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Pattern Synthesis in Butler-Matrix-Fed Cylindrical Antenna Array for Monopulse NR-IFF Radar Application

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Abstract

This paper presents the design and procedure of pattern synthesis in a cylindrical antenna array with electronic scan capability suitable for Non-Rotating Identification Friend or Foe (NR-IFF) radar system. To this purpose, 64 printed dipole antennas are placed around a cylindrical ground plane, out of which 16 elements in a 90-degree active sector are united to form the sum and difference radiation patterns required for monopulse technique. The electronic scan can be achieved through commutation of the active sector by a suitable feed network based on the Butler matrix, some variable phase shifters and SP4T switches. MATLAB and HFSS are linked together and particle swarm optimization algorithm is used to synthesize the desired radiation pattern in the active sector. This method is capable of taking into account the mutual coupling effect between the array elements and compensate for it during the design procedure.

Keywords: Butler Matrix, Cylindrical Antenna Array, IFF Radar, Pattern Synthesis, Beamforming Network

1. Introduction

The identification, friend or foe (IFF) system [1] is a well-established standard that was developed during World War II to identify friendly aircrafts from the foe's on the battlefield via radio communication. It consists of two parts, the interrogator and the transponder, where the interrogator is the asking part transmitting at 1030 MHz and receiving at 1090 MHz and the transponder is the replying part receiving at 1030 MHz and transmitting at 1090MHz. The interrogator is often a ground-based station and the transponder is often located on the aircraft. Nowadays, these identification systems are not only used for identification of targets' characteristics, but also for the management of air traffic control [2].

One of the requirements of the operational modes of an IFF radar is monopulse capability which refers to the radar's ability to extract range and direction from a single pulse. Monopulse radar avoids problems seen in conical scanning radar systems, which can be confused by rapid changes in signal strength and the system also makes jamming more difficult [3].

Although the antenna utilized for the interrogator used to be a linear antenna array piggybacked on the primary search radar to be co-rotated mechanically, it can be a cylindrical antenna array as well with its unique scan-invariant pattern characteristics and electronic rotation. Note that cylindrical antenna arrays are popular because of their capability to scan the radiation beam in all angles of the plane of array without any change in their radiation patterns and compared to linear and rectangular arrays they are less sensitive to mutual coupling between the elements. Moreover, the wraparound configuration of the cylindrical antenna array makes it suitable for installations where the antenna should wrap around a tower or a ship mast [4] [5].

In a cylindrical antenna array, the antenna elements remain stationary or non-rotating while the beam is steered electronically to scan the full 360 degrees around the array. Also the beam can be positioned selectively in any direction within microseconds. There are several feeding systems enabling the electronic rotation of a prescribed illumination over a subset of active radiating elements distributed around a cylindrical antenna array (i.e. the commutation of the active sector), however, the most robust antenna architectures satisfying the requirements of reliability are the ones based on the Butler matrix [6].

The Butler matrix [7] is one of the most important parts of a cylindrical antenna array, specifically for the electronic rotation of the main beam and the permutation of the amplitudes and phases applied to the radiating elements during the commutation of the active sector around the array [8].

It is the aim of this paper to demonstrate the pattern synthesis procedure in a Butler-matrix-fed cylindrical antenna array for the interrogator part of a monopulse non-rotating IFF (NR-IFF) radar through the concurrent use of MATLAB and HFSS. So in Section I we will first propose an architecture, based on the Butler matrix, for the realization of the antenna array of the interrogator and its feed network and then, the function of each sub-section of the architecture is explained and the points related to the design of each sub-section is discussed. Then in Section II the synthesis procedure is explained in a backward fashion (i.e. from the radiating elements at the cylindrical antenna array to the power divider feed network) and later in Section III the results are presented. Then a conclusion is drawn in Section IV and finally the references are listed in Section V.

