16th International Conference on DEVELOPMENT AND APPLICATION SYSTEMS, Suceava, Romania, May 26-28, 2022

Phase Shift Effects Analysis on Radiation Pattern of a Ground Plane Antenna Array

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Abstract—**This paper presents an analysis on the effect of the controlled phase shift introduced between feeding signals of an antenna array elements on modifying its radiation pattern shape. Following the idea of increasing measurements accuracy on phased antenna arrays, it was designed and built an antenna array containing two radiating telescopic elements located on a contiguous metal ground plane. All the hardware related to the functionality of the phased array was placed on the bottom of the ground plane. Even though the array was designed for the 915 MHz band, allocated to various useful satellite services, it is easily tunable in a wide range of other frequencies and also easily modifiable in a multi-element array, due to the design of the ground plane. This paper also shows a good agreement between the experimental results and those obtained from numerical simulations.**

Keywords—Phased antenna array; radiation pattern; beamforming; vector modulator; smart antenna array

I. INTRODUCTION

Phased antenna arrays are defining elements of complex intelligent antenna systems. One of their main advantages is the ability to modify their radiation pattern by electronic command and control, without requiring any moving parts [1], [2]. Interest in the development of smart antenna arrays, also called smart antenna systems, has grown in recent years due to their great potential for terrestrial and satellite telecommunications applications. State-of-the-art electronic devices have led to an increase in the use of smart antennas in very high frequency bands. Modern techniques and algorithms for digital signal processing have led to the extension of the term “beamforming” [2], [3] from the classical sense of "modeling" the radiation pattern of an antenna array, to a level that reaching to involve advanced algorithms that keep track of several important parameters in terms of signal quality (e.g. location of a communication terminal, distance to a transmitter, signal-to-noise ratio, etc.) [4]. All this aims to improve the quality of the received signals, directing the main radiation lobe towards the areas of interest (for emission mode) or minimizing the levels of unwanted signals (for reception mode). In most cases, the modeling of the radiation pattern of an intelligent antenna array is done by a controlled variation of amplitude, phase or both of these feeding signals parameters.

The present paper proposes an experimental analysis of the phase shift control efficiency on modifying an antenna array radiation pattern shape. The array contains two monopole radiant elements in 3λ/4 (three-quarter wavelength) configuration, located on a contiguous metallic ground plane. The advantages of using thus configuration and also of ground plane antennas have been analyzed in several previous theoretical [1] and practical [5], [6] studies. These highlighted the superior gain at medium elevations and the maintenance of a stable impedance close to 50 Ohm, used in most modern equipment. The unique way in which the antenna array was designed led to obtaining very good measurement results and it consists in placing below the ground plane (opposite side of the plane containing radiant elements) of all the elements related to the functionality of the array (transmission lines, radio frequency phase shifters, signal splitter), including a battery based, stabilized, nonradiant and autonomous power supply. As a result, the possible noise sources and common mode currents that could influence the measurements have been significantly reduced. Also, the Aluminum ground plane, specially designed to be compatible with the mechanical fixing system of the measuring equipment, offers the possibility to design multiple element phased antenna arrays, making way for further researches on phased arrays. Also, telescopic antennas were chosen as monopole radiant elements, which gives an accurate adjustment of the length, corresponding to a wide range of resonant frequencies desired. The antenna array that is the subject of this paper has been designed for the 915 MHz band, allocated to various useful satellite services, such as Broadcasting, Radio Location, LTE (Long Term Evolution), Narrowband Internet of Things (NB-IoT), etc.) The paper includes the aspects of the array design, the preliminary measurements, the results obtained after measuring the radiation pattern and the comparison with simulations results.

