Planar Multi-layer Passive Retrodirective Van Atta Array Reflectors at X-band

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Abstract—**Retrodirective array reflectors have found many applications in the area of collision avoidance systems, satellite communications and enhancing RCS in general. This paper presents two planar multi-layer passive retrodirective Van Atta array reflectors based on microstrip antenna operating at X-band. Theoretical analysis of the Van Atta array will be outlined, together with simulation results and RCS measurements of the planar Van Atta array reflectors. Future development in extending the bandwidth of the passive Van Atta array and further increase in RCS will also be discussed.**

Keywords— Retrodirective reflector; Van Atta; antenna array

I. Introduction

Retrodirective array reflectors, for which the reflected field has a maximum in the direction of incident plane wave, have found many applications in the area of collision avoidance systems [1], satellite communications [2], and enhancing radar cross sections (RCS) in general [3]. The two main types of retrodirective array are the phase-conjugated array and the Van Atta array. While the phase-conjugated array is very effective in achieving retrodirectivity, it requires active component such as mixers and a local oscillator, which increase the complexity and add to the weight and cost of an array [4].

The Van Atta array, first introduced by L. C. Van Atta [5], is the simpler design of the two. In an array of passive or active antenna elements, antennas are connected by transmission lines in pairs to the element located symmetrically to the array centre. The incident field received by each antenna feeds the corresponding antenna via transmission line and is reradiated. The phase distribution of the reradiated fields is the reverse of the received fields, and therefore reradiates the wave back towards the incident direction.

This paper presents the development of two planar multi-layer passive retrodirective Van Atta array reflectors for application at X-band: a single-polarisation array and a dual-polarisation array based on the square microstrip antenna elements. Theoretical analysis of the Van Atta array is outlined in Section II, with previous work on Van Atta array prototypes summarised in Section III. The multi-layer design methodology and results of the single-polarisation planar multi-layer array will be presented in Section IV, with a brief discussion of the results and future work to be given in Section V.

II. Theory of Passive Van Atta Array

To illustrate the operation of a Van Atta array, a simple 4-element Van Atta array is shown in Fig. 1. Each antenna is connected to its corresponding antenna located symmetrically about the array centre via transmission line, i.e. Antennas 1 and 4 are connected by a transmission line of length l_1, and antennas 2 and 3 are connected by a line of length l_2. The difference in line lengths can be a multiple of the wavelength, but for frequency invariant operation equal length transmission lines would be ideal. For a plane wave incident upon the array at an angle θ, a receiving phase lag of $\varphi = k_0 d \sin\theta$ is introduced between adjacent antenna, where $k_0 = 2\pi/\lambda_0$ is the free-space propagation constant and d is the antenna spacing. In general for a Van Atta array with N elements, the signal received by the n-th antenna can be given as [6]:

$$S_n^r = K_f E_0 G(\theta) e^{-j(n-1)\varphi} \quad (1)$$

where K_f is the antenna feed factor, E_0 is the electric field strength of the incident wave, and $G(\theta)$ is the gain of the antenna element at incident angle θ. This signal is fed to the connected antenna via the transmission line at which it will be reradiated. Therefore, there is a relative phase reversal for the reradiated wave across the array, as illustrated in Fig. 1, if all the transmission lines are of the same length. The reversal of the phase distribution of the received incident wave results in the reradiated wave having the maximum magnitude in the direction of the incident wave, thus achieving retrodirectivity. For a Van Atta array with N elements, the total reradiated field towards the incident wave direction θ is given by:

$$E_{rad}(\theta) = N\left[\frac{e^{-jk_0 r}}{r} e^{-j(N-1)\varphi} K_f E_0\right] G^2(\theta) e^{-jk_t l} \quad (2)$$

where k_t is the propagation constant of the transmission lines and l is their length. The reradiated field is proportional to the total number of elements and the square of the antenna element gain.

