TERAHERTZ-RESEARCH AT ERLANGEN UNIVERSITY LABORATORIES FOR HIGH FREQUENCY TECHNOLOGY

- A 5-YEARS REVIEW -

by

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Abstract

Research activities in the 0.1 to 2.5 Terahertz-range at Erlangen University Laboratories for High Frequency Technology follow two main directions: establishing measurement systems and developing components following engineering design rules, that means minimizing weight and power consumption and optimizing performance and reliability whenever possible.

The paper describes fundamental research on submillimeter wave measurement systems and the development and manufacturing of the associated components. One special aspect is the multi-diode multiplier array as a stable source for different frequencies. On the mixer side, improvements can be reported by using broadband if-path design of the whisker/diode-connections and by real noise matching of the embedded HEMT if-amplifier.
Some application examples are demonstrated in detail: a broadband dual polarization scatterometer of about 600 GHz, a 4-diodes harmonic generator network, a vector doppler radar at 280 GHz in a dielectric line integrated module and a quasi-optical submillimeter wave interferometer system near 300 GHz for measurement of complex dielectric permittivity with improved accuracy. The paper is closed with an outlook to possible THz-applications in the future including the frequency range 1 THz and above. The short range radiometric imaging of a living object is demonstrated as an example.

1 Introduction: THz-Activities in Germany

Terahertz research at Erlangen University Laboratories for High Frequency Technology (ERU-LHFT) is embedded in the corresponding research activities of other German and international institutions.
In Germany, research in the Terahertz region, which will broad-mindedly include the 0.1 to 10 THz frequency range, is performed at present in 12 university laboratories and in 10 non-university research establishments, such as the Max-Planck-Institutes (MPI) or the Institutes of the Deutsche Forschungsanstalt für Luft- und Raumfahrt e.V. (DLR). In addition, there are activities in industrial laboratories, but they are not included in this survey. In Fig. 1a, universities and these research establishments are listed alphabetically with the names of their locations.

What are the fields of interest in these different types of institutions? Here we must differentiate between the natural science objectives, such as studies of star formation in molecular clouds in astrophysics or the ozone layer depletion in the earth's stratosphere, and the engineering goals to produce devices and instrumentation which enable one to make the observation of the earth's atmosphere or of the sky behind it.

As can be seen in Fig. 1b, there are the three fields of interest such as astrophysics, earth's atmosphere or plasma interaction, where high performance Terahertz-instrumentation can well be used, but it does not matter whether this high performance is best achieved by a GaAs-diode or a Niobium based SIS contact: the main scientific goal is the observation of a CO-transition in the Orion nebula or of the ClO-increase in the earth polar stratosphere or of the temperature distribution in a fusion-plasma, respectively. On the other hand there are some laboratories, where the fabrication of good semiconductor and superconductor devices or of measurement systems for THz-frequencies lies in the center of interest, independent of the field of application. In reality, there are many cross correlations of interest in the same laboratory and between the various institutions. However, this is only one aspect of a fair competition as well as of a fruitful cooperation in the Terahertz community.

2 Experimental Facilities and Research Goals at the ERU-LHFT

The research activities at the ERU-LHFT will first be reported in a survey and related to the actual facilities in the different fields. A more detailed description of some examples will follow afterwards.
The historical background of our submillimeter wave activities were some millimeter wave radar experiments in the mid seventies. To improve lateral resolution, we decided to shorten the wavelength and this was the beginning of our research on optically pumped far infrared lasers in 1979. In the meantime we could extend our source facilities by some backward wave oscillators which have the advantage of tunability but suffer in most cases from a bulky power supply. This was the reason

why we started to develop very recently a new type of lightweight and highly-stabilized power supply for microwave tubes as noted in Fig. 2.
On the other hand one can see in the next row of this list, that the interest in higher frequencies, which can be generated very easily with the optically-pumped far infrared (OPFIR) molecular gas lasers, led to some investigations in this field ([A1] - [A13]) associated with the interest in improvements for the necessary pump lasers ([B1] - [B7]).
Without going into too much detail, we should only like to mention the real improvements in amplitude and frequency stability that we achieved with the principle of the ring-type-system ([A1], [A11]) and the reduction of weight and complexity by using the rf-gas-excitation with low frequencies (around 100 kHz) for the CO_2-pump laser [B2]. A further improvement in efficiency can be expected from the sandwich type OPFIRL ([A8], [A9], [A12], [A13]) and a real reduction in costs has been achieved by using microwave excitation and diffusion cooling for the CO_2-laser [B6].

It may still be an open question, whether a gaseous OPFIR-laser system can be regarded as being able one day to become space qualified - on the grounds, there is no question, that this type of Terahertz source is a very versatile, flexible and not too expensive system for new experiments in an university laboratory.

However, we are also interested in harmonic generators using semiconductor diodes, especially in the multidiode version ([C1] - [C4]). This theme is extended in the next chapter as one of our examples for a new circuit design concept.

In the next Fig. 3, our facilities are summarized to use or to fabricate passive components and networks for the THz frequency range . Up to a frequency of about 300 GHz we try to use hollow metal waveguides and we intend to be able to fabricate nearly all passive components in our own workshop. We have re-activated the claw flange system suggested by DE RONDE in the sixties because it allows a lower total network attenuation caused by the shorter lengths one needs for each component.
Most of our measurement systems are operated in quasi optics by using either a lens-guiding or a mirror-guiding system. The different categories of the principle of invariance [E1] allow one to design beam-wave-guide networks, where the beam waist diameter or their location does not vary with frequency and that means that the transmission characteristics can be very broadband, apart from special filter functions that are required. In addition we intend to construct the "mental substrate" for the quasi-optics networks in such a way so that it can be used very flexibly by changing special components (e.g. beamsplitters or polarizers) without any new adjustment [E4].
For three years, we have been able to fabricate wire grids with a specially designed machine. Another example from our workshop is the all-metal freestanding mesh (with differently polarized and unpolarized windows) as a beam splitter for directional low-loss coupling [D2]. MARTIN-PUPLETT-diplexers can be tuned by micro-processors and pre-set to an operation frequency within a tolerance of 2 µm.
A new field of investigation is how to fabricate and how to design Dielectric Integrated Networks, that can be operated in the THz-region [D3]. This theme will also be described in more detail in the next chapter.

In Fig. 4 our situation in submillimeter wave detection and sensing is summarized. We are not primarily interested in an extremly low-noise temperature behaviour but more in good calibration facilities for power detectors and in broadband matching to the rf- and to the if-side of Schottky diode mixers [F4]. Another point of interest is the reduction of losses between the if-output of any mixing element and the input of the following if-transistor amplifier by avoiding unnecessary transformations and by utilizing direct noise matching [F5]. Further studies are going on in analyzing Gaussian beam mode mixtures in quasioptical networks [F6].

