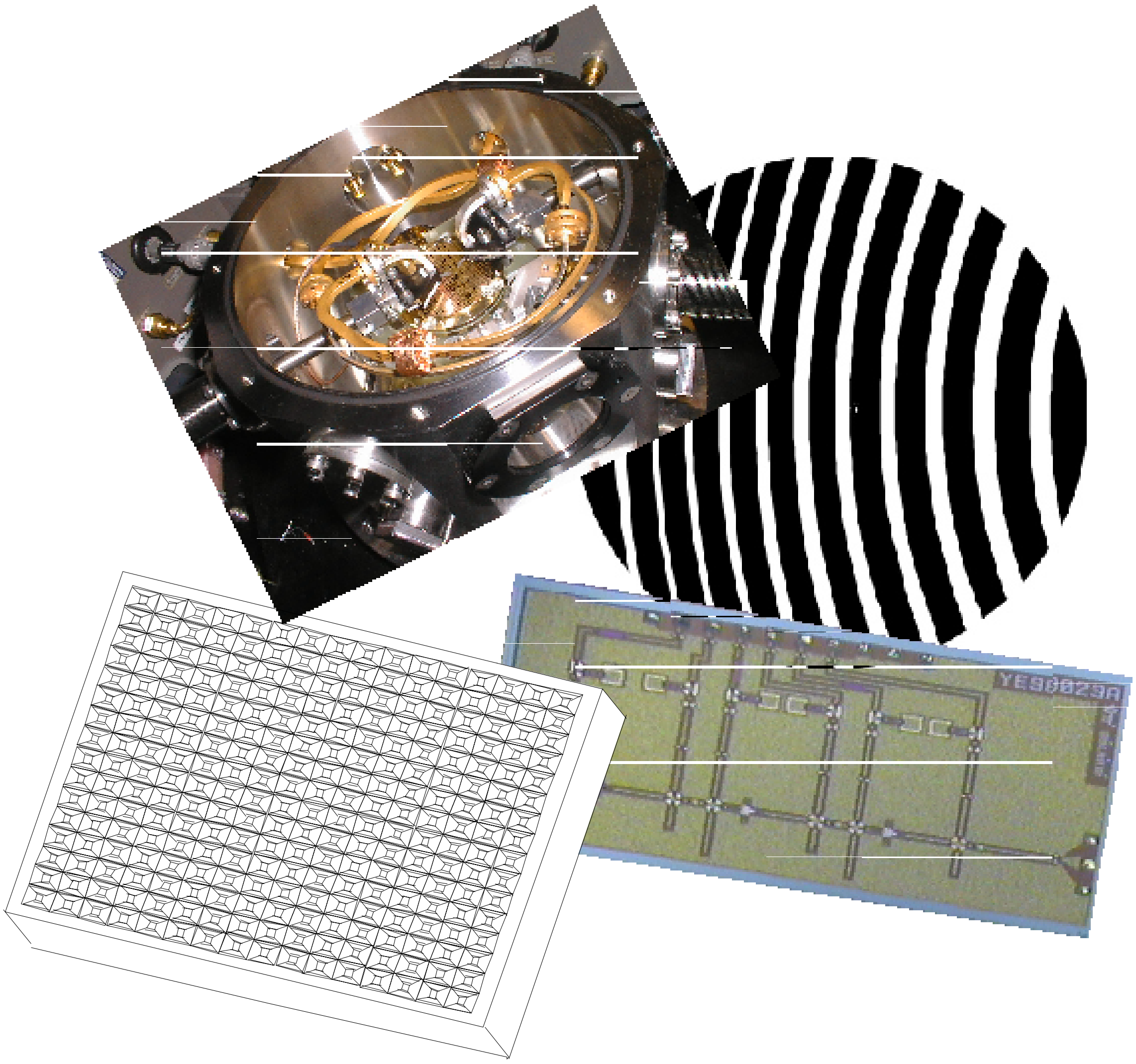
Research Activities of MilliLab 1997-1998



MilliLab

Millimetre Wave Laboratory of Finland – MilliLab

Joint laboratory between VTT and Helsinki University of Technology

esa *External Laboratory*

Research Activities of MilliLab 1997-1998

Editor
Jussi Tuovinen

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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
- ➢ Mm- and sub-mm wave antenna measurements
- ➢ 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 (1994–99).
- Hologram compact antenna test range for the tests of the Odin-satellite 1.1 m antenna at 119 GHz (1994–).
- 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 (1988–93).
- 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", ESTEC/Contract No. 11806/96/NL/CN.
- Participation in "Submillimetre integrated SIS imaging receiver technologies (SISIRT)", ESTEC/Contract No. 11653/95/NL/PB.

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 1997 and 1998, 6 Doctor of Technology, 8 Licentiate of Technology, and 29 Diploma Engineer degrees were awarded for to the students of Radio Laboratory. Abstract of the thesis, 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 12 research persons are working and eight man-years of work is annually carried out in MilliLab's projects. In general, over 20 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:
- S-parameter measurements
- Noise parameter measurements
- Cryogenic testing

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-parameters 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	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 Syntesisers	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

Taavi Hirvonen, Juha Ala-Laurinaho, Petri Piironen, Janne Häkli, Jussi Säily, Jussi Tuovinen, Arto Lehto, Antti V. Räisänen

Introduction

Measurement of 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. In a far-field, this quasi-plane wave is obtained by a long enough measurement distance. However, conventional 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. In the near-field measurement, the field radiated by the AUT is measured on a near-by surface by a probe antenna. The far-field radiation pattern is then calculated from measured samples. The number of samples is usually very large resulting in long measurement time. Therefore, the measurements system must be stable, and large memories and computing capacities are required. Also the probe positioning system has to be efficient and accurate.

In a CATR, a plane wave is generated by one or more reflectors, a lens, or a hologram. A reflector CATR requires large reflectors having 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 will become inconveniently large. The hologram is a potential solution to overcome the problems incurred with insufficient surface accuracy.

Hologram CATR

In Figure 1 is shown the layout of the hologram CATR. The feed horn radiates nearly a spherical wave, which is transformed into a plane wave by a planar binary amplitude hologram. The hologram is surrounded by absorbers to prevent reflections and direct radiation from the feed to the quiet-zone.

The hologram consists of narrow slots etched on the copper layer of a copper plated dielectric film. The hologram is very large in wavelengths and the 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

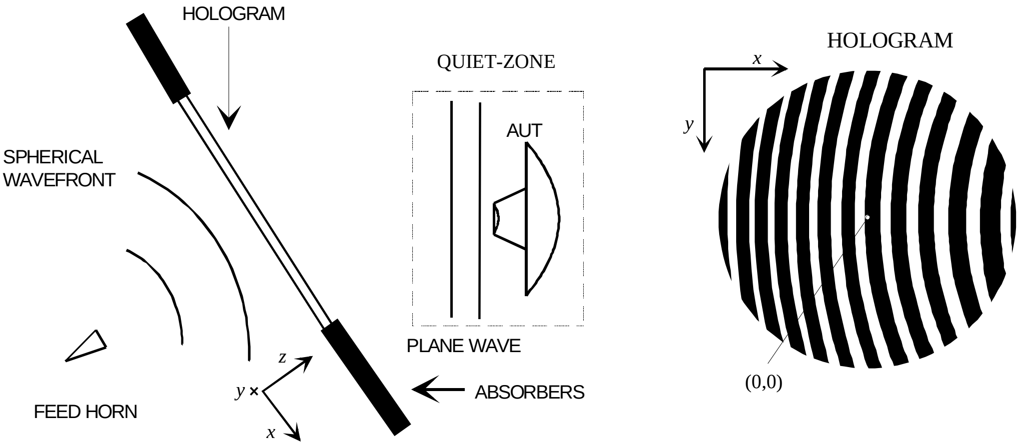

Figure 1. A hologram CATR, and an example of a hologram pattern

results [1,2]. 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.

Antenna measurements

A hologram CATR has been used for measurements of a planar radio link antenna and its development versions at 40 GHz [3,4]. For that purpose two holograms with shape of ellipse have been designed and fabricated (1.2 m × 0.7 m, and 1.5 m × 1.4 m). Comparison measurements have been done with the far-field technique and the near-field scanning techniques. Good agreement between the results has been obtained.

The Odin satellite is developed for monitoring aeronomical and astronomical spectral lines. The antenna of the Odin satellite has been tested with the hologram CATR at 119 GHz. The diameter of the main reflector is 1.1 m, and the hologram designed and manufactured for measurements is 2.4 m × 2.0 m producing a quiet-zone with diameter of about 1.4 m. The hologram was made from seven pieces spliced together with polyester tape. The imperfect joints between pieces affected the quiet-zone field quality. However, with a peak-to-peak amplitude ripple of about 2 dB the quiet-zone field quality was adequate for measuring the main beam of the Odin antenna. According to the measurements, the main beam radiation pattern of the Odin antenna is symmetric at 119 GHz.

Feasibility study of a submillimeter wave hologram CATR

The feasibility of the hologram CATR for submillimetre wave antenna measurements has been studied, and results are reported in, e.g., [5−7]. The main problems are related to the manufacturing: making of accurate hologram patterns, and making of large holograms. The joining of several hologram pieces with polyester tape does not provide accurate enough, firm joint between hologram pieces at submillimetrewave frequencies. The alignment error has been theoretically studied, and, according to the simulations, alignment error of about 0.1λ produces an extra phase ripple of about 20°. The random and systematic errors in the hologram pattern are also theoretically studied. Accuracy of available hologram manufacturing facility in Finland is adequate for producing holograms for 500 GHz, if the size of the hologram is limited to 600 mm × 600 mm.

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.

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4.2. Planar millimetre wave radio link antennas

Tomas Sehm, Arto Lehto, Antti V. Räisänen

Introduction

High-gain millimetre wave antennas are used in radio relay systems, which play an important role in mobile communication networks. Radio relay connections are today mostly used between base stations and the fixed network. They have a high capacity, a short set-up time and are flexible compared with cable connections. Parabolic reflector antennas are currently used as high-gain antennas in the millimetre wave region. A drawback of reflector antennas is the thickness of the antenna. It would be easier to hide the antenna if it were a lot thinner than the parabolic reflector antennas. There are several concepts of building planar high-directive antennas. Two major aspects limit the use of these antennas: one is the required bandwidth and the other the efficiency of the antenna (or the feed network). The electromagnetic field has to be distributed over a large aperture with a feed network. The losses in the feed network can be reduced by selecting a low-loss transmission line, but problems arise since the width of these transmission lines exceed half a wavelength. It is therefore not geometrically possible to feed each radiating element in parallel with a network in one plane without enlarging the element spacing beyond a wavelength. Parallel feed is needed to get a wide enough bandwidth and a one-plane concept to keep the construction of the antenna simple.

Feed network

The designed antenna consists of two parts: the feed network and the part containing the radiating elements. The feed network divides the input signal for 256 radiating elements. The elements are fed in parallel to avoid frequency dependence. The signal fed to the input port of the antenna is divided using power dividers in the feed network. The signal is divided into two parts in each junction, which means that the signal has to be divided eight times. In this way every element is fed by a waveguide of equal electrical length and the frequency dependence of the feed network is eliminated as much as possible. Losses in the waveguide as well as the reflection coefficient of the antenna must remain on a low level to ensure a reasonably good overall antenna efficiency. Circular and rectangular waveguides have low losses at 40 GHz. Manufacturing of the waveguides as well as T-junctions is easier if the waveguide is rectangular. This is why the rectangular waveguide has been chosen.

