Sweep-able sub-millimeter sources and detectors for THz Vector Network Analyzers and Applications

Presenter:
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Introduction.

In this talk, the THz device is an original Vector Network Analyzer which works from 8 GHz to 1000 GHz since more than ten years.

It is made from all solid-state components, producing CW high-frequencies by Schottky multipliers, and detecting them by Schottky harmonic mixing.

In the recent years, the fast improvements in Schottky diodes technology made a breakthrough for easier and more comfortable experiments.

Last months developments permit full-band 660-1000 GHz sweeps with ca 80 dB Dynamic Range.

SUMMARY.

- **I. Some fundamental aspects of millimeter-THz waves: Frequency/Wavelength/Period/Energy/BlackBody peak/Magnetic Field resonances.**

- **II. Phase measurement is important.**

- **III. CW generation and vector detection with Schottkys.**

- **IV. DILEMNA! Single Schottky tunable multiplier, or dedicated multiplication chains.**

  Advantages of Single Schottky: 140-1100 GHz frequency coverage, dynamic range > 120 dB up to 400 GHz, frequency sweep spans 10-25 GHz.

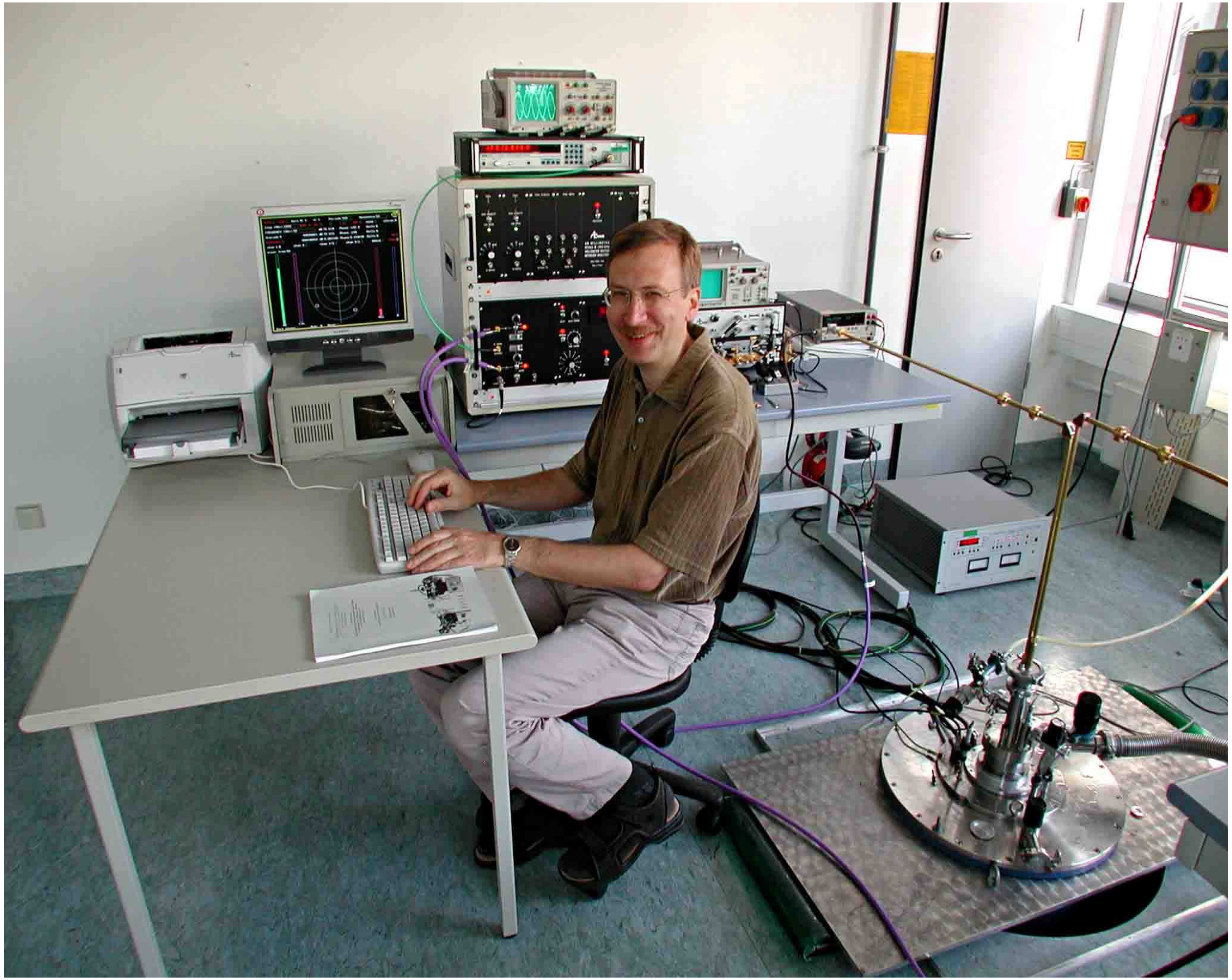
  Advantages of multiplication chains: best efficiency, 62-112 GHz, 124-224 GHz, 220-336 GHz, 660-1000 GHz full-band frequency sweep spans.

- **V. Various applications are shown all along the talk, concerning high magnetic field spectroscopy, antenna tests, imaging, materials characterization…**

I. Relevant aspects of our ca 10 GHz – ca 1000 GHz frequency domain expressed in different units.

Domain	Units	Atmosferic window, Molecular Radioastronomy Cosmic Background Radiation Telecom, Radar, Satcom High magnetic field MR				
Frequency ν	GHz	10	30	100	300	1000
Wavelength λ= c/ν	mm	30	10	3	1	0,3
Period T = 1/ν	pS	100	33	10	3,3	1
Energy E = hν	meV	0,04	0,12	0,42	1,24	4,2
Temperature T = hν/k	°K	0,1	0,29	0,96	2,89	9,6
Magnetic field B=hν/μg	Tesla for ESR	0,36	1,07	3,57	10,71	35,7

Prof. Vladislav Kataev with his16-1000 GHz equipment from AB MILLIMETRE for high-magnetic field studies at IFW, Dresden.



HIGH MAGNETIC FIELDS. The dual-frequency technique (here at 300 & 400 GHz) is useful for observation during long-duration magnetic field sweeps. Prof. M. Hagiwara, Osaka University.

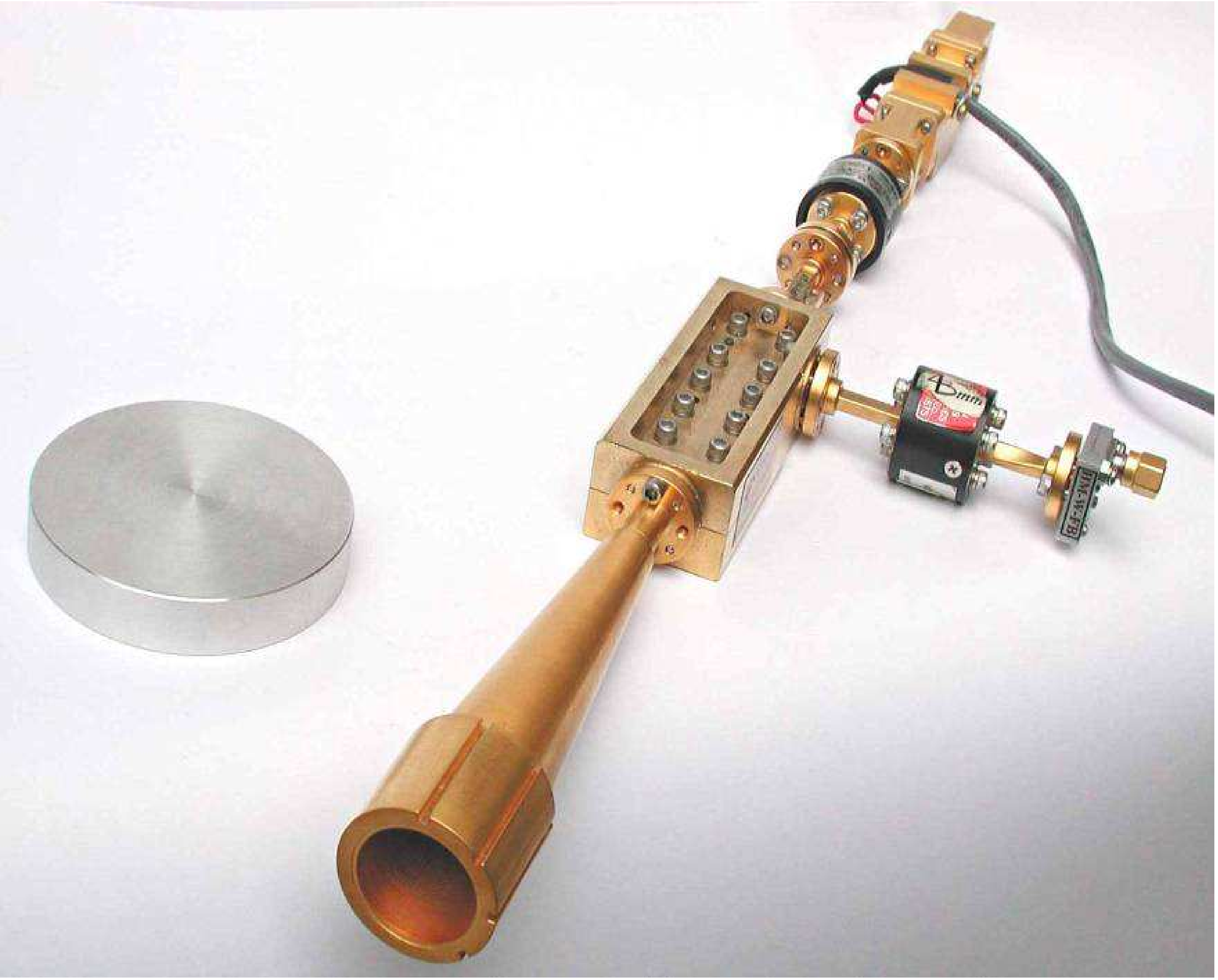
- **II. Why the phase measurement is extremely important:**

- Vector measurements give the complete information (S-parameters).

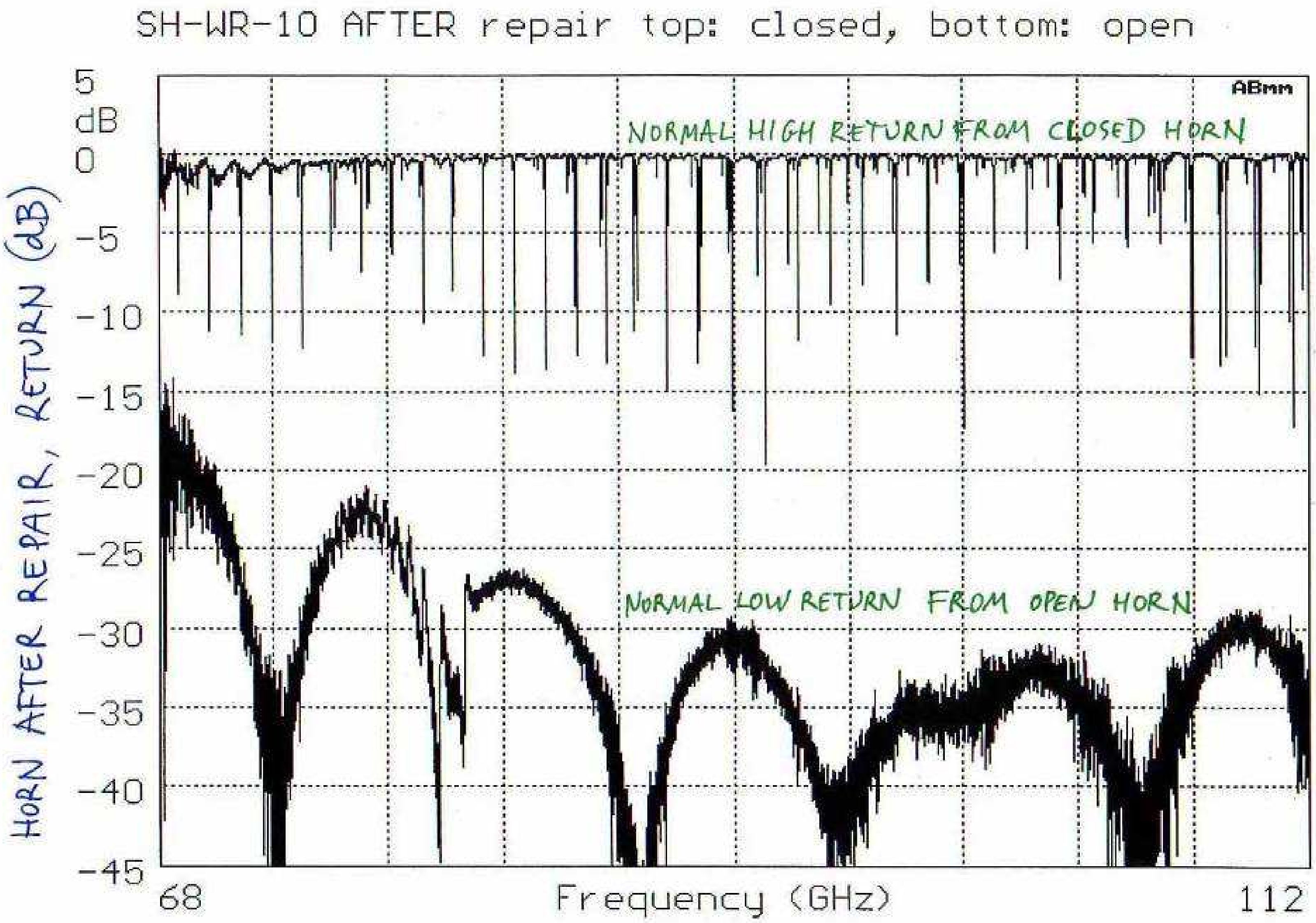
- Imaging gives the 3rd dimension (phase of a fixed frequency reflected signal, or by **FT of a frequency sweep** = time domain).

- Material Characterization, resonance fitting, etc.

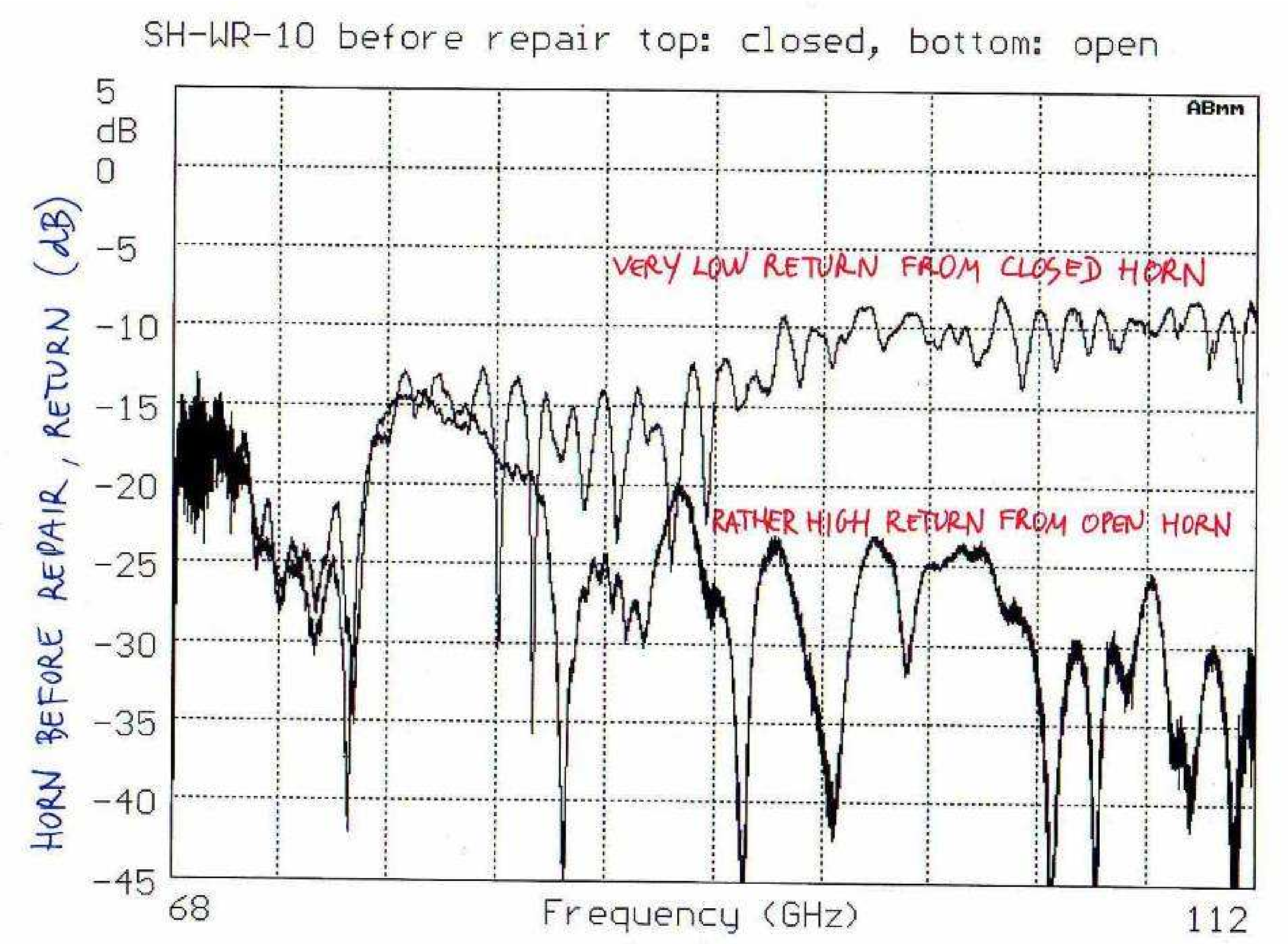
W-Band Return S11 setup. Control of a Scalar Horn



