Millimeter and Submillimeter Studies of Planar Antennas

H. van de Stadt, Th. de Graauw, A. Skalare[1],

R. A. Panhuyzen*, R. Zwiggelaar[2]

National Institute for Space Research, Landleven 12,

P.O. Box 800, 9700 AV Groningen, The Netherlands

*Department of Applied Physics, University of Groningen,

Groningen, The Netherlands

Abstract.

We report measurements of the properties of planar logperiodic and double dipole antennas in scale models around 10 GHz and in real size over the frequency range of 100 to 500 GHz.

In the scale model measurements we used an automated antenna range facility. We investigated single antennas as well as antenna arrays, mounted on substrates and on the backsurface of plano-convex lenses. The results of double-dipole antennas are superior to the logperiodic in the sense of slide lobe patterns, bandwidth and polarization behavior.

In the measurements between 100 and 480 GHz, we used an array of 3x3 logperiodic antennas in the focal plane of a lens with aspherical surfaces. All was mounted inside a dewar for liquid

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[1]Present address: Chalmers Technical University, Göteborg, Sweden.

[2]Present address: University College, London, England.

helium temperatures, as planar Nb SIS junctions were used as detecting elements. We measured nice beam patterns at the lower frequencies, both on-axis, as well as off-axis. At higher frequencies, we had high side lobe levels of irregular shape. Results are presented on the polarization properties and the influence of a reflecting, adjustable backshort.

1. Introduction.

Planar antennas have a number of properties that make them suitable for application in mm/submm heterodyne receivers. In this paper we will study some properties of broadside planar antennas, where the radiation is directed normal to a flat metal structure. The following properties are of interest:

- Sensitivity: Planar antennas can have high efficiencies and can easily be integrated with planar SIS or SIN junctions, which are presently the most sensitive kind of heterodyne mixer for mm/submm wavelengths down to .8 mm and possibly for smaller values.

- Bandwidth: Several types of planar antennas (logperiodic and logspiral) can be made nearly frequency independent and can be used over many octaves. Some associated properties are: their effective antenna size varies linearly with wavelength and they have relatively large feed angles. However, to effectively use the large bandwidth the local oscillator (LO or combination of LO's) must be tunable over the same bandwidth. For most oscillators a tunability of 30 % is already very difficult to realize. Thus the multi-octave bandwidth of some planar antennas seems to be not of much practicle interest for application in heterodyne receivers. This also implies that the limited bandwidth of dipole antennas seems to be not a severe drawback.

- Polarization: All commonly used LO's are linearly polarized. This does not automatically comply with logspiral antennas (circularly polarized) and logperiodic antennas (elliptically polarized and changing orientation with frequency). In this respect the arrangement of dipole antennas, as we have investigated, seems to be a good choice.

- Imaging: Planar antennas lend themselves for multi-element, imaging detector arrays much simpler than a multiplicity of horn-waveguide combinations. Some form of quasi-optical arrangement is required for optimum coupling of aperture ratios and to avoid problems with undersampling and/or crosstalk. The whole arrangement must be such that different elements of the imaging array should be easily servable and replacable. We looked for a structure where each antenna element can have its own lens, detector, IF output coupling leads and a fixed backshort. Also, the construction must be suitable for the implementation of SIS or SIN mixers, as their low LO power requirement allows application in mm/submm imaging arrays.

In this paper we first describe measurements on logperiodic antennas. Some of the less favourable properties led us to investigate some arrangement of dipole antennas. Several papers have been published (e.g. refs.2 to 4) using combinations of two full-wavelength dipoles as elements in an imaging array. In chapter 4 we will motivate our preference for an arrangement of four half-wave dipole antennas.

2. Scale Model Measurements of Logperiodic Planar Antennas.

Log-periodic antenna structures have been attracting attention for radio and microwave applications ever since the fifties, ref. 1. In recent years, some of the early designs have again become of interest for applications in the mm- and sub-mm-wave regime. The main reason is a desire for a broadband antenna, that lends itself well to integration with microcircuitry and active planar components, such as superconducting SIS and SIN mixers. In this chapter we present some of our scale model measurements at frequencies centered around 10 GHz.

For our study we have chosen the types of logper antennas as given in figure 1: 1a has symmetrical sectors 45°/135°; 1b is a slightly different version of 1a with 10°/120° sectors; 1c has straight and more denser teeth; 1d has teeth on only one side of the "core". In this chapter we discuss only a selection of many measurements. More detailed information can be found in ref.7.

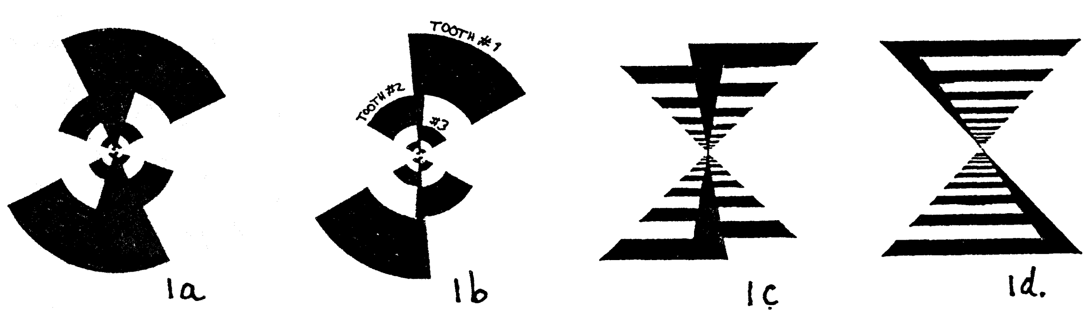

Fig. 1: Four different types of logperiodic patterns, as investigated in this study.

A large (154 mm diameter) model was made of the 10°/120° degrees antenna to study the reflection at various resonant frequencies. The reflection S_{11} was measured (Fig. 2) with a coaxial cable probing the antenna. It shows radiating resonances as dips in the trace. The size of the antenna is such as to put the resonance of the outer edge of the second tooth close to 2 GHz, i.e. the outer edge corresponds to roughly one quarter wavelength at that frequency. The sharp resonance at .64 GHz is due to an (unwanted) dipole resonant mode. Three of the desired tooth resonances occurred, but the one at the outside of the outermost tooth was very weak. The reason for this is the different boundary conditions for the resonating edge. The existence of a low-frequency limit for logperiodic antennas was mentioned already in ref.1, where a value of .9 GHz was mentioned for a 254 mm radius antenna. From the measurements we can deduce that the input impedance of our antenna varies between 120 and 225 Ohm.

