Design of smart multi-beam mm-wave antennas

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ABSTRACT

Multi-beam approaches using beam-forming antenna array architectures have been identified as one solution for overcoming the limited fields-of-view provided by highly directional mm-wave sensors. Rotman lenses offer a compact, rugged and reliable alternative to electronically scanned antenna technologies but architectures that operate at frequencies > 20 GHz perform poorly at higher frequencies on account of greater losses and dispersion. This paper outlines the design process for providing Rotman-based lenses, examining various levels of simulation that are needed for designs that function at K and W-band frequencies. The impact of using mictrostrip structures is demonstrated.

Keywords: Smart antenna, Rotman lens, beam-forming, microantenna arrays

1. INTRODUCTION

Sensors operating in the mm-wave (20-100 GHz) band have better poor-weather performance than those operating at IR and visible wavelengths and provide better spatial resolution (and target discrimination) than microwave systems.

Beamforming mm-wave antennas have numerous applications including radar, communication and biomedical systems, synthetic vision schemes and collision-avoidance systems. The strategy is to implement a beamforming Rotman lens-based antenna array,[1] operating at 35 GHz that can be monolithically fabricated so that it provides a low-cost testing platform of the design for a further version at 94 GHz. These frequencies are chosen because they are centres of atmospheric transmission bands, with the presence of O_2 and H_2O in the atmosphere causing absorption of mm-waves at 60 and 22 GHz respectively. Naturally occurring 35 and 94 GHz radiation propagates through cloud, smoke, fog and other such aerosols, as seen by the attenuation curve in Fig. 1. This property makes the use of these frequencies extremely attractive for remote sensing applications.

2. SPECIFICATIONS OF INTEGRATED DESIGN

The initial design that is being considered is a 35 GHz lens for steering five beams with a 40° scan angle. This provides a simple prototype to enable rapid development of the techniques required for the designs manufacture at low cost. In addition, a half-wavelength separation of beam-ports is achievable in this design and therefore spillover losses can be kept low.

The lens and the feeds are to be implemented using microstrip fed by bipolar antenna elements. This architecture is best suited for providing a compact structure that is planar and compatible with printed and monolithic fabrication. It is estimated that an eleven element array aperture of 41 mm is achievable at 37 GHz and an aperture of 16 mm at 94 GHz. Apertures of these sizes are suitable for collision-avoidance applications.

The second implementation of the design will utilise a horn-fed array since such a lens, as an aperture feed, promises high gain multi-beam coverage of a 40° field-of-view. This is desired in electronic warfare applications.

Aspects of the first implementation are addressed in this paper.

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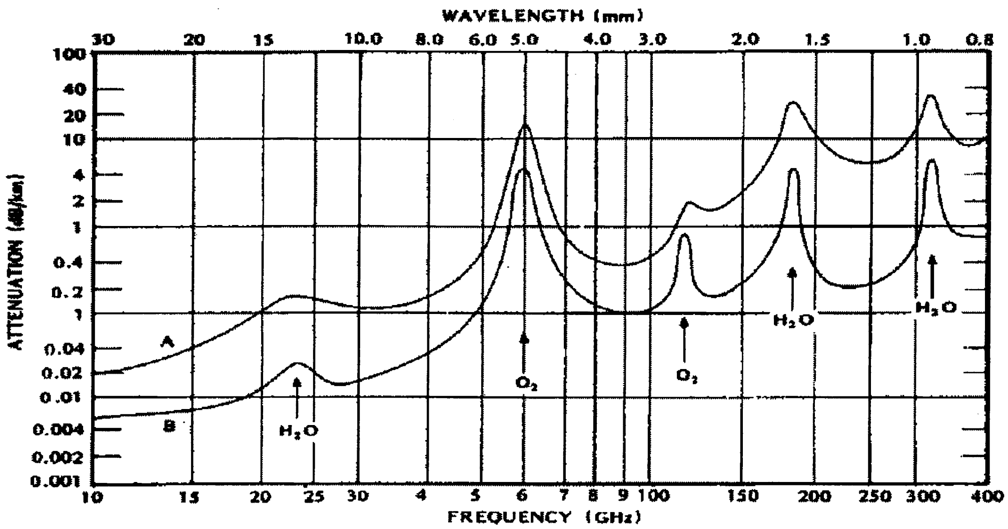


Fig. 1. The one way attenuation of electromagnetic radiation in the troposphere

3. SIMULATION

A Rotman lens consists of a parallel plate region (body) with beam ports and array ports distributed along opposite contours. The central beamport provides equal path lengths to each array element. An offset beam produces a path length difference and hence a phase gradient along an array, giving a steered beam.