The desired interrogator's antenna array must have the following specifications:

• Cylindrical array of 64 radiating elements with vertical polarization

• Production of sum and difference patterns

• Transmission at 1030±5 MHz

• Reception at 1090±5 MHz

• 360-degree electronic scan of sum and difference patterns along the azimuth

• The beamwidth of the sum pattern in azimuth must equal 7 degrees

• The maximum allowable sidelobe level of the sum pattern equals -25 dB

Here, it is worth mentioning that although the contents of this paper are much more detailed and somehow different, but sources [4] and [5] have been very helpful, so it is highly suggested that these two sources, and the architectures and results presented therein, be studied too.

2. Interrogator's Architecture

Fig.1 shows the proposed architecture for the interrogator section of an NR-IFF radar which is based on the rotational mechanism of the Butler matrix for the commutation of an active sector of 16 radiating elements around a 64-element cylindrical antenna array [8], [9] and [10].

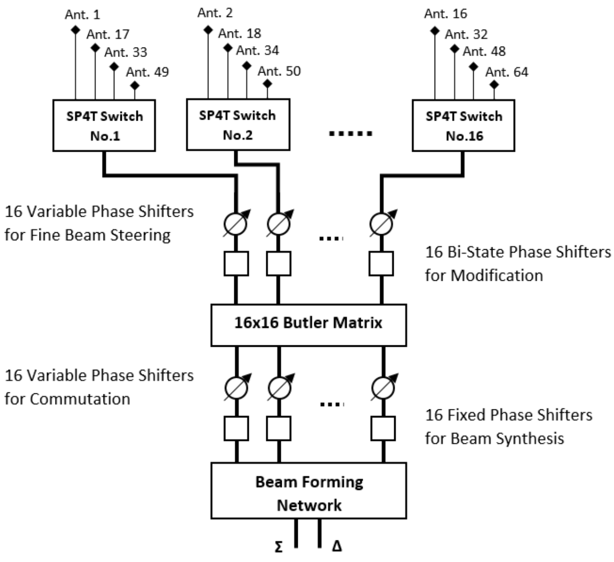

Fig.1. Proposed architecture for interrogator's antenna and its beam forming network

The proposed architecture works as follows: On the first floor and through the beam forming network, two sum and difference patterns are generated. For this purpose, for example a corporate feed network can be designed for the generation of the sum pattern and then a common method similar to the split-Taylor can be used to create the difference pattern by applying 180-degree phase shifts to half of the elements [11].

On the second floor, and in order to compensate for the phase differences caused by the presence of the Butler matrix, a number of phase shifters with fixed values are used. Moreover, it must be mentioned that in a cylindrical antenna array, there is always the need to compensate for the phase differences caused by the curvature of the array geometry [6], and now the presence of the Butler matrix adds some excess phases to these phase values caused by the curvature.

We know that in practice and in order to avoid the creation of back-lobes and grating lobes, the number of radiating elements in a cylindrical array is limited to an active sector of 90 to 120 degrees [4] (so the synthesis should be done for the elements of this active sector only). We also know that for the commutation of the active sector around the array, and because of consecutive switching of the elements, there is a need to continually rearrange and readjust the applied amplitudes and phases in the active sector between the old elements and the newly added ones. For this purpose, variable phase shifters are used on the third floor in addition to a Butler matrix on the fourth floor to make use of the rotational mechanism of the Butler matrix in the commutation process.

Here it is necessary to point out that as we know from the rotational mechanism of the Butler matrix, in order to complete the commutation process and fully rearrange the amplitudes and phases during the commutation, it is also necessary to use sixteen bi-state (0/180) phase shifters in the outputs of the Butler matrix and right before the switches on the fifth floor. Of course, during construction and if there is a need to make provision for the calibration of the phases or there is a need for finer steering of the beam, in this part, 16 digital phase shifters can be used instead of the mentioned bi-state phase shifters.

Considering that in the proposed architecture, the size of the active sector is chosen to be 90 degrees and only 16 elements out of the 64 elements will be used to create the sum and difference patterns, a 16x16 Butler matrix will be used for the commutation and rearrangement of the amplitudes and phases required to realize the radiation patterns. Thus, the active sector is composed of 16 antennas, and in order to cover all the 64 elements, sixteen SP4T switches are needed on the last floor as well.