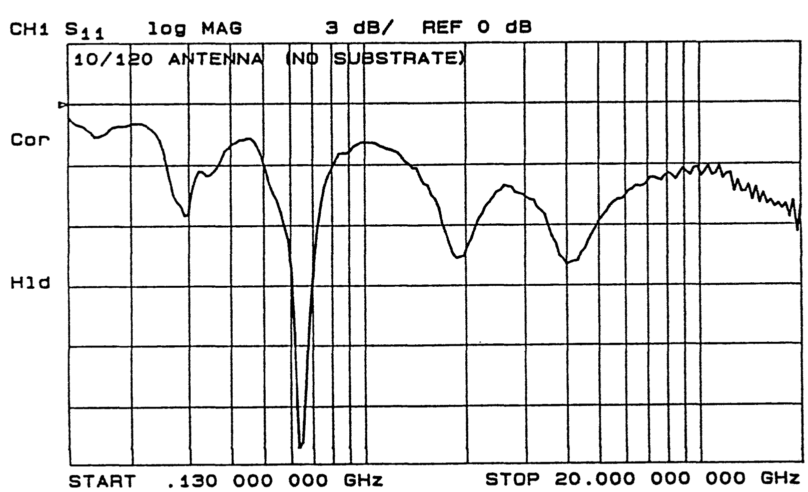

Fig. 2: The S11 reflection coefficient of antenna model 1b. There are 4 major dips in the trace. The two lower ones are unwanted dipole modes, the two higher ones (at 2 & 4 GHz) are the correct log-per modes in tooth#2 and tooth#3.

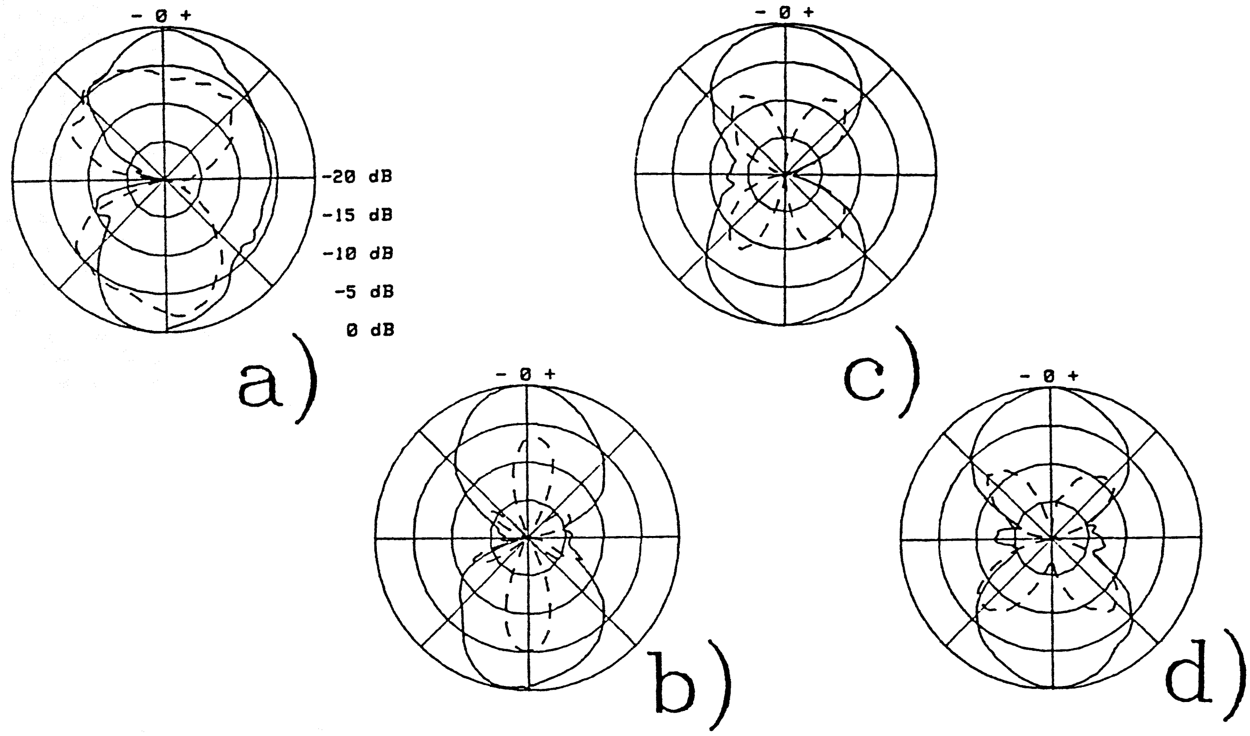

Fig. 3: H-plane radiation patterns of antenna 1a. The measurements were done in two different models, but the a/b/c/d figures can be compared by referring them to a frequency CF : a) 0.7CF, b) 1.0CF, c) 1.25CF, d) 1.5CF .

The dips in the S11 diagram at .64 GHz and lower frequencies are below the desired operating range of the antenna. As mentioned, they are caused by a type of dipole resonance, where the electrical currents are perpendicular to those in the correct log-per modes, and they give rise to cross-polarized patterns as shown in Figs. 3 and 5.

For the measurements of Fig. 3 the antenna structure 1a was supported by an electrically thin Kapton film. HP beam-lead diode detectors were used as power detectors. We actually used two models with diameters of 40 and 28 mm in order to cover an effective total bandwidth of one octave with an antenna measurement set-up suitable for frequencies between 8 and 12 GHz. Antenna patterns are measured 360 degrees round. In total more than 80 scans were made per antenna type. In Fig.3 we only show the H-plane data for structure 1a at 4 frequencies. E-plane and D-plane (diagonal) data show similar characteristics. The "CF" frequency roughly corresponds to the resonance frequency of the outer edge of the second tooth, counting from the perimeter of the antenna.

In Fig.3 co-polarized and cross-polarized patterns are indicated with continuous and dotted lines, respectively. Apart from the pattern at the lower end of the band (at .7 CF) the co-polarized radiation patterns are between 55 and 60 degrees wide (halfwidth at -10 dB level) and have fairly good quality. The level and shape of the cross-polarized patterns indicate that a strong dipole mode was excited. The lobes at +/- 45 and +/-135 degrees also occur in the H-plane.

The addition of a dielectric substrate has the general effect of directing the radiation into the dielectric, giving sometimes as much as 8 dB difference between the peaks of the front and back lobes of the antenna.