3 Examples of Measurement Systems and New Circuit Design & Technology

3.1 Dual-Polarization Scatterometry around 600 GHz

This is a 4-years project supported by the German National Science Foundation (DFG-Br 522/14) where we try to investigate how the scattering in different directions of a Gaussian beam from the surfaces of several natural and technical samples can be measured [E3]. In the frequency range from 0.1 to 10 THz, there is the situation that the wavelengths of the electromagnetic waves are of the same order of magnitude as the roughness of many body-surfaces. Therefore we cannot expect the pure diffusive scattering as is seen with visual light (Lambert's law), nor can we expect mirror-like reflection as we find at longer wavelengths. In many cases the polarization direction is also rotated by scattering so that we need two channels for measuring the co- and cross polarizations of the exact back-reflection and in addition two channels for the two polarizations at any angle of observation. In Fig. 5 the schematic of the measurement equipment is to be seen. As a signal generator, we use a wideband Russian BWO-tube, that can be tuned from 510 GHz to 700 GHz. In order to have a high dynamic range or a high sensitivity (necessary especially for the cross-polarization low level sidelobes) the heterodyn principle is utilized in all channels, where another BWO-tube or an OPFIR-laser may deliver the local oscillator power. Because of the fixed OPFIRL-frequencies a tunable if-microwave amplifier in the 2 to 20 GHz range is needed together with a broadband mixer design [F4].
By rotating the sample (device under test = DUT in Fig. 5) the angle of incidence θ_i can be changed. In addition the angle of observation Θ_{ob} can be changed independently. In Fig. 6, we can see how the transmitted beam hits the DUT at its waist. Assuming that the receiver optics selects again a Gaussian beam (of the lowest order) we can describe the scattered power in any direction from the scattered waves (and in the co- or cross-polarization) as is indicated in the upper part of Fig. 6. The lower part of Fig. 6 shows as one example the co-polarized power scattering versus the angle of observation for a slab of slate from a Norwegian rock (from the Porsanger Fjord). It should be remarked that in this case we found nearly no reflection peak at the angle $2\ \Theta_i = \Theta_{ob}$, ($45^\circ$) which is for $\theta_i = 22.5^\circ$ the glancing angle of reflection from a smooth plane mirror. In Fig. 7 you can see the very different scattering behaviour from three surfaces with different roughness of the same artificial stone "concrete". In the case (a) of the smooth surface we observe a high reflection peak at $\theta_{ob} = 2\ \theta_i$ as

is expected from a plane mirror.
In the case (c) a very rough surface of the concrete block scatters the incoming wave over a wide range of angles. Obviously the different sides of an "object of observation" can be recognized by the scattering angle spectrum provided the sides differ in roughness. These investigations , which we presently carry on for many frequencies and some objects of observation, may be important for future imaging applications, either in the active radar or in the passive radiometry mode [E5].

3.2 SubMM-Wave Permittivity Measurement

In many cases of designing a lens, a beam splitter or a dielectric waveguide for example, you need the exact value of the complex dielectric permittivity (ϵ_r and $\tan\delta$) at the actual operation frequency required for an application. There are many methods known in the literature for this problem. STÖCKEL [E7] improved one of the quasi-optical methods of interferometry by investigating the errors that arise, as we know today, mainly by the mismatch of the feed horn (of the source) and the mismatch of the detector.
In Fig. 8a, this measurement system is shown schematically in the upper part, followed by an "Interferogram" which is the voltage of the pyroelectric power detector versus the shifted way of the movable (rooftop) mirror. One should expect a sinusoidal function as an interferogram, but in reality there are a lot of distortions; that can best be recognized in the Fourier-transformed spectrum of the interferogram. This can be seen in the lower part of Fig. 8a where the interferogram distortions now are clearly observed as wavenumber-harmonics. In [E7] it is described in detail how this information can be use to minimize the errors, especially for the determination of the loss factor. Results of these measurements near 300 GHz at several dielectric materials are given in Fig. 8b.

3.3 Multi-Diodes Harmonic Generator

Varactor diode harmonic generators, pumped by a compact solid state fundamental source, are today the preferred local oscillators for space or airborne application. The problem is the decrease in harmonic power P_n with increasing harmonic number n and the decrease of the conversion efficiency η_n with increasing pump power P_1 beyond a maximum value. In any case, for a given diode, a given pump frequency and a desired harmonic number, there is a maximum harmonic power that cannot be increased further even when more pump power is available - the ultimate limit being the breakdown of the diode by the pump.

This problem can be solved by using more than one diode, sharing the pump power among many diodes, driving them in the maximum efficiency-point and combining thereafter coherently (!) the harmonic power wanted for the application. This principle has been proposed several years ago but could only recently be implemented in a reasonable approach.

In Fig. 9 the block diagram of the harmonic generation network is shown schematically. The one-diode network is seen in the upper part for comparison. If the efficiency η_n for the conversion from the fundamental pump power P_1 to the nth-harmonic power P_n includes the linear losses of the fundamental low-pass filter F_1 and the losses of the harmonic bandpass-filter F_n, then we could write

$$P_n = \eta_n P_1 \tag{1}$$

However we should have in mind, that η_n depends on the pump power P_1 itself.

In the lower part of Fig. 9 here for example in the 4-diodes-network the efficiency η_n has the same meaning, and in addition we assume that its value is the same for each channel a, b, c and d. Then we take into account the lossy transmission through the dividing part of the network and the phase shifters for the fundamental frequency by a scattering coefficient ${}^{\upsilon}s_1$ for each channel.

In a similar way on the output side, but now at one specific harmonic number n, the transmission through the combining network is described by the scattering coefficient ${}^{\upsilon}s_n$. Here we define the transmission paths for the dividing and the combining part, respectively, according to

$$\text{Maximum of } |{}^{\upsilon}s_1|^2 = 1/M \quad \text{(2a)}, \qquad \text{Maximum of } |{}^{\upsilon}s_n|^2 = 1/M \quad \text{(2b)}$$

in the limit of a loss-free network and with M the number of the similar channels.

In a very simple model, neglecting linear and nonlinear interaction at the other unwanted harmonics, we can calculate the power of the n-th harmonic at the output of the combining network (and only with proper tuning of the phase in each channel) by summing up the n-th harmonic power of each channel. In the case of proper phase matching this can be for the "Multi-Diodes-Generator"

$${}^{M}P_n = {}^{M}P_1 \cdot \eta_n \; M \sum \; |{}^{\upsilon}s_n|^2 \cdot |{}^{\upsilon}s_1|^2 \tag{3}$$

When the fundamental power ${}^{M}P_1$ is significantly larger than the optimum value P_1 for maximum efficiency η_n, and when the losses by the dividing and combining processes are significantly low, that means, Eqn. (2) is valid, we then can expect more harmonic power at the n-th harmonic than in the "One-Diode-Generator".

In a separate paper [C4] at this conference STEUP and WEBER will describe in more detail an experimental quadrupler system for 580 GHz output frequency following these principles.

3.4 Dielectric Integrated Networks

In contrast to continuous waveguiding for example by hollow metal pipes or metal strip conductors, the waveguiding in a beam waveguide happens discontinuously by a set of lenses or mirrors. The propagation of the em-wave between two lenses or mirrors can only be in a straight forward line, not curved as in a hollow pipe.

