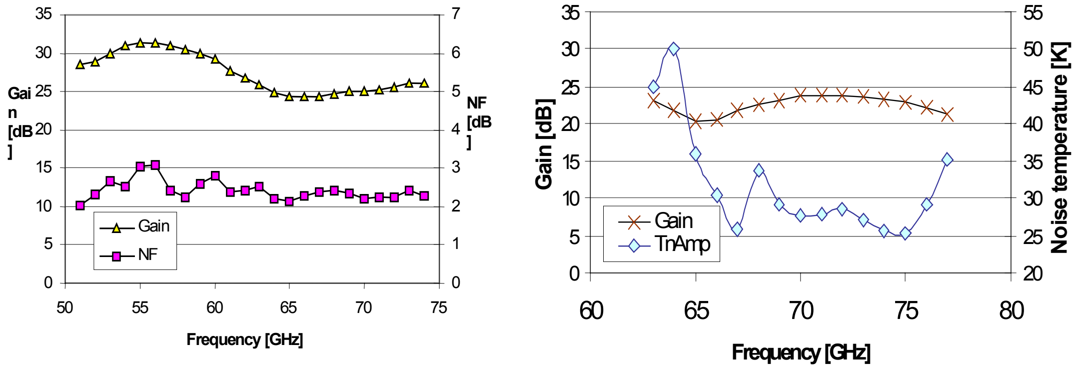


Figure 1. Photograph of a four-stage 70 GHz low-noise amplifier. Size is 2.1 x 0.8 mm^2.

Measured performance

Figure 2a shows the measured frequency response of the four-stage amplifier in room temperature. It has a gain of 25 dB and a noise figure of 2.5 dB at 70 GHz. Figure 2b shows the gain and noise temperature for one of the amplifiers packaged in a WR-15 waveguide housing. The noise temperature is below 30 K with a power consumption of 3.3 mW. The results have been reported in more detail in [1-4]



a) b)

Figure 2. a) Measured gain and noise figure of the four-stage LNA in room temperature. b) Performance of a packaged amplifier cooled to 20 K.

Conclusions

These foundry runs have greatly increased our understanding of the InP HEMT technology, and the latest results are already very promising in regard to the requirements of the Planck mission. Some work is still required to fine tune the performance once the foundry supplier is chosen.

Acknowledgements

This work has been supported by ESA contracts No. 12681/97/NL/NB "MMICs for Receiver Arrays" and No. 12851/98/NL/NB "Critical Technology for Millimetre Wave Radiometers".

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6.3. MEMS impedance tuners

Tauno Vähä-Heikkilä, Jussi Varis, Jussi Tuovinen

MilliLab, VTT Information Technology

Introduction

Optimum design of low-noise amplifiers, which usually determines the sensitivity of receivers, requires the knowledge of both transistors noise and S-parameters. On-wafer S-parameter measurements can be performed with standard measurement systems at least up to 110 GHz. However, noise parameter measurements are very challenging at millimeter waves. One of the main complication of noise parameter measurements as frequency increases is the increasing loss between the impedance tuner and device under test (DUT). It is essential to minimise this loss and to have the tuner as close as possible to the DUT. Ideally, an active probe tip with an impedance tuner should be used. Around 20 GHz this kind of tuner has been tried. However, at mm-waves these are not available in a practical form yet. The loss between the tuner and DUT reduces the maximum magnitude of the reflection coefficient or in other words the range of impedances possible to create at the input of the DUT. In the present MilliLab set-ups at V-band a loss of 1.5 dB exists between the tuner and DUT. The use of microelectromechanical systems (MEMS) techniques creates unique possibilities to realise very small size tuners, which can be placed close to the DUT. In this activity advantages of micromachining for realizing a practical impedance tuner will be studied.

The main application of the planned tuner will be to facilitate efficient on-wafer noise parameter measurements up to 110 GHz. On-wafer noise parameter measurements are one of the unique state-of-the-art capabilities in MilliLab, VTT Information Technology. The need for a new type approach in the present measurements systems has been seen important. Despite the planned main application is in the measurement methods developed, impedance tuner or part of them can be applied also for commercial and other applications. For example, adaptive or smart antennas need tuners and phase shifters.

Preliminary study for possibilities to use MEMS tuner at noise parameter measurements and possible design considerations have been started and is presented. Realisation of these tuners is planned to be a part of an ESA project.

Design for mm-wave micromechanical tuner

Impedance can be tuned by varying the electrical length of the transmission line. This can be done for example by sliding a planar tuning element on top of a planar transmission line or by switching metallic bridges.

Tuner design with planar sliders

By placing a solid metallic plate across coplanar transmission line, with a thin dielectric layer in between, a section of a lower-impedance transmission line can be formed [1]. The impedance discontinuity at the leading edge of the plate would result in the partial reflection of any incident signal being guided along the coplanar line. If instead of a solid metal plate a proper metal pattern is used, this reflection could be greatly increased and made to function over a well-defined and broad bandwidth. Ideally, the metal pattern covers the coplanar line for a distance of one quarter-wavelength of the desired working frequency, creating a section of lower-impedance line. The pattern then opens up to restore the original higher-impedance line for a distance of one quarter-wavelength. This can be repeated several times to create several impedance discontinuities, which together have a cumulative effect equivalent to one very large impedance discontinuity at the leading edge of the fist section. The impedance at the edge of tuning element with n sections would be

$$Z = \left(\frac{Z_{low}}{Z_{high}} \right)^{n} Z_{low} \tag{1}$$

where Z_{low} is the impedance of the sections of line covered by the metal pattern, and Z_{high} is the characteristic impedance of the line were it is left uncovered. In this equation, it is evident that with a large number of sections, Z can be made much lower than the Z_{low} created by a single covered section.

