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Application of Coherently Radiating Periodic Structures for Feeding Subarrays in Limited-Scan Arrays

ELIZVAN JUAREZ [1], MARCO A. PANDURO [1], DAVID H. COVARRUBIAS [1], ALBERTO REYNA [2] (Member, IEEE), AND CARLOS DEL RIO [3] (Senior Member, IEEE)

[1] Department of Electronic and Telecommunications, CICESE Research Center, Ensenada 22860, Mexico
[2] UAMR-R, Autonomous University of Tamaulipas, Reynosa 88710, Mexico
[3] Antennas Group, University Public of Navarra, 31006 Pamplona, Spain

CORRESPONDING AUTHOR: M. A. PANDURO (e-mail: mpanduro@cicese.mx)

ABSTRACT This paper presents a new design technique to improve the reduction of phase shifters using sub-arrays and CORPS (coherently radiating periodic structures) technology. The CORPS network generates the values of cophasal excitation with reduced input ports. These values feed an optimal sub-arrays structure. Furthermore, fixed and variable amplifiers allow a low SLL (side lobe level) by using a raised cosine amplitude distribution along sub-arrays inputs. The theoretical model of CORPS-Subarrays, numerical and experimental results of several design cases are presented. The proposed design achieves a ±14° scanning range with a higher reduction of phase shifters than other techniques presented previously in the state of art. This paper illustrates, as a contribution, the complete antenna system based on the fabrication of a prototype and experimental results to analyze the reduction capacity of phase shifters and scanning possibilities of the proposed methodology in antenna arrays. The experimental results of the BFN (beam-forming networks) prototype at 6 GHz for 11 antenna elements and 3 phase shifters are provided. The proposed design achieves a reduction of 72% of phased shifters with ±14° beam scanning and –15 dB of SLL.

INDEX TERMS Phased array, beam-scanning, subarrays, CORPS, phase shifters.

I. INTRODUCTION

THE PHASED arrays have become essential elements in new wireless technologies such as radar systems [1], satellites [2], mobile communications [3], and 5G networks [4]. These wireless technologies also require flexible antenna systems with the ability to handle one or multiple radiation beams simultaneously. Beam-forming networks (BFN) are capable of performing these features by providing the amplitude and phase values that generate the desired radiation pattern [5].

Normally BFN designs are composed by several electronic devices such as amplifiers and phase shifters placed in each antenna element, increasing the complexity and costs in large antenna arrays. This problem has motivated the search for new design techniques to reduce active devices and mainly the number of phase shifters, which can become the most complex components of the antennas system.

Thinned antenna array techniques optimize the active and non-active antenna elements reducing efficiently the electronic devices in the antenna system [6], [7]. Furthermore, this technique provides similar radiation pattern characteristics as large antenna arrays. However, reconfigurable properties are needed in the BFN to improve the characteristics of side lobe level (SLL) and beam scanning.

On the other hand, the technique of coherently radiating periodic structures (CORPS) has been studied for the reduction of phase shifters in the BFN [8]. Several CORPS network configurations have been analyzed for single and multi-beam applications [8], [9], [10], [11]. As a disadvantage, traditional CORPS designs deteriorate the phase slope when the number of layers is increased [12], which reduces the scanning capabilities and increases the SLL.

Recently, new CORPS configurations were implemented in linear and planar arrays [13], [14]. These designs generate the cophasal values needed to scan the radiation beam. In [15], CORPS network crossings are proposed to increase the reduction of phase shifters while maintaining low SLL.

Additionally, sub-arrays configurations provide an alternative by feeding one or more active antenna elements with a single electronic device (amplifier, phase shifters, et al.). Uniform [16], non-uniform [17], [18], and interleaved [19], [20] sub-arrays configurations have been studied for limited scanning and low SLL applications. These techniques trade-off the scanning range with the reduction capacity of phase shifter devices, i.e., the scanning range decrease as more active elements are grouped in sub-arrays.

Therefore, this paper proposes a new design technique to improve the reduction of phase shifters using sub-arrays and CORPS technology simultaneously. The CORPS network generates the values of cophasal excitation with reduced input ports. These values feed an optimal sub-arrays structure. As a result, the proposed design achieves a higher reduction of phase shifters than each technology implemented separately. Furthermore, fixed and variable amplifiers allow a low SLL by using a raised cosine amplitude distribution along sub-arrays inputs. The theoretical model of CORPS-Subarrays, numerical and experimental results of several design cases are presented. One contribution of this paper is the complete antenna system based on the fabrication of a prototype and experimental results to analyze the reduction capacity of phase shifters and scanning possibilities of the proposed methodology in antenna arrays. The experimental results of the BFN prototype at 6GHz for 11 antenna elements and 3 phase shifters are provided. The proposed design achieves a reduction of 72% of phased shifters with ±14° beam scanning and –15 dB of SLL.

II. CORPS-SUBARRAYS MODEL

Traditional phased arrays use a phase shifter and amplifier device in each antenna element to generate a radiation beam with low SLL, which is scanned by changing the phase slope and maintaining a desired amplitude distribution along the array. Thus, we proposed the configuration of CORPS-Subarrays shown in Fig. 1 to feed a linear array for low SLL and limited scanning range applications. This configuration presents two design steps: the first stage applies CORPS networks to reduce the number of input ports without deteriorating the cophasal values, this allows generate the linear phase slope necessary to scan the radiation pattern at the desired direction θ_0; the second stage uses aperiodic sub-array technologies to increase the phase shifters reduction and minimize the SLL. This reduces the number of phase shifter devices and keeps the SLL characteristics similar to a traditional phased array. Next, we describe the theoretical aspect of each design step.

