A PLANAR LOG-PERIODIC MIXTENNA FOR MILLIMETER AND SUBMILLIMETER WAVELENGTHS

Peter H. Siegel

National Radio Astronomy Observatory
Charlottesville, VA 22903

Abstract

A design for a combined planar mixer/antenna for use at near millimeter and submillimeter wavelengths is described. The antenna is one of the class of planar log-periodic structures originally developed by DuHamel and Isbell [1]. The active mixing element may be separately mounted or fully integrated with the antenna and can be either a planar Schottky diode or SIS (superconductor insulator superconductor) junction. The results of extensive antenna pattern and impedance measurements made on a microwave scale model are discussed. It is felt that the proposed mixtenna structure is suitable as a moderate bandwidth receiver or as an element of a focal plane or limited scan phased array.

I. Introduction

At millimeter wavelengths most heterodyne receivers contain a waveguide mixer with a whisker contacted Schottky barrier diode and a separate or integral feed horn for injecting the signal and local oscillator. Although they are difficult to fabricate and generally do not have reproducible electrical characteristics, waveguide mixers which perform near their theoretical limits have been constructed throughout most of the millimeter-wave band. However, at submillimeter wavelengths the small size and close tolerances required for optimum device performance have led many investigators to search for alternative mixer/feed horn structures. Recent interest in focal plane arrays for millimeter-wave astronomy, which require the production of many identical mixing elements, has also prompted research into simpler and more replicable receiver front ends.

One means of overcoming the tolerance constraints and reproducibility problems associated with waveguide mixers and whisker contacted diodes is to combine a photolithographically produced planar feed and a planar diode to form a structure which might appropriately be termed a mixing-antenna or mixtenna. An advantage to using a separate antenna and diode rather than a fully integrated structure is that it allows one to optimize individually or change the constituent components.

A variety of promising mixtenna structures have already been reported (see extensive bibliography in reference [2]). This short paper describes a very flexible mixtenna design, initially intended for single beam radio astronomy applications at submillimeter wavelengths, but potentially suited for use in multiple beam or limited scan phased arrays throughout the microwave/millimeter-wave bands.

II. Mixtenna Structure

The mixtenna design used for the current work (having a center frequency of 350 GHz) is shown in Fig. 1. It consists of a cavity-backed planar log-periodic antenna (described in section III) with a planar GaAs Schottky barrier diode mounted across the antenna terminals. The antenna, diode, and cavity housing are fabricated separately to facilitate optimization.

The antenna is to be constructed from 0.001" thick copper sheet using standard photolithographic techniques. No dielectric substrate is used permitting scaling of the design to very high frequencies without concern for undesirable surface wave modes which may be present even when the dielectric is only a small fraction of a wavelength thick [2]. The metallic ground plane surrounding the antenna (which can be extended without noticeable effect) shields structures present behind the antenna surface such as feed lines, filters or amplifiers.

The antenna will be soldered to a copper housing containing a cylindrical cavity which can be made very simply with a flat bottomed drill (size permitting, an adjustable short can be used in the cavity to add some degree of tuning to the structure). Other cavity shapes have been investigated and can be formed, if desired, by copper electroforming. The optimum cavity depth is slightly less than a quarter of a free space wavelength.

The nonlinear mixing element is to be mounted across the center of the antenna and held in place with epoxy. Connections for IF removal and DC biasing are via transmission line structures which begin on the antenna surface and extend behind the ground plane. The inherently large area of the diode chip is used to advantage by incorporating the bonding pads on the substrate into a transmission line matching structure for the antenna (see section IV). This should make the handling and replacement of a diode a relatively simple task, even at very short wavelengths.

Although no measurements have been made on the actual submillimeter-wave mixtenna, extensive scale modelling work in the microwave band has yielded considerable information on the individual antenna and mount characteristics, which it is felt, will be of interest to researchers working at both ends of the microwave/millimeter-wave spectrum.

III. Antenna Design

The planar circular-toothed log-periodic antenna was first described by DuHamel and Isbell [1] in 1957. The only changes which have been made to DuHamel and Isbell's original design are the addition of a cavity on one side of the antenna and the use of only a single pair of wide radiating "teeth" rather than many narrower ones.

With the cavity removed, the antenna radiates on both sides of, and perpendicular to, the ground plane, with linear polarization as indicated in Fig.1. The radiation characteristics are determined by the size and placement of the teeth (and gaps) which follow the relationships set out for all log-periodic antenna structures (see Johnson and Jasik [3] for an excellent review of the subject). The antenna pattern and impedance properties repeat periodically with the log of the frequency and when many sets of teeth are present very broad bandwidths may be obtained. The key to the success of this log-periodic design, as pointed out in [1], is that the pattern and impedance variation within one period (over the bandwidth at which a single tooth is resonant) is small.