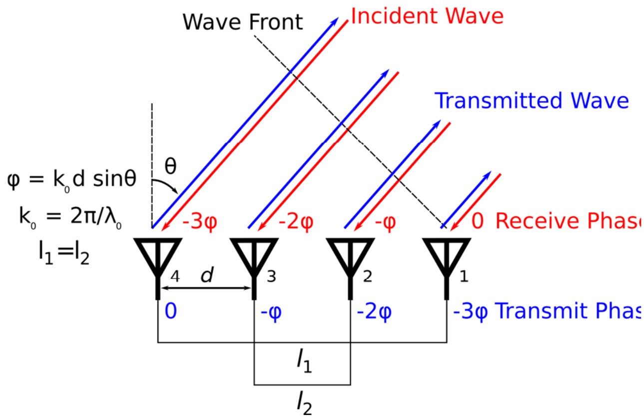

Figure 1. A simple 4-element Van Atta array.

Passive microstrip antenna elements will form the basis of a planar Van Atta array to be operated in X-band. In this arrangement the ground plane of the microstrip antenna acts as a metallic reflector which will influence the total field scattered by the array. Another scattering mechanism is the scattering from the individual antenna elements. The major scattering mechanisms from a planar Van Atta array are shown in Fig. 2, and they are: the reradiated field by the antennas, the scattered field by the terminated antennas, and the scattered field by the metallic ground plane. The two scattered fields have narrow beamwidth and their magnitude drops off very quickly away from normal incidence. Whereas the reradiated field as shown in (2) is generally a slowly varying function of incidence angle θ and it is the dominant contributor in the array's retrodirectivity. However, at normal incidence the magnitudes of the reradiated field and scattered field become comparable, thus generating a ripple in the total field magnitude for angles around normal incidence. Fig. 3 illustrates the typical normalised amplitude of the scattered field, reradiated field and the total field of a general planar Van Atta array [7].

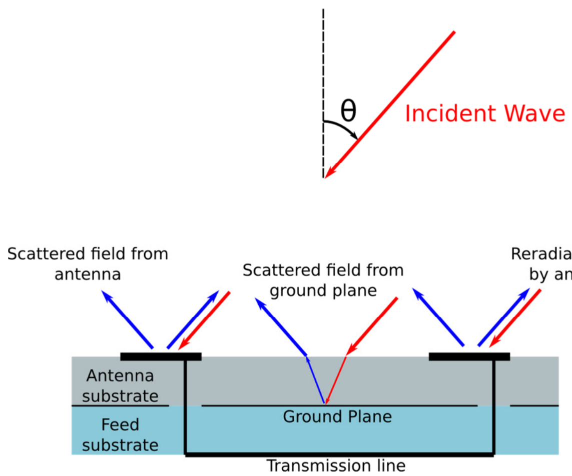

Figure 2. Scattering mechanisms from a planar Van Atta array reflector.

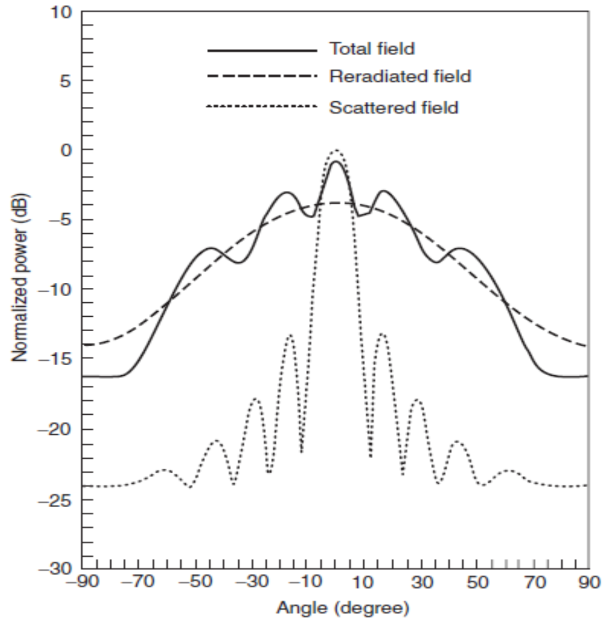

Figure 3. Scattered field, reradiated field and total field pattern of a general planar Van Atta array [7].