Discontinuous waveguiding is a form of weak-guiding, but with the advantage that the beam diameter even at the fundamental mode can be somewhat larger than the wavelength. We indeed often design a beam waveguide according to $3\ \lambda < w_0$, where w_0 is the half diameter of the smallest part, the waist, of a Gaussian beam. This leads to the consequence that the lateral and longitudinal dimension are in an acceptable range of millimeters even when the wavelength is in the submillimeter range. In contrast to this, the lateral size of hollow pipes or strip waveguides have to be smaller than the wavelength, which means that we have difficulties in handling, fabricating or mounting at dimensions below 100 µm.

Another point are losses of the em-waves, which increase with decreasing lateral dimensions. Hence the success of quasi optics can be well understood for these above-mentioned reasons. However, concerning mass production, there is one disadvantage of beam waveguide networks: they cannot easily be produced in an integrated form. A new approach to this problem has been proposed in our laboratory by B. STÖCKEL and will be presented at the coming IEEE-MTT International Microwave Symposium [D3].

In Fig. 10a the new concept of low-loss weak waveguiding at THz-frequencies by a dielectric core inserted in a dielectric substrate is compared with the waveguiding in a beam waveguide. The new idea is to use a very small difference in the diffraction index of the core strip (n_c) and the embedding substrate (n_s). In both dielectric materials the loss factor has to be as small as possible of course, but the gain of this concept is an increase of lateral size and that means a reduction of fabrication difficulties and hence of production costs. In Fig. 10b an experimental "Vector Doppler Radar" is shown which was fabricated in our laboratory using this principle. This network was selected as a candidate because it needs directional couplers as well as normal transmission lines and of course bends for a change of propagation directions. In addition, even antennas can be easily made by this concept which is currently investigated in more details in our laboratory.

As can be seen from the photograph of Fig.11 the plastic substrate (TPX) can be fabricated by milling as in our workshop, or by casting into a special matrix. The core material, in our case paraffin, is cast into the channels at a temperature of about 80 °centigrade.

Vector doppler radars need a frequency-shifted local oscillator, which is provisionally done in our experiment by an external mechanical modulator, as is indicated in Fig. 10b. The advantage of this principle is, of course, to be able to differentiate between positive and negative velocities of a moved target.

4 Possible Future Terahertz Applications

The very center of interest of this conference lies on space-qualified devices and systems operating in the THz region, as is clearly indicated in the conference's name. This technology is highly sophisticated, used in only a few missions and is therefore very expensive. Before this technology has spin-offs into a low-cost mass application beyond space missions, the market for these mass applications has to be found. Hence, it might be of interest, even for the Space Terahertz community, to look back to the earth for new applications beyond astrophysics and earth's observation from space.

In the next Fig. 12 we have listed four fields of applications which have the potential of mass applications, when they are needed or wanted from a market in the future. We know very well that all the titles in the list are more speculative than shown to be a requirement. But nevertheless, we believe we should think about the future.

On the other hand people have today the desire to be protected better against illness, or environmental poissoning or criminal attacks. In the field of medical diagnostics it would be very helpful if the individual state of health could be recognized by a pure non-invasive measurement from the skin or with an expiration from the lungs. Can anyone answer the question whether THz-spectroscopy of man's expiration could work as an early warning system, e.g. for lungs cancer, before we have investigated it? There is no question that security services would welcome any system that could detect reliably concealed plastic bombs or drugs. Another interesting field of application could be that of personal identification.

In the field of bio-chemical research many questions concerning real application of THz-frequencies are still open today. Possibly, the close range observation of gas products, from waste tips or the emission from plants may yield indications of imminent danger. Experimentally, however, we have demonstrated that radiometric imaging of plant-elements like blossoms or leaves is possible at 600 GHz [E5], [E6]). In the next Fig. 13 the black-and-white copy of a false-coloured picture taken with a lateral resolution of 2 mm (3600 pixels) of a maple leaf is presented. The different colours indicate different temperatures or different emissivities along the leaf . The biological or chemical background of this emission variation is not yet understood. However, we have seen for the first time through a new window with 600 GHz-eyes into the very manifold life around us.

5 Conclusions

We have tried to report briefly on a 5-years-Terahertz-research periode at Erlangen University Laboratories for High Frequency Technology by scanning the experimental facilities and scientific goals in the three fields: sources, passive components/networks and detecting/sensing. These investigations and results are documented in 41 publications, which are cited as references. Four topics are discussed in more detail to illustrate our spectrum. The authors would like to thank 53 students for their efforts during their diploma-thesis and pre-diploma-thesis-work, concerning THz-research, our staff members G. Bauer, H. Bergmann, H. Ertl, H. Frisch, L. Höpfel, M. Kühl, F. Krug, A. Oswald and J. Popp for their very appreciated support in manufacturing, organization and preparation, the national German Science Foundation DFG for financial support in 4 Submillimeter Wave projects and many friends in industry, research establishments and other universities for experimental support and advice.

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Universities	Laboratories for
1 TU Braunschweig	Semiconductors + Optics
2 U Bremen	Remote Sensing
3 TH Darmstadt	High Frequency Electronics
4 U Erlangen	High Frequency Technology
5 U Karlsruhe	High Frequency Technology
6 U Köln	Physics
7 TU München	Applied Electronics
8 TU München	High Frequency Technology
9 TU München	Walter-Schottky-Institute
10 U Regensburg	Physics
11 U Siegen	High Frequency Technology
12 U Stuttgart	Plasma Research
Research Establishments	**Institutes for**
13 DLR Berlin	Space Sensor Technology
14 DLR Wessling	High Frequency Technology
15 DLR Wessling	Optoelectronics
16 KFA Jülich	Solid State Physics
17 KFA Karlsruhe	Technical Physics
18 MPI Bonn	Radio Astronomy
19 MPI Garching	Extraterrestrial Physics
20 MPI Garching	Plasma Physics
21 MPI Lindau	Atmospheric Research
22 PTB Braunschweig	Frequency Measurement

(a) Locations and Institutions

ASTROPHYSICS	6, 13, 18, 19
EARTH'S ATMOSPHERE	2, 13, 14, 15, 21
PLASMA INTERACTION	12, 17, 20
FUNDAMENTAL PHYSICS and CALIBRATION	1, 10 22
SEMICONDUCTOR DEVICES	3, 7, 9
SUPERCONDUCTOR DEVICES	6, 10, 16
MEASUREMENT SYSTEMS	4, 5, 8, 11

(b) Research Topics

Fig. 1: Terahertz-Research Activities in Germany

MILLIMETER- and SUBMILLIMETER-WAVE SOURCES			
Facilities			Goals
BWO-TUBES		f/GHz	• Highly Stable Power Supply
RWO S 50	Siemens	33 - 51	
RWO S 60	Siemens	40 - 60	
RWO S 80	Siemens	60 - 90	
RWO S 110	Siemens	75 - 110	
RWO S 170	Siemens	110 - 170	
2PA T 56	E-Dynam	140 - 149	
TH 4219	Thomson	280 - 305	
TH 42 XX	Thomson	550 - 610	
OB 74	Moscow U.	520 - 705	
GASEOUS LASERS			• Stabilized
SMMW: Different Lines from OPFIR-Lasers with CH_3OH, $HCOOH$, CH_3F			• Ring-Type • Sandwich-Type
Pump-Lasers with CO_2			• Compact • RF-Excited
HARMONIC GENERATORS			• Multi-Diode
Experimental Test Chains 37.5 75 150 GHz 150 300 600 GHz			• Coherent Harmonic Combining • Open Structure