Power divider

A simple power divider for rectangular waveguides is the T-junction. A good matching of the antenna also requires good matching of a single T-junction. The matching of a T-junction without additional elements is poor and has to be improved. The improvement of the matching is done in two ways, partly by inserting a splitter in the junction and partly by placing a small pin in the input port of the junction [1]. By using a splitter in the T-junction it is possible to reach a reflection coefficient of about −15 dB. This is unfortunately not good enough for this kind of application. Another method of matching this circuit is to excite a second wave, which cancels out the wave reflected from the junction, if they are in opposite phase with equal amplitude. Simulated reflection coefficients of less than −20 dB over the frequency range 37.0–39.5 GHz have been achieved for one T-junction. The splitter is needed to realise unequal power division between the output ports and cannot be left out even if the matching goal can be reached with a matching pin alone. The unequal division is used to taper the amplitude distribution over the antenna aperture. A tapered amplitude distribution is applied in the H-plane to reach a lower sidelobe level. The construction of the T-junction is shown in Figure 1.

Radiating element

Due to geometrical restrictions it is not possible to achieve element spacings smaller than one wavelength with this type of concept. The grating lobes resulting from an element spacing larger than one wavelength can be eliminated by designing the radiating element so that the zeros in the radiation pattern of the radiating element coincide with the grating lobes in the array factor. The radiating element shall still be simple, but must have the radiation pattern desired to eliminate the grating lobes. This can be achieved with a modified box horn [2]. The total length of the radiating element is determined by the phase error allowed in the E-plane. By choosing the relative amplitude of the TE_{30}-mode excited in the box horn carefully, the zero in the radiation pattern of the box horn has been adjusted in such a way that the grating lobes are eliminated. By placing the radiating elements next to each other, a 16 × 16 element antenna array has been built, resulting in an aperture size of approximately 30 cm × 20 cm and a thickness of about 4 cm (see Figure 2) [2].

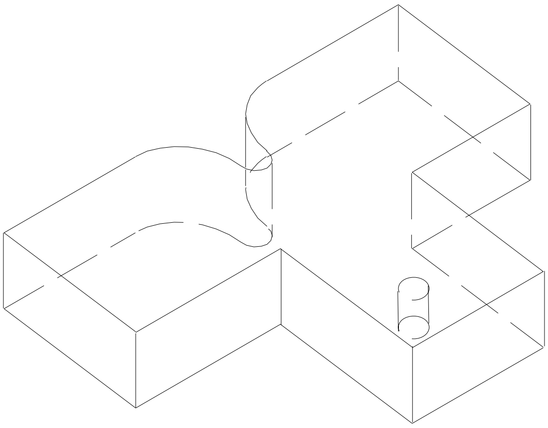

Figure 1. Matched waveguide T-junction.

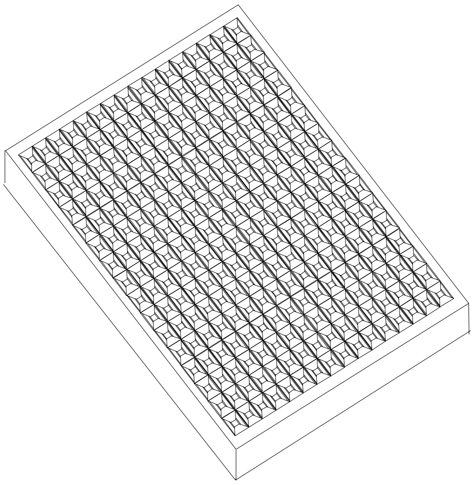

Figure 2. Planar antenna.

Combination of arrays

The level of the grating lobe in the H-plane due to the large element spacing can also be reduced by combining two arrays of box horns separated in the H-plane [3]. A 64-element antenna array of has been presented in [3]. A sidelobe level in the H-plane lower than –35 dB has been achieved at angles larger than 19° from the main beam as well as a gain higher than 30.4 dBi. The return loss of the prototype antenna was measured to be higher then 16.9 dB over the band 37–39.5 GHz.

Conclusion

A new antenna design has been developed, which is suitable for radio link applications. Two planar antenna arrays for the 37.0–39.5 GHz band have been constructed and measured. The thickness of the planar antenna is considerably smaller than the thickness for parabolic reflector antennas with the same performance. In addition the antenna is very simple, it consists of only two parts. The 256-element antenna has a measured gain of 37 dBi. The return loss is higher than 14 dB over the band 36.6–39.3 GHz.

Acknowledgements

The authors want to thank Mr Petri Mikkonen, Mr Jarmo Mäkinen, Mr Juhani Pursiheimo, Mr Mikko Saarikoski and Nokia Telecommunications for their support.

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5. Circuit and material testing

5.1. On-wafer noise parameter testing

Manu Lahdes, Jussi Tuovinen

Introduction

Optimum design of low noise amplifiers requires knowledge of both noise and S-parameters. Often noise parameters at mm-wave frequencies are not given by the transistor manufacturer or they have been derived by extrapolation from lower frequencies. Therefore, obvious needs exists for accurate measurement of the noise parameters. This paper presents a measurement system which allows simultaneous on-wafer noise and scattering parameter measurements at V-band. The system has been used in several Millilab projects (Planck, Cloud radar) for transistor characterization and device modelling.

In a direct noise parameter measurement different source impedancies are presented to the device under test (DUT) and corresponding noise figures are measured. There are four unknown noise parameters F_{min}, R_n, G_s, and B_{opt} so a minimum of four measurements are required. However, in order to minimize the effects of the measurement errors, additional measurements are done and curve fitting is applied. Cold-source measurement method [1-3] is used to measure the noise parameters of the DUT.

Measurement setup

A schematic of the setup is shown in Figure 1. The whole setup is controlled by a PC which is connected to measurement instrumentation via GP-IB bus. The data acquisition and necessary calculations are done by software written in-house. An automatic vector network analyzer (VNA) is used for system characterization and S-parameter measurements of the DUT.

For the accurate of interpretation of the measured results, wideband measurements are desirable. In the wideband setup, the receiver is based on the fundamental mixer with an IF of 10 MHz. The LO is a commercial product and is programmable. The noise figure of the mixer is expected to be about 10 dB. Because of this, the LNA in front of the mixer is very desirable. A wideband LNA base on InP MMICs is foreseen through the on going Planck LFI 70 GHz receiver development work in-house [4].

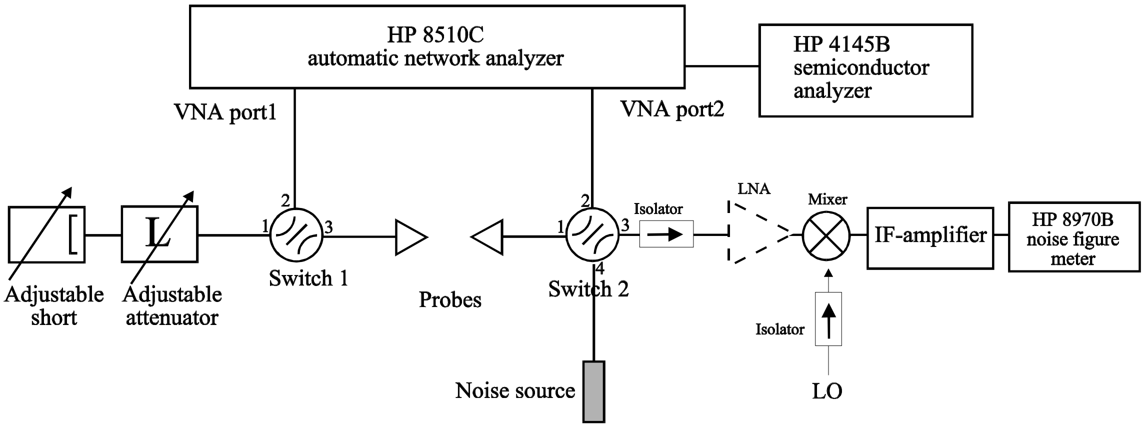

Figure 1. Wideband setup 50-75 GHz

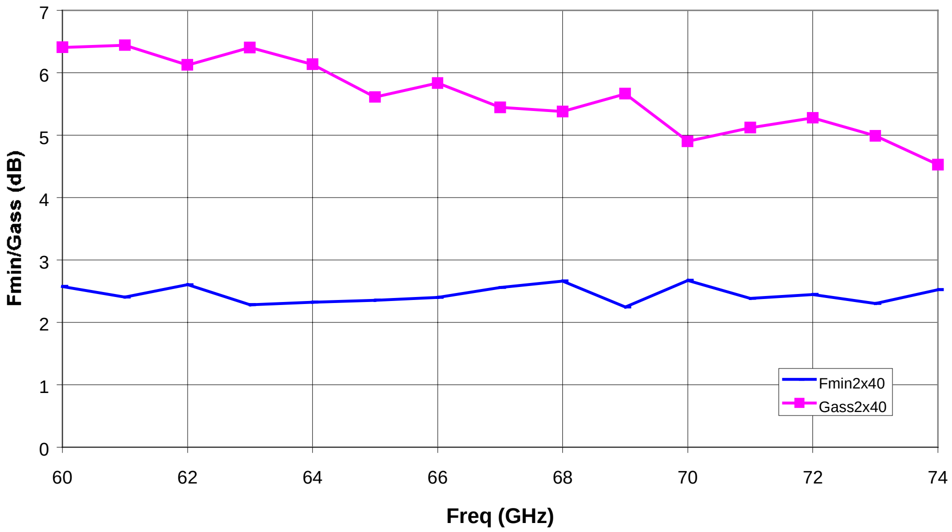

Figure 2. The measured minimum noise figure F_{min} and associated G_{ass}.

Measurement results

As an example of the measurement capabilities, the results of a DaimlerChrysler InP HEMT are shown in Figure 2. The HEMT was set to V_{ds} = 1 V and I_{ds} = 10 mA. The minimum noise figure varies between 2.3 and 2.7 dB. The mean value is 2.5 dB. The estimated uncertainty of the result is ± 0.5 dB (2σ).

Future plans

The noise parameter system will be improved by obtaining a commercial automatic tuner. The new tuner will improve accuracy and speed up the measurement process. The experince gained with the V-band system is used to build a new system to coverage the W-band.

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5.2. Cryogenic on-wafer measurements

Jussi Tuovinen, Manu Lahdes, Timo Karttaavi, Hannu Hakojärvi

Introduction

A breaktrough have been experienced in the possibilities to use MMICs at millimetre wave frequencies in the past few years. To take a full advantage of MMIC processing, efficient on-wafer testing is essential. Several driving forces both on the commercial and scientific side exists for designing and testing of MMICs. One of the main commercial applications are radio links up to 60 GHz and automotive radars at 77 GHz. A good example of scientific applications, where also low temperature testing is needed, is the European Space Agency Planck-mission to be launched in 2007. Planck will have InP HEMT based receivers at 30, 44, 70, and 100 GHz for the anisotropy measurements of the Cosmic Microwave Background. The Planck InP HEMT receivers will be cooled to 20 K, which means that also on-wafer testing is needed at cryogenic temperatures.

Here is reported a unique cryogenic on-wafer set-up for S-parameter measurements up 75 GHz as well as examples of measured results are given.

Set-up for S-parameter measurements

An on-wafer testing set-up inside a cryogenic dewar is shown in Figure 1. With this instrument, measurements down to 15 K and up to 75 GHz are possible. Stainless steel and copper waveguides without any real flexible waveguides are used. A maximum probe head movement of 6 mm x 30 mm is obtained. This is mainly due to the bending of the thin wall stainless steel waveguides. For 45 MHz to 62 GHz a semirigid 1.85 mm coaxial lines are used, which are much more flexible than the waveguides. Due to the limited movement range of the probe heads with waveguides, one- directional movement of 25 mm will be added to the cold chuck in the near future. The loss of the waveguide from outside to probe is about 1 dB. Cooling time for the cold chuck from 300 K to 15 K is 100 minutes and this is obtained using a closed cycled Helium refrigerator by Nagase Co.