The parameters α,β,σ and τ given in Fig. 1 were chosen, after extensive measurements on a scale model of the antenna in J-band (5.8-8.2GHz), to yield a design with high directivity, low sidelobe and cross polarization levels and low average terminal impedance over the desired operating frequency range (310-370 GHz in this instance). The antenna bandwidth (when no cavity is present) extends from roughly the frequency at which the arc length at the outer edge of the largest tooth is $\lambda/4$ to the frequency at which the arc length at the inner edge of the smallest tooth is $\lambda/4$. For the antenna in Fig.1 (without the cavity) only a single pair of radiating teeth is required to cover the frequency range from 250 to 500 GHz. This rather large period [τ=.25], requiring wide teeth, reduces the effects of dimensional tolerances and allows scaling to higher frequencies before being resolution limited by the photofabrication process.

The cavity is a TE_{11} mode circular waveguide with a diameter of $1.2\lambda_0$ (at the design center frequency) and is shorted $.21\lambda_0$ below the antenna surface. Its effects are: 1) a reduction of the frequency independence of the radiation patterns and the input impedance bandwidth to around 20% (for a fixed cavity depth), 2) a 3dB increase in the pattern directivity manifested by a narrowing of the E-plane beamwidth by roughly 30% and 3) a change in the average antenna input impedance from ≈150Ω real to ≈200-j30Ω over the operating band.

The far field radiation patterns at the design center frequency (at which the arc length at the center of the tooth is $\lambda_0/4$) and input impedance variation with frequency for the antenna of Fig.1, with and without a fixed cavity, are shown in Figs 2 and 3. The patterns were measured in an anechoic chamber at J-band using a scale model of the antenna. The antenna was driven, as suggested in [1], by a coaxial cable brought in to the center along the ground plane with its inner conductor connected to the opposite side of the terminal gap (a balanced line brought in to the terminals through the center of the cavity was also tried and yielded identical results). The cross-polar patterns (labelled xE and xH in Fig. 2) were measured with the polarization of the source (a standard gain horn) rotated 90°. Beam characteristics, derived by rotating the principle plane patterns about the vertical axis, are given in the figures.

The antenna input impedance (Fig.3) was measured as a function of frequency and cavity depth on the scale model using a microwave network analyzer whose reference plane was extended so as to fall at the end of the coaxial drive cable's outer conductor, i.e. at the center of the antenna. Measurements at only one cavity depth are shown.

A few antenna properties not apparent from the figures should be mentioned.

1). The measured phase variation over the main lobe is < $\lambda/16$ and there is a 180° phase change at the onset of the first principle plane sidelobe. 2). The patterns measured in the 45° planes show no increase in cross polarization as is the tendency in some horn antennas. 3). The level of cross polarization in the principle planes seems to be related to the distance of the radiating element (tooth) from the center of the antenna (and hence to α). This is consistent with the suggestion by Rumsey [4] that the cross polarization is due, at least in part, to the "bow-tie" mode on the central portion of the antenna. The cross polarization levels are also affected by the depth and shape of the cavity and can be significant even in antennas which do not have a cavity. 4). There is a slight rotation of the polarization with cavity depth and frequency. 5). The gaps beyond the radiating teeth may be shortened by as much as 25% without significantly changing the antenna performance. This is important if the antennas are to be arrayed as it allows closer packing. 6). The antenna properties are relatively insensitive to the choices of α,β,σ and τ and to dimensional tolerances.

To summarize, the planar log-periodic antenna with a single pair of teeth placed over a cylindrical cavity produces unidirectional radiation with a directivity near 10dB, sidelobe and cross polarization levels below 20dB and constant pattern beam shapes over a bandwidth of at least 20% (greater bandwidths are possible with an adjustable cavity depth). The antenna input impedance (≈200-j30Ω) is fairly constant with frequency although relatively high. In addition the antenna has physical properties which are insensitive to dimensional tolerances and has a form amenable to integration with a mixer or detector diode.

