Improved cross-helix array with efficient 360-degree steerable WPT for solar power satellite

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Improved Cross-Helix Array with Efficient 360-Degree Steerable WPT for Solar Power Satellite

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***Abstract*— In this paper, single and cross helix array structures, for solar power satellite WPT applications, have been simulated, with full wave simulations up to 200x100 unit cell (H x W = 6m x 6m) array size. Near field simulations computed the WPT power densities at distances up to 500 m from the array. The results presented, are the first validation that a large cross helix structure can provide enhanced, 360 degree steerable, WPT beamforming capabilities compared to a similarly sized single helix. Previous work has only validated single helix structures. As an example, a 100x100 single helix array with 5W per element was shown to produce a WPT power density of 93 W/m^2 at 500m, whereas a 200x100 cross helix structure, with double the number of elements produced a power density of 315W/m^2, which is an almost fourfold increase compared to the single helix. This clearly shows the increased aperture to be providing additional beamforming as well as the two times power increase from doubling the number of elements.**

Keywords*— *Antennas, Phased arrays, Antenna Radiation pattern, Wireless power transfer, Retrodirective, Helix antenna array, solar power satellite

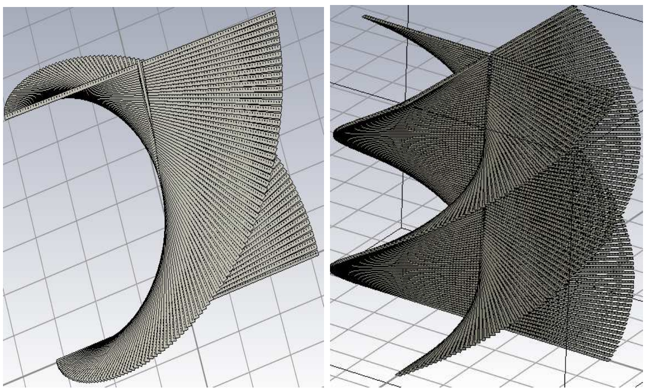
I. Introduction

The first solar power Satellite (SPS) has been proposed back in 1960s by Dr Peter Glaser [1]. Since then numerous concepts of new SPS design are also been proposed. Some examples are Alpha-SPS and Tethered- SPS [2]. They both use patch antennas as an array element due to its high directivity, versatile polarisation and good return loss. In 1975, the WPT project "goldstone" lead by NASA has successfully delivered 34kW power at 1.5Km distance with 82 percent rectenna efficiency [2]. The concept for SPS is proven to be viable from a recent feasibility study [3]. However, some of the SPS designs [3] focus on directional elements, where the limited angle for beam steering could become a problem when operating in space. To compensate this, a complex mechanical joint design has to be integrated in SPS. To simplify this, a array design with helical structure CASSIOPeiA [5] has been proposed by Ian Cash in 2017, which can provide 360° electronic beam steering, removing the need for a rotating joint between the antenna and PV cells within the SPS. The ultimate target for the CASSIOPeiA array is to deliver 2 GW power to earth from a geostationary orbit [3]. To achieve high efficiency the aperture of antenna size is set to be around 2 km x 2 km. At the earth the rectenna farm is proposed to be 6.7 x13km [3]. For other models the RF beaming device needs to be always perpendicular to the earth requiring physical rotation of a 2 km x 2 km structure.

The main aspect being addressed in this paper is the increased efficiency offered by a cross helix structure for 360° beam steerable WPT array for the SPS. Previously only single helix structures have been reported [5], with modeling based on array factors, rather than full wave EM models. In this paper we will validate large 200x100 unit cell cross helix arrays with full-wave simulations, clearly showing improvements in efficiency. These arrays will also be modelled with retrodirective beam steering [6], which has not been shown before for large cross helix arrays.

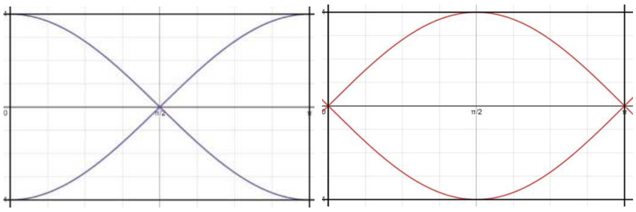
II. Theory

The beam forming efficiency within the near field region is dependent on the transmitted and received aperture, distance and wavelength [7], [8]. The Cross helix structure (Fig. 1(a)) theoretically has a larger Aperture than the single helix (Fig. 1(b)). Fig. 2 and Fig. 3 show the visible apertures when viewing the helix arrays along the azimuth plane. It is clearly seen that the aperture within any field of view for the cross helix is greater than the single helix.



