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Beam Control with Active Reflectarrays

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Active reflectarrays having beam control are presented in this paper. The steering capability is obtained by achieving different amplitude and phase of the scattered field from each reflectarray element, which is controlled by the use of an IQ modulator in some cases. An aperture coupled patch with perpendicular microstrip feeds is employed as radiating element. One of its ports is employed to receive the signal and the other to retransmit it with the phase and gain selected in the amplitude/phase control unit.

The beam control can be also obtained by means of switching circuit. A laboratory experience with 1-bit reflectarray of 4 × 4 elements shows the beam control performance, and a study to simplify manufacturing process of 3-bit reflectarray is also presented.

Key words: active antennas, active reflectarrays, beam control, beam steering capability

1 INTRODUCTION

A reflectarray is a type of antenna that combines the best features of conventional reflector with those of the phased printed arrays. In this structure a horn or small antenna array illuminates a planar array of microstrip radiators, which, by using suitable phasing circuits, converts an incident spherical wave into a plane wave, pointed at a chosen direction [1]. Their low cost, flatness, and easiness to install and manufacture convert these structures into ideal solutions to modern communication systems [2]. Moreover, the spatial signal distribution permits to eliminate the complexity associated to the microstrip feed distribution network.

The possibility of acting individually in each of their elements offers additional advantages derived from their power combining features. In this sense, amplifying functions have been added in individually phased active antenna elements [3]. Nevertheless, only a few works have considered the possibility of varying the scattered field phase from each element, achieving beam steering capabilities [4].

Taking into account these characteristics, a radiating unit with amplitude and phase control of the reradiate field is proposed in this paper to steer the main beam in the desired direction. It is based on the vector sum method, applying a DC voltage through the IF port of two double balanced diode mixers in a IQ configuration.

The radiating element of the reflectarray is an aperture coupled patch antenna with two perpendicular feeds. One of its ports is employed to receive the signal from the feeder while the other is used to retransmit it with the amplitude and phase selected in the vector summing unit.

Finally, a 4 × 2 reflectarray lab model has been designed, manufactured and measured. By means of an accurate adjustment of each element phase shift it is possible not only to convert the spherical wave into plane one but also to steer the main beam. In this sense, in order to demonstrate the proposed radiating architecture potentialities different radiation patterns have been measured.

Other of the objectives of this work was the study of reflectarrays with switches at the radiating elements, in order to have a control of the beam. The idea was to demonstrate that it is possible to control a switch placed on the radiator coupled line. This switch changes the length of the terminal stub, to provide a change of phase in the signal reflected by this element, and consequently to change the radiation pattern.

A second objective of this task was to know the difficulties of the manufacturing process of this kind of reflectors.

2 AMPLITUDE AND PHASE CONTROL UNIT AT EACH REFLECTARRAY ELEMENT

Figure 1 shows a scheme of the amplitude/phase control unit employed in each radiating element. The received signal is equally divided through a 90º hybrid coupler that excites the LO port of a mixer. By proper adjustment of the DC voltage in the IF port it is possible to vary the amplitude and to switch the phase, between two values with a 180º shift (depending on the DC sign), of the RF signals. Finally, these output signals are combined employing a Wilkinson circuit achieving a complete (360º) phase control range.

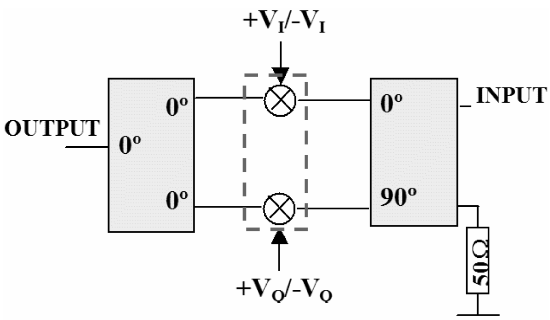

Fig. 1 Amplitude/Phase control unit used in each reflectarray element

In order to clarify this behaviour a summing scheme can be used. The output signal is the resultant vector obtained through a sum of two perpendicular variable vectors. Consequently, using a pair voltage conveniently selected, the magnitude and phase of the resultant vector may be controlled in a complete phase range.

3 APERTURE COUPLED PATCH DESIGN

An aperture coupled microstrip square patch antenna has been proposed as a building block of the reflectarray [5]. The patch has two microstrip feeds placed at perpendicular sides, exciting the TM01 and TM10 orthogonal modes for the same resonating frequency aimed to a simultaneous reception, in one of its ports, and retransmission of a microwave signal by the other. The dual feed provides a reasonable isolation between its two ports, an important characteristic when active elements are incorporated. The gain of the active path, from reception to retransmission, is limited by the isolation between both ports, achieving an unstable state when such condition is not fulfilled.