II. THEORETICAL CONSIDERATIONS

For a ULA (Uniform Linear antenna Array) having M elements placed along the x axis (Fig. 1), with distance d between elements, it can be considered that the distribution of the aperture is uniform, all the signals received by each element of the array have the same amplitude, normalized to 1 and the effects of the mutual coupling [7] between elements are

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neglected. Under these conditions, the mathematical expression for the magnitude of the complex signal (A_i) received by element i of the array, from a far field placed transmitter, can be written as:

$$A_i(\alpha) = A_e(\alpha) e^{jk_0(M-i)d\sin(\alpha)} \quad (1)$$

Where α is the incidence angle of the wave (considered plane) on the array, A_e (α) is the complex radiation pattern of an isolated radiator and $k_0 = 2\pi/\lambda_0$ is the free space wave number. In antenna array theory [1], the factor that is multiplied by the specific component A_e (α) of an element (also called the element factor) is called the array factor, because it confers the specific properties of the directivity characteristic of an antenna array. So the complex radiation pattern of an uniform linear antenna array can be written as:

$$A(\alpha) = A_e(\alpha) \cdot A_a(\alpha) \quad (2)$$

The array factor was noted by A_a (α). The introduction of a progressive phase shift θ_i between the ULA elements leads to a change in the expression of the array factor, as follows [8]:

$$A_a(\alpha) = \sum_{i=1}^{M} e^{j[k_0(M-i)d\sin(\alpha)-\theta_i]} \quad (3)$$

Where θ_i has the form:

$$\theta_i = -k_0(M-i)d\sin(\alpha_0) \quad (4)$$

The element number, i, can take values between 1 and M, and α_0 is the steered beam direction corresponding to θ_i. The maximum of the array factor is obtained when $\alpha = \alpha_0$. It follows from the above, that the radiation pattern of an antenna array, in this case linear, depends on the phase shifts introduced between the supply signals of the array elements. Therefore, if the introduced progressive phase shift can be controlled, the radiation pattern control is performed.

III. Methodology Used

The antenna array to be studied was used in transmission mode. The RF generator, antenna positioner and the data acquisition interface included in the "LabVolt" laboratory equipment for measuring the radiation pattern were placed at a level below the ground plane, so that any unwanted electromagnetic radiation emitted by them does not represent disturbing factors on the measurements. Simulations on the array response to the 915 MHz frequency of the RF signal were performed with MMANA-GAL antenna modeling and analyzing software [9], which uses an improved MININEC (Mini Numerical Electromagnetics Code) computation engine (relative to memory requirements and computational speed) to do the mathematical calculations required to perform far radiation field integrations. Those simulations provided the optimized values of the constructive parameters of the radiant elements which will be part of the experimental setup of the phased array. Once completed the design and construction of the transmission lines (TL), the correctness of their practical execution was verified, followed by their placement and fixing in well-established positions, below the ground plane. Two pairs of TLs were built, each pair consisting of two cables of equal length and also as short as possible, so as not to introduce significant attenuation of the RF signal. After the last checks, radiation patterns of the array were measured, corresponding for several phase shifts introduced between the supply signals of the elements. The results were compared with those obtained from the simulations. The scope was to observe the effects of these phase shifts on the orientation of the main lobes (beamforming experiment) of the radiation patterns (corresponding to the maximum radiated power) and the level of compliance with the simulation results, in the particular case of the proposed array analysis. A detailed description of the measuring setup, designed and practically performed, is presented in the following sections of this paper.

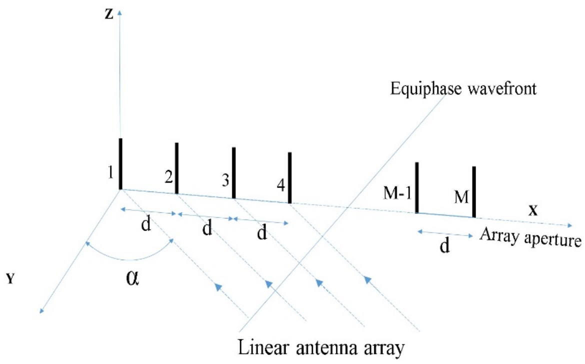


Fig. 1. Schematic representation of an uniform linear antenna array containing M radiant elements.

