Individual Grant Review Report for GR/R16945/01

"Monolithic Millimeter-Submillimeter Wave Active Conical Horn Antenna Arrays"

Background/International Context:

This project was funded to Dr Hao by EPSRC under the fast stream scheme in May 2001. The main objective was to characterise and implement a monolithic active conical horn antenna array for millimetre/submillimetre wave imaging applications. This proposal can be described as having two main aims:

- To research a fast and accurate electromagnetic algorithm to analyse the proposed conical horn antenna arrays;
- To design and build a demonstrator of the proposed active conical horn antenna arrays in order to validate the design methodology and simulation.

Imaging arrays can be used as millimetre wave cameras that allow one to see through human clothing for concealed weapon detection, as well as radio astronomy instruments for all weather conditions. For some time now, researches have been very active in California Institution of Technology, University of Michigan, Ann Arbor and TRW in USA. The work in UK started in late 90s with a project partially funded by ESTEC at Queen Mary, University of London. This fast stream fund has allowed that the innovation is continued in this area. In addition, the project has helped more novel approaches developed on a local distorted nonorthogonal Finite Difference Time Domain (FDTD) method (pioneered by Dr Hao), to strengthen and expand the UK position in this field. This can be evident from that the paper [1] published by Mr Vassileios Douvalis, who worked as the PhD research student for the project, was chosen as one of finalists in a student paper competition at IEEE International Symposium on Antennas and Propagations, Monterey, 2004. The paper was the only finalist from Europe. During the period of the project, Dr Hao has secured funding from EPSRC for two additional research projects as a principle investigator. He also successfully launched a new research area of metamaterials with its emphasis on numerical modelling and applications.

Key Advances and Supporting Methodology:

<u>Research Background</u>

A literature survey revealed that past attempts to analyse and design integrated horn antenna systems were restricted to the pyramid horns and a limited number of elements ([4]-[7]). This was firstly because the numerical methods for the design and verification of such complicated active antenna systems at millimetre/submillimetre frequencies were very limited. Accurate and fast numerical modelling by the FDTD method [2] was seen as the most valuable method of analysis for such structures; however it was constrained by computational power and memory. Secondly, limitations on current technologies indicated that the feasible horn which can be fabricated on silicon must be pyramidal in shape with only one particular flare angle (around 70^0) [4]. The main objective of this project was to research the characterization and implementation of monolithic millimetre-submillimetre wave active conical horn antenna arrays. Specifically, a 95GHz quasi-optically fed mixer integrated with an annular slot ring antenna was used as the basic element of the proposed active antenna array. It was fabricated on a very thin silicon substrate to eliminate the substrate modes. For efficient reception, a conical horn antenna array was fabricated using the micro-machining technique and placed on the top of active elements. The conical horn was, by virtue of its axial symmetry, capable of handling any polarization of the exciting modes. This new configuration, which had never been considered as a part of an integrated system, also had less manufacturing difficulties over pyramidal horn array scheme [4]. In this project, we also demonstrated a design approach, which included a novel unconditional stable local nonorthogonal FDTD technique on single conical horn antenna modelling. In addition, a novel method for the characterization of antenna array using a matrix manipulation technique was demonstrated.

<u>Late Time Instabilities in the Nonorthogonal FDTD Method and A New 'Time Sub-griding' Scheme</u>

In 1998, Hao *et al* [2, 8] modified the conventional NFDTD scheme within the underlying Cartesian coordinate system and only those cells closed to the curved boundaries were distorted. Namely, it was Local-distorted Nonorthogonal FDTD (LNFDTD), in which a Cartesian grid was used for the majority of the problem space and therefore less CPU time and memory were needed than the NFDTD. However, such a scheme suffered late time numerical instability even when the Courant criterion was satisfied. In this project, we demonstrated theoretically that the source of numerical instability in LNFDTD method was due to the inherent inability to satisfy the divergence free condition for the electric field in a source-free space. Conventionally, a unique time step was chosen for NFDTD simulation, and this approach was less efficient, particularly in LNFDTD. An efficient 'time sub-griding' scheme was proposed to reduce the late time instability of LNFDTD method when long time simulation was required.