Figure 2 illustrates the designed square patch. The active circuit and the feed microstrip lines

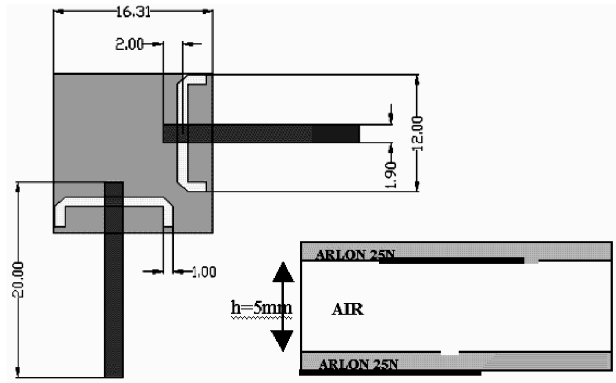

Fig. 2 Top and side view of the designed patch

have been printed in substrate ARLON 25N with $\varepsilon_r = 3.38$ and thickness of 30 mils (0.762 mm). In order to improve the gain and the bandwidth, the air is employed as »radiating« substrate. Consequently, an auxiliary layer is needed to print the patch on it. The frequency band around 5.8 GHz in our particular application, determines the dimensions.

A commercial EM simulator, Ansoft Ensemble, has been employed to design and analyse the structure. In Figure 3, the simulated and measured input matching and isolation between the two ports are shown.

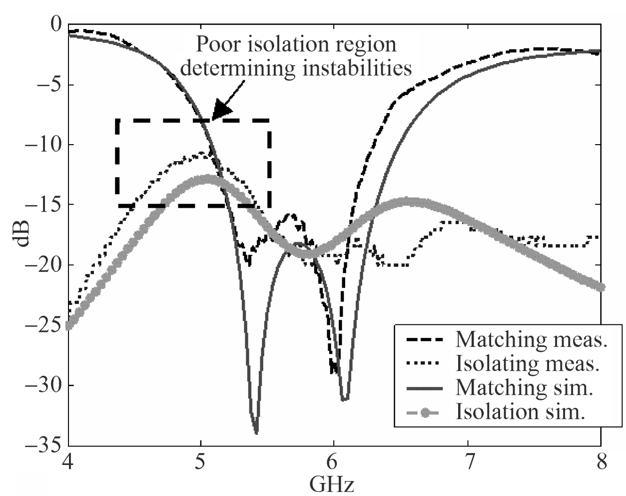

Fig. 3 Measured and simulate input atching and isolation

4 COMPLETE ACTIVE REFLECTARRAY ELEMENT WITH AMPLITUDE AND PHASE CONTROL

Finally the radiating element and the amplitude/phase control circuitry were integrated in the same PCB employing the AIA (Active Integrated

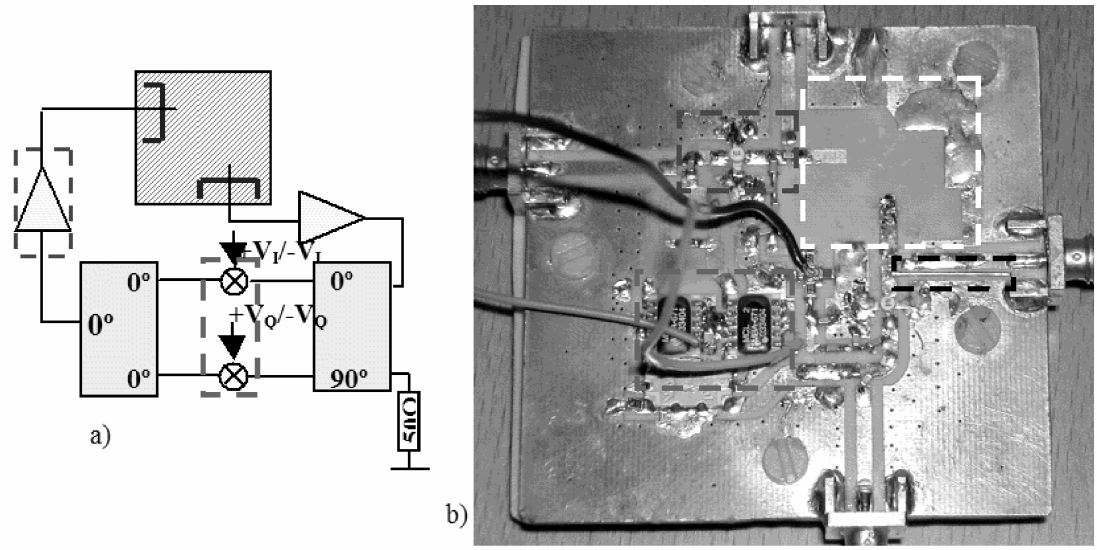

Fig. 4 a) Schematic and b) photograph of the reflectarray unit

Antenna) concept to minimise the cable and feeding line losses in a similar way to [6].

