A SUBMILLIMETER-WAVE HETERODYNE ARRAY RECEIVER USING A DIELECTRIC-FILLED PARABOLA: CONCEPT AND DESIGN

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Abstract

A novel quasi-optical receiver architecture with planar integrated antenna/active device capability has been described [1,2] which combines the features of a dielectric substrate lens and a parabolic reflector in a single structure termed a *dielectric-filled parabola*. This design can be used to form both single element and small array receivers operating in heterodyne or direct detection modes or can be configured as a transmitter for planar oscillator or frequency multiplier circuits.

In this presentation the heterodyne applications of the dielectric-filled parabola will be examined with an emphasis on small array systems. Measurements and calculations based on a microwave model of a single element receiver and a 10 element array will be given as well as some early details on a soon to be operating millimeter-wave system.

I. Introduction

At microwave and millimeter-wave frequencies the most sensitive heterodyne receivers generally make use of rectangular waveguide and some form of scalar feed horn for coupling energy into or out of a discrete nonlinear element usually mounted in close proximity to the guide. Over the years such systems have been highly optimized, originally for use with GaAs Schottky barrier diodes and later for integration with superconducting-insulator-superconducting tunnel junctions. The same basic waveguide structure has been used to produce heterodyne downconverters and frequency multipliers up to wavelengths as short as 0.5mm (600 GHz). Unfortunately, these waveguide systems are very difficult to fabricate at submillimeter wavelengths due to their small physical size and the necessity of coupling efficiently into a separately mounted mixer, multiplier or oscillator element. For this reason alternative mounting structures have been sought for some years.

One means of simplifying the fabrication of submillimeter wavelength receiver systems is to integrate the mixer or multiplier element with an appropriate photolithographically produced planar antenna thus eliminating both the feed horn and waveguide. Such systems are fairly common at microwave frequencies and are beginning to be reported upon more frequently at millimeter [3-13] and even submillimeter wavelengths [14-16]. However, there are some drawbacks to using planar integrated antenna structures at high frequencies. First, if the antenna is integrated on a substrate with a dielectric constant greater than 1, unless it is very thin (<0.1 wavelength), much of the input (or output) power can end up being lost in substrate modes [11] rather than being coupled to the nonlinear element. At 1 THz a typical planar antenna integrated on a quartz substrate would have to have a dielectric thickness of less than 15 microns. Second, most planar antennas have small effective apertures and hence very low directivity and therefore require very fast (low f#) optics for beam shaping and matching to the higher gain systems with which they are frequently associated. Finally, unlike waveguide systems, planar antennas have no dynamic tuning capability making intrinsic matching to a transmit or receive element essential.

The planar integrated receiver system which is referred to in this presentation has been described in a previous proceedings [1,2]. It is a variation on a concept originally proposed by Rutledge and Muha [7] to take advantage of the fact that a planar antenna on a dielectric half-space radiates preferentially into the dielectric. In their design a planar bow-tie antenna containing a detector at its apex was integrated on a dielectric substrate which was in turn attached to the flat surface of a hemispherical lens. Rays leaving this 'hyperhemisphere' are oriented near normal to the surface and hence trapped waves are eliminated. Our design combines the features of this dielectric-lens antenna system with the high gain of a parabolic reflector in a single structure which we have been calling a *dielectric-filled parabola* (DFP).

In the first part of the presentation the DFP characteristics will be summarized. This is followed (Section III) by microwave scale model measurements showing the beam patterns and input impedances of several common planar antenna structures when integrated on a DFP. Section IV contains a comparison of the measured and computed field distribution of a thin half-wave resonant dipole on a DFP at 10 GHz. In Section V the beam patterns of a small 2X5 element array on a DFP are presented and finally, in Section VI, we conclude with a description of a submillimeter-wave system now in the final stages of fabrication.

II. Design Concept

Fig. 1 shows a conceptual picture of a heterodyne array receiver system employing a dielectric-filled parabola. The DFP is formed from a plano-convex dielectric lens whose convex surface has been shaped into a parabola and metallized. The planar antenna and receiver elements are integrated onto the center of the flat surface of the dielectric lens; the focal point of the parabola (in practice it is more convenient to integrate the antenna elements on a separate planar dielectric substrate and glue it to the main assembly). The f/D ratio of the system is 0.25 but as we shall see the planar antennas do not fully illuminate the parabola and hence the effective f# is somewhat higher.

Some of the properties of the dielectric-filled parabola are listed below (for additional details see [1]):

1). The parabola and dielectric lens are combined into a single structure which produces a collimated output beam from a very broad beamed radiator with no additional optical components.

2). The parabola has an f/D ratio of 0.25 and thus can accommodate planar antennas with beamwidths approaching 180 degrees.

3). The parabolic face is in the far field of the planar antenna elements.

4). All paraxial rays entering the parabola travel an equal distance in the dielectric to the focal point.

5). There is an extensive flat dielectric surface which allows for the placement of integrated bias and or input/output transmission line structures for communicating with the receiving or transmitting element.

6). The planar antenna and receiver or transmitter element can be fabricated on a separate and relatively thick dielectric plate then glued in place on the dielectric-filled parabola facilitating fabrication, testing and optimization.

7). Signal power is incident on the flat side of the dielectric and so it is very easy to incorporate a quarter-wave matching layer to reduce input reflection loss.

8). For heterodyne receiver operation the local oscillator may be injected via a through hole at the center of the parabola's mirrored surface without additional signal beam blockage or complicated diplexing elements.

9). There are no struts or other free standing structures in front of the beam, only the integrated planar antenna elements themselves, making the whole unit self contained, compact and inherently robust.

10). For cryogenic operation the dielectric and hence the antenna elements can be very readily heat sunk to the cold plate through the metallic face at the rear of the parabola.

11). Off-axis antenna elements produce beams inclined to the optical boresight as in multi-beam phased array systems. For imaging applications the DFP should be placed behind the focal plane with an additional collimating lens out front to re-image the sky onto the antennas.