Fig. 2: MM- and SubMM-Wave-Sources:
Facilities and Goals at ERU-LHFT

TERAHERTZ-NETWORKS and PASSIVE COMPONENTS	
Facilities	Goals
HOLLOW METAL WAVEGUIDING	up to 300 GHz "Claw Flange"
Passive Components	Available
BEAM WAVEGUIDING	
with	
Lenses (PE, TPX, PTFE)	• Modular
or	• Broadband
Mirrors (plan, elliptical)	• Flexible Systems
Beam Splitter	• Unpolarized Metal Mesh
Wire Grids	25 µm Ø
MP-Diplexer	• Pre-setable
Pol-Rot., Phase S., Attenuator	• Available
Integrated THZ-OPTICS	at 300 GHz
Dielectric Lines	• Low Loss
Directional Couplers	• Single Mode
Antennas	• Low Sidelobes

Fig. 3: Terahertz Networks and Passive Components
Facilities and Goals at ERU-LHFT

SUBMILLIMETER WAVE DETECTION and SENSING

Facilities	Goals
THERMAL SENSORS	
Golay Cell Pyroelectric Detectors Large Aperture Sensors	
SCHOTTKY-DIODES	
Waveguide Mixers	Fundamental and Subharmonic Mode
Open Structure Mixers	• Broadband Design
IF-HEMT-Amplifier	• Noise Matching
Spectral Analyser-Frontends 90 - 140 GHz 140 - 220 GHz 220 - 300 GHz 400 - 460 GHz 560 - 600 GHz	
BEAM DIAGNOSTICS	
Near Field Sensing	• Mode Mixture Analysis

