# Integrated Millimetre Wave Antenna for Early Warning Detection

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## ABSTRACT

The potential of a passive integrated millimetre-wave radiometer is being investigated as a compact, low cost, all-weather complement or even alternative to current radar detection and imaging systems[1]. A major advantage of millimetre-waves over other radio frequencies, is the ability to propagate through smoke, fog and cloud, at certain 'window' frequencies.

The design of an integrated antenna, based on a constrained beamforming lens[2] is presented. The antenna is designed to simultaneously receive radiation from a wide field of view. The specified requirements of the system are low loss operation, long range detection and sidelobe radiation patterns to produce maximum resolution. The trade-offs needed to achieve these requirements are discussed. A low loss lens design yields a reduction in antenna bandwidth[3,4] and, as a result, the flexibility of the antenna to detect targets.

Characterisation of an existing 35 GHz 5-beam constrained lens[5] radiometer antenna provided a solid background for the development of a prototype 15 GHz unconstrained lens radiometer. Key results will be presented. The future aim is to produce a 35 GHz radiometer fabricated using MMIC technology to produce a target detecting antenna system for horizon early warning detection.

Keywords: Rotman Lens, Millimetre-Wave, Integrated, Microstrip, Horn Antenna Array

## 1. INTRODUCTION

The focus of attention on certain window frequencies at millimetre wavelengths is due to the ability of radiation in this band to this propagate through cloud, smoke, fog and other such aerosols, as seen by the attenuation curve[1] in Figure 1. The window frequencies concentrated on in this paper are at 35 and 97 GHz, about which minimum atmospheric absorption of radiation occurs. This property makes the use of such frequencies extremely attractive for remote sensing applications.

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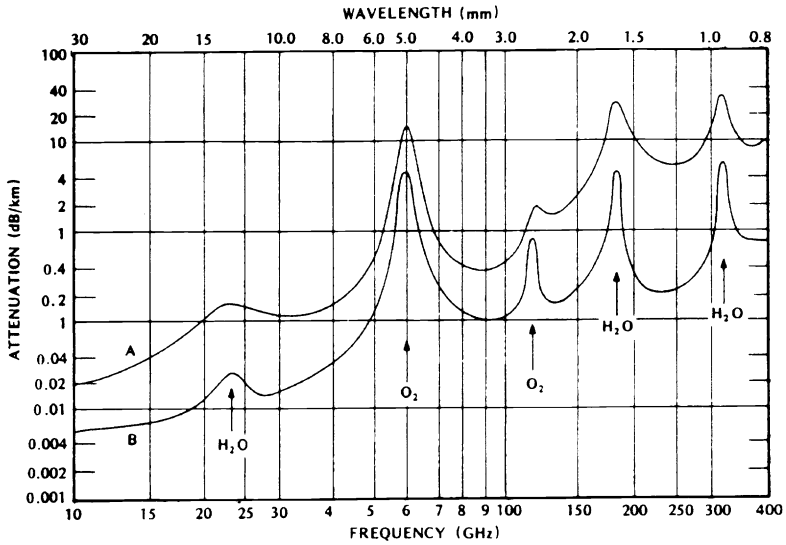


Figure 1: Average atmospheric absorption of mm-waves

An effective radar warning detection receiver requires high sensitivity and large field-of-view coverage. High gain with associated narrow beamwidth radiation patterns are achieved with sensors that are large compared to the wavelength of operation. Unfortunately, narrow beamwidth sensors have limited search area capability. Developing multi-beam beamforming antenna architectures around a certain aperture promise increased search area coverage with specified gain. To do this we make use of an electric lens with directional beams steered to focal ports along the back face of the lens.

The Rotman Lens a type of 'bootlace' lens is such a beamformer, an example of the shape is shown in Figure 2. A Rotman lens is generally the chosen multiple beamforming network because it provides the advantage of broadband performance and frequency invariant beampointing. The incident electromagnetic energy is received by a linear antenna array that produces a corresponding discrete set of inputs to the lens. Varied line lengths effectively delay the incoming signals relative to each other, ensuring phase consistency, and hence focus to the three perfect focal points on the back face of the lens.