In order to compensate the associated attenuation of the IQ control circuit two commercial amplifiers were added in each unit. In Figure 4 a clarifying schematic and a detailed photograph of the active element can be seen.

In the photograph some parts of the reflectarray unit have been highlighted. The MBA-671 mixers from Minicircuits and the NBB 400 amplifiers from RF Microdevices constitute the active parts with a power consumption of 665 mW. In the IQ structure, the input 90º hybrid coupler is a high--quality and small size commercial circuit from Anaren while the combination of the output signals of each mixer was done through a microstrip Wilkinson circuit specifically designed for it. To accurately adjust the phase/gain of each circuit, different SMA connectors were added to take samples of the signal in different parts.

The active control circuit was measured independently of the patch obtaining a maximum gain of 12 dB. Complete phase range was also measured for different gains.

Once the structure was measured with the SMA connectors without the antenna and verified its correct performance, the complete radiating structure was probed appearing undesired oscillating frequencies around 5 GHz. The problem comes associated to the poor isolation between the antenna ports at this band of frequencies, comparable to the gain of the active path, as has been highlighted in Figure 3. Consequently was necessary to eliminate this unpleasant effect. Taking into account the limited space available in the reflectarray a stub was added to reduce the coupling in the previous mentioned band, as can be observed in Figure 4.

5 STRUCTURE OF THE REFLECTARRAY WITH AMPLITUDE AND PHASE CONTROL

In Figure 5 the layout of the passive reflectarray is shown. In such antenna, the selected feeder is an aperture-coupled patch equal to the reflectarray radiating elements and transmitting with vertical polarisation. The active circuits, not included in this illustration in order to clarify the whole radiating structure, were inserted in the feed layer.

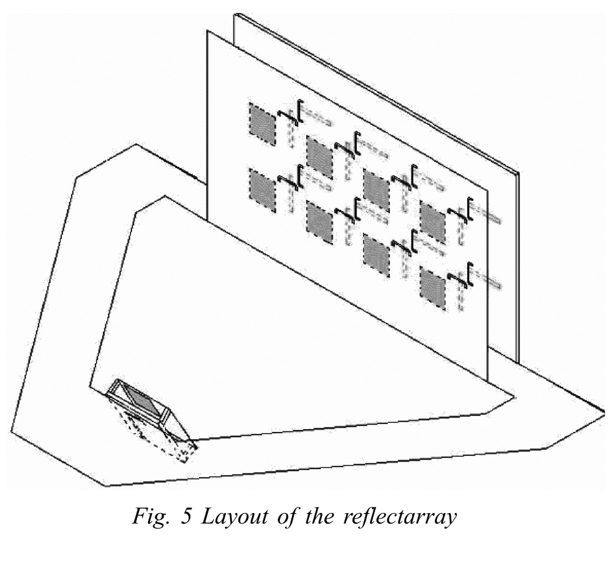

Fig. 5 Layout of the reflectarray

In order to avoid feed blockage an offset feed was used, placing the feeder at 200 mm down from the centre and 55 mm out from the array.

A photograph of the reflectarray feed layer is shown in Figure 6. As has been previously commented, each unit has two varying bias voltages to control the mixers and one fixed voltage to supply the amplifiers.

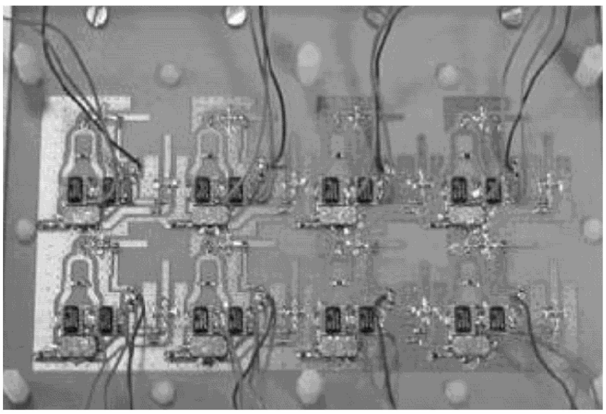

Fig. 6 Reflectarray feeding layer

Each element demands a phase-shift value as a function of its position with respect to the feeder to convert the spherical incident wave to a planar one. There are different ways to achieve the required phase-shift per cell, in [7] equal size patches are employed with passive delay lines of different lengths while in [8] the phase of the scattered filed is controlled by means of the patch size. Although these methods permit to assure the correct antenna performance in a higher bandwidth, the proposed system takes advantage of the total phase control in each element provided by the active circuit. Additionally, the possibility of controlling the phase shift between the patches permits to vary the main beam direction.