Figure 1. Cryogenic on-wafer measurement set-up

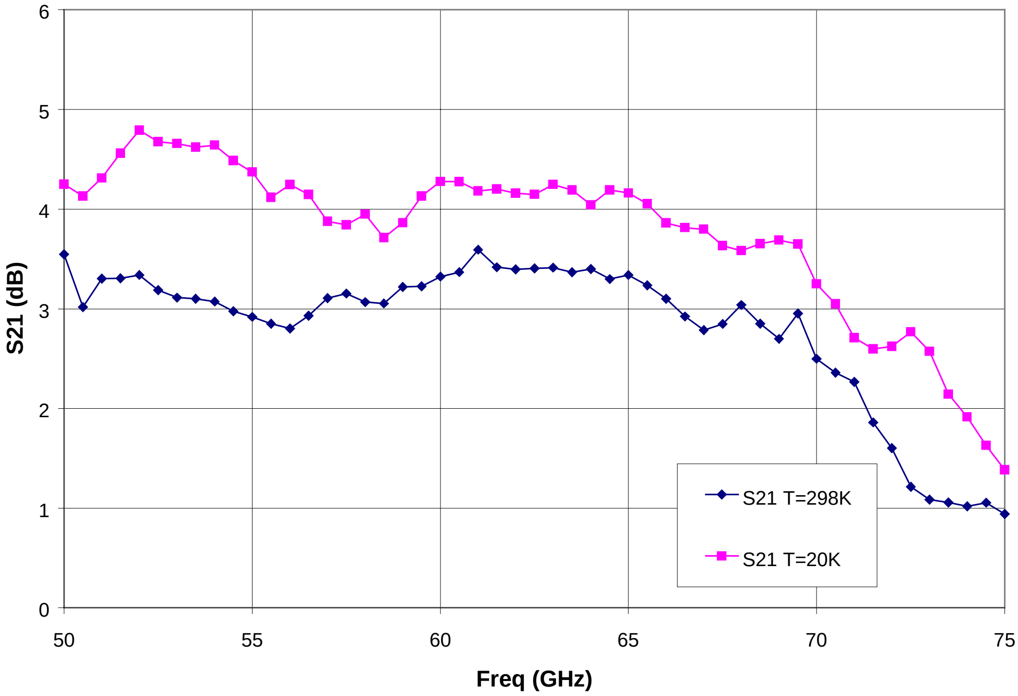

Figure 2. Measured on-wafer S-parameters of an InP HEMT 1-stage LNA at 298 K and 20 K.

Measurement results

As an example of measurement capabilities, Figure 2 shows S-parameters measured at room temperature and 20 K for an InP HEMT 1-stage LNA. As expected S_{21} has increased clearly at the same V_{ds} = 1.0 V and I_{ds} = 10 mA bias conditions. The increase in the magnitude of S_{21} is about to 1 dB.

Future plans

After obtaining experience with the 50-75 GHz waveguide set-up, the present capabilities will be extended for the 75-120 GHz range for S-parameter measurements. An other near future improvement will be the capabilities for noise figure measurement at cryogenic temperatures. For these measurement, a temperature controlled load to be used inside the dewar is under preparation. Furthermore, as mentioned above one-directional moving stage will be added under the cold chuck.

Acknowledgments

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5.3. Development of a primary power measurement standard

Juha Mallat, Sergey Dudorov, Antti V. Räisänen, Jussi Tuovinen

Introduction

Power measurement needs at high millimetre wave frequencies are becoming more important as technology is developing. Applications include measurement of output power from such devices as local oscillators and frequency multipliers. Additionally, the calibration of emerging portable power meters as well as harmonic levels of, *e.g.*, 60 GHz radio links is necessary. Currently, commercial calibration services with primary power measurement standards are available only up to 110 GHz, equivalent to the upper limit of waveguide size WR-10 (W-band). In MilliLab, due to the power measurement services already available to customers, an in-house power standard has been considered important and therefore an initial development of such a standard for 110–170 GHz (D-band) has been started.

Power measurement activity in MilliLab

MilliLab has a millimetre wave power measurement service based on using several commercial waveguide power meters and a quasi-optical power meter. This service provides power measurement capabilities which are available to space industry or ESA/ESTEC projects or other potential customers. However, currently MilliLab lacks a primary power reference for accurately determining the capabilities of its power meters. Up to 110 GHz, commercial calibration services are known to be available and one of MilliLab's power meters has been calibrated in 1998 in such a service.

Due to the interest in higher frequency bands and the need to have an in-house reference for power measurements at these bands, MilliLab has chosen to progress towards obtaining a primary power standard for its use. This activity has been started by a project aiming at the initial development for a primary power measurement standard for D-band, *i.e.*, 110–170 GHz.

Primary power measurement standards are usually designed by using the microcalorimeter principle (see Fig. 1). In MilliLab, there is available expert equipment (such as a network analyser, power meters and power generators) which is needed in designing, realising and testing of the essential millimetre components in a microcalorimeter or some other such system which is based on the RF-DC substitution principle.

A complete realisation of a microcalorimeter power measurement standard can formally be divided into the following steps:

A) A detailed study of existing millimetre wave primary power measurement standards

B) Design of a microcalorimeter

C) Construction

D) Testing & documentation

E) Accreditation

In the initial development project, a detailed study on existing lower frequency primary power measurement standards is being made. Furthermore, a detailed design of microcalorimeter parts (a thermal tank, a thermal load, thermopiles, power sensor) as well as procurement of parts will be performed.

Development in 1998

After some preliminary work, the project was formally started in November 1998 by initiating a literature review about calorimeters and other power standards applicable at millimetre wave frequencies. The review covers standards at NPL (UK), PTB (Germany), NIST (USA) and possibly some other institutes. Based on the review, different types of calorimeter standards and their merits and drawbacks can be compared. Thus also the key points in developing a very high frequency millimetre wave waveguide power standard will be identified. This will assist in choosing and adjusting the direction of further development suitable to MilliLab and its needs.

Acknowledgments

MilliLab receives funding for hardware from ESA/ESTEC.

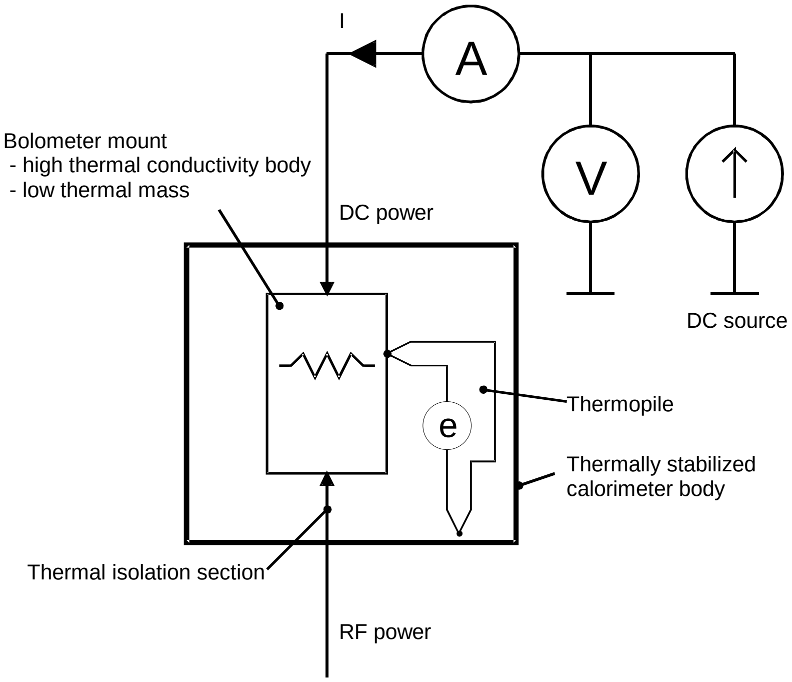


Figure 1. Principle of a microcalorimeter.

5.4. Quasi-optical material measurements

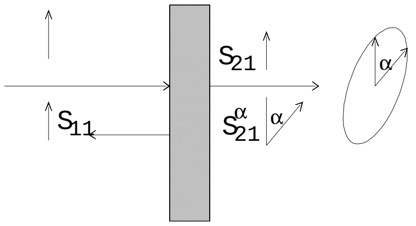
Arto Hujanen

Introduction

For measuring electromagnetic material properties of planar slabs we have developed a free-space measurement system in frequency range 5-110 GHz. The method is based on transmission and reflection measurements done by an automatic network analyser. The measurement setup consists of a pair of spot-focusing reflectors. The sample under measurement is placed in common focal plane of reflector antennas. Waveguide feeds are used as feeds for reflectors. We have two pairs of reflectors, one for frequency range 5-50 GHz and one for frequency range 50-110 GHz. The used calibration method is TRL (true, reflect, line). The time-domain gating is also used with TRL calibration. In the lower frequency range the other reflector can be rotated which make it possible to measure also chiral materials. The millimeterwave setup uses offset feeds avoiding blocking effect the feeds. The sample holder can be rotated which make it possible to measure transmission and back scattering versus incident angle.

Reflection and transmission-method

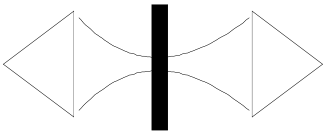
Principle
- planar slab under measurement
- based on transmission analogy
- reflected and transmitted fields are measured
- conventional(ε,μ) and chiral (ε,μ,κ) materials can be measured

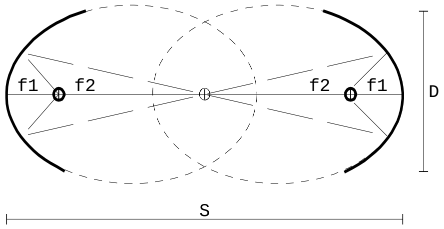


Conventional material	Chiral material
$\varepsilon_r = \frac{1-\Gamma}{1+\Gamma}\frac{k}{k_0}$, $\mu_r = \frac{1+\Gamma}{1-\Gamma}\frac{k}{k_0}$,	$\varepsilon_r = \frac{1-\Gamma}{1+\Gamma}\frac{k}{k_0}$, $\mu_r = \frac{1+\Gamma}{1-\Gamma}\frac{k}{k_0}$, $\kappa = \frac{-(\arctan(G)+m\pi)}{k_0 d}$, m = 0, 1, 2,..
where	where
$\Gamma = K \pm \sqrt{K^2-1}$	$\Gamma = K \pm \sqrt{K^2-1}$
$K = \frac{S_{11}{}^2 - S_{21}{}^2 + 1}{2S_{11}}$	$K = \frac{S_{11}{}^2 - S_{21}{}^2(1+G^2)+1}{2S_{11}}$,
	$G = \frac{S^{\alpha}_{21} - S_{21}\cos(\alpha)}{S_{21}\sin(\alpha)}$
$k = \frac{j}{d}(\ln(T)+n2\pi)$ n = 0, ±1, ±2,	$k = \frac{j}{d}(\ln(T)+n2\pi)$, n = 0, ±1, ±2,..
$T = \frac{S_{11}+S_{21}-\Gamma}{1-(S_{11}+S_{21})\Gamma}$	$T = \frac{S_{11}+S_{21}\sqrt{(1+G^2)}-\Gamma}{1-(S_{11}+S_{21}\sqrt{(1+G^2)})\Gamma}$

