Radiating Element Design for a Multi-Octave Phased Array Aperture

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Abstract

Previous work has characterised the performance of wideband arrays based upon the Vivaldi and the Highly-Coupled Dipole radiating elements. It was shown that, rather than something to be minimised or avoided, mutual coupling is a significant factor in achieving very wide bandwidths of operation. This work seeks to exploit the knowledge gained of the generic and element specific techniques in order to optimise the design of a multi-octave phased array.

Keywords: antenna, phased array, mutual coupling, multi-octave bandwidth

Introduction

With space at a premium and a need for increasing functionality at lower cost, multi-octave phased arrays will enable shared aperture systems to be designed incorporating multiple RF functions. To support the development of such arrays requires an understanding of the array environment.

In previous work [1], the performance of the Vivaldi and the Highly-Coupled Dipole (HCD) radiating elements were characterised using models of large finite arrays. It was shown that, rather than something to be minimised or avoided, mutual coupling is a significant factor in achieving very wide bandwidths of operation for phased arrays. For the two types of radiating elements investigated, the Vivaldi and the HCD, an increase in the levels of mutual coupling contributed to a reduction in the lowest operating frequency and, therefore, an increased bandwidth.

This work seeks to exploit the knowledge gained of the generic and element specific techniques in order to optimise the design of a multi-octave phased array. The steps taken towards this goal are described below.

Radiating Element Selection

As discussed above, two radiating elements were characterised as part of previous work. The HCD was initially based upon the element proposed by Munk [2], an example of which is shown in Figure 1. This shows an implementation using co-axial cables. However, in practice, a stripline feed is easier to fabricate.

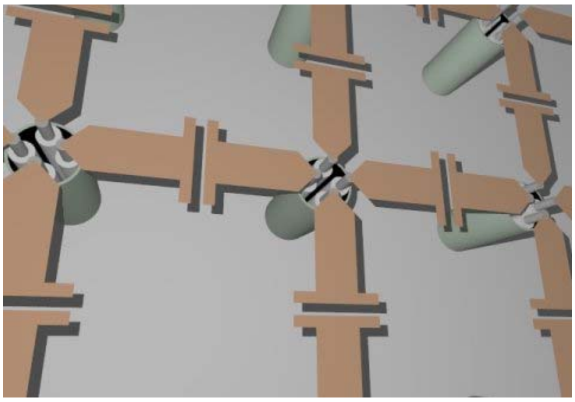

Figure 1 *An example of an array of Highly-Coupled Dipole (HCD) radiating elements*

Both the Vivaldi and the HCD were considered to be capable of the required bandwidth (the target requirements are discussed below). Achieving the required bandwidth was the principal criterion for selection. However, the HCD offered a number of other benefits. For example, it is a low profile element, with a ground plane spacing which is typically $\lambda_{max}/10$. This compares well with the Vivaldi which is typically $\geq \lambda_{max}/4$ [3]. It is also relatively straightforward to accommodate orthogonal elements with common phase centres, giving dual (independent) polarisations. The element that was therefore selected for further development was the HCD.

Design Parameters

The first task in the design optimisation was to identify the parameters that principally affected the element performance (e.g. factors determining achievable bandwidth and performance within that frequency band). Some of this information came from a review of previous work [1] but further development was required to understand the relationship between the multiple design parameters. Thus, a parameterised model was required which incorporated both generic and element specific features. The principal design features of this model that affect bandwidth are discussed below:

Inter-element capacitance. For the HCD, the inter-element capacitance is a significant parameter. Munk [2] uses an inter-digital capacitor and the effect of this is to increase the mutual coupling, particularly at the lowest frequencies. However, the HCD considered here is based upon a bow-tie dipole. In this case, the inter-element capacitance is an inherent feature due to the proximity of the parallel edges of the dipole arms. The capacitance is determined by the length and separation of these parallel edges (Figure 2) and the dielectric constant of the material supporting the dipole arms.