In such case, the field phase in each unit is calibrated independently to fulfil (1), [8–9]

$$\phi_i = k_0 \cdot (R_i - \tilde{r}_i \cdot \tilde{r}_0) \qquad (1)$$

where R_i is the distance from the phase centre of the feed to the element, $\tilde{r}_i$ is the vector from the centre of the array to the element, and $\tilde{r}_0$ is the unit vector in the main beam direction.

In order to vary the reflectarray beam pointing, the required phase-shift values per radiating unit were calculated following (1).

6 MEASUREMENT RESULTS OF THE REFLECTARRAY WITH AMPLITUDE AND PHASE CONTROL

A specific test set-up was implemented in an anechoic chamber to measure the described antenna. In such scenario, a perfect calibrated horn antenna was employed in reception to measure the reflectarray response, assuring a far field distance between them. As has been commented the radiation pattern phase evolution for each unit was calibrated in the main direction for different gains. In this way, it was possible to select those biasing points per unit to fulfil (1) for different pointing directions.

Due to the huge number of different controlling bias voltages and in order to generate a portable and compactness radiating structure a special bias control circuitry was also implemented. The required voltages per unit, obtained in a previous step, were then introduced in a hexadecimal table in the PC as a function of the required gain and phase. By means of a RS232 interface the PC and the control board are connected being able to provide the required bias to each mixer and amplifier. A rear view of the manufactured prototype can be seen in Figure 7.

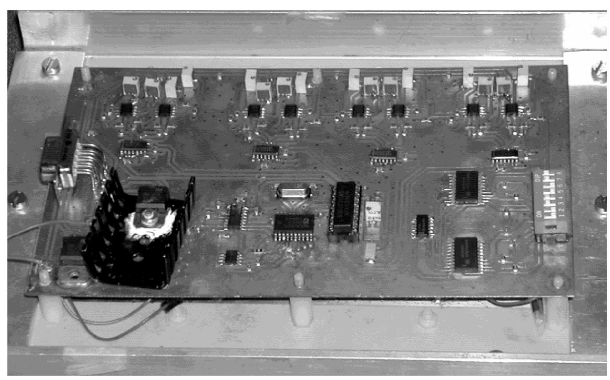

Fig. 7 Rear view of the final manufactured prototype

Finally, the reflectarray far field radiation pattern was measured for three main pointing directions (0º, 10º, −10º). The individual amplitude control would also permit to conform different amplitude distributions. In Figure 8, measurements of normalised radiation patterns for a uniform amplitude distribution have been represented. A comparative study between the resultant measurements and the calculated array factor of the retransmitted patterns has been done and illustrated in next figure.

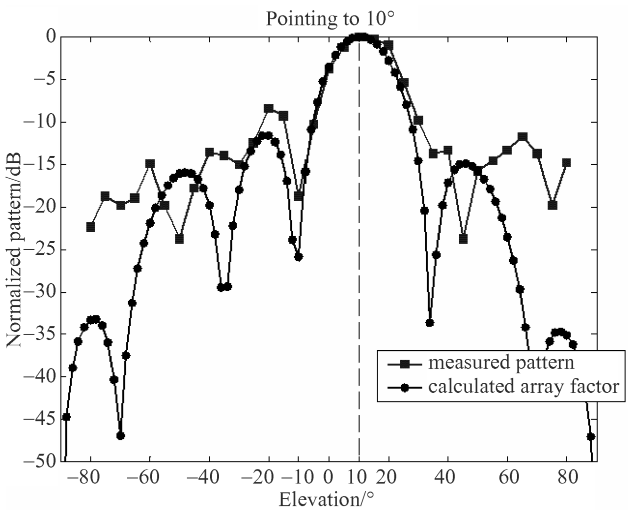

Fig. 8a Measured and calculated radiation patterns, for the 10° pointing direction

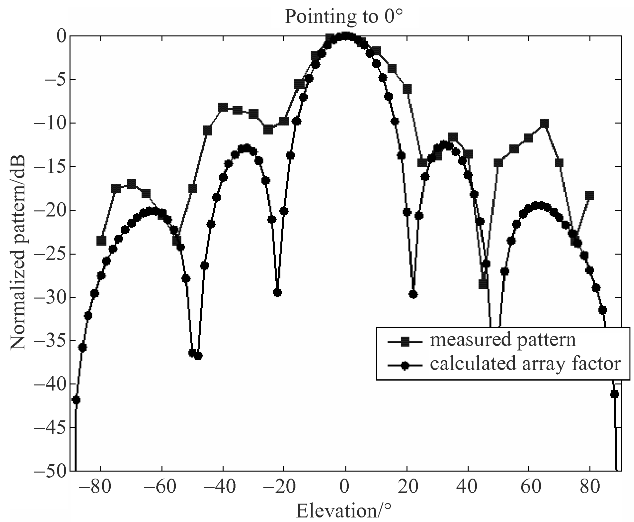

Fig. 8b Measured and calculated radiation patterns, for the 0° pointing direction