A. CORPS NETWORK DESIGN

CORPS networks distribute power in the network using splitting and recombining nodes. Split nodes obtain two signals with equal phases, and the recombination nodes generate a new signal by recombining two distinct signals. This principle allows controlling the BFN with reduced input ports. Fig. 2a shows the basic structure of a CORPS network of two inputs and three outputs (2 × 3 CORPS network) [8]. For this network, if $[\boldsymbol{U}]$ is the vector of complex inputs and $[\boldsymbol{C}]$ represents the behavior of a 2 × 3 CORPS network, the output vector $[\boldsymbol{V}] = [V_1\ V_2\ V_3]$ is given as:

$$[\boldsymbol{V}] = [\boldsymbol{C}][\boldsymbol{U}]^T \tag{1}$$

where

$$[\boldsymbol{U}] = [U_1\ U_2] \tag{2}$$

$$[\boldsymbol{C}] = \begin{bmatrix} \frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} \\ 0 & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{3}$$

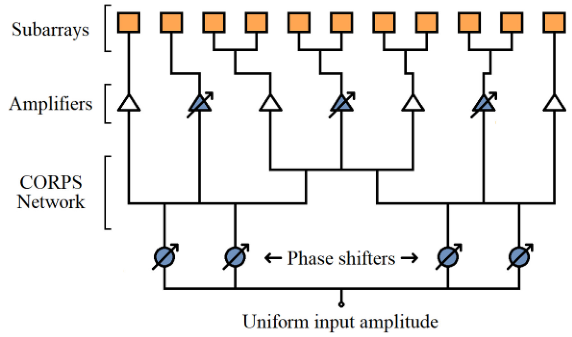

FIGURE 1. Proposed CORPS-Subarrays configuration for 11 antenna elements and ±14° beam scanning.

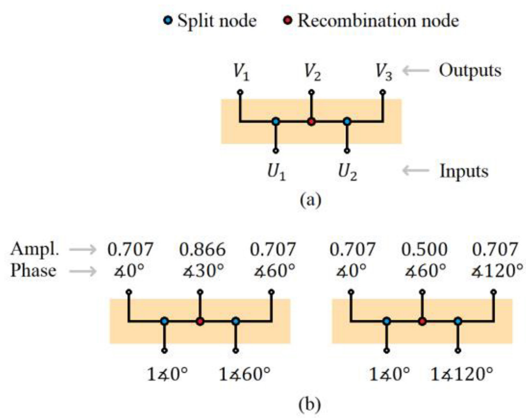

FIGURE 2. (a) Structure of a 2 × 3 CORPS network. (b) Behavior of the 2 × 3 CORPS network for a phase difference between adjacent ports of 60° and 120° degrees.

Fig. 2 shows the behavior of the 2 × 3 CORPS network when applying two signals of uniform amplitude with phase differences between adjacent ports of 60° and 120° degrees. In both examples, the phase values of V_1 and V_3 represent U_1 and U_2, respectively, due to only using split nodes for those ports. The phase value of V_2 is the average of the input phases of U_1 and U_2 because both signals have the same amplitude value when feeding the recombination node. However, the amplitude value for this port varies as a

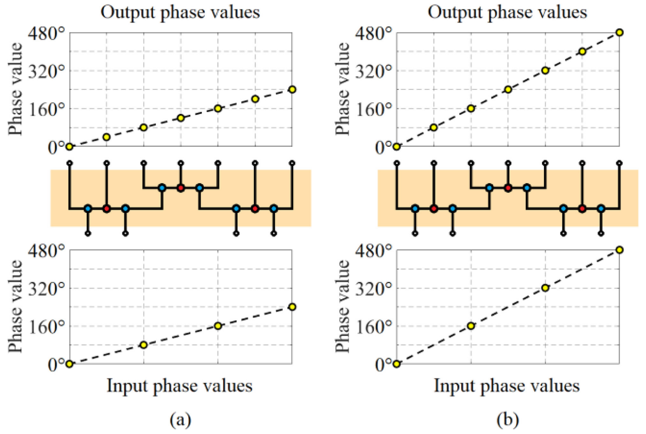

FIGURE 3. Behavior of phase values in a 4 × 7 CORPS network to apply a phase difference between adjacent ports of (a) 80° and (b) 160°.

function of the input phase slope and has more attenuation for values close to 180°. This attenuation can be suppressed by setting a variable amplifier at the output port of each recombination node [13], [21].

It is necessary to increase the number of layers of the CORPS networks to increase the phase shifters reduction. This has the disadvantage of deteriorating the values of the cophasal excitations and increasing losses due to energy dissipation [12]. The work cited in [13] proposes a solution to this problem by using a 4 × 7 CORPS network built by three 2 × 3 CORPS networks. Fig. 3 shows the behavior of the phase values for a 4 × 7 CORPS network to apply a phase difference between adjacent ports of 80° (Fig. 3a) and 160° (Fig. 3b). This network takes advantage of the phase interpolation property of 2 × 3 CORPS network to generate the ideal cophasal values using 4 input ports instead of 11 input ports.

For this work, a new 4 × 7 CORPS network was designed and simulated in CST Microwave Studio (see Fig. 4) for the center frequency of 6 GHz and with the following characteristics of the FR-4 substrate: a thick of 1.6 mm, relative permittivity of 4.2, and tangential losses of 0.025. The Gysel power divider [22] is utilized as a division and recombination node in the network, this was chosen based on its bandwidth characteristics, compact geometry, and ease of implementation in CORPS networks, offering advantages over other traditional power dividers. The Gysel power divider shown in Fig. 5a was optimized by full-wave simulation for the frequency of 6 GHz, it features a −10-dB impedance bandwidth of 3.5 GHz and transmission coefficients (S2,1 and S3,1) of –5 dB at 6 GHz (Fig. 5b).