12). Refraction at the air-dielectric interface increases the extent of off-axis beam tilt for a given lateral displacement of the antenna in the focal plane.

13). The number of array elements which can be accommodated in the focal plane of the parabola is a function of the aperture illumination and the effective f/D ratio and is limited by the acceptable levels of astigmatism and coma. These aberrations can be reduced by forming a shallower parabola on a thicker substrate (increasing the f/D ratio and using higher gain planar antenna elements) but at the expense of increased dielectric loss.

III. Microwave Model Measurements

In order to measure easily the performance of the DFP with a wide variety of antenna structures a microwave scale model of the feed system was fabricated. The parabola itself was machined on a numerically controlled lathe from two one-inch thick sheets of Emerson and Cuming Stycast HiK ϵ_r=4 material to simulate fuzed quartz. The pieces were glued together with Eccobond 45 mixed to a semi-rigid formulation. The diameter of the parabola was 8.4" and a separate 0.1" thick, 8.4" diameter plate for holding the antenna elements was added to the 2" thick lens to bring the f/D to 0.25. The parabolic surface was electroplated with a thin layer of silver and then electroformed copper was grown to a thickness of about 0.002".

The more complex shaped planar antennas (spirals and log-periodics) were fabricated from 0.005" thick sheets of copper using photolithography directly through rubylith masks and subsequent chemical etching. The rubylith masks were generated on an HP7550A digital plotter using a single point diamond scribe (available from EESOF) held in a custom made aluminum cartridge. The final antennas were either glued or taped in place on the dielectric-filled parabola. Measurements were made on thin and thick half-wave resonant dipoles, self-complementary and broad-toothed planar log-periodic antennas, bow-tie antennas, and log-spiral antennas.

Antenna power patterns were measured in an anechoic chamber using an automated position system constructed for this purpose and a specially modified HP415E SWR meter [17]. In all cases (except for the polarization measurements on the log-spiral) the transmit antennas were standard gain rectangular horns. The overall dynamic range was 40 dB over the frequencies considered.

Antenna input impedances were measured on an HP8410A network analyzer through feed cables (always a .047" diameter semi-rigid coaxial line) on the air side of the dielectric surface. The test signal reference plane was established at the end of the coaxial feed line by shorting the cable with silver paint (Silver Print type 22-201) which produced as good a short as pure indium even at 10 GHz. No error correction algorithms were employed and as the impedance measurements were affected somewhat by the feed cables, they should be taken as approximations only.

A summary of the data collected can be found in Figs. 2 and 3. For more details the reader is referred to [2]. In general, depending upon the application, any of the measured antennas might be used at high frequencies. The dipoles have the lowest input impedance (generally preferred for matching to most nonlinear elements used in low noise receivers), the log-spiral has the broadest bandwidth and the most circularly symmetric patterns. If cross polarization is a consideration, the log-periodic antennas are likely to give less satisfactory performance. The bow-tie has the most compact impedance locus but its H-plane patterns vary widely with frequency. For arraying, antenna physical size must be considered as well as desirable configurations for biasing and, if heterodyning, for intermediate frequency removal.

All of the antennas slightly underilluminate the dielectric-filled parabola. At submillimeter wavelengths this is not a serious problem as the parabola is physically small. At lower frequencies one could increase the focal length of the dielectric-filled parabola (improve the illumination efficiency) by using a thicker substrate to hold the antenna and forming a much shallower lens on the opposite surface of the dielectric. This will of course result in a longer dielectric path length and hence more transmission loss. Alternate optical systems with lower off-axis aberration are currently under investigation.

The input impedances of the antennas on the dielectric-filled parabola differ from those of the same antennas in free space and in general the real part decreases. The resonant frequency of the dipole antennas did in fact shift by approximately the square root of the mean dielectric constant of air and quartz as predicted in [18].

IV. Measured and Computed Field Distribution

To see how well we could predict the performance of a given antenna on a DFP we compared the measured far-field patterns of the thin dipole antenna (Fig.2A) with the patterns derived from the computed field distribution of a thin dipole on an infinite dielectric half-space [19-21]. The E and H plane field patterns published in [19] were applied to the surface of our parabolic lens (assuming no reflection at the edge) and the results are shown in Fig. 4 as dashed lines. We then used the equations in [22] to calculate the far field patterns. Unfortunately, the calculated patterns did not match our measurements as well as we had hoped. To determine why, we probed the field across the face of our 8.4" diameter parabolic stycast lens (with the metallization removed) at 10 GHz and obtained the field distributions shown in Fig. 4 as solid lines (the high frequency ripple is the result of reflections off the lens surface). The differences in the measured and calculated fields is quite marked and shows that the theoretical model we used is over simplified. The projected far field patterns from the probe measurements are shown in Fig. 5. Even here the agreement is only fair and further work in this area, both theoretical and experimental, is indicated.

V. Array Patterns

Of the antennas studied, the half-wave resonant dipole has an input impedance which most closely matches that of an SIS tunnel junction or Schottky diode element. It also satisfies the spacing requirements (in one plane) for contiguous beams on the sky and can be readily mated with surface oriented TEM transmission line (twin lead) for IF removal. A 2X5 element array of 10 GHz dipoles (length to width ratio of 10 to 1) was fabricated on our 0.1" thick, 8.4" diameter stycast plate using photolithography directly on the stycast which was first metallized with 50,000Å of evaporated copper. A beam lead detector diode (TRW A2S255) was silver epoxied to the terminals of each antenna and RF blocking capacitors (Dielectric Labs 1pF high frequency gap-caps) were placed at appropriate points across the IF lines to prevent RF leakage down the lines. Power was measured with an HP415E SWR meter [17] by modulating the transmitter at 1kHz.

Sample patterns for the extreme elements of the array are given in Fig. 6.