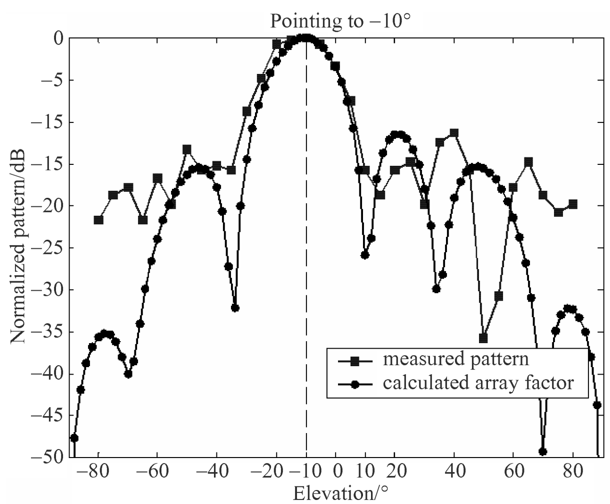

Fig. 8c Measured and calculated radiation patterns, for the −10° pointing direction

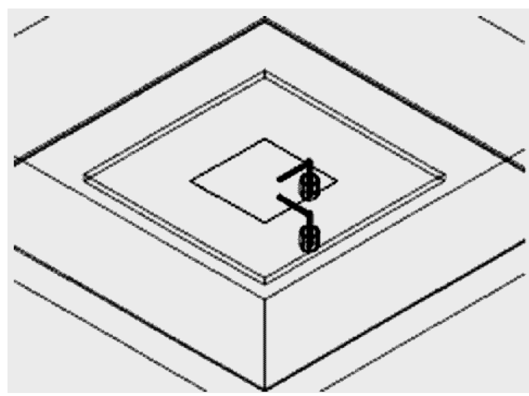

Fig. 9 Selected radiator for 1 bit switch reflectarray

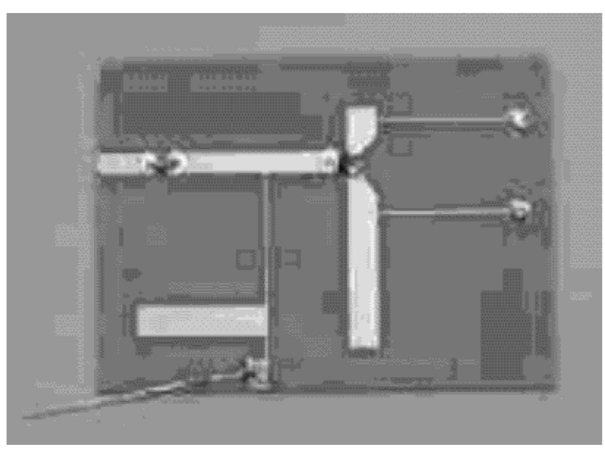

Fig. 10 Switch circuit of 1 bit

As can be seen the similarity among the obtained results and the calculated ones demonstrates the potentiality of the proposed architecture.

7 RADIATOR AND CIRCUITRY DESIGN OF THE SWITCHED BEAM REFLECTARRAY

Looking for the design of a demonstrator of the effect of a switch on the reflectarray surface, 2.2 GHz was selected as the working frequency of the prototype. This frequency value allows an easy manufacturing process of the reflectarray radiator, switching circuitry and its integration.

In order to have a radiating element with high level of stability from manufacturing parameters, it was studied several possibilities, and the selected element was a square microstrip patch, fed by a capacitive probe in »L« [10]. Figure 9 shows the configuration of this kind of radiator.

The Figure 10 shows the layout of the switch element, in a sample to the measurement of its electrical characteristics. It can be seen in this figure the lines of high impedance used to polarised the diodes.

The selected impedance of the line was 50 Ω. A capacitive element was used to the isolation of the measurement instrumental.

8 STRUCTURE AND MEASUREMENT OF 1-BIT SWITCHED BEAM REFLECTARRAY

The reflectarray prototype was divided in four sub-reflectarrays of 1×4 elements, with the following conditions:

- All of the switches at each sub-reflectarray are biased with the same DC voltage, so all of the radiating elements of each sub-reflectarray will be at the same state.
- There are only two different states per subarray. Each subarray state is related to a different length of the terminal stub of radiators, being $\lambda/4$ at the design frequency this length difference.
- So, if a subarray is at the state 1, the phase of its reflected signal is ($\alpha°$). On the contrary, if the subarray is at the state 2, the phase of its reflected signal is ($\alpha° + 180°$).
- The four sub-reflectarrays are placed in such way that the 4×4 reflectarray is obtained.
- There are only two states for the whole reflectarray. Each reflectarray state is the combination of different subarray states, as it is shown in the Table 1.