This paper describes the development of an integrated Rotman lens wide aperture antenna system for long range remote sensing applications. The characteristics of a K-band multibeam antenna system provide the basis for the development. The planned integrated antenna system will enable direction finding over a wide field of view and real time operation. since a characteristic of multibeam design is that there is no need to beamscan over any given search area. The implementation of this system is a significant step since macro designs are generally bulky and cumbersome, limiting practical use in many applications. The intended beamformer will employ an aperture horn array with reflectors.

### 1.1 Rotman lens design

The name is given after Rotman *et. al.*[2], who was the first to find a solution of the path length equality conditions to find the lens parameters that produce the three perfect focal points. This is achieved by allowing the aperture length of the antenna array $N$ to be different to the length of the array contour $Y$. That is the position of the array port elements is different to the array elements themselves. This design differs from the original design by Ruze[2], which had equal lengths leading to only two perfect focal points. The three focal points include one located on the axis distance $G$ from inner lens contour and other two at symmetric off-axis locations. The off-axis focal points produce plane wave fronts directed at an angle $\pm\,\alpha$ from the axis. Three degrees of freedom exist for this lens: the coordinates $z$ and $y$ of the beam and array port lens contours, respectively and the cable length $w$. These quantities are normalised to the focal length $F$ as follows

$$z = Z/F,\ \ y = Y/F,\ \ n = N/F,\ \ g = G/F, \text{ and } \ w = (W - W_0)/F,$$

these unknowns can be determined by solving the following[2]

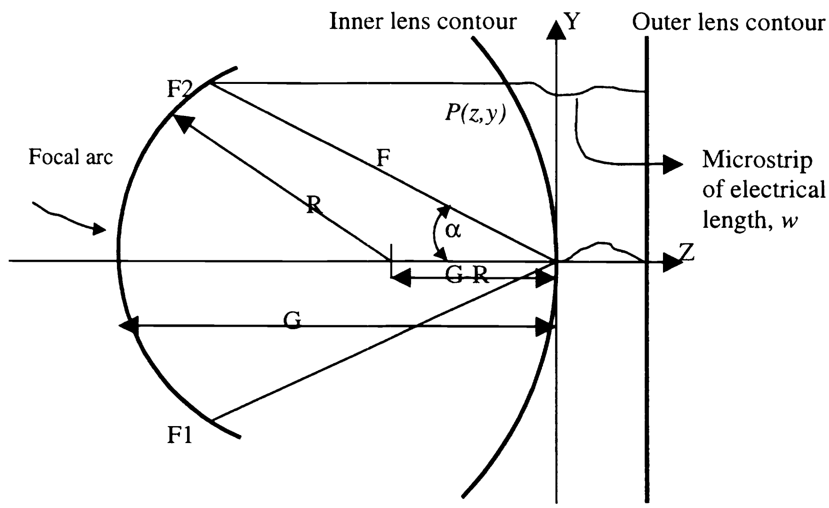


Figure 2: Rotman Lens Topology

$$w = (-B - B\sqrt{B^2 - 4AC})/2A$$

$$z = (n^2 b^2 - 2w + 2gw)/[2(g-a)],$$

$$y = n(1-w),$$

where

$$A = 1 - n^2 - \left(\frac{g-1}{g-a}\right)^2$$

$$B = 2g\frac{g-1}{g-a} - n^2b^2\frac{g-1}{(g-a)^2} + 2n^2 - 2g$$

$$C = g\frac{n^2b^2}{g-a} - \frac{n^4b^4}{4(g-a)^2} - n^2$$

and

$$a = cos\alpha, \ and \quad b = sin\alpha,$$

where $\alpha$ is the maximum scan angle or the angle at which perfect focus is desired. The centre of the circular focal arc is equal to ($G$ - $R$), where $R$ is the radius of the circular focal arc given by

$$R = \frac{(Fa - G)^2 + F^2 b^2}{2(G - Fa)}$$

### 1.3 SENSING APPLICATIONS

The integration of such a lens system is the next step in their evolution since the macro designs are generally bulky and cumbersome, limiting the practical use in many applications. An example of this is the 35GHZ radiometer discussed below, which weighed over thirty kilograms, an integrated system at the same frequency, weighed just 300grams. Integration will also cause a dramatic improvement in manufacture time and cost.

