Progress In Electromagnetics Research M, Vol. 111, 185–197, 2022

Pattern Reconfigurable End-Fire Antenna Array with High Directivity

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Abstract—This paper presents a highly directive pattern reconfigurable antenna array capable of switching single or multiple beams of high directivity in multiple directions. Each element is individually capable of providing radiation pattern of directivity 12 dB and realized gain of 10.2 dB. Here, eight directive array elements are arranged in a circular fashion resembling a fan along with a switching arrangement to obtain beam switching in the horizontal plane. Two or more elements can be excited simultaneously to obtain patterns in multiple directions. In another configuration, the elements are arranged around a cylindrical support resembling an umbrella structure to obtain azimuthal switching at a desired tilt. The ability to reconfigure patterns in desired direction facilitates their usage as base station antennas providing desired angular coverage to intended users only, resulting in least signal interference.

1. INTRODUCTION AND BACKGROUND

Pattern reconfigurable antennas of high directivity are relevant in the current wireless communication scenario involving high interferences and congestion, by virtue of the exponential boom in the number of cellular subscribers. Such antennas enable space division of the radiated power in point-to-point or point-to-multipoint connection, like in linking base stations and mobiles [1], automotive radars [2], military and mobile satellite communications [3, 4], etc. Directional beam switching can significantly improve system capacity, security, range, and signal to noise ratio. Besides, it eliminates the issue of power wastage, path loss, and information distortion due to the interference from undesired users which are otherwise unavoidable in the case of omnidirectional antennas.

Majority of pattern reconfigurable antennas reported in literature have low directivity while steerable directive antennas are hampered by design complexity, low gain, and limited scan range [5–8]. In reactively controlled arrays with central fed dipole and six parasitic dipoles arranged around a circle [5], loads connected to all parasitic elements around the driven element had to be tuned to provide a tilt of the beam angle. Optimized calculated loads were complex values making their practical realization a daunting task, and there was lack of control over the radiation characteristics of the array. Preston et al. [6] achieved electronic beam steering with an active patch element and four adjacent parasitic patches but produced just two beams with a gain of 2.4 dBi in the forward direction and 2.6 dBi in the backward direction. In [7], a pattern reconfigurable microstrip parasitic dipole array was designed with pin diode switches, but beam tilting was possible only at 0° and $+/-35°$. In [8], a super-directive beam switching two-element pifa array offered highly directive beams in just two directions $+/-60°$ with a measured gain of only 2.5 dBi. Mechanical realizations via actuators were bulky, and phased arrays require complex attenuators and phase shifters [9–11]. Detailed studies on Switched

Received 18 April 2022, Accepted 17 June 2022, Scheduled 13 July 2022
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Parasitic Antennas and Reconfigurable Antennas were done by Thiel and Smith [12] and Bernhard [13], respectively.

In this paper, we integrate the concept of high directivity end-fire antenna elements with beam switching such that highly directive antenna beams can be selectively oriented or switched in any desired direction. Further, the system can be configured for single or multiple sectored beams. This gives optimum performance without the drawbacks associated with the regular pattern reconfigurable antennas previously mentioned. In addition, the directivity values of the antenna elements demonstrated in this paper are greater than that provided by ordinary end-fire arrays with uniform excitation [14].

Table 1 shows a comparison between the proposed design and related works reported in literature in which the directivity and number of directions in which beams can be switched are compared.

Table 1. Comparison of proposed design with those reported in literature.

Work	Antenna structure	Switching mechanism	Number of beams	Directivity (dB)	Plane of beam switching
[15]	a) 5 disk loaded monopoles on circular ground plane b) Sector monopole array	By open and short circuiting parasitic elements	Five	a) 5.1 b) 4.7	Elevation
[16]	4 monopoles and 8 slots	SP8T	Eight	5	Azimuth
[17]	Dipole with H-shaped units	Pin diodes	Two	6.4	Elevation
[18]	4 arc dipoles	Pin diodes	Four	4.1	Azimuth
[19]	Four monopoles and six stubs	Pin diodes	Four	4	Azimuth
[20]	Dipole arrays on three substrates with supporting posts	Pin diodes	Five	6.5	Elevation
[21]	9 dipolar wire plates	By changing loads of parasitic elements	Eight	8.5	Azimuth
Our work	8 sets of arc dipole array	By selectively switching the elements	Multiple	12	Azimuthal switching in the desired elevation angle

The novelty of the work lies in the fact that unlike majority of the highly directive arrays reported in literature, the proposed reconfigurable array realizes azimuthal switching in the desired elevation angle and shows much higher directivity with satisfactory impedance matching, gain, efficiency, and bandwidth.

2. SWITCHABLE DIRECTIVE CIRCULAR ANTENNA ARRAY DESIGN

The proposed structure is a set of eight highly directive microstrip arc dipole based end-fire array antennas arranged in a circular shape on a plane which can be switched selectively for radiation along the directions of choice at an operating frequency of 5.8 GHz. Here, individual beams of high directivity or multiple beams in desired directions can be obtained. The advantage of the proposed structure lies in the fact that it is compact, and the beams are highly directive.