At the end, it must be mentioned that according to the desired vertical polarization, printed dipole antennas will be used as array elements, which obviously by combining all these elements with equal amplitudes and phases, the omnidirectional radiation pattern required for ISLS (interrogation sidelobe suppression) and/or RSLS (receiver sidelobe suppression) will be easily realized. Note that as a protection mechanism, side-lobe replies (i.e., “false targets”) are prevented by ISLS technique in transponders. Also further protection can be provided by receiver side-lobe suppression (RSLS) in the Interrogator using an omnidirectional pattern [12].

Rogers 4003 (with the dielectric constant of 3.55 and the loss tangent of 0.0027) with a thickness of 60 mil will be used to design different parts of the structure

3. Synthesis Procedure

It has been proven that in a cylindrical antenna array where the elements are arranged around a circle along the azimuth and on a straight line along the elevation, it is possible to synthesize the radiation patterns along the azimuth and along the elevation independently from each other [13]. Here, we only focus on the synthesis of the sum pattern along the azimuth (the difference pattern is subsequently derived through splitting).

We first start at the inputs of the radiating elements of an active sector and perform the synthesis of the radiation pattern there. For this purpose and in order to take into accounts all the important design factors such as the mutual coupling, we directly work with the whole array of printed dipoles adjacent to a cylindrical ground plane in HFSS and then link HFSS with MATLAB and use a numerical algorithm such as Particle Swarm Optimization (PSO) to work out the required amplitudes at each element. Note that the required phases (commonly known as collimating or focusing phases) are calculated with the help of the existing formula based on the array radius and elements' spacing relative to the design wavelength [6]. We then move backward floor by floor until we reach the design of the beam forming network.

There is no need to say that the synthesis of the pattern along the elevation can be easily done by adjusting the inter-element spacing and phase progression along the few elements of each radiating column (if one decides to use more than one element along the elevation to form a so called radiating column) according to the acceptable tolerance for sidelobe level and/or the direction of the mainbeam from the horizon.

4. Synthesis Results

The formula related to the electric field of a cylindrical antenna array along the azimuth is given below [6].

$$E(\phi) = \sum_{n} V_n EL(\phi - n\Delta\varphi) e^{jkRcos(\phi - n\Delta\varphi)} \quad (1)$$

Where the phases are referenced to the center of the circle, and identical radiating elements with constant angular distances of $\Delta\varphi$ from each other are assumed along the circumference of a circle with the radius R, and each element is directed outwardly along the radius. V is the voltage and k is the wave number. Also, $EL(\phi)$ represents the radiation pattern of each element, and because it is transferred from its local coordinate system to a common global coordinate system, it is written as $El(\phi\text{-}n\Delta\varphi)$, where $n\Delta\varphi$ is equal to the angular placement of the *n*-th element.

In order to steer the main beam of the cylindrical array to an arbitrary angle ϕ_0, the phases obtained from the following relationship (a.k.a. collimating or focusing phases), must be applied to the elements [6]:

$$\psi(n) = -kRcos(\phi_0 - n\Delta\varphi) \quad (2)$$

As a result, in a cylindrical array, the radiation function of the steered electric field is equal to [6]:

$$E(\phi) = \sum_{n} |V_n| EL(\phi - n\Delta\varphi) e^{jkR[cos(\phi - n\Delta\varphi) - \cos(\phi_0 - n\Delta\varphi)]}$$

(3)

Considering that initially our goal is to synthesize the sum pattern in an active sector and along its boresight, and if the presence of the Butler matrix, and the phase shifters before and after it, are temporarily ignored, we can compute the required amplitudes and phases for the formation of the mentioned sum pattern at the entries of the radiating elements with the help of (3).

For this purpose, it is assumed that out of the 64 elements, 16 radiating elements are located in the first quadrant of the trigonometric circle such that the boresight of the resulting active sector is exactly equal to 45 degrees and the elements are at angular distances of 360/64=5.625 degrees from each other.