Military detection is one of the areas of greatest activity in millimeter waves. One of the reason for the use of mm-wave antenna for these applications is that these systems have small apertures available for antennas and mm- wave antennas provide small apertures for a given gain and beamwidth. In addition to that, mm-wave devices are currently used in many other areas such as in communications, satellite, and biological applications.

## 2. TESTING OF A 35 GHZ SYSTEM

An antenna system, designed by Dr. Ken Harvey built at the Defence Science and Technology Oraganisation (DSTO) was tested in order to determine how well the system met the design specifications and hence assess the potential for use in various applications.

### 2.1 System design

The system design consisted of a 5-beam radiometer antenna with an operational centre frequency of 35 GHz and a bandwidth of 4 GHz. The inter-beam crossover points were designed to be at the –3dB level. The beamwidth of each beam was required to be 2°. The design also aimed at achieving low sidelobe levels in the vicinity of 20 dB below the main peaks. The five beams would each be displaced by two degrees with a 2° beamwidth each giving a total field of view of 10° (total scan angle).

Due to possible high spillover levels in the Rotman lens the design was implemented using a constrained metal lens[5] instead. It was felt that this would provide better performance in a passive detection application. The design also relied on the position and dimensions of the beam ports if misalignment occurred the result was in sufficient illumination of the front face of the lens. These design parameters have a direct relationship to the beamwidth, and so in order to achieve the desired beamwidth and crossover points it was found that the horn antennas required would no longer fit adjacent to one another in the array environment. The solution was to construct the system using two parallel lens structures, each addressing separate beams in the FOV, Figure 3. Each lens incorporated one perfect focal point, yet both with different beam angles to allow alternate beams to evenly scan the target area.

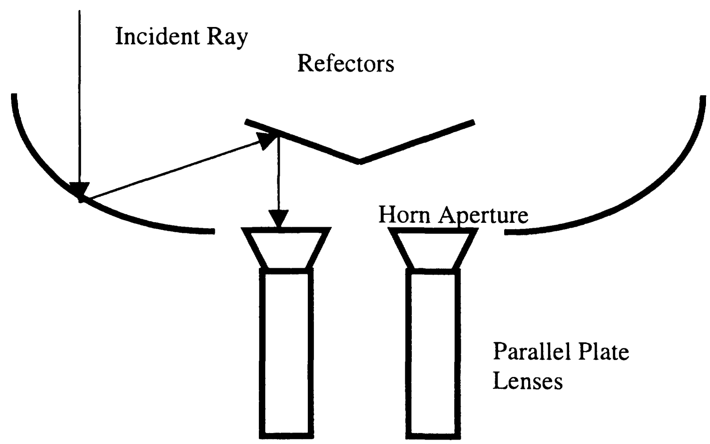


Figure 3: Top View of Antenna setup

### 2.2 Test results

Values for the beamwidths, the system bandwidth and the crossover points were measured for each of the five separate output ports. These were determined by examining the radiation patterns developed from each of the outputs. The shape of the radiation patterns would also provide crucial information on the sidelobe levels for each lens, as well as information on whether the directionality of the system met specifications. Plots of the theoretical and measured radiation patterns of the overlapping beams are shown in Figure 4.