(a) Single Helix 100x100 Elements (b) Cross Helix 200x100 Elements

Fig. 1. Proposed Helix Configurations for SPS WPT



(a) 0° Azimuth (b) 90° Azimuth

Fig. 2. Visible apertures of single helix

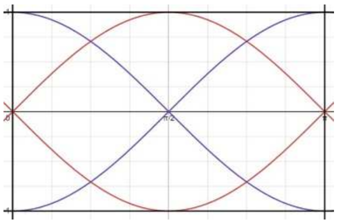


Fig. 3. Visible aperture of cross helix at 0° Azimuth

This increase in aperture can be shown theoretically by overlapping 0° and 90° structures, this proves that the cross helix exhibits a 40% aperture increase (Eq. 1)

$$A_{SingleHelix} = \frac{4H\,W}{\pi}$$

$$\frac{4(\pi)1}{\pi} = 4$$

$$A_{CrossHelix} = 2\left(\frac{4H\,W}{\pi}\right) \text{ - Overlap area}$$

$$A_{CrossHelix} = 5.65$$

$$A_{CrossHelix} = \frac{5.65}{4} = \frac{2}{\sqrt{2}} \quad (1)$$

In equation 1, H is the height of both single and cross-helical structures. W is the width of the structure. Assuming an identical structure exists at both transmitter and receiver, using the methods of [7] an 8x8 single helix model will have a 78% efficiency at a distance of 6.5m. (Fig. 4) whereas the cross helix can achieve 96% efficiency. Considering using the Cross helix as a transmit aperture, with the receiving aperture remaining unchanged, the Cross helix would still provide 12% more transmit efficiency.

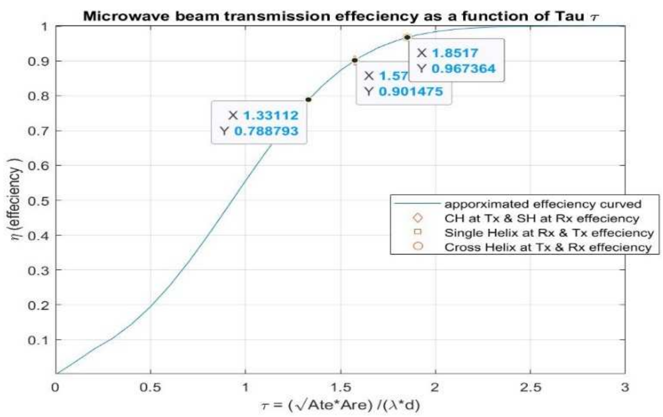


Fig. 4. WPT Efficiency graph plot for single and cross helix arrays

III. Simulation Results

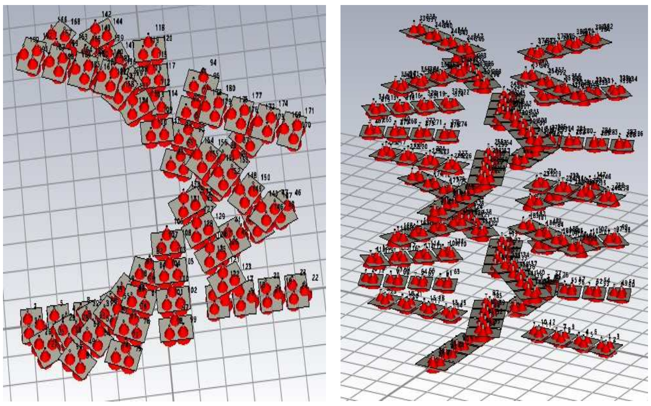
A. 8x8 single helical array

Following the design principle on section II. An 8x8 single helix array, Fig. 5(a), is created for benchmarking with the cross helix Fig. 5(b). The simulation model has been designed to be of reasonable size to allow fast full wave simulations of the entire structure, and is intended for future practical implementation. Simulations were carried out using CST Microwave Studio. For better power density the unit cell periodicity (unit cell spacing) has been increased from half wavelength spacing to 5/6 wavelength. The central area has a 300mm diameter gap intended to provide cabling and support structures.