In order to design a lens that will perform at mm-wave frequencies, three different levels of simulation are being considered. The results associated with the first two levels are reported here in detail. The third level deals not only with the simulation but also validates certain aspects of the model.

Level one simulation involves the numerical optimisation of the Rotman geometry using ideal models.[3,4] The lens is modelled using geometric optics. No coupling between input and output ports is considered with all ports matched and reflections and attenuation ignored.

Level two simulation addresses the non-ideal effects of the microstrip and how adopting various antenna element options affect performance.[5] Level two simulations include optimising the bandwidth performance of the lens.

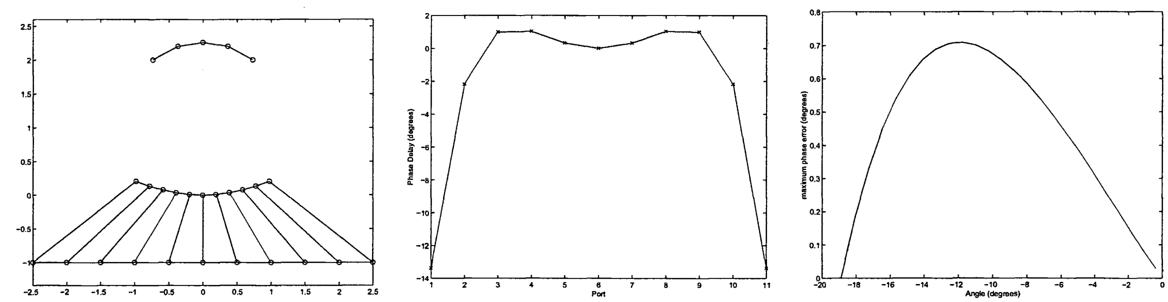
Level three simulation utilises an electromagnetic simulation program such as Micro-Stripes[6] to calculate the S-matrix of various sections of the design such as ports and junctions. At this level, effects considered include the coupling between adjacent input or output ports, reflections, and unmatched ports. An electromagnetic simulation of the antenna element feeds could also be included. It is expected that only through the careful implementation of level three studies would our model be able to accurately predict the performance of the lens structure.

4. RESULTS

4.1. Level 1 Ideal Modelling

Scattering matrices have been used exclusively throughout the simulation because the matrix approach allows a complete model of the lens to be developed. Initially three scattering matrices are generated, S_B accounting for the Rotman lens body, S_W for the path delays between antenna elements and associated antenna ports on the inner lens contour and S_A for the phase delays between incoming rays onto the antenna array. Combining these matrices provides the output at each port due to any given incident wave.

The design of the lens or matrix S_A is governed by the Rotman-Turner design equations that are derived by viewing the geometry of the lens. Fig. 2(a) shows the layout of the eleven antenna element, five beam port configuration under consideration where the opposite contours are clearly shown. A normalised focal length ratio of g = 1.06 is used with the off-axis focal point angle of 20°. Fig. 2(b) shows the desired path lengths that are needed to link antenna elements to their corresponding antenna ports. Fig. 2(c) displays the maximum phase error versus angle. For the three focal points there is no phase error at all. Between these points the phase error remains $< 0.7°$. Fig. 3(c) then displays the idealised seven-beam radiation pattern. The average side lobe level for an array aperture with antenna elements spaced 0.5 wavelengths apart is -30 dB Fig. 3(a). Clearly, the amplitude and phase performance of the idealised design is acceptable.