IV. Antenna Array Design and Definition

The design of the array and defining its construction parameters was done first, through various simulations, performed for an antenna system containing two vertical monopole radiant elements having three - quarter wavelength, placed on a ground plane and located at a distance of λ/2. A shorter spacing reduces gain and increases the effects of mutual coupling on impedance, resonant frequency, and SWR. A greater distance, first of all, leads to the appearance of secondary lobes, which are unwanted in the experiment described here. The characteristics of the ground plane led to the imposition of a relatively high value for the dielectric constant and conductivity, respectively ε = 500 and σ = 100000 mS/m. It is worth mentioning that the MMANA-GAL tool, despite its simplicity, is more than accurate enough to simulate simple antenna systems, as described in this paper, this software also being able to take into account the mutual coupling effects between antenna elements [7] and moreover, can calculate the solutions of the field equations even if phase shifts are introduced between the feeding signals of the radiant elements. A 3D image of the array on which the simulations were performed using the MMANA-GAL software can be seen in.Fig. 2

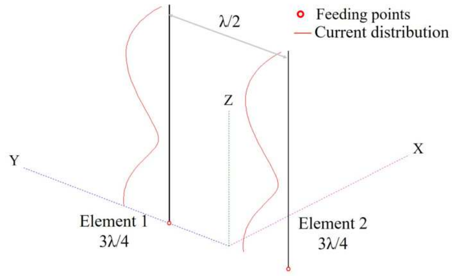


Fig. 2. . A 3D view of the simulated antenna system containing two vertical monopole elements located on the ground plane. The distance between the elements was λ/2.

V. Simulation Results of the Antenna Array

Fig. 3 shows the results obtained after the simulation regarding the Complex Impedance (a), SWR (Fig. 3 b), GA (Gain relative to isotropic radiator) and F / B (Front to Back ratio) (Fig. 3 c). As can be seen, the impedance in the simulation was around 57 Ohm, SWR reached a value very close to 1 and the resonance was close to that required (915 MHz). Also, a good compromise was reached between GA and F / B, after the simulation based on the optimized parameters of the array.

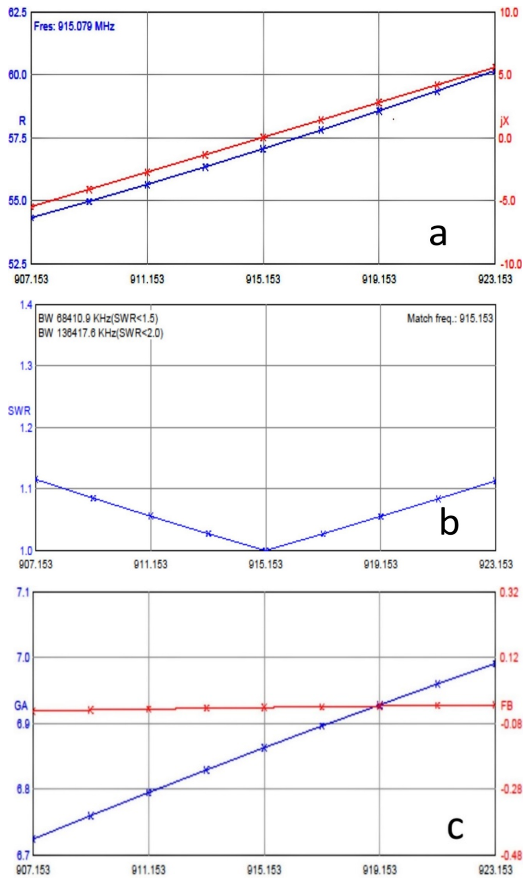


Fig. 3. Simulation. Complex impedance of the two-element antenna system (a), the SWR (b), Gain (GA) and the F/B (Front to Back Ratio) (c).

