Dielectric Embedded Multi-Beam Adaptive Array Antenna

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This article introduces an antenna array of vertically polarized monopole elements that uses coupling with a dielectric material and neighboring parasitic elements to formulate a single and multiple directional far-field radiation pattern with the intention of steering the radiation lobe for applications involving wireless computing. The proposed advantage is in the minimization of the number of monopole elements needed to formulate the radiation lobes subsequently reducing the radial size of the antenna structure. Where as previously reported arrays of thirteen monopole elements have been given, this array features only six monopole elements, with a steerable azimuth gain of 5.90 dBi and a beamwidth of 75° at 2.4 GHz. This article further presents an optimised antenna structure and the subsequently produced single and dual radiation lobes using a single and dual RF sources respectively.

Key Words: Adaptive array, Dielectric embedded array, Wireless computing.

1. Introduction

In recent literature a thirteen monopole array antenna consisting of two circular arrays of six parasitic elements and one central element which featured a combination of switched parasitic and switched active elements was proposed by Smith [1] for Space Division Multiple Access (SDMA) applications. It was shown by Smith that by using simultaneous active elements and appropriate positioned switched parasitic elements, simultaneous multi-directional radiation lobes maybe generated and rotated throughout the azimuth plane effectively allowing multiple users on the same channel whose signals are in different directions moreover, reduction of multi-path fading effects are also promoted due to the angular diversity of the antenna array. A version of this antenna was later proposed by Lu where the elements were embedded into a dielectric material to reduce physical size. Seemingly a size reduction of 60 % was achieved using a Nylon dielectric material with an ε_r of 4.5 [2]. This paper follows on from Lu's work and proposes an antenna referred to as a Dielectric Embedded Multi-Port (DEMP) array antenna, where the term *port* is used in this paper to refer to an RF excitation terminal. The proposed antenna structure will be shown to be capable of producing and rotating single and dual radiation lobes throughout the azimuth plane, however rather then using parasitic elements to form a directional pattern, this structure uses eccentric positioned (not centered in the dielectric material) active elements in the dielectric material effectively forming desired radiation patterns by coupling with the dielectric material and the induced fields in the remaining elements rather then solely relying on neighbouring elements as in the case of the switched parasitic or reactively loaded array antennas [3]. Where as Smith and Lu antenna arrays featured thirteen elements, the array presented in this paper only contains six while still producing significant radiation gain and desirable radiation characteristics. The following section will present the propose antenna array structure while section 3 introduces the method used to design and optimise the antenna structure. Section 4 details the measured radiation characteristics for single and dual beam operation with section 5 providing a conclusion.

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2. Proposed Antenna Array

The functionality of the proposed antenna is based on the work presented in 1975 by Wu [4], who presented a dipole antenna positioned eccentric in a circular shaped dielectric material. It was shown by Wu when a monopole or dipole antenna is centrally placed in a dielectric with uniform thickness the produced far field pattern is omni-directional, however when the antenna is relocated somewhere along the radii of the material, the fields inside the dielectric material will not by symmetrical and thus with proper placement a directional radiation patterns maybe formed. The structure proposed by Wu only consisted of a single dipole antenna in the dielectric material with the intended applications including trailing-wire transmitting and receiving antennas for submerged divers, submarines and surface antennas for communication between missile silos [4]. The proposed array of six monopole elements which are vertically polarised and positioned in a circular array at 60° intervals are illustrated in Fig. 1 which also shows the elevation θ and azimuth ϕ angle conventions. The finite ground topology of the DEMP antenna is somewhat unconventional and is explained further on.