In order to synthesize the sum pattern, the particle swarm optimization (PSO) algorithm is used (for more information on the particle swarm optimization algorithm, refer to [14]). According to what is known about the effect of the radius on the argument of the Bessel functions (which appear in the phase mode analysis of cylindrical arrays) [6], an algorithm was written in MATLAB to increase the radius of the array incrementally and for each radius, run the PSO algorithm to find the best solution for both 1030 MHz and 1090 MHz frequencies simultaneously (of course, with more emphasis on the frequency of 1030 MHz as is explained later). In order to incorporate the effect of directive elements the radiation pattern of each element was assumed to be of the form $0.5(1+\cos\varphi)$.

During the application of the PSO algorithm, equation (3) was used and the fitness function was chosen to be the combination of the deviation from the desired half-power beamwidth and the deviation from the desired maximum sidelobe level as follows:

$$Fitness = \left(w_1 \left|BW_{3dB} - BW_{3dB}^{des}\right|\right)^3 + \left(w_2 \left|SLL - SLL^{des}\right|\right)^3 \quad (4)$$

In the above relationship, BW_{3dB} and SLL represent the half-power beamwidth and the maximum sidelobe level respectively, and the weights w_1 and w_2 must be chosen according to the acceptable accuracy and tolerance for the final values of the half-power beamwidth and the maximum sidelobe level at the end of the algorithm. The superscript "*des*" indicates the desired value that is considered as the optimization goal. Furthermore it should be noted that the power 3 was chosen so that if at the end of each iteration of the algorithm, the difference between the obtained value and the desired value is greater than the acceptable tolerance, this difference is shown in a more drastic and destructive way and on the contrary as soon as the said difference for the half power beamwidth or the maximum sidelobe level (whichever happens first) reaches a value less than the acceptable tolerance, its effect on the fitness function is reduced at once and the focus of the algorithm in the upcoming iterations shifts towards improving the other parameter.

According to the above explanations, for the more important frequency of 1030 MHz, $w_{1_{1030}} = 50$ was chosen to achieve a tolerance of 0.02 degrees in the value of the half-power beamwidth, and $w_{2_{1030}} = 10$ was chosen to achieve an accuracy of 0.1 dB at the maximum sidelobe level. Also, for the frequency of 1090 MHz, $w_{1_{1090}} = 2$ was chosen to achieve 0.5 degree accuracy in half power beamwidth and $w_{2_{1090}} = 0.5$ to reach 2 dB tolerance on the maximum sidelobe level. In addition, it must be mentioned that in each iteration of PSO algorithm, the fitness function for the sum pattern in both frequencies 1030 MHz and 1090 MHz is calculated and then combined with the coefficients of 0.7 and 0.3, respectively, so that the main focus of the algorithm is more on finding the most suitable solution in the frequency of 1030 MHz.

Regarding other important parameters in PSO algorithm, it should be added that the value of the inertial weight ω is formulated in a way to decrease linearly from 0.9 to 0.4 across the iterations. Also, the number of particles is chosen to be 15 and the number of total iterations of the algorithm is set to be 50. The values of the cognitive rate c_1 and the social rate c_2, which respectively encourage each particle to search individually in unknown places or to trust the results of other particles' searches, are both set equal to 0.35. Also, absorbing boundary condition was used to limit the solution space of each particle.

In Fig.2, the radiation patterns for both frequencies of 1030 MHz and 1090 MHz are super imposed and the best result obtained for the half-power beamwidth of 7 degrees and the maximum sidelobe level of -25 dB assuming the inter-element spacing of $0.585\lambda_0$ is illustrated.