VI. Preliminary Measurements on the Two Element Antenna Array

A. Procedures and Methodology Followed

The whole mechanical system of the experimental setup has been designed to be perfectly compatible with the antenna fixing mechanism used by the LabVolt antenna positioner. The ground plane was made of 1.5 mm thick aluminum sheet, cut in a circular shape so the diameter of the circular disc obtained was 1 m. The radiant elements were constituted by telescopic antennas, both fixed on SMA (Amphenol) connector structures by tinning and machined so that two identical elements were finally obtained. A ZFSC-2-5-S "Minicircuits" Splitter [10] was used to divide the radio frequency signal into two identical ones. Before proceed to dynamic measurements, the signals from the splitter outputs were viewed with a two-channel "Tektronix" TDS 820 digitizing oscilloscope, to verify the equality of their amplitudes. The tuning of the two-element antenna array to the resonant frequency of 915 MHz provided by the generator within the LabVolt laboratory equipment, was performed with a VNA (Vector Network Analyzer), "Anritsu" MS8212E series. Fig. 4 (a) shows a view from below the ground plane, and Fig. 4 (b) also reveals the upper part of it. The ground plane of AUT (Array Under Test) was provided with two metal rods that make it compatible with the fixing system of the "LabVolt" antenna positioner. Starting from the values calculated by the simulation software, the lengths of the two telescopic elements were adjusted to have the same value and the resonant frequency to be close to 915 MHz.

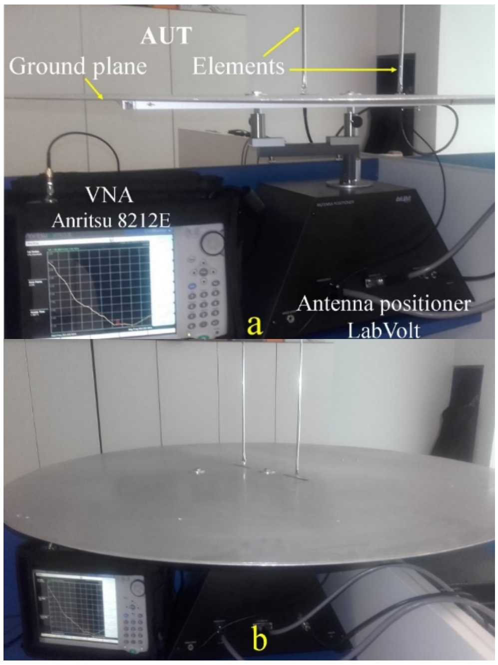


Fig. 4. The measurement setup for tuning the two-element antenna array.

B. Results of Preliminary Measurements

The obtained results upon antenna array measurements can be seen in Fig. 5. A good VSWR was obtained, less than 1.1 Fig. 5 (a), corresponding to the resonance at the target frequency, 915 MHz. The Smith chart indicates in Fig. 5 (b) that the system impedance is close to 50 Ohm at a resonant frequency of approximately 915 MHz. This impedance is stable in relation to the frequency and is due to the 3λ/4 configuration of the elements and last but not least, the ground plane contributes to the stability of the system parameters.

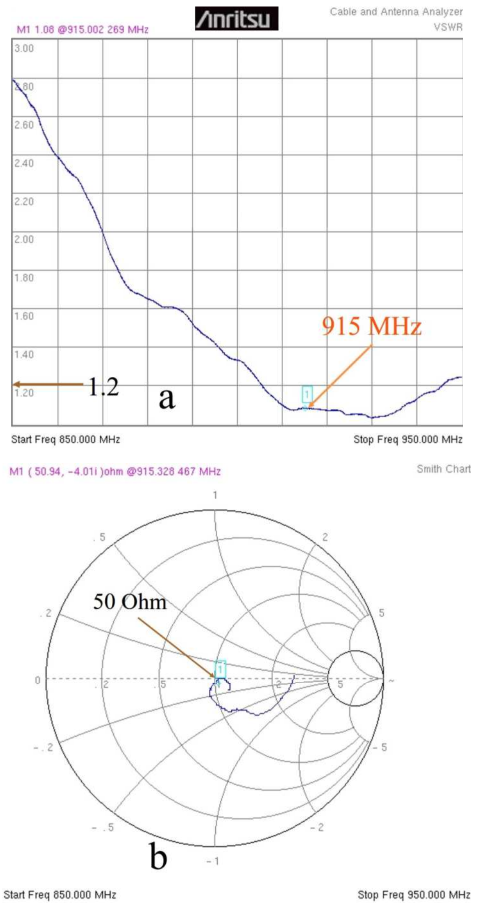


Fig. 5. Results of preliminary measurements of the VSWR (a), and Smith chart (b) on the two-element antenna array, performed with Anritsu MS8212E Vector Network Analyzer.