Figure 1 shows the concept of the 5-section planar impedance tuner. ε_r is the dielectric constant of the substrate, ε_r^i is the dielectric constant of the insulator. This kind of structure allows a variation for the electrical length of the transmission line by varying the position of the sliding tuner. Tuning element can be moved by using electrically-controlled actuators.

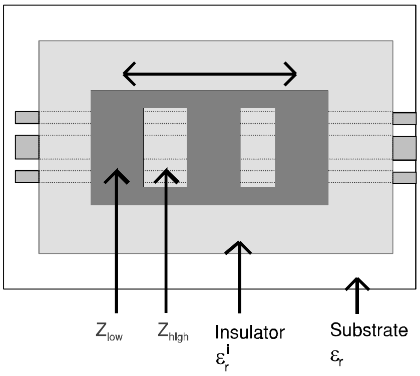

Figure 1. 5-section planar impedance tuner.

Tuner design with MEMS switches

Impedance (and the phase velocity) of a transmission line can be tuned by capacitively switching MEMS switches on and off [2]. Feasible components based on MEMS switches are, e.g.,capacitive shunt switch, resistive series switch, and distributed MEMS transmission lines (DMTL). When a DC bias is applied to a capacitive switch, the voltage difference between the signal line and ground pad generates a strong electric field underneath the membrane of the MEMS switch, which will force the membrane to snap down (pull-down condition). The inherent elasticity of the metal will help to bounce the membrane back to original state after the bias is released. MEMS switch is shown schematically in Figure 2.

This type of tuner can be like the phase shifter. The phase shifter consists of a coplanar waveguide transmission line loaded periodically with several shunt MEMS capacitors. Thus the circuit can be considered as a transmission line whose impedance (phase velocity) can be varied by switching the MEMS capacitive switches on and off. For example, the stub-series-type tuner can be realised with a switch design like shown in Figure 3. In the design, the MEMS switches form bridges over the CPW, and with a pair like switch 1 and switch 2 in Figure 3 suitable electrical lengths can be selected.

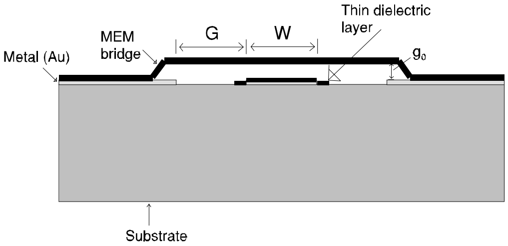

Figure 2. MEMS switch.

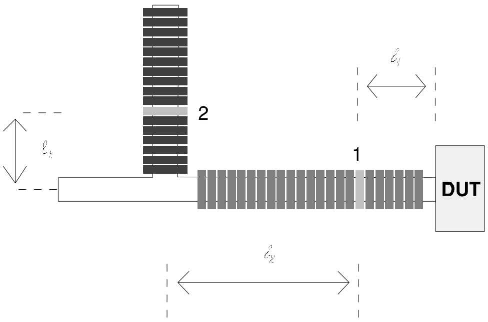

Figure 3. Phase shifter type impedance tuner.

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6.4. Low loss dielectric waveguides

Dmitri Lioubtchenko[1], Sergey Dudorov[1], Juha Mallat[1], Jussi Tuovinen[2], Antti V. Räisänen[1]

[1]MilliLab, Radio Laboratory, Helsinki University of Technology
[2]MilliLab, VTT Information Technology

Introduction

Problems in single-mode metal waveguide applications appear at frequencies above 75 GHz. This is most notably due to increasing losses when the operation frequency increases and waveguides get smaller. MilliLab is doing research to overcome such problems especially in relation to the power standard development. The use of a thin wall waveguide (of nickel) is typically needed in a primary power standard but there are complications. At high millimeter wave frequencies these are related to manufacturing, power propagation, and thermal isolation characteristics. Dielectric waveguides are promising to be used instead of metal ones due to low propagation losses and better thermal isolation possibilities. The dielectric waveguides should have extremely low propagation losses at high frequencies if made of monocrystalline materials. However, the experimental performance and matching with metal waveguides need studying and development.

Here we present, as an example of our activity initially in W-band at around 100 GHz, some computer (FEM) simulation and experimental results of a Dielectric Rod Waveguide (DRW) made of single crystal sapphire. Simple tapering was used for waveguide matching (Fig.1). However, different tapers give different results [1-3]. Simulation results show that the tapering in *E*-plane is better for matching (here to a WR-10 metal waveguide).

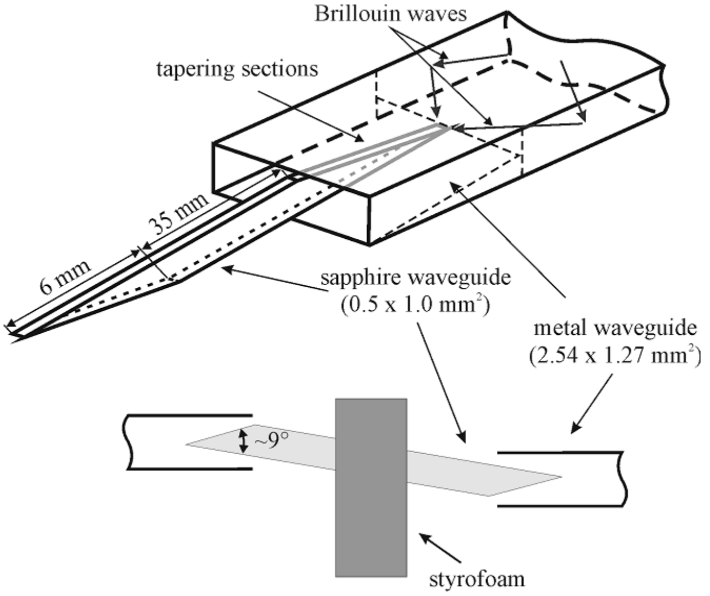

Figure 1. Experimental set-up for a sapphire DRW section between metal waveguides.