The stability analysis started by assuming a plane electromagnetic wave having its usual representation:

$$\vec{E}(u^1,u^2,u^3,t)=\vec{\varepsilon}(t)\cdot e^{-j\cdot\vec{k}\cdot\vec{r}} \qquad (1)$$

The electromagnetic field that existed in a region can always be represented with a linear superposition of the above waves, which satisfy the wave equation:

$$-(\nabla\cdot\nabla)\vec{E}+\nabla(\nabla\vec{E})=\frac{-1}{c^2}\cdot\frac{\partial^2\vec{E}}{\partial t^2} \qquad (2)$$

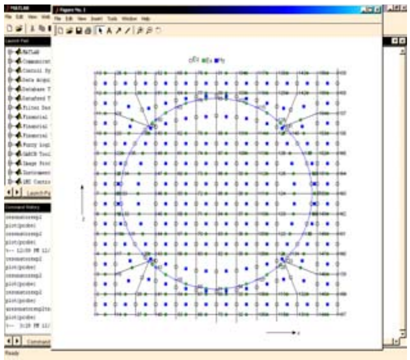


Fig. 1. The cross section of a cylindrical PEC resonator and its LNFDTD meshes

Detailed definitions of equations (1) and (2) can be found in [9]. In the LD-NFDTD grid, equation (2) became:

$$\nabla\cdot\vec{E}=-2j\exp(-j\vec{k}\cdot\vec{r})\Big(\sum_{i=1}^{3}\varepsilon^i(t)\cdot\frac{k_i\Delta(u^i)}{2\cdot\Delta u^i}\Big)-2j\exp(-j\vec{k}\cdot\vec{r})\cdot\sum_{i=1}^{3}\varepsilon^i(t)\cdot\frac{u^i\cdot\Delta(k_i)}{2\cdot\Delta u^i}$$
$$=-j\exp(-j\vec{k}\cdot\vec{r})\cdot\sum_{i=1}^{3}\varepsilon^i(t)\cdot u^i\cdot\frac{\Delta(k_i)}{\Delta u^i}\neq 0$$

The above non-zero result came from the unitary vectors of the local bases in the mixed coordinate system used in the LNFDTD scheme, in order to conform to the arbitrary shaped boundary, they can not remain constant throughout the computational space. Consequently, the introduction of the skew cells underlying within the Cartesian coordinate system did not enforce the divergence free condition for the electric field in a source-free space. In a classic Yee's space lattice, the electric field presents its divergence-free nature, which was not true in LNFDTD scheme. This phenomenon can be responsible for the late time instabilities that occur in the LNFDTD even if the Courant criterion is satisfied. It was apparent that a more subtle treatment was needed on the curved cells that conform to the boundary of electromagnetic structures.

Fig. 1 showed the example structure simulated using LNFDTD method. This was a two dimensional circular Perfect Electric Conductor (PEC) waveguide resonator. Fig. 2 demonstrated time domain signals of the H_y component of the TE mode in the PEC cavity resonator. It clearly showed that the algorithm went unstable above 1400 time steps. Conventionally, a unique time step was chosen for NFDTD simulation, and this approach was less efficient and very time-consuming, particularly in LNFDTD. This was because, in LNFDTD, the time step required for the distorted cells was considerable smaller than that used for Cartesian cells. The proposed novel approach was to treat the curvilinear cells in a "time subgriding" manner and let the algorithm run with a time step that was a fraction of the one used in the Cartesian cells: $\Delta t_{novel}=\Delta t_{conventional}/n$ (*n* is an integer). In order to have conformity between the orthogonal and no-orthogonal regions, nonorthogonal electric and magnetic field iteration must be performed *n* times more inside the curvilinear cells. Figure 3 showed the time domain signals probed in the PEC resonator. Even at 4000 time steps (the same Δt as the previous example: $\Delta t_{conventional}$), the algorithm remained stable.