III. PASSIVE VAN ATTA ARRAY PROTOTYPES

Two passive Van Atta array prototypes were constructed, with the 16-element array arranged in a 4 x 4 formation and the 64-element array arranged in an 8 x 8 formation [8]. Probe-fed square microstrip antenna was chosen for its simplicity in fabrication and the ability of dual-polarisation operation. SMA connectors are soldered on the ground plane with the centre conductor feeding each element, and the elements are connected by coaxial cables of equal length to its counterpart in the opposite quadrant of equal distance from the array centre, thus achieving retrodirectivity in both azimuth and elevation. As reported in [8], the measured monostatic RCS of the 16-element prototype array demonstrated a reasonable agreement with simulation, with a maximum RCS level of around -5 dBm^2 and a 3 dB beamwidth of around 60° at 9.5 GHz. Likewise the measured monostatic RCS of the 64-element prototype array demonstrated an excellent agreement with simulation, with maximum RCS level of around +5 dBm^2 and a 3 dB beamwidth of just above 60°. Due to the routing of coaxial cables behind the ground plane, both of these arrays are not of a pure planar form factor.

IV. MULTI-LAYER PLANAR VAN ATTA ARRAYS

Routing of the feeding network is an important issue to consider in fabricating a Van Atta array. Transmission lines of equal length are preferable in maintaining the constant phase delay across a wide bandwidth. In previous array prototypes the antenna elements are connected with equal length coaxial cables routed behind the ground plane. However as the number of elements increases routing of coaxial cables becomes quite cumbersome. A possible solution is to utilise transmission lines for the routing network and distribute them across different layers of the printed circuit board (PCB), i.e. multi-layer routing [9].

A. *Design Methodology*

In order to successfully produce a multi-layer device that performs within the required performance specifications, a rigorous process was put into place that spans from the design phase to the fabrication of the device. Important considerations, such as selecting and engaging with the preferred PCB manufacturer to obtain the relevant multi-layer process specifications and to obtain a suitable computational electromagnetics (CEM) tool that can accurately predict real world performance of the fabricated multi-layer device, were decided early in the process to support and facilitate the overall design methodology. Main steps in this methodology include:

1. Knowledge of the fabrication/manufacturing processes, capabilities and limitations – This is to ensure the multi-layer design is compatible with the manufacturing process and capability. Factors such as availability of PCB materials, layer thickness, the type of bond film, track width, minimum hole and via size will need to be taken into consideration. PCB manufacturers generally published a guideline which contains all of the relevant manufacturing process specifications [10].

2. Optimise microstrip patch elements and transmission lines for patch dimensions and layer structure – The fundamental building block of the array will be optimised in a CEM tool to obtain its dimension and the thickness of the antenna substrate material. Frequency domain solvers based on the finite-element method have been demonstrated to be more suitable for planar antenna structures [11], and therefore the commercially available CEM software package HFSS [12] was chosen to perform simulations of the multi-layer structure. It is important that the periodic boundary condition is invoked inside the antenna model to take into account of interactions between neighbouring elements.

3. Designing the layout of the feed network – For a small array this can be done manually using a PCB design tool. For larger arrays the complexity of multi-layer may require the use of a rule-based automatic routing algorithm.

4. Simulate the complete array to ensure specifications are being met – This is the critical step where the full multi-layer device is simulated using the CEM software. If required, iterate through the design process until specifications are being met.