Fig. 6(a) shows the 2D beam pattern cut for 8x8 Helical array at $\phi = 30°$. The Main lobe gain is 21.6dBi and the difference between main lobe and the highest side lobe is -14.2 dBi. The WPT power density produced at 6.5m is 229W/m^2

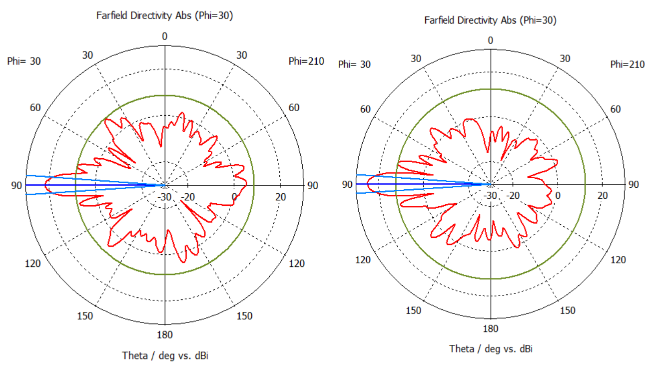
B. 16x8 Cross helical array

The 16 x 8 cross helix array is similar with a single helix array in terms of unit cell arrangement. The main difference is arranging these unit cells with cross layer configuration, with double the overall number of unit cells. Fig. 6(b) shows the 2D beam pattern cut for 16x8 Cross Helical array at $\phi = 30°$. The Main lobe gain is 24.8dBi and the difference on the highest side lobe is -13.7 dBi. The power density at 6.5m is 825W/m^2. Power densities for both single and cross helix structures are summarised in Table 1.



(a) 8x8 Single Helix (b) 16x8 Cross Helix

Fig. 5. 8x8 and 16x8 Single and Cross Helix Array Models



(a) 8x8 Single Helix (b) 16x8 Cross Helix

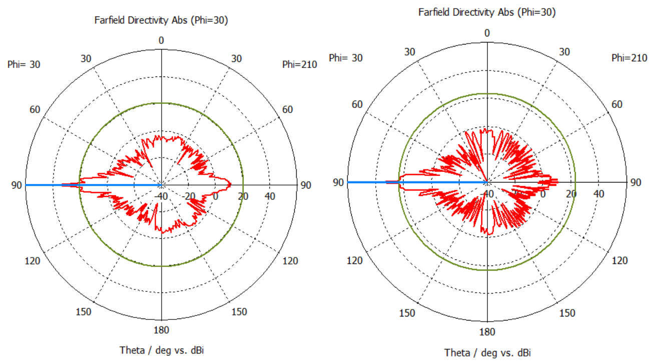
Fig. 6. Radiation patterns of single and cross helix Arrays at $\phi = 30°$

TABLE I. POWER DENSITIES FROM 8X8 AND 16X8 ARRAYS

$0.7x1m^2$ structure	power/element	Tot. power in	power density @ 6.5m
single helix	$5W$	983W	$229W/m^2$
Cross helix	$5W$	1966W	$825W/m^2$

C. *100x100 single helix array*

In order to predict the beam forming for a larger structure demonstration which is similar scale compared to JAXA [9], a 100x100 helix array [6 meter x 6 meter] (Fig. 1(a)) is simulated at ϕ =30°. All of these simulations employ a retro directive method of beam steering, from phase conjugation of an incident plane wave [6]. Element power was set to 5W. Fig. 7(a) shows the 2D beam pattern cut for a 100x100 single helix array at ϕ = 30°. In phi = 30°, the Main lobe gain is 38.8dBi with 0.8° degree-3dB-beam-width and the difference between main beam and the highest side lobe is -18.8 dBi. The WPT power density at 500m is 92.62W/m^2.



(a) 100x100 Single Helix (b) 200x100 Cross Helix

Fig. 7. Radiation patterns of large helix Arrays at ϕ = 30°

D. *200x100 cross helix array*

A 200x100 cross helix array [6 meter x 6 meter] (Fig. 1(b)) was simulated at ϕ =30°. The power input per element is the same 5W as per the 100x100 single helix structure. With double the number of elements within the same volume, it is expected that the power density will be doubled. Although the near field simulation results actually showed a power density at 500m of 315.5W/m2 (Table 2), which is a three times increase from the single helix. This shows the increased aperture to be providing additional beamforming as well as the increased power from the elements. At phi = 30°, Fig. 7(b), the main beam directivity is 40.9 dBi and side lobe level 23.5 dBi.