A Stable Non-orthogonal FDTD Method

In the above study, it was demonstrated that the instability of NFDTD was inherent. Although a 'time-subgriding' approach was developed to reduce the late time instability, an unconditionally stable NFDTD was still not obtained. In this project, we developed a novel approach to discretize the Maxwell's Equations only using the covariant components. It was demonstrated that the new NFDTD algorithm was stable over very long period of numerical simulation. Moreover, the algorithm was less computationally intensive than other NFDTD methods [2, 8-10] where both of the covariant and contravariant components were needed. The first step to achieve this was to discretize Maxwell's equations in the non-orthogonal coordinates. For a set of general coordinates (u^1,u^2,u^3) with unitary vectors $(\vec{a}_1,\vec{a}_2,\vec{a}_3)$ the equation can be rewritten as

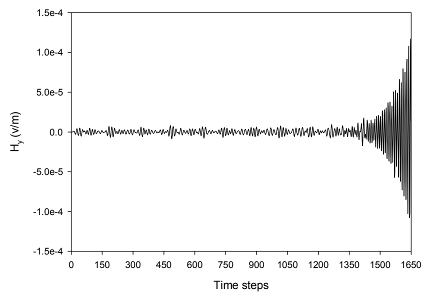


Fig. 2. Time domain H field showing instability using conventional time steps

$$\varepsilon\cdot\frac{\partial\vec{E}}{\partial t}=\frac{1}{\sqrt{g}}\cdot\left[\frac{\partial h_3}{\partial u^2}\cdot\vec{a}_1-\frac{\partial h_3}{\partial u^1}\cdot\vec{a}_2\right] \qquad (3)$$

There were two ways to discretise equation (3) as a central difference approximation in the nonorthoognal coordinate system.

1) Take the dot product of (2) with the reciprocal basis vectors, hence:

$$\varepsilon\cdot\frac{\partial e^1}{\partial t}=\frac{1}{\sqrt{g}}\cdot\left[\frac{\partial h_3}{\partial u^2}\right] \qquad (4)$$

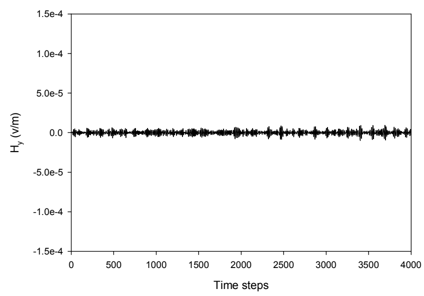


Fig. 3. Novel time-sugridding shows improved numerical stability

2) alternatively, take the dot product of (3) with the unitary basis vectors, thus

$$\varepsilon \cdot \frac{\partial e_1}{\partial t} = \frac{1}{\sqrt{g}} \cdot \left[\frac{\partial h_3}{\partial u^2} \cdot g_{11} - \frac{\partial h_3}{\partial u^1} \cdot g_{12} \right] \tag{5}$$

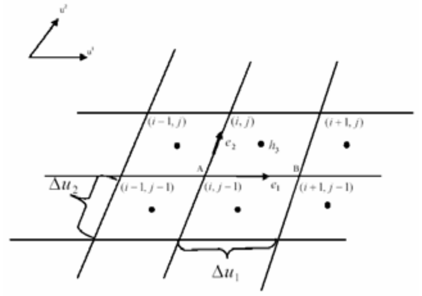


Fig. 4. Illustration of the field components' position in the new NFDTD scheme

As usual, (5) can be approximated as a central difference equation on the non-orthogonal grid. Fig. 4 depicted the placement of the various components. They occupy the same places as the standard non-orthogonal FDTD formulation but this time the contravariant components were missing. The derivative becomes:

$$\frac{\partial h_3}{\partial u^1} = \frac{h_3(B) - h_3(A)}{\Delta u_1} = \frac{h_3(i+1,j) + h_3(i+1,j-1) + h_3(i-1,j) + h_3(i-1,j-1)}{4 \cdot \Delta u_1}$$

The new scheme was tested on the same structure as shown in Fig. 1. Its stability can be found in Fig. 5, where time samples of the magnetic field inside the resonator were shown. The algorithm remained stable even when the number of the time steps reached 180,000. On the contrary, when the conventional nonorthogonal FDTD method was applied using the same time step, the simulation went unstable after 10000 steps. The proposed technique was also tested for its accuracy. The simulated resonant frequencies were compared with the theoretical values as well as with the results yielded from a traditional NFDTD algorithm [11]. The overall agreement was very good.