W-Band Repaired Scalar Horn tested by Return

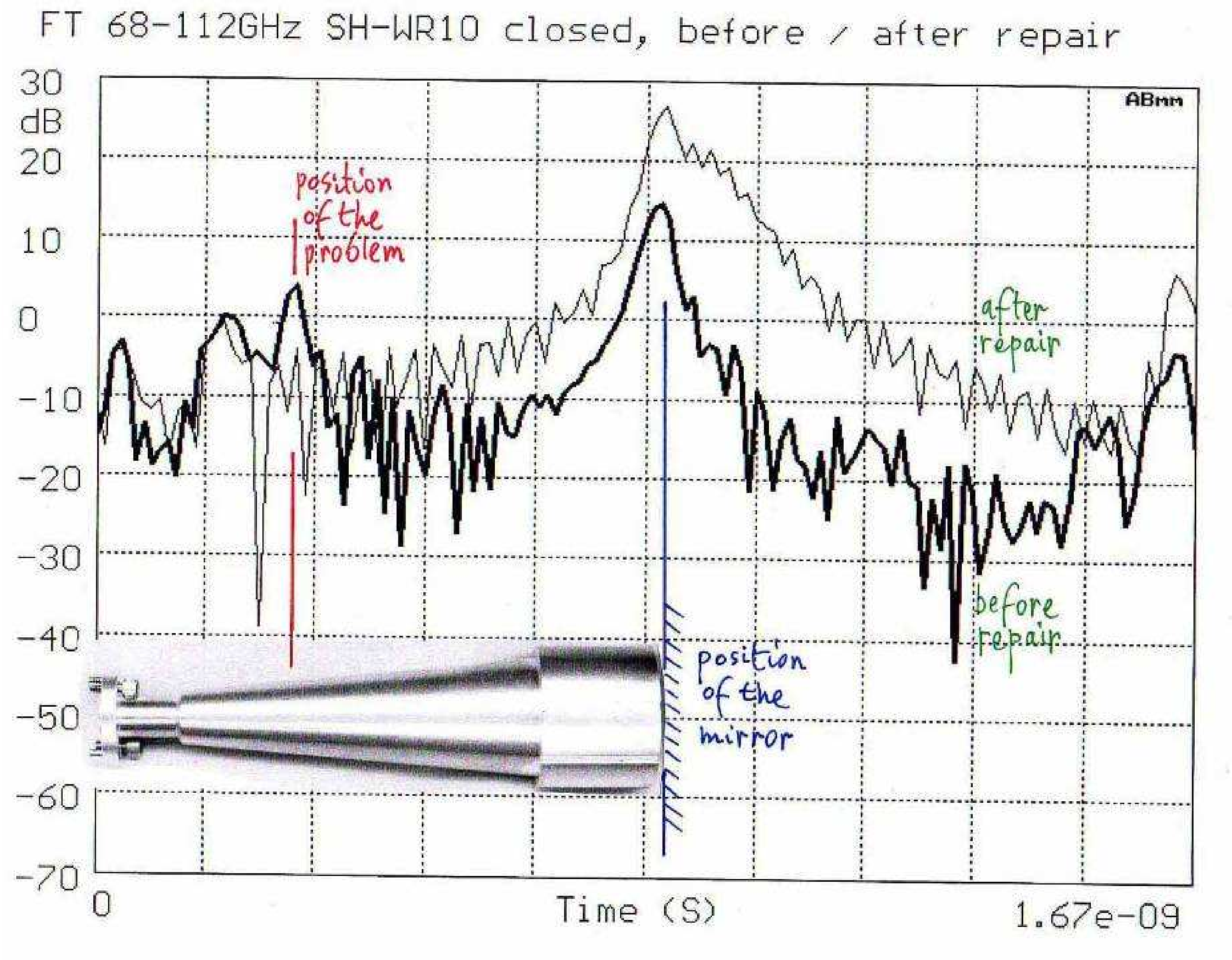


Defective W-Band Scalar Horn observed by Return



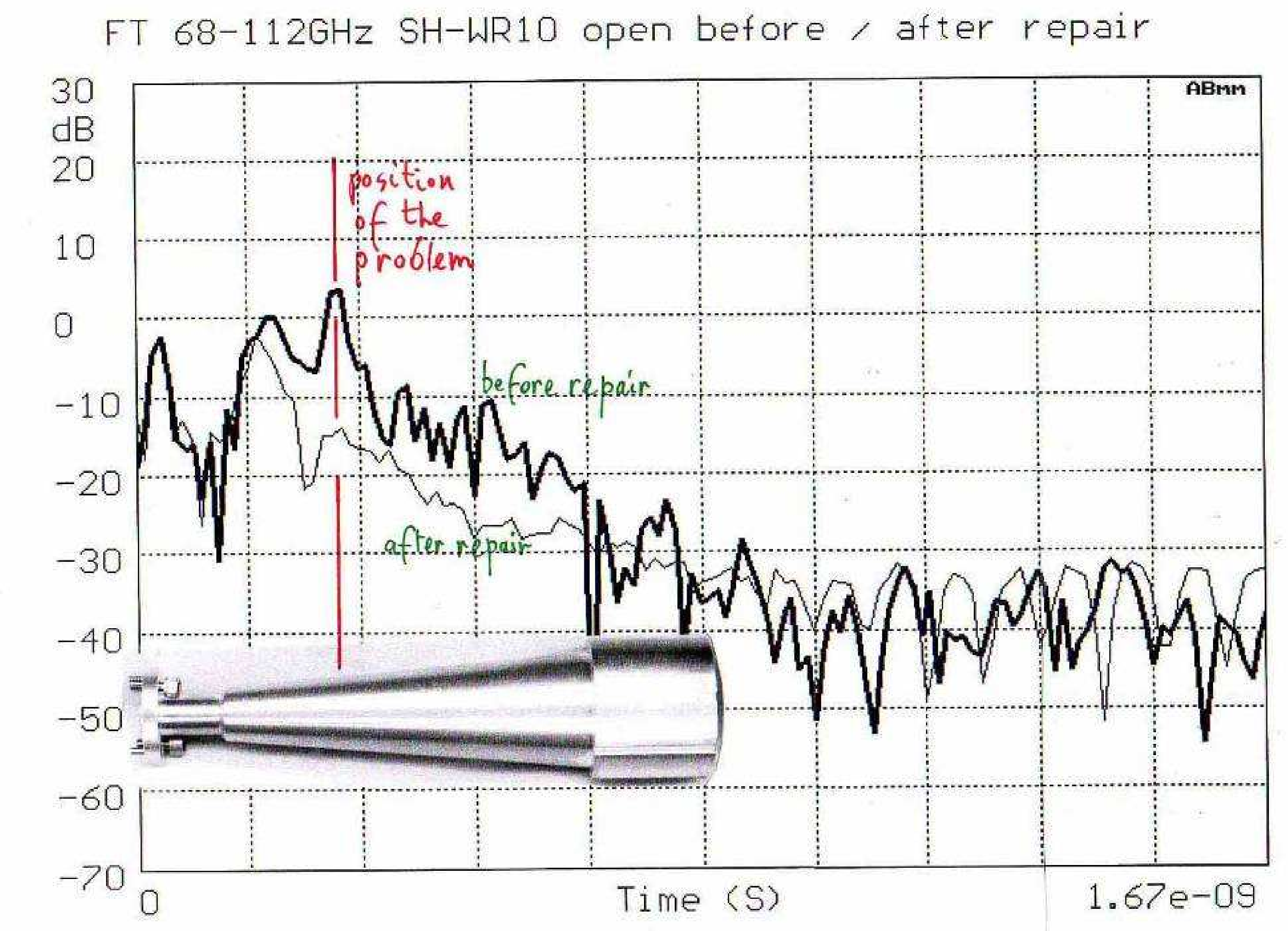
Imaging inside a component.

Fourier Transform of Returns, with Horn closed by a mirror

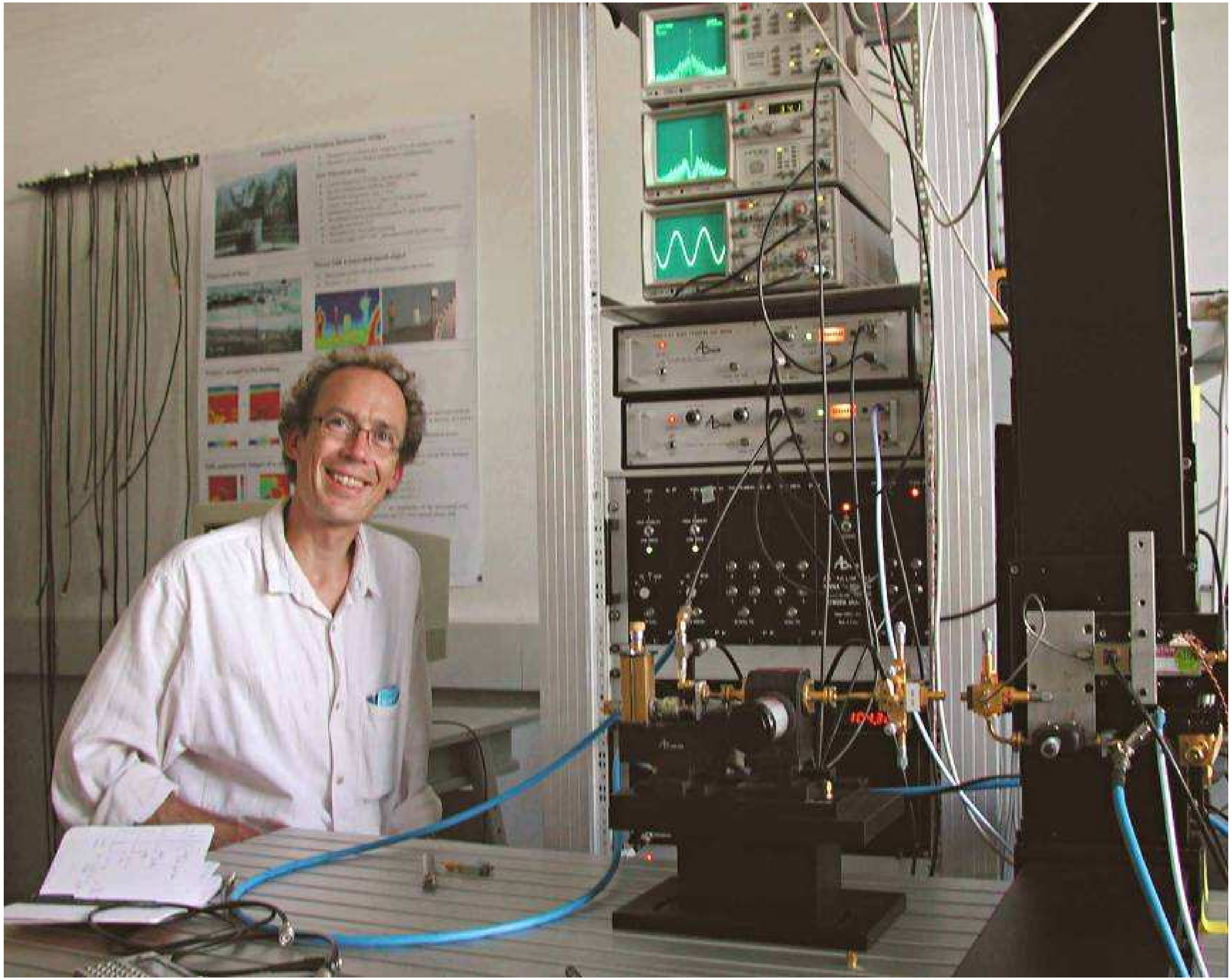


Imaging inside a component.

Fourier Transform of Returns, with open Horn

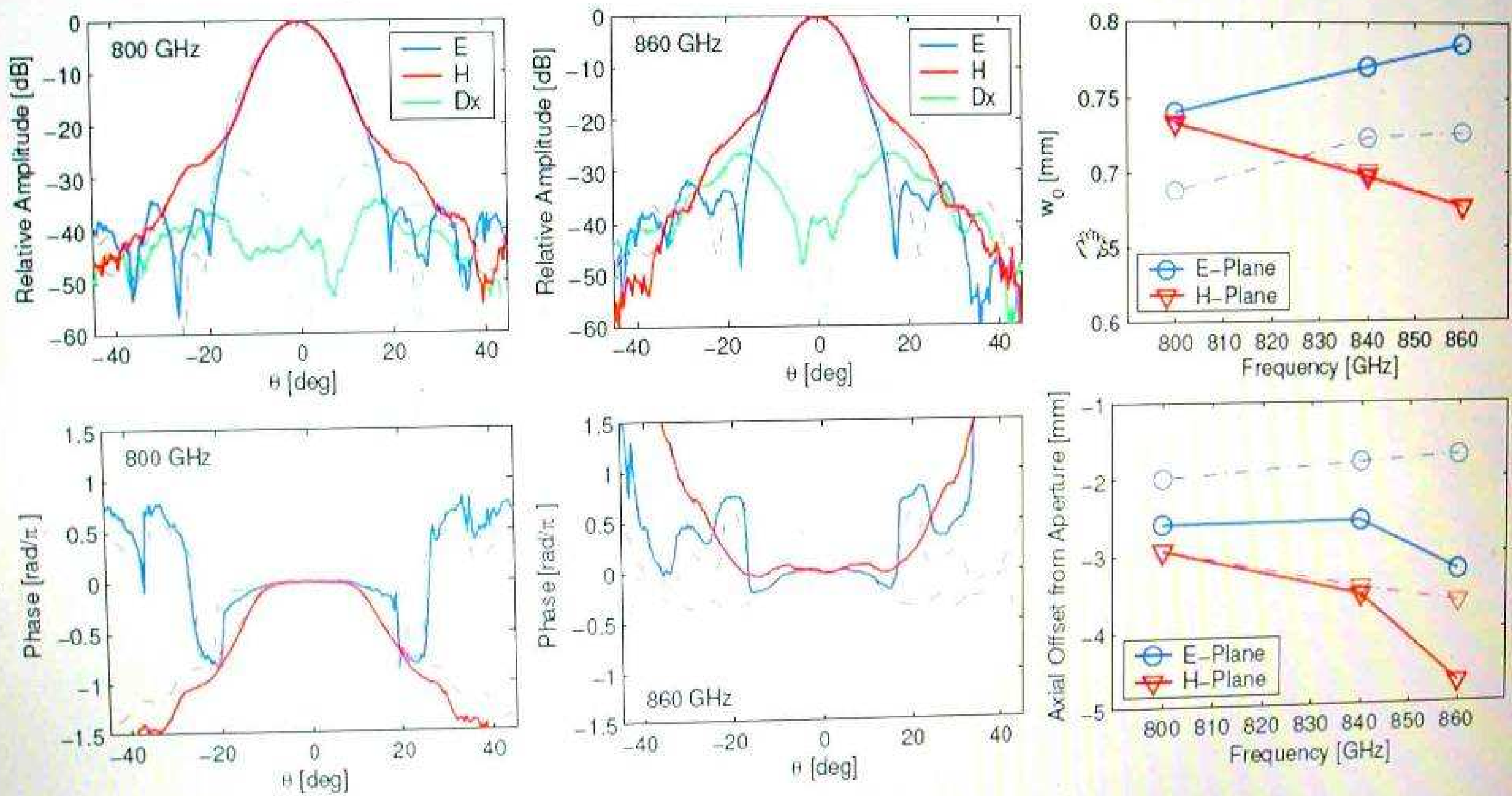


Antenna pattern. Phase center determination for aeronomie satellite. Axel Murk makes QO vector characterization at Institute of Applied Physics IAP, University of Bern, Switzerland. MVNA since 1998.



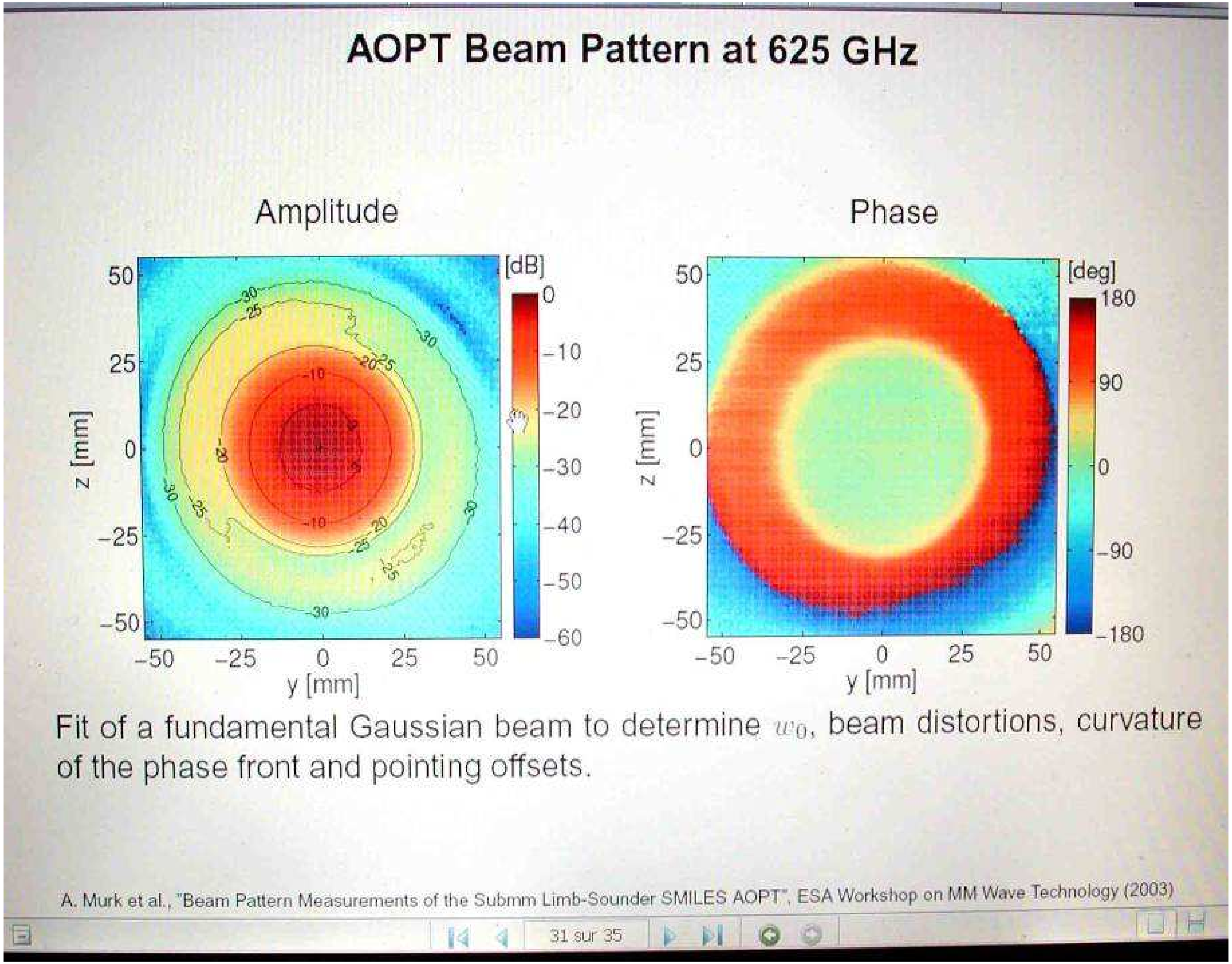
Beam Pattern of a Smooth-Walled Horn Antenna

Measurements (solid lines) and simulations (dashed) from 800–860GHz.
Fit results for the beam waist and phase center position (right column).



D. Rabanus, C. Granet, A. Murk, T. Tils, "Measurement of a smooth-walled spline-profile feed horn", IR Phys. & Technology 2006.

From Axel Murk, IAP, Bern, an extremely good Gaussian beam of a 625 GHz satellite system observed with the MVNA.



- **III. The System. CW generation and vector detection of millimeter-THz waves with solid-state electronic components:**

- The AB Millimetre’s Millimeter Vector Network Analyzer MVNA-8-350 offers the widest frequency coverage 8-1000 GHz thanks to an original phase reference.

- The Schottky diode is the necessary non-linear device. Single-Schottky devices remain very performant. Multi-Schottky combinations and chains are very much improving, and more easy to use.

AB MILLIMETRE's MVNA SCHEMATIC DIAGRAM

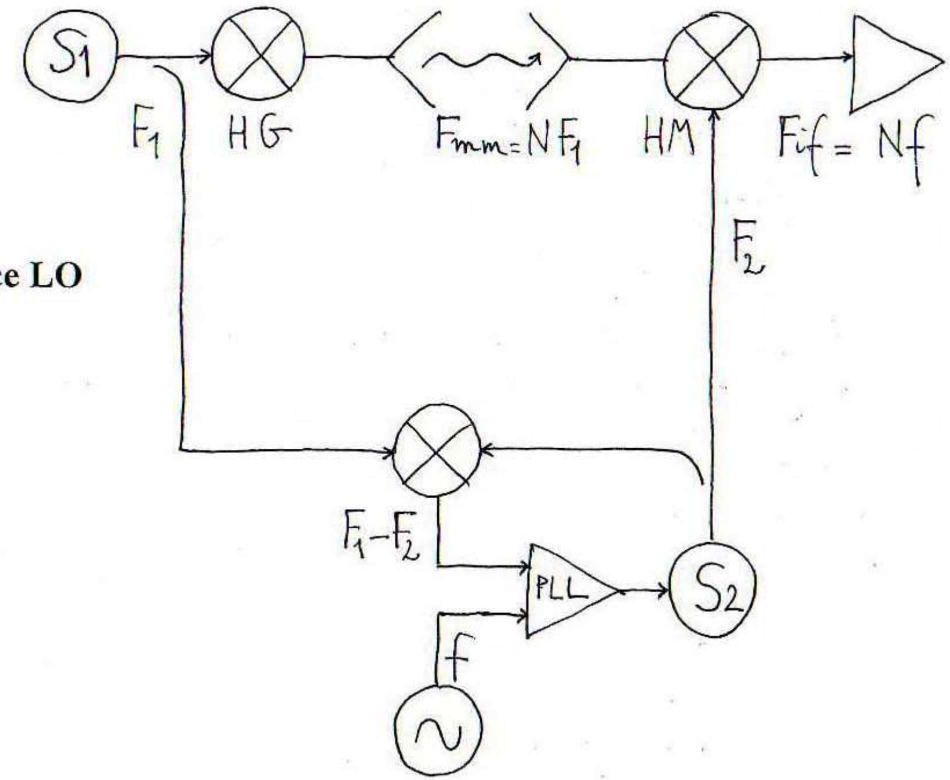
THE AB MILLIMETRE's PHASE REFERENCE (PATENTED)

• **Same Harmonic Rank at source and detector**
N1 = N2

• **S2, the detection LO, is PLL-linked to S1, the source LO**
F2 = F1 - f
so that the phase noise of both LOs is the same:
Φ2 = Φ1

Therefore the detected Phase Noise cancels itself:
Φif = | N1 . Φ1 - N2 . Φ2 | = 0

Advantages:
- **Simplicity, light mm heads**
- **Good signal and good dynamic range**
- **No need for any smmWaves Directional Coupler**
- **Possible dual-frequency technique**



IV. The DILEMNA: I. Multiplication chains, improving rapidly in the recent times, or:

II. Single-Schottky, universal multiplier (generating a comb of frequencies)

COVERING 62 – 1000 GHz

I MULTIPLICATION CHAINS

		OUTPUT (GHz)	M from W-Band
• an input	×6	62 – 112	1
•	×9	108 – 168	
•	×6 ▷ ×2	124 – 224	2
•	6 ▷ ×3	210 – 336	3
	6 ▷ ×2 ×2	248 – 448	4
	6 ▷ ×3 ×2 or 2×3	372 – 672	6
•	6 ▷ ×3 ×3	680 – 1000	9