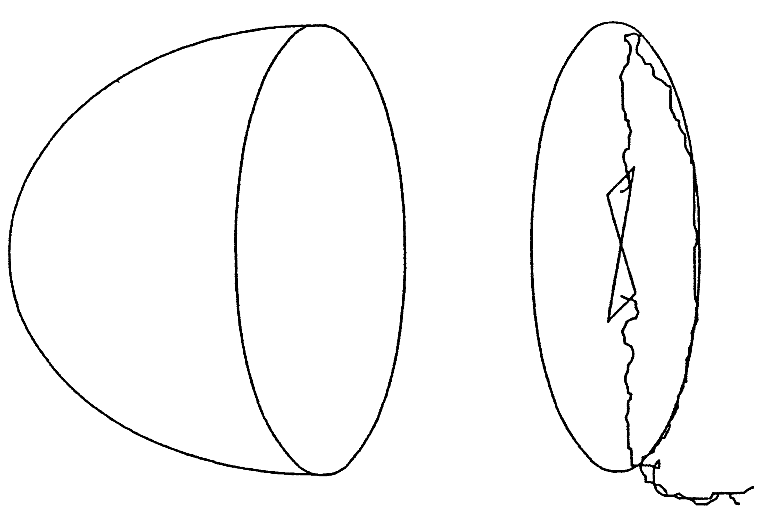

Fig. 4: Schematic view of the High Density Polyethylene (HDP), ellipsoidal lens (dielectric constant 2.31) + antenna-on-Kapton.

A series of measurements has been made with a log-periodic antenna on a thick dielectric lens, see Fig. 4, in order to increase the directivity. Fig. 5 shows this is indeed the case. However, two other effects are also visible: 1) there is a rather high sidelobe pattern in the backward direction and 2) the cross-polarization is rather high over the whole band. The reason is partly that the current distribution in the antenna structure varies with frequency, which makes the main polarization plane change with frequency. Independent measurements showed that the main polarization plane actually varies more than +/-20 degrees. The other effect is the generation of a circularly polarized component. This was confirmed by measuring patterns in a series of different planes relative to the antenna. If the antenna beam had been plane polarized, one of the planes would radiate all the power into one of its two polarizations. In the lens-antenna combination this is not the case.

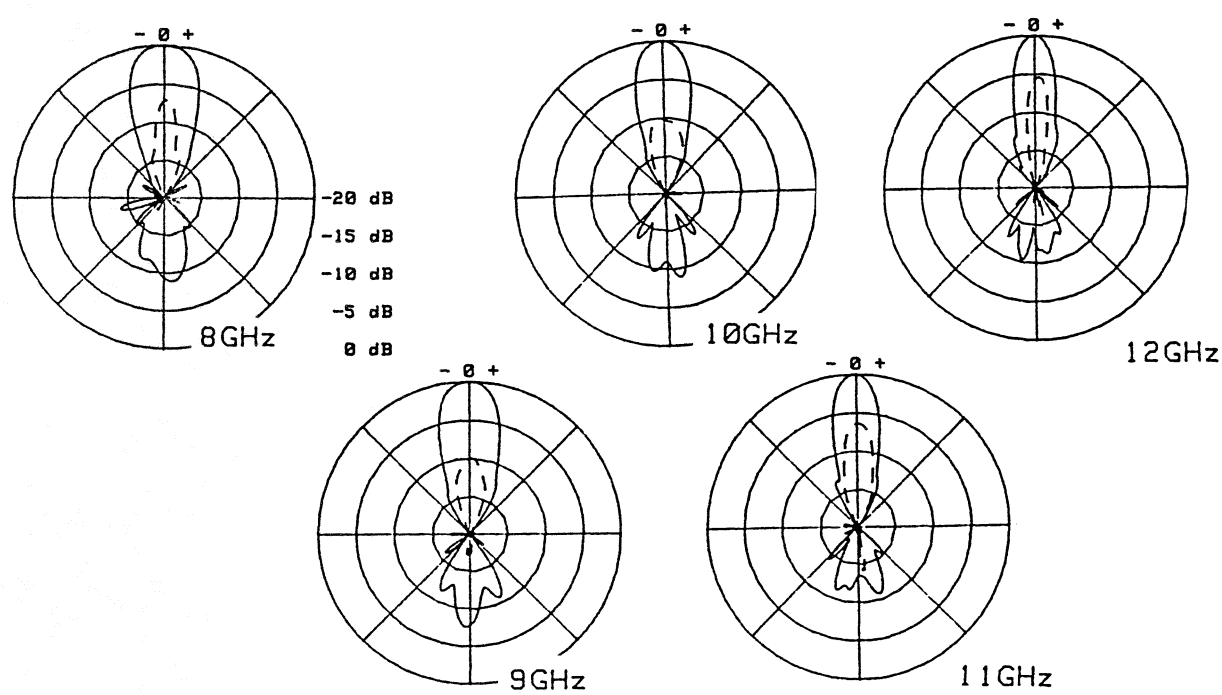

Fig. 5: E-plane measurement of antenna model 1a with a poly-ethylene lens at frequencies of 8, 9, 10,11 and 12 GHz.

An improvement in the polarization properties was expected from the antenna with straight and denser teeth, Fig. 1c. But the resulting radiation patterns look very much like the ones in the previous Fig. For the antenna with straight teeth on only one side (Fig. 1d) it turned out that a dipole resonance was excited along the free edge of the antenna and therefore the polarization properties were also not improved.

3. Mm and Submm Measurements of a Logperiodic Array.

We have built a 3x3 element array of logperiodic antennas. The diameter per element is 4.6 mm in order to study properties for frequencies of 100 GHz and higher. The inter-element spacing is 6 mm, the substrate 200 μm thick glass. Measurements were done using beam lead diodes, bismuth bolometers and Nb SIS mixers as detectors.

In order to be able to use SIS mixers we have constructed an optical arrangement in a cryostat of Infrared labs., Tucson, with an enlarged body so that we have an internal height of 10 cm available, see Fig. 6. The arrangement uses a 40 mm diameter polyethelene window and a movable reflecting backshort. We can use reflectors of 14 mm diameter for single antenna elements or 20 mm diameter for an array of 3x3 elements. The reflector can be moved over 4 mm distance. Efficient cooling of the SIS detector substrate is achieved by four clamping springs, to be mounted (but not present) on the four inner screws of Fig. 7.

As shown in Fig. 6 we have chosen for an optical arrangement with a single-element, free-standing lens, made of HDP. It was machined on a standard lathe and uses higher order, aspheric lens surfaces in order to get good off-axis imaging quality.