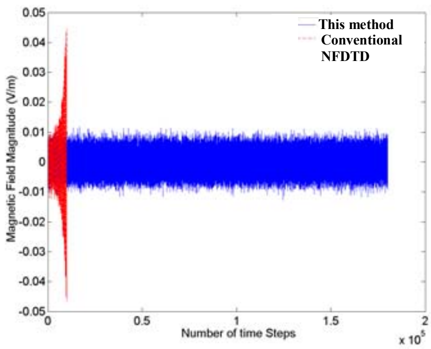


Fig. 5. Stable magnetic field signature in time domain with the new method compared to that with the traditional NFDTD scheme

<u>A Conical Horn Antenna with Hard Surfaces</u>

In recent years, there have been increasing interests in the application of hard surfaces in antenna engineering. The hard surface was generally defined as a surface along which the density of power flow had a maximum, for any polarization of the electromagnetic field [12]. Alternatively it can be looked upon, as a wall at which there was infinite electric and magnetic conductivity in the direction of wave propagation and can be realized by using longitudinally corrugated surfaces. The corrugations had to be properly chosen so as to permit the propagation of a plane TEM wave. Previous analysis on hard cylindrical horns revealed better performance in terms of low cross-polarization levels. Moreover, it was proved that hard horns were more suitable for cluster feeds of satellite antennas due to the reduction of the spill over loss. Other applications were in the area of limited-scan arrays and quasi-optical amplifiers. In addition, the hard corrugated surfaces can be seen as a class of electromagnetic band-gap (EBG) structures and hence increased the domain of foreseen applications dramatically. In this project, the concept of hard surfaces was used to alleviate some design difficulties arising from current silicon fabrication technologies, which were unable to reproduce the smooth surface and must compromise with the staircase solution depicted in fig.6. As in the case of smooth horn antenna modeling, the proposed LNFDTD method was applied to accurately represent the cylindrical sections that comprised conical hard surfaces. Fig. 7(a) showed the radiation patterns of a hard horn antenna calculated using both the mode-matching technique and the FDTD simulation. The agreement between the methods was very close. Fig. 7(b) compared the radiation performance between the smooth and the hard conical horn antennas. It can be seen that the co-polarization patterns did not bear great differences; however, the differences in the x-polarization curves were obvious and confirmed the general advantage of the hard horns over the smooth horns in lower cross polarization levels [13].

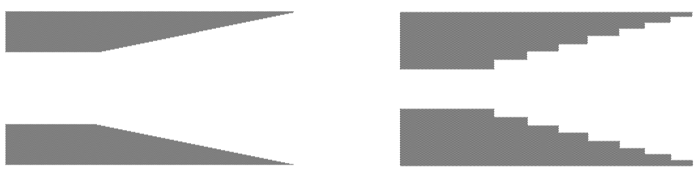
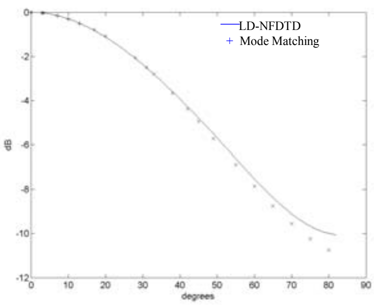
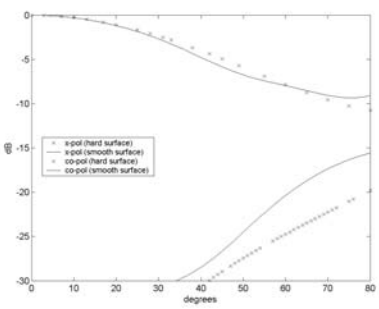


Fig. 6. A conventional smooth conical horn (left) and the proposed conical horn with hard surfaces (right)



(a)



(b)

Fig. 7. (a) Comparison of the radiation pattern as calculated by NFDTD simulation and the Mode Matching Technique (E-plane)
(b). Co- and x-pol comparison between a smooth and a hard horn