VII. PRACTICAL ACHIEVMENT OF THE ANTENNA ARRAY'S RADIATION PATTERN MEASUREMENT SETUP

The radiation pattern measurement chain consists of the transmission and the reception part. The phased antenna array has been prepared for the transmission mode. A block diagram of the transmission part of the measuring setup can be seen in Fig. 6 in which the circle represented by an interrupted line symbolizes the ground plane. All the elements figured inside that circle are those fixed on the ground plane. RF generator, Teensy 3.6 microcontroller and the computer PC 1, are out of the ground plane. When acquiring any radiation pattern, the antenna positioner in the LabVolt system performs a 360 ° rotation, together with the antenna array, around the center of its disk. The signals received by the Yagi-Uda antenna which is also part of the LabVolt equipment, are further amplified and processed by the equipment's data acquisition interface (DAQ) and then sent to the computer PC 2 (Fig. 7). Through the specialized software of the measurement system, the received signal-level at fixed angular intervals is recorded and processed so the radiation patterns acquired are displayed. Fig. 8 reveals a photo with the complete setup of the phased antenna array prepared for measurements of its radiation pattern. The signals obtained at the output of the RF phase shifters (PS) were visualized with the oscilloscope, in order to ensure that their shapes and amplitudes correspond to the operation in normal parameters, of the phase shifters. Those are based on the RF Vector Modulator integrated circuits, AD8340 [11], made by "Analog devices", which can introduce phase shifts in the range (0 °- 360 °) between the signals applied to their inputs. The control voltages required for these circuits to achieve the desired phase shifts are obtained by the DAC 8554 (Digital-to-Analog Converter) circuit (included in the PS module) which is digitally controlled by Teensy 3.6 (Fig. 6) microcontroller.

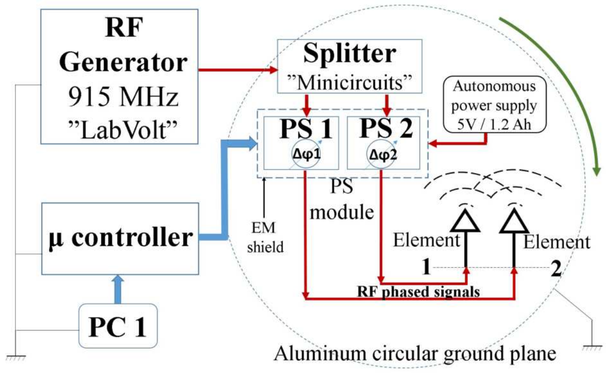


Fig. 6. Measurement setup for the phased antenna array radiation pattern. Transmission part schematic representation.

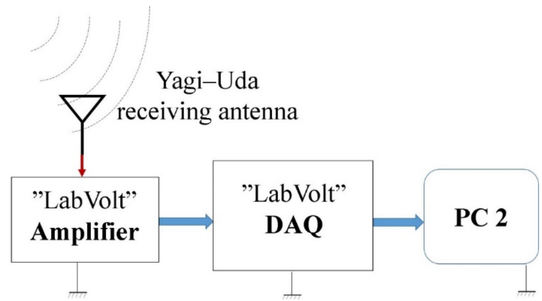


Fig. 7. Block diagram of the receiving part used in the measurements on the phased antenna array radiation pattern.