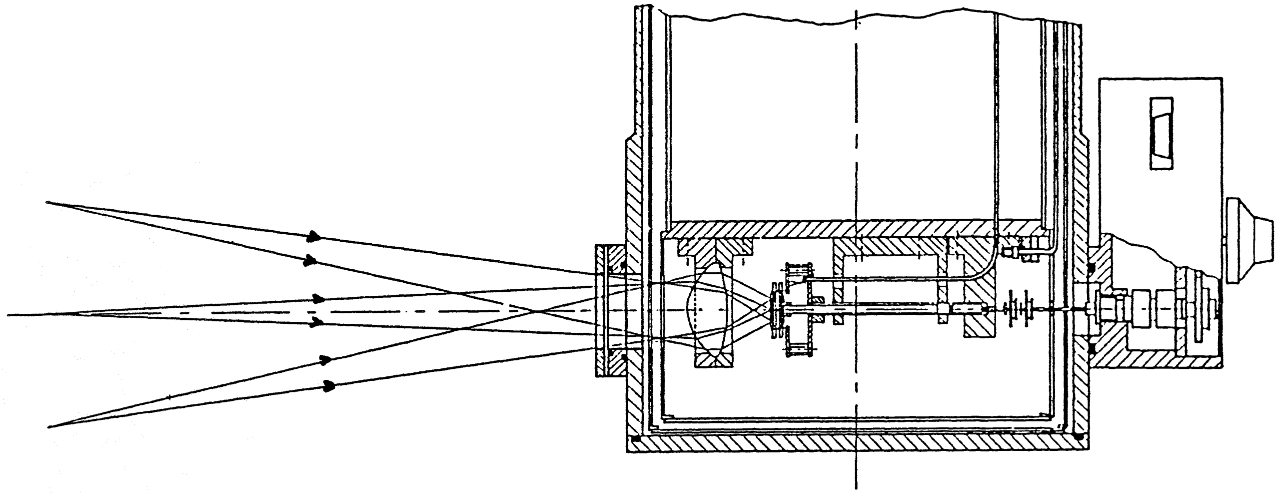

Fig. 6: Schematics of the array dewar with lens, planar antenna array and adjustable backshort on cold plate of He vessel.

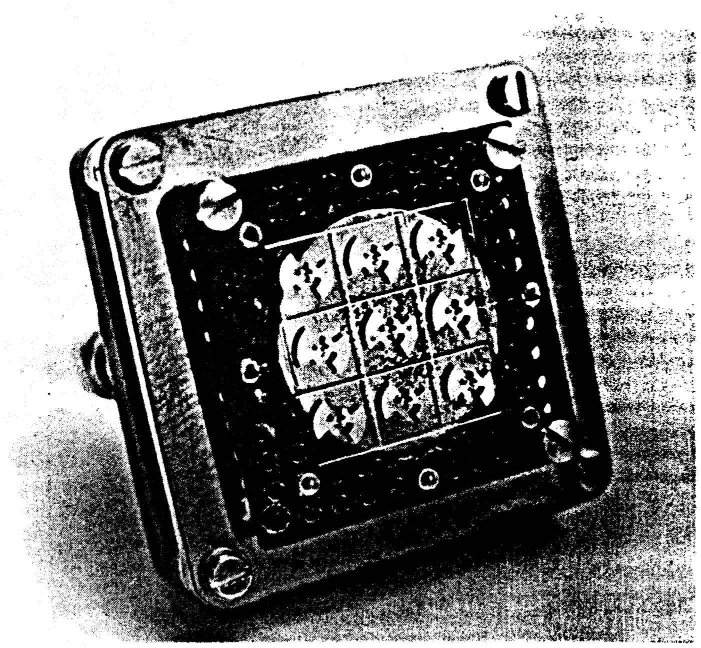

Fig. 7: Photograph of 3x3 element logperiodic planar array in a mounting with a reflecting backshort. The wires ($25\mu m$ Au) to the centre element are visible

In Fig. 8a we show the antenna pattern of a single on-axis antenna element (without neighboring elements) for 106 GHz. The reflecting backshort was adjusted for optimum signal level. The pattern shows good agreement with a computed Airy pattern, which is based on diffraction as it occurs due to the 40 mm diameter dewar window. The half power beam width is 8.5° for the -10 dB points. The side lobe levels are at a quite acceptable level of $\approx$-17 dB.

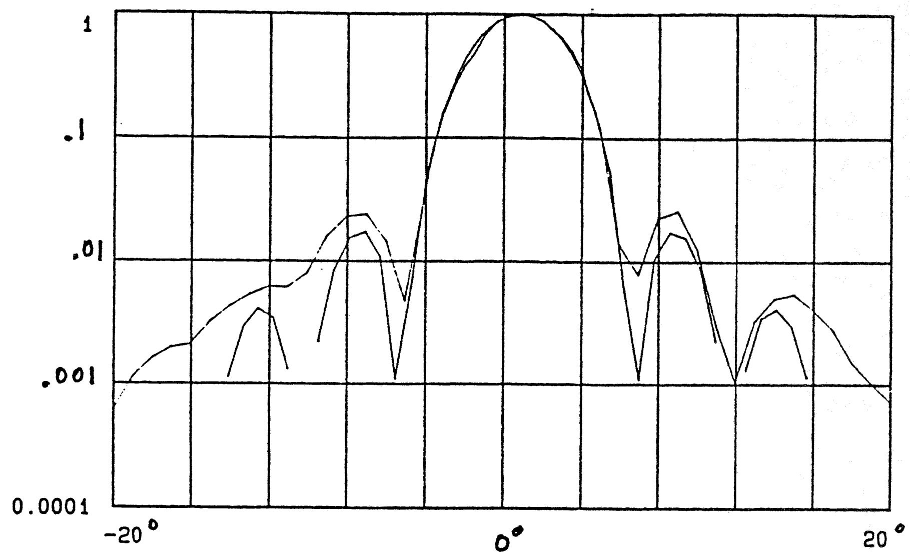

Fig. 8a: E-plane pattern of on-axis logper element at 106 GHz with a beam lead planar Schottky diode as a detector. Data are compared with a computed Airy pattern.

In Fig. 8b we show the antenna patterns for an on-axis and an off-axis array element at 106 GHz. The circumstance that the elements are surrounded by other array elements seems to broaden the beam width (to 10.6°). Also, the distinct side lobes of Fig. 8a have disappeared.