The rapid rise of the coma lobe for the extreme off-axis elements is expected but its absolute level is somewhat higher than predicted by the Ruze analysis [22]. Cross polarization levels (not shown) were also higher than expected (up to 10 dB below the peak for the corner elements). Mutual coupling has not as yet been measured. Some of these problems may be due to the fact that the array model is operating at one-half the lower frequency limit of intended use where the parabola is only 7 free space wavelengths in diameter. At this frequency diffraction effects are sure to be significant. We are currently fabricating a 20 GHz array with the same parabola to reduce the influence of diffraction.

VI. Fabrication

At the time of this symposium our first submillimeter-wave DFP units are being fabricated and testing should begin in a couple of months. Our initial design has an RF center frequency of 230 GHz and an IF of 1.4 GHz but the mount has been fabricated so that operation at a higher frequency simply requires changing out a separate antenna/diode plate. The same mixer mount is used for single antennas and for arrays of up to 10 elements. Measurements are planned using both SIS tunnel junctions and planar GaAs Schottky barrier diodes as the downconverting elements.

A machinist's drawing of the ten element heterodyne array system is shown in Fig. 7. The receiver subsystem is fabricated in five parts; 1) the dielectric-filled parabola, 2) a separate substrate (of the same dielectric material) containing the planar antennas, receiver elements and biasing and intermediate frequency removal lines and RF filters, 3) a separate quarter-wavelength thick matching layer, 4) a metallic holder for the parabola containing the local oscillator feed (a pyramidal horn), a balun transformer and matching section and a standard 50 ohm OSSM connector for output coupling and 5) a cover plate which clamps the antenna substrate and matching layer to the flat side of the parabolic lens and encloses the IF matching network.

The dielectric parabola is ground onto one side of a flat, .788" (2cm) diameter, 0.197" (0.5cm) thick disk of fuzed quartz (Infrasil T17) using lathe shaped meehanite cast iron laps. The laps are machined on a numerically controlled lathe. Three separate laps are used during the lens grinding process which is accomplished by impregnating the lap with aluminum oxide (30, 10 and 5 micron grits were used) and pressing it up against the fuzed quartz disk which is slowly turned about its axis on a small lathe. The final parabola is thinned to .187" to allow room for the .010" thick quartz substrate containing the planar antennas and downconverting elements. Infrasil T17 was used as the substrate material because it has an especially low water content and thus a fairly low loss tangent in the submillimeter-wave band. Any low loss dielectric which can be machined or ground could be used bearing in mind that the incident radiation will undergo a substantial reflection upon hitting the surface of the dielectric unless a suitable matching layer is added.

Once ground and polished the parabolic substrate lens is vacuum coated with a 50Å thick chromium adhesion layer followed by several skin depths of gold. A small rectangle (sized to match the LO feed horn aperture) was masked off at the center of the parabola before plating. The parabola described here has an intended lowest operating frequency of 200 GHz. The choice of diameter is a compromise between aperture size and dielectric loss.

The substrate containing the antennas, downconverting elements and IF lines is composed of .010" thick .788" diameter polished quartz disks of Infrasil T17. For our initial tests and to facilitate optimization the mixing elements and planar antenna structures were fabricated separately. The antennas and IF lines are formed in a chrome-gold lift-off process. They consist of half-wave resonant dipoles 0.002" wide by 0.016" long with a terminal gap of 0.001" at the center. Coplanar lines (twin lead) are used for IF removal. The lines are each 0.0005" wide and are spaced 0.001" apart and have an impedance of about 200 ohms to match the IF output impedance of the downconverting elements. Separate RF blocking capacitors composed of a 3000Å SiO insulating layer and a top layer of aluminum were formed across the IF lines $\lambda/4$ and $3\lambda/4$ back from the dipoles. The ends of the coplanar line flare out to bonding pads at the edge of the quartz wafer where they are wire bonded to planar balun transformers which surround the parabola. The transformers [23] convert the balanced 200Ω twin lead directly to 50Ω coax through a quarter wavelength long coplanar waveguide section. They are formed on Epsilam 10 (ϵ_r=10) and are designed to work from 1-2 GHz.

The first downconverting elements to be tested will be JPL fabricated NbN/MgO/NbN SIS edge junctions [24] which have been formed on .010" thick quartz wafers and diced into chips of .002"x.005"x.001" (width x length x thickness). The junctions have typically an area of $<.2\mu m^2$, a current density of $\approx 3\text{x}10^5 A/cm^2$, a resistance of 50Ω and an ωRC product <1 at 230 GHz. The chips are placed device side down across the terminals of the planar antennas and soldered in place. Soldering is facilitated by evaporating a 3000-5000Å thick layer of indium over the SIS tunnel junction leads during fabrication. Mixing measurements with separately mounted planar GaAs Schottky diodes of similar dimensions are also planned.

The holder for the parabola is fabricated from brass and contains a parabolic depression for accurately mating to the quartz lens. The center of the housing contains a pyramidal feed horn (for LO injection) which is wire electro-discharge machined (EDM) into the block as the first step of the machining process. The feed horn tapers to the face of a standard WR-3 waveguide flange on the rear of the holder. Higher frequency waveguide LO injection is accomplished by mating a transition which continues the taper to a desired final waveguide size. The holder also contains the stripline channels for the balun transformer/impedance matching sections.

A brass top plate holds the quarter-wave matching layer and serves to clamp the whole assembly together. It also encloses the balun transformers and coax connectors. The matching layer for 230 GHz is a 0.010" thick teflon disk with a small hole at the center which surrounds the antennas.

VIII. *Summary*

A novel planar integrated antenna feed system has been described. Although intended for submillimeter wavelength heterodyne applications it can be used over a wide range of frequencies and in a variety of modes; as a receiver or transmitter, in a heterodyne or direct detection mode, with a single element or with a modest focal plane array. It combines the high directivity of a parabolic reflector with the convenience of a substrate lens on which both planar antenna elements and receiving or transmitting devices can be integrated. It allows some control over the output beam and can match very broad beamed radiators to high f-number systems. The design is inherently robust, easy to fabricate, can be scaled to very high frequencies and is cryogenically coolable.