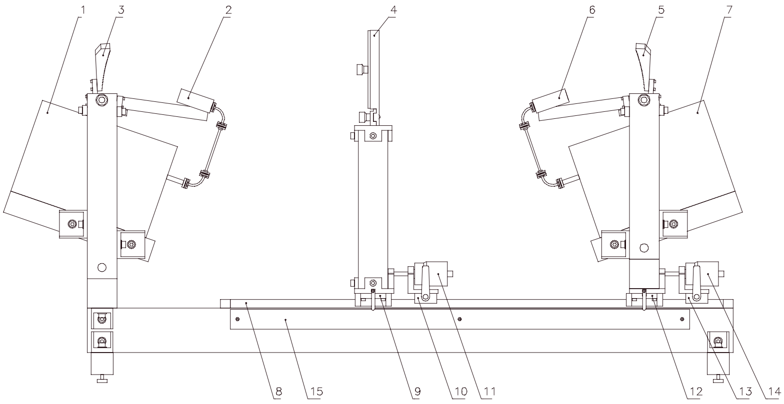
Measurement setup

- two elliptical reflector antennas
- sample in common focus, feed in the other focus
- focusing beams avoiding edge diffraction from the sample



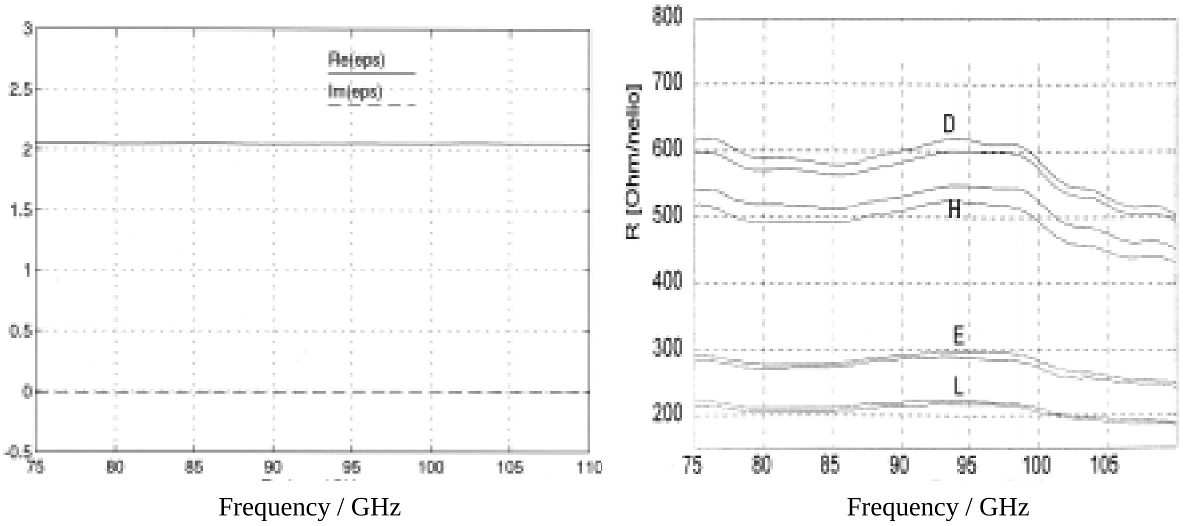


- two measurement setups: 5-50 GHz and 50-110 GHz
- waveguide feeds
- focusing area: ≈ 1 λ (5-50 GHz) , ≈ 25 mm (50-110 GHz)
- TRL calibration and time domain gating



Measurement setup for 50-110 GHz (3,5 reflectors, 2,6 waveguide feeds, 4 sample holder, 1,7 ANA's millimeterwave test sets).

Measurement examples



Measured dielectric constant of the teflon sample (reference value ε_r=2.052±0.0.025 and measured square resistance of thin concuctive polymer sample at W-band).

5.5. Open resonator for material measurements

Juha Mallat

Introduction

MilliLab has an open resonator which can be used for measuring dielectric properties (permittivity and loss tangent) of low-loss materials. The high-Q hemispherical resonator was already previously developed for measuring at 100 GHz materials for fusion reactor windows and lenses of millimeter wave receivers [1]. A millimeter wave network analyser is necessary in the measurements because they are based on monitoring a change of resonance characteristics when a sample is inserted in the resonator. Currently MilliLab has a vector network analyser (MVNA with extensions, by AB Millimetre) capable of operation at least up to 700 GHz. This network analyser and the open resonator can be used to study material characteristics at much higher frequencies than what was possible earlier [2]. Test measurements have been performed up to 665 GHz with this system configuration.

Description of the resonator and the measurement principle

The hemispherical open resonator consists of a plane metal mirror and a spherical metal mirror above it facing it. Gaussian beam mode resonances can be created in the structure by feeding to it RF power via a coupling hole in the middle of the spherical mirror. Another coupling hole near the first hole is used for coupling power also out of the resonator. These two signal ports are used to measure the transmission (S_{21}) response of the resonator system. The response is typically dominated by a multitude of resonance peaks which all have their own center frequency and bandwidth. These parameters can be measured with a high-performance network analyser.

The resonance frequencies of the empty resonator depend on the length of the resonator, the radius of curvature of the spherical mirror and three resonant mode indexes. When a material sample is placed on the plane mirror, the resonance frequencies of each mode will change depending on the dielectric characteristics of the sample. Any loss in the sample will also change the bandwidth of the resonance peaks from the values measured with the resonator when it is empty and without the sample. Thus, by using suitable equations, the permittivity and the loss tangent of the sample can be calculated from measurement results taken first without and then with the sample in the resonator.

The suitable mode for the measurements is the basic Gaussian mode which can be in practice identified by using diaphragms of differing sizes. The resonance peaks of the basic mode will remain best unaffected when diaphragms with a decreasing hole diameter are inserted in the resonator.

Typically low-loss dielectric materials are measured with the resonator method. The samples have to be disc-like and they have some optimum thickness values for best results. A high quality (Q) factor of the resonator and thus inversely a small bandwidth of the resonance peaks are beneficial to making accurate loss tangent measurements.

Development in 1997–98

The open resonator was tested at frequencies of several hundreds of GHz when the new extensions to MilliLab's MVNA network analyser became available, first ESA-1 and then later ESA-2 extension. The resonator was found to operate extremely well even at that high in the millimetre and submillimetre wave bands. For example, at 380, 476, 570 and 665 GHz measurements showed Q-values of about 86 000, 151 000, 50 000 and 166 000, respectively [3]. Additionally, while measuring some samples, for example the birefringence of Teflon was noticed at even 665 GHz. This kind of performance with high Q-values is promising in view of future measurement applications and further testing of dielectric material samples in MilliLab.

Acknowledgments

MilliLab wishes to thank Dr. P. Goy from company AB Millimetre, France for kind cooperation in testing the resonator in measuring dielectric properties of materials at high millimetre and submillimetre wave frequencies while simultaneously the ESA-1 and ESA-2 extensions to MilliLab's MVNA had their operation verified after final assembly in MilliLab. We are grateful also for other cooperation in connection to MVNA and measurements with it.

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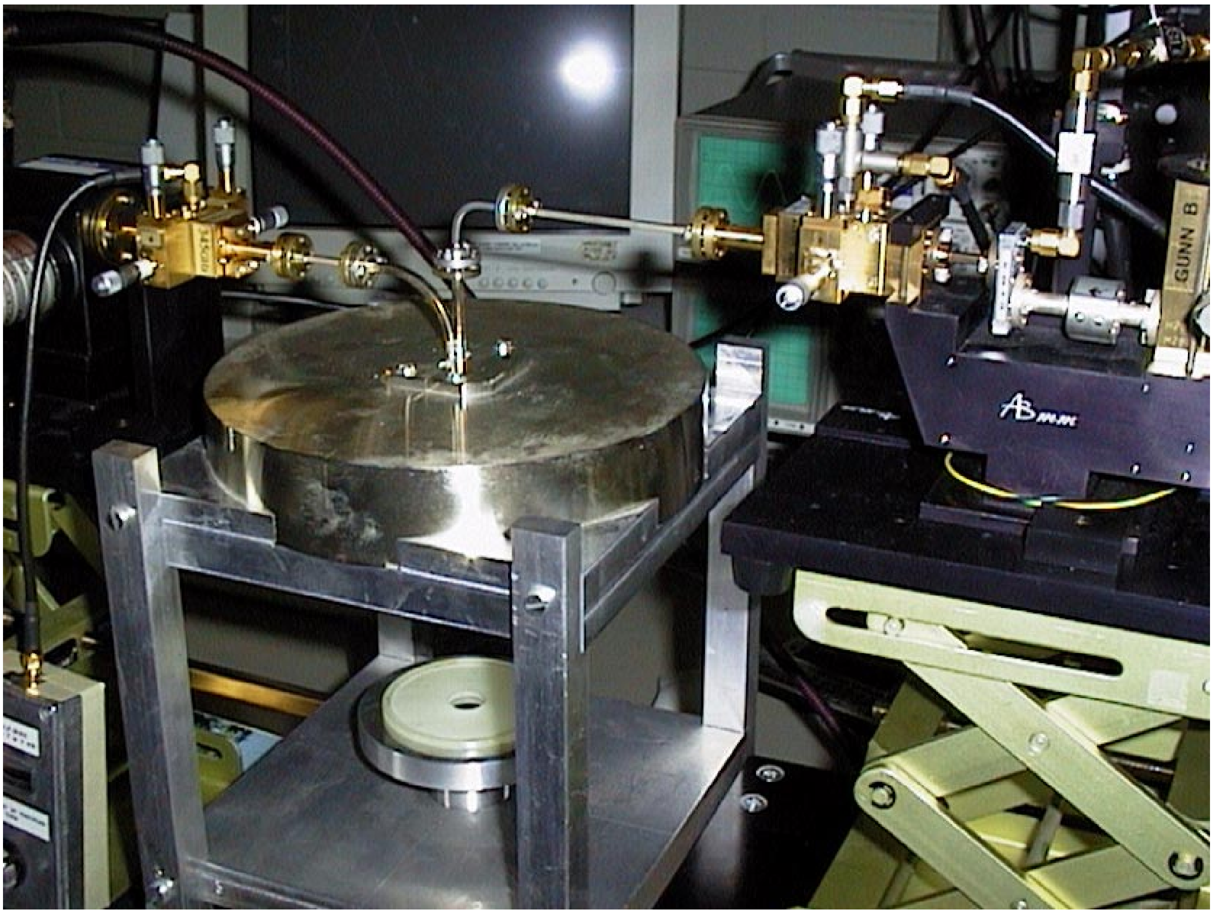

Figure 1. The open resonator used in MilliLab.

6. Systems, components, and circuits

6.1. Planck LFI 70 GHz receivers

Jussi Tuovinen, Timo Karttaavi, Manu Lahdes, Nicholas Hughes[1], Pekka Kangaslahti[1], Juha Tanskanen[1], Petri Haapanen[1], Hanna Salminen[1], Petri Jukkala[1], Olli Koistinen[2], Seppo Urpo[2]

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[2]Metsähovi Radio Observatory, Helsinki University of Technology, Espoo, Finland

Introduction

The aim of the European Space Agency (ESA) Planck mission, to be launched in 2007, is to measure the Cosmic Microwave Background (CMB) anisotropy with a great angular resolution (10' at 100 GHz) and radiometric sensitivity ($\Delta T / T = 4.3 \times 10^{-6}$) [1]. 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 off-set 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.

70 GHz Activities

The 70 GHz receivers, excluding the horns and OMTs, will be build by the Finnish team [2]. 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 and the presently on going ones are:

- PHASE 00: This will provide a selection of MMIC building blocks developed using an 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 (Planck Pre-Phase B Activity). This activity is necessary for the advanced evaluation of the TRW MMIC process and selection of the most suitable MMIC source.