2.1. End-Fire Antenna Array Element Design

Each microstrip arc dipole based end-fire array comprises a driven element, a parasitic reflector element, and four directors as shown in Figure 1. The design of two elements — reflector and driven element — is optimised initially, and arc directors are added. Further, a glass epoxy FR4 substrate ($\varepsilon_r = 4.4$, thickness = 0.8 mm) on which the dipoles are printed is shaped into a trapezoid to attain higher directivity. The detailed design of this antenna array element has been reported by the authors

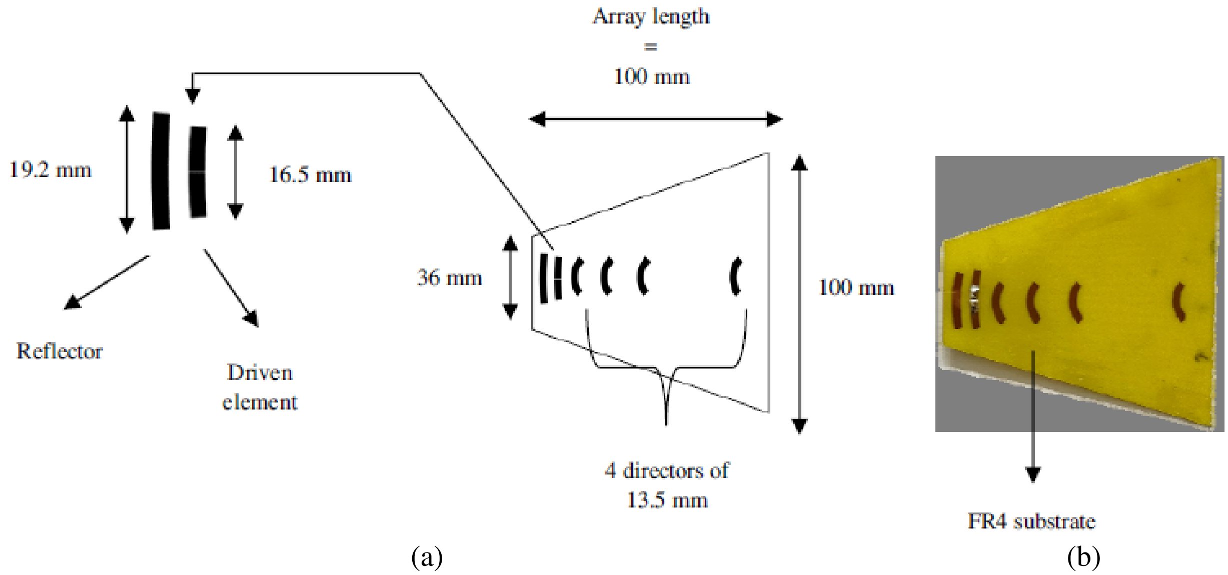

Figure 1. (a) Schematic and (b) fabricated prototype of the end-fire antenna element.

earlier [22], where the antenna is shown to exhibit radiation in the end-fire direction with a directivity of 12 dB and a realized gain of 10.2 dB at the resonant frequency of 5.8 GHz. The measured 2 : 1 VSWR bandwidth is 400 MHz with an efficiency of 70%.

Return loss and gain plots for single array element are shown in Figures 2(a) and 2(b), respectively. S_{11} value is -20 dB, and the gain is 10.2 dB at the resonant frequency of 5.8 GHz. The measured co-polar and cross polar patterns in E-plane and H-plane are depicted in Figures 3(a) and 3(b), respectively.

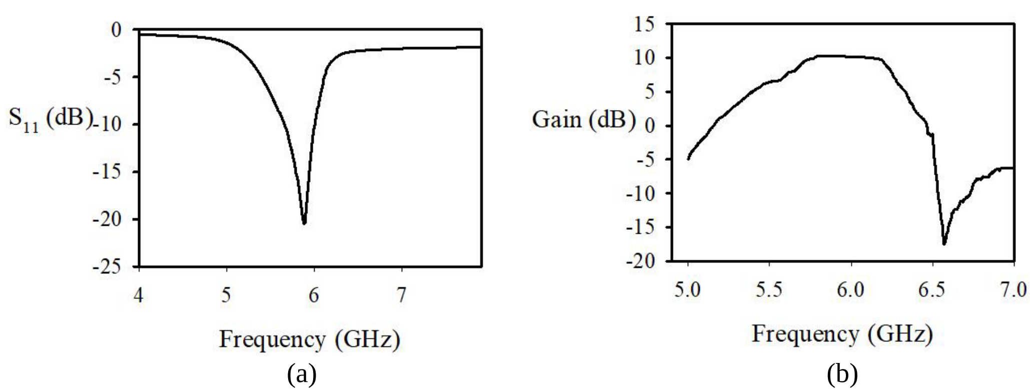

Figure 2. (a) Return loss and (b) gain plot for single directive array element.

2.2. Switchable Circular Array

Having designed a single directive element as detailed above, eight such elements are arranged to form a circular array (in the xy plane) as shown in Figure 4. The shorter edges of the trapezoid shaped antenna elements meet at their vertices forming a regular octagon. When elements are selectively chosen, beam steering is observed in the azimuthal plane (the plane containing the array).

This array can produce single beam or multiple beams using the arrangement described in the following sections.

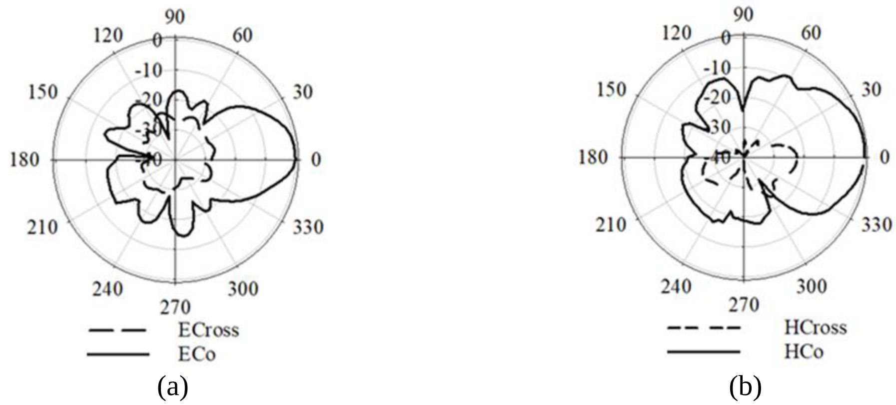

Figure 3. Measured co-polar and cross-polar patterns in (a) E plane, (b) H plane.