TABLE II. POWER DENSITIES FROM 100X100 AND 200X100 ARRAYS

$6x6m^2$ structure	power/element	Tot. power in	power density @ 500m
single helix	$5W$	51kW	$92.62W/m^2$
Cross helix	$5W$	102kW	$315.5W/m^2$

IV. PRACTICAL IMPLEMENTATION

The proposed practical implementation of a 16x7 cross-helix array is shown in Fig. 8. The antenna elements are mounted in metal boxes which contain the retrodirective phase conjugating circuits. The boxes are mounted on a 3D printed structure where each antenna box is supported on rails such that its position and element spacing can be readily adjusted. Each of the "arms" contains a 4 element sub array and is mounted on a central support column. One of the advantages of the cross helix array, is that the absence of antennas in the centre of the array allows for power and reference phase cables to be housed in the central support column.

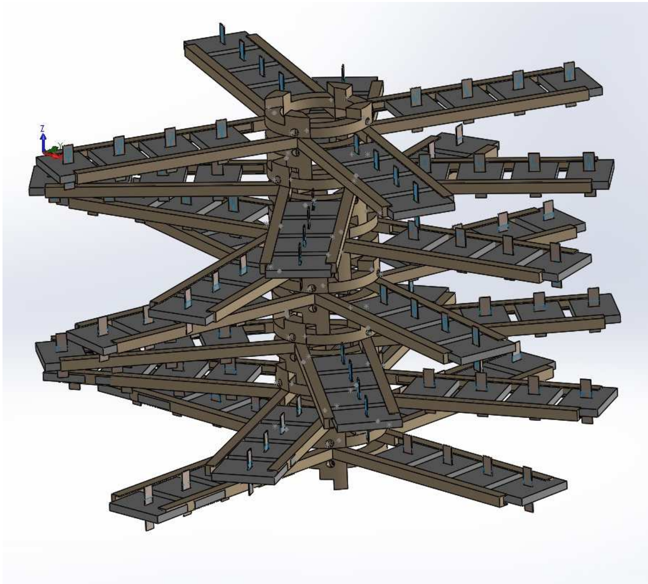
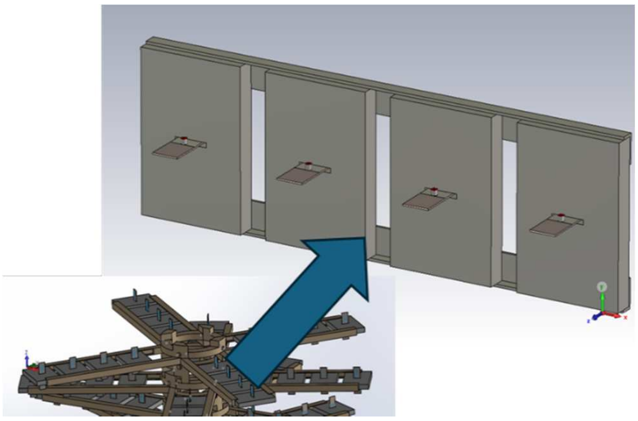
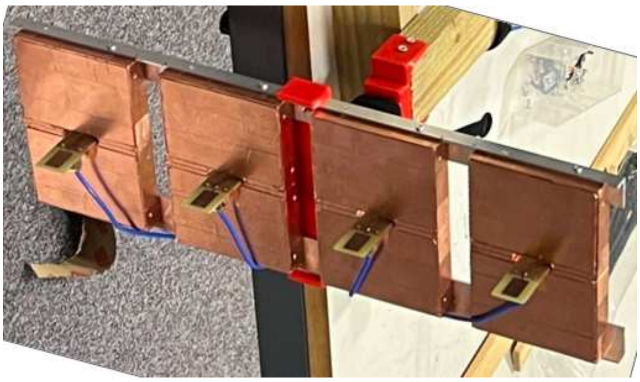


Fig. 8. Proposed practical implementation of a 16x7 cross-helix array with 3D printed mounting structure



(a) 4 element sub array



(b) Fabricated 4 element sub array

Fig. 9. 4 element sub array for practical implementation

At the time of writing this paper, a practical implementation of a 4 element subarray (Fig. 9) has been fabricated and measured for radiation pattern characteristics. Fig.10 shows the radiation pattern of a single element in azimuth. This produces a relatively omnidirectional pattern (ignoring the positioner shadowed region). The antenna element has a gain in the region of 3.56 – 4.2 dBi when compared to a reference dipole. Fig 11. Shows the 4 element array measurement, where all elements are fed in phase from a passive power splitter. The results of the array being measured in the roll axis are shown in Fig. 12. Here the results agree well with the predicted, where two main peak beams are produced at the front and back of the array (2&3). In the end fire direction, smaller peaks are produced (1&4). This is expected for a 4 element sub-array, although when combined into the 16x7 cross helix array and steered retrodirectively, it is expected that a main peak beam will result, which can be steered 360° in azimuth, with minimum amplitude ripple.