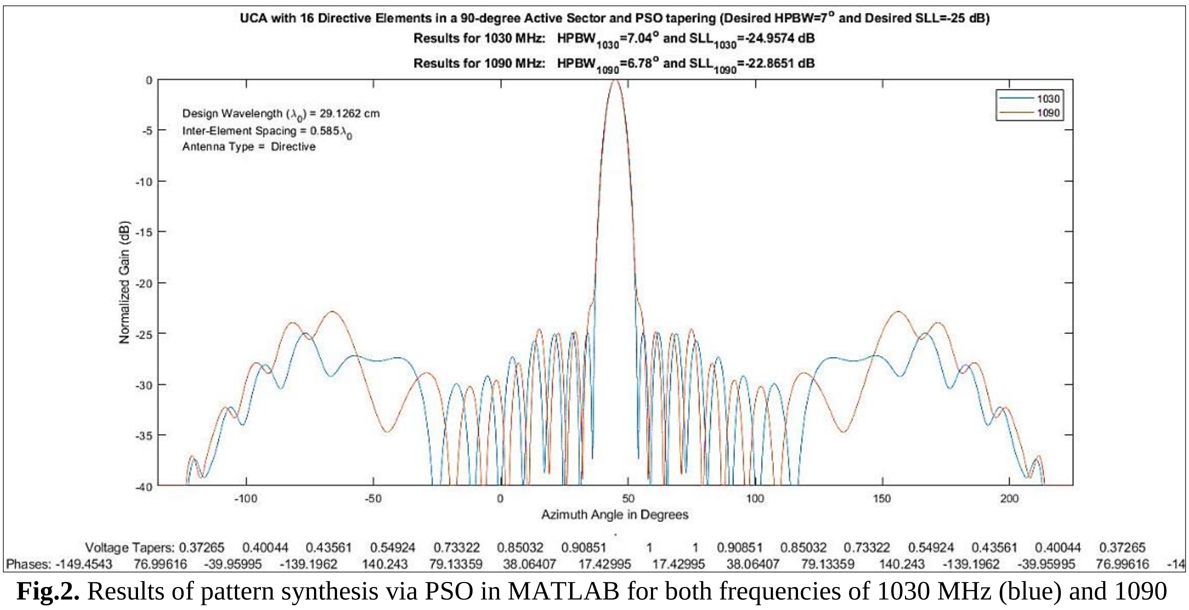

Fig.2. Results of pattern synthesis via PSO in MATLAB for both frequencies of 1030 MHz (blue) and 1090 MHz (red)

Next and in order to further increase the accuracy of the synthesis results, especially in order to take the effect of the mutual coupling between elements into account, we apply the PSO algorithm written in MATLAB directly to a cylindrical antenna array simulated in HFSS software.

For this purpose, first a printed dipole antenna was designed and simulated in the frequency range of 950 MHz to 1215 MHz (for joint use in IFF radar and Link-16 communication channel). Then the dimensions of the antenna were optimized in the vicinity of a ground plane and finally by placing 64 such antennas around a cylindrical ground plane, an antenna array was designed and simulated, the shape of which is shown in Fig. 3.

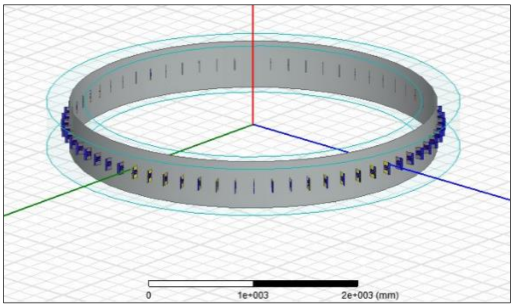

Fig.3. 64-element cylindrical antenna array for direct pattern synthesis in HFSS

As was previously discussed about the effect of the radius of the array (or in other words, the distance between the elements in terms of wavelength) on the argument of the Bessel functions which appear in the phase mode analysis, in the case of the full wave analysis too, perhaps at first the best strategy seems to be to increase the size of the radius of the array incrementally and then run the optimization algorithm directly in HFSS at each radius. However, it should be warned that due to the very large dimensions of the array and the limitations in the processing resources, this method will be very time-consuming and practically infeasible.

Therefore, in an alternative attempt and in order to choose the best radius of the array before the application of the time-consuming PSO algorithm in HFSS, instead the omnidirectional radiation pattern of the 64-element cylindrical array was simulated first in both frequencies of 1030 MHz and 1090 MHz by increasing the radius of the array step by step. Then the amount of the ripple in the resulting omnidirectional patterns were measured at each radius to find the largest radius possible that results in the lowest amount of ripples in the omnidirectional radiation pattern in both of the mentioned frequencies.