Forming a directional radiation lobe is achieved by changing the position of the RF source between the monopole elements while multi-lobe radiation maybe achieved using simultaneous active elements. The intended application of the antenna array is for wireless computing using the 802.11b standard therefore the frequency region of interest was 2.4 - 2.5 GHz. A cross section of the DEMP antenna is illustrated in Fig. 2, the array is situated on a finite ground skirt and embedded by Poly-Vinyl Chloride (PVC) with a specified ε_r of $3-j0.12$ and corresponding loss tangent of δ of 0.04 at a frequency of 1 MHz

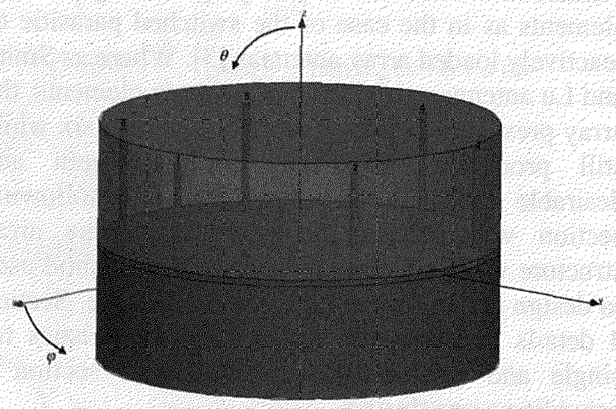

Fig. 1. Illustrated of the 6-Element (DEMP) array showing the arrangement of the monopole elements

The elements are held in position by an FR4 fibre glass printed circuit board (PCB) containing a single sided conductive ground plane. Each element of the array may become active as such was connected to a SMA connector mounted flush to the ground plane on the bottom-side of the PCB as depicted in Fig. 2. A hollow cylindrical shaped ground skirt extending in the z-axis was used in order to obtain reduction in the elevation of the principal radiation lobe. According to Weiner this is achieved due to the ground currents in the skirt normal to the horizontal plane and therefore contributing with the monopole elements to radiation below the lateral ground plane [7]. It was shown by Schlub in [8] the ground skirt must be at least 0.25λ in order to achieve maximum gain in the horizontal plane. The ground skirt also allows for an accessible RF port underneath the elements and minimizes a planar ground plane hence creating an ergonomic structure.

3. Antenna Realisation

While derivations for the current distribution and radiated fields have been provided by Wu [2] and King [5], [6] for an eccentric embedded dipole antenna, no consideration has been given for a monopole antenna on a finite ground plane also, as the intended applications involved the dielectric embedded antenna submerged in a large body of conductive water a majority of the work proposed on solving for the radiated fields was based on the ambient medium having a significant conduction loss then the dielectric material, making the presented field equations inappropriate as a design tool. As such simulation and optimisation was considered the most convenient and effective design tool.

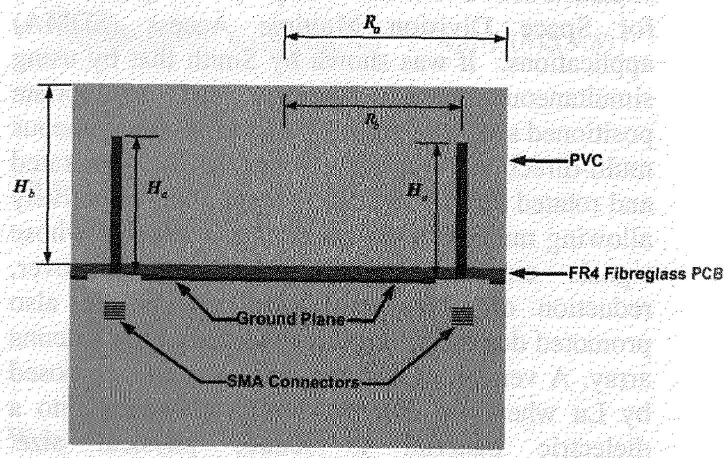

Fig. 2. Illustrated side view of the 6-Element (DEMP) Antenna

Optimisation of the antenna structure was carried out using a single objective Genetic algorithm (GA) and a finite element package. The optimisation parameters include the element height H_a, the PVC height H_b, PVC radius R_a and the radius of the element array R_b as these parameters effect the produced far field radiation pattern. The fixed parameters include the element diameter and length of the ground skirt which were 0.008λ and 0.25λ respectively at 2.4 GHz.