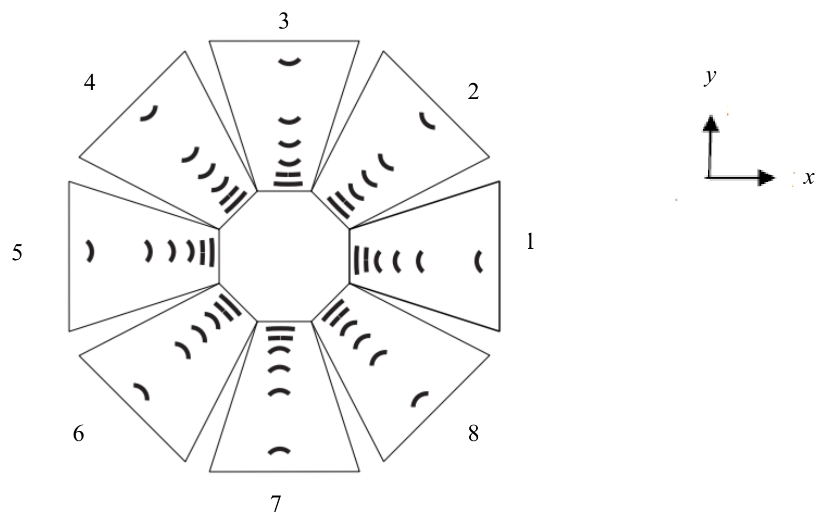

Figure 4. Circular array with eight directive antenna elements.

2.2.1. Single Beam Switching

When antennas are excited individually, each antenna radiates a pattern of high directivity in its end-fire direction. This is achieved by connecting the antennas to the output ports of an SP8T RF switch as shown in Figure 5. RF signal is given to the input port of the switch. Eight output ports of the

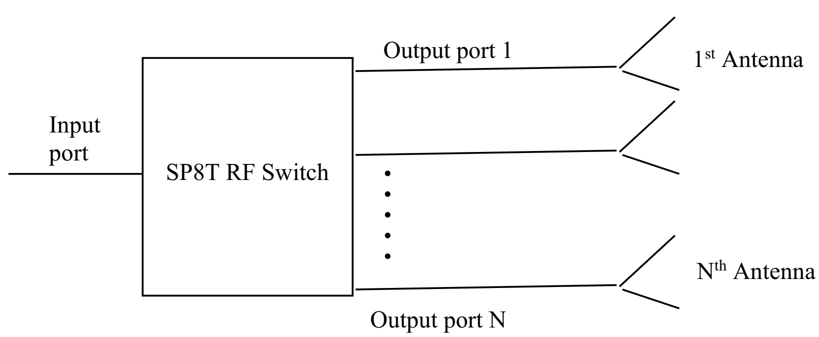

Figure 5. Individual excitation of antennas.

switch are connected to eight antennas in the array via coaxial cables. When appropriate TTL logic is applied to the control pins of the switch, the corresponding antenna gets excited, thereby radiating in its end-fire direction. The switch used here is Techniwave absorptive coaxial type RF switch.

2.2.2. Multiple Beam Switching

When two or more antennas are excited simultaneously using the switching arrangement shown in Figure 6, patterns can be produced in multiple directions.

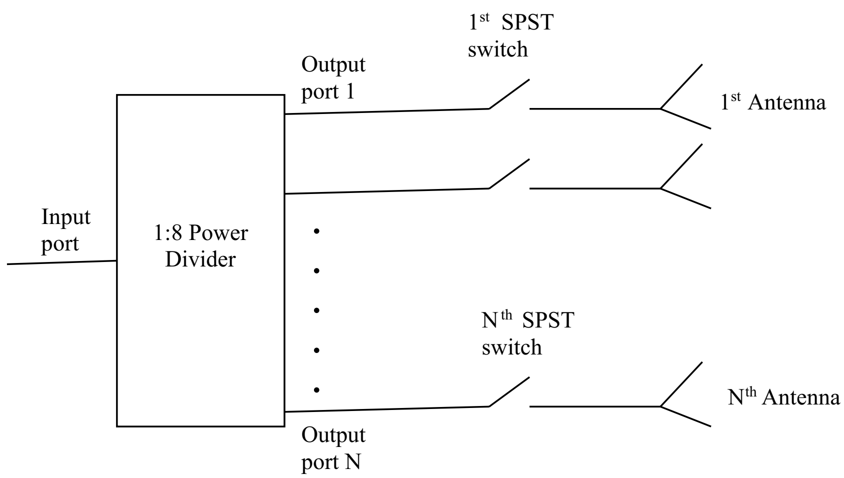

Figure 6. Simultaneous excitation of two or more antennas.

RF signal is given to the input port of ZB8PD 1 : 8 power divider. The antennas are connected to the output ports of the power divider, using independent switches as shown in Figure 6, so that any number of switches can be activated. In the measurement setup, due to the non-availability of adequate number of identical switches, the required antennas are manually connected to the ports with other ports terminated in matched loads.

2.3. Simulated Results

The co-polar radiation patterns of the circular array at 5.8 GHz, when antennas 1 to 8 are excited individually, are depicted in Figures 7(a)–(h). Simulated directivity varies from 11.5 to 12 dBi, and simulated gain varies from 9.6 to 11 dB in the frequency band. Each antenna radiates with directivity 12 dB, with half-power beamwidths of 40° and 50° in orthogonal planes. The main lobe of antenna 1 lies along phi = 0°. The main lobes of antennas 2 to 8 are directed 45° apart with a beamwidth of 40°.