Results

Single-mode rectangular dielectric waveguides with cross section of 0.5x1.0 mm^2 with refractive indexes 3.0 (sapphire) and 3.41 (silicon) were simulated. It was found that in spite of small aperture overlapping, good transmission characteristics are obtained (better than -20 dB return loss and 0.16 dB insertion loss – this in total with two transitions). The simulation results are shown in Fig. 2.

Experimental results for monocrystalline sapphire DRW in the frequency range of 75-110 GHz are shown in Fig. 3. It can be seen that the standard metal waveguide section has an insertion loss of 0.4-0.55 dB while the sapphire one has it mainly between 0.1 and 0.3 dB and sometimes even near 0.05 dB. From 98 GHz upwards the losses increase and decrease approximately between 100-103 GHz. This can be explained by difficulties of the excitation occurring due to tapering sections, which are non-symmetrical with respect to the optical axis of the DRW. The discrepancy of S_{21} curves (Fig. 3a) for three different DRW might be due to their small non-identities.

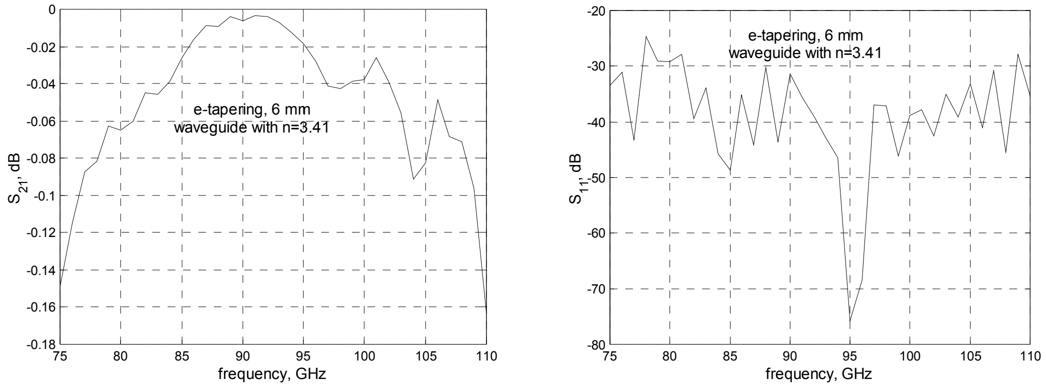

Figure 2. S-parameter simulation results for a silicon waveguide with tapering in E-plane.

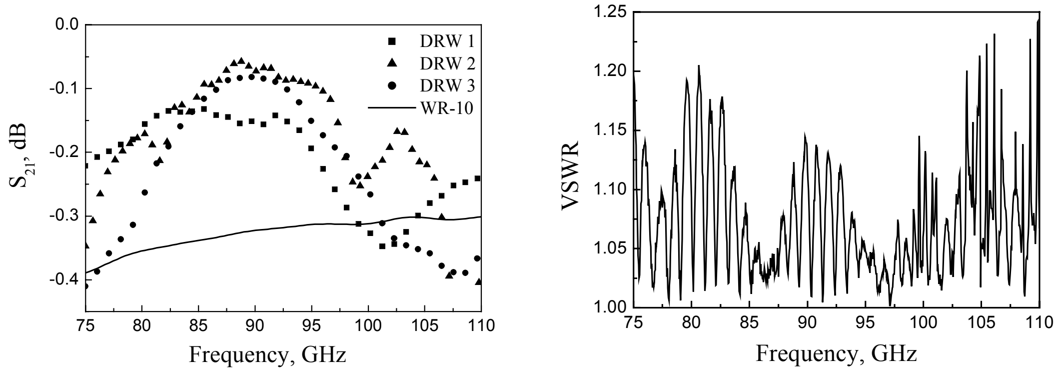

Figure 3. Transmission characteristics of three different sapphire waveguides and typical VSWR.

Conclusions

In conclusion, we can say that a DRW with high permittivity can have low loss and be well matched with a single-mode metal waveguide (Fig. 3). In addition, DRW makes possible excellent thermal isolation due to an air gap between metal waveguide and DRW. Thus, the use of DRW instead of a standard thin wall metal waveguide as an isolation section in a primary power standard is attractive. Future work will focus to DRW development at around 170 GHz and at even higher frequencies.

Acknowledgments

This work is supported by ESA/ESTEC investment funding to MilliLab and funding from Academy of Finland.

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6.5. Passive components for mm- and submm-wave receivers

Ville Möttönen[1], Petri Piironen[1, 2], Antti Räisänen[1]

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[2]ESTEC-European Space Agency, Payload Systems Division (TOS-ETP), Noordwijk, The Netherlands

Introduction

More effective passive components and circuit topologies are required in order to increase sensitivity and integrability of mm- and submm-wave receivers. Passive receiver structures are developed within several independent projects or studies. The main work is done in two ESA projects, KASIMIR- and hologram project.

KASIMIR-project

KASIMIR-project for developing integrated receiver front-end techniques and European planar Schottky diodes at mm and submm wavelengths was started in 1996 and continued through 1997–2000 [1]. The prime contractor of the project is Astrium GmbH (former DaimlerChrysler Aerospace/Dornier Satellitensysteme GmbH) and the sub-contractors are Chalmers University of Technology (CUT), Ecole Polytechnique Fédérale Lausanne (EPFL), Gesamthochschule Wuppertal (GHW), Radiometer Physics GmbH (RPG), Technical University of Darmstadt (TUD), and HUT/Radio Laboratory. In addition, MilliLab became involved in 1997.

