Ultra-Wideband Tightly Coupled Phased Array Antenna for Low-Frequency Radio Telescope

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Abstract— This paper introduces a novel approach to a broadband array design for a low frequency radio telescope. It presents a low profile ultra-wideband tightly coupled phased array antenna with integrated feedlines. The approach consists of applying broadband techniques to an array of capacitively coupled planar element pairs with an octagonal fractal geometry, backed by a ground plane. Designed as a low cost, low loss, dual-polarized wideband array, this antenna is optimised for operation between 50 and 250 MHz. Simulations have shown that the antenna has a wide-scanning ability with a low cross-polarisation level, over the operational broad frequency range.

1. INTRODUCTION

Nowadays, inherently low profile ultra wideband phased array antennas are significantly in demand especially for low frequency band radio telescope applications. Tightly coupled phased arrays (TCPAs) have a significant feature to imply low profile ultra wideband antennas. This feature is critical to deploy and develop radio telescope in space base station. It is also important for other applications such as advanced defence and commercial communication systems.

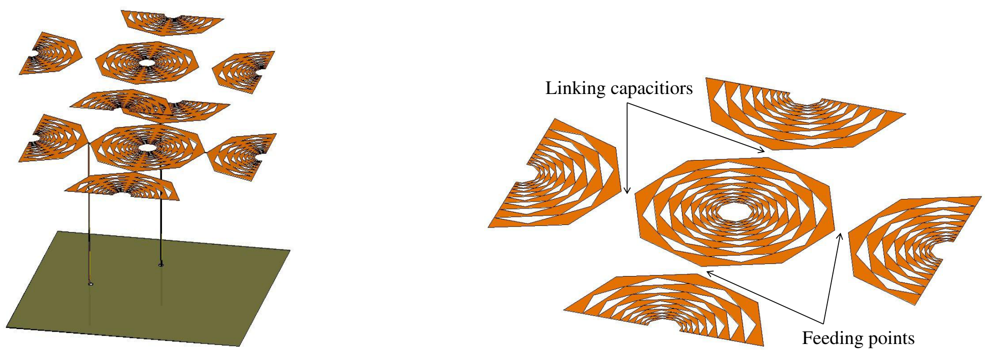
Characteristically, the tightly coupled arrays are planar elements with strong mutual coupling. Each element array acts as an aperture array rather than discrete elements. The inter element capacitive coupling is used to counteract the ground plane reactive impedance and maintain a real input impedance over a wide bandwidth. This paper presents a tightly coupled array of a conformal performance while maintaining a low profile of roughly $0.05\lambda_{low}$ where λ_{low} is the wavelength at the lowest operational frequency of the operating bandwidth [1]. However, the Vivaldi antenna is widely used as an ultra-wideband antenna, but it exhibits a profile of $0.5\lambda_{low}$ which is too thick especially in the low frequency range [2]. Additionally, the bunny ear elements also provide an ultra-wideband performance with low profile of about $0.125\lambda_{low}$ but still thick for low frequency applications [3].

This work aims to enhance the bandwidth of a proposed TCPA, operating between 50 and 250 MHz to operate from 50 MHz to 400 MHz, using a resistive frequency selective surface. The Frequency Selective Surfaces (FSSs) were first demonstrated by Ben A. Munk and used in airborne applications [4]. Recently, many researchers proposed FSS designs for different microwave applications, such as radar absorber [5], and applications associated with radome design for radar systems [6]. In [7] an artificial dielectric material was placed on a frequency selective surface to absorb the energy of electromagnetic waves at a particular frequency or range of frequencies. Also, a resistive FSS was used in [8] to enhance the bandwidth of an ultra-thin absorber. A tightly coupled bowtie array with a resistive FSS layer has shown to exhibit a $21:1$ bandwidth with VSWR < 3 in [9], implemented in an infinite array configuration.

The paper is organised as follows: in Section 2, capacitively coupled phased array design and analysis are presented. Section 3 describes new broadbanding technique used to enhance the bandwidth performance of the proposed capacitively coupled phased array, whilst the analysis of an infinite array is also presented. The conclusions are subsequently driven in Section 4.