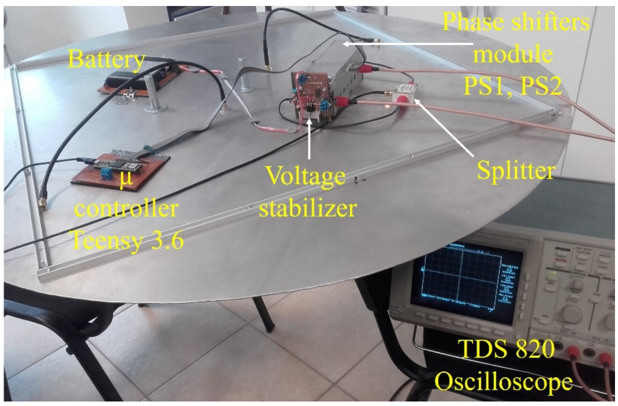


Fig. 8. Physical setup for measuring the radiation pattern of the two-element phased antenna array.

VIII. RADIATION PATTERN MEASUREMENT

A. Procedures Followed

As can be seen in Fig. 9, the receiving antenna has been fixed on a base-rod that can slide relative to a tripod stand, so that the height of the antenna from the ground can be changed. The Yagi-Uda antenna has the possibility to be oriented along the imaginary line that joins its top with the center of the array, thus forming an angle (α in Fig. 9) to the horizontal. Because the measurements were performed indoor, for a good concordance with the results of the simulations, several positions of the receiving antenna were experimented, both in the azimuthal plane and in that of the elevation (angle α), in order to reach where disturbing influences were minimal. An optimal elevation angle of about 20 ° has been reached. The antenna positioner on which the AUT was fixed, rotated clockwise from 0 ° to 360 °, while the DAQ processed the received signal and sent it to the computer (PC 2 in Fig. 6). The obtained resolution of the radiation pattern was 1 °, in the azimuthal plane.

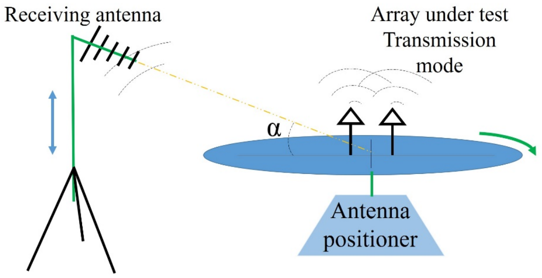
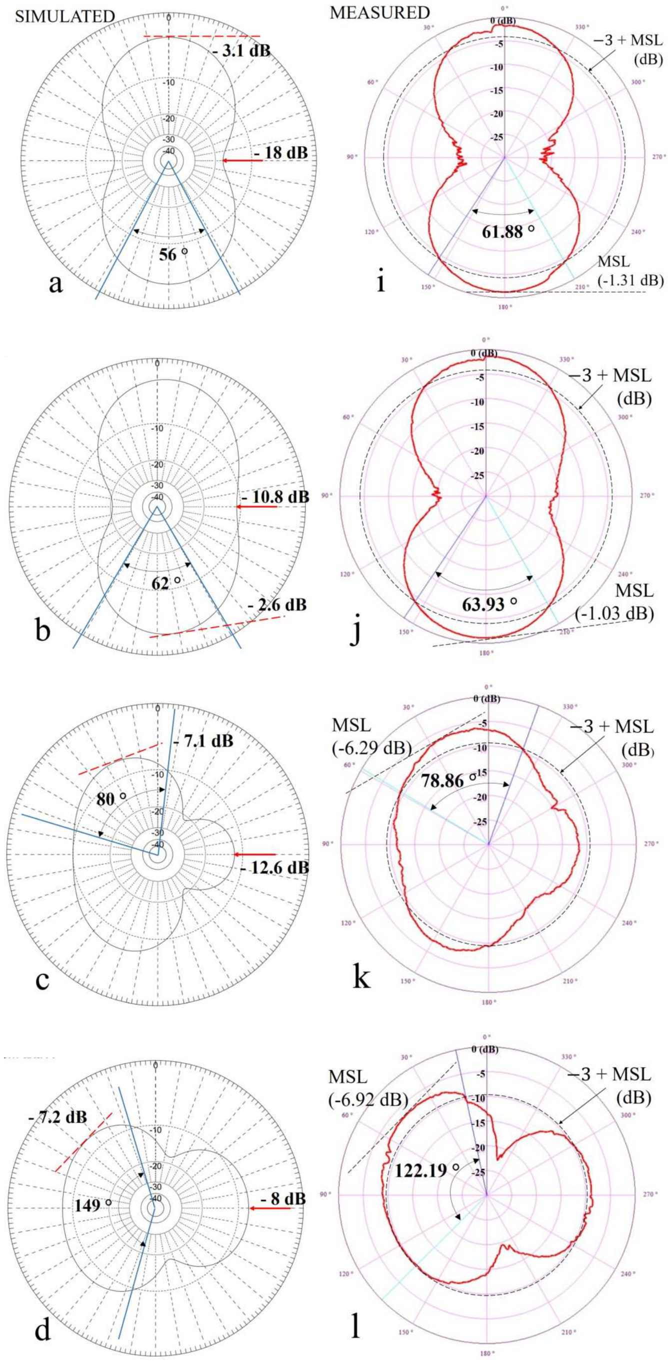