The goal of the project is to fabricate 650 GHz quasi-vertical Schottky diode mixers using both open structure and waveguide techniques. HUT is responsible for a subharmonic waveguide mixer and EPFL together with CUT for a fundamental open structure mixer. RPG fabricates the block of the subharmonic waveguide mixer and designs a fundamental waveguide mixer. TUD develops the Schottky diodes required in the mixers. Furthermore, GHW concentrates on the antenna lens analysis for the open structure mixer. Expertise of MilliLab aids the Schottky diode modeling efforts of HUT.

The waveguide mixer is based on the subharmonic mixing principle where the LO frequency is only about one-half of the RF frequency. The mixing is accomplished with an anti-parallel pair of quasi-vertical Schottky diodes integrated into a single GaAs chip. The advantage of this is an inherent fundamental mixing rejection. The structure of the mixer is sketched in Figure 1. An integrated diagonal horn antenna is used as the signal feed. RF and LO signals are input to on a quartz substrate soldered diode chip through rectangular waveguides and a quartz microstrip filter. The ends of the filter work as probes for RF and LO waveguide to microstrip transitions. The impedance matching is provided by series and parallel waveguide tuners. The produced IF signal is output through an IF filter and a coaxial connector.

The main work has been done on the preliminary characterisation and modelling of diodes and designing of the quartz filters and mixer block. The design of the 650 GHz waveguide mixer was preceded by a set of scale models (5, 10, and 220 GHz). The tests of a 220 GHz mixer have yielded a single sideband (SSB) noise temperature of 3500 K and conversion loss of 9.2 dB with an applied LO power of 3.5 mW [2]. Currently, the 650 GHz mixer is being assembled so that required tests could be finished by the end of the summer 2001.

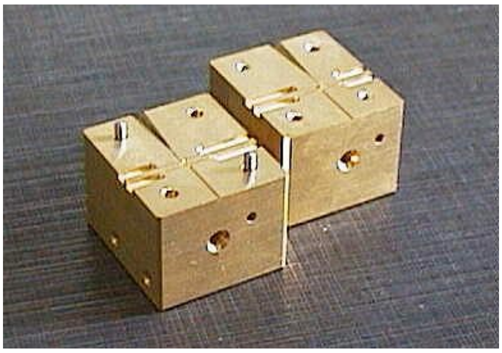

Figure 1. Photograph of split-blocks of a 650 waveguide mixer.

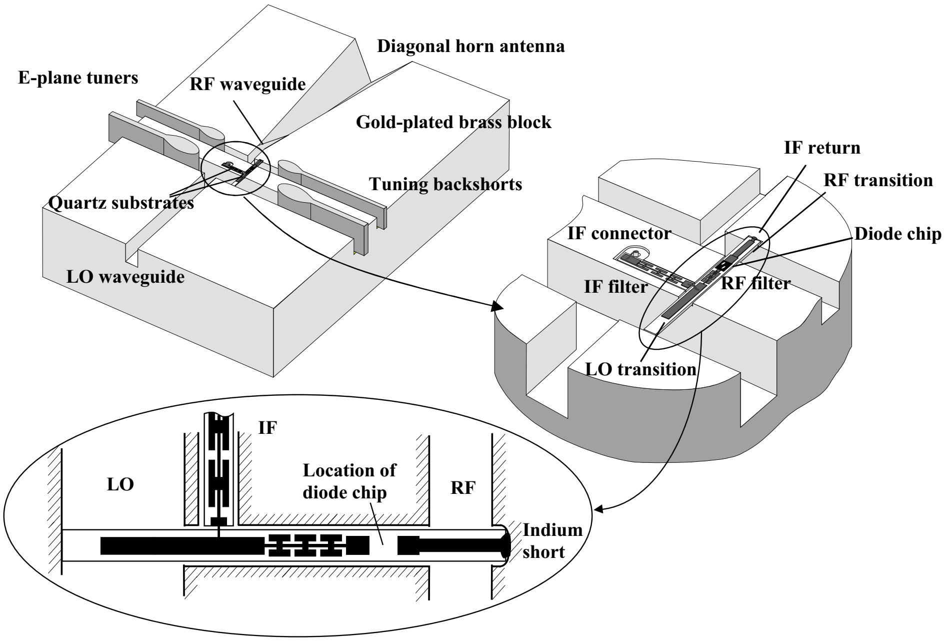

Figure 2. Structure of a 650 GHz subharmonic waveguide mixer.

Hologram project

A submillimetre-wave receiver with a harmonic mixer is needed in order to construct a phase-locked BWO source for a hologram-based compact antenna test range. In addition to phase locking, the new receiver could be used as the actual receiver in antenna tests instead of a current whisker-diode-based receiver.

The receiver will comprise an integrated structure of a diagonal horn antenna and fifth-harmonic mixer with planar Schottky diodes. The operational RF band is designed to 500–700 GHz with the corresponding LO band as 100–140 GHz. The receiver will have waveguide access ports and a mixer circuit on a quartz substrate with a coaxial IF output.

Other developments

Receiver structures are also being developed in other studies, e.g., new waveguide-to-coplanar-waveguide transitions especially suitable for MMIC designs, a new tunable waveguide backshort, and a wideband bias-T [3].

Acknowledgments

Works are mainly supported by ESA/ESTEC (contracts No 13096/NL/SB and No 11806/96/NL/CN), Technology Development Centre (Finland), and the Academy of Finland.

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7. Abstracts of examination theses

Thesis for the degree of Doctor of Technology, January 22nd, 1999
Jian Zhang
Diode modeling and circuit design of microwave and millimeter-wave frequency multipliers and mixers

ABSTRACT

This work contributes to two research fields: 1) the step recovery diode (SRD) and its applications; and 2) the quasi-vertical planar diode and its application in millimeter- and sub-millimeter-wave mixers.