Next Phases will be PHASE Ib: EBB (Elegant Breadboard Model), starting year 1999; PHASE Ic: Main Batch MMIC Manufacture, 2000; PHASE II: MMIC Qualification, 2000; PHASE III: EM (Electrical Model), 2001; PHASE IV: QM (Qualification Model), 2001; PHASE V: PFM (Proto Flight Model), 2002; PHASE VI: FS (Flight Spare), 2004.

Receiver architecture

The baseline 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

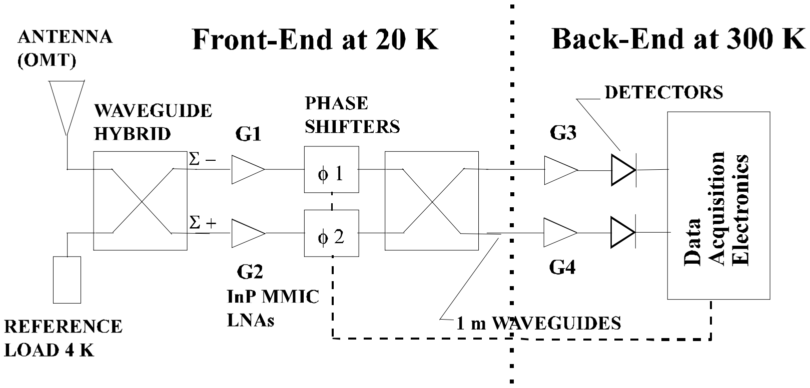

Figure 1. Baseline Planck LFI receiver, with a waveguide first hybrid.

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 waveguide structure (like a magic-T) is planned to be used as the first hybrid.

Development and testing of MMICs

Parallel evaluation is carried out between two InP semiconductor processes for making the needed MMICs (DaimlerChrysler gate length $L_g=0.18$ μm and TRW $L_g=0.1$ μm). First, LNAs and hybrids have been received from the DaimlerChrysler wafer run. The main production run for the flight chips is scheduled for 2000-2001. Important part of the challenging MMIC development for the Planck are good testing facilities of the devices directly on-wafer before the chips are packaged. Special effort has been focused to develop on-wafer noise parameter testing for 50-75 GHz [3] and cryogenic measurements system up to 110 GHz. Both, the MMIC development and testing are described separately in more detail in this report.

Conclusions

From the receiver architecture point of view, the most critical aspects of the receiver is the low 1/f noise performance. MMIC technology with InP HEMTs will be used in the receiver. Key components will be the low noise amplifiers with a total gain of about 65 dB. First 70 GHz MMIC components have been processed at DaimlerChrysler Research Centre.

Acknowledgments

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 Technology Development Centre, Finland.

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6.2. MMIC Low Noise Amplifiers for 70 GHz

Timo Karttaavi, Manu Lahdes, Pekka Kangaslahti[1], Juha Tanskanen[1], Olli Koistinen[2] Hanna Salminen[1], Jussi Tuovinen, Nicholas Hughes[1], Petri Jukkala[1], Seppo Urpo[2]

[1]Ylinen Electronics Co., Kauniainen, Finland
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Introduction

European Space Agency's Planck-mission aims to use monolithic low-noise amplifiers in its 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 planned. The primary European candidate is the process from DaimlerChrysler Research Center in Ulm, Germany. The first production round at DaimlerChrysler was completed towards the end of 1998. A second foundry run using the same process is planned for July 1999. In addition to this TRW InP process in California will be evaluated, and some LNA designs have been submitted for processing during summer 1999.

Amplifier design

Indium-based HEMT processes are still very much research oriented and under constant development. Generally foundries are not able to provide the support usually available for more mature technologies. In practice the most important consequence is that device models are more limited and uncertain, or downright unavailable. In the case of DaimlerChrysler we decided to measure transistor S- and noise parameters from a test wafer, and use these results in the design process. The measured minimum noise figure of a $0.18\mu m \times 80\mu m$ device was 2.5 dB with an associated gain of 6 dB at 70 GHz.

Several single- and multi-stage amplifiers as well as test structures were designed together with Ylinen Electronics Company. The emphasis during the first design round was more in verifying component models and modeling procedures, and not so much in fulfilling specifications implied by the Planck program. Also, at this point all measurements have been done on-wafer, although the final versions will be housed in waveguide fixtures.

Figure 1 shows a photograph of a three stage amplifier. The DaimlerChryler process uses coplanar waveguides without via-holes or bottom metallization. The main advantage of this, along with lower cost, is that the substrate can be left thicker, since the thickness does not affect the line impedance as strongly, as in the more traditional microstrip technology. This is especially important with Indium-Phosphide, as the material is even more fragile than Gallium-Arsenide.

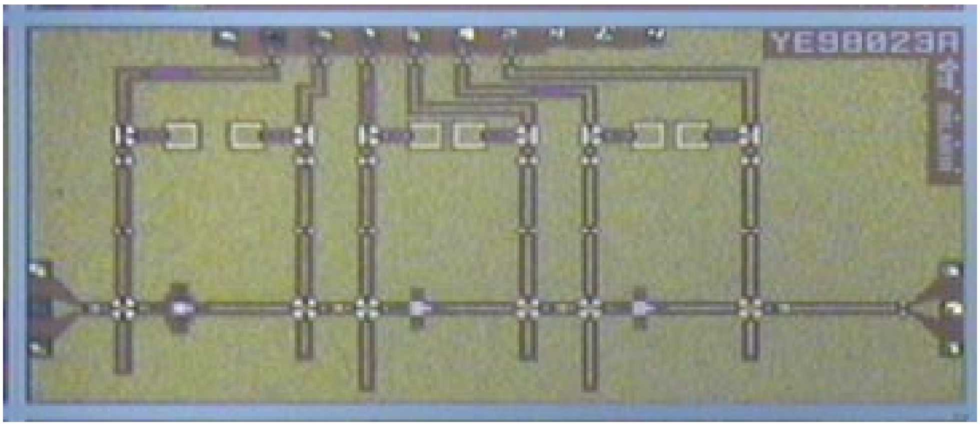

Figure 1. Photograph of a three-stage 70 GHz low-noise amplifier chip

Results

Figure 2 shows the measured frequency response of the three-stage amplifier. It has a gain of 9 dB and a noise figure of 5.5 dB at 70 GHz. Single stage amplifiers showed a gain around 3 dB and a noise figure around 3.5 dB at 70 GHz. The results are more closely reported in [1].

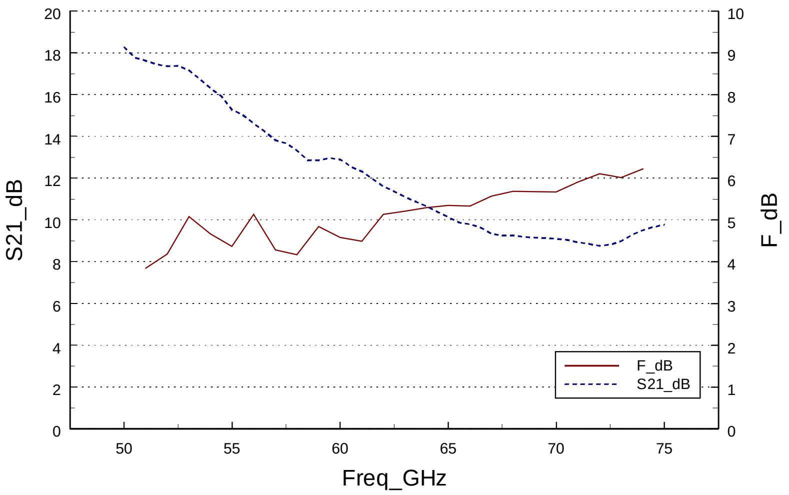

Figure 2. Measured gain and noise figure of the three-stage LNA.

This kind of performance falls somewhat short of our expectations. The difference in gain between the measurements and the simulations in the case of the three-stage design shown above is 5 dB at 70 GHz. The measured noise figure is 1 dB higher than simulated. This is partly due to process variations, which resulted in e.g. a lower than expected device transconductance. Another problem with the simulations is the transistor model. It seems that the de-embedding of parasitics from the test wafer measurement data was not adequate considering the high operating frequency. With improved transistor models in the design process we should attain a performance closer to the theoretical. In addition, the foundry intends to shorten the gate length from 0.18 µm to below 0.15 µm, which should help us in achieving more promising results with regard to the Planck requirements.

Conclusions

The first DaimlerChrysler InP MMIC production round has shown that there is room for improvement both in the design and in the manufacturing. Some iteration is necessary to find the true potential of the technology. Amplifier circuits from a forthcoming TRW run will provide another important reference point.

Acknowledgments

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. Odin satellite 119 GHz receiver front-end

Juha Mallat, Petri Piironen, Antti V. Räisänen

Introduction

The Odin front-end project aims to develop a space qualified spectral line receiver at 119 GHz for a small Swedish satellite [1] in co-operation between HUT Radio Laboratory and Ylinen Electronics, Co. The HUT contribution comprises the design of a Schottky diode mixer, a temperature compensated resonant ring filter for LO-RF diplexing, an SSB filter, a Potter feed horn, and the space qualification tests. The project started in 1994.

Front-end details

The main component in the front-end (see Fig. 1) is a Schottky diode mixer [2] which is a single planar diode mixer. A temperature compensated ring filter [3] is used as a diplexer for signal (RF) and local oscillator (LO) power. Besides being a good diplexer, the ring filter also filters out LO noise sidebands. These noise sidebands would degrade mixer performance if they were not filtered and thus attenuated in the input signal band. The receiver will work in a single-sideband mode and due to this also an SSB filter is integrated into the ring filter in the signal input waveguide. A Potter feed horn is the feed horn for the receiver. The RF amplifier to be used directly after the feed horn has been developed elsewhere.

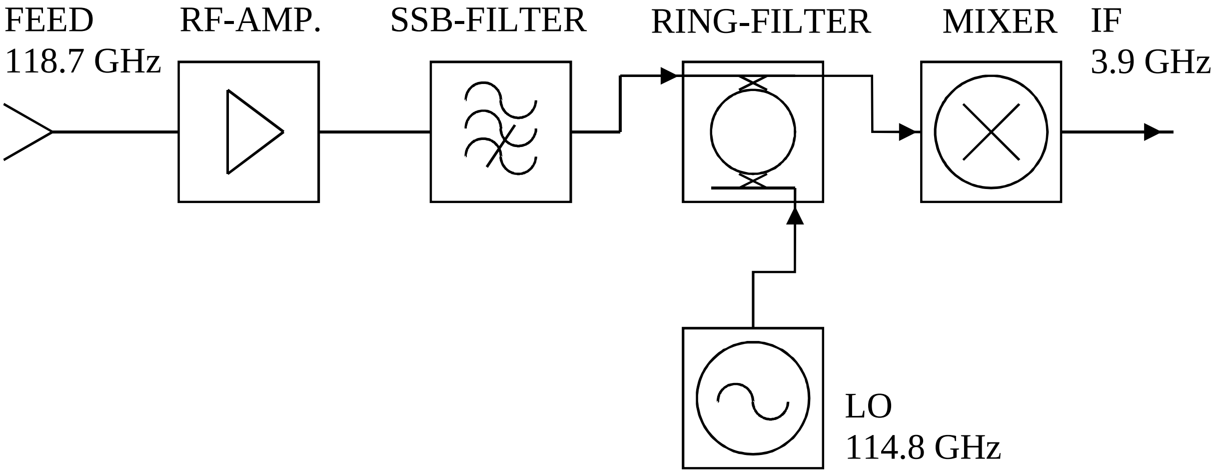

Figure 1. Block diagram of the 119 GHz Odin receiver front-end.