IV. Incorporation of the Mixer Diode

The mixing element (initially a planar GaAs Schottky barrier diode [5] and in the future perhaps an SIS junction) is mounted, substrate side down, across the terminals of the antenna as shown in Fig.1 (the diode must have at least one terminal DC isolated from the antenna ground plane to allow for biasing and intermediate frequency removal). Extended bonding pads on the top surface of the diode chip are used to form low impedance (<50Ω) microstrip lines with the antenna's central metallic region acting as a partial ground plane. On one side of the diode (the anode in our case) the microstrip line extends for $\lambda_g/2$ (at the signal frequency) and is then shorted, by means of a small gold ribbon, to the antenna surface. On the opposite side of the diode the microstrip extends $\lambda_g/4$ (at the signal frequency) and is left floating with respect to the ground plane. The resulting input impedance as seen by the diode (obtained from scale model measurements) is shown in Fig.3b.

The diode chip with its extended bonding pads performs two desirable functions; first it transforms the relatively high antenna input impedance to a much lower value at the signal frequency (a theoretical investigation of a typical pumped Schottky barrier mixer diode using the computer program in [6] indicates that the best results will be obtained with an antenna whose input impedance is ≈20+j30Ω), and second it produces an open circuit at the sum and all even harmonic sideband frequencies. A further advantage of this configuration is the ability to optimize the impedance presented to a given diode by varying the dimensions of the diode chip. The disadvantage of using the extended bonding pads in a matching structure is of course a reduction in the mixtenna bandwidth (as is apparent from Fig.3b).

V. Antenna Design Variations

Before concluding, it may be of interest to mention one of the antenna design variations which has been studied as an alternative to the cavity backed configuration of Fig.1. A structure which is potentially useful in conjunction with the planar log-periodic antenna was described by Rutledge, Neikirk and Kasilingam [2]. These authors point out that an antenna on an infinitely thick dielectric preferentially radiates into the dielectric. They then take advantage of this by placing planar antennas on dielectric lenses. This approach has been tried with the planar log-periodic antenna using, as a substrate, a hemispherical stycast lens (ε_r=4) having a $\lambda_g/4$ teflon matching layer on its surface. For optimum pattern characteristics the free space antenna dimensions were reduced by 1.64x, an amount slightly greater than $\sqrt{(\varepsilon_r+1)/2}$.

The measured radiation patterns (at the design center frequency) and input impedance as a function of frequency (both measured on a J-band scale model) are shown in Figs.2c and 3c. As expected, there is less frequency dependence in the radiation patterns and the input impedance bandwidth is greater than with the cavity backed design however, our low dielectric constant lens resulted in the appearance of a significant amount of back radiation. Of more concern is the presence of much higher levels of cross polarization (>15% of the total beam power) which may be due to an increased presence of the bow-tie mode on the structure.

To reduce the excessive back radiation without increasing the lens dielectric constant, a cavity was added to the free space side of the antenna. Its effects were: 1) a lowering of the back radiation to acceptable levels and 2) a slight reduction of the cross polarization levels to ≈12% of the total beam power which is however, still considerably higher than in the lens-less design. The input impedance levels were not significantly affected.

Although it appears that the lens backed log-periodic antenna still has some problems which must be worked out, the concept is appealing, especially at high frequencies, since it is a more rigid structure than the cavity-backed antenna, which has no substrate. It also has inherently more frequency independent radiation patterns and greater impedance bandwidth and allows some control of the antenna beam shape through the design of the lens.

VI. Summary

The design of a combined mixer/antenna for submillimeter wavelengths has been given. The antenna consists of a substrateless cavity-backed planar log-periodic element with a single pair of radiating teeth. The pattern and impedance variation with frequency, as measured on microwave scale models of the antenna, were found to be small over a period and an antenna bandwidth of 20% was easily obtained. The calculated illumination efficiency for a parabolic reflector is close to 75%. The most serious limitation is the high level of cross polarization which may be due to a TEM type bow-tie mode on the antenna. The antenna input impedance is fairly constant although high (typically 200Ω real part) over moderate bandwidths. All of the antenna properties were found to be insensitive to dimensional tolerances.

The mixer diode is mounted across the center of the antenna and extended bonding pads are used in a transmission line matching structure to reduce the antenna input impedance to a value which is more optimum for the diode (at the sacrifice of instantaneous bandwidth).

A variation of this design using a log-periodic antenna on a thick substrate lens may have some promise as a more broadband mixtenna element if the high levels of cross-polar radiation can be reduced.

Acknowledgements

The author would like to extend his thanks to the following people who contributed substantially to the results presented in this paper: A.R. Kerr, S. Weinreb, M.C. Crawford, J. Boutelle, P. Napier, D. Rutledge, R.J. Mattauch, W. Bishop, K. McKinney, G. Green, D. Robison, H. Schwartz, H. Miller, M. Eilenfeldt, W. Luckado, G. Taylor and M. Dillon.