2. CAPACITIVELY COUPLED PHASED ARRAY ELEMENT DESIGN

A TCPA is an array of very closely spaced elements, frequently separated via tip capacitors. The tip capacitors are adjusted to provide wideband performance. The aperture elements are Tightly Coupled Fractal Octagonal rings Array (TCFOA) backed by a ground plane. Therefore, a strong mutual coupling is utilised between the elements resulting in a continuous current distribution array. The geometry and characterization of TCFOA element is introduced in an infinite array environment. The radiators or receptors are dual polarised via two orthogonal feeding points, in each element the centre ring is shared between other two rings. An impedance transformer layer, known as a matching layer, is placed at a certain distance above the radiator layer. The matching layer is a scaled down version of the radiating elements, applied to enhance the bandwidth of the array. The scaling factor used to form the matching layer was 0.9. Figure 1 illustrates the unit cell of the TCFOA element antenna design. The space between the adjacent elements is 800 mm, which is slightly greater than half wavelength at the highest frequency (250 MHz for this unit cell). The unit cell covers frequency range from 60 MHz to 250 MHz. The distance from the radiators to the matching layer is 235 mm while the ground plane is placed at 390 mm from the radiators. To lower the array's operating frequency, capacitors are used in the gap between the neighbouring rings at the tip ends. The gap between the rings is 5 mm. These capacitors are bulk capacitors of 3 pF. The array design parameters are jointly optimized together, using Genetic Algorithm implemented in Matlab to validate a perfect match via commercial software Ansoft HFSS v12. The objective of this optimisation is to reduce the VSWR values over the operating frequency band of the antenna array. An iteration of nine scaled and subdivided octagonal rings are proposed to create an aperture array of fractal geometry patches. The bandwidth performance of the periodic array is sensitive to the outer and inner diameter of the fractal rings. Therefore, the optimised values of both the outermost and the innermost ring radius are 197.5 mm and 170 mm respectively.



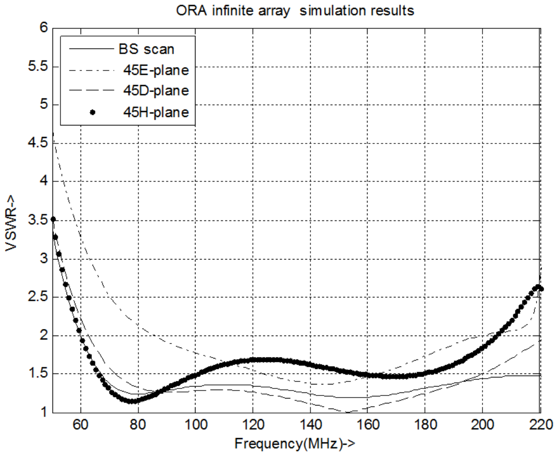
(a) Unit cell

(b) Radiating element configuration

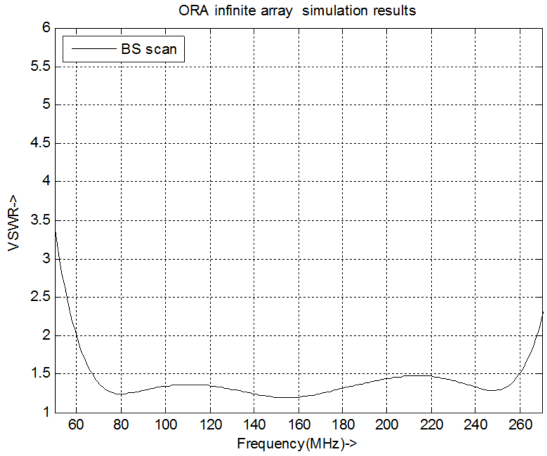
Figure 1: Geometry of TCFORA unit cell with the feeding lines.

A stripline line was introduced to provide a balance feed to the TCFOA, this feeding line was first presented in [10]. To match antennas input impedance with a 50 Ω input SMA connector, an impedance transformer was implemented with the stripline design. This feeding lines have a significant feature of a low insertion loss. For an ultra wideband performance, the single-ended feeding lines were optimised with the unit cell. As a result, the stripline length is 503.5 mm. Thus, an extra part of the body is reaching out the ground plane. Comparing with the tightly coupled dipole presented by Munk et al. [11], the candidate array design offers a convenient integration with the feeding lines.

To further demonstrate the validity of the proposed design, a full-wave simulation data is presented. The unit cell is modelled using periodic boundary conditions. Although the infinite array approach provides a rapid computational analysis, it does not account for the finite array edge effect. The finite arrays edge and corner diffraction affects the outer periphery elements causing a mismatch. As a result, the impedance of the edge and corner within the finite array size differs significantly from the infinite array. Therefore, the finite array bandwidth is degraded and several redesign steps are required to achieve the intended operational bandwidth. The broadside as well as the scanning active VSWRs of an infinite dual-polarised TCFOA was calculated using HFSS over a unit cell. The VSWR performance shown in Figure 2 suggests that satisfactory scanning properties and wideband performance could be achieved over 4.4 : 1 frequency band. Figure 3 illustrates that the TCFOA antenna design has a wideband performance with a stable low-cross polarisation level across the bandwidth from 60 MHz to 266 MHz.