The performance of an ideal DEMP antenna would give a reflection coefficient S_{11} of zero and a maximized directivity between an arbitrary angle in the horizontal plane defined by ψ and conversely a minimization of directivity in the remaining horizontal region. The implemented fitness function used by the GA is given in equation (1) where $D(\phi)$ is the simulated H-Plane normalized to the maximum simulated directivity at $\theta = 90^\circ$.The GA sought to maximize this function in order to find the optimal structural parameters.

$$f = \left(1-|S_{11}|^2\right)\left(\int_{360^\circ-0.5\psi}^{0.5\psi} D(\phi)\,d\phi\right)\left(\int_{0.5\psi}^{360^\circ-0.5\psi} D(\phi)\,d\phi\right)^{-1} \quad (1)$$

4. Optimised Antenna Array

Subsequently the optimised structural dimensions of the antenna were found to be a H_a of 0.22λ, H_b of 0.253λ, R_a of 0.408λ and R_b of 0.337λ with respect to 2.4 GHz after approximately 200 simulations were completed. The constructed antenna is shown in Fig. 3 which was hand built in a manner of hours. The ground skirt was fabricated from brass sheet metal and soldered to the PCB.

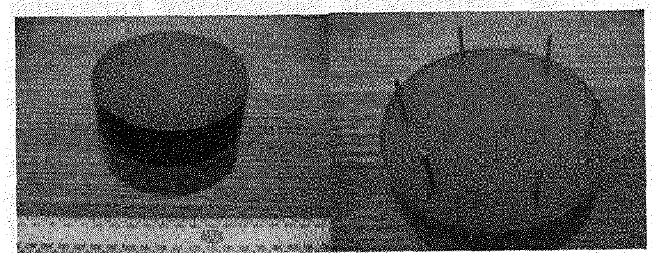

Fig. 3. Constructed 6-Element dielectric embedded multi-port antenna with and without PVC material

4.1 Single active element

The measured reflection coefficient S_{11} as a function of frequency for a single active element is given in Fig. 4 as well as the simulated response, all other elements were floating. As shown the antenna is resonant at the frequency band of interest with a -10dB bandwidth of approximately 500 MHz. The additional resonant frequency seen at approximately 2.15 GHz was unexpected and was considered due to the finite air gap between the element and PVC altering the feed point capacitance. The radiation pattern at 2.45 GHz when element 1 has an RF source is given in Fig. 5 along with the simulated pattern showing a high degree of consistency.

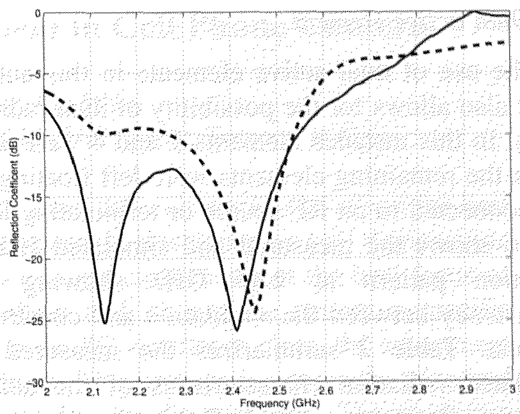

Fig. 4. Measured and simulated S_{11} as a function of frequency, measured (-) ; simulated (--)

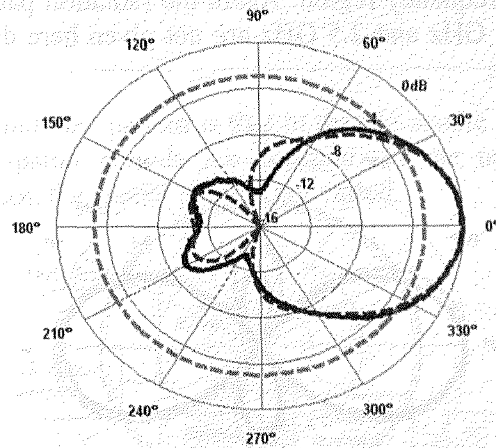

Fig. 5. Measured and simulated H-Plane radiation patterns at 2.45GHz for a single active element, $\theta = 90^\circ$, Measured (-); Simulated (--); 3dB Beamwidth (--)