For simultaneous communication in different directions, multiple antennas are to be excited in different combinations. The optimal combination for maximum directivity is when two adjacent antennas are excited simultaneously. S_{11} plots for different switching states do not show much variations as illustrated in Figure 8(a). Gain plot for simultaneous excitation of adjacent antennas 1 and 2 is depicted in Figure 8(b). The co-polar and cross polar patterns for this excitation are shown in Figure 9. All other combinations result in patterns in different directions. Figures 10(a)–(e) illustrate the radiation patterns formed for different excitation combinations at 5.8 GHz. Following is some of the observations based on Figure 10.

i) For simultaneous excitation of two adjacent antennas, the resultant pattern is formed between the main beam directions of those two antennas. For example, Figure 10(a) shows the pattern formed for simultaneous excitation of antennas 1 and 2. The pattern of directivity 11 dB is produced between the main beam directions of antennas 1 and 2.

ii) Excitation of more than two adjacent antennas produces a wider beam between the main beam directions of those antennas. For example, excitation of antennas 1, 2 and 3 produces a beam between the main beam directions of 1, 2, and 3 as illustrated in Figure 10(b).

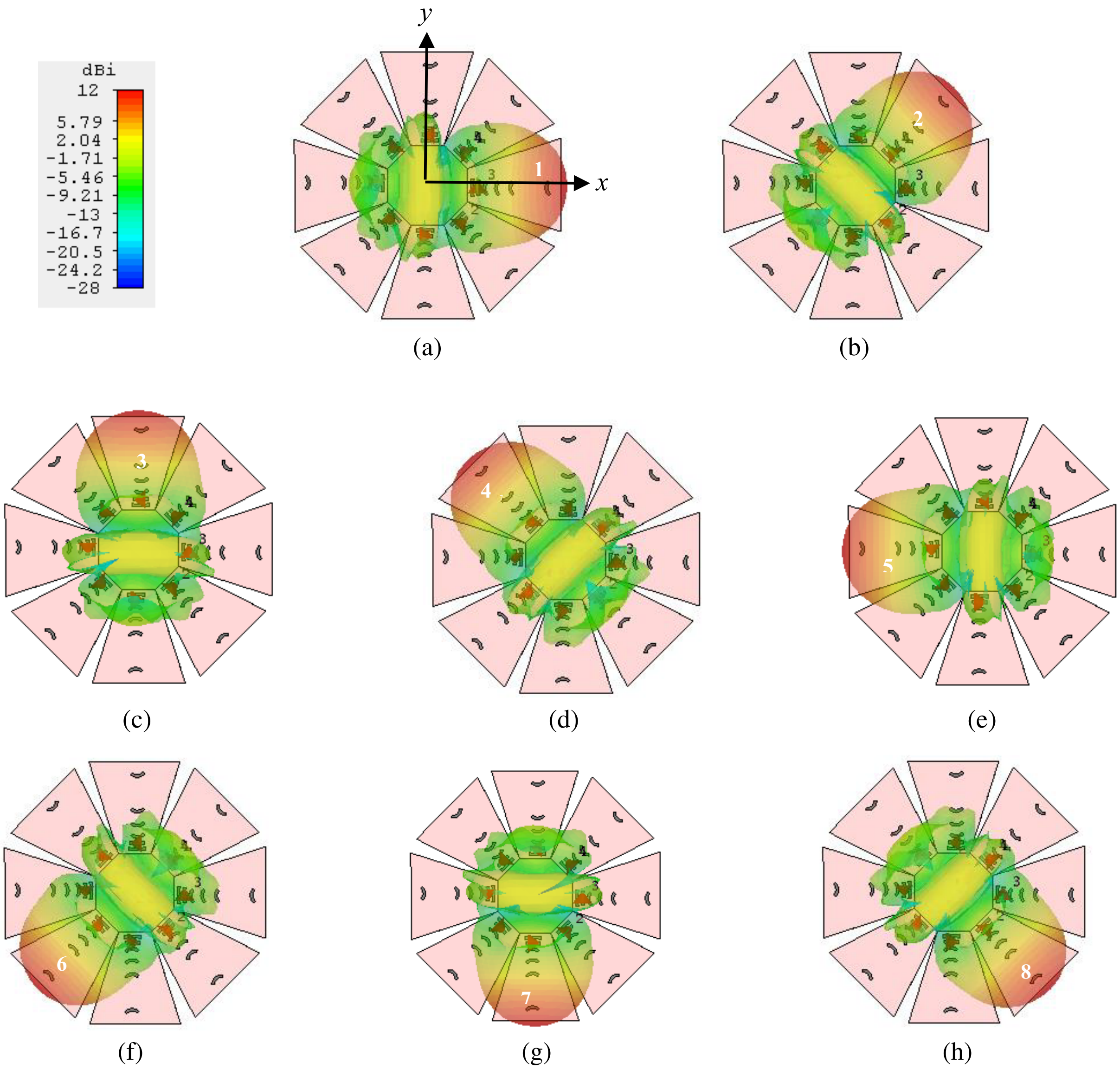

Figure 7. Simulated co-polar radiation patterns for individual excitation of antennas, (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, (g) 7 and (h) 8.