The state of the art of the SRD and its applications are reviewed from the very beginning up to now. This review gives a broad overview of the SRD and its applications. It shows also the great prospect of the SRD being utilized in the millimeter-wave range. To make the simulation of SRD circuits easier, a new SRD model for CAD is developed by considering the transition process in the SRD. Furthermore, a method for improving the efficiency of CAD of SRD frequency multipliers is proposed. A systematic design of an SRD frequency multiplier is implemented with computer-aided design tools. The experiment shows that the simulated results can be used to guide the multiplier design very well to achieve high conversion efficiency. In addition to this, a fast and accurate technique for characterizing the SRD by using a network analyzer is developed. A flexible test fixture is designed for measuring SRD chips. A more accurate SRD model is established experimentally.

The novel quasi-vertical planar Schottky diode is being developed in prospect of replacing the whisker contact diode, which is used in the millimeter- and sub-millimeter-wave waveguide and open structure mixers. Wide-band equivalent circuits of the single quasi-vertical planar Schottky diode (QVPSD) and the quasi-vertical planar anti-parallel Schottky diode (QVPAPD) pair for millimeter- and sub-millimeter-wave mixers are developed. These equivalent circuits are used in the simulation and optimization of millimeter- and sub-millimeter-wave subharmonic mixers. The modeling of quasi-vertical planar Schottky diodes provides accurate models for the design and simulation of millimeter- and sub-millimeter-wave subharmonic waveguide mixers.

Thesis for the degree of Doctor of Technology, July 9th, 1999
Petri Piironen
Microwave circuits and systems for space applications

ABSTRACT

Microwave and millimeter wave technology has an ever growing importance in the field of radio astronomy, Earth observation, and telecommunications. Many of these applications are space-borne which gives advantages such as wide radio link coverage, avoidance of atmospheric attenuation, rapid world-wide observation capability, or powerful observation techniques. In the future, all these applications will extend towards millimeter and submillimeter waves. These frequencies are seen important in molecular spectrum detection and analysis for the needs of astronomy and Earth observation. At higher frequencies, future radio communication systems can attain more bandwidth for wide-band applications.

Development of low-noise receivers is a key issue in the exploitation of the new frequency ranges. In addition, the opaqueness of the atmosphere at higher millimeter and submillimeter waves addresses the importance of space-borne astronomical observations in the future. Currently, however, the available technology, unreliability, and cost limit the performance of millimeter and submillimeter wave space receivers. The environmental circumstances and the emphasised reliability requirement set the main guidelines for a space qualified design.

A 22 GHz receiver for the Radioastron space-VLBI mission has been constructed and space qualified by analysis and test. Low noise, phase stability, and amplitude stability have been the key goals in the VLBI compliant design. For a low noise, a cooled HEMT amplifier has been designed. Integrated hybrid circuit technology and thermal stabilization have been utilized in striving the stability requirements. The receiver has undergone a full space qualification program and a reliability analysis.

A tunerless cryogenic millimeter wave ring filter has been designed for a space application within the Odin space project. Detuning of the center frequency caused by thermal deformations has been compensated by a novel mechanism based on the use of two materials with different temperature expansion coefficients. An improvement of 1:8 in the detuning of the center frequency, compared to an uncompensated ring filter, is achieved. The new design avoids the use of external tuning actuators even in applications where a wide operational temperature range is of interest. Thus, the new ring filter is especially advantageous in space-borne millimeter wave receivers.

A planar Schottky diode mixer at 119 GHz for the Odin space mission has been designed, built, and space qualified. By using a planar air-channel diode, the unreliable whisker contact can be avoided. The planar diode approach results in a more rugged structure which has a comparable performance to its whisker contacted counterpart. The planar structure has been demonstrated to withstand cooling to low temperatures.

Considering future sub-millimeter wave space missions, the Schottky mixer technology has several advantages over SIS and bolometer techniques that make it attractive for many forthcoming ESA missions. An ESA/Dornier technology development project for such mixers has been started and a submillimeter wave mixer design has been carried out as a part of this thesis.

Thesis for the degree of Doctor of Technology, February 25th, 2000
Tomas Sehm
Development of Low-Profile Radio Link Antennas for Millimeter Waves

Abstract

This thesis deals with the development of low-profile high-gain millimeter wave antennas for radio link applications, and with antenna measurement techniques. The topic is currently important, since the use of radio links has increased along with the building of mobile phone networks, as they provide a means of quickly and cost-effectively establishing a high-capacity connection between two fixed locations. The radio link terminals are placed on roof tops etc., where they are visible and alter the appearance of the environment. An inconspicuous radio link terminal would solve this problem, and a low-profile antenna is needed to achieve this goal.

Construction of high-gain low-profile millimeter wave antennas is demanding, since the required antenna performance level is high. In this thesis a low-profile antenna design, with high gain, low sidelobes, and simple construction is presented. The antenna consists of a feed network and radiating elements. The feed network is made up of rectangular waveguides connected with T-junctions. The T-junctions have been improved by inserting a splitter and matching pins, thus realizing high return loss and unequal power division ratios. The low loss of a rectangular waveguide enables high efficiency and gain, despite the parallel feed needed for wideband operation. The radiating elements are modified box horns. The nulls in the radiation pattern of the box horns are used to reduce the level of the grating lobes caused by the large element spacing. The large element spacing is a prerequisite for a parallel feed network of rectangular waveguides in one plane. The grating lobes are also eliminated by a combination of sideways shifted arrays. The antenna design has been used for the radio link bands 37–39.5 GHz and 57.2–58.2 GHz. A measured gain of 37 dBi was realized at 39 GHz with a 256-element array. Over the 37–39.5 GHz band the H-plane radiation pattern of a 64-element array complies with ETS 300 197 with 5 dB margin, the gain is greater than 30.4 dBi, and the return loss is more than 16.9 dB. The measurement results for the 57.2–58.2 GHz band are: gain 36 dBi and return loss > 14 dB, while the H-plane sidelobe level is well below the maximum set by ETS 300 408. The antenna thereby fulfills the requirements for radio link antennas.