The above was done and at first the largest possible inter-element spacing that leads to the lowest amount of peak-to-peak ripple in the omnidirectional radiation pattern in both frequencies 1030 MHz and 1090 MHz was seen to be 0.565λ, which resulted in a peak-to-peak ripple of 0.64 dB at 1030 MHz and a peak-to-peak ripple of 0.74 dB at 1090 MHz,.

Unfortunately, after many attempts, it became apparent that by choosing the mentioned spacing between the elements, acceptable results could not be obtained because at the end of each run of the PSO algorithm, the maximum side lobe levels obtained were always about 3 dB higher than the targeted value. Therefore, we inevitably opted for the next inter-element spacing, which is larger than the aforementioned value, but still leads to the lowest amount of ripple in the omnidirectional radiation pattern, and thus the next inter-element spacing of 0.605λ, which leads to a peak-to-peak ripple of 0.71 dB at the frequency of 1030 MHz and a peak-to-peak ripple of 1.15 dB at the frequency of 1090 MHz was chosen.

After determining the radius of the array, we initially applied the values obtained from the synthesis in MATLAB to the 16 antennas of the active sector, the result of which are shown in Fig. 4. In this regard, it should be noted that the phase value related to each element (which are directly extracted from the existing formula (2)) was recalculated according to the inter-element spacing of 0.605λ, and the amplitudes of the elements from MATLAB which were in terms of voltages, were converted to wattages in order to be applicable in the Driven Modal analysis of HFSS.

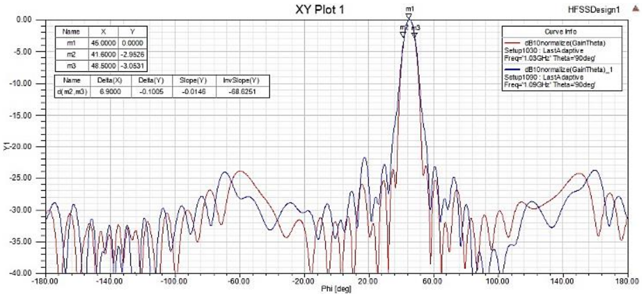

Fig.4. Sum patterns at 1030 MHz (red) and 1090 MHz (blue) if MATLAB's results are applied crudely to elements of active sector

Unfortunately, as can be seen in Fig. 4, for several reasons, especially the effect of mutual coupling between the elements, the results deviate slightly from the targeted values such that at the frequency of 1030 MHz, the maximum sidelobe level has increased to -23 dB.

Therefore, it is confirmed that in order to improve the results, it is better to perform the synthesis of the sum pattern directly in HFSS; But first we must create a link between MATLAB and HFSS so that the PSO algorithm is coded and run in MATLAB, then the results of each iteration of the algorithm are applied to HFSS through Visual Basic scripts, and the post-processing results from HFSS are saved to a Microsoft Excel file for MATLAB to read and measure the beamwidth and the maximum sidelobe level of the sum pattern, and repeat the particle swarm optimization algorithm.

It is very important to pay attention to the fact that due to the heavy processing in HFSS and possible memory shortage and in order to avoid long runtime of the PSO algorithm, first of all, the important parameters in the convergence of the PSO algorithm, i.e. the number of particles, the number of iterations, the cognitive rate c1 and the social rate c2 should be optimized in MATLAB in a way to get the best result in the shortest time possible.

For this purpose, during the implementation of the PSO algorithm in MATLAB, the convergence was calculated and illustrated, and after changing the values of the aforementioned parameters many times, the algorithm was adjusted in a way to obtain the best solutions in a maximum of 50 iterations (assuming 15 particles).

The final results for both 1030 MHz and 1090 MHz due to PSO pattern synthesis in HFSS via MATLAB are shown in Fig. 5 (sum patterns) and Fig. 6 (difference patterns).