A considerable effort was put in developing, testing and analysing the ring filter with a novel compensation mechanism for temperature related passband shift. The mechanism is needed beacuse the receiver front-end has to stay operational in a wide temperature range but external actuators and control systems to retune the ring filter are highly unwanted. The developed self-contained mechanism is thus most suitable for use in the Odin 119 GHz receiver or any other similar space application. The mechanism minimises unwanted LO power level changes which would otherwise occur due to filter passband shifts in a varying temperature.

Overall development in 1997–98

In 1997, the last flight model (FM) units were completed and the devices were delivered to Ylinen Electronics, Co. for integration into the 119 GHz FM. The first functional tests on the FM were carried out in co-operation between Ylinen and HUT. The results were positive and the receiver was sent to Chalmers University of Technology (CUT) for further tests with the associated quasioptics. These tests, however, brought out problems related to the CUT-made lenses and the receiver electromagnetic susceptibility. Solving these problems was started by CUT, Ylinen Electronics, Co., and HUT in late 1997. The acceptance and functional tests of the FM receiver were continued in 1998. After the EMC and mechanical tests were completed the 119 GHz front-end was forwarded again to Sweden.

In addition to the development of the front-end, HUT assisted several times in the measurements of the front-end in CUT in Gothenburg, Sweden in 1997–98. Measurements of the Odin antenna were also performed in Linköping by using a hologram CATR developed in HUT.

Future

System level EMC tests are due to take place in Sweden. Also some antenna related test measurements are to be performed in Toulouse, France by using the hologram CATR. This is expected to take place in spring 1999. The latest information of the expected launch date for Odin is that the launch will take place in March in year 2000.

Acknowledgments

The Odin Project Group, Swedish Space Corporation, Stockholm, Sweden, the Chalmers University of Technology, Gothenburg, Sweden, Ylinen Electronics, Co., Kauniainen, Finland, and previous workers in HUT Radio Laboratory in connection to Odin are acknowledged for their fruitful cooperation. This work has received funding from Technology Development Centre, Finland.

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6.4. Millimetre and submillimetre wave integrated receiver front-end technology development

Ville Möttönen, Petri Piironen, Antti V. Räisänen, Jian Zhang

Introduction

“Millimetre and submillimetre wave integrated receiver front-end technology development” is an ESA program that was started in early 1996 in order to investigate and advance future millimetre and submillimetre wave receiver technologies for satellite-borne atmospheric observations (atmospheric chemistry research). The goal of the project is to fabricate 650 GHz integrated antenna/mixer front-ends which are qualifiable for the low Earth orbit environment. Parallel front-end designs use both open-structure and waveguide type approaches: 1) open-structure type, fundamentally pumped mixer using a Si-dielectric lens together with a ring-slot radiator, single Schottky diode, and a coplanar circuit; 2) open-structure type, fundamentally pumped mixer using a Si-dielectric lens together with a double-slot radiator, single Schottky diode, and a microstrip circuit; 3) waveguide type, subharmonically pumped mixer using an integrated diagonal horn, anti-parallel diode pair, and a microstrip circuit.

Receiver front-end design

A step-by-step development strategy has been applied to the front-end designs. Final 650 GHz designs are preceded by a set of scaled models to verify theoretical optimisations. Verifications of the open-structure type front-ends are done at 65 GHz and of the waveguide front-end at 5, 10 and 220 GHz. HUT Radio Laboratory is responsible for the waveguide mixer and Ecole Polytechnique Fédérale de Lausanne, Switzerland, together with Chalmers University of Technology (CUT), Sweden, for the open-structure mixers. So-called quasi-vertical Schottky diodes (QVD) developed at the Technical University of Darmstadt (TUD), Germany, are used in all front-ends. A Schottky diode modeling is aided by wideband measurements done by MilliLab. Bergische Universität Gesamthochschule Wuppertal, Germany, analyses the silicon lens needed for the ring-slot and double-slot radiators. Measurements of the open-structure mixers are carried out by CUT. The prime contractor of the project is DaimlerChrysler Aerospace, Dornier Satellitensysteme GmbH, Germany.

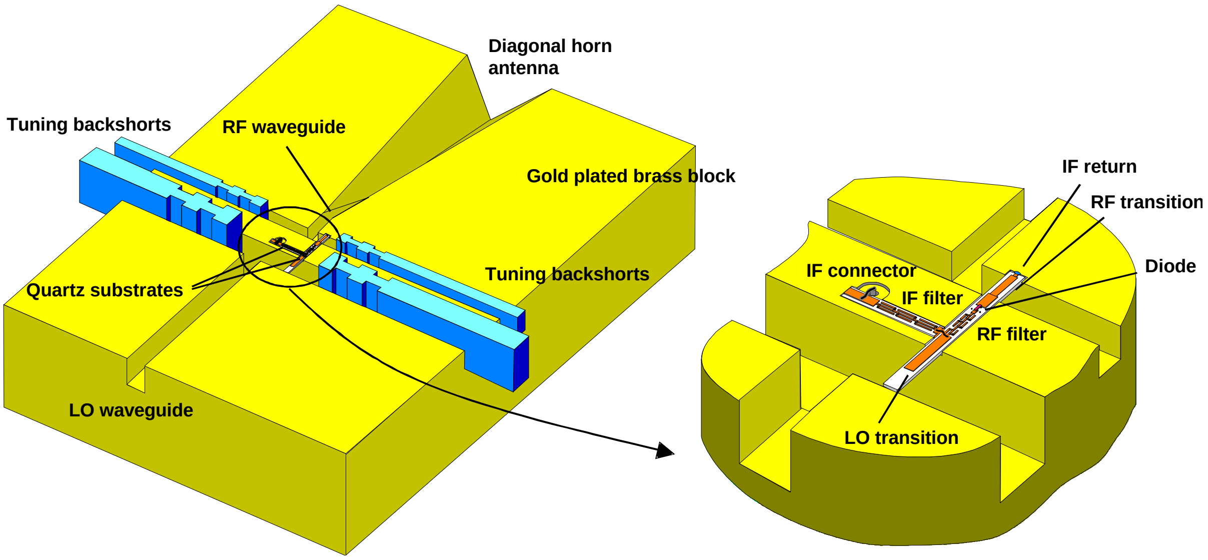

Figure 1. 650 GHz subharmonic waveguide mixer.

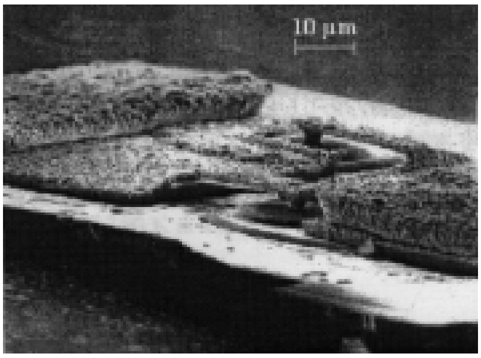

Figure 2. Anti-parallel pair of quasi-vertical Schottky diodes on single GaAs chip.

650 GHz subharmonic waveguide mixer

An important part of the project is to develop European Schottky diodes. To compete against whisker-contacted and planar Schottky diodes, a QVD structure has been developed by TUD. The 650 GHz subharmonic waveguide mixer (Figure 1) employs an anti-parallel pair of quasi-vertical Schottky diodes on a single GaAs chip shown in Figure 2. Waveguide mixer blocks are designed by applying split-block techniques [1]. The RF is input through an integrated diagonal horn antenna and a 440 μm × 220 μm rectangular waveguide. The 320 GHz LO pump signal uses a WR-3 (860 μm × 430 μm) waveguide. Two tunable backshorts are used to match each of the RF and LO. The tuning of the backshorts is accomplished by a separate precision mechanism. Blocks are milled of brass and finally gold-plated. The fabrication is carried out at Radiometer Physics GmbH, Germany. The QVD diode chip is placed on a quartz substrate which, in turn, is mounted into a microstrip channel located between the RF and LO waveguides. There are two microstrip channels: one for the RF and one for the IF filter substrate. Filters that are also required for matching purposes are realised on quartz using microstrip techniques. The filters are connected together with a gold bond wire. The substrates are glued to the bottoms of the microstrip channels. Transitions from the waveguides to the microstrips consist of microstrip parts extending into the waveguides. The IF output is through a coaxial connector which is bonded to the end of the IF filter.

Performance of 220 GHz mixer

To optimise and verify the submillimetre waveguide mixer design, a 220 GHz scaled mixer was designed, fabricated, and measured. As a difference to the 650 GHz mixer, it has scaled block dimensions but the diode chip is the same. Also, it uses an external pyramidal horn antenna. The measured results of the 220 GHz mixer are a 9.2 dB mixer conversion loss and a 3520 K SSB mixer noise temperature. These figures were obtained at 215 GHz and 107 GHz RF and LO frequencies, respectively. The LO power was 3.5 mW. The series resistances of the two diodes in the applied chip are 11 Ω and 12.5 Ω and the ideality factors are 1.29 and 1.28, respectively. The measured conversion loss value is comparable to those of the best published subharmonic planar Schottky diode mixers at this frequency range, but the noise temperature is somewhat higher. It should be emphasized that the diode chip is optimised for 650 GHz and not for 220 GHz.

Acknowledgements

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6.5. European Minor Constituent Radiometer, EMCOR

Jyrki Louhi, Mikael Gustafsson, Juha Mallat, Antti V. Räisänen

Introduction

An EU project in the field of Environment Programme, EMCOR (European Minor COnstituent Radiometer) is a joint project between seven European laboratories: Bordeaux Observatory (France), Paris Observatory (France), Centro Astronomico de Yebes (Spain), University of Bern (Switzerland), Rutherford Appleton Laboratory (United Kingdom), University of Bremen (Germany) and Helsinki University of Technology (Finland) [1]. The objective of the project is the definition and the construction of a sensitive millimeter wave heterodyne receiver in order to measure faint spectral lines of various minor constituents of the stratosphere from the ground. The instrument operates in a frequency range of 200-210 GHz, in which there are many spectral lines of various molecules of interest (such as ClO, N_2O, SO_2, HNO_3, O_3), to study the chemical composition of the stratosphere. The role of HUT Radio Laboratory was to design and construct the phase-locked local oscillator system as well as the IF chain [2].

Details of development in HUT

To great extent the development in HUT was focused to the local oscillator system. Some system options were available and the best of them was selected for realisation. In order to meet the requirements of the EMCOR instrument (frequency coverage of 201–210 GHz, minimum output power of -20 dBm, electrical tuning of the output frequency with steps of 50 MHz), the designed local oscillator system is based on two varactor tuned Gunn oscillators at 100–105 GHz, which are phase-locked to a stable frequency synthesizer. The actual local oscillator output frequency of 201–210 GHz is generated by employing a frequency doubler, from which the power is fed to the quasi-optics via a Pickett horn antenna. The measured output power level of the doubler is more than -15 dBm over entire frequency range which fulfils the required minimum power level of -20 dBm.

The warm IF chain includes further amplification after the cryogenic cooled HEMT amplifier in order to reach the power level sufficient for the acousto-optical spectrometer. The IF chain includes also IF processing, which makes it possible to optimise separately the centre frequency of the radiometer front-end as well as the centre frequency of the spectrometer. In order to meet the requirements, the constructed IF chain includes four amplifiers, a mixer, four filters, a coupler, a detector and a step attenuator. The measured gain flatness of the chain was 2 dB, which fulfils the required flatness of 3 dB. The change in gain was measured to be 1 dB when the physical temperature changed by 15 ºC. The measured Allan variance minimum was at 200 seconds while the measured 1 dB gain compression point occured at 11.8 dB, which both fulfil the requirements.