Fig. 9. The arrangement of the Array under test and the Yagi-Uda receiving antenna within the radiation pattern measurements.

B. Experimental Results and Discussion

Fig. 10 (i – p) reveals the measurement results obtained using the LabVolt laboratory equipment. The validity of those measurements was verified by the simulation results presented in Fig. 10 (a – h). After many tests in different positions of the Yagi antenna, the elevation angle of about 20 ° was chosen, corresponding to which SNR was optimal. The measurement results revealed in Fig. 10 correspond to the phase shifts of 0 ° (i), 60 ° (j), 120 ° (k), 150 ° (l), 180 ° (m), 210 ° (n), 240 ° (o) and 270 ° (p). The simulation and measurement results, corresponding to the same phase shift, are placed in adjacent images in Fig. 10. Emphasis was placed on highlighting the orientation of the main lobes according to the phase shift angles, in accordance with the results of the corresponding simulations performed with MMANA-GAL antenna analyzing tool. The values of the measured amplitudes (expressed in dB) are relative to the power of the signal emitted by the array and the noise coming from the environment of the measurement setup, while in the simulation, they are relative to an isotropic radiator. The indoor conditions in the laboratory made it possible to distance the receiving antenna to about 1.5 m (which falls within the specifications of the measuring equipment). The resulting radiation patterns correspond to the azimuthal plane (E-plane). The MSL (Maximum Signal Level) values are provided by LabVolt equipment and refer to the maximum value of the signal amplitude in the entire radiation pattern, keeping the elevation angle constant. To illustrate the opening of the HPBW (Half Power Beamwidth) corresponding main lobes, the diagrams were completed with an auxiliary circle corresponding to the value of -3 dB, value that added to MSLs (also negatives), revealed the HPBW of main lobes. These values are relevant in the practical aspects, for the characterization of the opening angle of the main lobes of any antenna array and are shown in Fig. 10 (the values expressed in degrees). It can be seen that there is a good match between the experimental and simulation results performed, also and with those presented in [2]. Although research on radiation pattern modeling based on the variation of the amplitude of array elements excitation signals, shows that this method is relatively