As a difference from the design shown in [13], the proposed network in Fig. 4 eliminates the phase offsets (transmission line segments) at the output ports of the CORPS network to facilitate the sub-arrays implementation. This causes a phase difference of ≈ 102° between ports {5, 6, 10, and 11} and {7, 8, and 9}, as illustrated in Fig. 6. This phase difference is adjusted (considered) in the sub-arrays network.

The prototype for the 4 × 7 CORPS network is fabricated on FR-4 with surface mount resistors Vishay FC0603 (50 Ω) and SMA connectors PE44198. Fig. 7 shows the measured reflection coefficients obtained for the CORPS network (illustrated in Fig. 4). The –10-dB impedance bandwidth is ≈ 3 GHz, from 4.6 to 7.6 GHz. The measured transmission coefficients at the frequency of 6 GHz have a value of S5,1 = –6.3 dB, S6,1 = –9.6 dB, S6,2 = –9.7 dB, S7,2 = –10.5 dB, and S8,2 = –12.6 dB shown in Fig. 8a; S8,3 = –14.2 dB, S9,3 = –10.8 dB, S10,3 = –9.9 dB, S10,4 = –9.7 dB, and S11,4 = –6.9 dB shown in Fig. 8b. These values indicate a good performance agreeing the simulated values and have the most significant divergence at port 11 (of ≈ 1.3 dB at 6GHz).

The 4 × 7 CORPS network can be extended to feed more antenna elements using different configurations such as 6 × 9, and 8 × 11 CORPS networks. Thus, Fig. 9 presents how to generate larger CORPS structures without deteriorating the values of cophasal excitations. First, the 4 × 7 CORPS network is divided into three blocks: *A*, *B*, and *C*. Then, block *B* is replicated to generate a new CORPS network with *M* input ports and *S* output ports. Therefore, if *M* is an even number of input ports, the relation of *M* and *S* is given as:

$$S = 2M - 1 \tag{4}$$

An analysis of the performance of CORPS networks in different sub-array configurations is described in the next sections.

B. SUB-ARRAYS

Sub-arrays are an alternative to simplify the antenna system in applications with limited beam-scanning. In these configurations, more than one element is fed by an amplifier and phase shifter. Uniform sub-arrays have the main disadvantage of having a reduced scanning range due to the appearance of grating lobes in the visible range. These scanning characteristics are improved using non-uniform sub-array techniques [17], [18].

Traditionally the phase excitation value in each sub-array is calculated using the center position of the sub-array, generating a non-uniform phase slope when different sizes of sub-arrays are used. Instead, we propose to use a uniform phase slope generated by the CORPS network. Therefore, the phase value α'_s of the subarray $s = [1, 2, 3, \ldots, S]$ is calculated by the following expression:

$$\alpha'_s = -\frac{N-1}{S-1}(s-1)kdsin(\theta_0) \tag{5}$$

where d is the spacing between antenna elements, k is the wave coefficient, N is the number of antenna elements of the array, and θ_0 is the desired scanning direction.

Figure 10 shows an example of the radiation pattern performance for a sub-arrays configuration using the traditional and proposed phase values, non-uniform and uniform

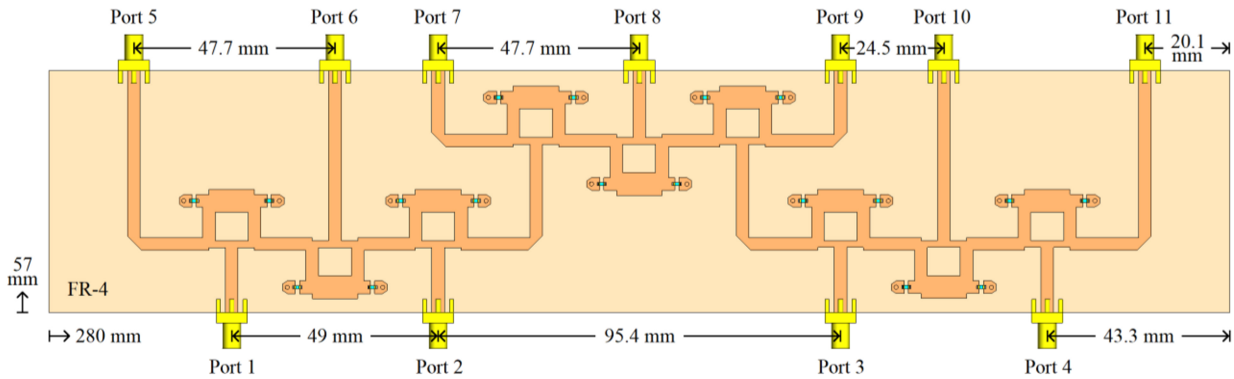

FIGURE 4. Proposed design of the 4 × 7 CORPS network.