Fig. 4: SubMM-Wave Detection and Sensing
Facilities and Goals at ERU-LHFT

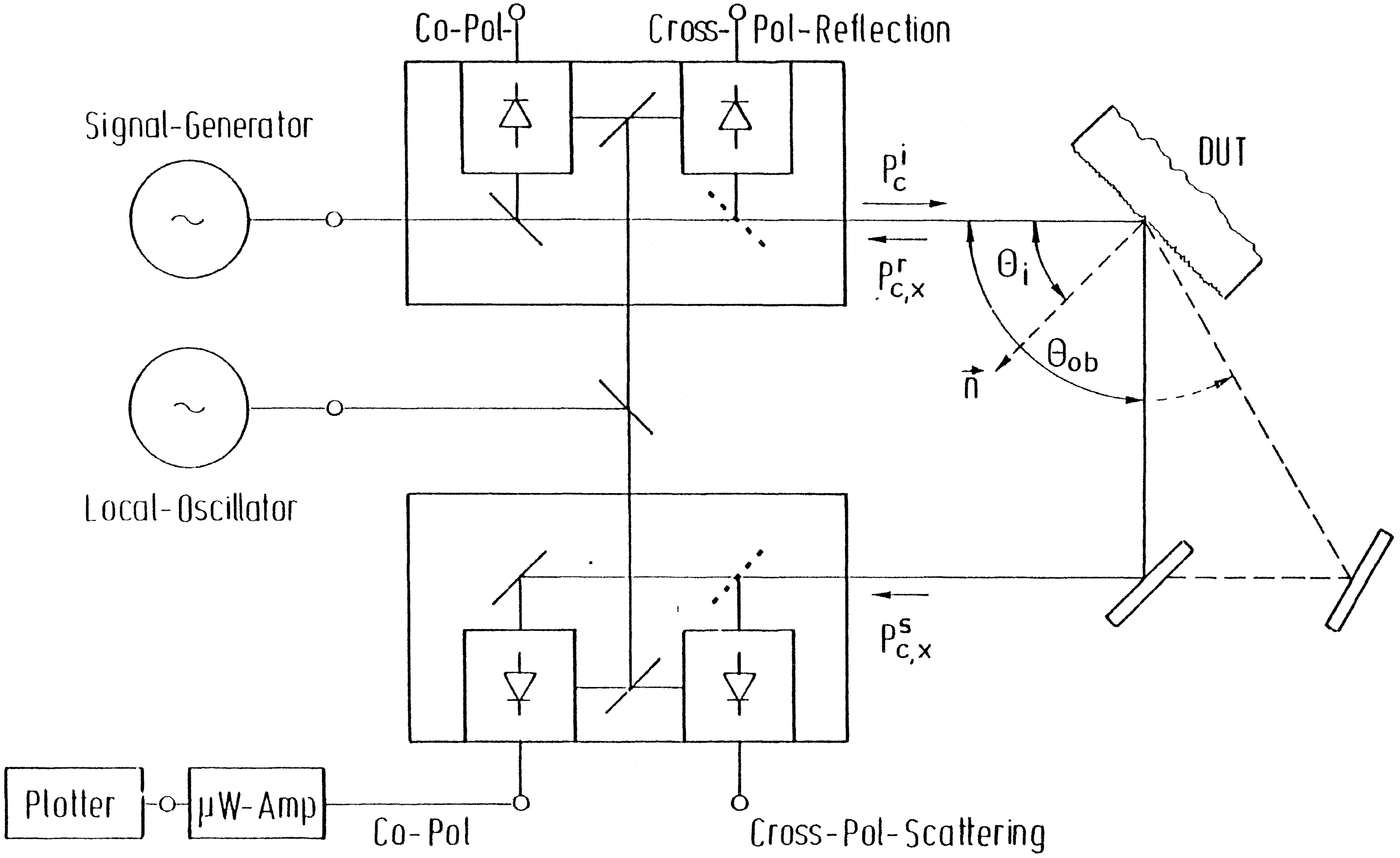


Fig. 5: Two-Polarization Multi-Angle SubMM-Wave Scatterometer

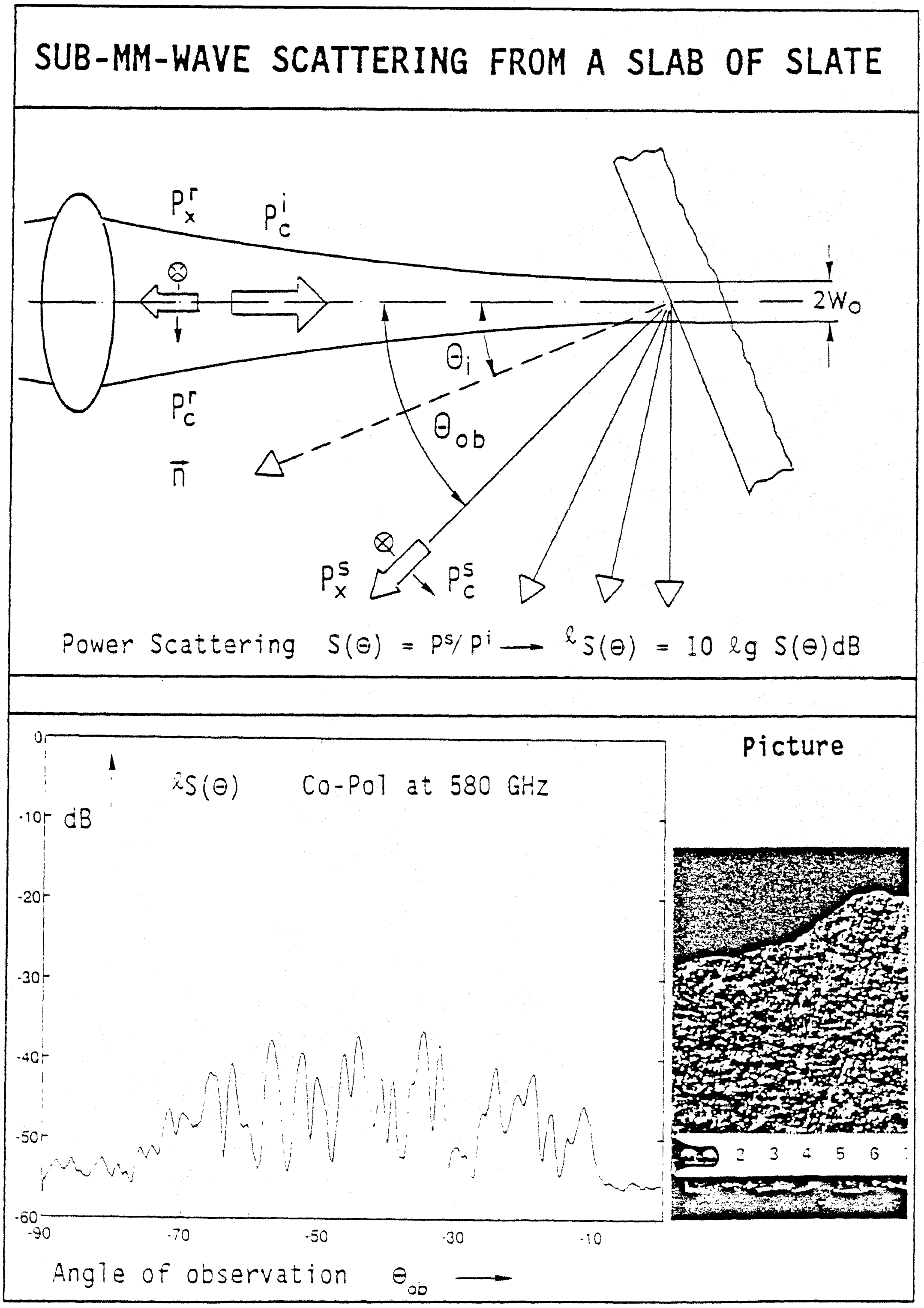


Fig. 6: SubMM-Wave Scattering from a Slab of Slate