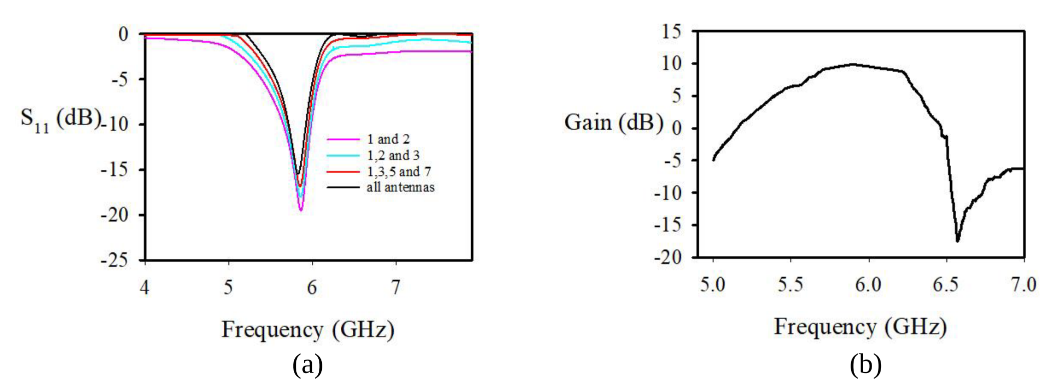

Figure 8. (a) S_{11} plots for different switching states and (b) gain plot for excitation of two adjacent antennas.

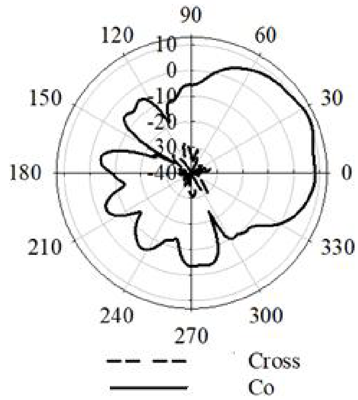

Figure 9. Co and cross polar pattern for simultaneous excitation of adjacent antennas 1 and 2.

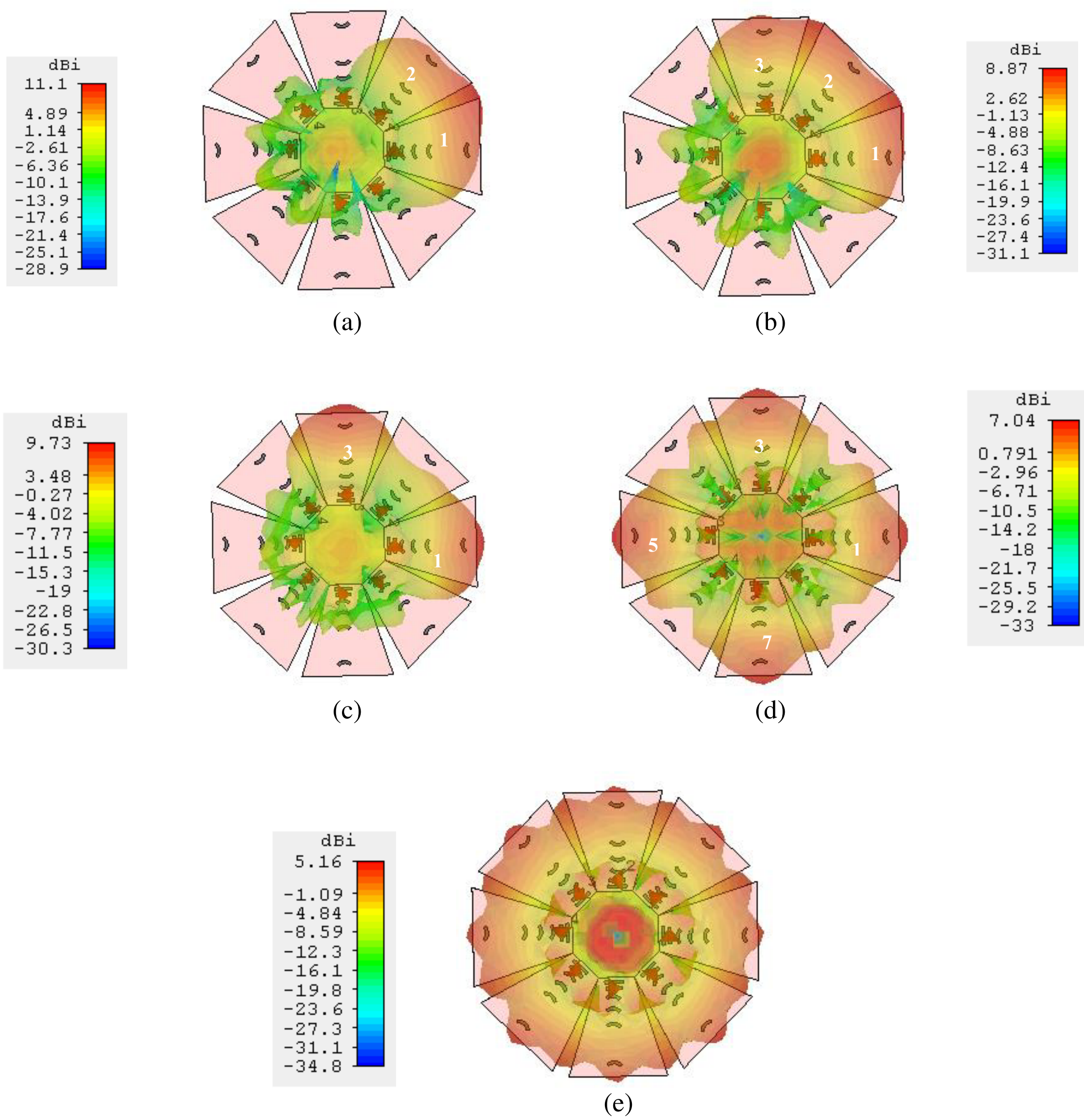

Figure 10. Simulated radiation patterns for various combinations of excited antennas, (a) 1 and 2, (b) 1, 2 and 3, (c) 1 and 3, (d) 1, 3, 5 and 7, (e) all antennas.

iii) Excitation of two or more nonadjacent antennas produces two or more patterns in the main beam directions of those antennas. This is illustrated in Figures 10(c) and 10(d).