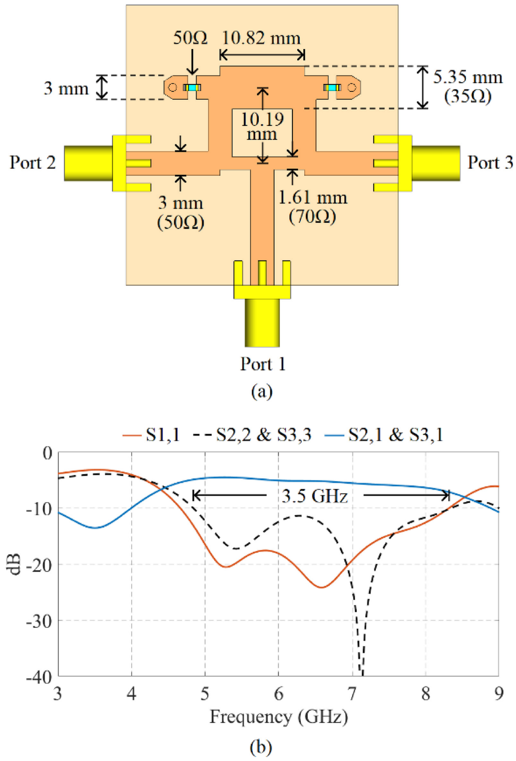

FIGURE 5. (a) CST model of the Gysel power divider. (b) S-parameters obtained by full-wave simulation.

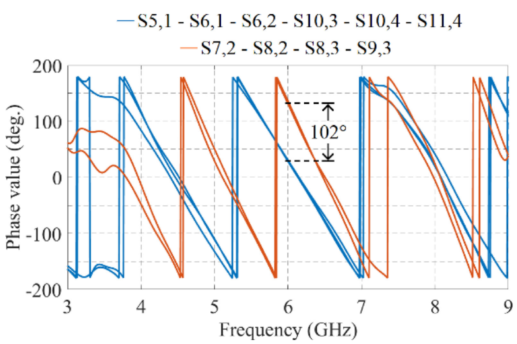

FIGURE 6. Behavior of the phase versus frequency for the 4 × 7 CORPS network.

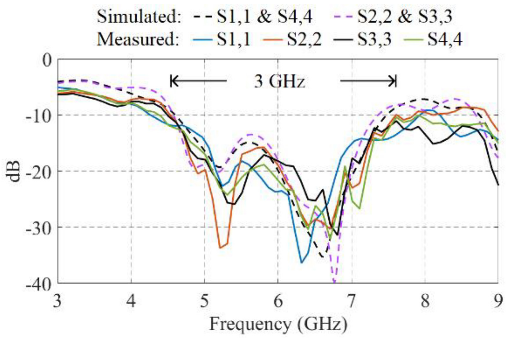

FIGURE 7. Reflection coefficients for the 4 × 7 CORPS network.

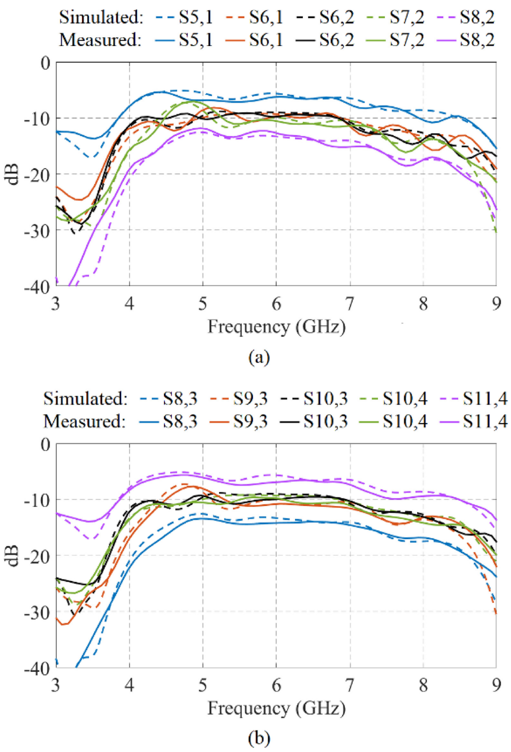

FIGURE 8. Transmission coefficients for the 4 × 7 CORPS network: (a) inputs 1 and 2, (b) inputs 3 and 4.

phase slope, respectively. The proposed phase value achieves a $SLL = -16$ dB in the beam-scanning direction of $\theta_0 = -11^\circ$. This represents a deterioration of 0.6 dB as compared to the SLL obtained with the traditional phase values ($SLL = -16.6$ dB). As an advantage, the CORPS network generates the proposed phase values using fewer input ports.

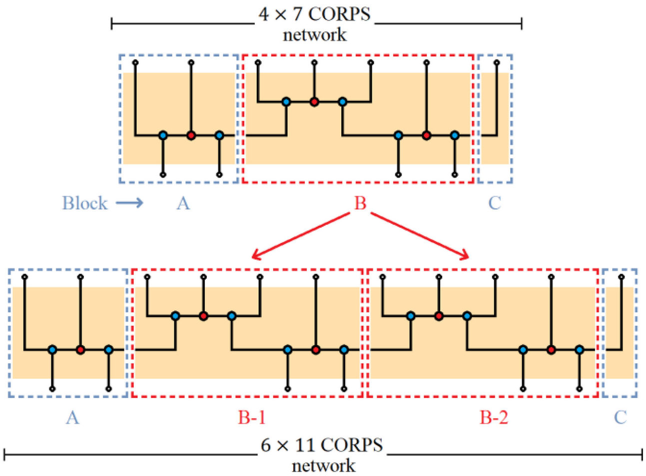

FIGURE 9. Construction of a 6 × 11 CORPS network.