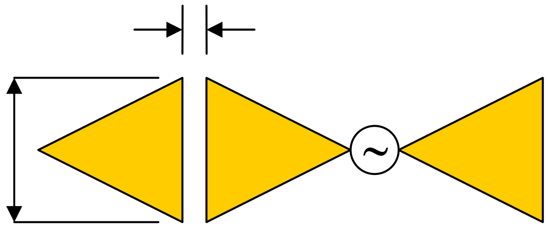

Figure 2 *Parameters affecting inter-element capacitance in an array of Bow-tie dipole elements*

Dielectric loading. Dielectric loading of the front face of the array was previously found to improve both the bandwidth and the performance at large array scan angles. This loading consisted of either single or double layers, but they were relatively thick, approximately $3\lambda_{min}/4$. However, alternative dielectric structures were investigated (Figure 3) which were typically $\leq \lambda_{min}/4$. These thinner structures are important in terms of the overall height and weight of the array.

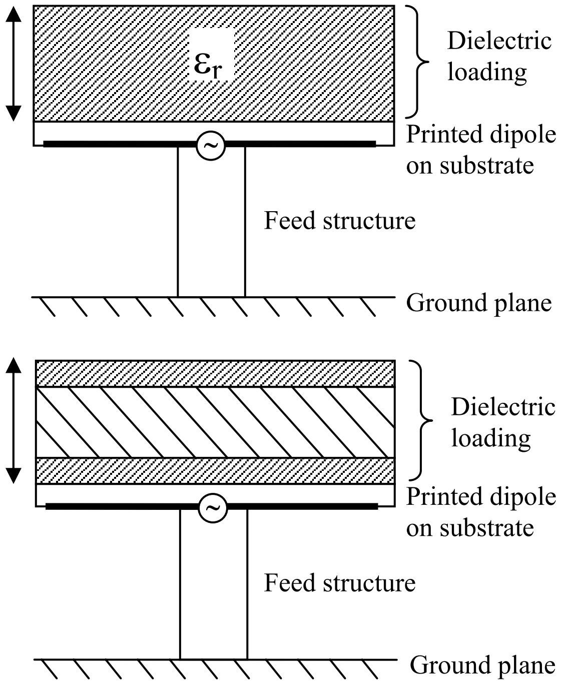

Figure 3 *Two forms of dielectric loading on top of the HCD element*

Ground plane spacing. As stated previously, the ground plane spacing is typically $\lambda_{max}/10$. Therefore, increasing the ground plane spacing will, in principle, reduce the lowest operating frequency. To achieve this reduction though, other parameters, such as the inter-element capacitance need to be adjusted to offset the degraded passive input match that the proximity of the ground plane creates.

Element spacing. The element spacing was also considered as a design parameter. Although there is a maximum value, beyond which array grating lobes will exist in real space, performance at the top of the frequency band can be manipulated by varying this spacing.

There are several other parameters, such as those relating to the antenna feed, the dielectric constant of the dipole substrate, etc. These parameters generally do not affect the bandwidth, but do affect the active VSWR within the achievable frequency range.

EM simulation of phased arrays

There are a number of techniques for simulating the performance of a phased array antenna. Each technique has a number of benefits and limitations. For example, the use of periodic boundary conditions allows the performance of an element immersed in an infinite array to be predicted. The duration of these simulations tend to be relatively short, but they produce results at only one array scan angle and give no information about elements near the edge of a finite array. Full-wave simulations of large finite arrays are computationally expensive, but can provide information for every element in the array. This information includes the mutual coupling from which the active VSWR can be calculated for all required array scan angles [1].

Given that a large number of design iterations need to be considered as part of the element optimisation, speed of analysis was considered the most important attribute. Thus, the design optimisation used models of elements immersed in an infinite array.

The software used for predicting the performance of each element design was the BAE SYSTEMS ATC code “AGATE”, based upon the Finite-Difference Time-Domain (FDTD) technique. The great advantage of a time domain code is that a single simulation can provide the performance at all frequencies within the specified bandwidth. This is significant when predicting the performance of the array over multiple octaves.

Each design iteration was evaluated by predicting the active VSWR at three array scan angles; boresight (BS), and 50° from boresight in each of the E- and H-planes (E50 & H50). The results from these three simulations were then combined to give a single cost function for the optimisation process.