The measurement of large antennas at millimeter wavelengths requires a large separation between the antennas used in the measurement. This difficulty can be overcome by using either a compact antenna test range (CATR) or near-field scanning techniques. A hologram-based CATR and planar near-field scanning at 39 GHz have been tested in this work. The feasibility of planar near-field scanning at submillimeter wavelengths is also investigated.

HELSINKI UNIVERSITY OF TECHNOLOGY

ABSTRACT OF THE
LICENTIATE'S THESIS

Author:	Ville Samuli Möttönen
Name of the thesis:	Subharmonic waveguide mixers for millimeter waves
Date:	29. 4. 1999
Number of pages:	82
Faculty:	Department of Electrical and Communications Engineering
Professorship:	S-26 Radio Engineering
Supervisor:	Professor Antti Räisänen
Reviewer:	D.Sc. (Tech.) Jyrki Louhi

In this licentiate's thesis, subharmonic waveguide mixers have been successfully designed, constructed, and tested for millimeter wavelengths. This thesis work is part of the European Space Agency research project called KASIMIR. The goal of the project is to fabricate 650 GHz integrated antenna/mixer frontends utilising open-structure and waveguide type approaches. Based on the outcomes of this work a suitable mixer topology for the 650 GHz subharmonically pumped waveguide mixer has been adopted.

In this thesis, quasi-vertical Schottky diodes have been applied in mixers for the first time. The subharmonic millimeter wave mixers employ a GaAs diode chip comprising two quasi-vertical Schottky diodes in an anti-parallel configuration. These European Schottky diodes are fabricated at the Technical University of Darmstadt.

Two different split-block type waveguide mixer designs have been tested at the 210–220 GHz RF frequency range with a fixed LO frequency. The best SSB results are a conversion loss of 9.2 dB and noise temperature of 3520 K. DSB results are 7.3 dB and 2330 K, respectively. The results have been achieved at 215 GHz RF frequency by using 3.5 mW LO power at 107 GHz. Measurement results of the conversion loss are comparable to the best published results of subharmonic planar diode mixers around 215 GHz frequency. The noise performance is somewhat worse. It should be noted that the parameters of the diodes on the chip are designed for the use in the 650 GHz mixer. This degrades the performance at 215 GHz in a mixer circuit which is a scaled version of the 650 GHz mixer circuit. However, the results achieved with the millimeter wave mixers in this work predict an excellent mixer operation at 650 GHz.

In this thesis, it has also been verified the usefulness of modern simulation tools in the modeling of the Schottky diode chip, in predicting the conversion efficiency of the mixer, and in the design of the mixer structure and circuits.

Keywords: Conversion loss, millimeter waves, noise temperature,
quasi-vertical Schottky diode, waveguide mixer, subharmonic

HELSINKI UNIVERSITY OF TECHNOLOGY LICENTIATE'S THESIS
ABSTRACT

Author: Juha Miikka Tanskanen
Title: InP HEMT low noise amplifier at 70 GHz
Date: 10.5.1999 Number of pages: 59
Faculty: Department of Electrical and Communications Engineering
Professorship: S-26 Radio Engineering
Supervisor: Professor Antti Räisänen
Second examiner: Docent Pertti Ikäläinen

The design of monolithic millimeter wave low noise amplifiers at 70 GHz was carried out using DaimlerChrysler commercially available indium phosphide (InP) high-electron-mobility transistor (HEMT) process. InP HEMTs were employed in coplanar waveguide (CPW) circuits. Design of the low noise amplifiers (LNAs) was based on the on-wafer measurements of separate transistors. Test transistors were 2x40 μm PHEMTs on a quarter wafer. S-parameters were measured from 45 MHz to 110 GHz. Noise parameters were measured from 60 to 74 GHz and the noise model was based on those measurements. DC measurements were carried out at room temperature as well as at cryogenic temperatures. Noise measure M was plotted with V_{ds} ranging from 0 to 3 V and I_{ds} from 0 to 10 mA. Using that information the optimum bias point was found at V_{ds}= 1 V and I_{ds}= 10 mA. The minimum noise figure F_{min} was 2.4 dB, the noise resistance R_n 7 Ω and the optimum noise impedance Γ_{opt}= (0.37∠175°) at 64 GHz.

Comparison between wafers was done and the test wafer was clearly the best. Noise performance fluctuates with time. Last wafer shows the worst performance in noise. Also the transconductance of transistors in the test wafer was higher (g_m= 70 mS) than that in the two received designed wafers (g_m= 45 and 54 mS).

One single stage and two two stage LNAs were designed for the Planck mission. LNAs were optimized for 63-77 GHz range and measurements were performed up to 75 GHz. The performance of the processed circuits was measured using on-wafer probes. The performance of the best two stage amplifier between 63-75 GHz range was: gain better than 2 dB and noise figure between 5 and 6 dB. The bandwidth of the measured LNA was significantly narrower than the simulated one. One stage amplifier showed also lower gain than the simulated one. The measured gain was higher than 2 dB between 63-75 GHz range and the noise figure less than 4.5 dB. These results agree with the earlier DC measurements.

Finally, the transistor model was adjusted for better agreement between the measured and the simulated values. Major changes were made for transconductance and smaller changes for external and internal output capacitances and output inductance.

Initially, the amplifiers were intended to be measured at cryogenic temperatures. In these process runs there were LNAs which were designed for frequencies below 70 GHz. Those LNAs were designed for a narrower bandwidth, they operated better and will be measured at cryogenic conditions with on-wafer probes.