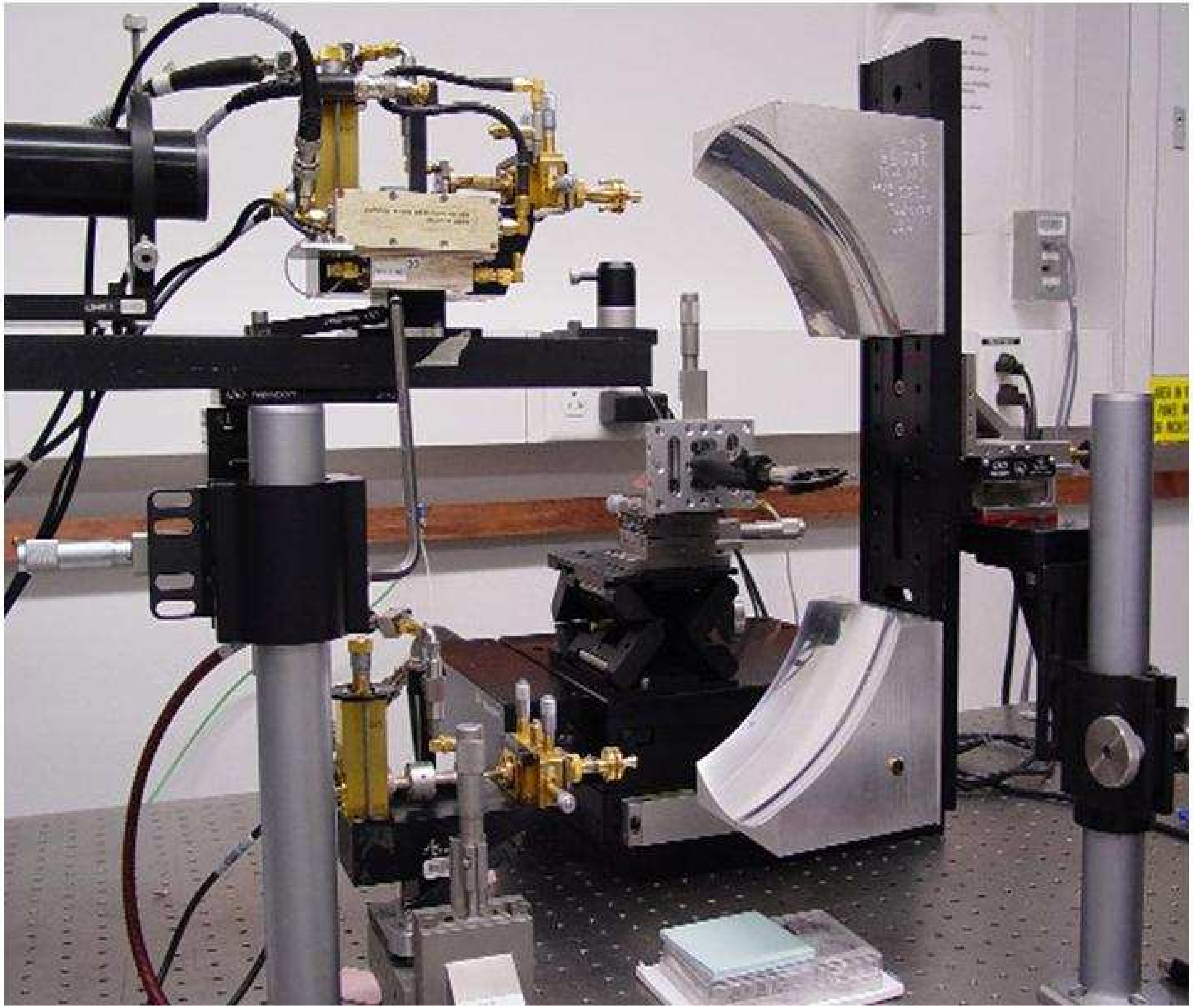
5 SETUPS

II SINGLE SCHOTTKY TUNABLE MULTI-HARMONIC MULTIPLIER

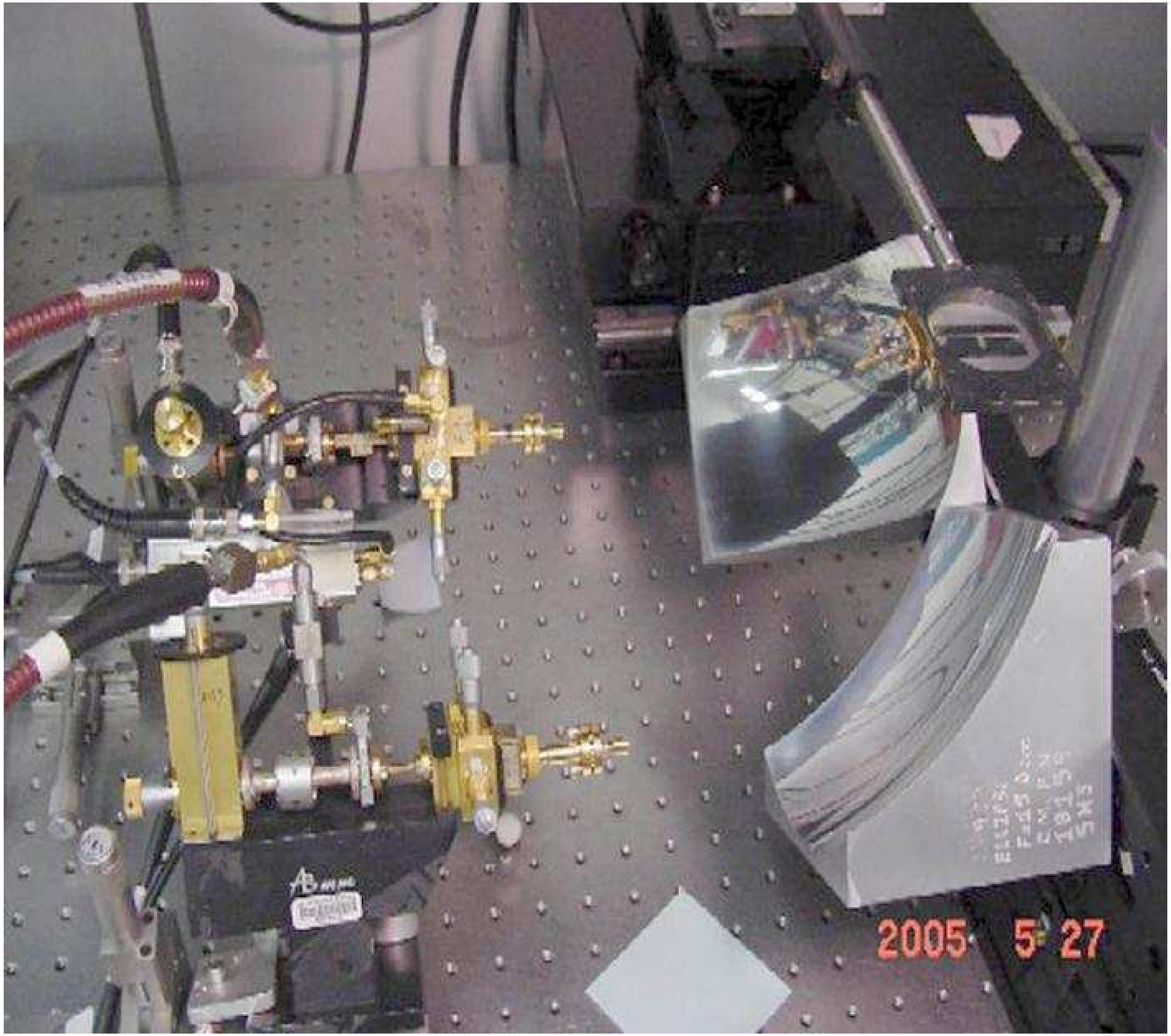
•	6 ▷ ×M MU, HIGH PASS FILTER	140 – 1000 GHz	$2 \leq M \leq 10$

SINGLE SETUP

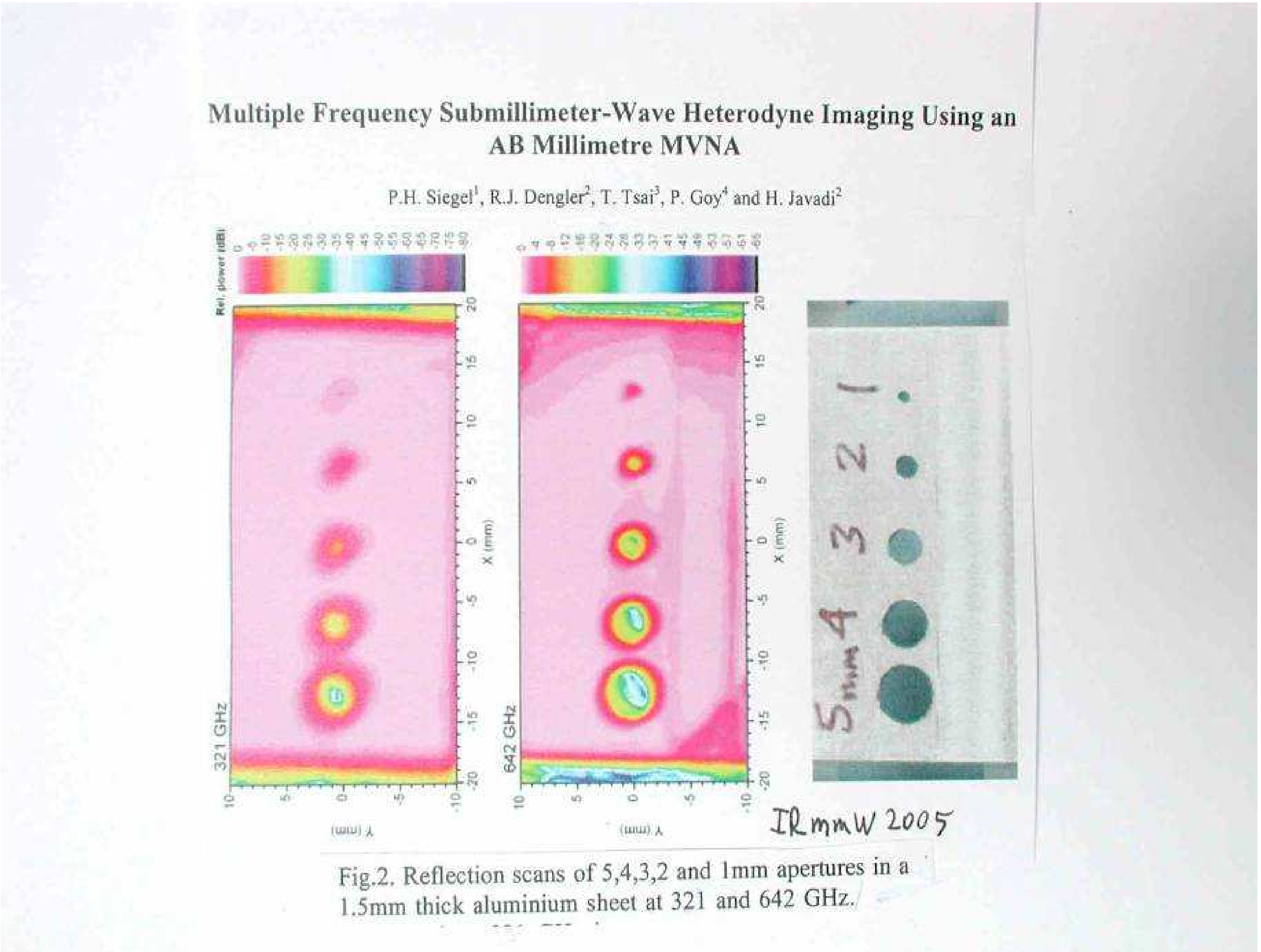
JPL, Peter Siegel's Group. Transmission setup.



JPL, Reflection setup.



Imaging is also a very important application, as developed at Jet Propulsion Laboratory (Peter Siegel's group). Wavelength aspect.

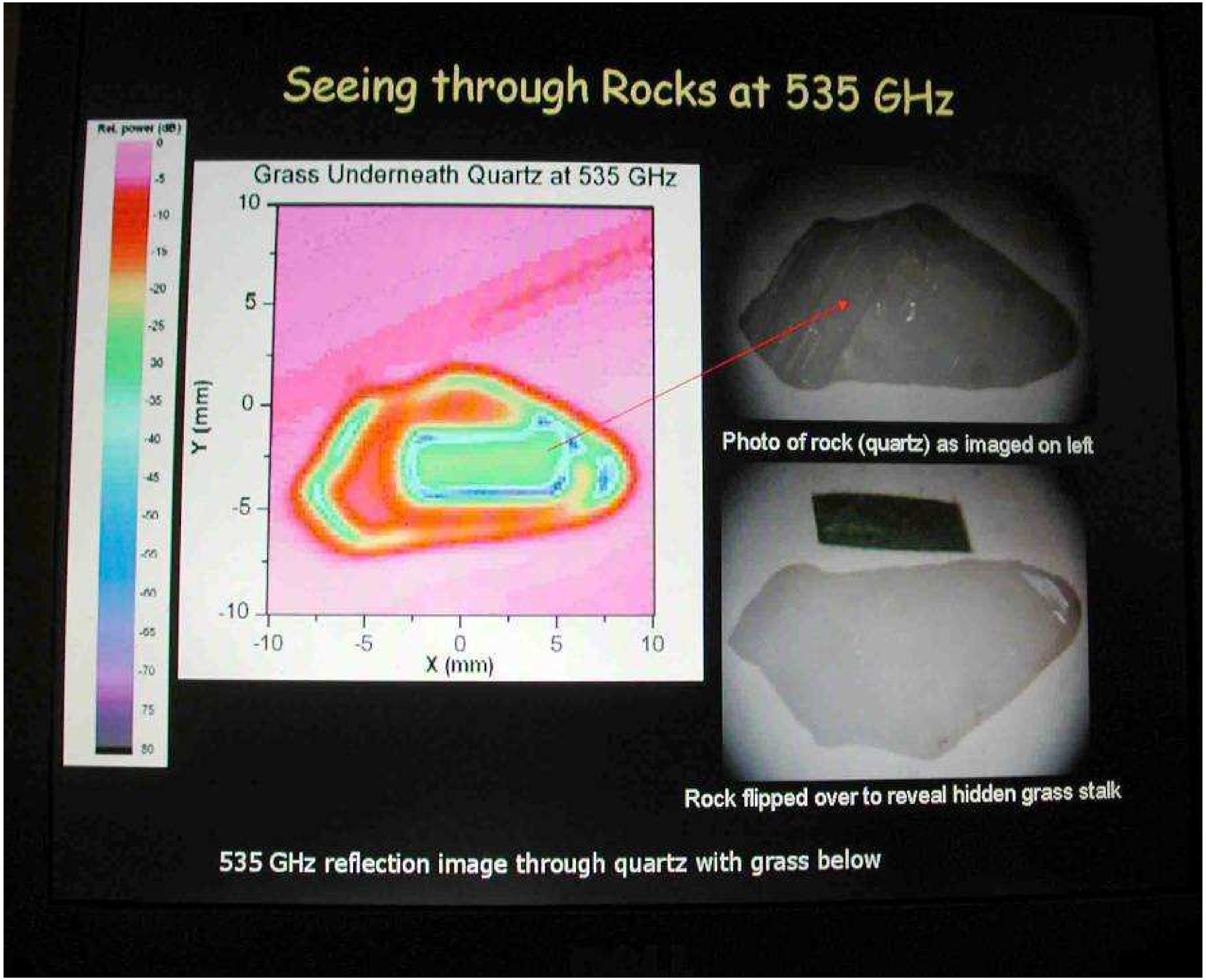


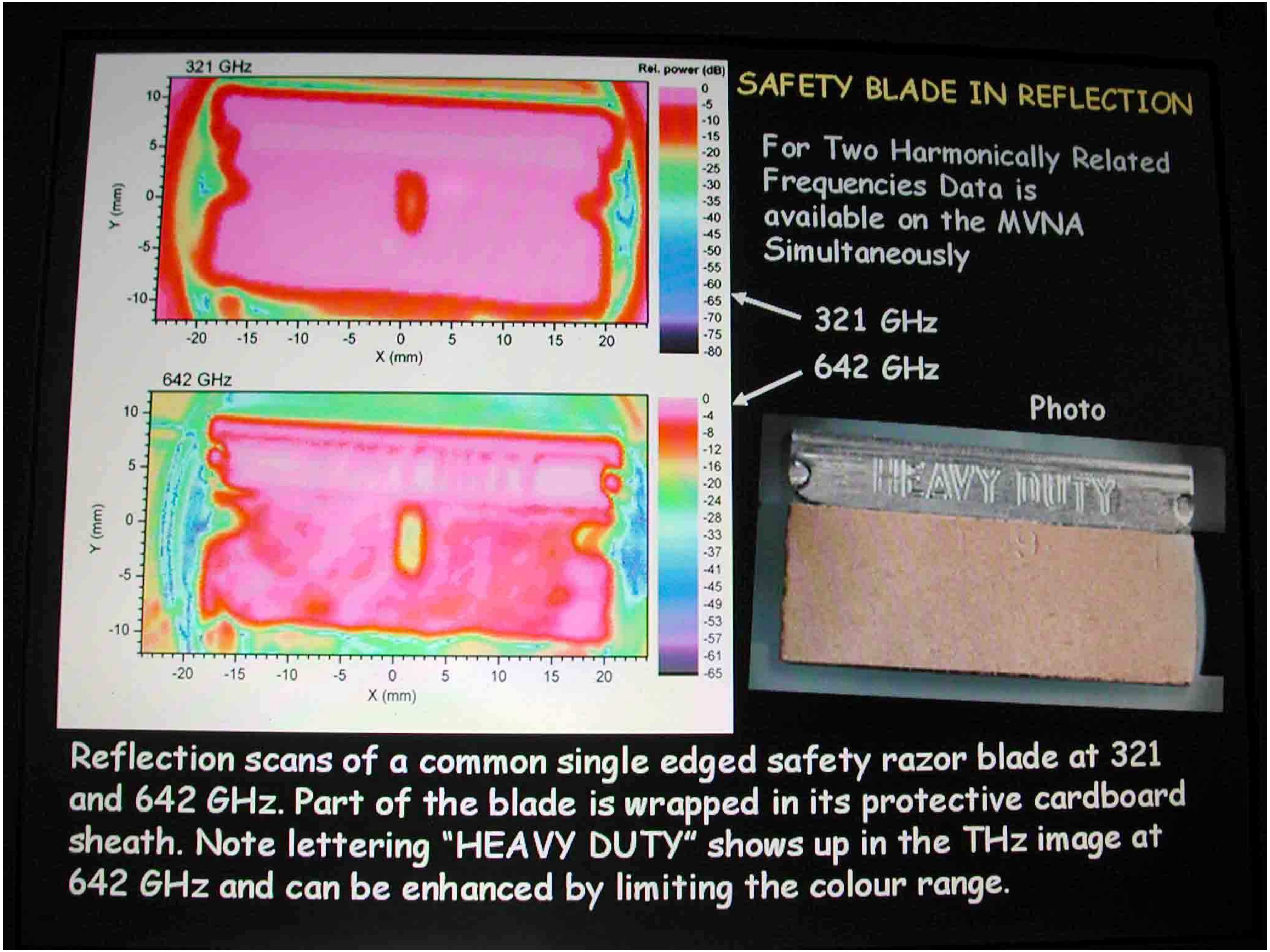
Multiple Frequency Submillimeter-Wave Heterodyne Imaging Using an AB Millimetre MVNA