During 1997 the construction and testing of the LO system and IF chain were completed and the integration of the entire radiometer system was started in Bern, Switzerland. Integration and testing was continued in 1998 and the instrument was installed at the “top of Europe”at Jungfraujoch (3500 m asl) in Switzerland in September 1998.

In May 1998, the EMCOR project was presented in full international coverage to a numerous worldwide audience of attendees in the 2nd ESA Workshop on Millimetre Wave Technology and Applications: Antennas, Circuits and Systems [3].

Acknowledgments

HUT Radio Laboratory received funding for this project from the European Union and the Academy of Finland. Radio Laboratory is grateful to all of its European partners for excellent cooperation in the EMCOR program. We also acknowledge the precious cooperation and expertise of Ylinen Electronics, Co., Kauniainen, Finland in design, manufacturing and testing of the synthesiser and phase-locked loop.

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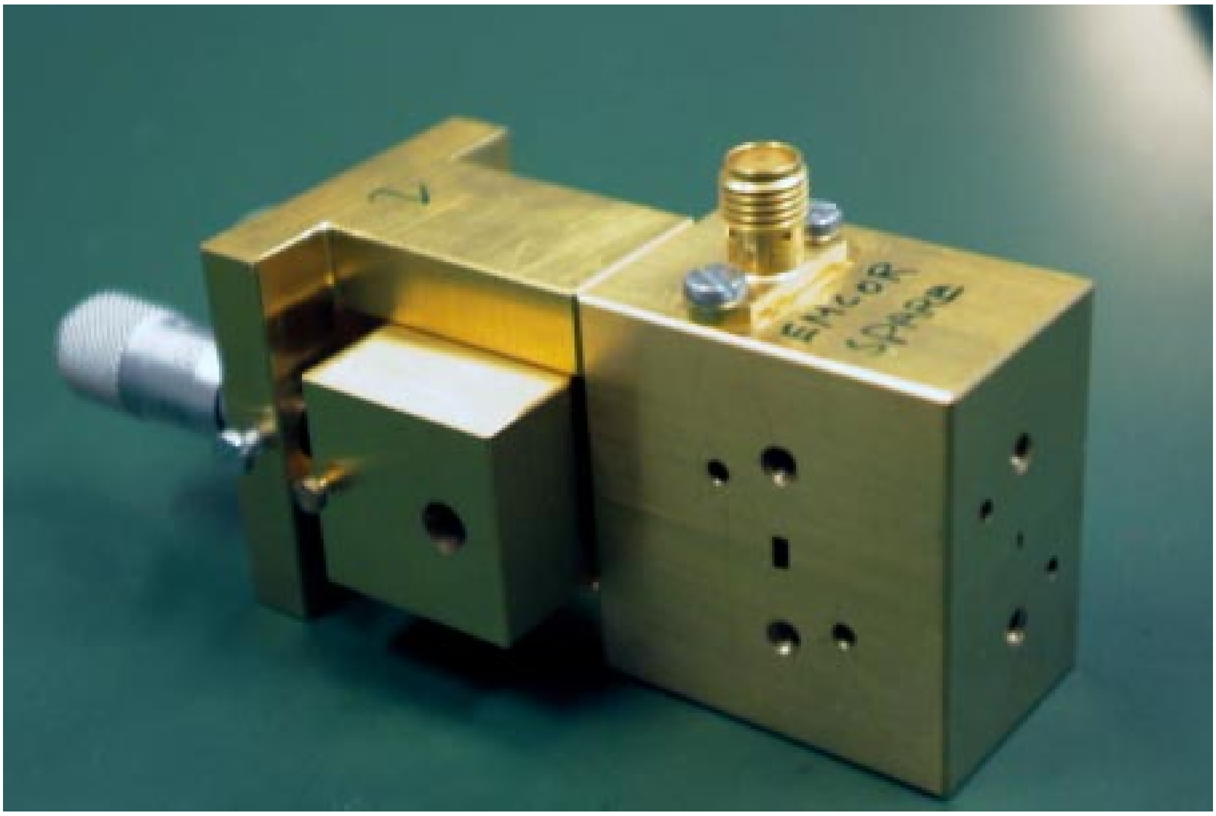

Figure 1. The spare doubler for EMCOR local oscillator chain.

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 millimetre-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, October 17th, 1997

Taavi M. Hirvonen

Quasioptical Methods for Antenna Measurements

Abstract

This thesis deals with the quasioptical methods for antenna and material measurements. The work in this thesis may be divided into three parts: 1) a lens type of compact antenna test range (CATR) and a near-field analysis of a thick lens and horn combination, 2) a hologram type of CATR, and 3) measurement of low-loss dielectric materials for quasioptical components with an open resonator.

A CATR has a great potential for testing electrically large antennas of remote sensing and radio astronomical satellites. However, the application of conventional reflector type CATRs becomes increasingly difficult, thought not impossible, above 100 GHz due to the tight surface accuracy requirements for the reflectors. In this thesis, the use of a shaped dielectric lens and a planar computer-generated hologram have been studied to overcome the problems incurred by the use of reflectors with insufficient surface accuracy. The required field-quality of the quiet-zone is driven by the required measurement accuracy of the antenna under test (AUT). Typical requirements at millimeter wavelengths are a peak-to-peak amplitude ripple less than 1 dB and phase ripple less than 10°. With a hologram CATR a peak-to-peak amplitude and phase ripple under 1 dB and 10°, respectively, have been achieved both theoretically and experimentally at 119 GHz.

Whenever dielectric components are used for collimating electromagnetic fields, a precise knowledge of the dielectric properties of the material is essential. Thus, precise material measurements with an open resonator are included in this work. The aim of this work was to build a facility for precise measurement of the dielectric properties of low-loss materials. The uncertainty of the measurement is 0.02–0.04 % for $\varepsilon_r'(\varepsilon_r > 2)$ and $6-40\times10^{-6}$ for $\tan\delta \quad (10^{-4} \le \tan\delta \le 10^{-3})$.

The contents of the thesis is divided into two parts: 1) a general overview of antenna and material measurements main emphasis being on the millimeter wave antenna measurement techniques and on the theoretical background of this thesis work, and 2) the published reports on the theoretical and experimental work.

Thesis for the degree of Doctor of Technology, October 10th, 1997

Jouni Kaarlo Tervonen

Empirical Modelling of the Effects of Tropospheric Scintillation on Radiowave Propagation for Satellite Communications

Abstract

Small-scale turbulent fluctuations of the refractive index along a propagation path cause amplitude, phase, and angle of arrival variations known as tropospheric scintillation. The theory of scintillation and the several prediction models available are summarised. Scintillation is an important phenomenon particularly for low elevation paths and for low fade margin systems.

Radio wave propagation measurements using 19.8 and 29.7 GHz beacon signals from the Olympus satellite were operated by the Radio Laboratory of Helsinki University of Technology at a mean elevation angle of 12.7° at Kirkkonummi (60.22 N, 24.40 E) in Finland. Because of the low elevation angle, the measurements at this site are suitable for scintillation analysis. The measurement system evolution and the resulting data sets suitable for the scintillation analysis and the analysis procedures are described.

In order to improve prediction models one needs statistical results from many sites. Therefore, the various aspects of scintillation are studied both by analysing only our own measurements and by comparing our results with those of many other sites found in open literature.

The frequency dependence of scintillation, as observed from measurement results at various sites, shows remarkable differences. No convincing correlation of this effect could be found with any meteorological or system parameter, except a slight correlation with the elevation angle. Both theoretical and the experimental study showed that scintillation is polarisation independent.

The prediction models by KARASAWA et al. [IEEE Tr. Ant. Prop., 1988, **36(**11), 1608-1614] and by ITU-R use the wet part of refractivity N_{wet} as the only meteorological parameter. Our analysis shows that a significant correlation between N_{wet} and scintillation variance can be found using averaging of only three days instead of one month stated by the prediction models. New methods are introduced including cloud information (cloud amounts of Cumulus or Cumulus and Cumulonimbus type clouds) together with N_{wet}. The new features improve the prediction accuracy of the diurnal behaviour of the scintillation standard deviation. Prediction of the monthly scintillation standard deviation is still further improved by using annual average of other cloud parameters (integrated water content or probability of heavy clouds).

There is only a small difference between measured fade and enhancement distributions at Kirkkonummi. Both the fade and enhancement distributions are best predicted by the fade distribution of Karasawa et al. or by the enhancement distribution of OTUNG [IEEE Tr. Ant. Prop., 1996, **44**(12), 1600-1608] (the summer months and annual statistics). The normalised distributions of signal fade and enhancement have significantly varying shapes at various sites. Improved models for the normalised fade and enhancement distributions as a function of the elevation angle or the long term standard deviation are introduced.

The scintillation effect on the cumulative distribution of total fade is very small at Kirkkonummi. Assumption of scintillation and attenuation to be statistically independent is the best way to combine the total fade distribution. The fade dynamics change dramatically with or without scintillation. The majority (90-99%) of fades below 10 dB are caused by scintillation. The average fade duration statistics are dominated by scintillation fades. The scintillation fade or enhancement events themselves are short: less than 10 seconds.

Thesis for the degree of Doctor of Technology, June 23rd, 1997

Jyrki Tapio Louhi

Development of Schottky varactor frequency multipliers for submillimeter wavelenghts

Abstract

This thesis deals with millimeter and submillimeter wave Schottky varactor frequency multipliers, which are used to generate all-solid-state local oscillator power of heterodyne receivers.

In order to optimize a frequency multiplier, a good model of the nonlinear device is needed. Although the Schottky diode (varactor) is a well-known device, its behaviour under rapid pumping in a millimeter or submillimeter wave frequency multiplier has not been understood well enough. The main emphasis of this thesis work has been in the modelling of a small area Schottky varactor under fast pumping. A physical model for electron velocity saturation has been added to the varactor model. A more accurate capacitance model has been derived for a small-area Schottky varactor. Through numerical simulations, the shape of the depletion layer during fast pumping has been studied. Rules for optimization of submillimeter wave Schottky varactors have been developed. The theoretical findings are compared with experimental results published in the literature or obtained during this work. In addition, the design, construction, and testing of a doubler and tripler for millimeter wavelengths are described.

The thesis is divided into two parts. The first part presents an introductory overview to the submillimeter wave Schottky varactor frequency multipliers. The second part includes six papers, which deal with modelling and optimization of the Schottky varactor device as well as experimental work on frequency multipliers at millimeter wavelengths.

Thesis for the degree of Doctor of Technology, September 26th, 1997

Jie Xu

Application of numerical methods to modeling of microwave and millimeter wave circuit structures

Abstract

In this dissertation two numerical methods have been investigated for modeling microwave and millimeter wave circuit structures. One is the Method of Moments (MoM) that is a powerful technique for handling electrically small structures. The other numerical technique investigated is the Finite Difference Time Domain (FDTD) method which is a powerful tool for dealing with complicated structures and wideband applications.

The whisker mount structure has been used in microwave and millimeter wave circuits for decades. For the first time a thorough numerical simulation of the whisker mount in a rectangular waveguide via the Method of Moments has been carried out in this thesis.

Numerical simulations of whiskers with different diameters, orientation angles and shape have been done. Theoretical difficulties involved in the numerical modeling work have been effectively solved in this work. Validity and accuracy of the computer codes are verified by good agreements of modeling results with scaled model measurement results. It has been shown that the whisker diameter strongly affects reactance of its embedding impedance for commonly-used whiskers in millimeter wave circuits. The effect of whisker diameter on the resistance part of the embedding impedance is quite minor. It has also been shown that the whisker orientation angle does not have a profound effect on the embedding impedance of whiskers with commonly-used diameters and lengths in millimeter wave circuits. The results from this research provide valuable assistance to designers using the whisker mount structure.