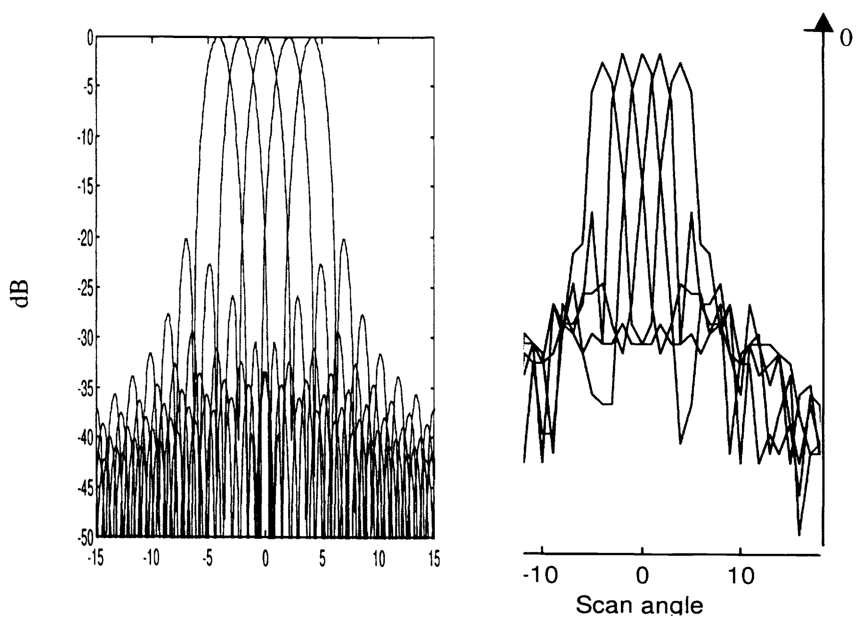


Figure 4: Theoretical (left) and measured (right) radiation patterns of the 5RA system.

The measured radiation patterns show a nicely spread out set of beams, each at the required two degree separation. The inter-beam crossover levels are at the designed –3 level and each beam meets the expected 2° beamwidth, but with a drop off in peak gain levels for the outside ports. The sidelobe levels of below -25dB were satisfactory, also the peaks seen on the two offset ports (upper lens) were found to be erroneous possibly due to reflections in the lens medium.

These results show that the antenna performed as expected, meeting the criterion for crossover points, sidelobe level, beamwidth and scan angle. The parameters from this system now form the basis of the integrated design specifications.

## 3. SPECIFICATIONS OF INTEGRATED DESIGN

A prototype design is based around a Rotman style lens operating at a centre frequency of 15 GHz, for ease of manufacture and testing. The final aim for the sensor design is to scale this prototype system for operation, firstly, at 35 and then to 97 GHz, the window frequencies mentioned above. The lens will steer 5 beams with a $20^{\circ}$ scan angle (4 degrees per beam). This is based on the assumption that any threat perceived will be from a known general direction and so a complete horizon view ($180^{\circ}$) is not required. The desired range is from between 7 to 10 km, so losses must be kept to a minimum.

The lens and the feeds are to be implemented using microstrip fed by an aperture horn antenna array in waveguide. This is the first known horn fed microstrip lens system. The signals are received by the lens system and fed to the detection stage by coaxial cable. The main advantage is that printed circuit board type lenses are smaller compared to parallel plate lens design of Rotman *et. al.* because the lens size is inversely proportional to the permittivity $\varepsilon_r$ of the substrate of the circuit board material [5]. Another reason is that this type can be produced in laboratory more easily and hence cost will be kept low.