KEYWORDS: LNA, HEMT, MMIC, V-band.

HELSINKI UNIVERSITY OF TECHNOLOGY

ABSTRACT OF THE
LICENTIATE'S THESIS

Author:	Jussi Säily
Name of the thesis:	Instrumentation and testing of a submillimeter-wave compact antenna test range based on a hologram
Date:	10.12. 1999
Number of pages:	81
Faculty:	Electrical and Communications Engineering
Professorship:	S-26 Radio Engineering
Supervisor:	Professor Antti Räisänen
Reviewers:	Dr. (Tech) Juha Mallat

In the near future, many scientific satellites carrying millimeter- (30-300 GHz) and submillimeter-wave (>300 GHz) instruments and antennas will be launched. These satellites are mainly used for astronomical observations and remote sensing of the Earth atmosphere. Testing of the high gain, electrically large antennas is difficult and there are no verified test ranges for over 500 GHz. Antenna testing can be done with far-field, near-field, and compact antenna test ranges (CATR). The CATR is the most feasible for high millimeter- and submillimeter-wave antenna testing. The CATR may be based on a reflector, a lens, or a hologram.

A submillimeter-wave compact antenna test range based on a hologram was manufactured and tested in this licentiate's thesis. The hologram modulates the incoming spherical wave and radiates a plane wave into a certain direction. The quality of the plane wave is essential in antenna measurements. The volume where the plane wave is accurate enough is called the quiet-zone volume of the CATR. The antenna-under-test must fit inside the quiet-zone volume.

The manufactured hologram CATR is based on a 60 cm diameter planar binary amplitude hologram designed for 310 GHz. The quiet-zone area at 1.5 meter distance from the hologram was measured to be about 25x20 cm^2. Measurements were done with the receiver mounted to a large planar scanner.

In the thesis, a phase-locking system for a submillimeter-wave backward-wave oscillator (BWO) was also developed. The phase-locked BWO can be used as a high-power transmitter in compact antenna test ranges. Single-sideband (SSB) phase noise spectrum at 1 kHz–4 MHz distances from the carrier frequency was measured for the BWO at 310 GHz. The measured SSB phase noise in this range was better than -75 dBc/Hz except for some discrete interference spikes.

Keywords: Hologram, compact antenna test range, submillimeter-waves, phase-locked loop, backward-wave oscillator (BWO)

HELSINKI UNIVERSITY OF TECHNOLOGY

ABSTRACT OF THE
LICENTIATE'S THESIS

Author:	Timo Karttaavi
Name of the thesis:	Transistor Modeling for a Millimeter Wave Low-Noise Amplifier
Date:	April 1, 2000
Number of pages:	69
Faculty:	Department of Electrical and Communications Engineering
Professorship:	S-87 Electronic Circuit Design
Supervisor:	Professor Veikko Porra
Second examiner:	Dr. Pekka Kangaslahti

A small-signal model is determined for an indium phosphide high electron mobility transistor (HEMT) to be used in the design of a 70 GHz low-noise amplifier (LNA). First, an overview of InP HEMT technology and different modeling practices for use in millimeter-wave low-noise amplifiers is given. To investigate the chosen modeling procedure three different transistors have been tested. One of them is a DaimlerChrysler InP HEMT which was used in a monolithic LNA design. The remaining two are pseudomorphic GaAs-based devices. The scattering parameters of these transistors have been measured up to 75 GHz. Noise parameters have been measured between 60 and 75 GHz. Methods for extracting the parasitic and intrinsic equivalent circuit parameter values are evaluated. To enable linear simulation under varying DC operating conditions analytical formulas for the bias dependence of the intrinsic parameter values are developed. The basic FET Noise models are presented, and Pospieszalski noise models for the transistors are defined. Bias dependence for this model is also considered. The extracted model for the DaimlerChrysler HEMT is evaluated through the design, fabrication and testing of three 70 GHz LNAs. Two of these are single-stage and one is a three-stage design. Due to problems with processing and initial design information the performance of the amplifiers does not fully correspond to the potential of the process. An analysis of these reasons is given. With an adjustment of the transistor model to match the actual produced transistors a good agreement between the measured and simulated values is achieved. With a short overview of low-temperature effects some cryogenic test results for the amplifiers are also shown.

Key words: HEMT, LNA, V-band, small-signal model

HELSINKI UNIVERSITY OF TECHNOLOGY

ABSTRACT OF THE
MASTER'S THESIS

Author: Hanna Salminen

Name of the Thesis: Monolithic integrated mixer at millimeter wavelengths

Date: 1st February, 1999 **Number of Pages:** 65

Faculty: Department of Electrical and Communications Engineering

Professorship: Radio Engineering **Code:** S-26

Supervisor: Prof. Antti Räisänen

Instructor: Pekka Kangaslahti, Lic. Tech.

The purpose of this work was to design, process and measure a monolithic integrated mixer for a 34 GHz traffic counter equipment. Philips PHEMT process was used and two different mixer designs were maunufactured: a resistive I-Q mixer and a resistive balanced mixer. Simulations used a transistor large signal model, which was especially suitable for modelling FET's in the resistive operating region.

The transistors of the I-Q mixer had four finger gates, each finger being 11 μm wide. In simulations, these transistors had output impedances of 50 ohms and no matching circuits were used. The 90° phase difference between RF signals in the drains of the two transistors was created with a Lange coupler. The local oscillator signal was led to the gates through a Wilkinson power divider, which was a microstrip design. In measurements the mixer showed good matching and isolation, but at low intermediate frequencies showed high conversion loss in I and Q channels (20 dB 21 dB respectively). Therefore the mixers noise temperature was too high to measure.