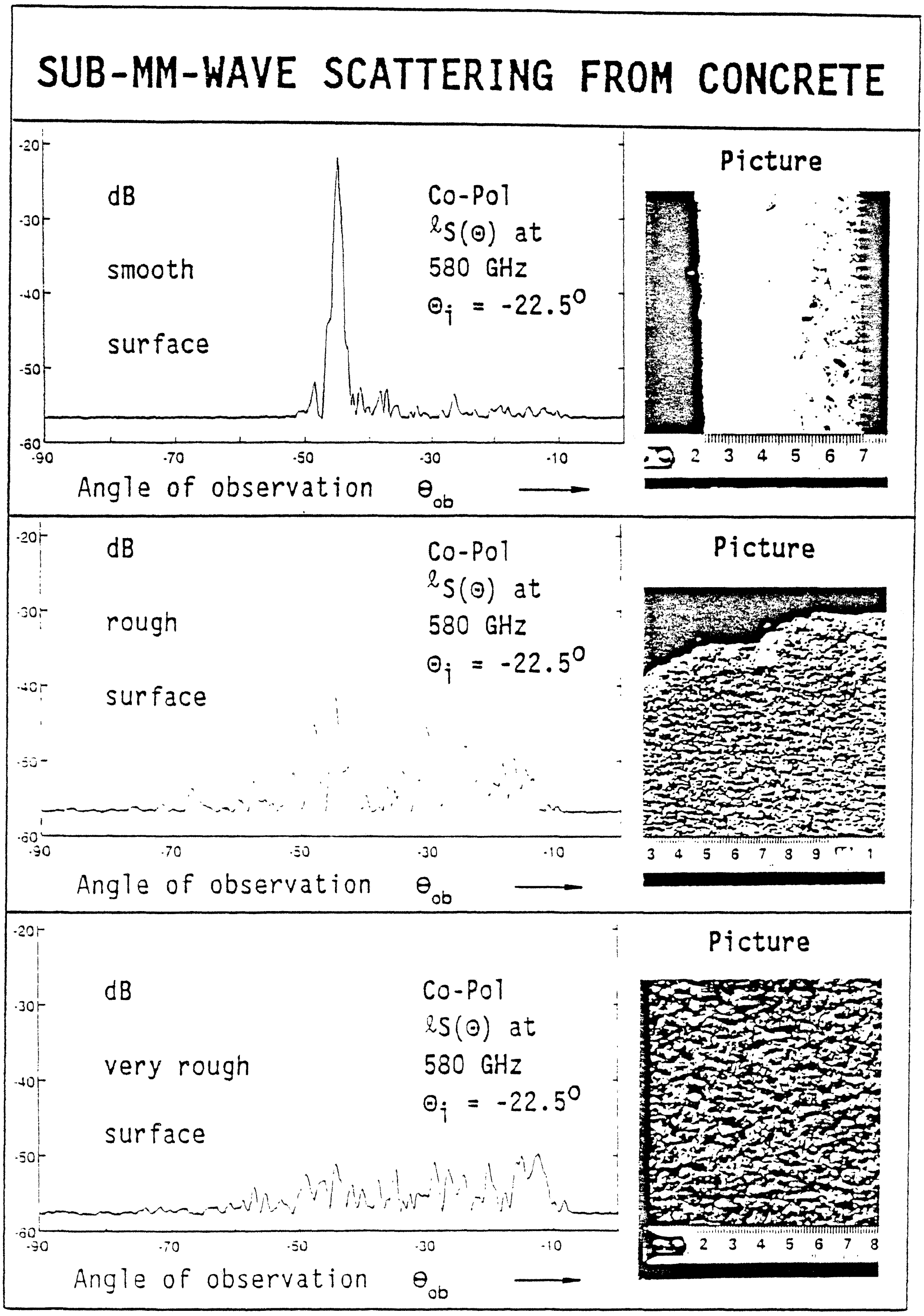


Fig. 7: Sub-MM-Wave Scattering from Concrete

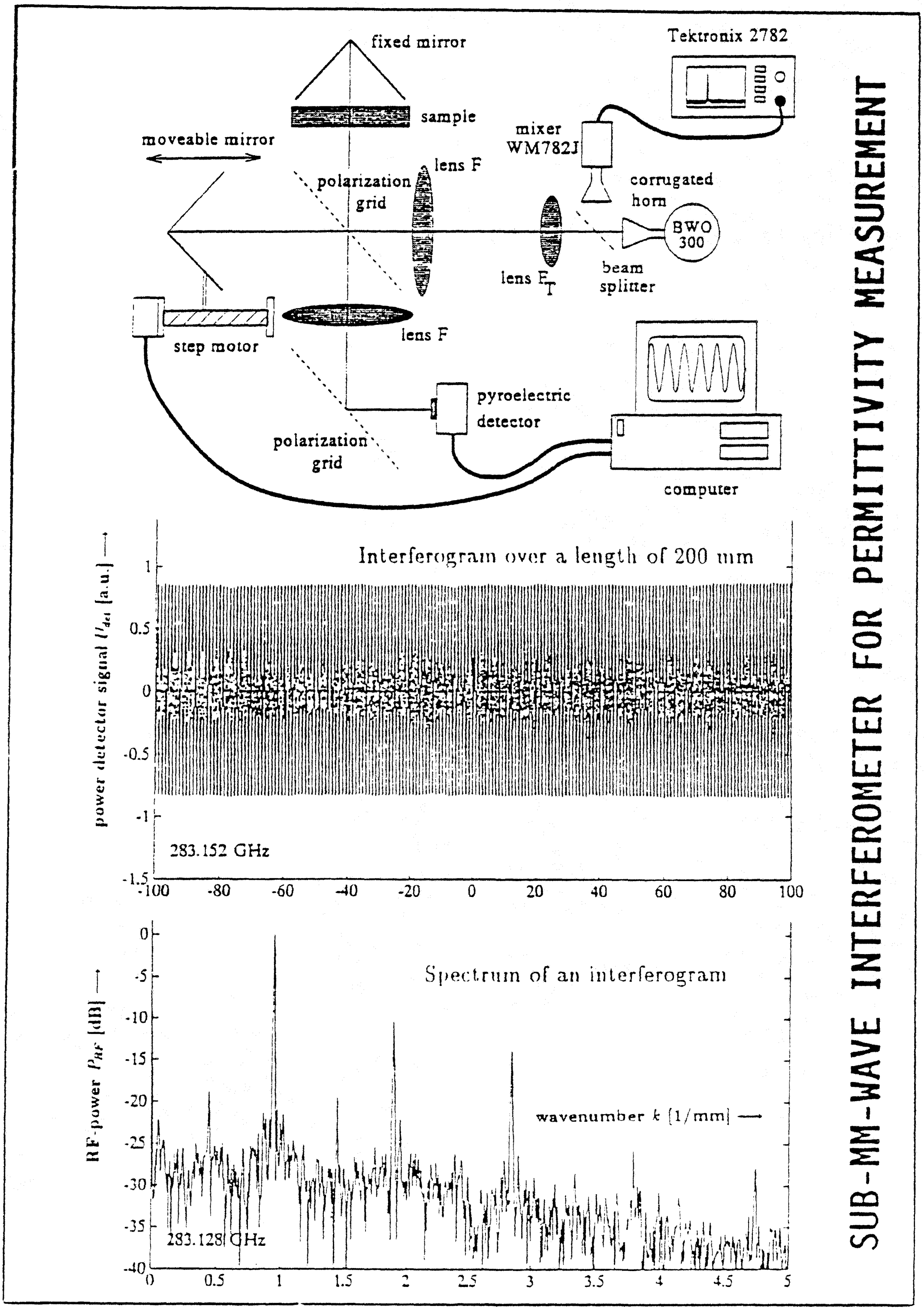


Fig. 8: SubMM-Wave Interferometer for Permittivity Measurement
(a) Block Diagram, Interferogram and Spectrum