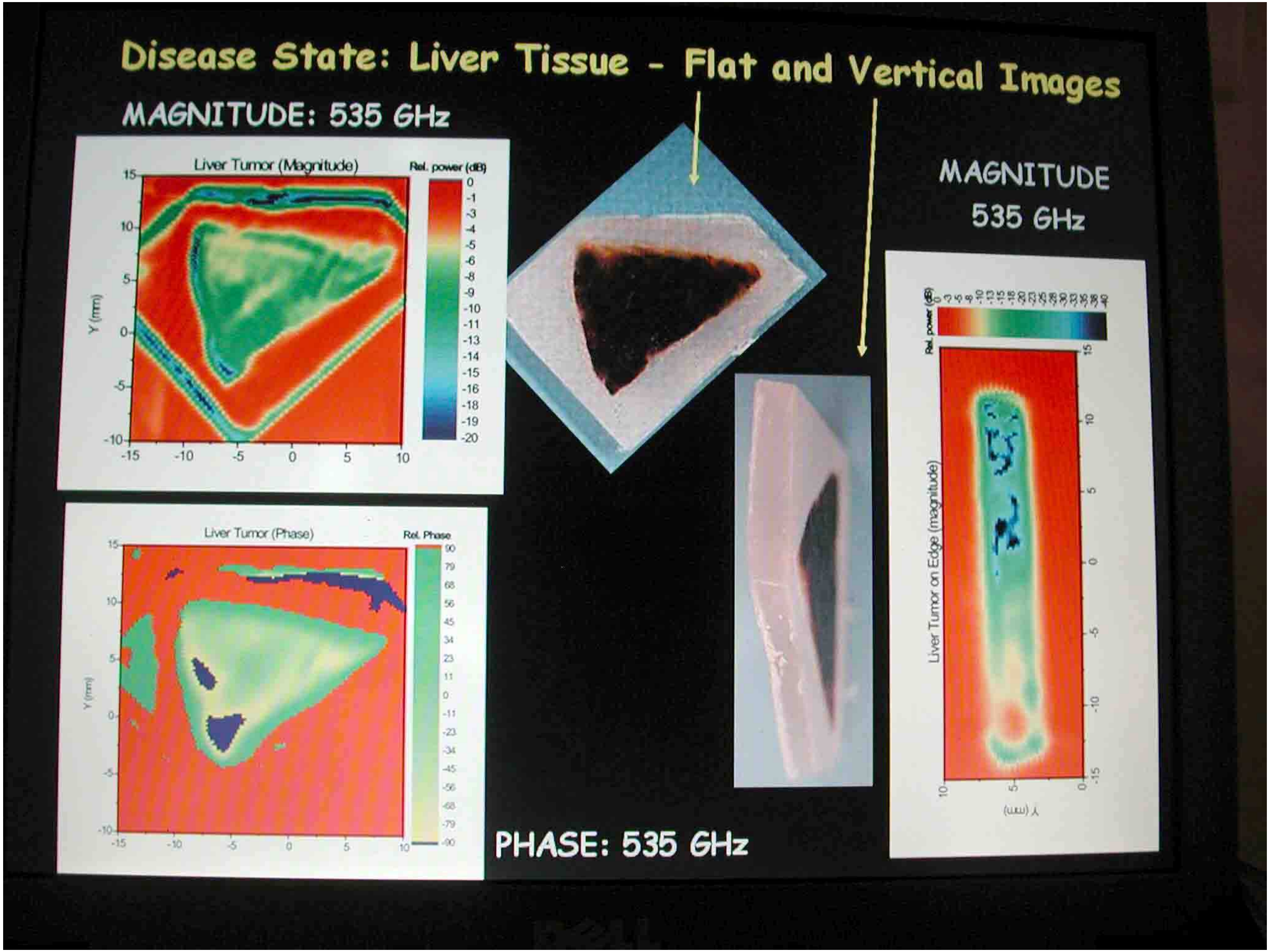
P.H. Siegel[1], R.J. Dengler[2], T. Tsai[3], P. Goy[4] and H. Javadi[2]

Fig.2. Reflection scans of 5,4,3,2 and 1mm apertures in a 1.5mm thick aluminium sheet at 321 and 642 GHz.

Imaging. Hidden objects seen by transparency. Dielectric aspect.



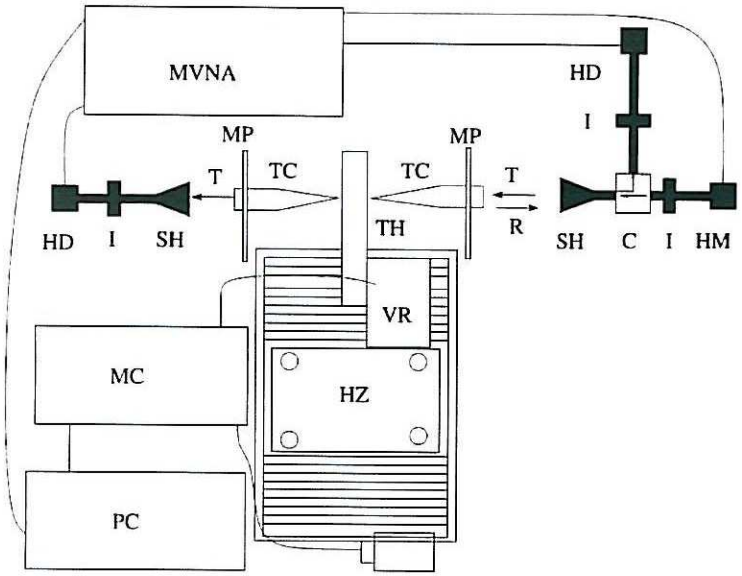

SAFETY BLADE IN REFLECTION
For Two Harmonically Related Frequencies Data is available on the MVNA Simultaneously
321 GHz
642 GHz
Photo
HEAVY DUTY
321 GHz
642 GHz
Rel. power (dB)
X (mm)
Y (mm)
Reflection scans of a common single edged safety razor blade at 321 and 642 GHz. Part of the blade is wrapped in its protective cardboard sheath. Note lettering "HEAVY DUTY" shows up in the THz image at 642 GHz and can be enhanced by limiting the colour range.



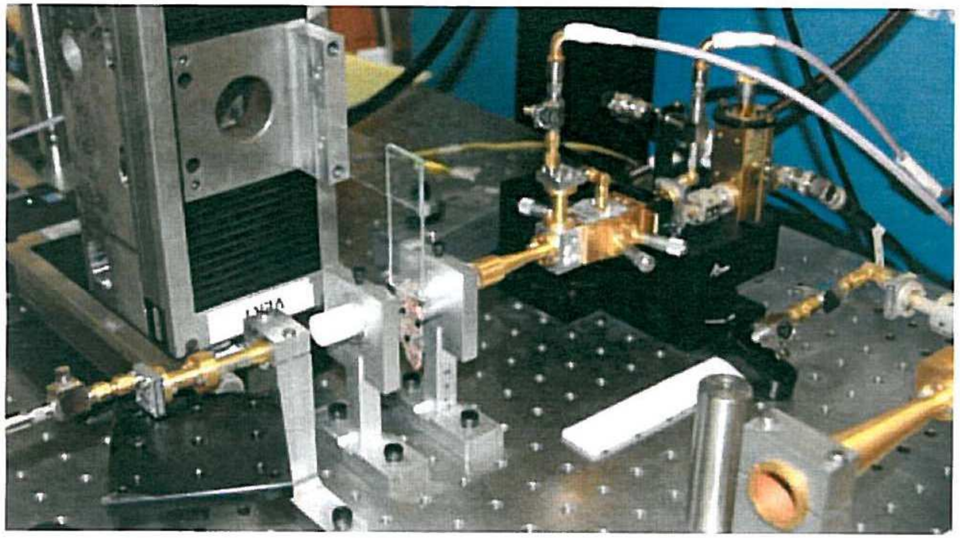
Disease State: Liver Tissue - Flat and Vertical Images
MAGNITUDE: 535 GHz
Liver Tumor (Magnitude)
Rel. power (dB)
Y (mm)
Liver Tumor (Phase)
Rel. Phase
MAGNITUDE
535 GHz
Liver Tumor on Edge (magnitude)
Y (mm)
PHASE: 535 GHz

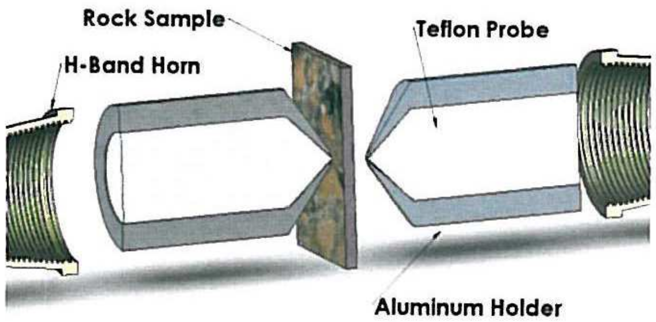
Prof John Scales, at left, with his AB MILLIMETRE's equipment for R/T measurements in a 2-lens 70-260 GHz bench, Colorado School of Mines, Golden, CO, USA.

MVNA Imaging System

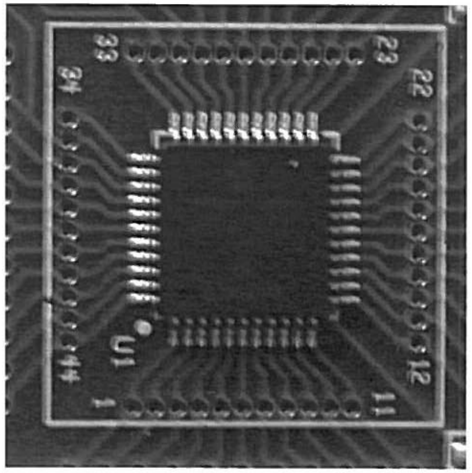


- 70 - 260 GHz
- Microwave source with frequency multipliers
- Heterodyne detection
- Planar samples

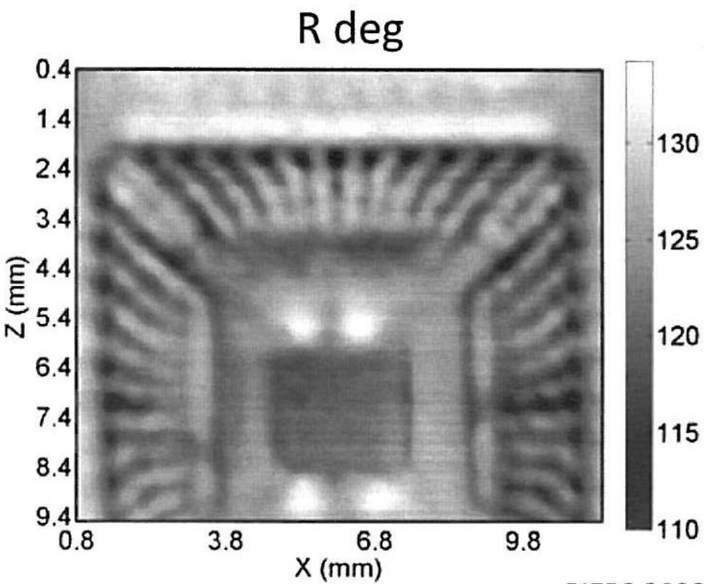


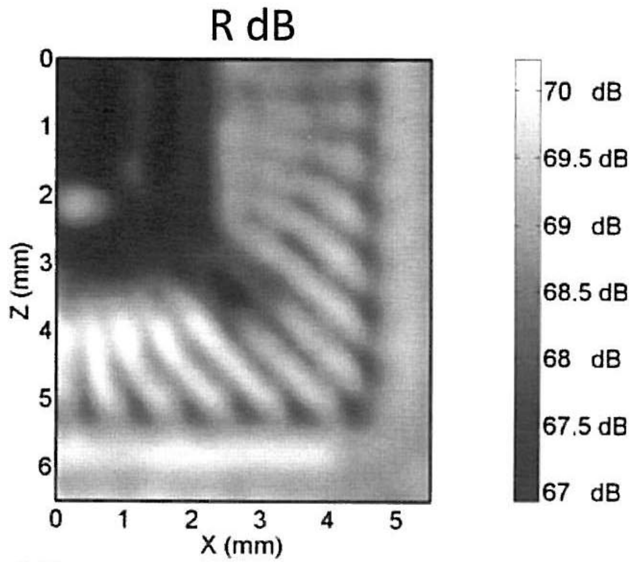


Metal Embedded in Dielectric



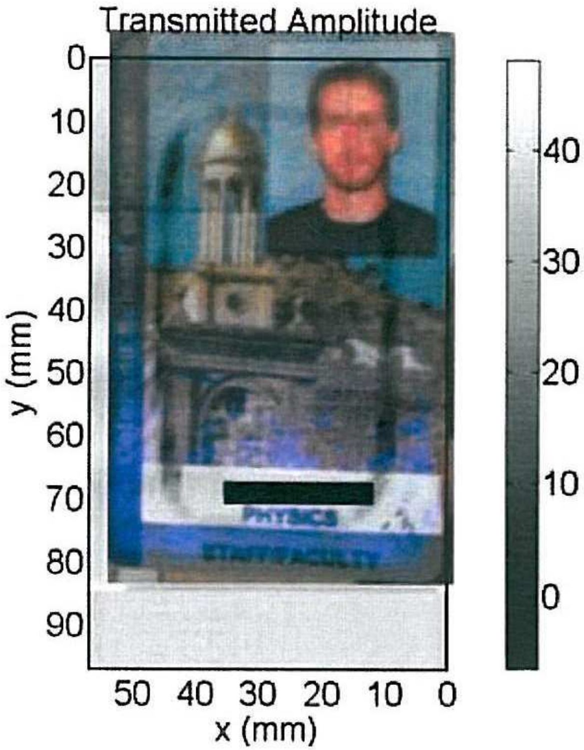
TQFP package
1mm high
0.4mm pitch

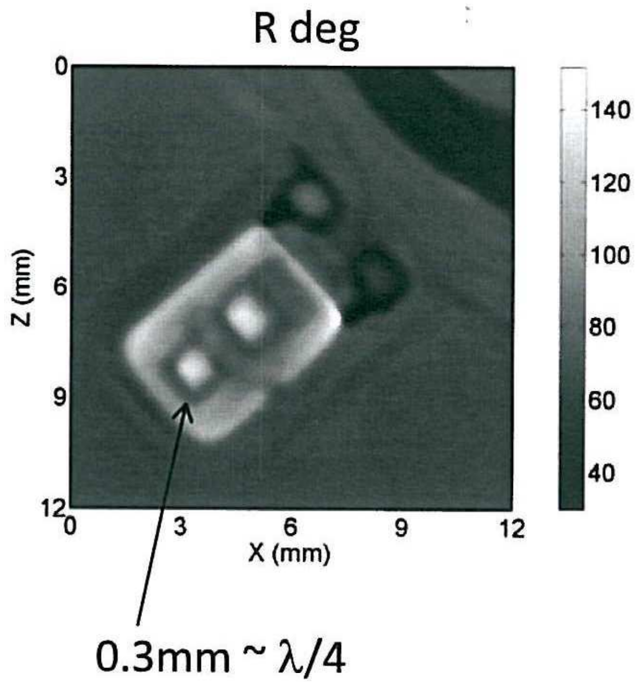




John Scales School of Mines, Golden Co

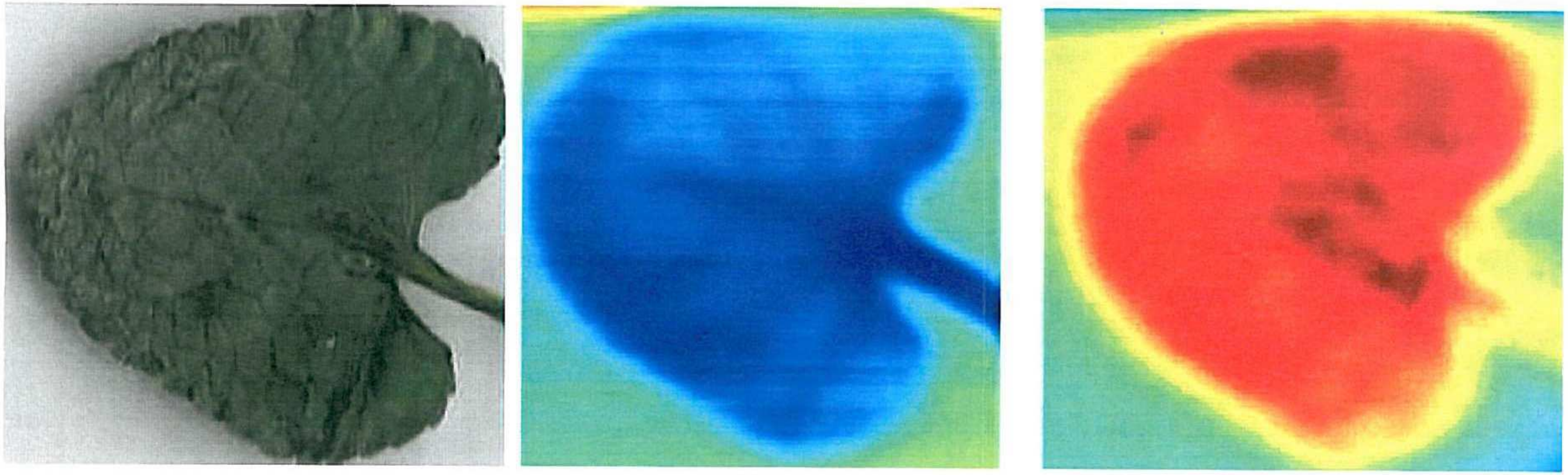
Metal Embedded in Dielectric





violet leaf

transmitted E field at 260 GHz



13 mm

phase

amplitude

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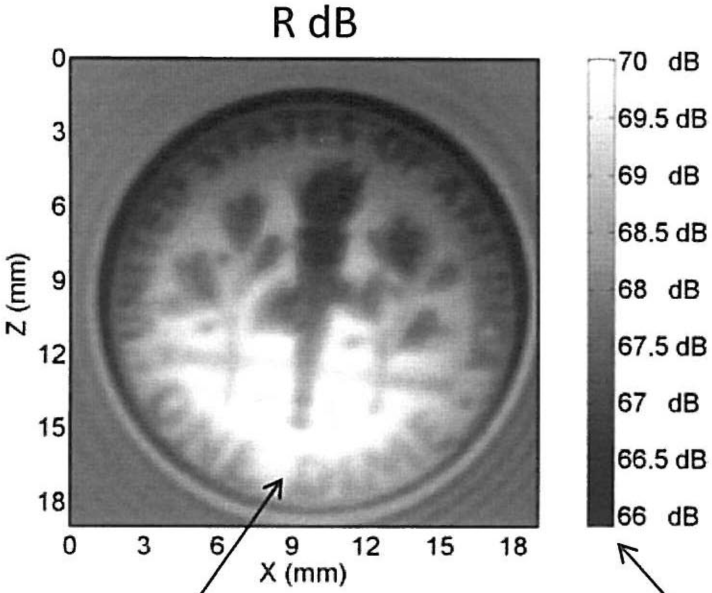
Topography Imaging