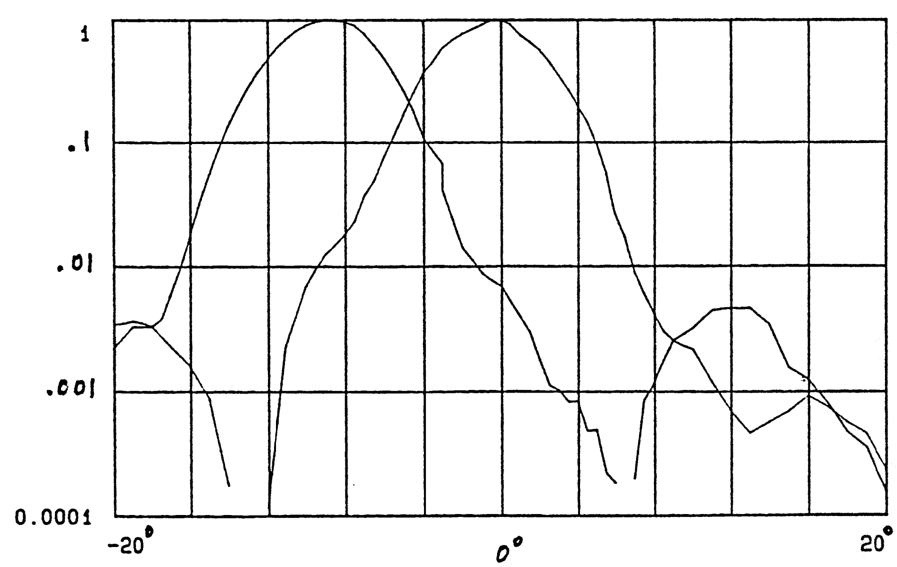

Fig. 8b: E-plane antenna patterns of on-axis and off-axis logper elements measured at 106 GHz with bismuth bolometers as detectors. No off-axis degradation is apparent.

In Fig. 8c we show the same results as Fig. 8b, but now at a frequency of 220 GHz. Compared with a computed Airy pattern at that frequency shows that the array element yields now the same diffraction limited resolution as an isolated element and there is no degradation when we go off-axis.

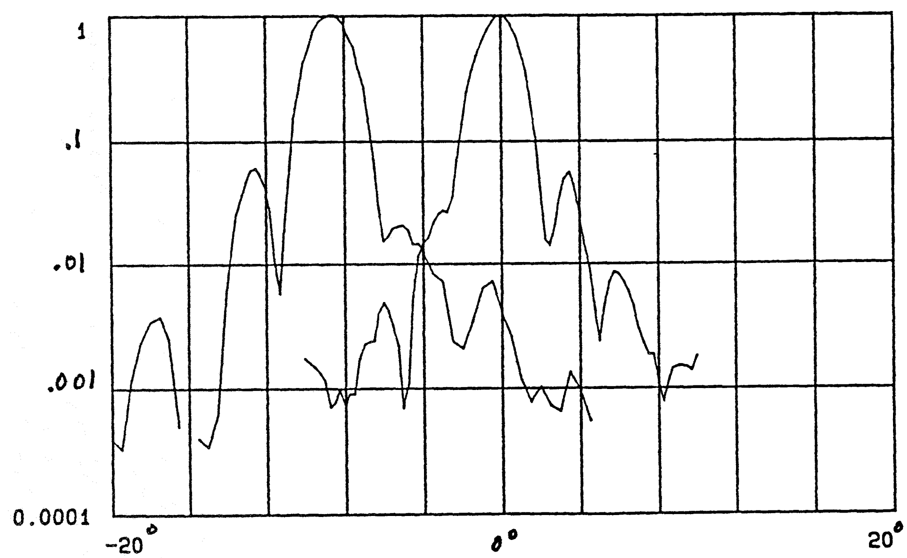

Fig. 8c: E-plane antenna patterns of on-axis and off-axis logper elements measured at 220 GHz with bismuth bolometers as detectors. No off-axis degradation is apparent.

In Fig. 8d we show the same results as in Figs. 8b and 8c, but now at a frequency of 483 GHz. Here we see a considerable degradation of the beam quality as compared to the diffraction limited beam quality. The central beam gets much wider and the level of the sidelobes is increasing considerably. Two reasons can be the origin of these phenenomena: 1) substrate effects (the substrate thickness is 200 μm, while the wavelength is 621 μm); 2) interference effects. The latter may be due to detection or reradiation of more than one set of teeth. Also the presence of the backshort can give rise to unwanted interference effects.

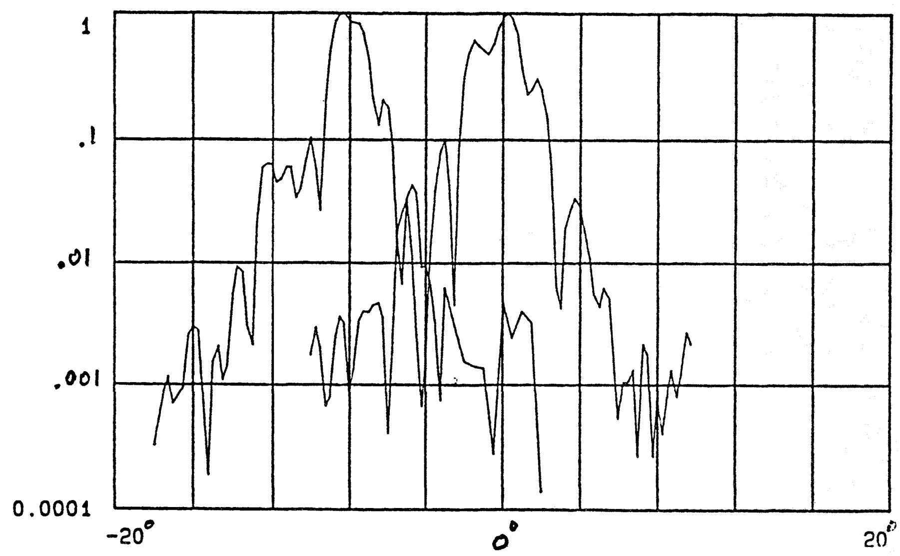

Fig. 8d: E-plane patterns of on-axis and off-axis logper elements measured at 483 GHz with bismuth bolometers as detectors. Considerable off-axis degradation is present.

Some antenna patterns were also measured with a Nb SIS mixer as a detecting element. Essentially the same patterns were measured as with bismuth bolometers.

Finally we analyzed the polarization behaviour as a function of frequency. Due to the curvature of the teeth in logper antennas one can expect a considerable change in orientation of the optimum detection angle for linearly polarized radiation. In Fig. 9 we present this angle as a function of frequency. We used two carcinotrons covering a range of 182 to 273 GHz. The change in orientation at 211 GHz is probably because the effective part of the antenna changes from one tooth to a smaller tooth. This is a worrying aspect of logper antennas, as was already clear from the scale model measurements in the preceding chapter.