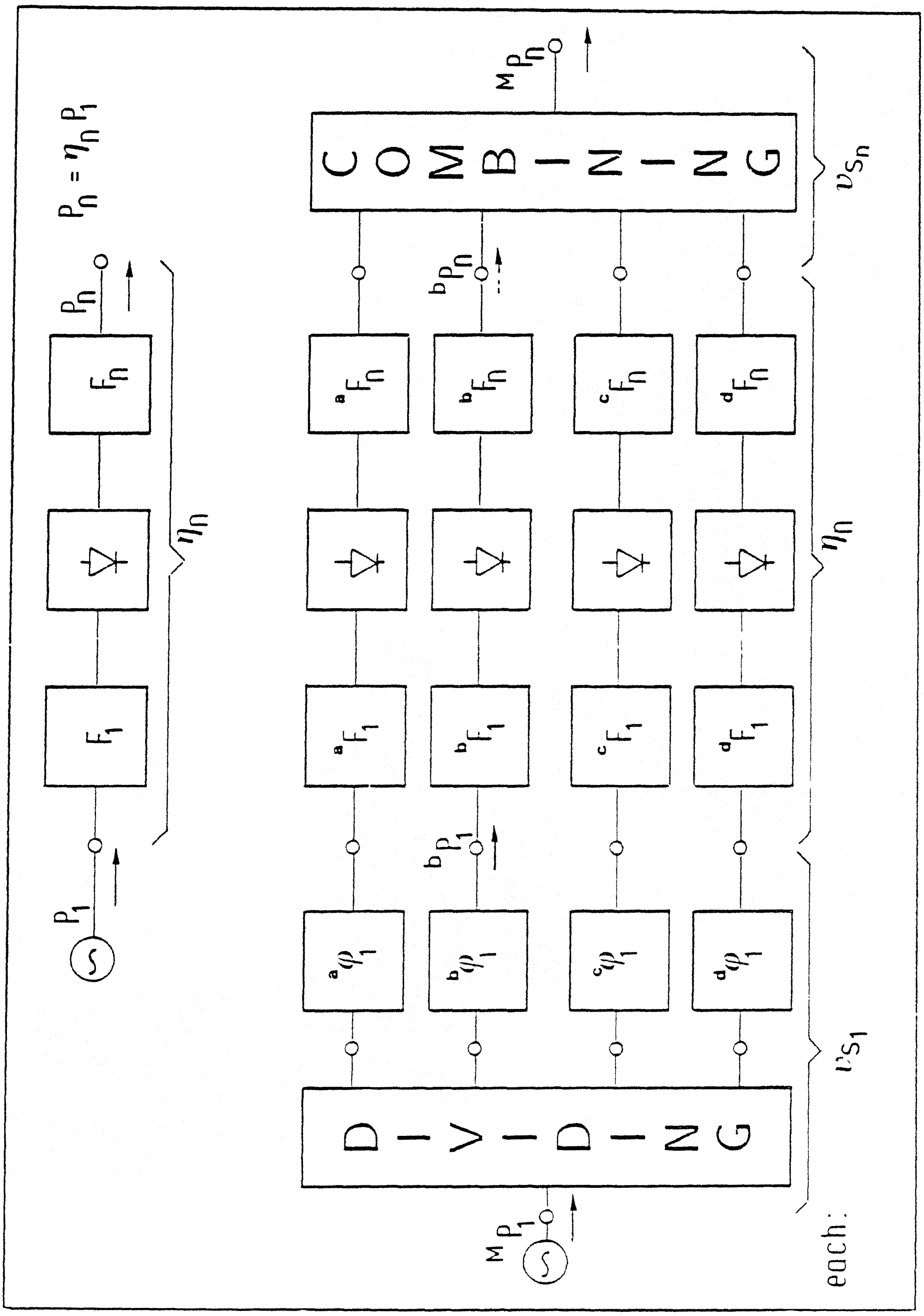
Experimental results

Material	Thickness [mm]	Frequency [GHz]	ε_r	$\tan\delta$ $\times 10^3$
Paraffin 48°C	4.87	283.388	2.264	2.0
Paraffin 48°C	4.87	294.425	2.260	8.2
Paraffin 48°C	7.92	283.387	2.260	0.6
Paraffin 48°C	7.92	294.424	2.265	2.6
Paraffin 72°C	4.63	283.389	2.272	6.0
Paraffin 72°C	4.63	294.426	2.260	10.5
Paraffin 72°C	7.41	283.388	2.268	8.2
Paraffin 72°C	7.41	294.427	2.260	7.0
TPX no. 1	5.07	283.386	2.122	1.0
TPX no. 1	5.07	294.424	2.114	1.6
TPX no. 2	5.07	283.387	2.133	2.5
TPX no. 2	5.07	294.423	2.114	0.32
Spectralon	5.45	279.723	1.724	22.5
Spectralon	5.45	292.816	1.710	22.5
Spectralon	5.45	301.539	1.728	19
Teflon	9.06	295.760	2.046	0.6
Teflon	9.06	301.548	2.038	1.1

B. STÖCKEL: Quasi-Optical Measurement of
Complex Dielectric Constant at 300 GHz.
Int. Journal of Infrared and Millimeter Waves,
Vol. 14, No. 10, 1993, 2131 - 2148

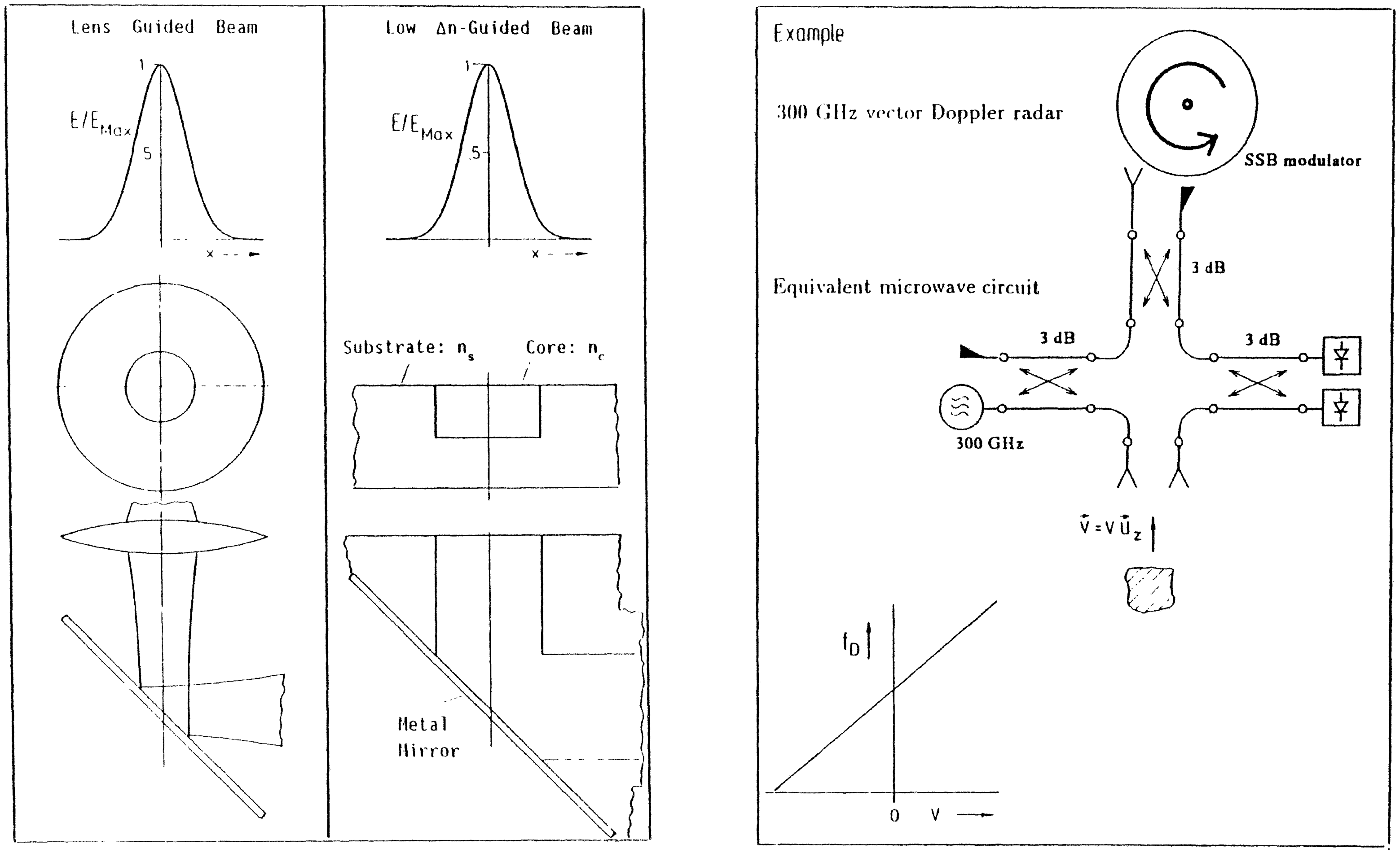
SUB-MM-WAVE INTERFEROMETER FOR PERMITTIVITY MEASUREMENT

Fig. 8: SubMM-Wave Interferometer for Permittivity Measurement
(b) Experimental Results near 300 GHz