Due to symmetry of the structure, excitation of antenna pairs which are at similar angular orientations produces similar patterns of same directivity. The result of any other excitation will be the combined effect of the observations listed above. It is clear that when multiple antennas are excited, we get multiple beams with lesser directivity, and when all eight antennas are excited simultaneously, an omnidirectional pattern is formed as shown in Figure 10(e).

2.4. Measured Results

The circular array fabricated on an FR4 substrate is mounted on a turn table in an anechoic chamber as shown in Figure 11.

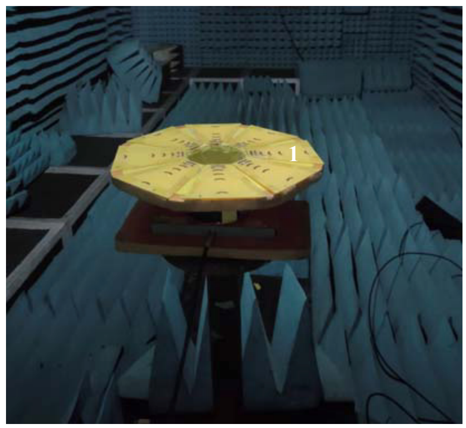

Figure 11. Pattern measurement setup of circular array.

The structure is connected to the network analyser through an SP8T switch so that the antennas can be excited one at a time. To switch multiple patterns, power divider circuitry with each antenna connected through independent switches is used. Here any combination of antennas can be excited. Figure 12 shows the measured radiation patterns for some typical combinations of excited antenna elements in the circular array. When being excited individually, each element produces a highly directive pattern in the radial direction of the array. The measured half-power beam-width is about 40° in the horizontal plane for individual excitation of antennas.

Hence, with reconfigurable patterns of high directivity, the circular array can cover almost the entire azimuthal plane in the desired directions. Besides, the proposed structure can also selectively produce wider beams in the azimuthal plane covering larger angles.

3. UMBRELLA ANTENNA ARRAY

While the antenna array design discussed so far is successful in generating reconfigurable pattern, its variations are restricted to the azimuthal plane due to the planar shape. Now, the same antenna elements are rearranged in a 3D manner (Umbrella shape), so that azimuthal switching of patterns can be realized at any desired elevation angle depending on the opening of the umbrella shape.

Here, the array elements are arranged in the form of an umbrella at the base of a cylindrical support. Switches or power divider arrangements can be mounted at the back of the structure as illustrated in Figure 13(a). When the structure is arranged as shown in Figure 13(b), it can be used to radiate patterns in the elevation plane along different azimuth directions. The simulated co-polar patterns at 5.8 GHz for individual excitation of antennas 1, 2, and 8 are shown in Figures 14(a)–(c). This arrangement can tilt the beam in elevation plane and makes it suitable for base station antenna applications.

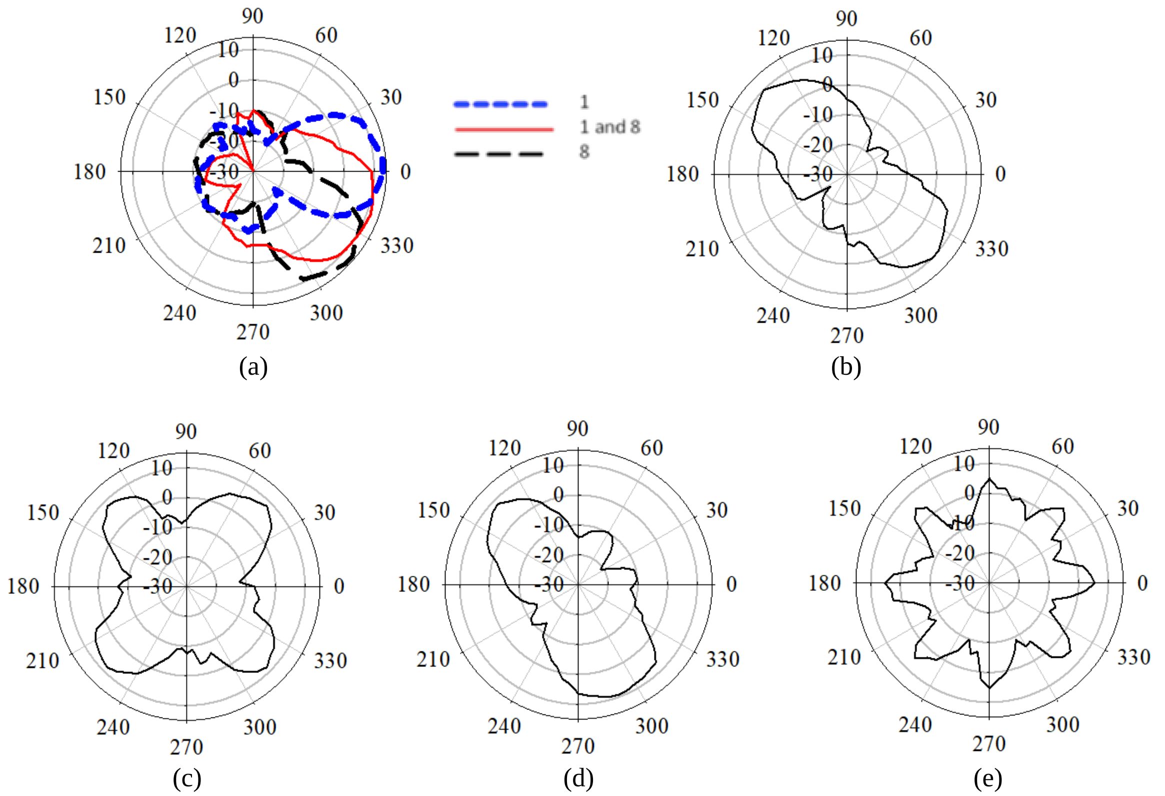

Figure 12. Measured patterns for various combinations of excited antennas, (a) 1 and 8 separately and simultaneously, (b) 4 and 8, (c) 2, 4, 6 and 8, (d) 4, 7 and 8, (e) all antennas.