References

1). R.H. DuHamel and D.E. Isbell, "Broadband logarithmically periodic antenna structures," IRE Nat. Conv. Rec. Part 1 Antenna and Prop., pp. 119-128, March 18-21, 1957.

2). D.B. Rutledge, D.P. Neikirk and D.P. Kasilingam "Integrated-circuit antennas," Infrared and Millimeter Waves,Vol. 10, Chapter 1, pp. 1-90, 1983, Academic Press.

3). R.H. DuHamel and G.G. Chadwick, "Frequency-independent Antennas," Antenna Engineering Handbook Chapter 14, pp. 14-1 to 14-44, edited by R.C. Johnson and H. Jasik, New York, 1984 McGraw-Hill Book Co.

4). V. H. Rumsey, Frequency Independent Antennas, New York, 1966 Academic Press.

5). These diodes are being fabricated by R. J. Mattauch, W. Bishop and K. McKinney at the University of Virginia Semiconductor Device Laboratory.

6). P.H. Siegel, A.R. Kerr and W. Hwang, "Topics in the optimization of millimeter-wave mixers," NASA Tech. Paper 2287, March 1984.

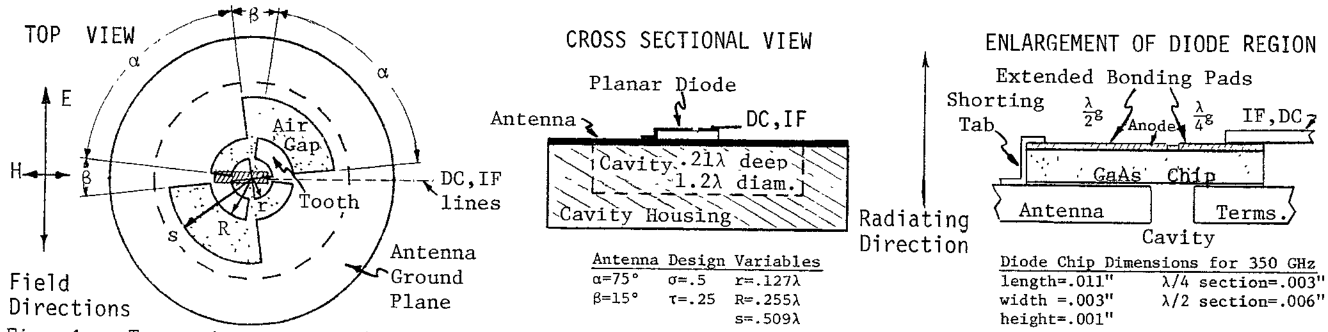
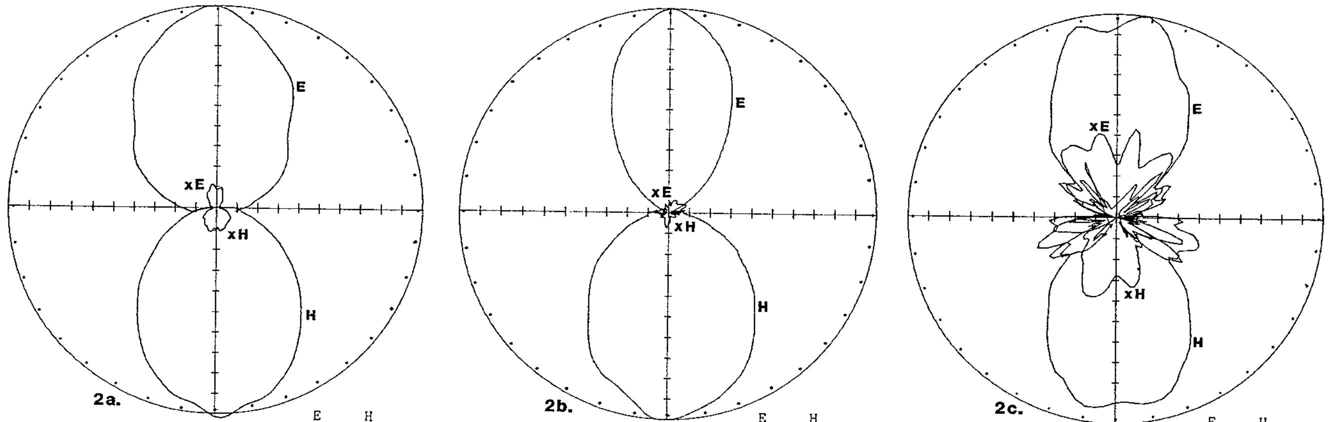


Fig. 1. Top and cross sectional views of the cavity-backed log periodic mixtenna showing the important antenna design variables and approximate diode chip dimensions for operation at 350 GHz.