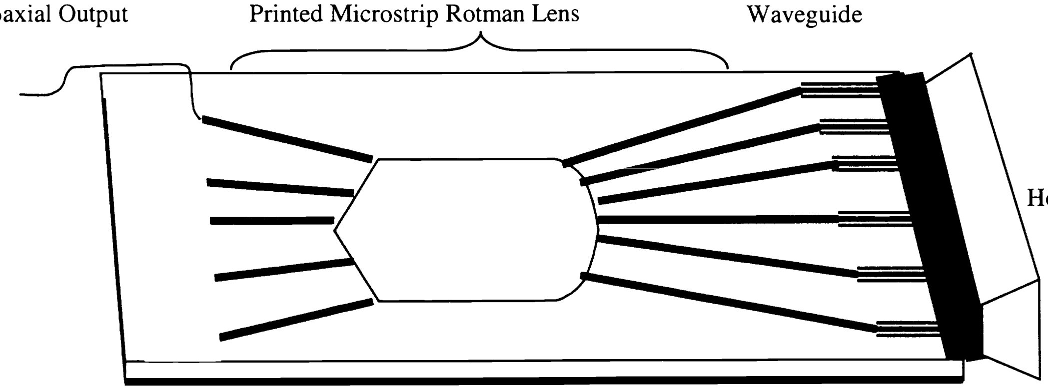


Figure 5: The Integrated System

### 3.1 PRACTICAL LENS DESIGN

One of the problems that were found from the measurements, is increasing of sidelobe levels due to internal reflection of the lens. More energy is wasted because of the rising sidelobe levels. Hence one of the major practical issues is the improvement of the Rotman lens design to reduce these effects. Various methods can be used: integration of dummy ports[5]; sidewall wings; and array impedance matching are some of the methods possible. The transitions from the lens medium to the microstrip feed lines are flared to provide an impedance match from essentially a parallel plate to rectangular waveguide transition. This also allows the whole of the back face to be illuminated and minimises the reflections at the transition. The topology of the integrated system can be seen in Figure 5. The theoretical radiation patterns for the 5 beam lens system with no correction for reflections are shown in Figure 6. The plots show that each beam has a $4^o$ beamwidth. The sidelobe regions are relatively high, the reduction of any internal reflections using the above-mentioned methods will reduce these lobes.

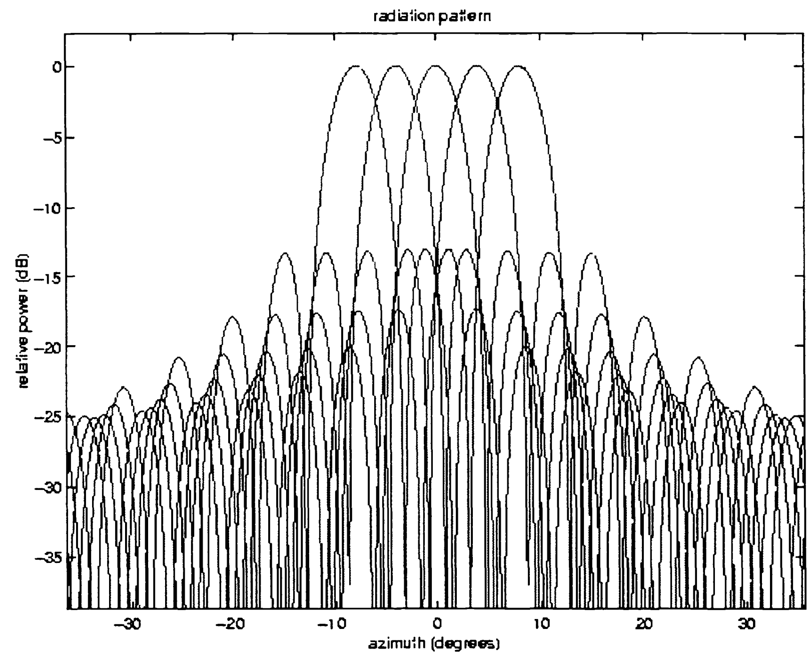


Figure 6: Theoretical 15 GHz Radiation Pattern.

### 3.2 Physical implementation of transitions

The management of transitions is certainly crucial to the effectiveness of the design. The flaring of the microstrip lines provides an effective impedance match, to minimise reflections of the signal. The lines will be matched to a standard 50 Ω connector as will be used with the coaxial cable.

The most difficult transition is from the horn waveguides to the microstrip lines. This will be done by using a fin line approach, that is, a printed piece of substrate inserted into the waveguide, coupling the field onto the microstrip[6,7]. The particular solution to be implemented, starts as an antipodal fin line, with the printed strips on opposite sides of the substrate. The layout of such a transition can be seen below, in Figure 7.