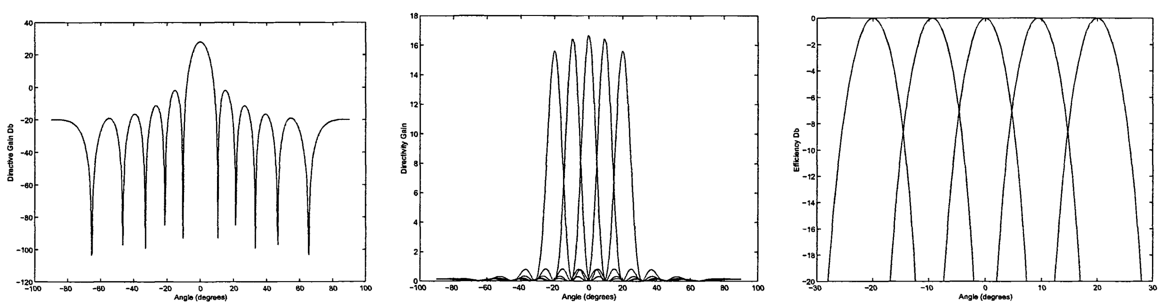


(a) Lens Layout

(b) Path delay versus antenna element

(c) Phase error versus beam angle

Fig. 2. Basic Rotman Lens Design



(a) Sidelobe Level

(b) Directivity

(c) Losses

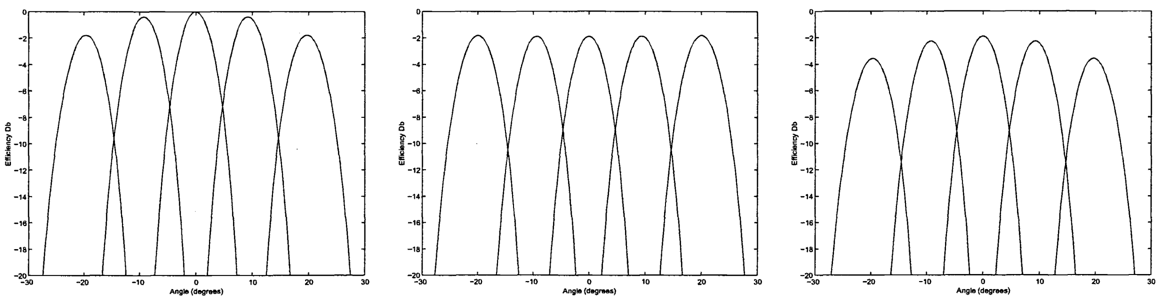
Fig. 3. Level 1 Simulation Results

4.2. Level 2 - Non-Ideal Modelling

We now show the adverse affect on performance of using non-ideal antenna elements within a microstrip lens structure. For this simulation, the S_A matrix is altered to account for attenuation in microstrip and a S_W matrix that uses non-ideal dipoles as antenna elements is considered.

We would expect some power to be lost in the load and we should also be able to see the effect of the antenna gain dropping for angles other than zero degrees. Our model predicts an attenuation of 2 dB due to the microstrip line, as seen in Fig. 4(a), and the half wave dipole will produce attenuation increasing from zero to 2 dB as we approach ± 20° as shown in Fig. 4(b).

At this point all simulations have been carried out at 37GHz. We are also interested in the performance of the lens above and below this frequency. This is achieved by varying the wavelength and repeating the process over the