The balanced mixer had two transistors with four finger gates, each finger being 15 μm wide. The matching of the circuits was performed with a matching network. In simulations RF matching of the balanced mixer was -25 dB @ 34 Ghz and LO matching was -35 dB @ 34 GH with conversion losses IF1 = 11 dB and IF2 = 15 dB.

Keywords: monolithic, millimeter wave, mixer, HEMT, conversion loss.

HELSINKI UNIVERSITY OF TECHNOLOGY
ABSTRACT OF THE MASTER'S THESIS

Author:	Janne Häkli
Name of the thesis:	Feed System for Hologram Compact Antenna Test Range
Date:	21.5.1999
Number of pages:	83
Faculty:	Electrical and Communications Engineering
Professorship:	Radio Engineering
Supervisor:	Prof. Antti Räisänen
Instructor:	Lic. Sc. (Tech.) Juha Ala-Laurinaho

In this master's thesis a dual reflector feed for a hologram compact antenna test range (CATR) was studied. The hologram is a frequency and polarisation dependent focusing element in a CATR. A decrease in the frequency and polarisation dependency and a simplification of the manufacturing of the hologram is possible by an appropriate modification of the incident field of the hologram.

The theoretical basis of the calculation of the radiation of a reflector antenna was first studied. Geometrical and physical optics with geometrical and physical theory of diffraction applied to the diffraction of a wedge were investigated. Some synthesis methods for dual shaped reflectors were also studied. The amplitude pattern of a corrugated horn was measured at 310 GHz. The design of a dual reflector feed system is based on the radiation pattern of the feed horn. The requirements for a dual reflector feed system for a hologram CATR and possible feed structures were investigated.

The selection of the feed system structure is based on the desired incident field of the hologram, the shape of the radiation pattern of the feed horn, the size of the power source and on the selection of the hologram focal length. An estimate for the minimum reflector size determined by the feed geometry was calculated for dual shaped hyperbolical reflectors. The minimum diameter of the main reflector was found to be 13–20 cm and for the subreflector the minimum diameter calculated was 6–15 cm, when the hologram diameter was 60 cm. Alternative feed systems based on a shaped lens or on a dielectric film with modified transmission coefficient were also briefly studied.

Keywords: submillimeter waves, compact antenna test range, CATR,
hologram, dual shaped reflectors, dual reflector feed

HELSINKI UNIVERSITY OF TECHNOLOGY

ABSTRACT OF MASTER'S THESIS

Author:	Heikki Tuohiniemi		
Name of the thesis:	Design parameters for a 58-GHz radio hop		
Date:	06.09.1999	**Number of pages:**	97
Department:	Department of Electrical and Communications Engineering		
Professorship:	S-26 Radio Engineering		
Supervisor:	Professor Antti Räisänen		
Instructor:	Neil Forknall, M.Sc.		

The purpose of this master's thesis is to find out what the parameters are that should be taken into account when a 58-GHz radio hop is planned. The effect of the most important parameters have been calculated and compared with the measurement results which have been published in scientific journals.

After reading through this thesis the reader will have good understanding of how different phenomena affect millimeterwave propagation at 58 GHz. The chapters begin with a short description of the phenomenon and after the description the theoretical basics and formulae are presented.

It was found that ITU-R (International Telecommunication Union Radiocommunication assembly) approximation formula gives unrealible values for oxygen attenuation in a non-standard atmosphere at frequencies around 58 GHz. A new and more accurate approximation calculation method for the oxygen attenuation is presented.

The most common drop size distribution models are presented (Laws and Parsons, Marshall and Palmer and Joss et al.). Some less used drop size distribution models that might be more suitable for 58 GHz are also presented.

In addition to these issues, this thesis focuses on several other topics, i.e. the reflections and transmission coefficient of different building materials, the effect of the radome on a radio's performance, the possible applications for a 58-GHz radio, etc.

Keywords: Atmospheric attenuation, TDD, LBT-rule, ETS 300 408, 58 GHz , drop size distribution

HELSINKI UNIVERSITY OF TECHNOLOGY

ABSTRACT OF THE
MASTER'S THESIS

Author and name of the thesis:
Kirsi Karlamaa
Design and construction of the 43 GHz VLBI receiver at Metsähovi

Date: 6.6.2000 **Number of pages:** 67

Department:
Electrical and Communications Engineering

Professorship:
S-26 Radio Engineering

Supervisor:
Professor Antti Räisänen

Instructor:
Lic.Sc.(Tech.) Olli Koistinen

In this thesis a septum type orthomode transducer for VLBI use at 43 GHz was designed and constructed. The orthomode transducer extracts the incoming signal into two orthogonal modes of circular polarization.

In the theoretical section the basic theory of radio astronomy and interferometry as well as the special demands for the high frequency VLBI receiver are revieved. Properties of electromagnetic waves such as the polarisation ellipse, Stokes parameters and crosspolarisation are presented.

The orthomode transducer is mechanically placed inside the cooled front-end. The orthomode transducer is a three port device. The input consists of two identical rectangular waveguide ports while the output is a square waveguide. The septum between the waveguides is designed as a function of λ_0 to minimize the reflection coefficient and keep the output phase angel as close to 90° as possible.The function of the orthomode transducer is to devide the signal into left and right cicular polarization. For purposes of analysis we can consider the orthomode transducer as a four-port network.

We found first fringes at 43 GHz between Metsähovi and Effelsberg Radio Observatory. In this fringe test we used continuum and spectral line sources. We present good fringes on source 3C279, correlation coefficient versus baseline plots and autocorrelation spectrum. A fringe plot is a summary of station-based information including tape playback errors, phase calibration phases and amplitudes and it has also baseline-based information including fringe amplitudes, phases and delays.

Keywords: VLBI receiver, cryogenic front-end, septum polarizer, fringe plot

8. Publications

8.1. Books or book chapters

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8.6. Patents

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