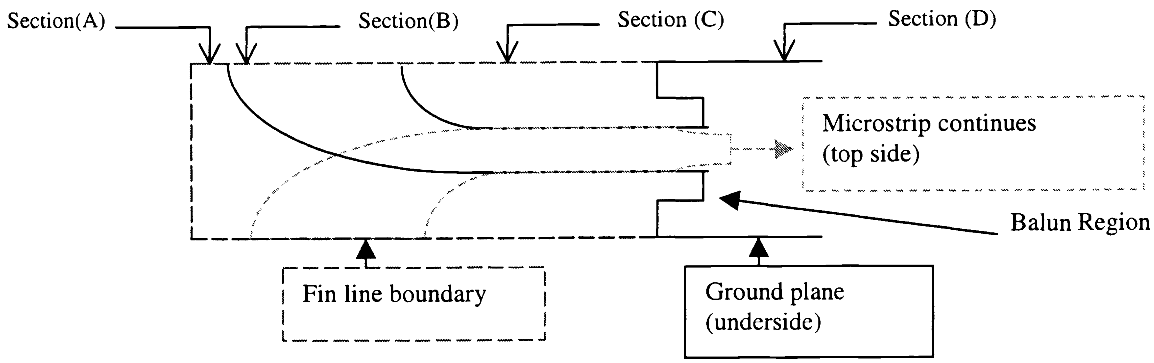


Figure 7: Antipodal Fin Line Waveguide to Microstrip Transition

The line could be considered as a double ridged waveguide, with two thin ridges, one opposite to the other. The substrate has tapers printed on both the top and bottom. The bottom tapers into the microstrip ground plane, via a 'balun' region, which provides impedance matching, while the top metalisation tapers into the microstrip line itself. The field transition can easily be visualised using the fact that the field lines will be perpendicular to the metalisation.

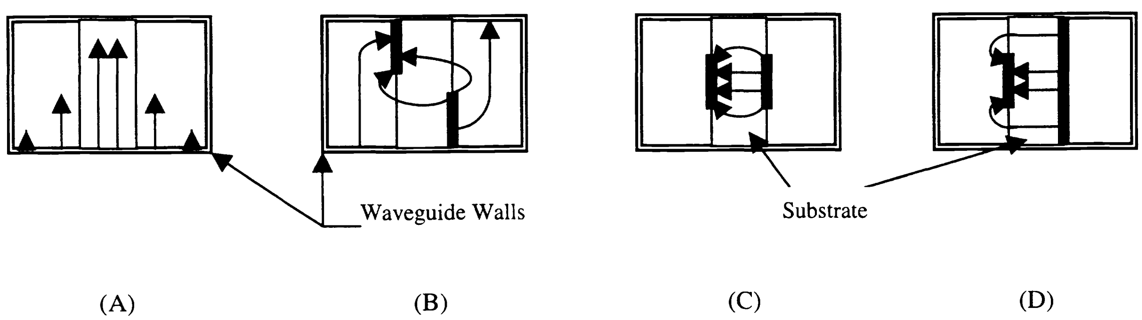


Figure 8:Cross Sectional View of Field Rotation within Fin Line Transition

Figure 8(A) shows the field within the dielectrically loaded waveguide, with the field lines concentrated within the dielectric slab within the waveguide. Figure 8(B) shows the antipodal fin lines, and the fields beginning to rotate towards the fin lines. As the lines taper in towards the microstrip section(D), via a broad-side coupled suspended strip line configuration, (cross Section(C)), an electric field rotation of 90 degrees can be observed.

It should be kept in mind that the long term goal of this project is to move to the 35 and 97GHz window frequencies mentioned in section 1, noting that fin lines are particularly useful in the millimetre wave band, especially from 30 to 140GHz[6]. These methods provide practical advantages over ridged waveguide transitions, which are difficult to manufacture at such high frequencies.

The fin line approach does produce a relatively wide band transition, although it was selected on the strength of its' suitability to the system as a whole. Firstly, with the 90 degree rotation of the E field, we can stay in the E plane by simply rotating the waveguide, to have the shortest side parallel with the front aperture. This will successfully allow the placement of enough horn antennae to achieve the required beam width from the Rotman lens. Secondly, the integration of the transition onto the substrate itself provides an even more compact solution, which allows the previously tricky manufacture of the transition, to be done with the etching of the substrate, which is relatively easy, especially at higher frequencies.

## 4. CONCLUSION

The use of a beamformer has been shown to be suitable for detection applications. The work presented here will be expanded to provide an optimal design and performance for an integrated 15 GHz system. A $20^{\circ}$ scan angle with maximum possible gain and low sidelobe levels are the principal design specifications. Crucial to the design is the minimisation of losses in the system, this is achieved through effective lens and horn designs. Another important design feature is to ensure the efficient matching of transitions from the different media within the system minimising reflections through the system. This will be tested with the novel use of a horn antenna array and the associated waveguide to microstrip transmission. This development will examine the capabilities and flexibility of integrated systems whilst increasing the directionality of the beams. Future work will lead to the integration and scaling to the 35 and 97 GHz window frequencies. Integrated systems at this level further reduced in dimensions would make compact detection systems a very portable, manoeuvrable and attractive possibility.

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