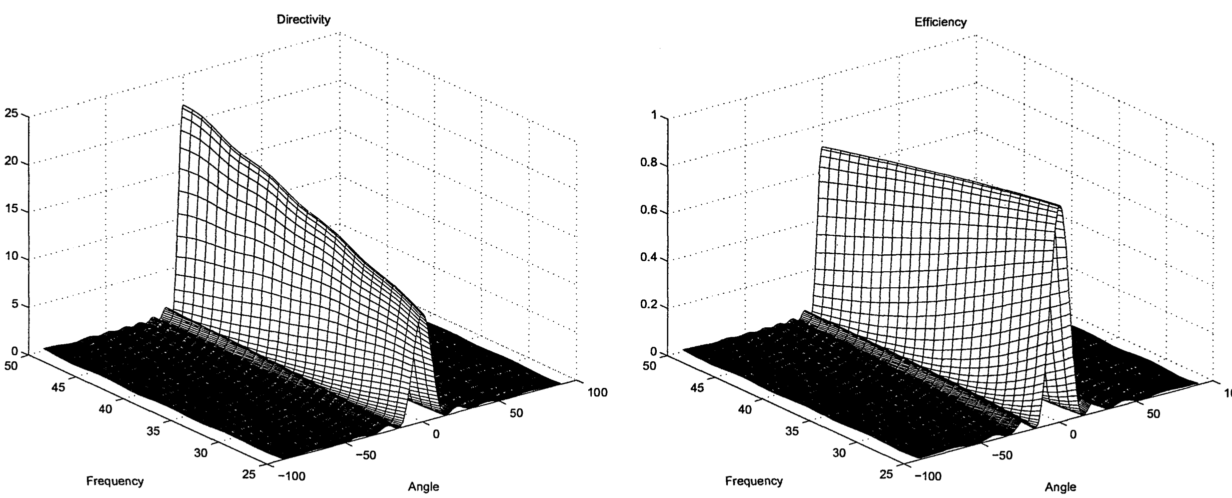


(a) Loss due to dipole antenna. No attenuation due to microstrips or impedance mismatch.

(b) Loss due to microstrip. Antennae are assumed ideal and no attenuation due to impedance mismatch.

(c) Total loss due to dipole antenna and microstrips. No attenuation due to impedance mismatch.

Fig. 4. Level 2 Simulation Results



(a) Directivity

(b) Loss

Fig. 5. Frequency dependence of Rotman lens. Isotropic frequency-independent antennae have been assumed while calculating these figures

desired frequency range. In Fig. 5(b) we can see that as the frequency increases the attenuation in the microstrip increases, reducing the efficiency of the system. In Fig. 5(a) we notice that the directivity of the device is increased with frequency since the effective aperture is being increased.

4.3. Level 3 - Electromagnetic Modelling

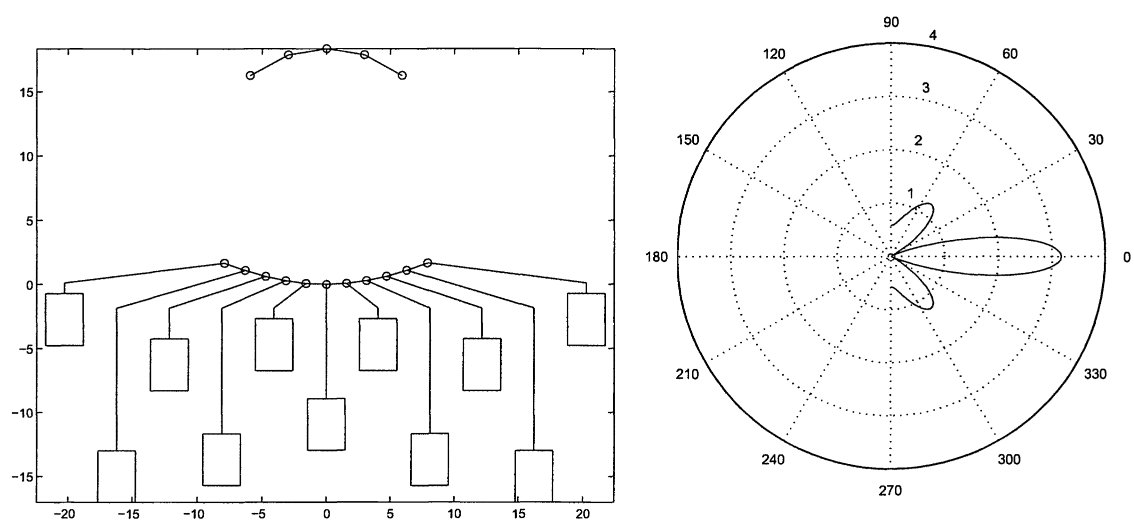
Producing a full simulation using software such as Micro-Stripes is not realistic due to the excessive processor time required. To combat this we have sought to produce a model that is initially simple and modular. By developing the modules we may easily increase the complexity and accuracy of the results.