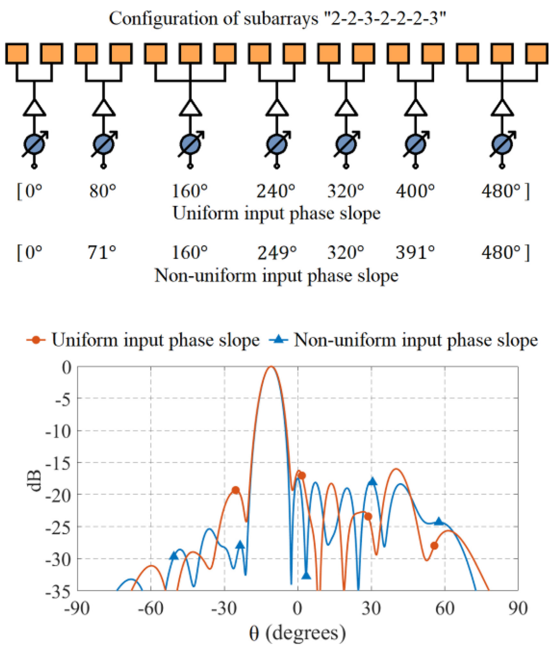

FIGURE 10. Comparison of the radiation pattern applying a uniform and non-uniform phase slope.

Usually, sub-arrays techniques use an exhaustive method to analyze all combinations to group the antenna elements. This causes long computational times in array systems of many antenna elements. Then, a fixed number of sub-arrays (S) and a maximum number of elements per sub-array ($S_{\max}$) can be defined to simplify the search for combinations.

In the proposed design of CORPS-Subarrays shown in Fig. 11, the output ports of the CORPS network are connected to a set of amplifiers, and these amplified signals feed each sub-array. Thus, the I_s value is the product of A_s and I'_s, and the amplification value A_s is calculated as:

$$A_s = \frac{I_s}{I'_s} \tag{6}$$

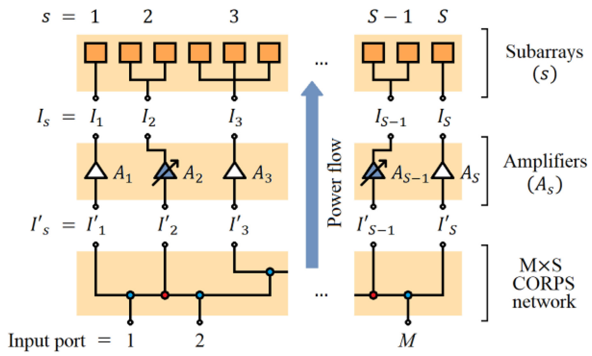

FIGURE 11. Proposed CORPS-Subarrays configuration for N antenna elements, M input ports and S subarrays.

where I'_s is the amplitude value at the outputs ports of the CORPS network, and I_s represents the raised cosine amplitude distribution desired to obtain a scannable beam with low SLL, which is given as:

$$I_s = \frac{1 + cos\left(\frac{d_s \cos^{-1}(2a-1)}{0.5L}\right)}{2} \tag{7}$$

where L is the array's aperture, a is the taper value, and d_s is the distance from the geometric center of the array to the center of s^{th} sub-array. The a value represents a compromise between SLL and beam width, i.e., as the SLL decreases, the beam width increases. A value of a = 0.5 (6 dB taper) is selected to generate a radiation beam with a SLL < –15 dB.

The maximum scanning direction is found by applying the maximum phase vector generated by the CORPS. Typically, the radiation pattern presents better radiation characteristics at smaller scanning angles.

Then, we propose the following steps to analyze all combinations of sub-arrays and classify those combinations by their radiation characteristics.

1) Define the variables N, a, M, and S.
2) Calculate the α'_s, I'_s, and A_s values by applying the maximum phase slope in the input ports of the CORPS network.
3) Create all sub-arrays combinations for N antennas, S sub-arrays, and $S_{max} = 3$.
4) Calculate the radiation pattern to measure the SLL and main beam direction of each combination.
5) Select the combination with the best beam scanning performance.

Next, the previous methodology is applied to design linear array systems using CORPS and sub-arrays, and we describe the details of the fabrication of the prototype of the full antenna system and the obtained experimental results.

III. EXPERIMENTAL RESULTS

In order to evaluate the performance of the proposed technique in different design cases, an analysis of CORPS-Subarrays configuration for different values of N, M, and S was achieved. First, the application of the previous procedure

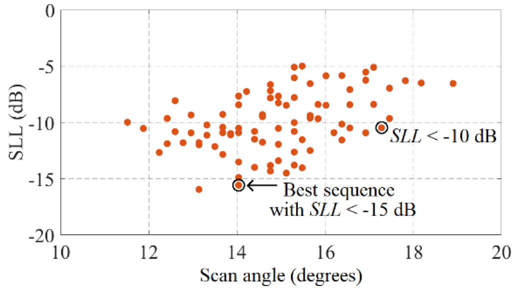

FIGURE 12. SLL versus scan angle for all combinations of CORPS-Subarrays with $N = 11$, $a = 0.5$, $M = 4$, and $S = 7$.

was considered for a system of 11 antenna elements and the next parameters were set in the proposed algorithm: $N = 11$, $a = 0.5$, $M = 4$, and $S = 7$. Thus, Fig. 12 shows a graphic of the SLL versus scan angle obtained in the radiation pattern of all combinations generated. This figure helps to select the best sub-arrays combination (or sequence)

considering the maximum scan angle with a $SLL <$ –15 dB, which is "1-1-2-2-2-2-1". In addition, it is interesting to note that for a $SLL <$ –10 dB the maximum scanning direction is 17.2°. Therefore, the proposed algorithm can be applied considering different design cases with different requirements of SLL.