The beam patterns and antenna input impedances have been measured for a number of different planar antenna elements on this dielectric-filled parabola from 4 to 12 GHz using a frequency scaled model. The results of these measurements show clearly that the system performs well. The patterns of a small array of 10 dipole elements were also presented and show somewhat higher than expected off axis aberrations. Our first attempts at analysis have been only partially successful and more work is indicated.

A millimeter/submillimeter wave system has been fabricated and detailed assembly procedures are given. RF measurements using both NbN SIS tunnel junctions and GaAs Schottky barrier diodes will be performed over the next several months.

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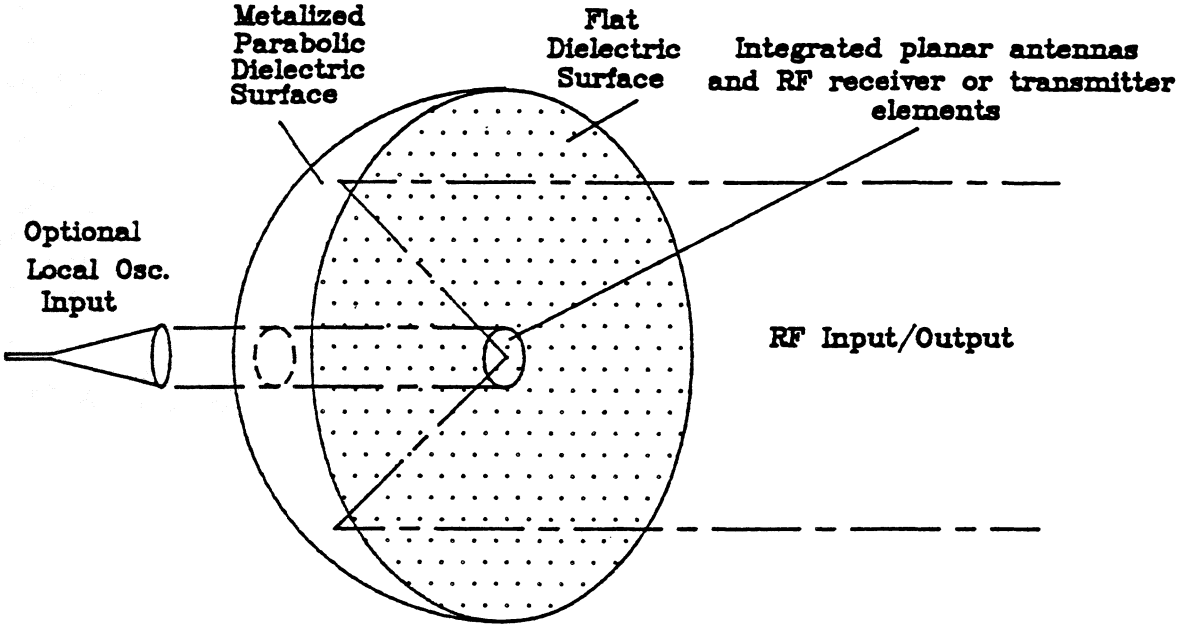
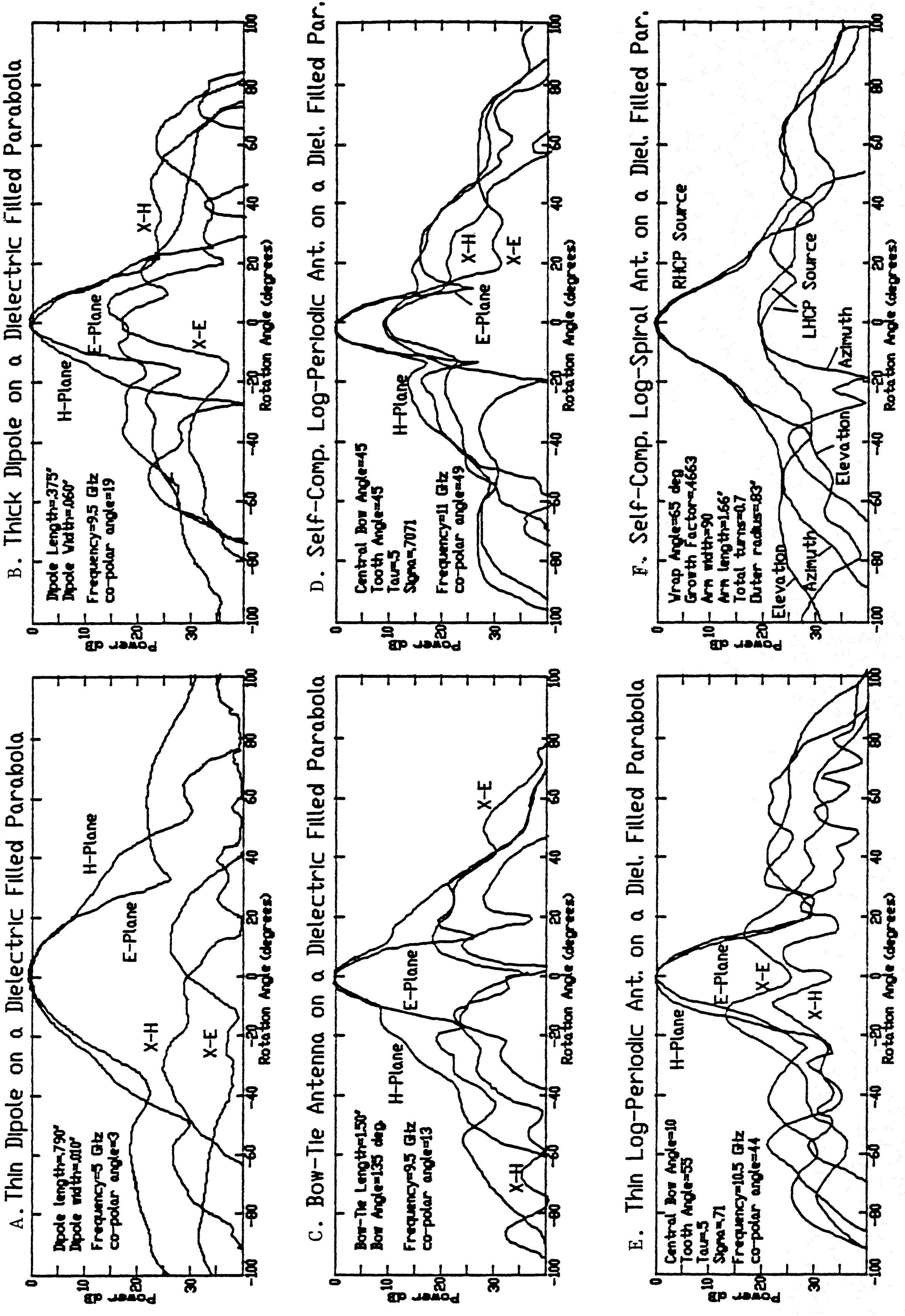