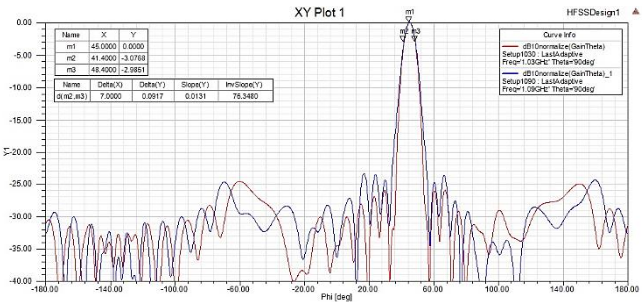

Fig.5. Final results of PSO for synthesis of sum pattern in HFSS at both 1030 MHz (red) and 1090 MHz (blue)

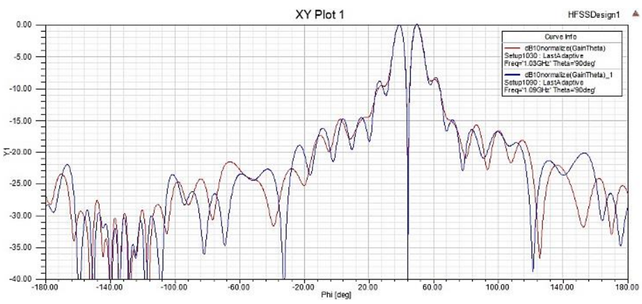

Fig.6. Difference patterns at both 1030 MHz (red) and 1090 MHz (blue)

In Table 1, the values obtained from the synthesis for the amplitude and phase of each element in the active sector, obtained from the application of the PSO algorithm in HFSS, are listed.

Table 1. *Final results of PSO for amplitudes and phases required at elements in active sector*

Amplitude and Phase Distribution @ Element Input Results of PSO Algorithm in HFSS (Printed Dipole, Cylindrical Ground, Spacing=0.605λ, SLL=24.5dB, HPBW=7 Design Freq.=1030MHz, PSO Params: Np=15, Ni=40, C1=C2=0.25)			
Element No.	Wattage (Norm.)	Voltage (Norm.)	Phase (Degree)
1	0.116	0.340	156.21
2	0.121	0.348	18.09
3	0.167	0.408	-102.86
4	0.204	0.451	154.51
5	0.407	0.638	71.19
6	0.814	0.902	7.99
7	0.889	0.943	-34.48
8	1.000	1.000	-55.82
9	1.000	1.000	-55.82
10	0.889	0.943	-34.48
11	0.814	0.902	7.99
12	0.407	0.638	71.19
13	0.204	0.451	154.51
14	0.167	0.408	-102.86
15	0.121	0.348	18.09
16	0.116	0.340	156.21

Next, by extracting the scattering matrix (S-Matrix) equivalent to the Butler matrix and with a simple mathematical relationship resulting from the solution of an N by N system of equations, the amplitudes and phases at the input ports of the Butler matrix can be obtained in a backward fashion.

In this regard, it is worth mentioning that if all the input ports of the NxN Butler matrix (that is, the ports on the side of the beamforming network) are represented with the subscript "in" and all the output ports of the Butler matrix (that is, the ports on the side of the array antenna) are represented with the subscript "out", then the equivalent scattering matrix of this structure has the dimension of 2Nx2N and the relation between the mentioned voltage waves and the scattering matrix is as follows (note that all the values are complex numbers):

$$\begin{bmatrix} \tilde{V}_{in1}^{-} \\ \tilde{V}_{in2}^{-} \\ \vdots \\ \tilde{V}_{inN}^{-} \\ \tilde{V}_{out1}^{-} \\ \tilde{V}_{out2}^{-} \\ \vdots \\ \tilde{V}_{outN}^{-} \end{bmatrix}_{2N\times 1} = \left[\tilde{S}\right]_{2N\times 2N} \begin{bmatrix} \tilde{V}_{in1}^{+} \\ \tilde{V}_{in2}^{+} \\ \vdots \\ \tilde{V}_{inN}^{+} \\ \tilde{V}_{out1}^{+} \\ \tilde{V}_{out2}^{+} \\ \vdots \\ \tilde{V}_{outN}^{+} \end{bmatrix}_{2N\times 1} \quad (5)$$