Table 1 **Phase distribution at both sub-reflectarray states**

Sub-reflectarray	1	2	3	4
State 1	$\alpha°$	$\alpha°$	$\alpha°$	$\alpha°$
State 2	$\alpha°$	$\alpha° + 180°$	$\alpha°$	$\alpha° + 180°$

In the reflectarray state 1, all of the subarrays are at the same state, so it will have a sum pattern. On the contrary, in the reflectarray state 2, the subarrays are at different state, and they are combined in the way to obtain a null of the radiation pattern.

Figure 11 shows the configuration of the reflectarray. In order to know the behaviour in a repetitive process, the reflectarray was designed using a module of 2×2 elements. Figure 12 shows different components of the module, during the assembly process, and Figure 13 shows a view of the final prototype of the reflectarray in the measurement system.

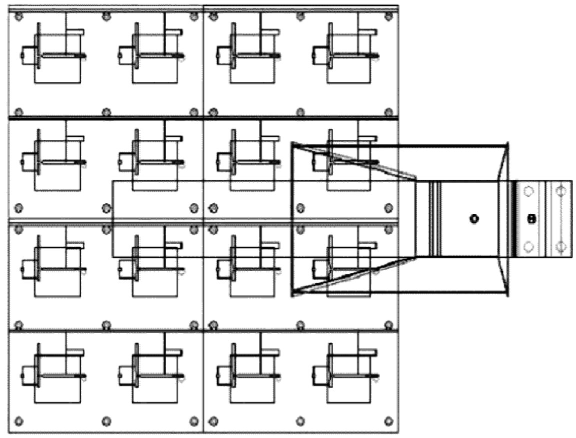

Fig. 11 Layout of the 1 bit switch reflectarray

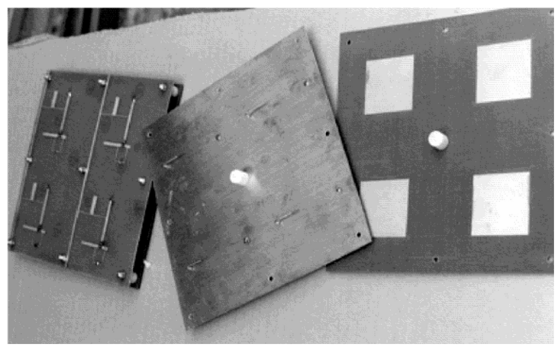

Fig. 12 Components of the manufactured reflectarray

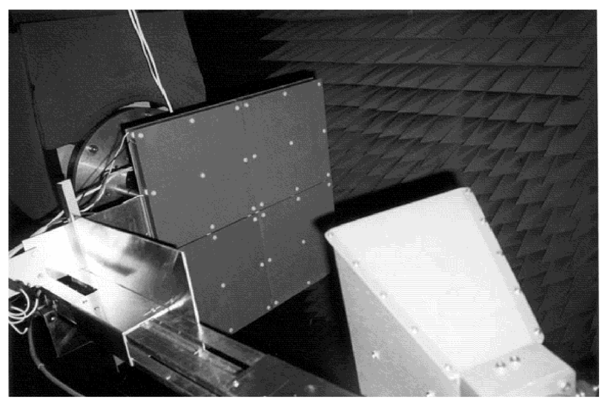

Fig. 13 Final prototype of the 1 bit switch reflectarray

Figure 14 shows the measurement at both states.

The ripple obtained in the sum pattern is due to the presence of the feeder. This effect was verified

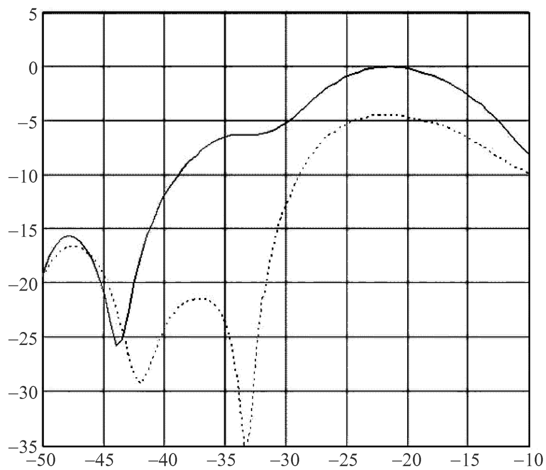

Fig. 14 Measurement of the two states of the prototype

by means of the measurement of a ground plane in the position of the reflectarray. Figure 15 shows a comparison of the measured sum pattern and its simulation including the radiation due to the feeder. The result of the measurement of the ground plane is also shown in the Figure 15.

9 FUTURE DEVELOPMENTS ON SWITCHED BEAM REFLECTARRAYS

One of the problems that the experience has shown, is the manufacturing of reflectarrays with radiators having different terminal stubs. Nevertheless, there is a reflectarray configuration, which allows that all of the elements have the same switching circuitry. It is the case of the Figure 16, where it is implemented at each radiator a circuit of 3 bits. All of the radiators have the same circuitry, and consequently the manufacturing process is not difficult, and it can be made a modular development, without dependence of the number of radiators of reflectarray.