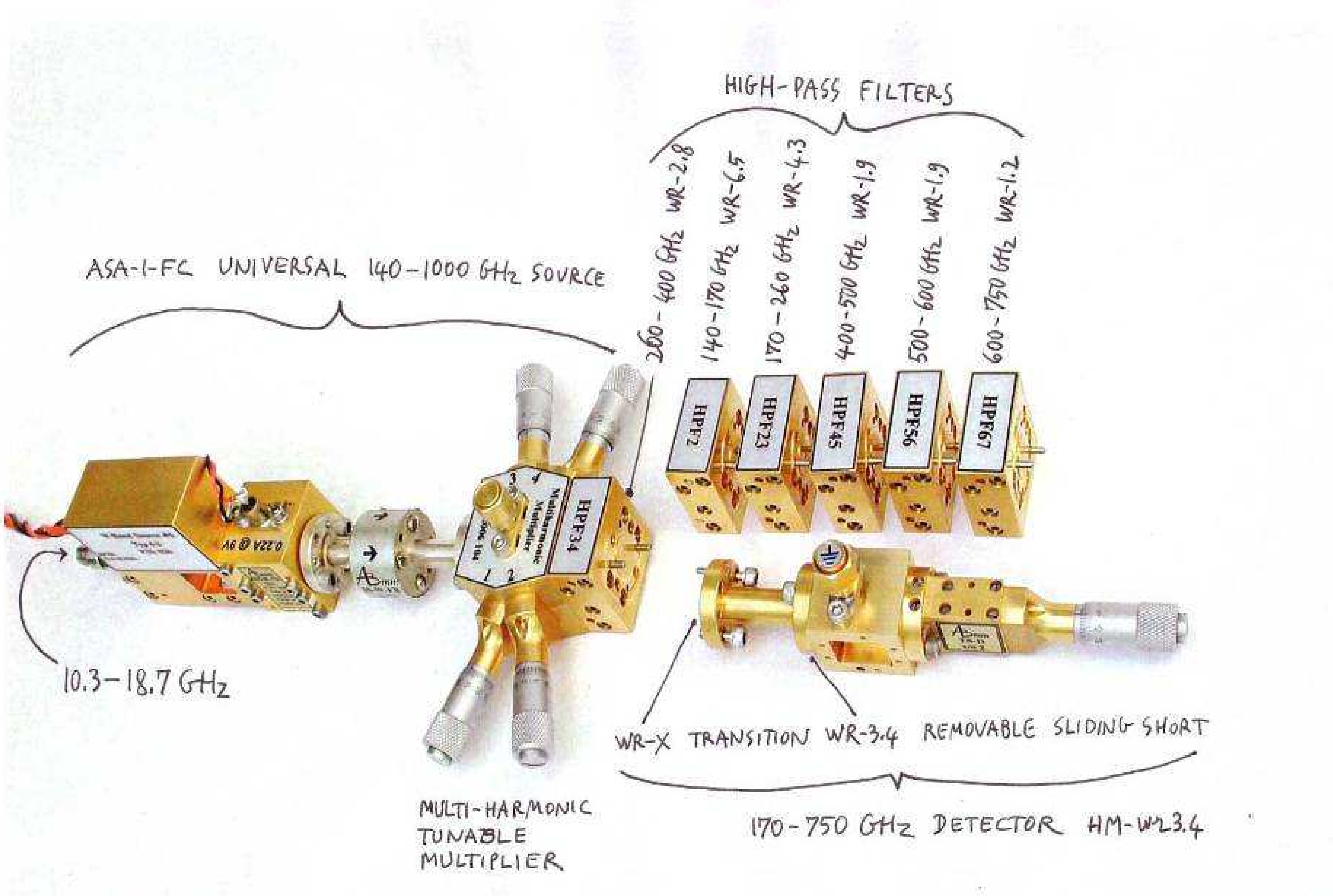


Thickness of letters ~ 0.5mm

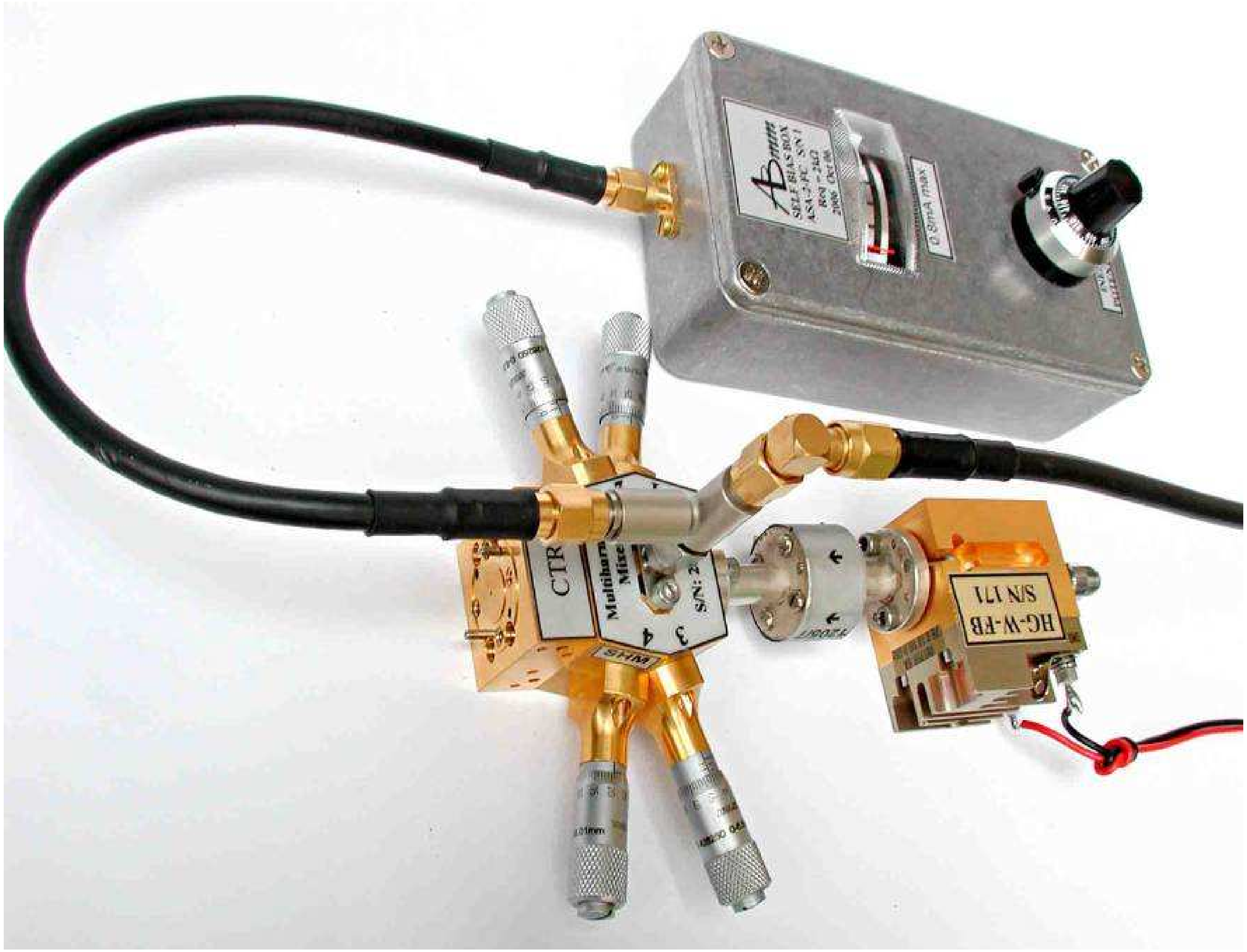
4dB dynamic range
Larger reflection from flat areas
Height variation across dime ~ 0.05mm

New LOs since 2006, instead of the Gunn oscillators. A frequency multiplier (sextupler at left), submitted to a 10.3-18.7 GHz frequency, delivers a few mW to the amplifier at right. This amplifier gives 10-40 mW from 62 to 112 GHz. This is a sweepable source.

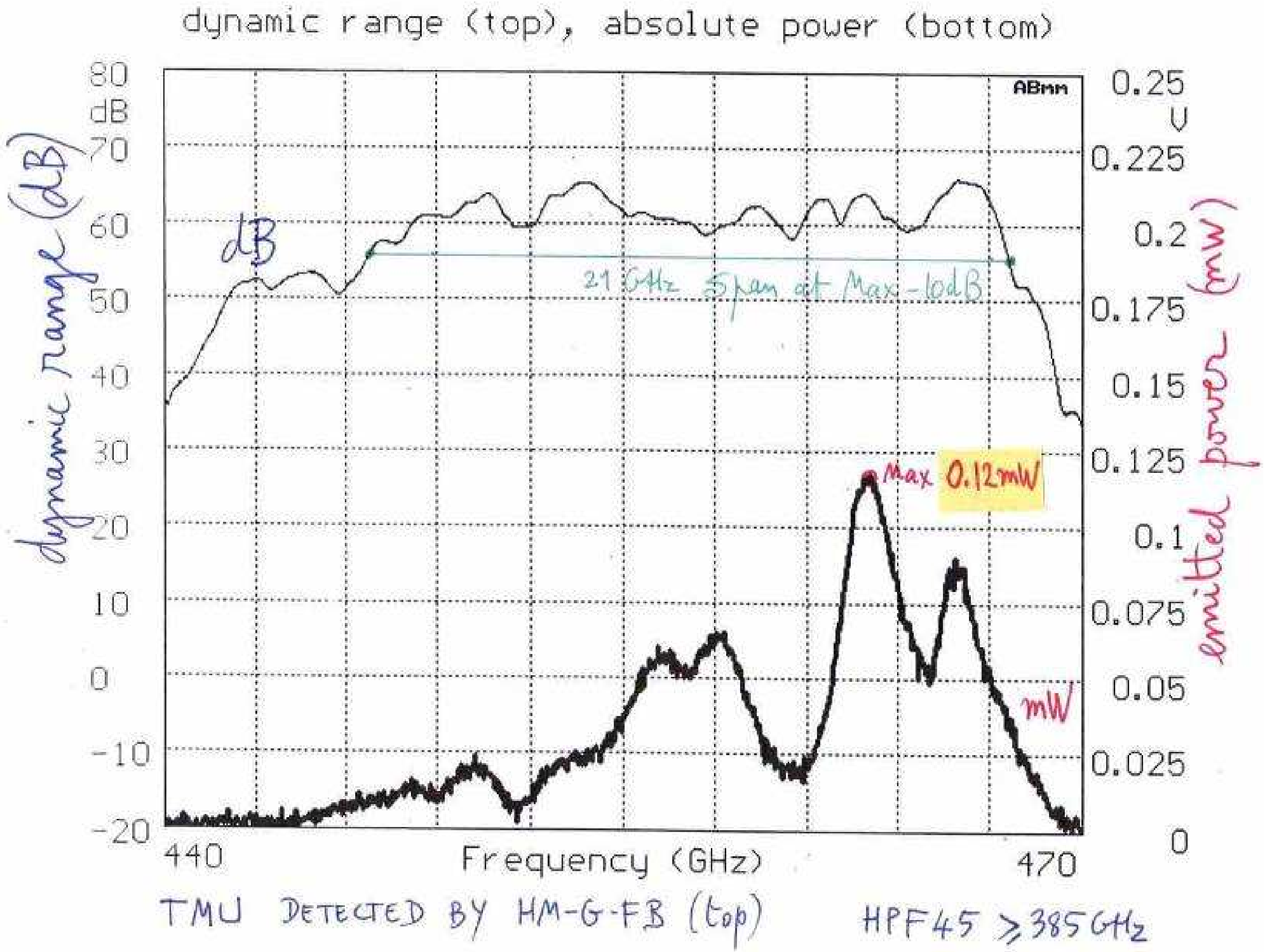
SINGLE SCHOTTKY at the Multi-harmonic Tunable Multiplier. Rather simple and efficient setup covering several millimeter-submillimeter bands (140-750 GHz). The source is called ASA-1. The detector, called HM-wr3.4, is submitted to a centimeter LO through its top SMA-F connector, where is collected the IF detected signal.



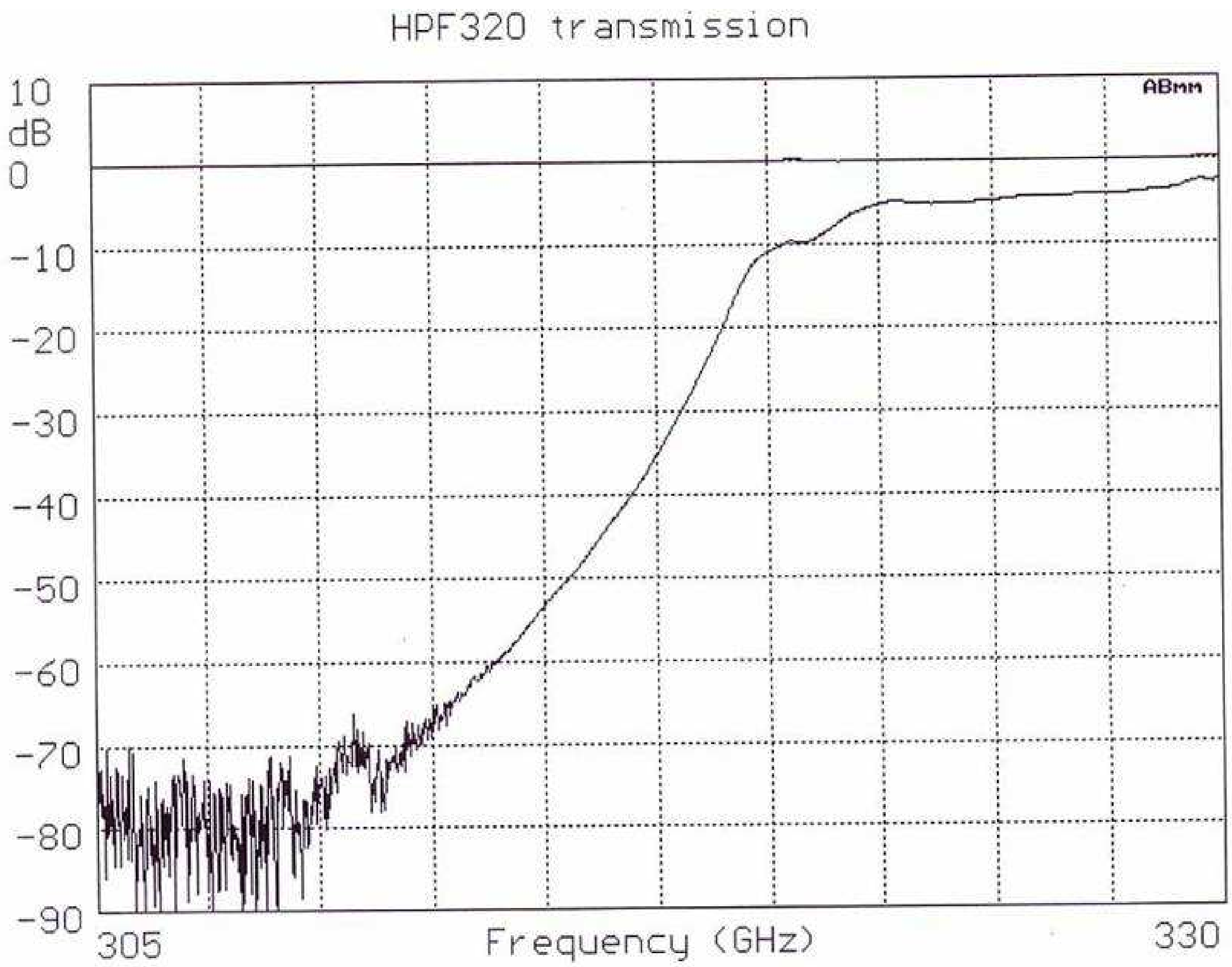
When it is needed to go up to 1THz , the detection is operated by the 2nd tunable extension called ASA-2, with a Sensitive Harmonic Mixer SHM, quite similar to ASA-1, with a W-band sweeper LO. SHM IS A SINGLE-SCHOTTKY DEVICE.



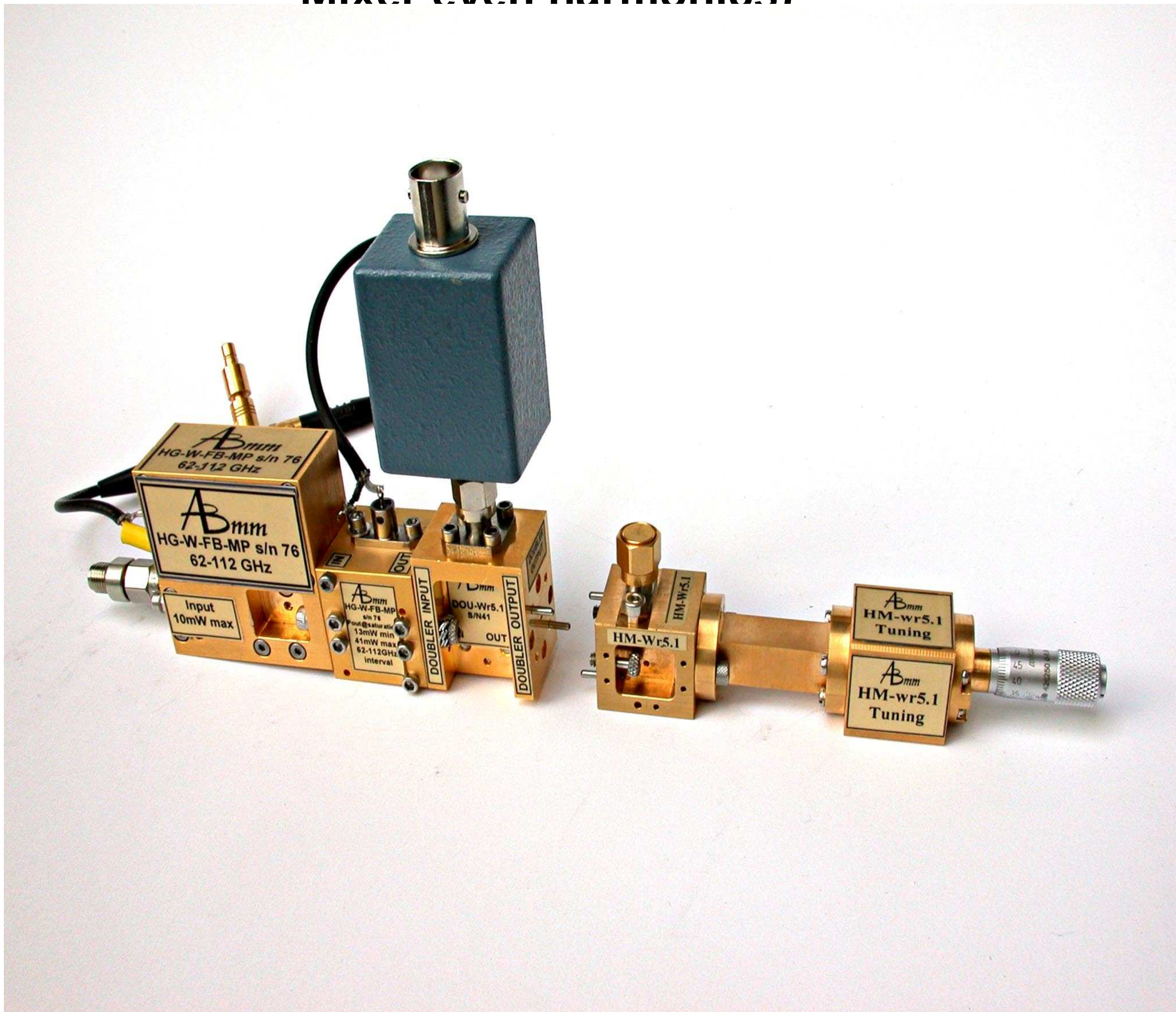
Sweepability of the source ASA-1. MVNA detected signal in dB (top), and absolute power delivered by the source ASA-1 after tuning ca 460 GHz.



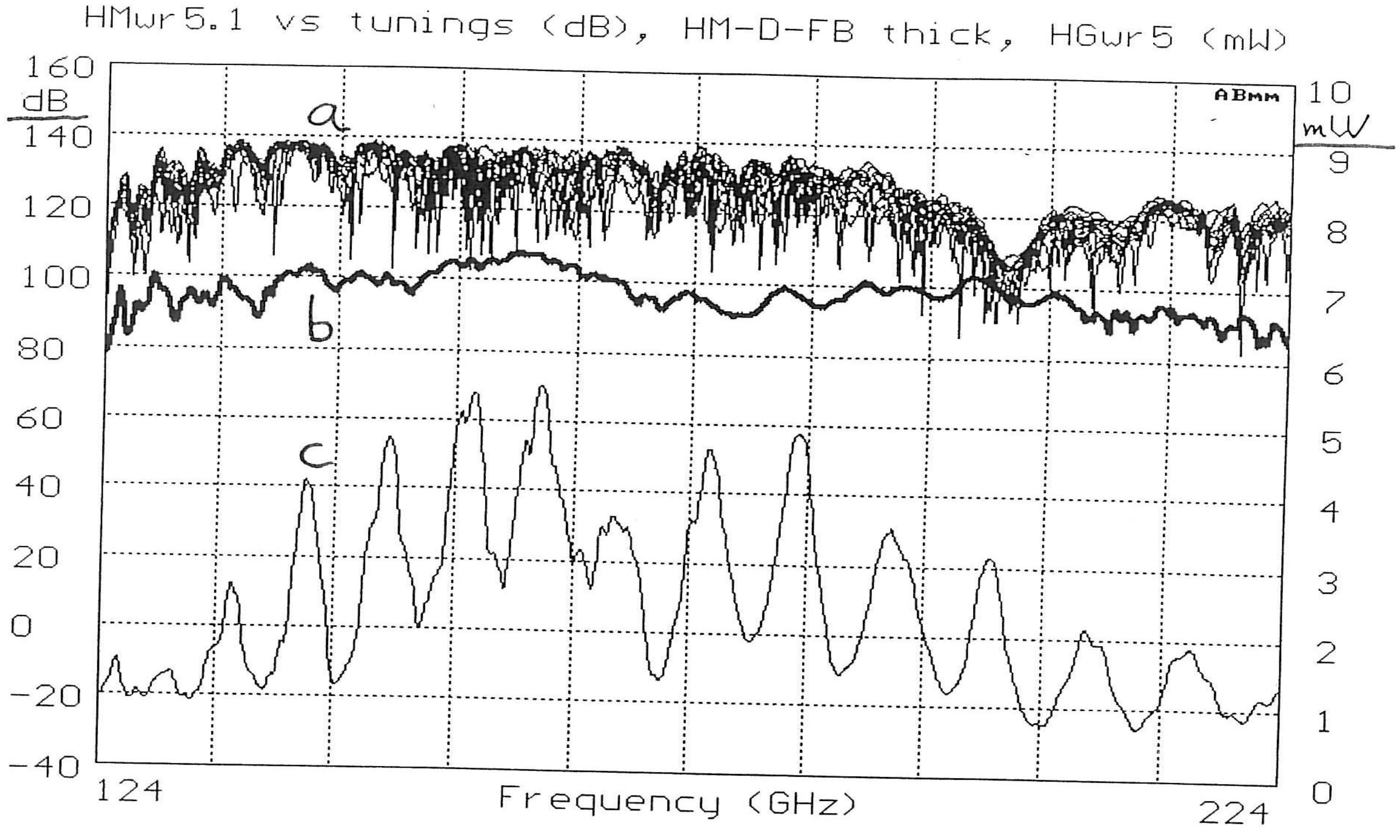
Waveguide component characterization. High-Pass Filter observed by transmission in a single sweep.