B. *16-Element Single-Polarisation Array*

Fig. 4 shows the top and bottom layer of the fabricated single-polarisation multi-layer 16-element array. It has a physical dimension of 80 mm x 80 mm x 2 mm, with the elements in 4 x 4 arrangement to achieve retrodirectivity in both azimuth and elevation planes. The feeding network consists of 8 microstrip transmission lines, with the lines having equal length to maintain a constant phase delay across each antenna element pair, being routed on the bottom layer. The square microstrip antenna elements are etched on the top layer with each element connected to the feeding network by a probe via. Antenna elements are isolated from the feeds by a copper ground plane. CEM simulations of the array were performed using HFSS to confirm its retrodirectivity performance. The array design is sent to the PCB manufacturer for fabrication after the simulation results have been confirmed to satisfy the required specifications.

Anechoic chamber measurements were performed on the 16-element multi-layer Van Atta array, with the array oriented such that the co-polarisation response occurs on the vertically polarised channel. Comparisons of the simulated RCS response and the RCS measurement in VV-polarisation across the azimuth and elevation planes at 9.75 GHz are shown in Fig. 5 and Fig. 6 respectively. Very good agreements can be observed between the simulated and measured RCS showing retrodirective behaviour across a beamwidth of close to 60° in both azimuth and elevation planes.

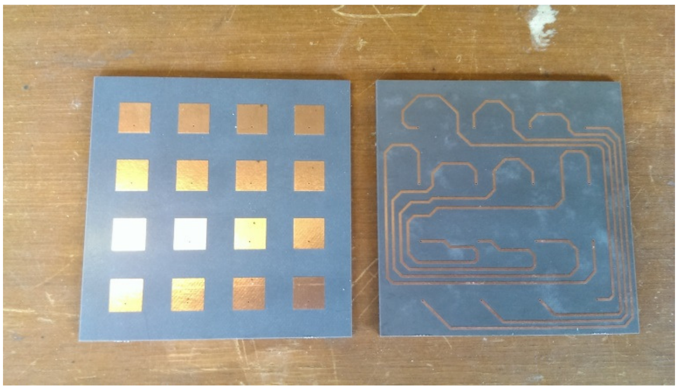

Figure 4. Fabricated 16-element Van Atta array showing the top element layer (left) and the bottom feed layer (right).

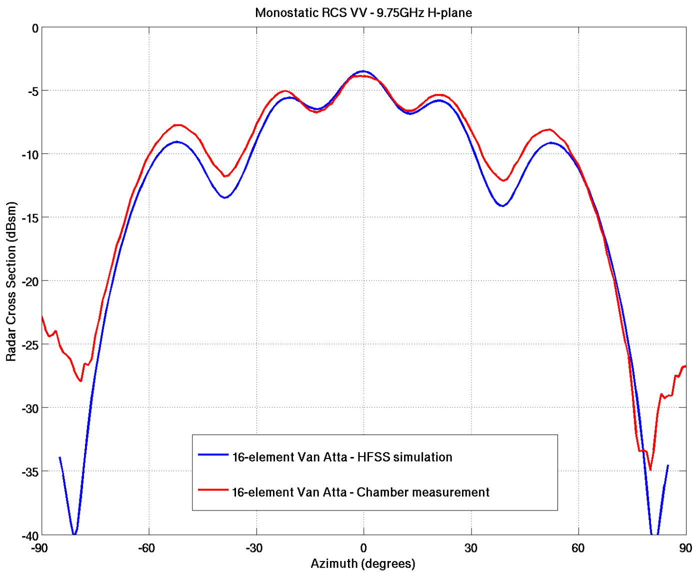

Figure 5. Monostatic RCS of the multi-layer 16-element single-polarisation Van Atta array in VV-polarisation across the azimuthal H-plane at 9.75 GHz – HFSS simulation (blue) and the chamber measurement (red).