Optimisation Process

The parameterised model of the HCD element contained a large number of variables. The optimisation would therefore be a computationally expensive process. For this reason, a brief review of potential techniques that were suitable for optimising a wideband radiating element in an array environment was undertaken.

Parameter sweeps. This involves stepping each parameter through a pre-determined range. This was considered to be very inefficient.

Gradient optimisers. ‘Hill climbers’ which are efficient for finding local minima/maxima in well behaved functions.

Global optimisers. These are less ‘efficient’ than hill-climbers but avoid local minima/maxima. Examples include Simulated Annealing (SA) and Genetic Algorithms (GA).

The Genetic Algorithm was selected for this optimisation since it is tolerant of large numbers of parameters, multiple minima and noisy or discontinuous functions (e.g. resonances). There are many implementations of GA’s and a more detailed review of this class of optimiser subsequently identified the Micro Genetic Algorithm (µGA) [4,5]. This has a typical population of 5 individuals rather than 100’s and is considered to be more efficient than a standard GA

The µGA can be described in the following way:

1. A µ-population of five designs is generated randomly.
2. The fitness of each design is determined and the fittest individual is carried to the next generation (elitistism).
3. The parents of the next generation of individuals are determined using a tournament selection strategy. In this strategy, designs are paired randomly and compete to become parents of the remaining four individuals in the following generation.
4. Children are produced by randomly selecting each bit in the chromosome from one of the two parents (uniform crossover).
5. The convergence of the µ-population is checked. If the population is converged (95% of all bits in the chromosome are identical), go to step 1, keeping the best individual and generating the other four randomly. If the population has not converged, go to step 2.

Note that mutations are not applied in the µGA since enough diversity is introduced after convergence (step 5). Another significant aspect is that, apart from the first generation, only four individuals are evaluated for each generation. This results in reduced computational requirements. When executed on a PC cluster, each individual can be evaluated in parallel resulting in a very high throughput for each generation.

The Micro-Genetic Algorithm (uGA), when coupled with the FDTD algorithm, therefore offers a robust optimisation process for wideband antennas.

Optimised Element Performance

The optimisation process required a cost or fitness function to be derived for each individual. This was based upon the target performance, which is listed in Table 1.

Characteristic	*Value*
Frequency Range	2.7 – 10.8GHz (4:1)
Active VSWR	Desirable: 2:1 Acceptable: 2.5:1
Scan range	±60° in all planes
Polarisation	Dual linear (Orthogonal)

Table 1 *Target performance requirements.*

The cost function needed to differentiate between resonant features and ensure acceptable performance over as much of the scan volume as possible. To achieve this, the cost function was defined as follows:

$$Fitness = \sum_{f=1}^{n} \sum_{\theta,\phi} \begin{Bmatrix} if\ \rho(f,\theta,\phi) \geq \alpha\ then \\ \left[\rho(f,\theta,\phi) - \alpha + 1\right]^2 \end{Bmatrix}$$

where the number of frequency points, f are defined as $n = (10.8 - 2.7)/0.05$, and $\rho(f,\theta,\phi)$ is the active reflection coefficient in dB at each frequency point from the three angles of scan (BS, E50 & H50). α is the threshold or target value for the active reflection coefficient and was set to be -10dB (~2:1 VSWR). Thus, the goal of the optimisation is to minimise the fitness function.

The optimisation process was not entirely automatic, since periodically, it would be stopped and the results and parameters assessed. The optimisation would then be restarted with a refined set of parameter constraints. Occasionally, aspect of the geometry, such as the dielectric loading were also changed. When combined with the fact that intermediate optimisation results were retained, valuable knowledge regarding the HCD element characteristics were obtained.

Using the μGA, good results have been achieved with up to 100 generations (approximately 400 element designs evaluated). This represents a significant reduction over a standard GA for which a typical population size is likely to be in the range of 100-200 individuals.

The performance achieved by the best individual is presented in Figure 4. The horizontal scale represents the frequency, the vertical scale represent array scan angle for each of the scan planes and the colour represents the amplitude of the active VSWR. As can be seen, an active VSWR of 2:1 (grey to white colour scale) is achieved over most of the frequency/scan volume. At some frequencies this level of performance is achieved at array scan angles of up to 70°.