N=12 MULTIPLICATION CHAIN. 124-224 GHz source (sextupler, amplifier 62-112 GHz, doubler) and detector (WR-5.1 Harmonic Mixer even harmonics)



Dedicated Multiplier N=12. Dynamic Range (dB) at left.
a) Detection by the tunable detector at various tuning positions.
b) Detection with a Flat Broadband detector.
c) Measured power of the source (mW) at right.



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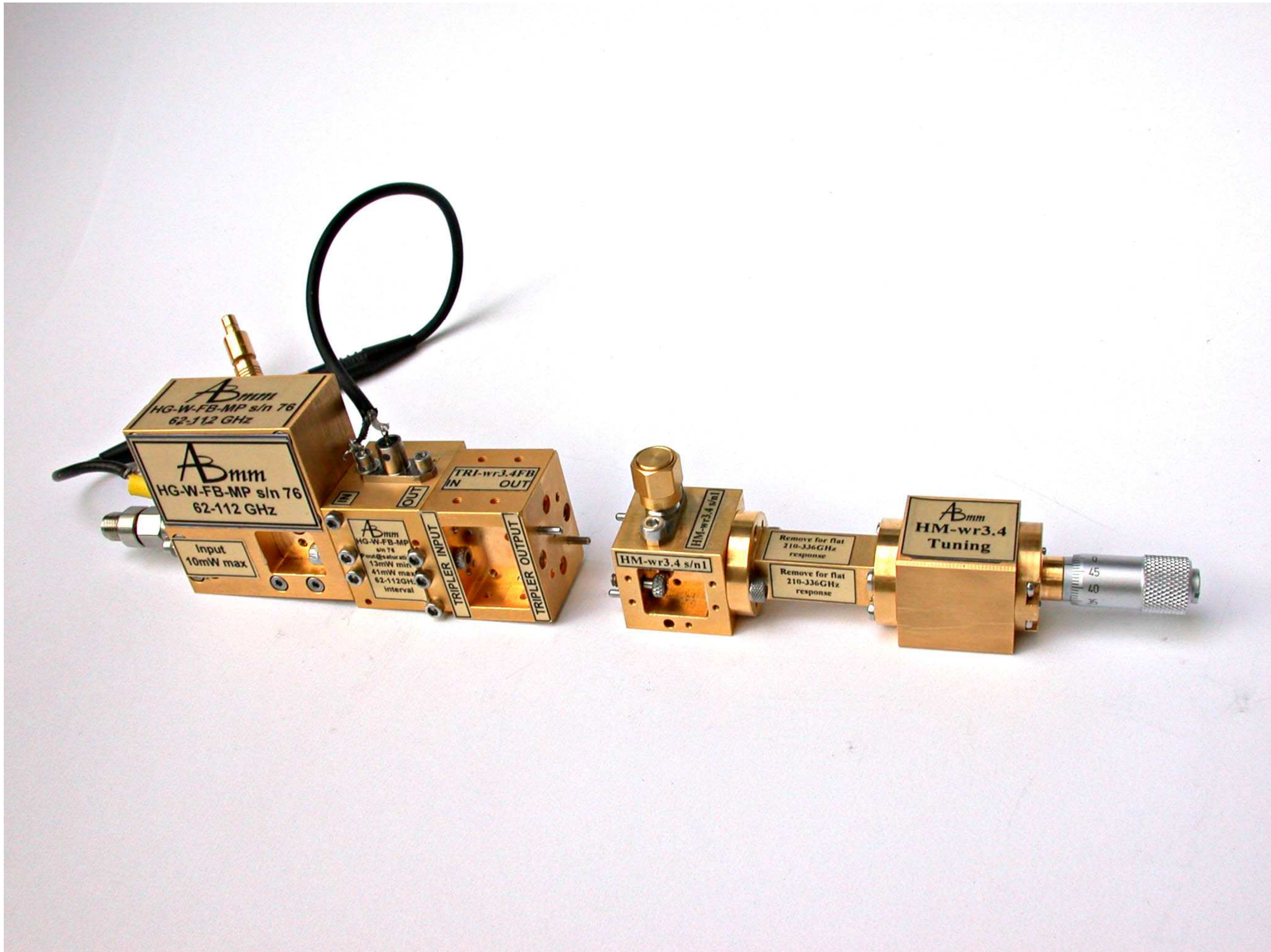
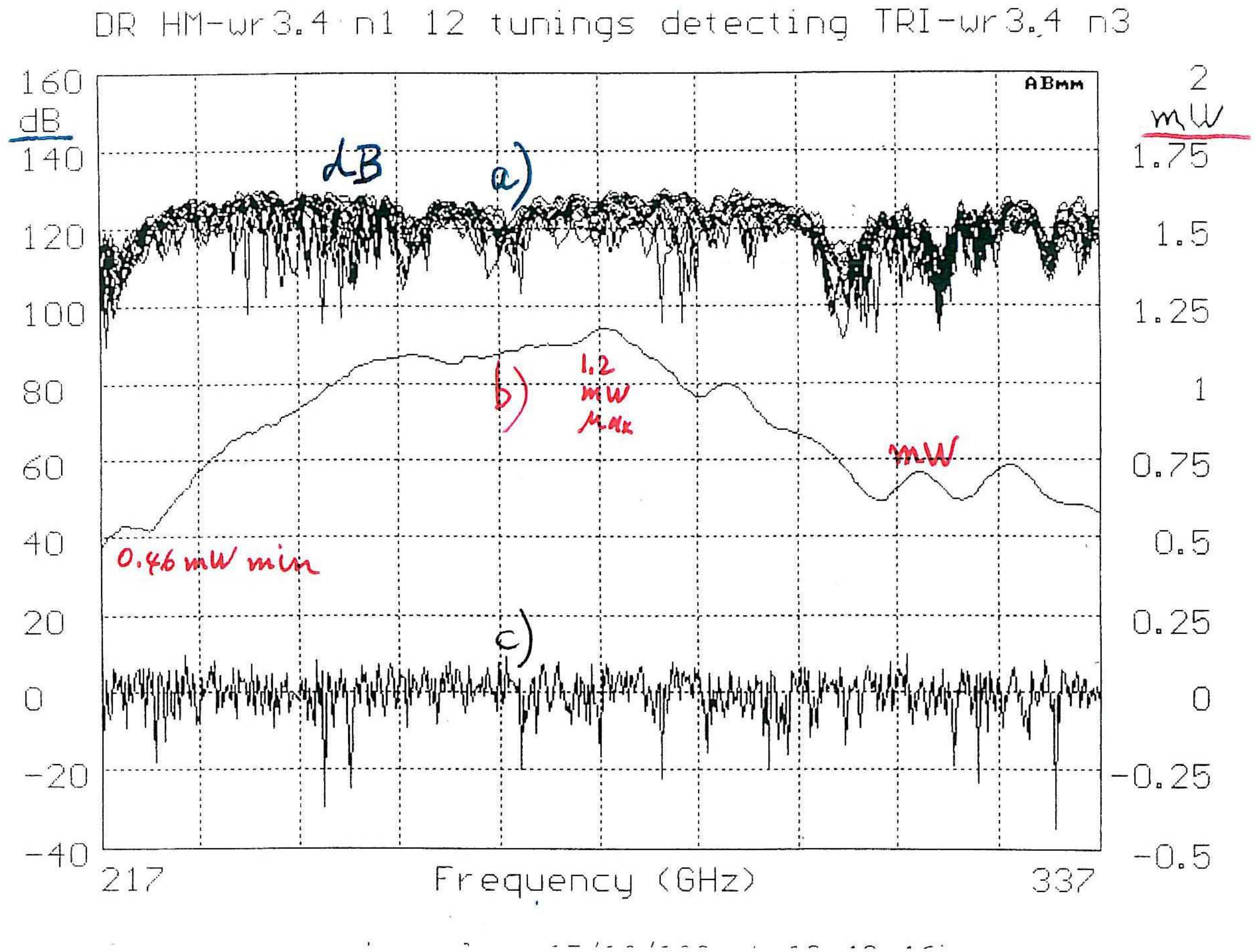
List of printed registers datrxp/losalam

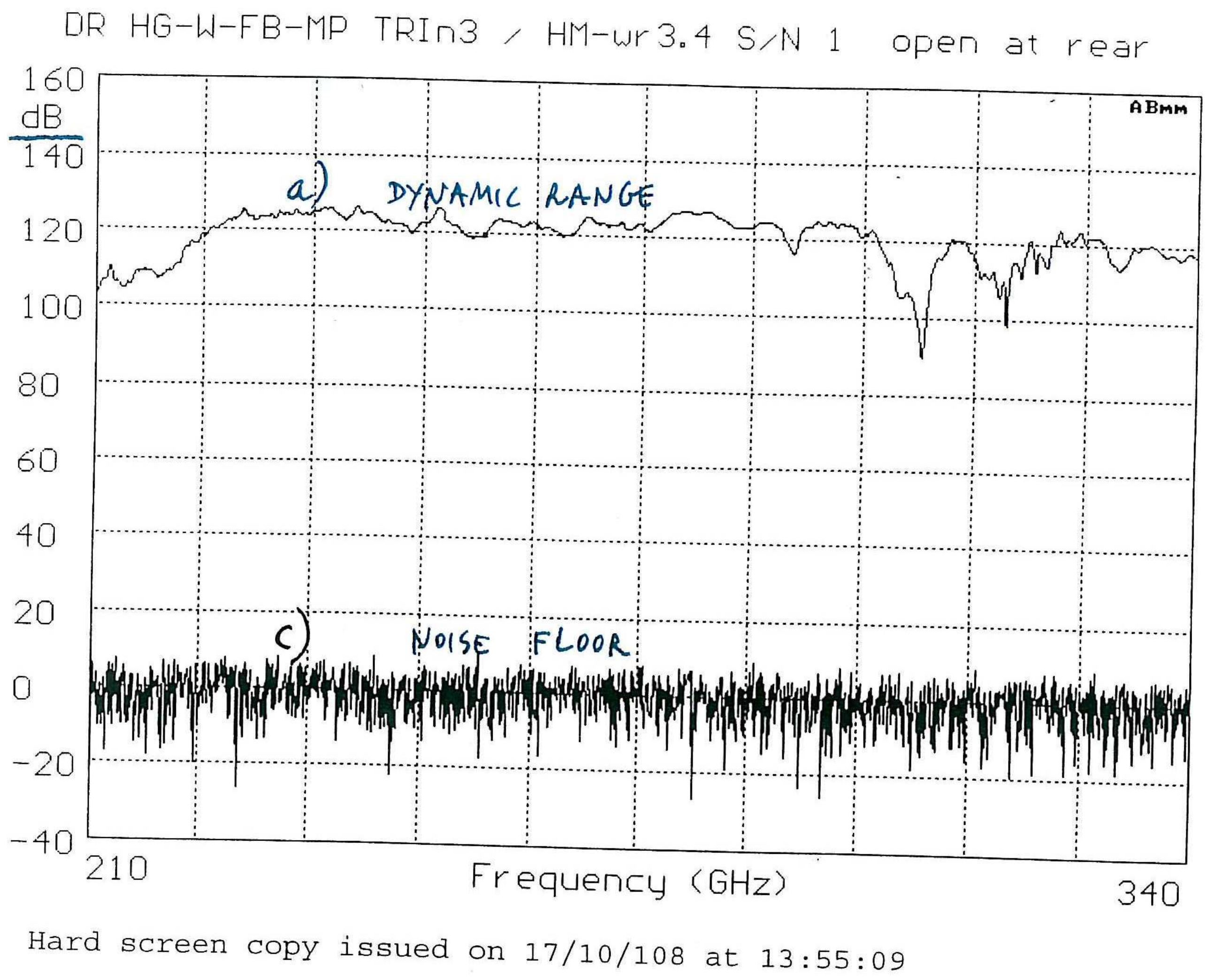
N=18 MULTIPLICATION CHAIN. 220-336 GHz source (sextupler, amplifier, tripler) and tunable detector (WR-3.4 Harmonic Mixer, even harmonics)



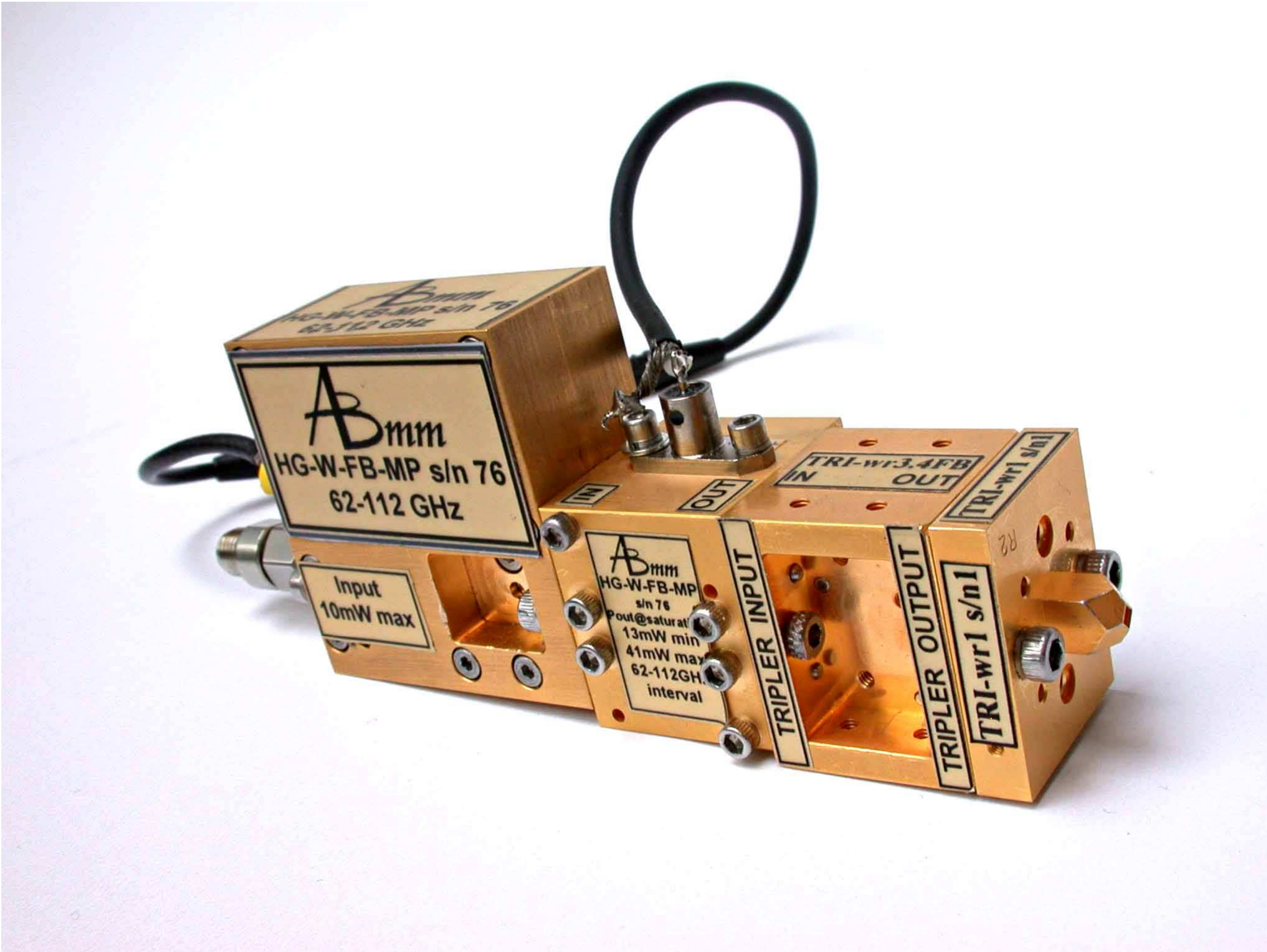
Dedicated Multiplier N=18. Dynamic Range (dB) at left.
a) Detection by the tunable detector at various tuning positions.
b) Measured power of the source (mW) at right.
c) Noise floor (dB).



Dedicated multipler N=18, Dynamic Range (dB) when removing the tunable short of the Harmonic Mixer (for obtaining flat response).



N=54 MULTIPLICATION CHAIN. **660-1000 GHz source (sextupler, amplifier, tripler, tripler with Diagonal Horn output).**



Power emitted from the N=54 multiplier (cascaded sextupler, tripler, tripler).