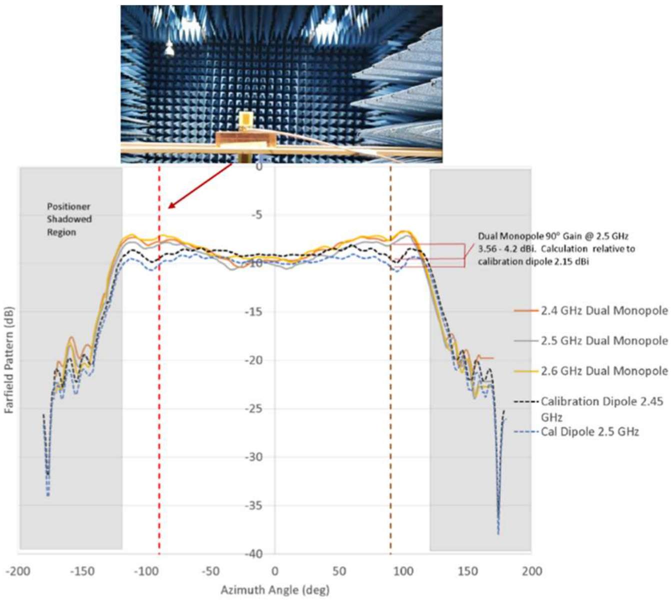
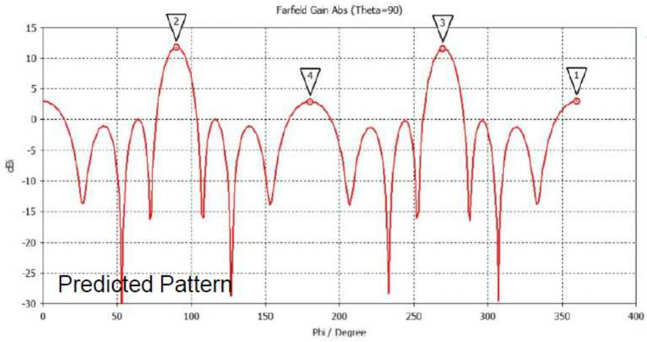
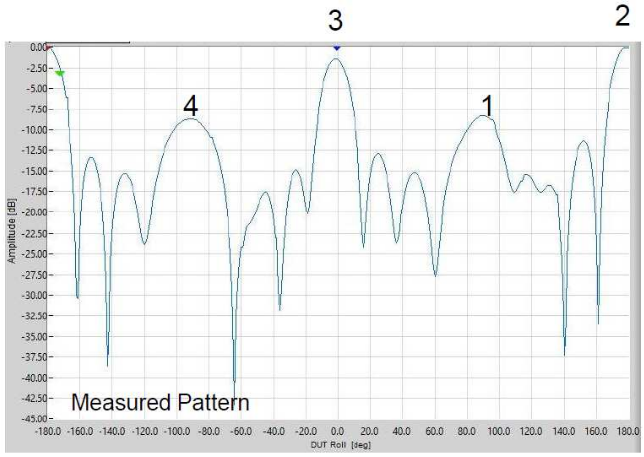


Fig. 10. Measured radiation pattern of single element in Azimuth

Fig. 11. Experimental Setup for radiation pattern of 4 element sub array



(a) Predicted Results



(b) Measured Results

Fig. 12. Radiation Pattern Results of 4 element practical sub array

V. Discussion and Summary

In this paper, single and cross helix array structures have been simulated with full wave simulations up to 200x100 array size. The results from the cross helix are very encouraging, making it an ideal contender for the SPS, as it can provide 360° beam steering capability without the need for any mechanical rotation. The results shown in this paper are the first validation that a large cross helix structure can provide enhanced WPT beamforming capabilities compared to a similarly sized single helix. As an example, a 100x100 single helix array with 5W per element was shown to produce a WPT power density of 92.62 W/m^2 at 500m, whereas a 200x100 cross helix structure, with double the number of elements produced a power density of 315.5W/m^2, which is almost a fourfold increase compared to the single helix. This clearly shows the increased aperture to be providing additional beamforming in addition the two times power increase from doubling the number of elements. At the time of writing this paper, a practical implementation of a 4 element subarray of the larger array has been fabricated and measured for radiation pattern characteristics. Measured results show very close agreement with predictions.

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