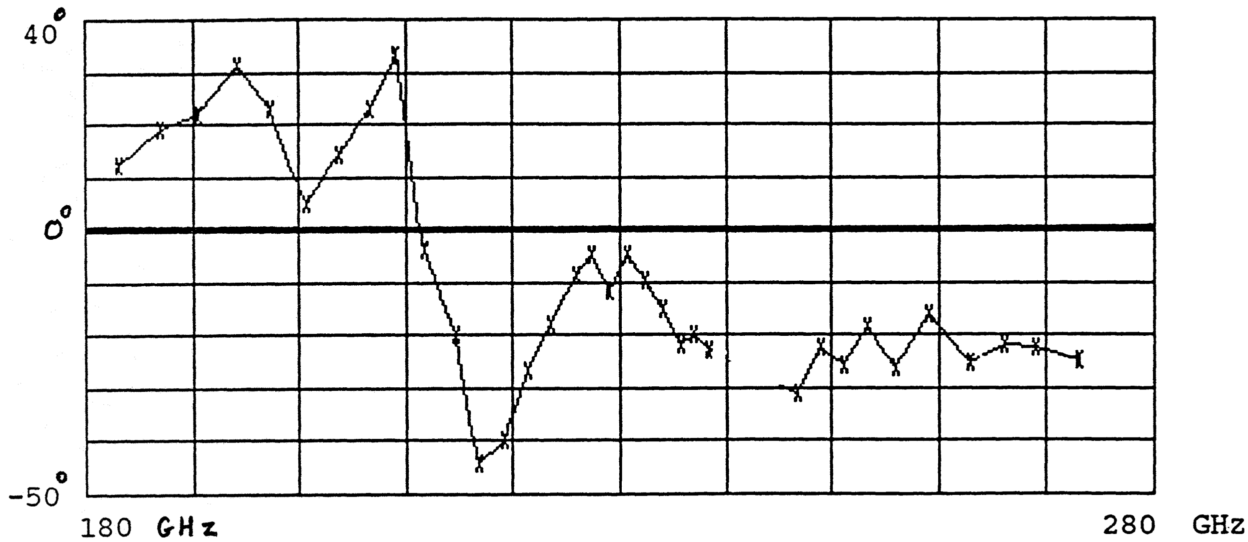

Fig. 9: Measured orientation of the linear polarization angle of a logper antenna as a function of frequency.

4. Scale Model Measurements of a Planar Dipole Array Antenna.

Several designs have been published of planar full-wave dipole antennas for imaging applications (refs. 2 to 4). In this paper we present a modified configuration using two half-wave dipoles at a spacing of about one half wavelength from each other (Fig. 10). The good sides of this antenna are its polarization properties and the fact that the beamwidth can be balanced in the E- and H-planes. The main beam, which is rather wide, is symmetrical in the forward and backward directions. This means that the antenna has to be backed by a reflector plane, and that it is useful primarily for illumination of reflectors.

We have studied the antenna in two configurations. In the first it was supported only by a thin Kapton™ film, thus simulating its free space properties. In the second the antenna was mounted between a thick polyethylene lens, and a quarter wavelength thick polyethylene slab ($\epsilon_r \approx 2.3$) backed by a metallic reflector (Fig. 12). The diameter of the lens was 110 mm. All measurements were made in a 7-14 GHz computer controlled antenna measurement range. A Hewlett-Packard HSCH-5330 beam lead diode was bonded into each design with indium solder and used for direct detection of the signal.

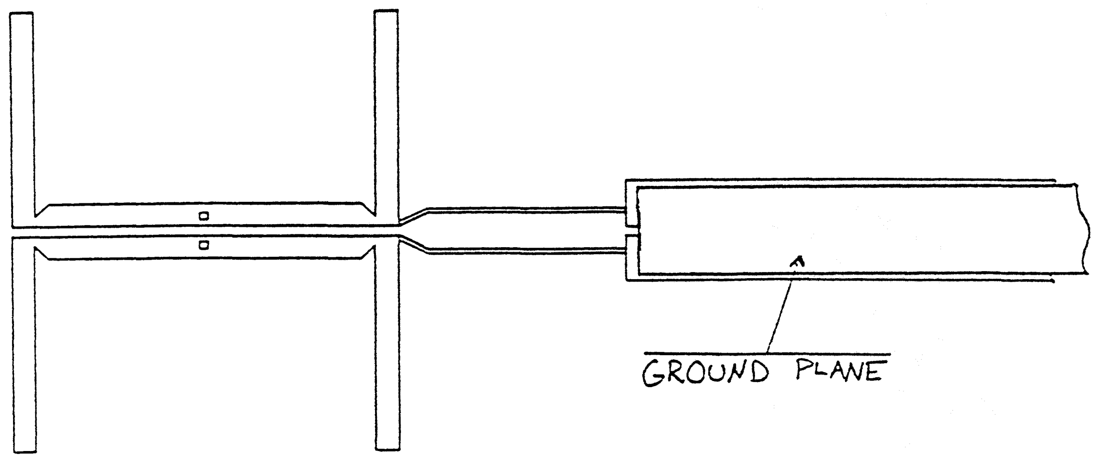

Fig. 10: The antenna with two (half-wave) dipoles. A conducting backshort plane at a quarter wave behind this plane creates an image of two more elements. Detectors are mounted midway between the two dipoles, DC and IF leads are on the right.

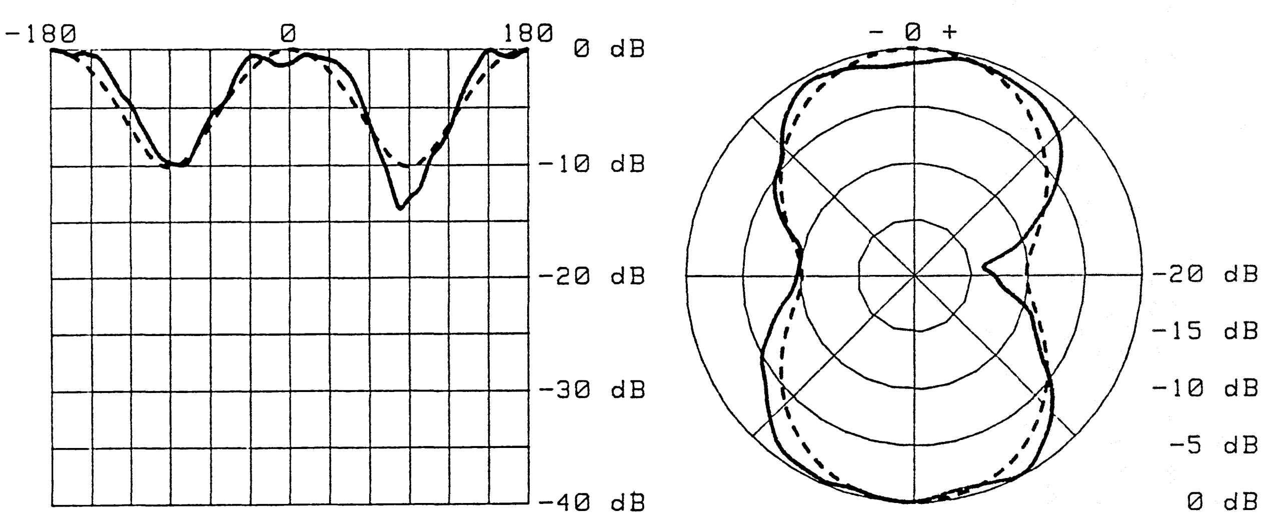

Fig. 11: Comparison between the calculated (dashed) and the measured (continuous) H-plane radiation patterns of the antenna without lens.