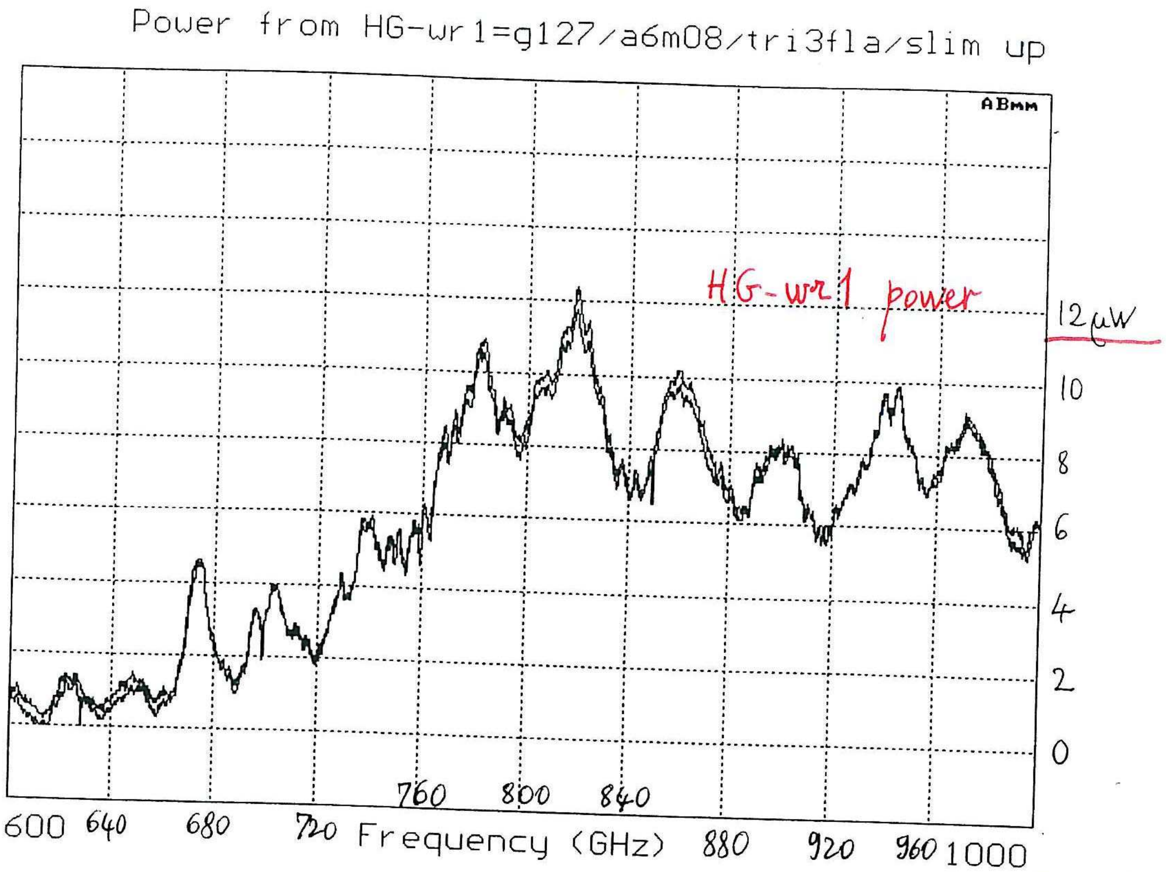
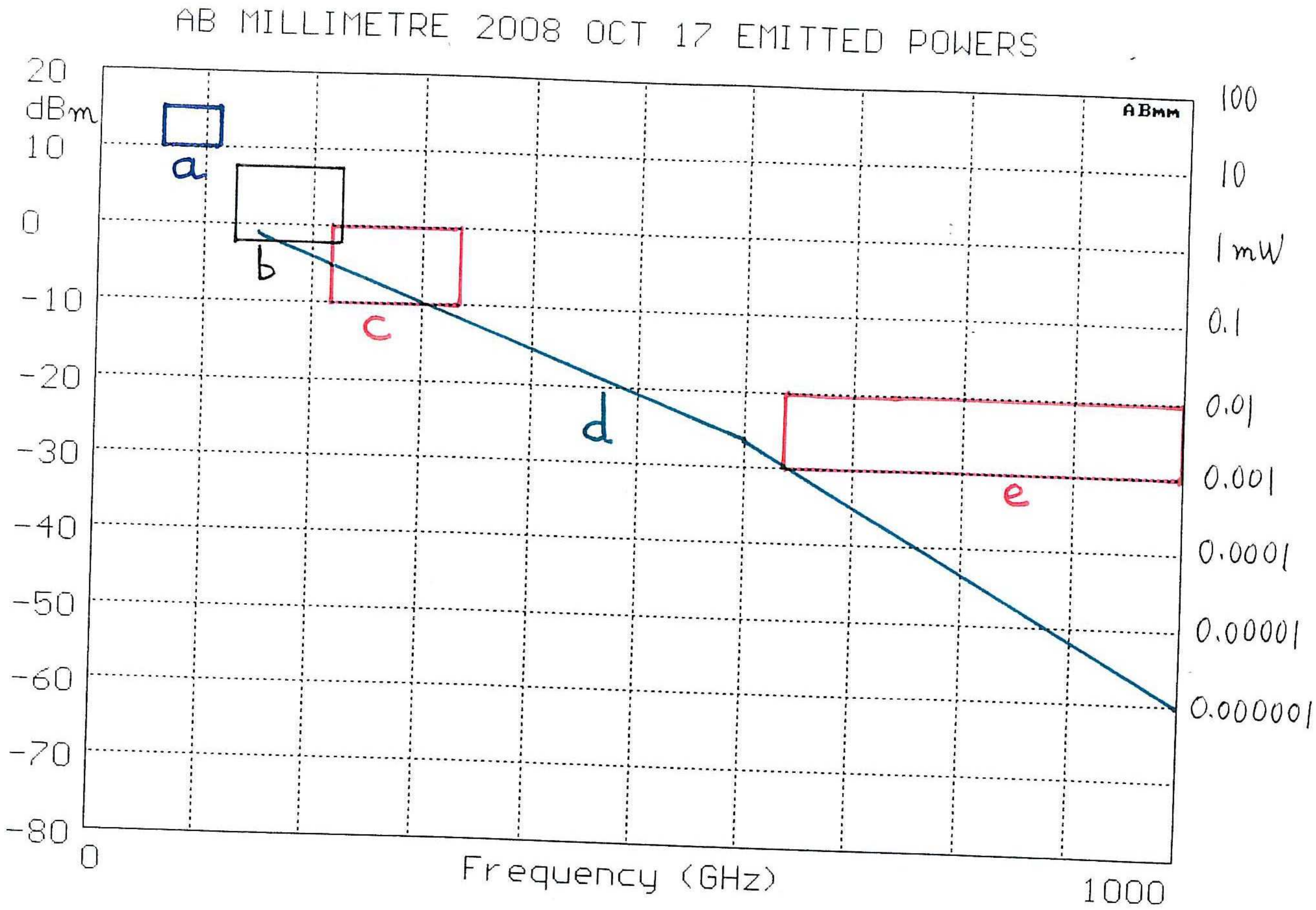
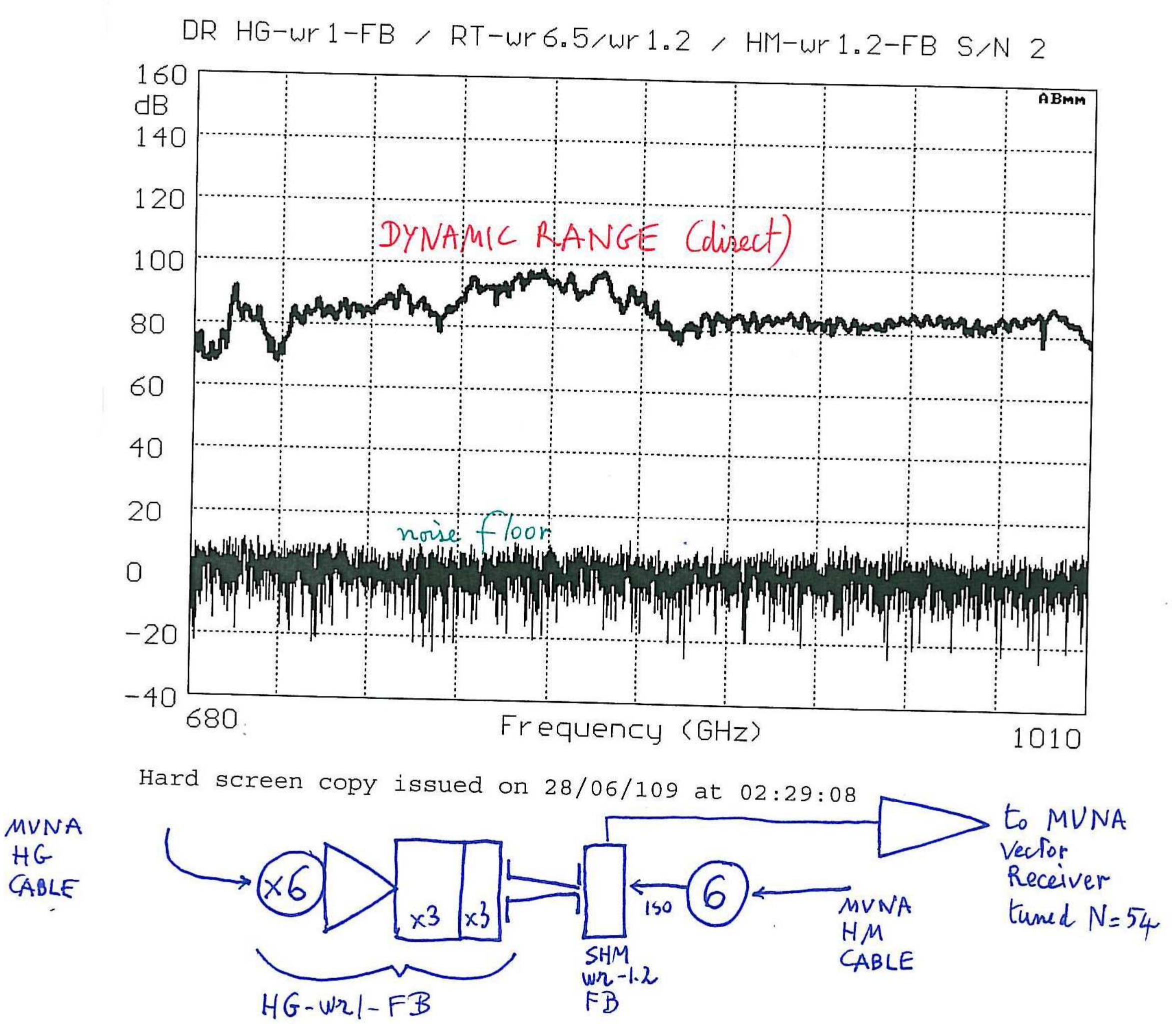


FIG. 12a

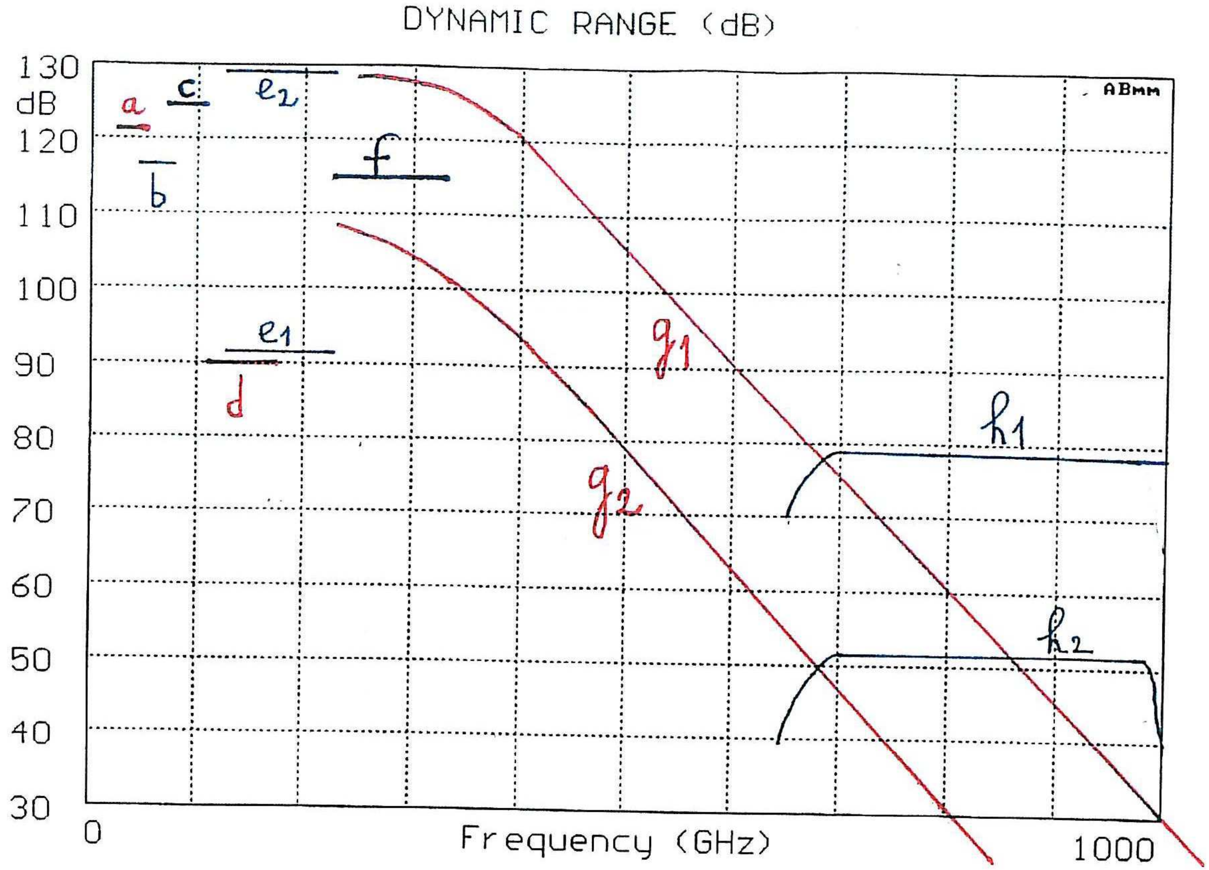
Available powers at AB MILLIMETRE.
a) Amplified sextupler, b) cascaded with Doubler, c) cascaded with 1st Tripler, e) 1st Tripler cascaded with 2nd Tripler.
d) Multiharmonic Multiplier (ASA-1 extension).



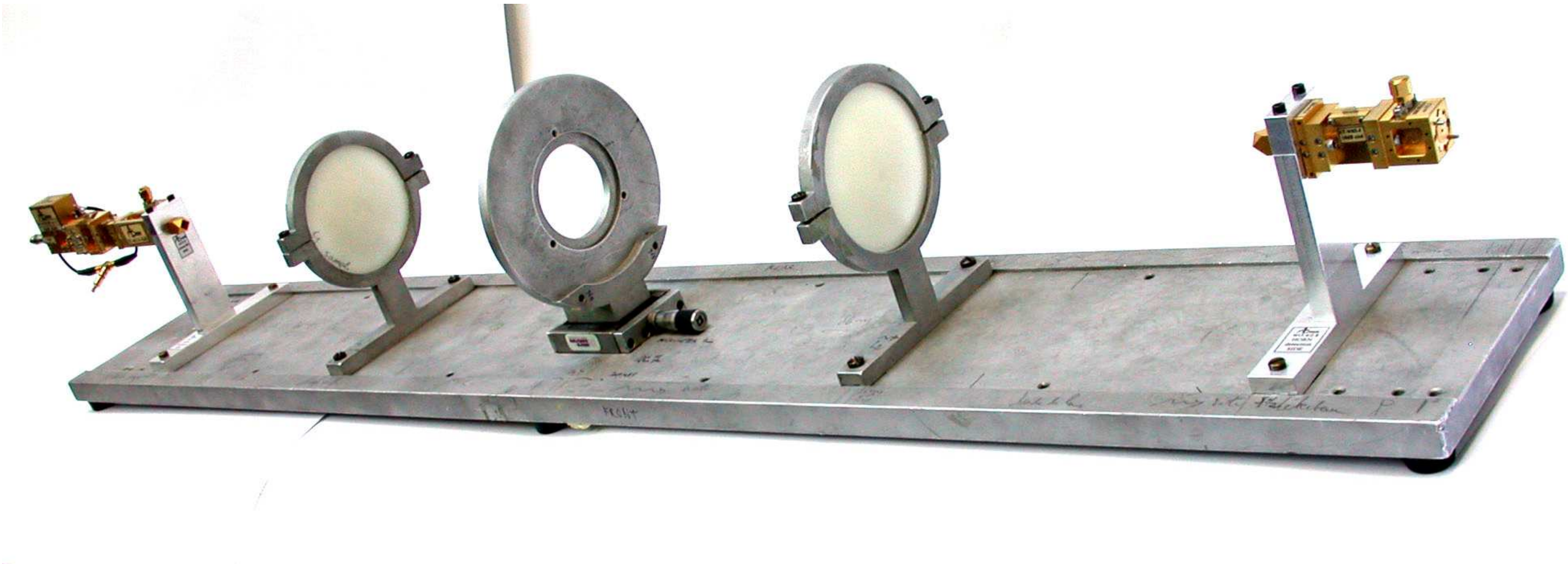
N=54 MULTIPLICATION CHAIN. Wide-band 660-1000 GHz source HG-wr1-FB detected by the Flat Broadband detector HM-wr1.2-FB. No tuning.



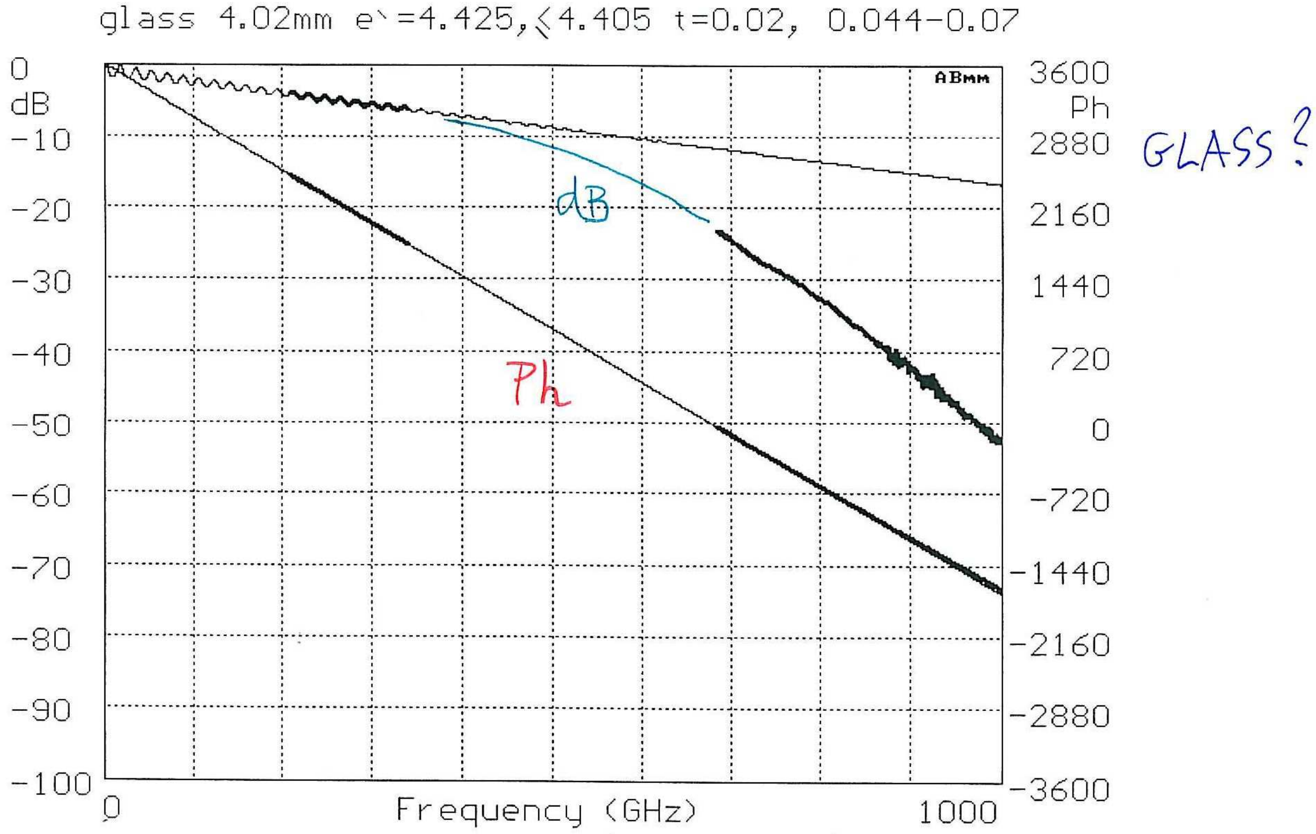
AB MILLIMETRE 2009 JULY 29, observed Dynamic Range DR with different available heads. Only g1, g2 and h2 are not full-band span sweeps (using tunable extensions ASA-1, ASA-2, and tunable HM-wr3.4).



Two-lens Reflection R / Transmission T Quasi-Optical QO bench equipped with WR-3.4 heads (220-336 GHz coverage).



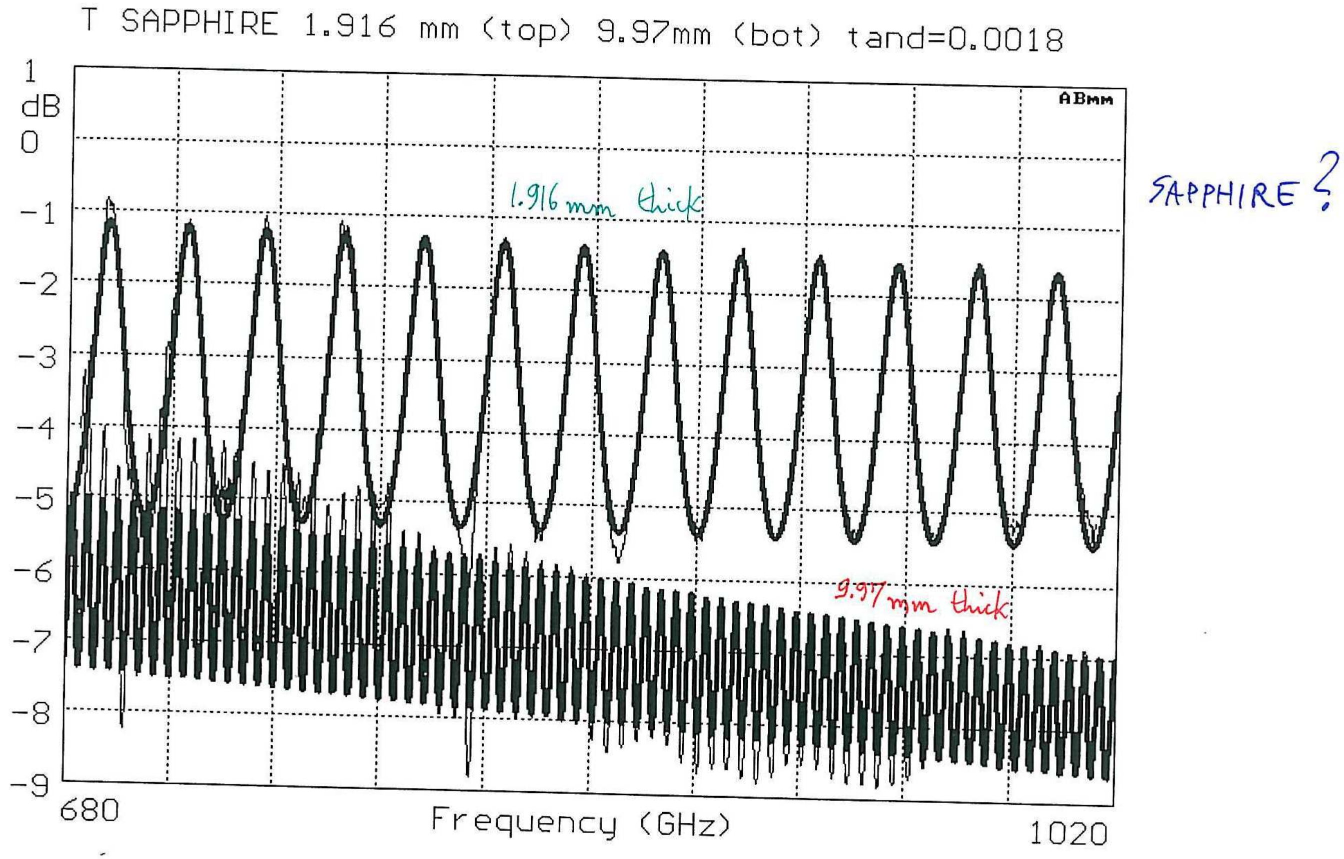
It would be nice to find a low-loss material for THz lenses. Glass, as measured in the T 2-lens QO bench is extremely lossy: see the decay of amplitude, much faster than the value extrapolated from the measurement around 300 GHz. On the contrary, the Phase variation is quite compatible with the lower frequency values, meaning no noticeable



Hard screen copy issued on 23/06/109 at 00:26:15

List of printed registers
F:/DATAXP/BENCHOBS\ENS4_02.MSN uw tr FTFT 20/06/09 22:06:04ens4.02d29

N=54 MULTIPLICATION CHAIN APPLICATION. Sapphire is an exceptionally good dielectric material around 10 GHz, when cooled. It is lossy at room temperature ca 1THz.