(a) The scanning performance for four directions



(b) The broadside scan performance

Figure 2: The VSWR for an element in the infinite array.

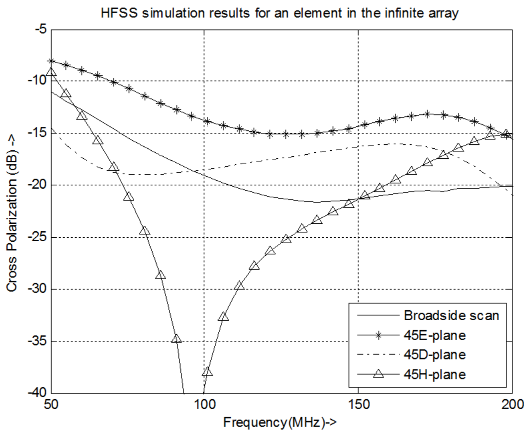


Figure 3: The cross polarization level in dB for an element in the infinite dual polarized array.

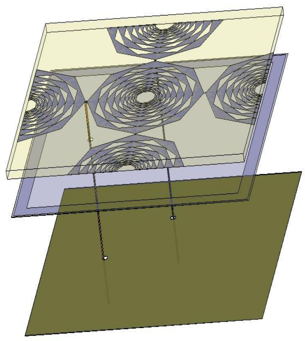


Figure 4: Geometry of the TCFORA unit cell with the resistive FSS.

3. CAPACITIVELY-COUPLED ARRAY WITH RESISTIVE FSS

In general, a tightly coupled array bandwidth is limited by the ground plane. More precisely, an array with a ground plane spacing of h is short circuited at the upper bond of the operational band at $f_{upper} = c/2h$. In other words, the upper bound bandwidth of any TCPAs is limited due to ground plane Z_{GP} given by:

$$Z_{GP} = j\eta_0 \tan(\beta h) \tag{1}$$

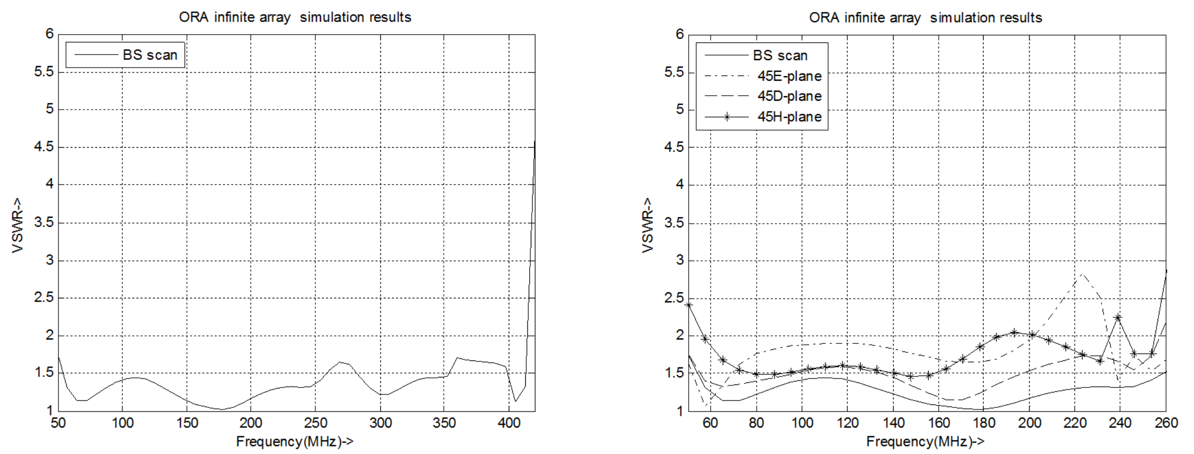
where η_0 is the substrate impedance (in this array it is free space), β is the substrate propagation constant, and h is the array spacing above the ground plane. The array depicts a resonance peak at $h = c/2f_{upper}$, because the ground plane impedance becomes $Z_{GP} = 0$.

Sating that a conformal array is short circuited when $h = \frac{\lambda_H}{2}$ (where λ_H is the wavelength at the highest/upper operational frequency), a method to alleviate ground plane effect is required. Though Electromagnetic Band Gap structures (EBG) were proposed to overcome the ground plane effect, it operates only over limited bandwidth [12]. Ferrites were also used to improve bandwidth, but their weight limits their applications [13]. In order to avoid boresight radiation cancellation from the ground plane image current, this paper proposes inserting a resistive FSS between the radiating elements and the ground plane. The resistive FSS suppresses the interfering of the ground plane reflection, increasing the bandwidth performance of the capacitively coupled array.