Fast Array Analysis Using a Combination of FDTD and Matrix Manipulation Techniques

Often, the Method of Moments (MoM) is invoked to solve the integral equations that arise from the formulations pertaining to the mutual coupling effect in antenna arrays. However, the computational power needed was proportional to some power of the number of the unknowns. The problem remained for other numerical methods such as the FDTD algorithm although the computational burden was only linearly proportional to the simulated space. So far only very few attempts were launched towards the implementation of an efficient way that did not require impractical computer resources to analyze medium sized arrays [14]. Nevertheless, the results were achieved with the use of a medium power workstation. In this project, we developed a novel method that drastically reduces the amount of computer resources needed for an FDTD analysis of antenna arrays. It combined FDTD with a so-called 'Matrix Manipulation Technique'. Specifically, the antenna array characteristics were manipulated from radiating and scattering fields which were obtained from FDTD simulation on single elements and arranged in matrices. A flow chart illustrating the detailed procedure of the new method can be found in [15].

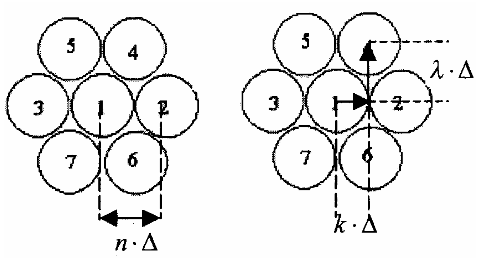


Fig. 8. Prototype of a 7-element conical horn array

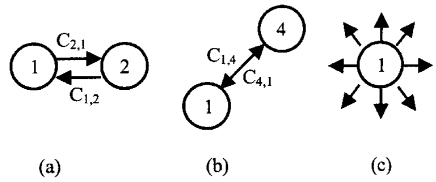


Fig. 9. Sub-arrays in the Matrix Manipulation Program

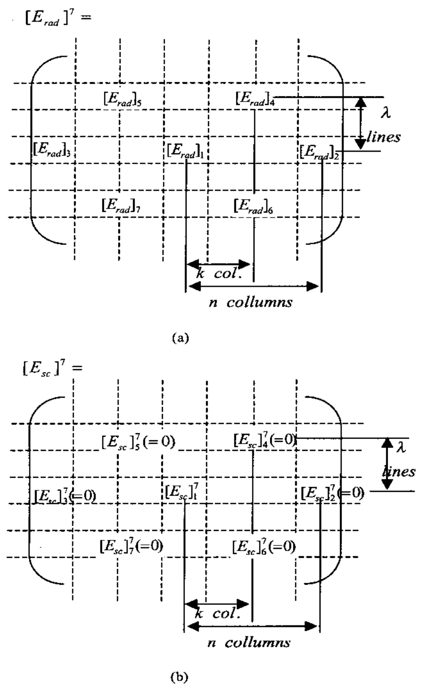


Fig. 10. A matrix representation of radiating and scattering fields in 7-element conical horn antenna array

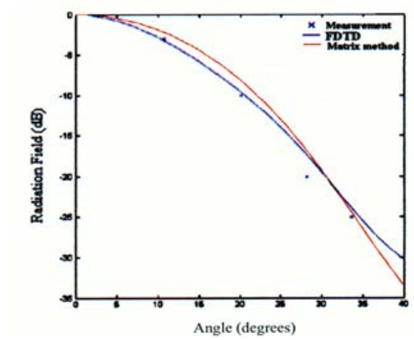


Fig. 11. Radiation pattern simulated using the matrix manipulation technique and its comparison with those from measurement and FDTD only simulation.