Fig. 1: Sketch of the dielectric-filled parabola used in a heterodyne receiver configuration. The down converting elements and associated antennas lie on the focal plane of the parabola (f/D=.25). Radiation from the antenna elements predominates in the dielectric (as opposed to the air) approximately in the ratio $\epsilon_r^{3/2}$ [11]. Bias and intermediate frequency lines are integrated on the flat surface of the dielectric. A quarter-wavelength thick dielectric matching layer can be placed over the existing surface to minimize reflective losses.



A. Thin Dipole on a Dielectric Filled Parabola

B. Thick Dipole on a Dielectric Filled Parabola

C. Bow-Tie Antenna on a Dielectric Filled Parabola

D. Self-Comp. Log-Periodic Ant. on a Diel. Filled Par.

E. Thin Log-Periodic Ant. on a Diel. Filled Parabola

F. Self-Comp. Log-Spiral Ant. on a Diel. Filled Par.

Fig. 2: Principle and cross polar plane antenna power patterns of six planar antennas on a dielectric-filled parabola. In each case the measurement was performed by sampling the field with a coaxial line brought in on the air side of the lens (ϵ_r=4). No matching layer was present. The beam width in 2a. is larger than the other plots because the measurement frequency was halved.

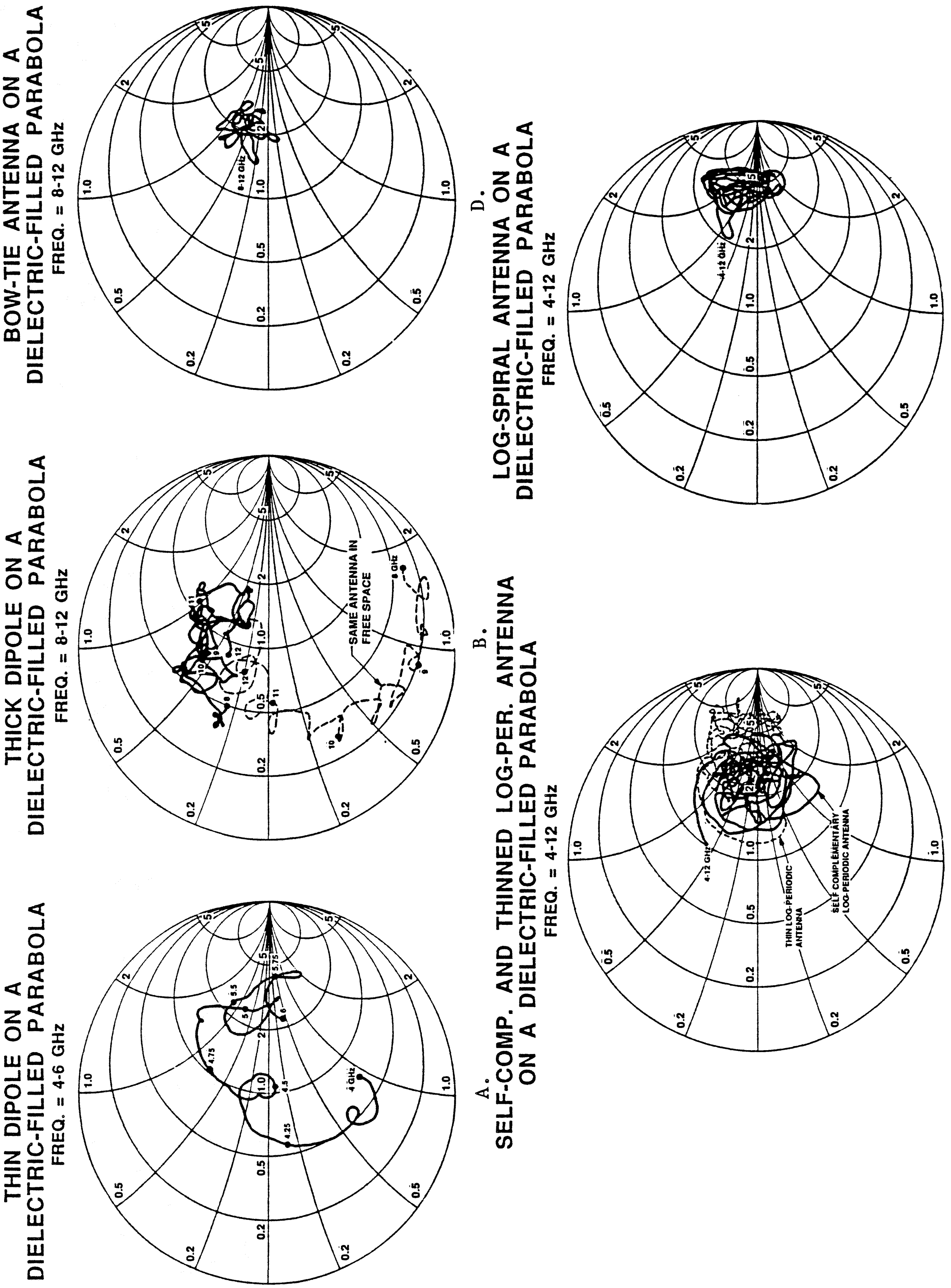


Fig. 3: Smith chart plots showing the input impedances for the six antennas shown in Fig. 2 on a dielectric filled parabola. An 8410A network analyzer was used for the measurements with the reference plane formed by shorting the end of the coaxial sampling cable. The dipoles contained a bazooka balun transformer and a short length of balanced line between the reference plane of the test cable and the antenna terminals. No correction algorithms were performed on the data.