Table 1 shows the measured gain, beamwidth and front to back ratios at 2.4 GHz, 2.45 GHz and 2.5 GHz showing the measured gain varied between 5.9 dBi and 4.36 dBi for 2.4 GHz - 2.5 GHz respectively. The beamwidth however remained relatively stable between 2.4 GHz - 2.5 GHz with minimum and maximum recorded values of 75° and 78.5° respectively. The radiation patterns at 2.4 GHz and 2.5 GHz are not given here due to brevity

Table 1. Measured gain (AG), Beamwidth (BW) and Front to Back Ratio (FBR) for a single active element

Frequency	AG	BW	FBR
2.4GHz	5.90dBi	75°	18.5dB
2.45GHz	5.18dBi	78.5°	15.5dB
2.5GHz	4.36dBi	78.5°	14dB

4.2 Dual active element

The use of dual active elements in this antenna array also allows for the possibility of dual radiation lobes. In this instance elements 1 and 4 were active while the remaining elements were left floating (*i.e.* not connected to an RF source or terminating load). Fig. 6 shows the measured and simulated H-Plane radiation pattern at 2.45 GHz showing high consistency between the simulation and constructed antenna. Table 2 summarizes the measured and simulated radiation characteristics of the antenna structure. Referring to Table 2 the measured gain is seen to vary between 3.5 dBi and 2.2 dBi between 2.4 GHz and 2.5 GHz respectively while the beamwidth varies between 60.5° and 53° for the same frequency region. Again the radiation patterns for 2.4 GHz and 2.5 GHz are not given here due to brevity.

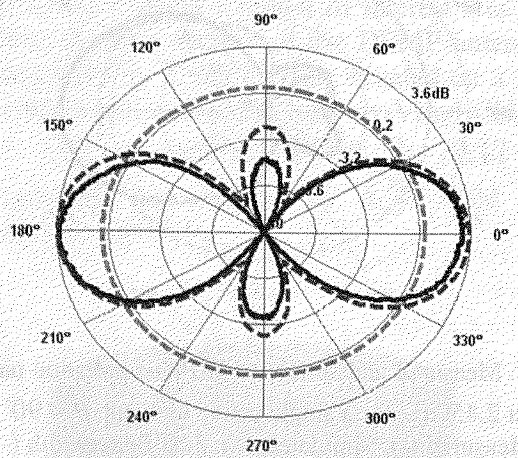

Fig. 6 Measured and simulated H-Plane radiation pattern at 2.45GHz for dual active elements $\theta = 90^{\circ}$ Measured (-) ; Simulated (--); 3dB Beamwidth (--)

Table 2 Measured gain (AG), Beamwidth (BW) and Front to Back Ratio (FBR) with dual active elements

Frequency	AG $\phi = 0^{\circ}$	AG $\phi = 180^{\circ}$	BW $\phi = 0^{\circ}$	BW $\phi = 180^{\circ}$
2.4GHz	3.5dBi	3.5dBi	60.5°	60.5°
2.45GHz	3dBi	3.5dBi	53°	55.8°
2.5GHz	2.2dBi	2.76dBi	53°	55°

5. Conclusions

Rather then forming directional radiation fields solely using neighboring monopole elements, this paper considers the notion of forming directional radiation fields using an eccentric monopole element in a dielectric material. Six-elements were arranged in a circular array allowing a steerable radiation lobe by changing the position of the RF source. An optimised antenna was constructed and subsequently its radiation characteristics were measured in an anechoic chamber showing the formation of single and dual radiation lobes in the horizontal plane. It is believed the advantage of this array is in the reduction in the number of array elements needed to formulate a radiation lobe of significant gain due to the coupling to the embedded dielectric material and consequently reducing the radial size of the antenna and complexity of the control circuit.

Future work at present consists of the realization of this antenna with different shaped dielectric materials which may allow for multi-band operation and unique shaped radiation patterns.

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