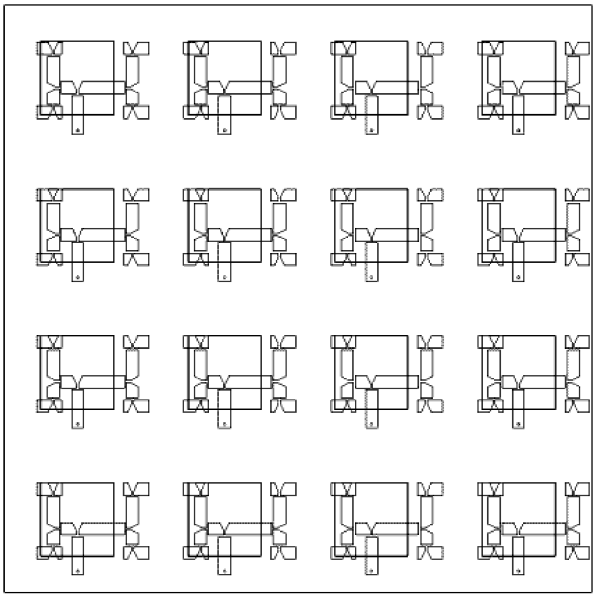

Fig. 16 Layout of the reflectarray with 3 bits phase shifter at one polarization

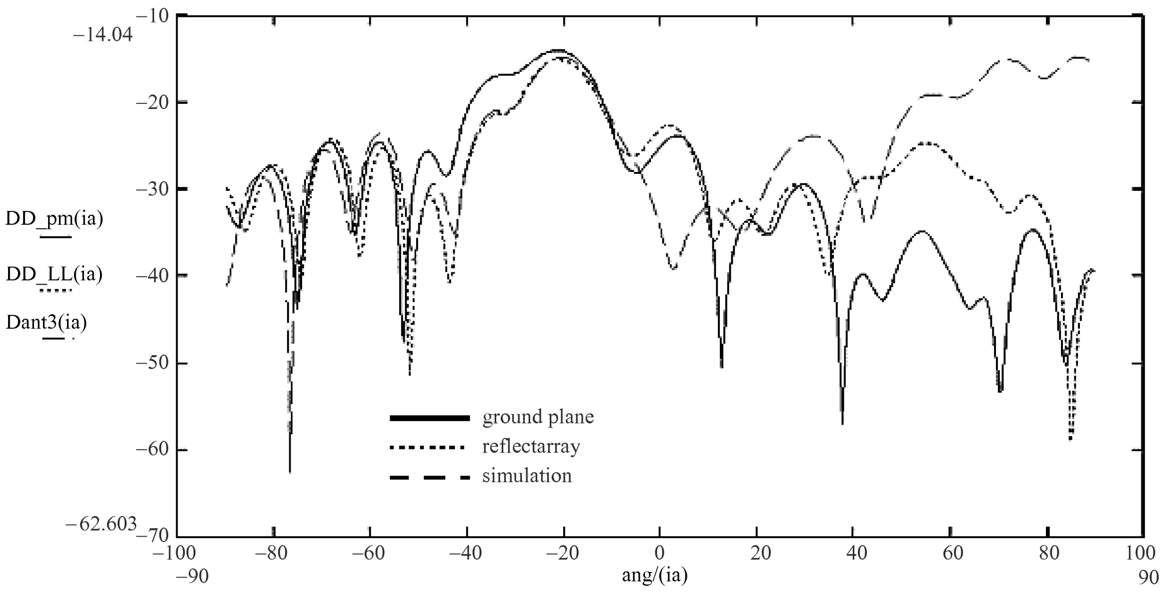

Fig. 15 Comparison between measurement and simulation

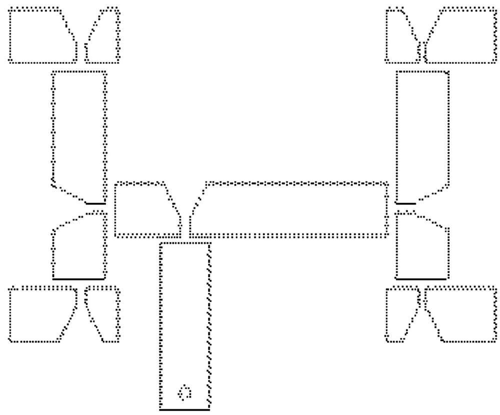

Fig. 17 Detail of the 3 bits phase shifter

Figure 17 shows a detail of the 3 bits phase shifter.

One of the advantages of this element if the stability on losses at any state of the phase shifter, because all of diodes are working at any state.