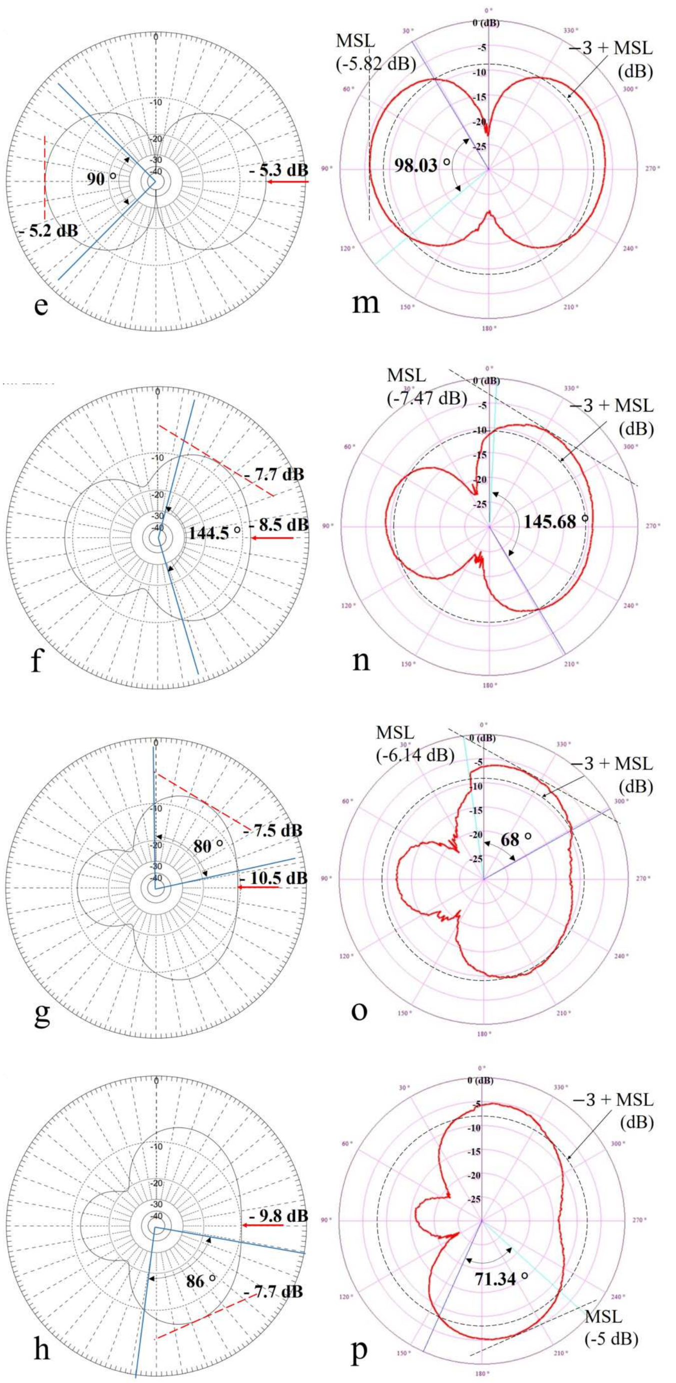


Fig. 10. Simulated (a – h) and measured (i – p) radiation patterns of the two-element ground plane phased antenna array, for different phase shifts.

easy to implement, does not provide results corresponding to large scanning angles [12]. The main lobes orientation in the directions predicted by the theory implemented in the simulation software, by controlling only the phase shift, without varying the feeding signals amplitude or/and frequency, revealed the radiation pattern modeling efficiency using that method. Also, the radiation pattern resolution was improved, compared to radiation pattern measurement results on arrays that uses radials instead of ground plane, for impedance correction at a relatively stable value [13].

IX. Conclussions

The development of the presented phased antenna array measuring setup, offered a good accuracy of indoor, near-field conditions radiation patterns measurement, by minimizing environment and auxiliary hardware influences. The versatility of the ground plane within the array offers by design the possibility of extending the research on multi-element phased antenna arrays, also the study of their behavior at higher frequencies. The efficiency of introduced controlled phase shifts on radiation pattern modeling, was highlighted. The presented research has shown that it is possible to implement beamforming in the developed antenna array, by using phase taper only. The choice of the ground plane variant led to obtaining pure directivity characteristics, without secondary lobes, increasing also the efficiency of the array by minimizing radiant losses. The 3λ/4 configuration, although it offered a superior gain and the impedance stability (50 Ohm), can be replaced with any other, due to facility offered by setup design.

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