Fig. 13 shows the behavior of the phase and amplitude values for the best configuration (CORPS-Subarrays). This sub-arrays sequence "1-1-2-2-2-2-1" (with the 4 × 7 CORPS network) generates a radiation pattern with low SLL (–15.8 dB) for the scanning direction of $\theta_0 = 14°$. The main beam is scanned in the interval $-14 < \theta_0 < 14°$ by modifying the input phase slope in the CORPS network (as observed in Fig. 14) and with the best performance of SLL (–18 dB) at $\theta_0 = 0°$.

To analyze the performance of the proposed technique in different design cases, an analysis of CORPS-Subarrays configuration for different values of N, M, and S is shown in Table 1. For these configurations, the subarrays sequence for the maximum scanning angle with $SLL <$ –15 dB is found by applying an input phase slope of 160° in the CORPS network.

As illustrated in Table 1, if the size of the sub-array (and the number of antenna elements) increases, the scanning range is reduced because the phase is distributed over a larger number of elements. Therefore, to improve the scanning range for a fixed number of antenna elements, increasing the number of ports in the CORPS network is necessary. It is interesting to observe the different configurations that can be generated for different number of input ports of CORPS networks.

Fig. 15 shows the behavior between the maximum scan angle for different CORPS-Subarrays with a SLL value below –15 dB. It is interesting to observe the trade-off between the number of antenna elements and the maximum scan angle.

In order to validate the simulation results, the design configuration considering the obtained sequence for $N = 11$

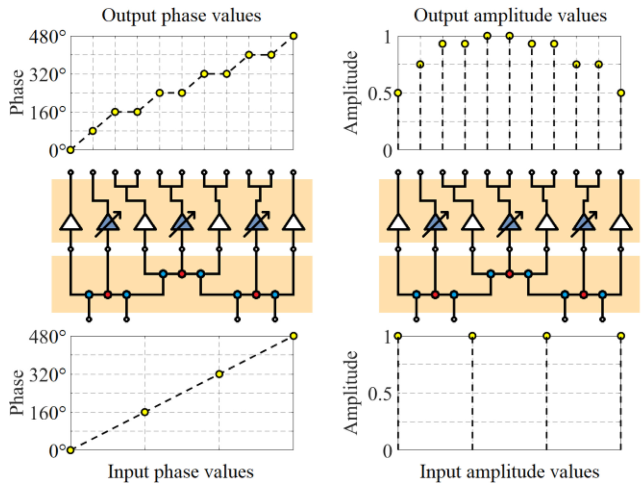

FIGURE 13. Behavior of phase and amplitude values in CORPS-Subarrays for the best sequence of sub-arrays.

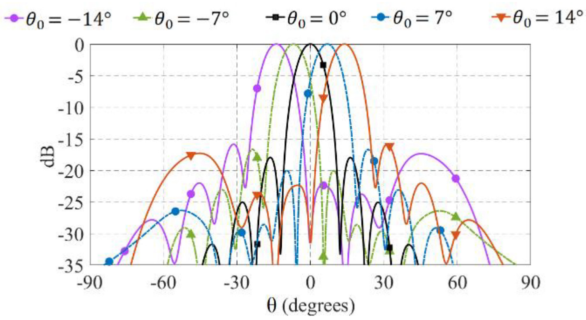

FIGURE 14. Beam-scanning for the best configuration of CORPS-Subarrays for $N = 11$, $a = 0.5$, $M = 4$, and $S = 7$.

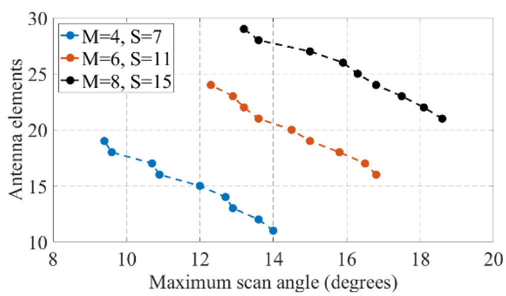

FIGURE 15. Behavior of maximum scan angle with $SLL <$ –15 dB for different CORPS-Subarrays configurations.

and the 4 × 7 CORPS network was fabricated in a full system prototype as illustrated in Fig. 16. The system based on a linear array uses a circular patch [23] of FR-4 substrate with *radio* = 13.02 mm and *thickness* = 1.6 mm at a central frequency of 6 GHz. The complete array system consists of: a linear array of 11 antenna elements, 7 sub-arrays (considering the best sequence "1-1-2-2-2-2-1"), the attenuators stage, the 4 × 7 CORPS network and the power division with phase shifting. Every block was simulated and constructed on FR-4 substrate, with careful consideration to achieving good impedance matching. Transmission lines of different length are used to generate the phase shifts. The

TABLE 1. Sub-arrays sequences for different configurations of the proposed design.