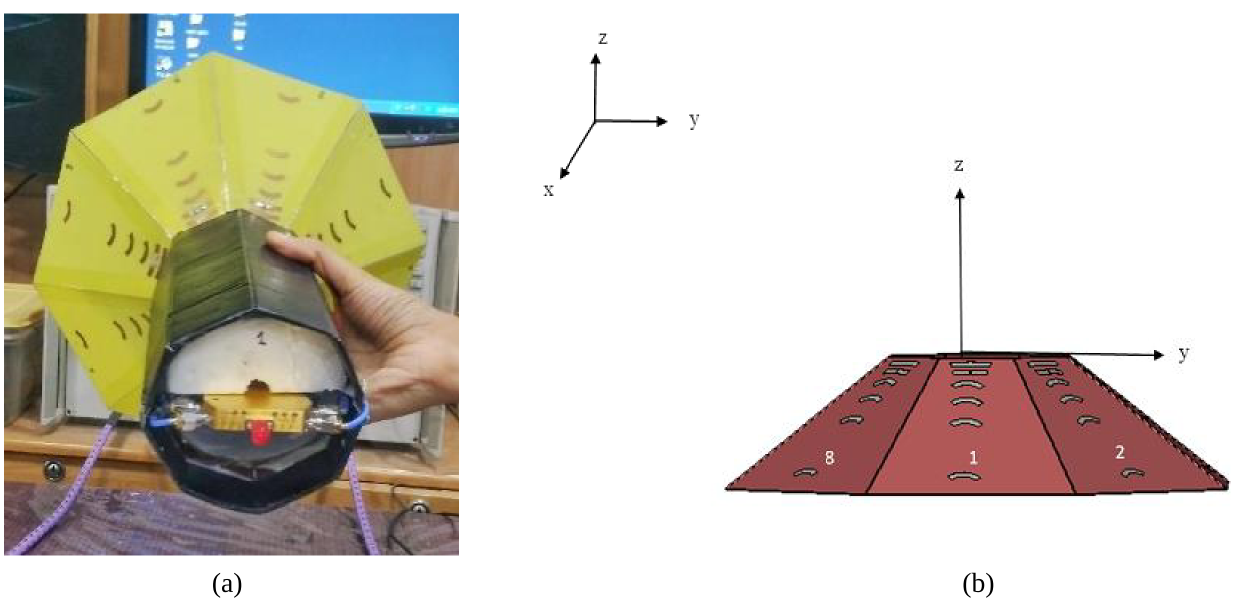

Figure 13. (a) Umbrella structure. (b) Arrangement of the structure for use as base station antennas.

3.1. Simulated Results

When antennas are excited individually, each antenna radiates a pattern of directivity 12.1 dB in its end-fire direction, and azimuthal switching is obtained at any desired tilt angle. When two or more adjacent or non-adjacent antennas are excited simultaneously, observations are similar to the ones explained in Section 2.3.

Figures 15(a)–(d) illustrate the co-polar patterns for various combinations of excited antennas at 5.8 GHz. When two adjacent antennas are excited, patterns are produced with directivity 12.3 dB. Here too, just as in the case of circular array, patterns of maximum directivity are formed for individual excitation of antennas and for simultaneous excitation of two adjacent antennas. S_{11} plots for different switching states almost remain the same as illustrated in Figure 16(a). Gain plot for simultaneous excitation of adjacent antennas 1 and 2 is shown in Figure 16(b). The co and cross polar patterns for this excitation are depicted in Figure 17. All other combinations result in patterns of lower directivity in multiple directions.

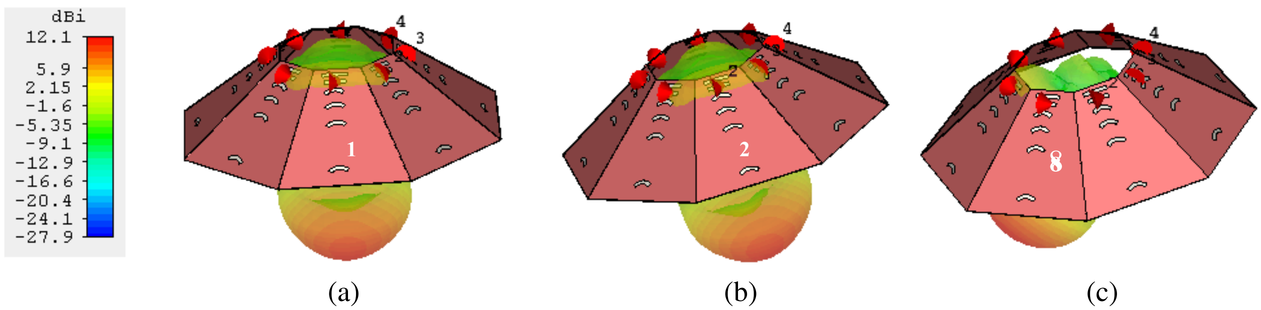

Figure 14. Simulated co-polar radiation patterns for individual excitation of antennas, (a) 1, (b) 2 and (c) 8.