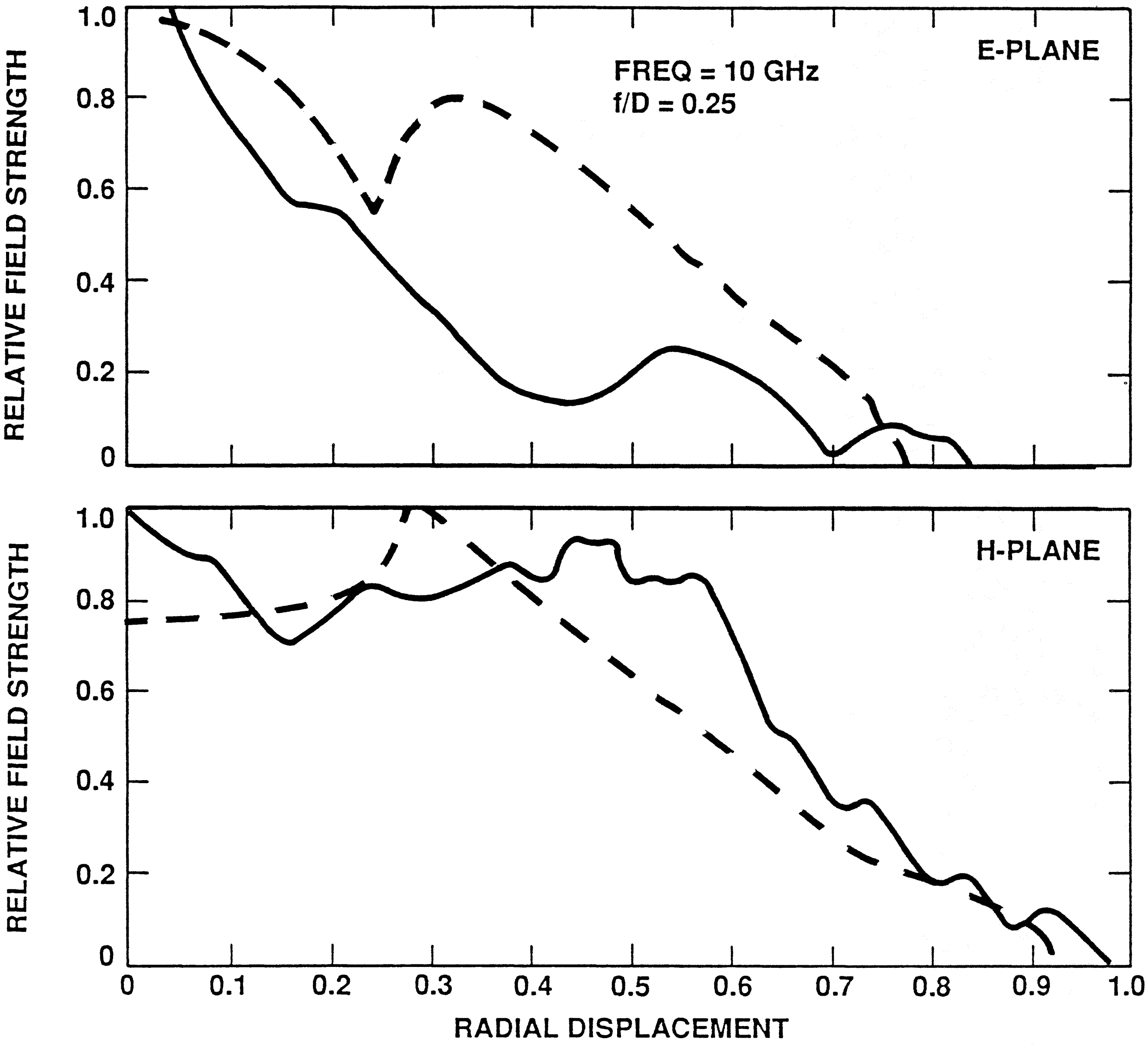


Fig. 4: A comparison of the calculated (dashed) and measured (solid) field strength along the surface of a dielectric-filled parabola with a thin dipole antenna at the focal point at 10 GHz. The calculations are based on data published in [19]. The measurements were made with a dipole probe placed in intimate contact with the lens surface. The excessive ripple is due to reflections off the air-dielectric interface.