It should be noted that when using the above relationship, the amplitudes (in terms of voltages) and phases synthesized at the output ports of the Butler matrix (i.e. at the entrance of the elements) are placed in the lower half of the vector matrix related to negative voltage waves and by solving the above system of equations, the required amplitudes and phases to be applied to the input ports of the Butler matrix appear in the upper half of the vector matrix related to positive voltage waves and thus the above relationship changes as follows:

$$\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ V_{out1}e^{j\psi_1} \\ V_{out2}e^{j\psi_2} \\ \vdots \\ V_{outN}e^{j\psi_N} \end{bmatrix}_{2N\times 1} = \left[\tilde{S}\right]_{2N\times 2N} \begin{bmatrix} V_{in1}e^{j\zeta_1} \\ V_{in2}e^{j\zeta_2} \\ \vdots \\ V_{inN}e^{j\zeta_N} \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}_{2N\times 1} \quad (6)$$

Where, the voltage waves are represented in terms of amplitudes and phases.

Thus, we put the values obtained from the synthesis of the sum pattern in HFSS into $V_{out_n}e^{j\psi_n}$ (n=1,2,…,16), and by solving the above system of equations, we calculate the required amplitudes and phases at the input ports of the Butler matrix, the results of which are listed in the Table 2.

Table 2. *Amplitudes and phases required at input ports of Butler matrix*

Amplitude and Phase Distribution @ Re-Num BM Input Results of Inversion by S Matrix in ADS (Printed Dipole, Cylindrical Ground, Spacing=0.605λ, SLL=24.5dB, HPBW=7)			
Re-Num Port No.	Wattage (Norm.)	Voltage (Norm.)	Phase (Degree)
1	1.000	1.000	-105.45
2	0.729	0.854	16.96
3	0.546	0.739	138.02
4	0.424	0.651	-94.95
5	0.252	0.502	-9.77
6	0.128	0.358	35.04
7	0.044	0.211	77.19
8	0.066	0.258	118.67
9	0.066	0.258	118.67
10	0.044	0.211	77.19
11	0.128	0.358	35.04
12	0.252	0.502	-9.77
13	0.424	0.651	-94.95
14	0.546	0.739	138.02
15	0.729	0.854	16.96
16	1.000	1.000	-105.45

In this regard, it is necessary to mention that due to the complexity of the Butler matrix structure and in order to save time, ADS software was used to compute the scattering parameters of the Butler matrix and after simulating the entire structure and its connections in the mentioned software and with the help of the S-PARAMETERS engine, the components of the scattering matrix were extracted. Also note that the numbering order of the input and output ports of the Butler matrix is as is required for the correct application of linear phase shift during the commutation of the active sector (hence the name "Re-Num" in the table) [8].

At the end the main problem in designing the beamforming network is the need to implement two separate feed channels to realize both sum and difference patterns; Therefore, in an attempt to minimize the hardware complexity, the use of a method similar to split-Taylor in linear arrays was chosen [11]. In other words, to generate the difference pattern, one can make use of the amplitudes related to the sum pattern with 180-degree phase shifts applied to half of the array elements. The main advantage of the split-Taylor method is the use of only one set of weights for the elements.

5. Conclusion

In this paper the design and pattern synthesis procedure of a cylindrical antenna array with electronic scan capability suitable for a monopulse Non-Rotating Identification Friend or Foe (NR-IFF) radar system was presented. To this purpose, 64 printed dipole antennas were placed around a cylindrical ground plane, out of which 16 elements in a 90-degree active sector were united to form the sum and difference radiation patterns required for monopulse technique. The electronic scan was achieved through commutating the active sector by a suitable feed network based on the Butler matrix, some variable phase shifters and SP4T switches. MATLAB and HFSS were linked together and particle swarm optimization algorithm was used to synthesize the desired radiation pattern in the active sector.

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