The proposed method has been applied in the modelling of a 7-element conical horn antenna array, in which the central element was excited in phase with and 10.5dB above the 6 surrounding elements (Fig. 8). It can be seen that the array can be decomposed into three sub-arrays/elements shown in fig 9 (a), (b) and (c) respectively. The process was under the assumption that the second order neighbour scattering interactions were too weak and hence can be neglected. Only the coupling effect produced by the central element was considered. The matrix manipulation method recorded the interaction of the elements 1-2 (Fig. 9a) and 1-4 (Fig. 9b) separately, as well as the radiation of element 1 alone (Fig. 9c). Now that both the radiation and coupling effects were calculated as sub-matrices, we can gather them into one radiation and one coupling global matrix. These matrices represented snap-shots of electric and magnetic fields in sub-computational regions (Fig. 10) and hence the total field of the array can be obtained as:

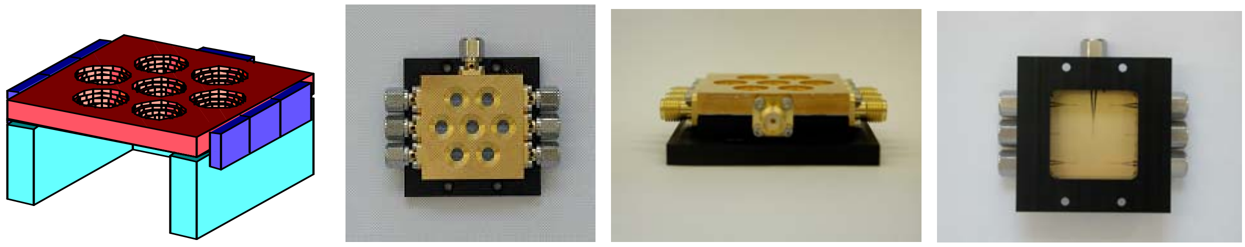
$$[E_{total}] = [E_{rad}]^7 + [E_{sc.}]^7 \quad (6)$$

$$[H_{total}] = [H_{rad}]^7 + [H_{sc.}]^7 \quad (7)$$

Equations (6) and (7) contained all the data that the near-to-far field algorithm needed to calculate the radiation pattern of the array. In Fig. 11, the radiation patterns of the conical horn array (Fig. 8) obtained from measurement, FDTD and the Matrix Manipulation method were compared and it showed very good agreement. A comparison of computer resources needed for the Matrix Manipulation and FDTD only methods can be found in [16].

The Active Conical Horn Antenna Array

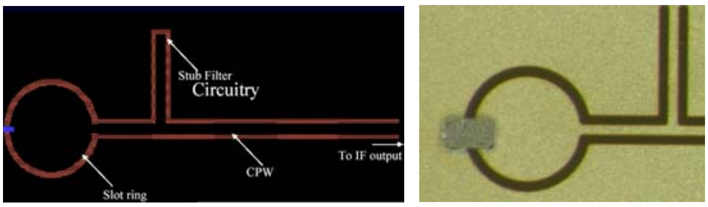
There were many challenges in constructing low noise quasi-optical receivers at millimetre and submillimetre wavelengths. At such high frequencies, substrate modes are often excited and hence the antennas resulted in poor radiation patterns and low efficiency. One solution was using extended dielectric-substrate lenses to suppress the substrate modes [7]. Unfortunately, although a focusing lens can produce desirable radiation patterns, it was also responsible for wave losses inside the dielectric material. To overcome this difficulty, many researchers tackled the problem by developing and optimizing high-efficiency integrated horn antennas [5]. The horns were usually made by anisotropic etching of silicon in an ethylenediamine-pyrocatechol solution. This widely used approach naturally formed pyramidal horns bounded by crystal planes in silicon, which fixed the flare angle of the horn at 70 degrees. The angle was too large to obtain a satisfactory radiation pattern. In this project, the aforementioned hard surface conical horn was used (Fig. 12) and a detailed design procedure can be found in [2].



(a) (b) (c) (d)

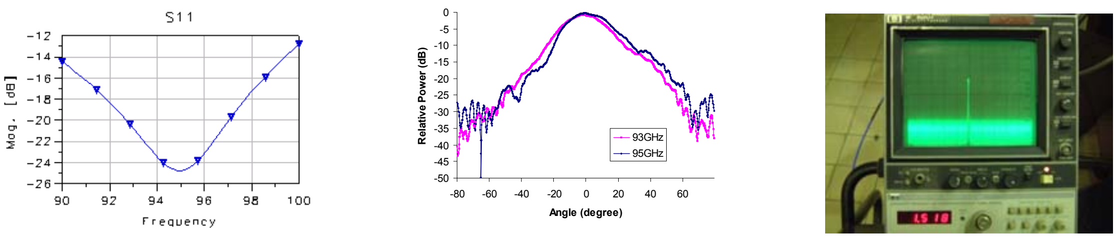
Fig. 12. (a) A three dimensional view of the proposed hard surface conical horn antenna array with its supporting structure
Photographs of the fabricated hard surface conical horn antenna array with its associated slot ring mixers
(b) top view; (c) side view; (d) bottom view