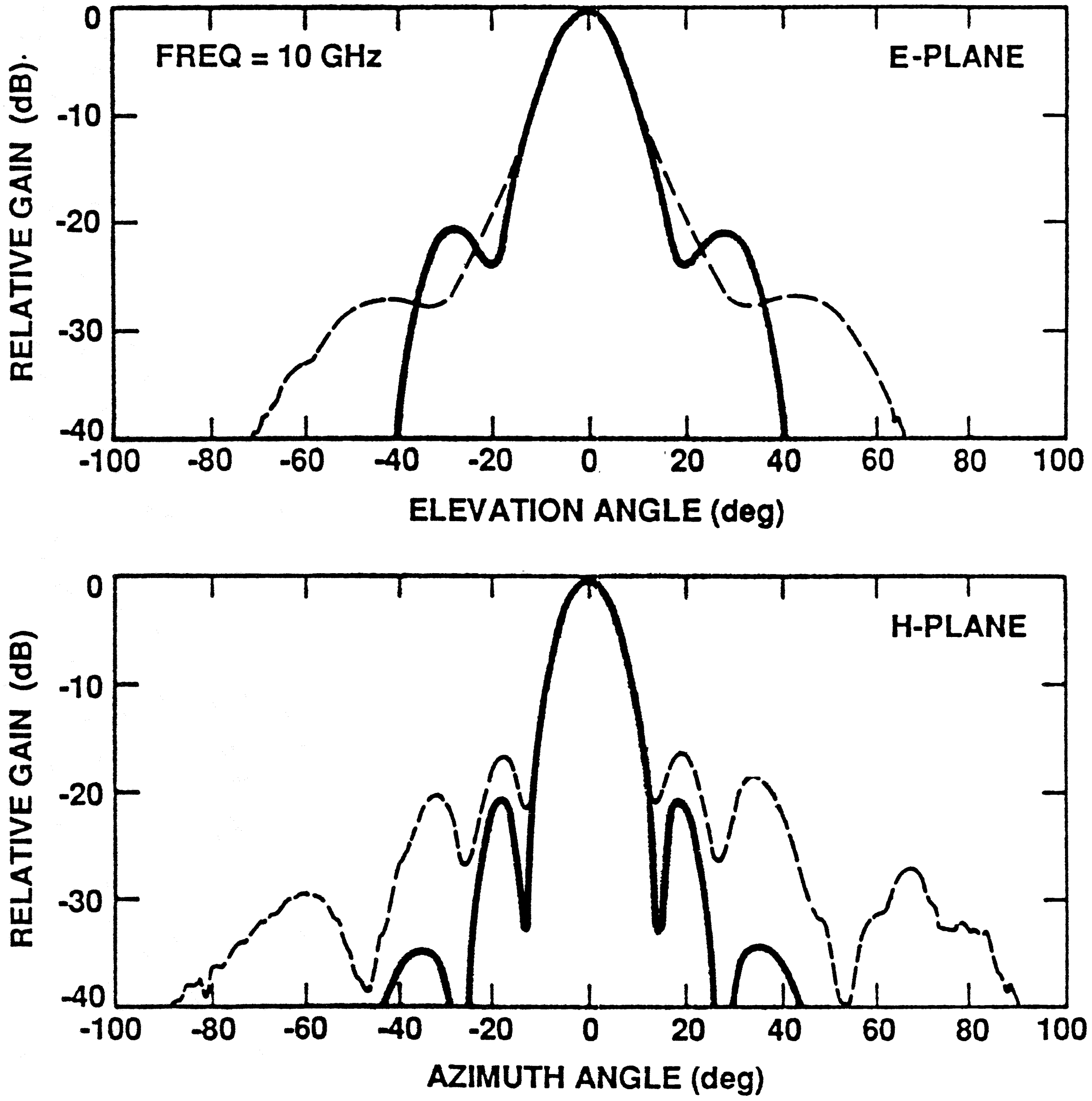


Fig. 5: The far field patterns of a thin dipole on a dielectric-filled parabola calculated from the measured field distributions of Fig. 4 (solid) and those actually measured at 10 GHz (dashed).