2a.

	E	H
3dB beamwidth (deg)	66	66
13dB beamwidth (deg)	159	138
Cross-Polar Power (%)	0.9	2.2
Beam Efficiency (%)	50	49
Directivity (dB)	6.0	6.5
Taper Efficiency (%)	73	77
Spillover Efficiency (%)	47	47

2b.

	E	H
3dB beamwidth (deg)	48	69
13dB beamwidth (deg)	101	142
Cross-Polar Power (%)	2.2	0.4
Beam Efficiency (%)	97	99
Directivity (dB)	12.1	9.2
Taper Efficiency (%)	79	77
Spillover Efficiency (%)	93	96

2c.

	E	H
3dB beamwidth (deg)	48	63
13dB beamwidth (deg)	118	129
Cross-Polar Power (%)	24.2	10.9
Beam Efficiency (%)	51	74
Directivity (dB)	8.3	8.6
Taper Efficiency (%)	76	77
Spillover Efficiency (%)	50	73

Fig. 2. Co-polar (E,H) and cross-polar (xE,xH) plane linear amplitude pattern plots at the scaled design center frequency of 6.92 GHz for a) the log-periodic antenna with no cavity present, b) the same antenna with a $.21\lambda_0$ deep cavity and c) the same antenna scaled down in size by 1.64x with a hemispherical $\varepsilon_r=4$ dielectric lens and no cavity. The H-plane patterns have been rotated about the horizontal axis for clarity. All patterns have been normalized to their own E-plane maxima. In a) only the forward lobes are plotted (antenna rotation limits were -100° to +100°). The directivities and efficiencies indicated in the figures assume that the patterns are symmetrical about the vertical axis and include power lost to cross polarization. Taper efficiencies are when feeding a parabola with a -13dB edge illumination.

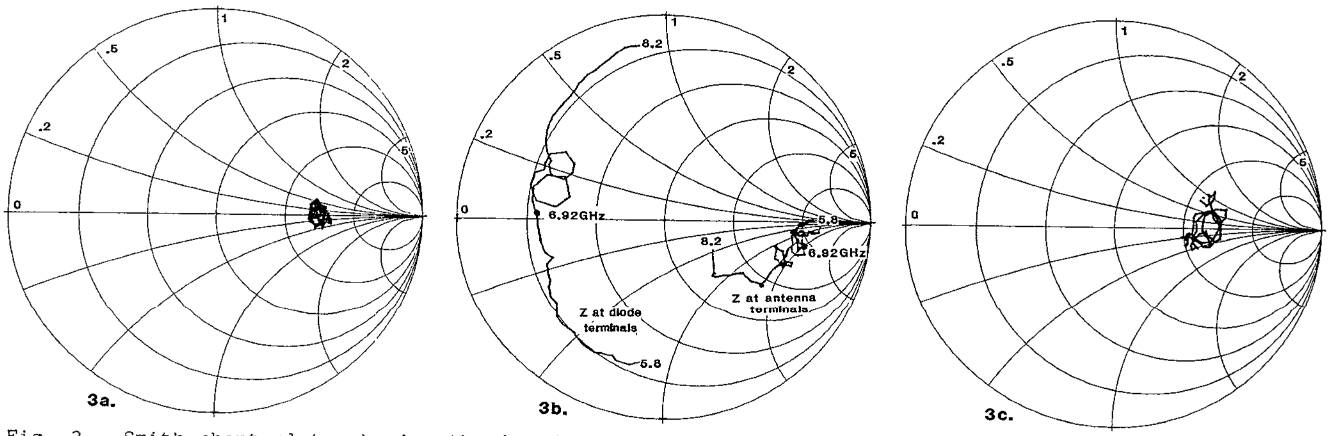


Fig. 3. Smith chart plots showing the impedances at the terminals of the log-periodic antenna of Fig. 1: a) without any cavity, b) with a $.21\lambda_0$ deep cavity and c) with the antenna scaled down in size by 1.64x and placed on an $\varepsilon_r=4$ hemispherical dielectric lens. Fig.3b. also shows the impedance presented to the diode through the matching structure formed by the GaAs diode chip. The data were collected on a J-band scale model and are shown over a frequency range of 5.8 to 8.2 GHz. The design center frequency for the antenna was 6.92 GHz. All impedances are shown normalized to 50 ohms.