In the measurements of the model on the Kapton film the DC bias line turned out to make the H-plane antenna pattern slightly assymetrical. The characteristic impedance of the line was therefore lowered by a piece of copper tape which was placed on the back side of the Kapton film. (This arrangement Fig.10 was also used in the measurements with the lens). The antenna pattern was measured at several frequencies between 8 and 12 GHz and found to be satisfactory at 9.5 to 12 GHz. As an example the H-plane pattern at 10 GHz is shown in Fig.11 together with the theoretical diffraction pattern.

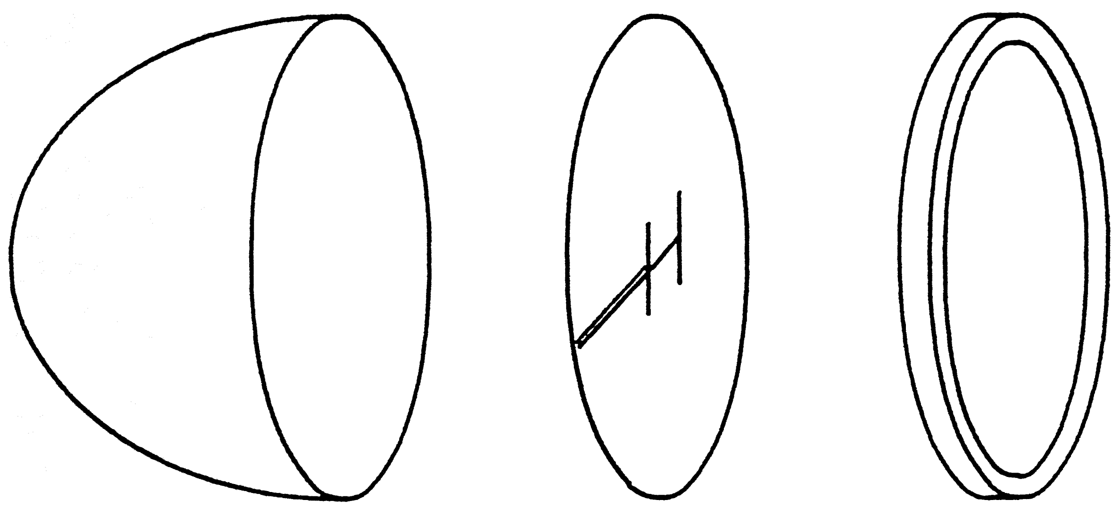

Fig. 12: An exploded view of the HDP lens, the kapton film with dipoles and a quarter wavelength slab with ground plane.

The purpose of using a lens and a reflector was to focus the main beam and remove the back lobe of the dipole feed. The lambda quarter slab was made from the same material as the lens to avoid problems with substrate modes. The physical size of the dipole array was scaled down to correct for the dielectric constant of the plastic. Since many antenna types have large amounts of cross-polarization in the 45° diagonal (D-) planes, we also did measurements in that plane.