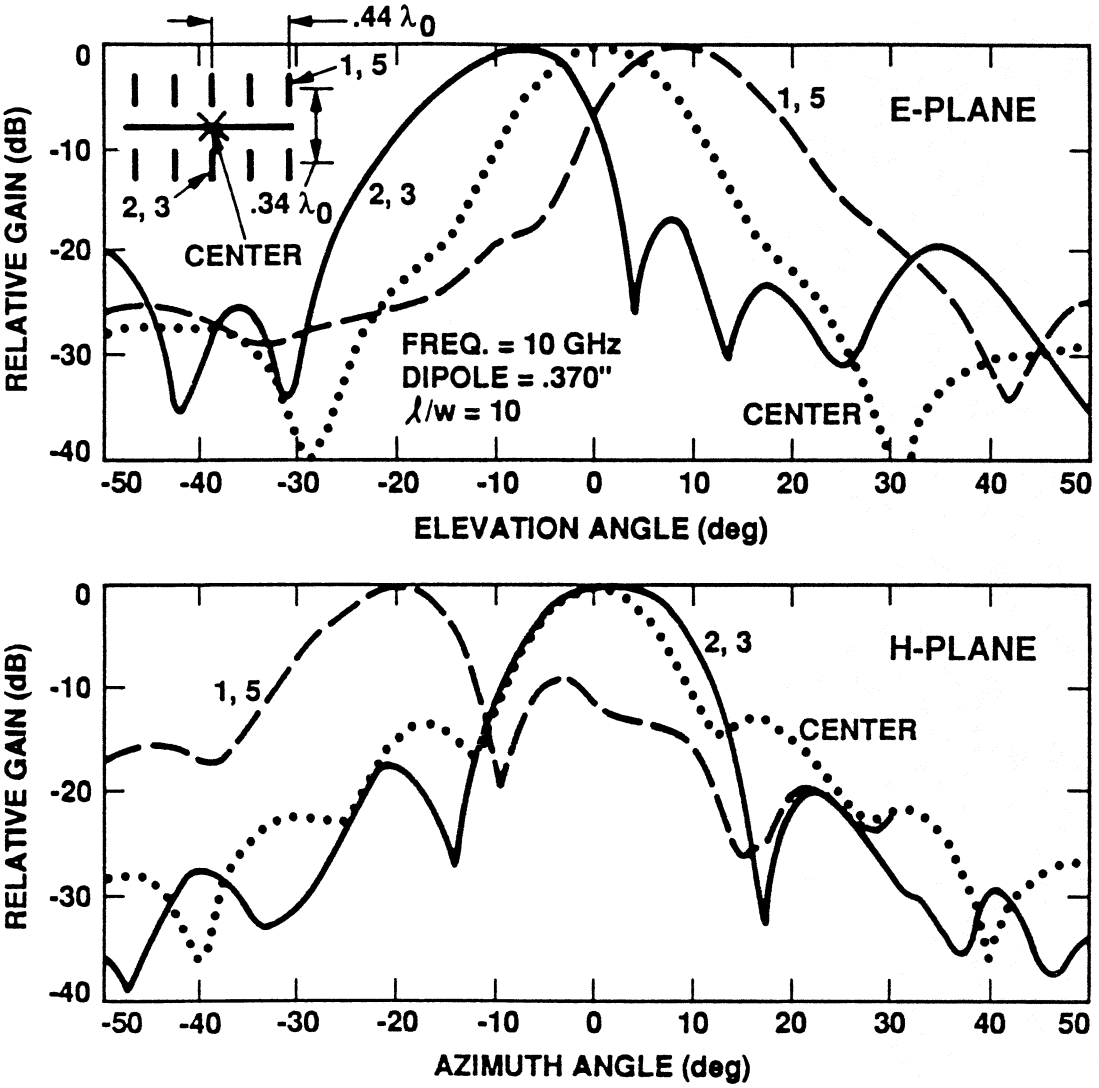


Fig. 6: The measured power patterns of several of the offset antennas of a 2x5 10 element thick dipole array (length to width = 10) on a dielectric-filled parabola at 10 GHz. At this frequency the parabola is only 7 wavelengths in diameter and diffraction effects may be significant.

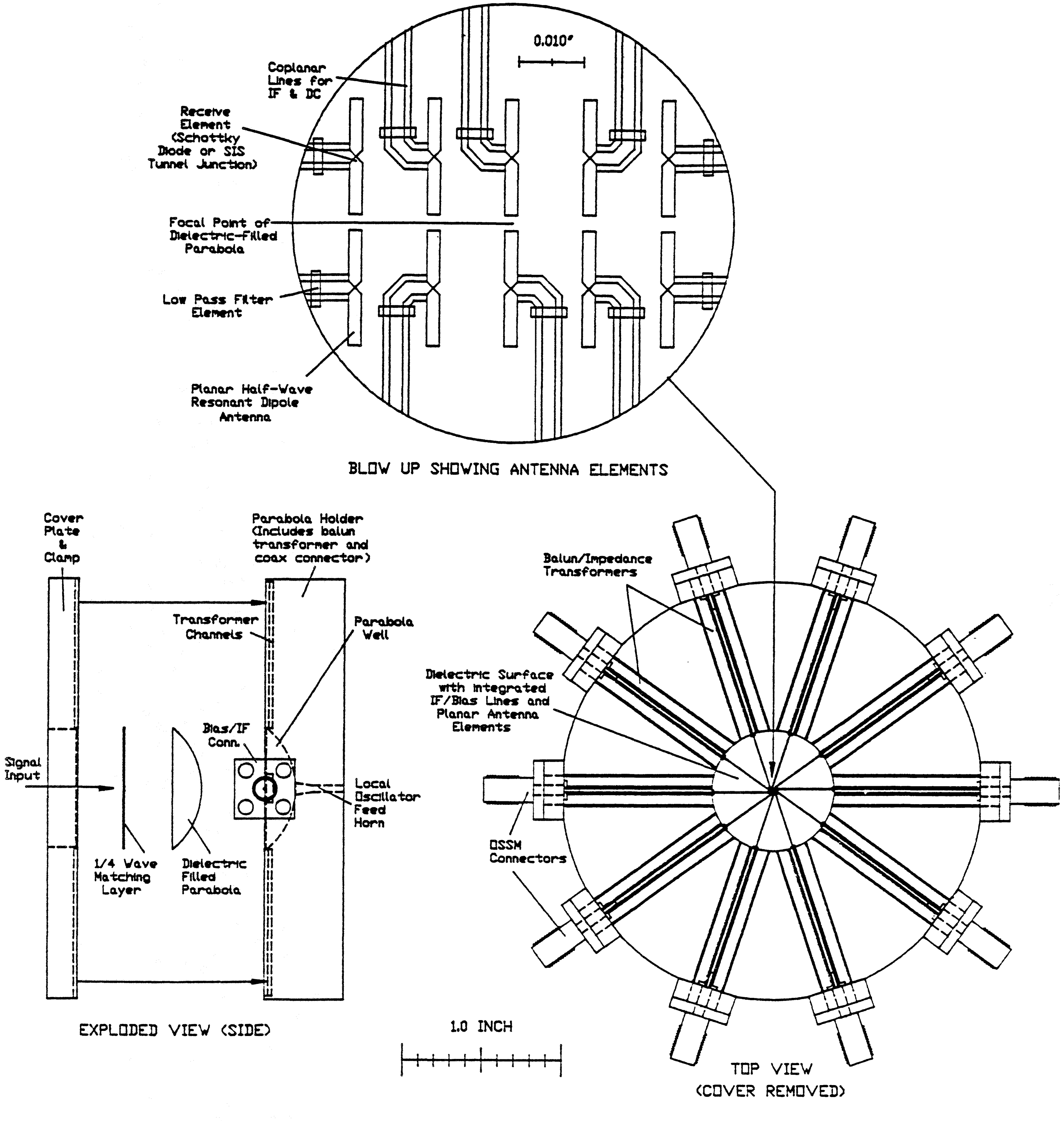


Fig. 7: Machinist's views of a complete millimeter/submillimeter wavelength heterodyne array receiver using a dielectric-filled parabola. Each array element has an SIS tunnel junction at its apex. The SIS junctions and antennas have initially been formed separately (for 230 GHz operation) but will eventually be fully integrated. The junction parameters are chosen so as to be well matched at both the RF and IF frequencies. LO injection is via a feed horn integrated into the rear of the holder. Coplanar lines (twin lead) containing low pass filter elements (gap-caps) are used for IF removal and DC biasing. Balun transformers surrounding the parabola convert the 200Ω twin lead to 50Ω coax. A teflon matching layer reduces input signal reflection loss.