CORPS ports ($M \times S$)	Antenna elements (N)	Max. beam-scanning	Sub-arrays sequence
4 × 7	11	±14.0°	1 1 2 2 2 2 1
	12	±13.6°	1 2 1 2 2 2 2
	13	±12.9°	1 2 2 2 2 1 3
	14	±12.7°	2 2 2 2 2 1 3
	15	±12.0°	2 2 2 2 2 2 3
	16	±10.9°	2 2 3 2 2 2 3
	17	±10.7°	3 2 2 2 3 2 3
	18	±9.6°	3 2 2 3 3 2 3
	19	±9.4°	3 3 2 3 2 3 3
6 × 11	16	±16.8°	1 1 1 2 1 2 1 2 1 2 2
	17	±16.5°	1 2 1 2 1 2 1 2 1 2 2
	18	±15.8°	2 1 2 1 2 1 2 2 1 2 2
	19	±15.0°	2 2 1 2 1 2 2 2 1 2 2
	20	±14.5°	2 1 2 2 1 2 2 2 1 2 3
	21	±13.6°	2 2 2 1 2 2 2 2 2 1 3
	22	±13.2°	3 1 2 2 2 2 2 2 1 2 3
	23	±12.9°	3 1 2 2 2 2 2 2 1 3 3
	24	±12.3°	3 2 2 2 2 2 2 2 2 2 3
8 × 15	21	±18.6°	2 1 1 1 2 1 1 2 1 2 1 1 2 1 2
	22	±18.1°	2 1 1 2 1 1 2 1 2 1 2 1 1 2 2
	23	±17.5°	2 1 1 2 1 1 2 1 2 1 2 1 2 1 3
	24	±16.8°	2 2 1 2 1 2 1 2 1 2 1 2 1 1 3
	25	±16.3°	3 1 1 1 2 2 1 2 1 2 1 2 2 1 3
	26	±15.9°	3 1 2 1 2 1 2 1 2 2 1 2 1 2 3
	27	±15.0°	3 1 2 2 1 2 1 2 2 2 1 2 2 1 3
	28	±13.6°	3 1 2 2 1 2 2 2 1 2 2 2 1 2 3
	29	±13.2°	3 1 3 1 2 2 1 2 2 2 2 1 2 2 3

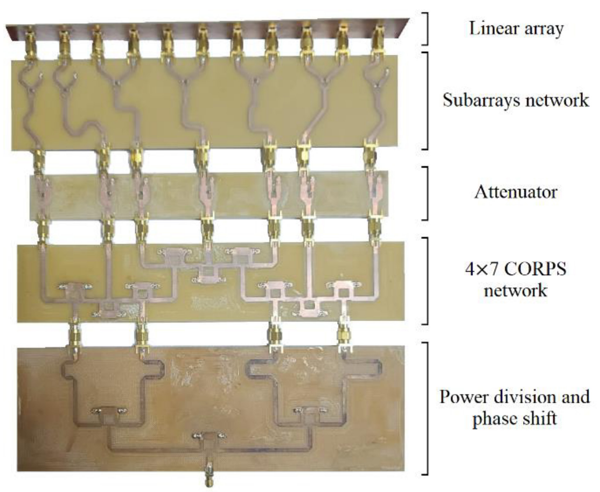

FIGURE 16. Prototype of the complete antenna system for the CORPS-subarrays configuration.

attenuators are built using Wilkinson power dividers and with resistors of surface mount (50 and 100 Ohms) [24] as illustrated in Fig. 17.

Fig. 18 illustrates the active reflection coefficients for the antenna system considering the farthest scanning direction $\theta_0 = -14°$. As illustrated in Fig. 18, the value of the active reflection coefficient of the array system of 11 antenna elements is below –10 dB for all scanning directions. Therefore, the complete antenna system illustrates a fine matching for the desired frequency. In this design, the bandwidth performance is limited mainly by the antenna element, therefore, wideband elements can be considered to improve the proposed design in future works.

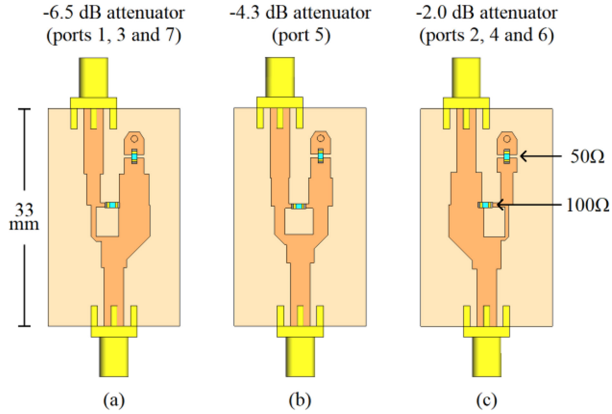

FIGURE 17. Schematic circuits for the built attenuators.

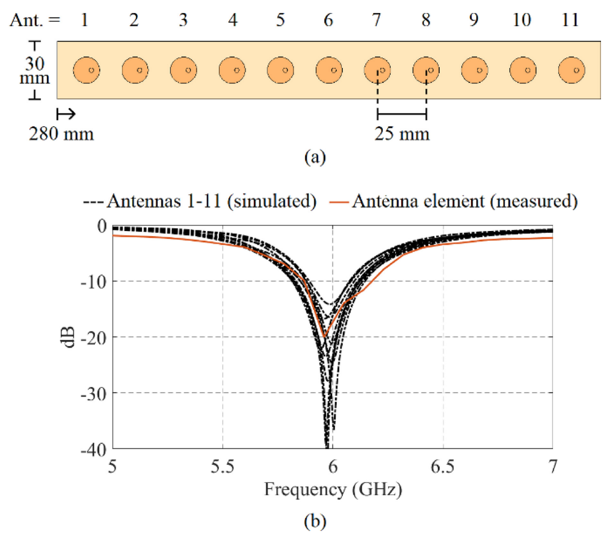

FIGURE 18. Active reflection coefficients for the antenna system considering the farthest scanning direction 0 = –14°.