The annular slot mixer was designed to resonate at 95GHz. It was based on a 300um thick *Si* substrate with a CPW line as IF output (Fig. 13a) The planar Schottky diode was integrated with the slot antenna to produce a single chip millimetre wave receiver module (fig. 13b). The LO signal was injected quasi-optically. The diode down converted the RF signal (95GHz) to an intermediate frequency (IF) of 2 GHz. The IF line was attached to an SMA connector. Although these connectors were very lossy at 95GHz, an extra IF filter was designed to provide additional rejections of the RF signal. From a simple harmonic balance analysis with the DiodeMX programme, the computed conversion loss was about 6.5dB, which is a typical value for a single mixer. The simulation of the annular slot as an antenna was done by a commercial available software package called Agilent-ADS (Advanced Design System). Fig. 14a showed the simulated slot ring resonance at 95GHz. The final demonstrator was measured at QM's antenna laboratory. Some example radiation pattern can be found in Fig. 14b. Fig. 14c showed a received IF signal well above 30 dB over noise floor.



(a) (b)

Fig. 13. (a) A layout of 95GHz slot ring mixer with an IF filter in ADS simulation
(b) A photograph of slot ring mixer on silicon substrate



(a) (b) (c)

Fig. 14. (a) Simulated slot ring resonance at 95GHz using Agilent ADS.
(b) Measured E plane radiation pattern of active conical horn antenna array at 93 and 95 GHz respectively.
(c) Measured IF signal using Agilent spectrum analyser.

***Project Plan Review*:**

The aims of this research project were achieved. Some minor differences between the proposed methodology and the research programme occurred. Specifically, the discrete Green's Function FDTD method was not adopted since it was designated for perfect conductive objects and had many restrictions when applied into arbitrary dielectric objects. However, a more efficient approach, namely the Matrix Manipulation technique was proposed instead for modelling the antenna arrays.

Research Impact and Benefits to Society:

The relationship with the Millimetre Wave Technology Group, Space Science and Technology Department, Rutherford Appleton Laboratory (MMT) was enhanced. They fabricated the active slot ring antenna arrays, conical horn antennas and offered packaging for the final demonstrator. Some of the work has been further exploited for another EPSRC project GR/S63557 to investigate the integration of photonic devices with EBG antennas, which now employs Mr Douvalis as an RA. It is apparent that the future imaging array technology will be largely based on active integration and system-on-chip technologies. The use of conical horn antenna arrays and perhaps EBG in the future will bring more degrees of freedom in millimetre/submillimetre wave antenna design. Indeed, the work proposed in this project has been included in a bid for DTI Basic Technology Programme by Queen Mary jointly with BAe System *etc,* which has successfully passed the first review stage. Academically, the stability analysis of LNFDTD and a novel stable nonorthogonal FDTD algorithm was developed and is seen as extremely beneficial to computational electromagnetic community. In addition, the paper submitted to IEEE International Symposium on Antennas and Propagations, Monterey, 2004, was chosen as one of finalists in a student paper competition. Two journal and seven conference papers were published and two more journal publications are in preparation.

Explanation of Expenditure:

Spending was basically in agreement with what was planned in the original project proposal. The only difference occurred was in the cost of travel. This was because increasing registration fees (e.g. IEE conferences) and airfare. However, it was offset by the surplus from the computer equipment purchase, where the cost of PC was seen reducing dramatically.

Further Research or Dissemination Activities:

Extensive measurement of the antenna array will be continued and an appropriate measurement approach is being considered, and it is expected that this work will lead to one more journal publication. A possible project of developing a 300GHz version of imaging arrays has been discussed with MMT, RAL and it is hoped that it can be funded in the near future.

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