To tackle more general distributed structures encountered in Microwave Integrated Circuit (MIC) and Millimeter Wave Integrated Circuit (MMIC) designs, the Finite Difference Time Domain method has also been investigated in the second part of this thesis. The new stable formulation for multiple-cell lumped circuit sources proposed in this thesis greatly enhances the FDTD's capability to model both distributed structures and lumped circuit elements. It has been shown that in order to ensure stable FDTD simulations all the electric field terms in lumped element region should be time-averaged for multiple cell formulations. Future work in this area should extend the new FDTD formulation for lumped circuit sources into other lumped circuit components, like capacitors, inductors and transistors.

HELSINKI UNIVERSITY OF TECHNOLOGY

ABSTRACT OF THE
LICENTIATE'S THESIS

Author: Juha Ala-Laurinaho

Name of the thesis: Simulation of a hologram at radio frequencies

Date: 27.3.1998 Number of pages: 72

Faculty: Electrical and Communications Engineering

Professorship: S-26 Radio Engineering

Supervisor: Prof. Antti Räisänen

Reviewer: Dr. Tech. Taavi Hirvonen

In this licentiate's thesis, the simulation and the design of the holograms for compact antenna test ranges at radio frequncies are studied. A hologram transforms a spherical wave to a plane wave needed in antenna measurements. The plane wave satisfies the amplitude and phase requirements in the quiet-zone.

The simulation is based on the combination of the finite-difference time-domain (FDTD) and the physical optics (PO) methods. FDTD-simulation gives the transmitted field of the hologram. The radiated field of the hologram aperture can be calculated by PO.

The optimization of a hologram is an iterative procedure. Both the amplitude and the phase of the quiet-zone can be corrected. Amplitude correction can be done by changing the weighting function, which affects the widths of the slots. The amplitude can be corrected by changing the carrier frequency, which determines the leaving angle of the plane wave. The phase correction affects the places of the slots. The quiet-zone field can be optimized also by transferring or rotating the feed.

A hologram for the measurements of the antenna of the Odin-satellite is designed at 119 GHz. The hologram is an ellipse (semiaxes 1.2 m and 1.0 m), which contains seven pieces. There are alignment errors between the pieces of the hologram, which deteriorates the field of the quiet-zone. The Odin-antenna measurements will be carried out during spring 1998.

A linear antenna-array (22 cm × 2 cm) has been measured at 39 GHz. Measured results agree very well with the ones obtained from near-field measurements. A larger hologram for testing planar link antenna (20 cm × 30 cm) has been designed. The hologram is combined from four pieces. The tape used affects the quiet-zone field.

A tolerance analysis has been carried out at 500 GHz. The effects of the systematic and random errors in the widths of the slots on the quiet-zone field are studied. A hologram can be manufactured at 500 GHz, if the hologram is made of one piece. The bandwidth of the hologram is about ± 5–10%

Keywords: Hologram, compact antenna test range, CATR, millimeter waves

HELSINKI UNIVERSITY OF TECHNOLOGY **ABSTRACT OF THE LICENTIATE'S THESIS**

Author: Jaakko Juntunen

Name of the thesis: Reduction of numerical dispersion in FDTD method through artificial anisotropy

Date: 28.7.1998 **Number of pages:** 88

Faculty: Electrical and Communications Engineering

Professorship: S-26 Radio Engineering

Supervisor: Prof. Antti Räisänen

Reviewer: Prof. Keijo Nikoskinen

In this licentiate's thesis, a simple and computationally low-cost method is presented to substantially reduce the numerical dispersion inherently present in the finite-difference time-domain (FDTD) method. Any material modelled with FDTD looks slightly anisotropic in the sense that a plane wave propagates with different velocity along different directions. This phenomenon is called numerical dispersion and it is dependent on the frequency as well. The technique presented in this work is based on careful choice of anisotropy parameters to be used in the algorithm to act against the numerical dispersion. Both 2D and 3D cases are considered.

The numerical dispersion turns out to be worst with FDTD cells that deviate much from square (2D) or cube (3D) shape. In these "bad" cases the reduction works best, the reduction factor being up to 8 in 2D and up to 7 in 3D.

The most severe limitation of the method is that the design of the compensation parameters is for single frequency only. However, the compensation can be used in rather wide-band simulations also, as discussed in a separate chapter.

An associated subject is the absorbing boundary conditions needed in the anisotropic model. Although in the compensation the anisotropy is of simple diagonal type, more general absorbing boundary conditions are developed to include general constant permittivity and permeability tensors.

Keywords: Numerical dispersion, FDTD method, anisotropic media, absorbing boundary conditions

HELSINKI UNIVERSITY OF TECHNOLOGY

ABSTRACT OF THE
LICENTIATE'S THESIS

Author: Tomas Sehm

Name of the thesis: Development of planar radio link antennas for millimeter waves

Date: 14.11.1997

Number of pages: 93

Faculty: Electrical and Communications Engineering

Professorship: S-26 Radio Engineering

Supervisor: Prof. Antti Räisänen

Reviewer: Dr. Tech. Arto Lehto

In this licentiate's thesis, a planar millimeter wave antenna for radio links is designed. The requirements for the antenna are: gain higher than 32 dBi, return loss over 15 dB, and the H-plane radiation pattern must fulfill the ETSI-standard. The frequency range of operation is 37.0–39.5 GHz. The antenna must also be simple and inexpensive to manufacture.

The designed antenna has 256 radiating elements and consists of two parts. One contains the feed network and the other the radiating elements. The feed network is built of rectangular waveguides and T-junctions. The T-junctions are matched by placing a small tap in each output port of the T-junction. A rounded divider has also been used in the T-junctions to improve the matching and to enable unequal power division.

The radiating elements are placed in two groups, which are shifted sideways in the H-plane in relation to each other. In this way, the grating lobe resulting from an element spacing larger than one wavelength in free space is eliminated. Modified box horns are used as the radiating elements. The E-plane shape has been optimized in order to achieve as small a phase error in the aperture of the radiating element as possible. In the H-plane, one can change the aperture field by changing the shape of the horn. In this way, a radiation pattern with low sidelobes can be achieved for the antenna array.

The measured results for a 4×16-element array are presented in this thesis. The results show that the antenna array works as designed. The 64-element array has a measured gain over 30.4 dBi and a return loss over 16.9 dB in the frequency range 37.0–39.5 GHz. The sidelobe levels in the H-plane are at least 5 dB below the maximum level set by the ETSI-standard.

Keywords: Planar antenna, radio link antenna, box horn, millimeter wave antenna

HELSINKI UNIVERSITY OF TECHNOLOGY

ABSTRACT OF
THE LICENCIATE THESIS

Author:	Petri Lehikoinen	
Name of the thesis:	Quasi-optical design of a submillimeterwave integrated receiver	
Date:	23.05.1997	Number of pages: 90
Department:	Electrical and Communications Engineering	
Professorship:	S-26 Radio Engineering	
Supervisor:	Prof. Antti Räisänen	
Reviewer:	Dos. Jussi Tuovinen	

This thesis is part of an ESA/ESTEC SISIRT project, in which the feasibility of an integrated receiver in an imaging array is studied. Concept of 9 separate elliptical antireflection coated silicon lenses with double dipole feed antennas with backing reflector in a hexagonal grid with undesampling factor of 3.8 is chosen as the test imaging array to be build.

Based on multimode Gaussian beam representation the power coupling efficiency of corrugated horn and elliptical dielectric lens antennas to a Cassegrain antenna is calculated. The power coupling efficiencies of 84 %, 77 % and 70 % were calculated for corrugated horn, antireflection coated elliptical silicon dielectric lens with a double dipole with backing reflector and double slot antenna, respectively. In a focal plane imaging array antennas are placed in a tight grid and therefore one needs to make the corrugated horns physically smaller, which reduces power coupling efficiency to a level very similar to that of the dielectric lens antennas.

In an antenna array there is a clear correlation between the aperture efficiency and antenna separation. The closer the antennas are packed, the lower the aperture efficiency. In an array of 9 elliptical antireflection coated silicon lenses with double dipole antenna and backing reflector in a hexagonal grid the aperture efficiency is only about 30 % for an undersampling factor of one. Hexagonal grid offers better packing density and undersampling factor than rectangular grid.

For high resistivity silicon, normal silicon and Stycast the dielectric constant and power attenuation coefficient were measured at room temperature and at 4 K with Michelson interferometer at a frequency range of 400 - 1500 GHz. At 500 GHz the following results were obtained: for the high resistivity silicon at room temperature $\varepsilon_r = 11.7 \pm 0.4$, $\alpha = 0.066 \pm 0.02\ \mathrm{cm}^{-1}$, and at 4 K $\varepsilon_r = 11.6 \pm 0.4$, $\alpha = 0.05 \pm 0.015\ \mathrm{cm}^{-1}$; for normal silicon at room temperature $\varepsilon_r = 11.5 \pm 0.4$, $\alpha = 3.5 \pm 0.5\ \mathrm{cm}^{-1}$, and at 4 K $\varepsilon_r = 11.4 \pm 0.4$ and $\alpha = 0.2 \pm 0.03\ \mathrm{cm}^{-1}$; for Stycast at room temperature $\varepsilon_r = 5.2 \pm 0.5$, $\alpha = 10.2 \pm 1\ \mathrm{cm}^{-1}$, and at 4 K $\varepsilon_r = 5.2 \pm 0.5$ and $\alpha = 3.4 \pm 0.4\ \mathrm{cm}^{-1}$.

Keywords: dielectric lens antennas, Fourier-transform spectroscopy, Gaussian beam, imaging array, integrated receiver, SISIRT, SIS-junction

HELSINKI UNIVERSITY OF TECHNOLOGY

ABSTRACT OF THE MASTER'S THESIS

Author:	Mikael Gustafsson		
Name of the Thesis:	The IF chain of a joint European 200 GHz radiometer for atmospheric monitoring		
Date:	18.8.1997	**Number of pages:**	66
Dept.:	Department of Electrical and Communications Engineering		
Professorship:	Radio Engineering		
Supervisor:	Professor Antti Räisänen		
Instructor:	DTech Jyrki Louhi		

The earth is surrounded by the ozone layer which is located in the stratosphere. The ozone protects the nature from receiving too much ultraviolet radiation. The disappearance of the stratospheric ozone produces a high risk for the health of human being, animals and plants, which is why the amount of ozone has to be monitored. A suitable equipment is a radiometer which is a highly sensitive receiver. In this master's thesis a millimeter wave radiometer and especially its IF chain has been studied.

In the beginning of the thesis different radiometer types are dealt with, especially the total power radiometer and the Dicke radiometer. The EMCOR project is introduced, which is a joint European project, the purpose of which is to measure ozone and ClO. In the thesis the different parts of the EMCOR radiometer are dealt with: SIS mixer, quasi-optical system, cryogenic system, local oscillator, and especially the IF chain.

The local oscillator and IF chain are constructed at Helsinki University of Technology. The main objectives of the thesis were to design, construct and test the IF chain. The purpose of the IF chain is to amplify and down-convert the signal, so that it can be detected with the acousto-optical spectrometer.

Four filters and one coupler have been designed and constructed for the IF chain. One important feature of the IF chain in a radiometer is its stability, which can be measured and improved with the help of the Allan variance method. The gain of the IF chain is 55 dB, gain flatness is under 2 dB, bandwidth is 1 GHz and the Allan variance turnpoint is over 200 s. The output power 1 dB gain compression of the IF chain occures at 11 dBm and the measured noise temperature is 760 K.

Keywords: Radiometer, mm-waveband, IF chain