As it can be seen in Figure 16, the size of the element circuitry of 3 bits is too big to be implemented at both polarisations in the same layer. Nevertheless, the advantage of the selected kind of feeding is the possibility to separate by means a coax cable, the input port of the radiator versus the input port of the microstrip circuit. So, the second polarisation switching circuitry can be placed at other layer as it is shows in Figure 18, it is only

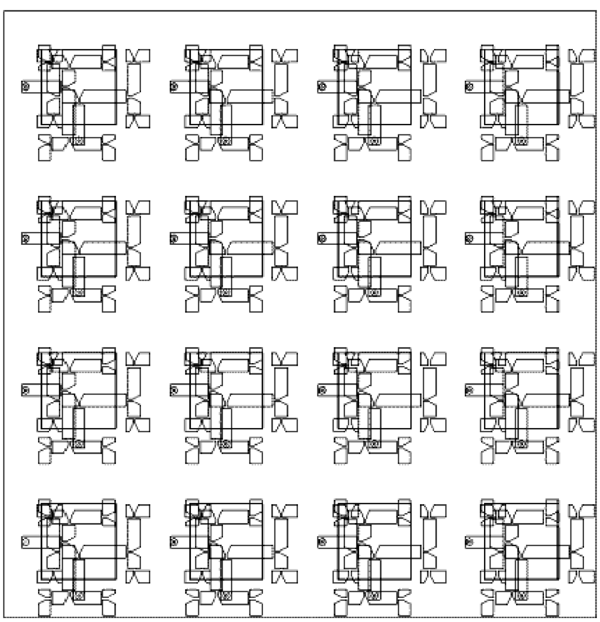

Fig. 18 Layout of the reflectarray with 3 bits phase shifter at both polarisations

necessary to have knowledge of the length of this separation cable to be compensated in the other polarisation circuit.

Figure 19 shows a lateral view of the reflectarray module of 4×4 radiators, having three substrate layers: one per the upper metallic shape of the patch, and the others per each polarisation phase shifters.

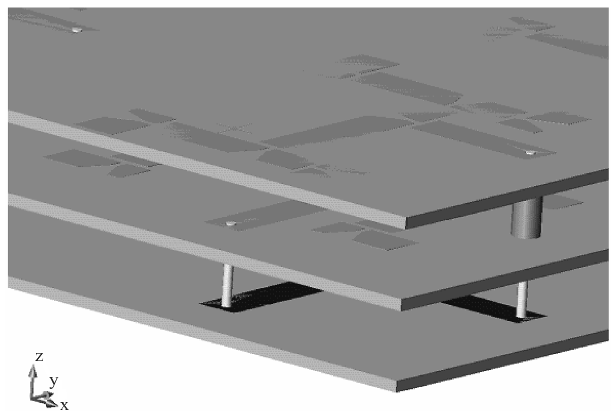

Fig. 19 Detail of the radiator layer distribution of 3 bits phase shifter at both polarisations

10 CONCLUSIONS

An active reflectarray with beam steering capabilities has been designed, manufactured and measured. Based on a IQ configuration, the amplitude and phase of the scattered field for each of its radiating units have been varied. The obtained phase control permits to achieve the required phase-shift, not only to convert the spherical incident wave into a plane one but also to steer the main beam. On the other hand, different amplitude distributions with different gains can be easily implemented by using these elements. The measurements of the radiation pattern pointing to different elevation angles have demonstrated the potentiality of the proposed architecture.

Also, a study to demonstrate the behaviour of future switched beam reflectarrays has been carried out. The complexity of the manufacturing process is clear, and different suggestions have been proposed in order to minimise it, being the more important of them a modular design based on the use of 3 bit phase shifter.

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Kontrola snopa aktivnih reflektorskih nizova. U ovom su radu prikazani aktivni reflektorski nizovi s kontrolom snopa. Sposobnost zakretanja snopa dobivena je primjenom različitih amplituda i faza raspršenog polja iz elementa reflektorskog niza, koji je kontroliran uporabom IQ modulatora. Kao zračeći element upotrijebljen je patch spregnut preko otvora s okomitim mikrotrakastim pobudnim linijama. Jedan od njegovih prolaza je iskorišten za prijam signala, a drugi za reemitiranje istog signala s fazom i pojačanjem odabranim u kontrolnoj jedinici amplitude i faze. Kontrola snopa može se također dobiti pomoću prekidačkog sklopa. Laboratorijska iskustva s 1-bitnim reflektorskim nizom s 4×4 elementa pokazuje preformance kontrole snopa, a također je prikazano i istraživanje na pojednostavljenju proizvodnog procesa 3-bitnog reflektorskog niza.

Ključne riječi: aktivne antene, aktivni reflektorski nizovi, upravljanje snopom, zakretanje snopa

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