(a) One Diode System (b) Four Diodes System

Fig. 9: Sub-MM Schottky Diode Harmonic Generator



(a) Beam Guiding Facilities

(b) Realization Example: Vector Doppler Radar

Fig. 10: Dielectric Integrated Network

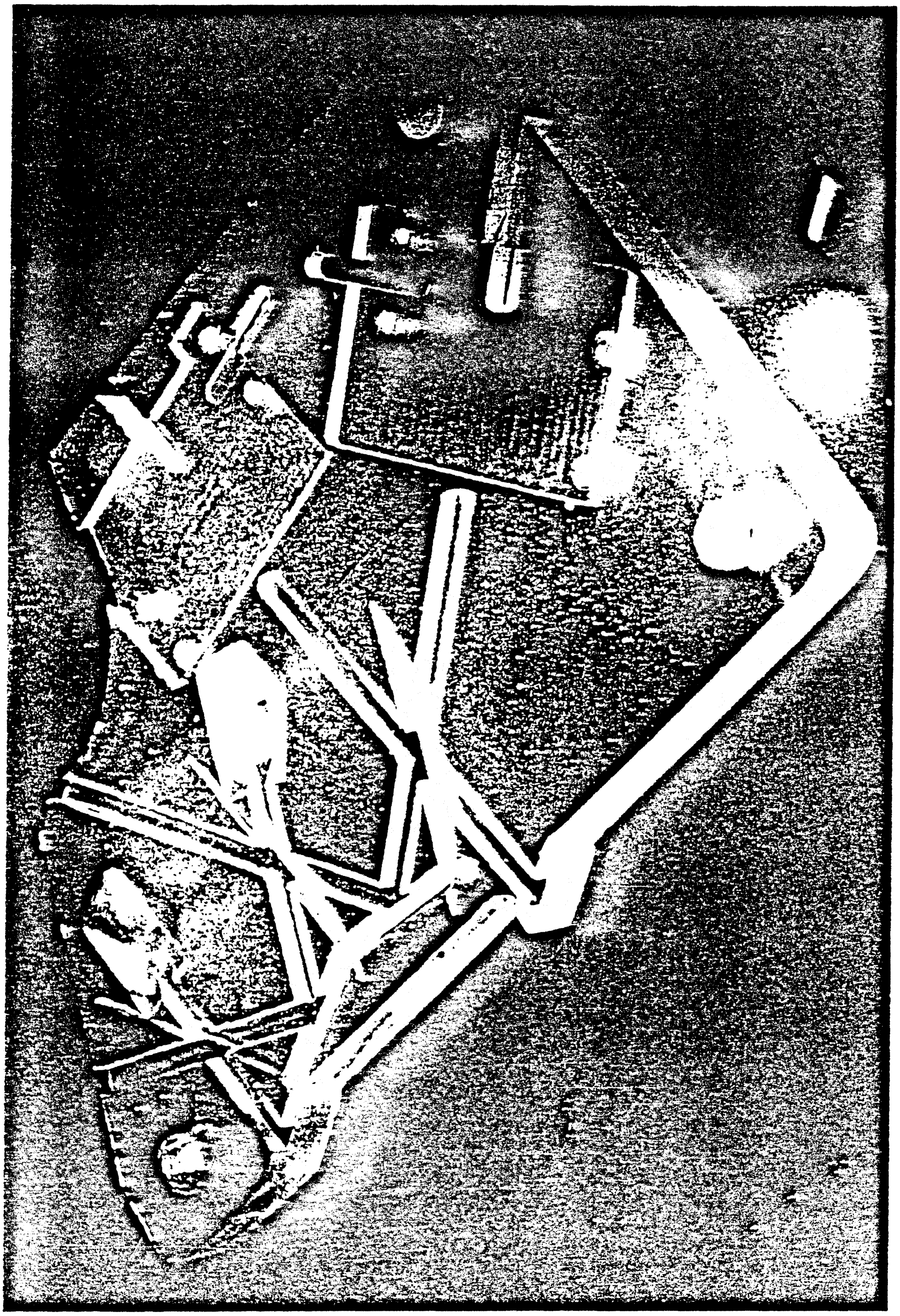


Fig. 11: Picture of the Substrate for the 300 GHz-Dielectric Integrated Vector Doppler Radar

FUTURE TERAHERTZ APPLICATIONS
beyond Astrophysical, Atmospherical & Plasma Research

* MEDICAL DIAGNOSTICS
- Multifrequency Reflection from Skin
- Multifrequency Emission from Tissue
- Spectroscopy of Expiration

* BIO-CHEMICAL RESEARCH
- Spectroscopy of Gas-Products
- Radiometry of Plants
- Environmental Early Warning Systems

* SECURITY CHECK-UP
- Detection of Conceiled Drugs
- Detection of Conceiled Bombs
- Biometrics: Identity Verification

* SHORT RANGE INFORMATION
- Use of Attenuation Screening

Fig. 12: List of Possible Future THz-Applications

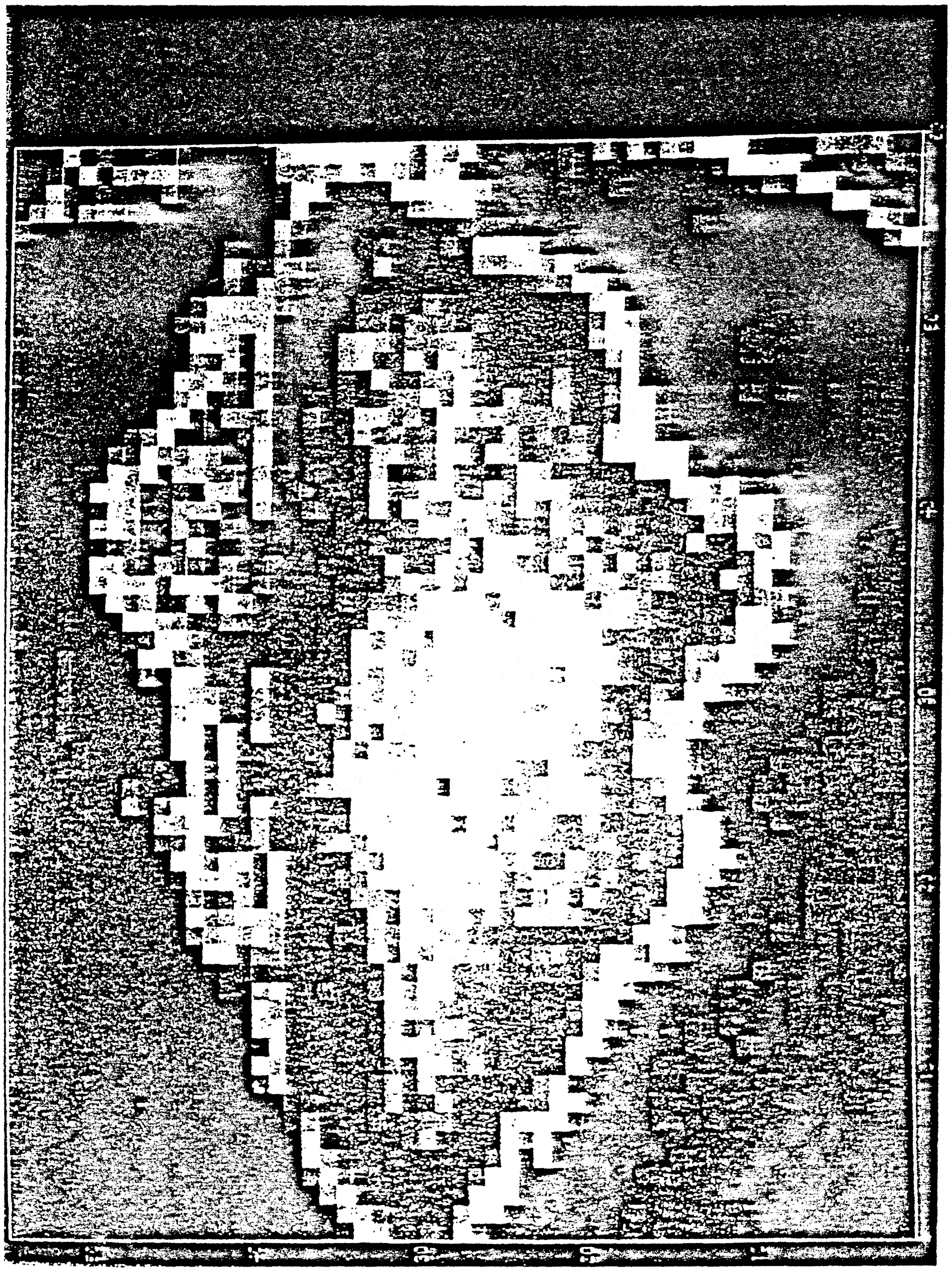


Fig. 13: Short Range Radiometric Image of a Maple Leaf at 585 GHz