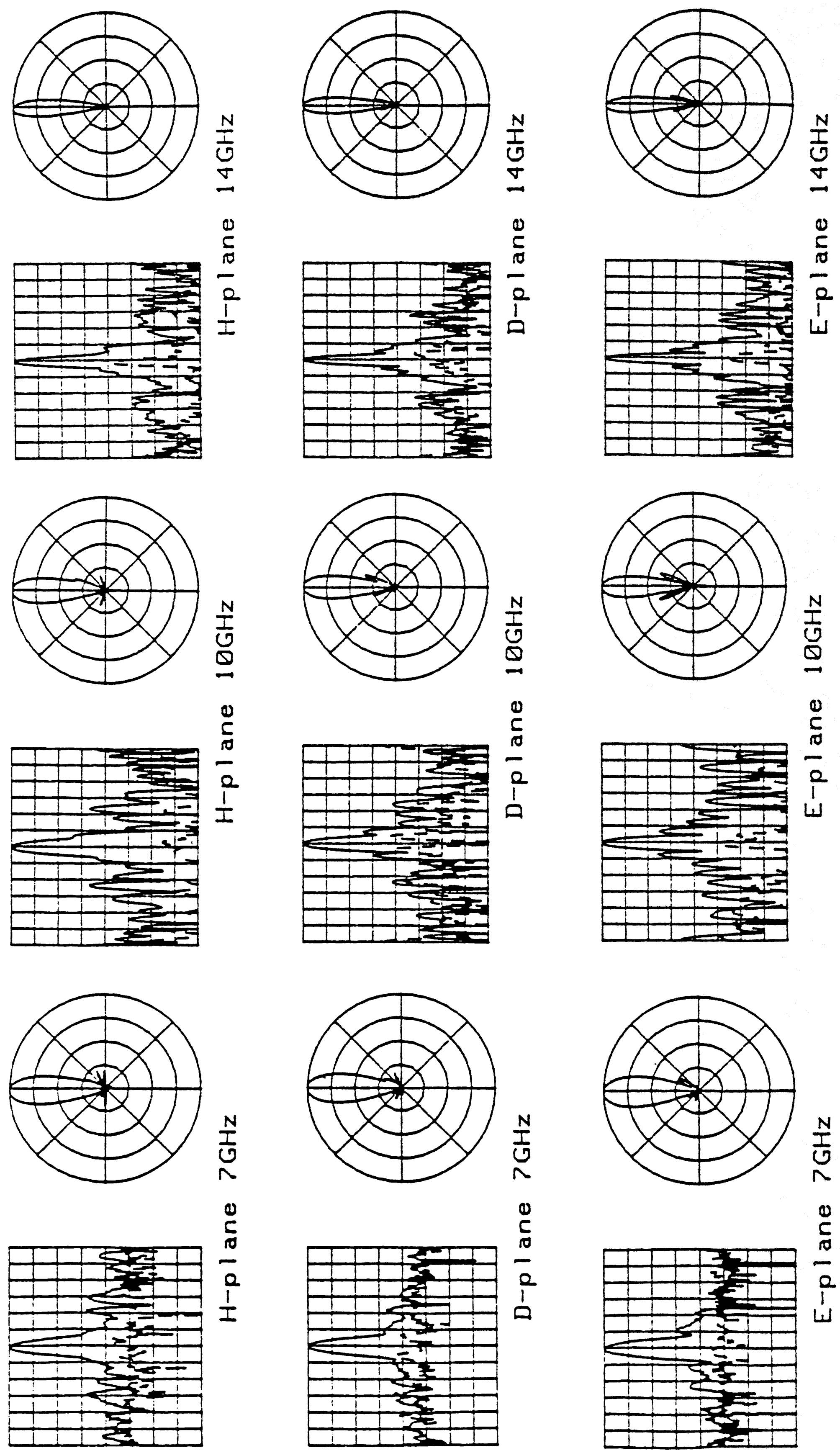

Fig. 13: Measured co- and cross-polarized patterns in H-, D- and E-planes for dipole arrangement with lens and fixed backshort at frequencies of 7, 10 and 14 GHz. Data are over 360° with 5dB/div.

Measurements were made in the 3 planes at 8 different frequencies from 7 to 14 GHz, but to conserve space only the patterns at 7, 10 and 14 GHz are shown in Fig. 13. The patterns are of good quality over the whole octave with sidelobe levels in most cases below -15 dB and cross-polarization below -20 dB. The E/H/D-plane beam widths are well balanced, but since they are diffraction limited, they decrease as the frequency increases.

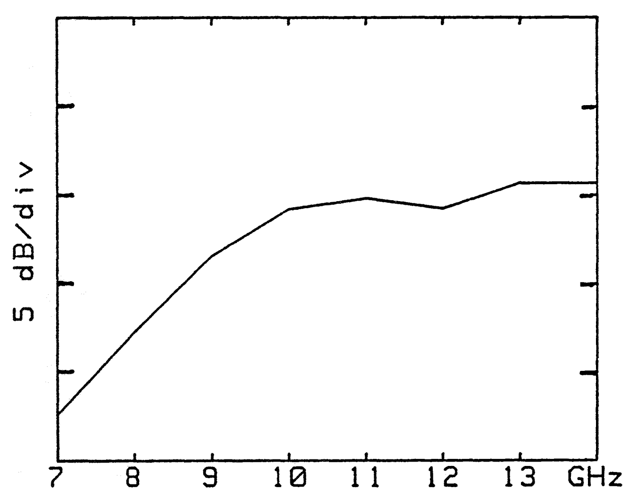

Fig. 14: Detected power as a function of frequency for the dipole antenna with lens and backshort. Systematic errors resulting from frequency dependence of the source power and detector sensitivity have not been corrected for.

The radiation pattern of the antenna is good over the whole octave of bandwidth available in the antenna range. However, the detected signal level is affected by the frequency, Fig. 14. The coupling drops off below 10 GHz, probably because the dipoles are not resonating properly there. Towards the higher end of the band it looks better. Here, the coupling is probably helped a bit by the narrowing beamwidths of both the dipole/lens antenna and the transmitting horn in the antenna range.

It is our feeling that the dipole array + lens antenna may be a good alternative for sub-mm wave low noise mixer applications. Therefore, we are currently planning two experimental recivers at 100 and 350 GHz, using SIS junctions as mixer elements.

5. Conclusions.

From our study of planar logperiodic antennas we come to the following conclusions with respect to bandwidth (see chapter 2): The lower bandwidth limit was defined by two effects: 1) the occurrence of low frequency "dipole" resonance modes, which produce cross-polarized radiation, and 2) the lowest proper "log-per" resonance occurs when the second tooth in the structure is active. The upper bandwidth limit occurs when the dielectric substrate of the antenna is a quarter wavelength (in the substrate material) thick, where the radiation pattern starts breaking up into several lobes.

Within their usable bandwidth log-per antennas radiate very wide beams (see chapter 2). A lens directly in front of a logper antenna improves the beamwith to acceptable values. However, the cross-polarization properties are not good. The generation of a circularly polarized component and a frequency dependent orientation further complicate the picture. A free standing lens with a logper antenna and reflecting backshort in its focus shows roughly the same polarization behaviour (see chapter 3).

We have investigated an antenna consisting of an arrangement of four half-wave dipoles (see chapter 4). We have demonstrated the following properties: It has strictly linear polarization, more than 30 % bandwidth, easy connection to IF leads and excellent beam patterns. For applications where the extreme bandwidth of log-periodic structures is not needed, these properties make the dipole arrangement much to be preferred.

The dipole arrangement can be positioned at the flat back surface of a thick lens. Together with a fixed backshort it yields a simple, rugged and easily replaceable construction. For imaging arrays the individual lenses per element mimimize crosstalk that could otherwise occur via reflections in a common lens or a common substrate. The absence of moving backshorts results in a particularly simple construction.

Acknowledgements.

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References.

1. R.H. DuHamel and D.E. Isbell, "Broadband Logarithmically Periodic Antenna Structures", 1957 IRE National Convention Record, pp. 119-128, 1957.

2. P.T. Parrish, T.C.L.G. Sollner, R.H.Mathews, H.R.Fetterman, C.D. Parker, P.E. Tannenwald and A.G. Cardiasmenos, "Printed Dipole-Schottky Diode Millimeter Wave Antenna Array", SPIE Millimeter Wave Technology, 337, 49-52, 1982.

3. W. Chew and H.R. Fetterman, "Printed Circuit Antennas with Integrated FET Detectors for Mm-Wave Quasi-Optics", IEEE Transact. on Microw. Theory and Techn., 37, 593-597, 1989.

4. J.A. Taylor, T.C.L.G. Sollner, C.D. Parker and J.A. Calviello, "Planar Dipole-Fed Mixer Arrays for Imagig at Millimeter and Submillimeter Wavelengths", 1985 Intl. Conf. IR and Mm Waves, p.187-188, W1.7, 1985.

5. G.M. Rebeiz, W.G. Regehr, D.B. Rutledge, R.L. Savage and N.C. Luhman, " Submillimeter-wave Antennas on thin Membranes", Int.J. IR and MM Waves, 8, 1249-1255, 1987.

6. H. van de Stadt, "Test of Planar Imaging Array", SRON internal report, Groningen, october 1989.

7. A. Skalare, "Scale Model Measurements of Log-Periodic Antenna Structures", SRON internal report, Groningen, january 1990.

8. A. Skalare, "A Dipole Antenna Feed for a Dielectric Lens Surface", SRON internal report, Groningen, january 1990.