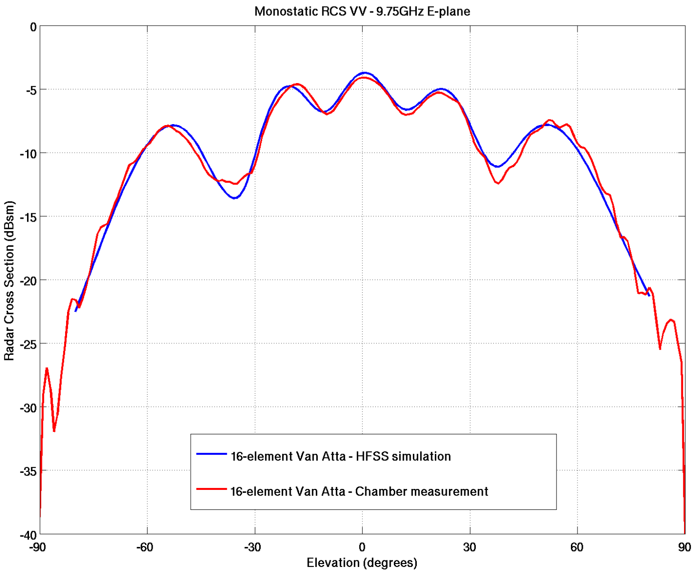

Figure 6. Monostatic RCS of the multi-layer 16-element single-polarisation Van Atta array in VV-polarisation across the elevation E-plane at 9.75 GHz – HFSS simulation (blue) and the chamber measurement (red).

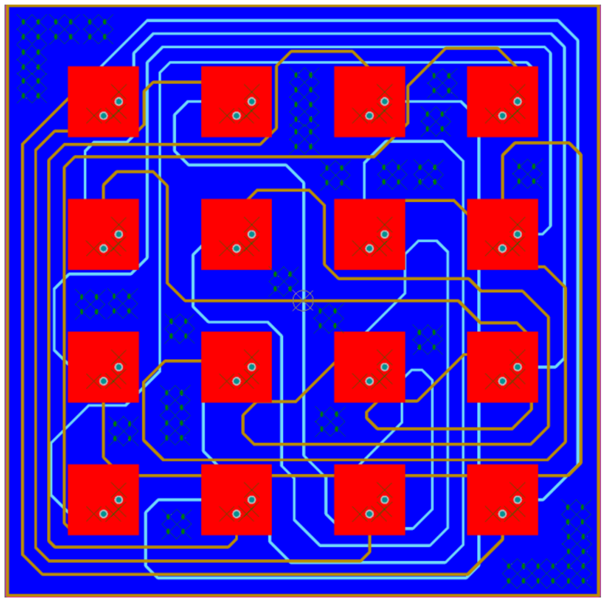

Figure 7. Layout of the dual-polarisation 16-element multi-layer Van Atta array. Copper ground planes separate the antenna elements, the first stripline feed layer and the second stripline feed layer.

C. 16-Element Dual-Polarisation Array

Fig. 7 shows the layout of the 80 mm x 80 mm x 3 mm dual-polarisation multi-layer 16-element Van Atta array, with the 4 x 4 arrangement to achieve retrodirectivity in both azimuth and elevation planes, for both V and H polarisations. The feeding network consists of 16 striplines, with the lines having equal length to maintain a constant phase delay across each antenna element pair, being distributed across two PCB layers separated by ground planes. This dual-polarisation array has been fabricated with the RCS measurements commencing shortly and results will be presented at the symposium.

V. Discussions and Future Work

In this paper, the theory of passive Van Atta array has been discussed. To realise a planar array design and overcoming the challenge of transmission line routing, an 80 mm x 80 mm x 2 mm multi-layer 16-element Van Atta array with a microstrip transmission lines network has been successfully fabricated, with anechoic chamber measurement results demonstrating co-polarisation retrodirectivity in both azimuth and elevation planes. The multi-layer design methodology outlined in this paper provides a rigorous process for the design and fabrication of future multi-layer devices. For future work a number of improvements can be implemented to enhance the RCS response and bandwidth of the Van Atta array. Active devices can be used to amplify the received signal before it is reradiated, and therefore increase the array's RCS. Antenna designs such as the bow-tie and stacked elements can also be used to extend the bandwidth response of the Van Atta array.

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