We may now use electromagnetic modelling software in two ways. The first is to check our assumptions such as the magnitude of losses due to microstrip lines and junctions. We are able to validate our assumption that the microstrip lines will match the antenna.

We may also use the software to provide additional detail as required during development. We can approach a design problem in two ways. We may use the software to address the problem in our simulation or we may alter the design to minimise the effect on the system.

We are interested in the mutual coupling between antenna and the mismatch between microstrip and the body of the lens. Preliminary simulations using micro-stripes has yielded losses of around 2-5 dB when the microstrip is directly connected to the body of the lens. Tapered transmission lines yield much lower losses[7,8] however, comprehensive simulation of these geometry have not been completed.

5. IMPLEMENTATION OF DESIGN



(a) Layout utilising Patch antenna

(b) Vertical Directivity

Fig. 6. Design of prototype lens

We have discussed the process used to construct a model of a Rotman lens geometry. Now with the aid of this model we are able to quickly examine the effects of various design changes. Fig. 6(a) shows a design of a Rotman lens. We have used patch antennae because of the ease of which they are mounted and matched to microstrip, and their low levels of coupling. The fact that patch antenna radiate perpendicular to the surface they are mounted on, allows us to move the antenna vertically without disturbing the performance of the antenna in the horizontal plane. By fully utilising this idea we are able to keep the microstrip lines as straight as possible and avoid potential discontinuities. If the antenna are sufficiently far apart we need not include mutual coupling in our model. One important impact of this design is the reduction in the vertical beam-width. This can easily be plotted using the same ideas already discussed above. The results of these calculations are shown in Fig. 6(b).

6. DISCUSSION

The modelling shows that a working integrated planar lens array for mm-wave operation in short range collision-avoidance type applications is achievable using microstrip technology. Our model predicts that a microstrip-based design will have an attenuation in the mainbeam of 2dB as we can see in Fig. 4(c). Previous studies of similar designs have reported 2.5 dB mainbeam losses overall[9] so it is clear that minimising the microstrip paths within the lens will be a major factor in optimising performance.

The results reported are preliminary because our model does not include any of the electromagnetic effects such as coupling between ports, reflections and the existence of propagating multiple modes. We intend to use electromagnetic simulation programs to generate the scattering matrices of geometries which include those associated with the interfacing structures into and out of the body of the Rotman lens. Ultimately, our approach should predict the sidelobe levels and mainbeam gains that are to be achieved with a fabricated device.

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REFERENCES

1. W.Rotman and R.F.Turner, "Wide angle microwave lens for line source applications," *IEEE Trans. Antennas Propagate* **Ap-11**, 1963.
2. A. Mohamed, A.Campbell, D.Goodfellow, D. Abbott, H. Hansen, and K. Harvey, "Intergrated millimetre wave antenna for early warning detection," in *SPIE*, 1999.
3. R. C. Hansen, "Design trades for rotman lenses," *IEEE Trans. Antennas Propagate* **39**, april 1991.
4. A. Peterson and E. Rausch, "Scattering matrix intergral equation analysis for the design of a waveguide rotman lens," *IEEE Trans. Antennas Propagate* **47**, pp. 870–878, may 1999.
5. A. Balanis, *Microwave Engineering*, Harper and Row, 1982.
6. Kimberly Communications Consultants Ltd., *Micro-Stripes 4.0*, 1999.
7. M. Michaelides, "Microstrip transmission lines: impedance matching, coupling and filtering," *Mullard Technical communications* **116**, october 1972.
8. L. Musa and M. Smith, "Microstrip port design and sidewall absorption for printed rotman lenses," in *IEEE proceedings*, 1989.
9. D. Abbott and A. Parfitt, "Collision avoidance device using passive millimetre-wave array based on insect vision," in *Proc. MICRO 97 Melbourne*, 1997.