The active VSWR in the frequency range of 2.7 to 10.8GHz (4:1) and array scan angle of up to 60° in all three planes (E-plane, H-plane and Inter-cardinal plane [ϕ = 45°]) meets the acceptable target requirement. If the maximum array scan angle is relaxed then the bandwidth achieved is in excess of 4.5:1.

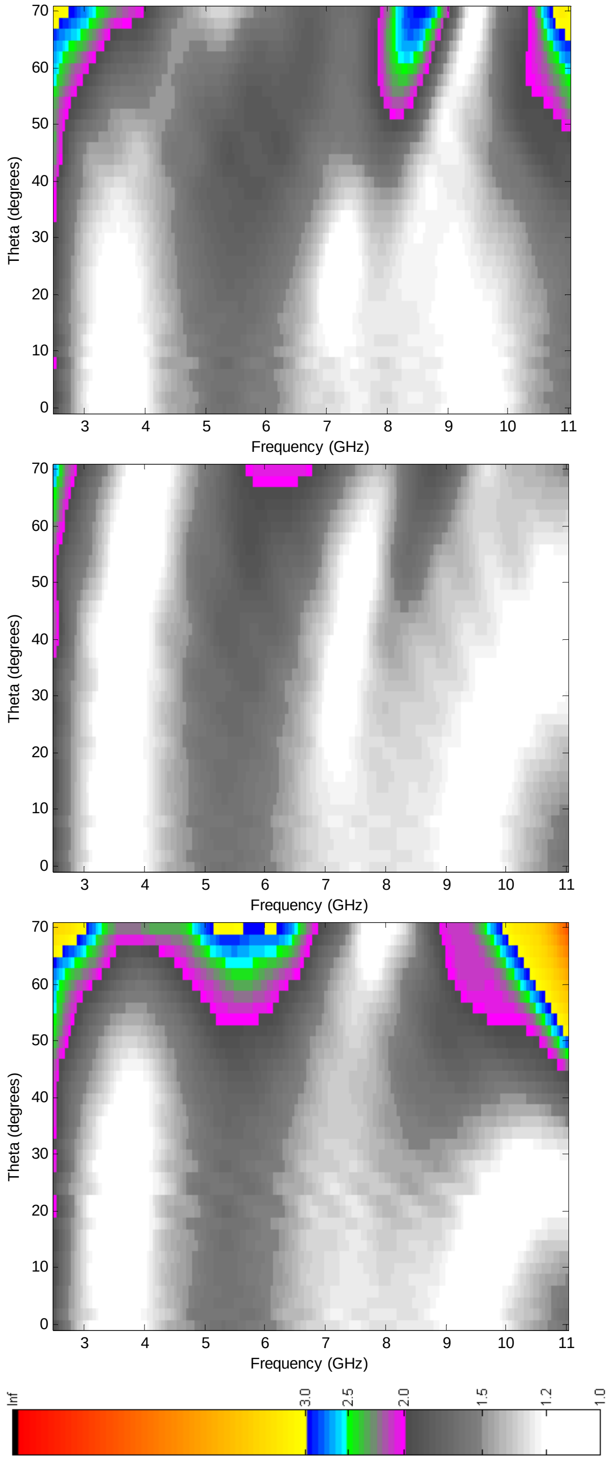

Figure 4 *Active Match vs. frequency and angle of scan for E-plane (top), Inter-cardinal plane (middle) and H-plane (bottom).*

Conclusions

This work has exploited previous knowledge gained of the generic and element specific techniques in order to optimise the design of a multi-octave phased array based upon the Highly-Coupled Dipole (HCD) radiating element.

The design parameters have been established that allow the HCD element performance to be manipulated over a very wide bandwidth. A robust optimisation process, which coupled the Micro-Genetic Algorithm (uGA) with the FDTD algorithm, was then employed in order to achieve a radiating element design capable of operating over a 4:1 frequency range and array scan angles of at least 60° in all planes.

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