To serve this purpose, a unit cell is loaded with a square ring of a resistive FSS. Figure 4 depicts the configuration of the capacitively coupled array with the resistive FSS. The array unit cell is modelled with the stripline feeding lines. The physical array design parameters are obtained through the same aforementioned optimisation procedure. The resistive FSS loop is printed on a Polyethylene dielectric substrate of 0.2 mm thickness, this square ring loop is an ohmic sheet of $75\,\Omega = sq$. However, inserting FSS in the array leads to severe losses. A superstrate layer of a Polyethylene dielectric substrate (60 mm thickness) is mounted over the radiating elements. Both the FSS and the superstrate must be designed together in tandem. The purpose of a dielectric superstrate layer is to alleviate FSS losses. In addition, this layer behaves as a matching impedance transformer. In an infinite array TCFOA configuration, using superstrate in conjunction with FSS leads to a 8 : 1 bandwidth with VSWR < 2. Hence, this unique aspect of the array maximizes the bandwidth by a factor of 2 dB, resulting in a very low profile TCFOA.

The main layer is linearly distributed pairs of fractal octagon rings, perpendicular to each other. The element unit cell spacing is 730 mm, and the array is dual polarised. The array is capacitively coupled by inserting bulk capacitors at the end tips of adjacent rings, the value of these capacitors is 3 pF. The array is backed by a ground plane at 390 mm. The overall profile of the TCFOA with FSS is 450 mm (element spacing 730 mm), while it is 625 mm for the previous TCFOA design(element spacing 800 mm). Thus, the advantage of this arrangement presents a very wide bandwidth with a lower profile. This is a considerable feature for large scale arrays applications, and it facilitates low cost for the mass production.

The optimized infinite TCFOA with FSS scan performance is shown in Figure 5. The array with FSS exhibits a wideband performance, exceeding TCFOA without FSS. The Ludwing third definition of cross polarisation is used. And the cross polarisation of the immersed element scanned to four typical directions is illustrated in Figure 6. A stable cross polarisation performance is observed, and also it can be remarked easily that FSS geometry shows it is polarisation intensive.



(a) The broadside scan performance

(b) The scanning performance for four directions

Figure 5: The VSWR for an element in the infinite array with a resistive FSS layer.

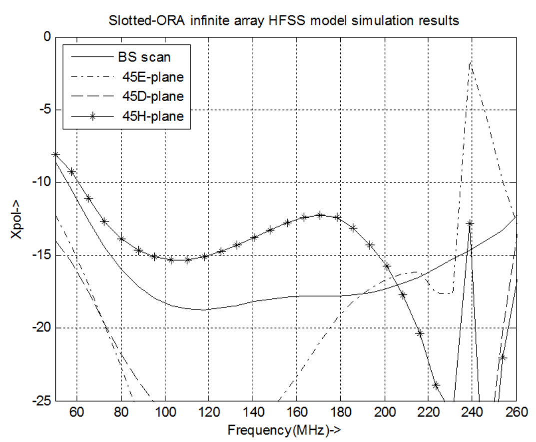


Figure 6: The cross polarization level in dB for an element in the infinite dual-polarized array.

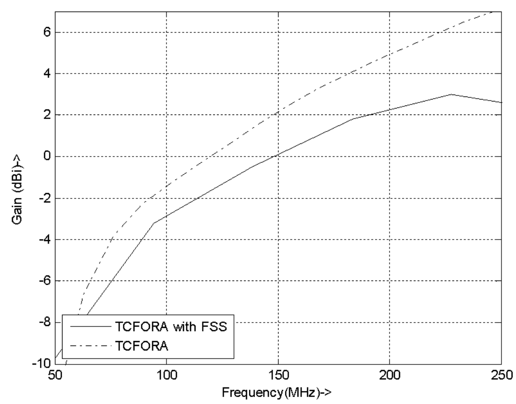


Figure 7: The gain for the immersed element in an infinite array.

Figure 7 illustrates that the presence of FSS cause some reduction in the gain (efficiency), this might be due to the power dissipated in the resistance of FSS.

4. CONCLUSION

In this paper, it has been shown that a properly designed resistive frequency selective surface, in tandem with a dielectric superstrate presents an inherently low-profile ultra-wideband phased array for a low-band radio telescope. The resistive FSS conjugated with a superstrate was demonstrated to significantly increase the array bandwidth. The infinite array environment achieves 8 : 1 bandwidth with VSWR < 2. The array thickness at the lowest operational frequency of 50 MHz is slightly greater than 0.058λ.

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