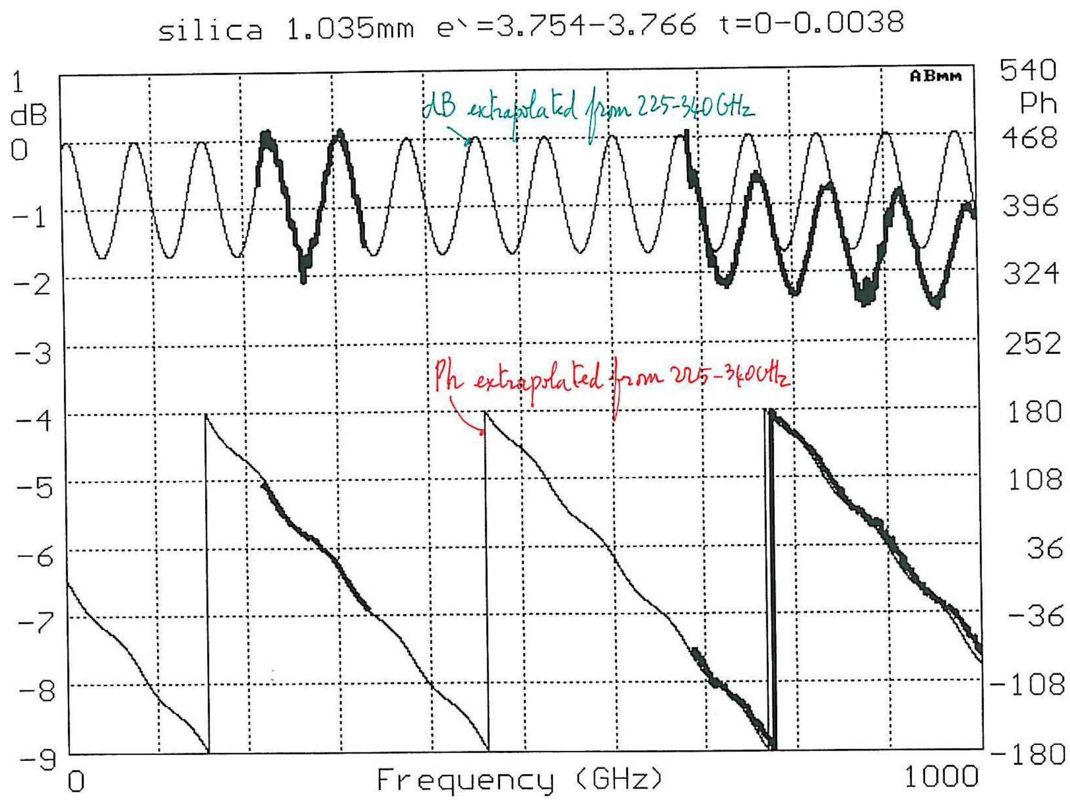


Hard screen copy issued on 28/06/109 at 02:39:20

List of printed registers
F:/DATAXP/HM800N2\BS2S9.MSN tr FTFT 26/06/09 16:33:56 s9
F:/DATAXP/HM800N2\BS2S9.MSN tr FTFT 26/06/09 16:35:33 s2

N=18 and N=54 MULTIPLICATION CHAINS APPLICATION.

Silica loss is small around 300 GHz. It becomes large around 1 THz. There is no noticeable variation of the permittivity.

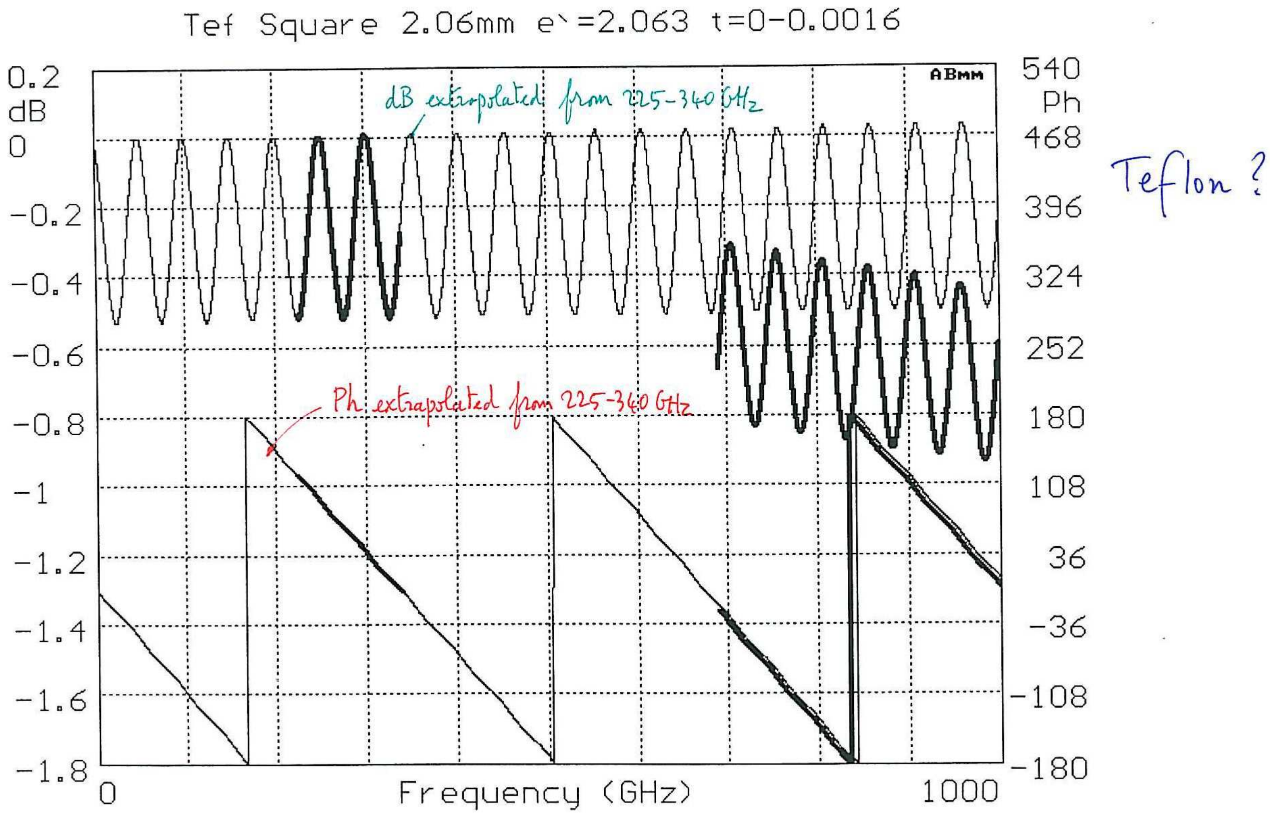


Hard screen copy issued on 30/06/109 at 23:08:13

List of printed registers
F:/DATAXP/2LENS3\BO1035DB.MSN tr FTFT 17/06/09 19:05:20 v1.035-1
F:/DATAXP/2LENS3\BO1035DB.MSN eFit D122/06/09 17:14:17 ens1.035-1
F:/DATAXP/2LENS3\BO1035DB.MSN tr FTFT D122/06/09 17:14:17 ens1.03

N=18 and N=54 MULTIPLICATION CHAINS APPLICATION.

Teflon is used for windows and lenses in the millimeter waves domain. It becomes lossy around the THz.

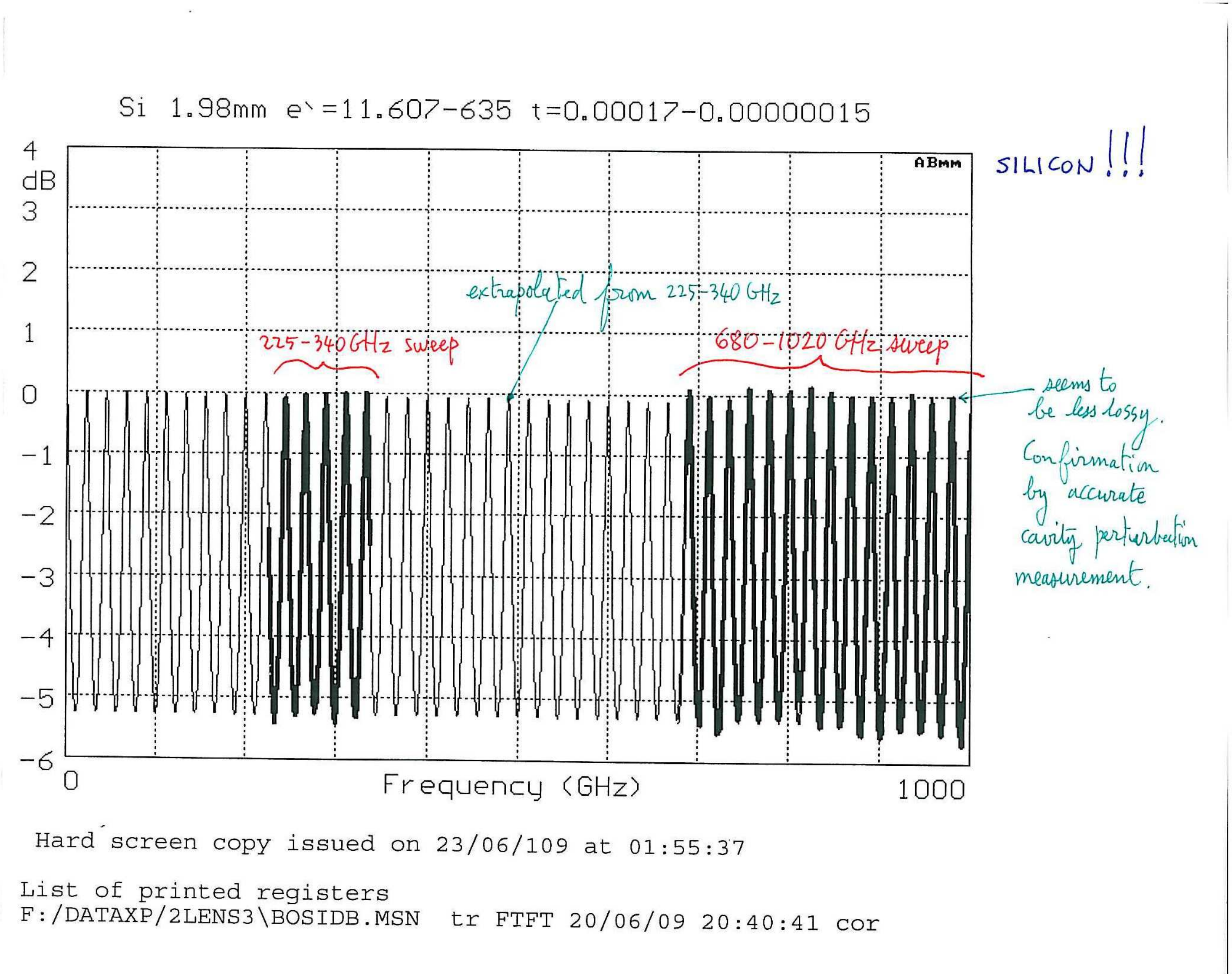


Hard screen copy issued on 30/06/109 at 23:13:12

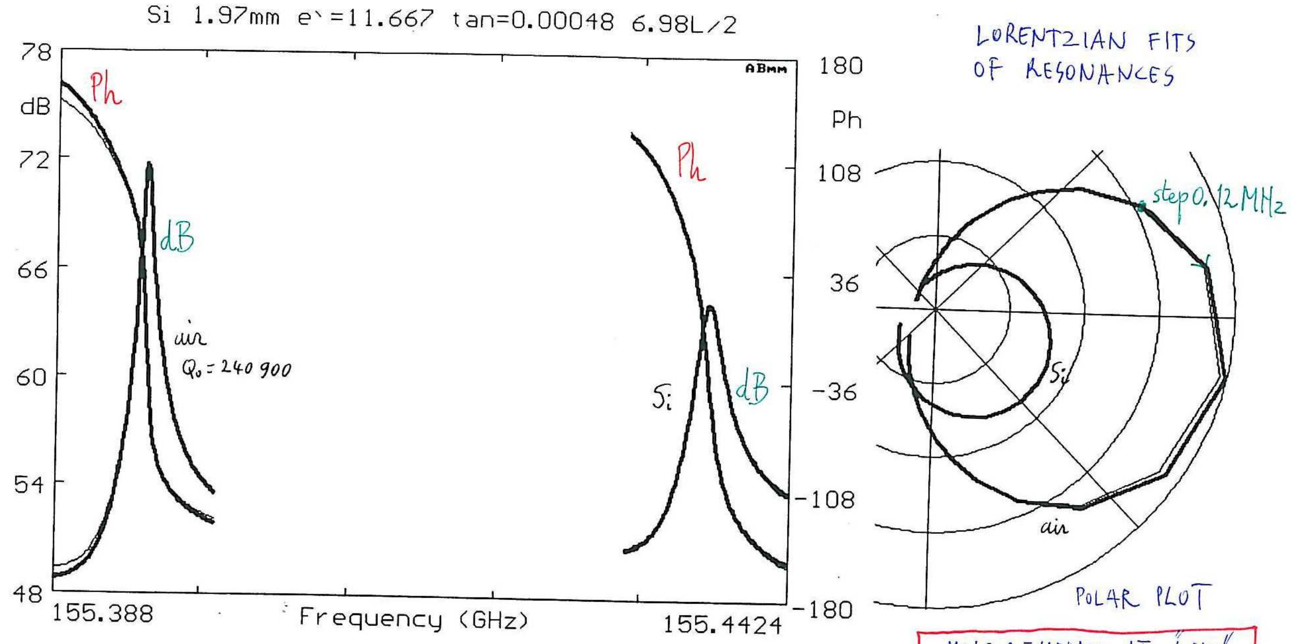
List of printed registers
F:/DATAXP/2LENS3\BOTEFL.MSN fit tr FTFT 17/06/09 14:34:31 tefcar2.09©
F:/DATAXP/2LENS3\BOTEFL.MSN fit 21/06/09 23:11:56 tefcarnb
F:/DATAXP/2LENS3\BOTEFL.MSN fit tr FTFT 21/06/09 23:11:56 tefcarnb

N=18 and N=54 MULTIPLICATION CHAINS APPLICATION.

High-resistivity silicon appears as an excellent dielectric material at THz frequencies, perhaps better there than around 300 GHz.



Open cavity perturbation technique is necessary when the loss of any dielectric material is low, like here in silicon.



Hard screen copy issued on 03/05/109 at 21:47:14

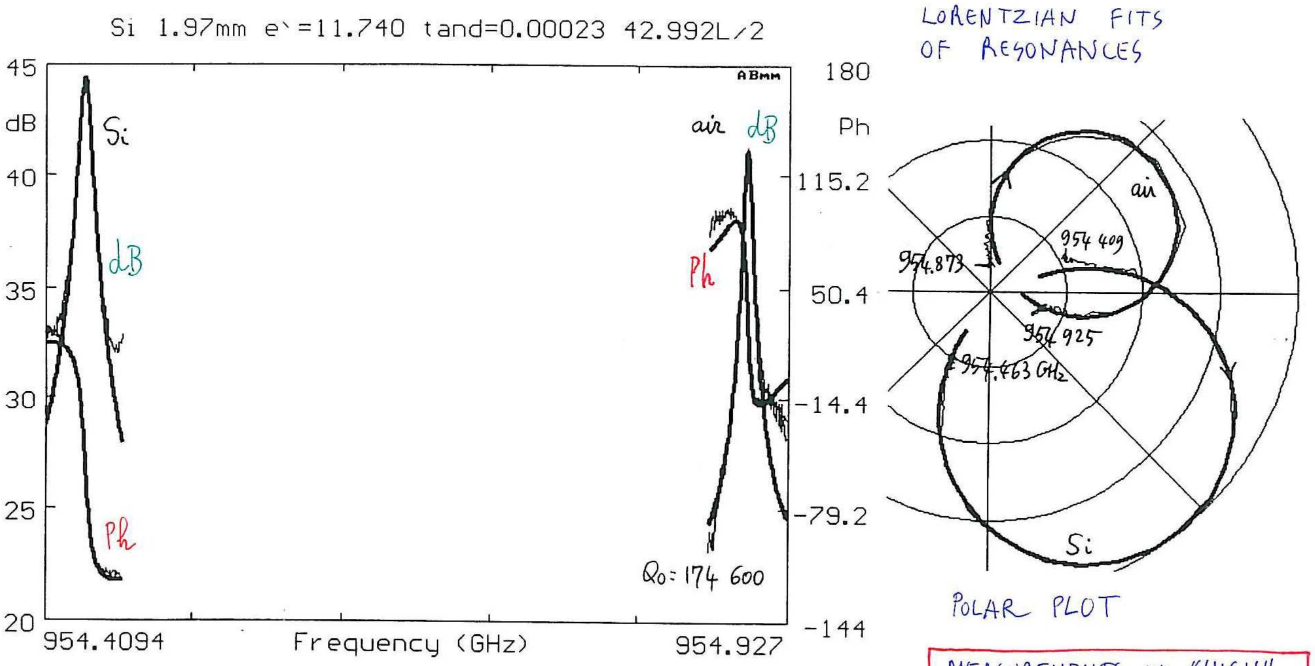
List of printed registers
F:/DATAXP/SILICON\C155E97B.MSN 01/05/09 15:48:27 d926 s1 nodia
F:/DATAXP/SILICON\C155E97B.MSN 01/05/09 15:52:24 air d926 dia30
F:/DATAXP/SILICON\C155E97B.MSN Fit 01/05/09 15:52:24 air d926 dia30
F:/DATAXP/SILICON\C155E97B.MSN Fit 01/05/09 15:48:27 d926 s1 nodia

MEASUREMENTS AT "LOW" FREQUENCIES: ca 132, 155, 178, 198, 222, 332 GHz give:

$\varepsilon' = 11.663 \pm 0.025$

$\tan\delta = (4.8 \pm 1.4) \times 10^{-4}$

N=54 MULTIPLICATION CHAIN APPLICATION. This measurements confirms that silicon presents a very low loss, which is slightly lower around the THz than around 300 GHz. At the same time there is a slight increase of the permittivity.



Hard screen copy issued on 03/05/109 at 20:58:58

List of printed registers
F:/DATAXP/HILLTAL1\C954E97.MSN 02/05/09 19:13:51 s1 dia20
F:/DATAXP/HILLTAL1\C954E97.MSN 02/05/09 19:23:21 air d750 dia15
F:/DATAXP/HILLTAL1\C954E97.MSN Fit 02/05/09 19:23:21 air d750 dia15
F:/DATAXP/HILLTAL1\C954E97.MSN Fit 02/05/09 19:13:51 s1 dia20

MEASUREMENTS AT "HIGH" FREQUENCIES: ca 666, 821, 956 GHz give
$\varepsilon' = 11.753 \pm 0.03$ increases
$\tan\delta = (2.6 \pm 1.2)\,10^{-4}$ decreases

- Conclusion.

- **The AB MILLIMETRE's Vector Network Analyzer permits the full band sweep spans in the frequency intervals 8-336 GHz (DR>110 dB) and 660-1000 GHz, DR ca 80 dB.**

- **The 140-1000 GHz interval can be covered by only two tunable heads (ASA-1 and ASA-2), however the frequency sweep spans are limited to ca 20 GHz.**

- **Applications are in Electrical Engineering, Radioastronomy, Aeronomy, Fusion Plasma, High magnetic fields, imaging, antennas, components, metamaterials and materials characterization, etc.**