Fig. 19 shows the complete antenna system in the anechoic chamber to take experimental measurements of the radiation pattern. Then, Fig. 20 illustrates the radiation pattern generated by experimental measurements and its comparison with respect to the simulated case (CST) at $\theta_0 = -14°$. The results obtained by experimental measurements agree very well the simulation results. These results obtained by measurements and simulations reveal that the design method using CORPS and sub-arrays achieves to reduce the number of phase shifters in a 72%. This reduction capability is reached considering a SLL performance of ≈ –15dB for the beam-steering range of $-14° < \theta_0 < 14°$.

Table 2 shows a comparative evaluation of then proposed technique considering other works previously published in the literature. This evaluation and comparison is made considering the next design variables: the percentage of phase shifters reduction, the number of phase shifters employed, the SLL performance, the beam-scanning range, the number

TABLE 2. Comparison between linear phased arrays with a reduced number of phase shifters.

Reference	Number of antenna elements	Number of phase shifters	Number of variable amplifiers	Phase shifters reduction	Main beam scanning range	Peak side lobe level
This work	11	3	3	72%	±14°	–14.5 dB (measured)
[9]	10	8	8	20%	±30°	–19 dB
[25]	4	3	-	25%	±24.5°	–10 dB
[20]	28	14	-	50%	±24°	–15 dB
[13]	7	3	3	57%	±25°	–18 dB
[18]	30	12	-	60%	±14°	–15 dB
[26]	5	2	-	60%	±8°	–15 dB
[15]	9	3	5	66%	±25°	–19 dB
[21]	8	2	8	75%	±18.5°	–9 dB

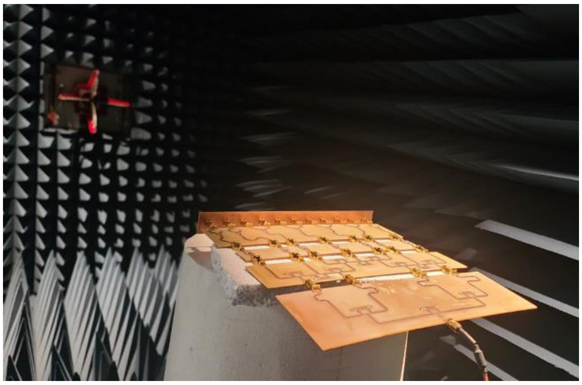

FIGURE 19. Complete antenna system in the anechoic chamber to take experimental measurements of the radiation pattern.

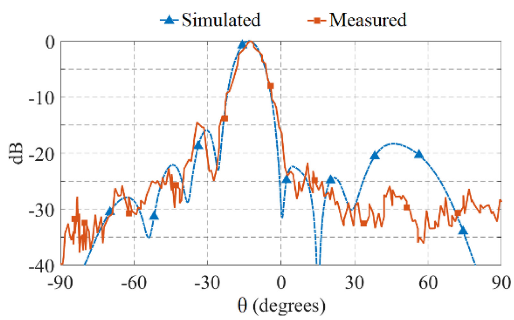

FIGURE 20. Radiation pattern obtained by experimental measurements and its comparison with respect to the simulated case at ($\theta_0 = -14°$).

of variable amplifiers and the number of antenna elements. Table 2 illustrates that the proposed design methodology (using CORPS and sub-arrays) provides the best design trade-off in terms of phase shifters reduction (72%), beam-scanning range (±14°) and SLL (–15dB). The highest case of reduction of phase shifters for linear arrays is 75% [21] for a beam-scanning range of (±18°). However, that case presented a SLL performance of –9dB.

The proposed technique has many freedom degrees to try improve the performance features. For instance, other optimization techniques could be considered to find the optimal values of amplitude and phase to reduce the SLL. Additionally, aperiodic array configurations could help to eliminate the amplifiers and consequently reduce the backward length of the BFN. Finally, the performance in the reduction capability of this design methodology could be extended for two dimensional arrays. All these topics can be considered as an extension of this work.

This paper only analyzed linear arrays systems. However, more array system architectures can be studied and analyzed in the future work to find different types of operation and performance. Furthermore, different array architectures can be used in a defined application in order to find the best configuration to reduce phase shifters or active devices. The optimization and creation of new and better antenna systems is a research problem that remains open for all the antenna community.

The design methodology illustrated in this work can be considered as an excellent option for reducing the number of phase shifters or active devices in linear antenna array systems.

IV. CONCLUSION

This paper illustrated how to combine CORPS technology and subarrays to reduce the number of phase shifters employed in a linear array system. A methodology was proposed to determine the best subarrays sequence considering that a CORPS network feeds the subarrays. The CORPS network generated the values of cophasal excitation with reduced input ports.

The performance of the proposed technique was analyzed for different design cases. The subarrays sequence for the maximum scanning angle was found considering a *SLL* < –15 dB by applying an input phase slope of 160° in the CORPS network. If the size of the sub-array (and the number of antenna elements) increases, the scanning range was reduced. Therefore, to improve the scanning range for a fixed number of antenna elements, increasing the number of ports in the CORPS network was necessary.

The presented methodology illustrated that using CORPS and sub-arrays a reduction of 72% was achieved in the number of phase shifters. This reduction capability was reached considering a SLL performance of ≈ –15dB for the beam-steering range of $-14° < \theta_0 < 14°$. This was validated by experimental measurements and numerical simulations, the experimental measurements agreed very well the simulation results.

Furthermore, the proposed design methodology (using CORPS and sub-arrays) provided a good design trade-off in terms of phase shifters reduction (72%), beam-scanning range (±14°) and SLL (–15dB), with respect to other works previously published.

The design methodology illustrated in this work can be considered as an excellent option for reducing the number of phase shifters in linear antenna array systems.

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