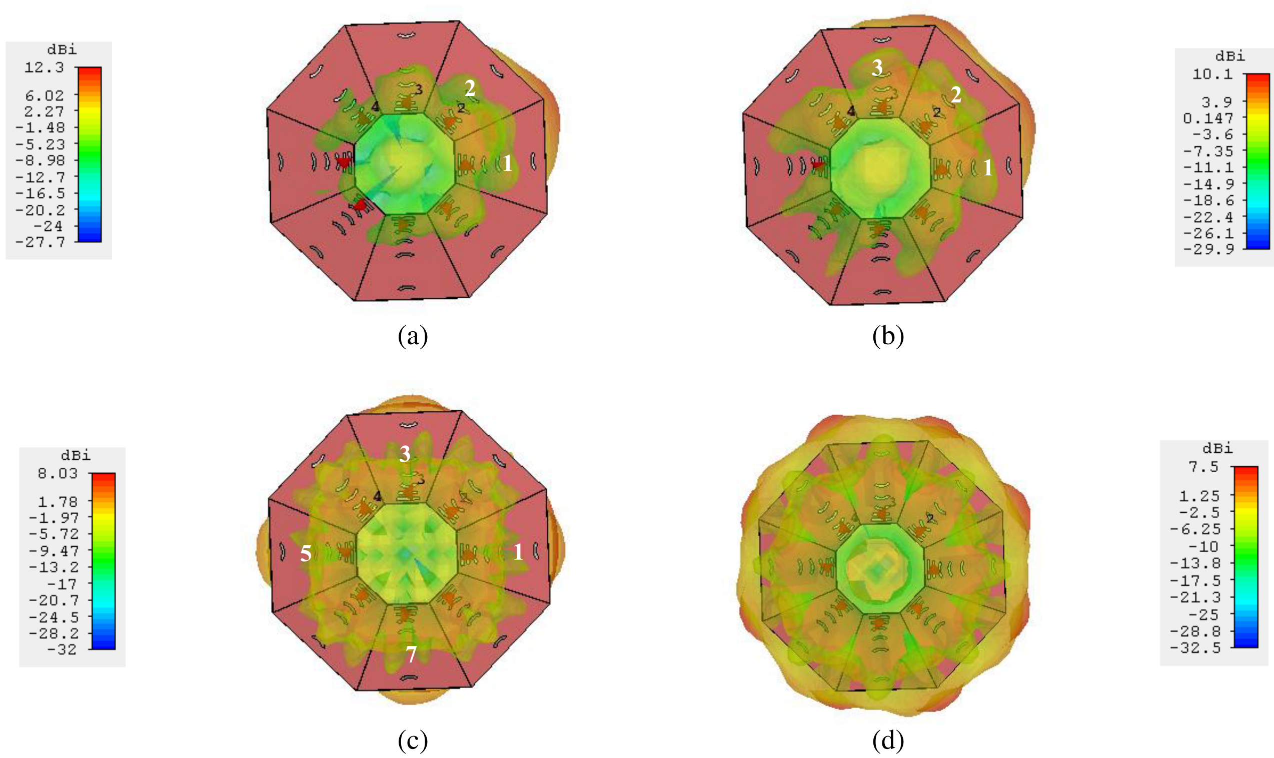

Figure 15. Simulated co-polar radiation patterns for various combinations of excited antennas, (a) 1 and 2, (b) 1, 2 and 3, (c) 1, 3, 5 and 7, (d) all antennas.

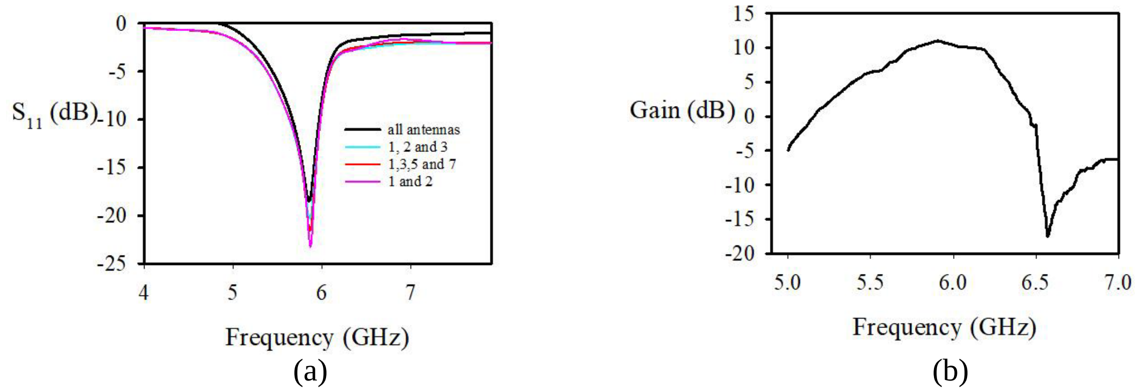

Figure 16. (a) S_{11} plots for different switching states and (b) gain plot for excitation of two adjacent antennas.

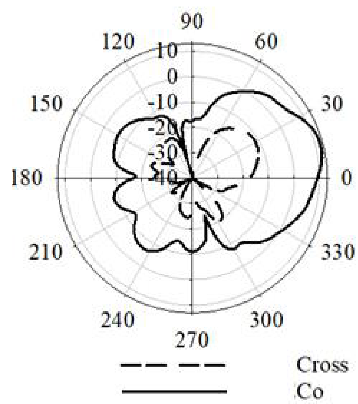

Figure 17. Co and cross polar pattern for simultaneous excitation of adjacent antennas 1 and 2.

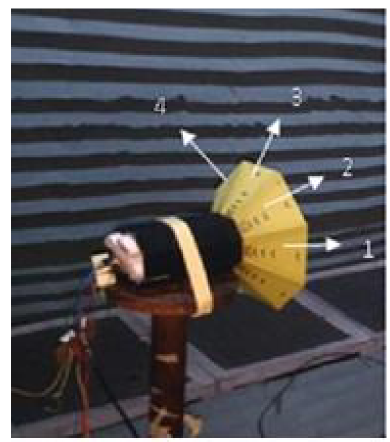

Figure 18. Arrangement of umbrella structure in anechoic chamber.

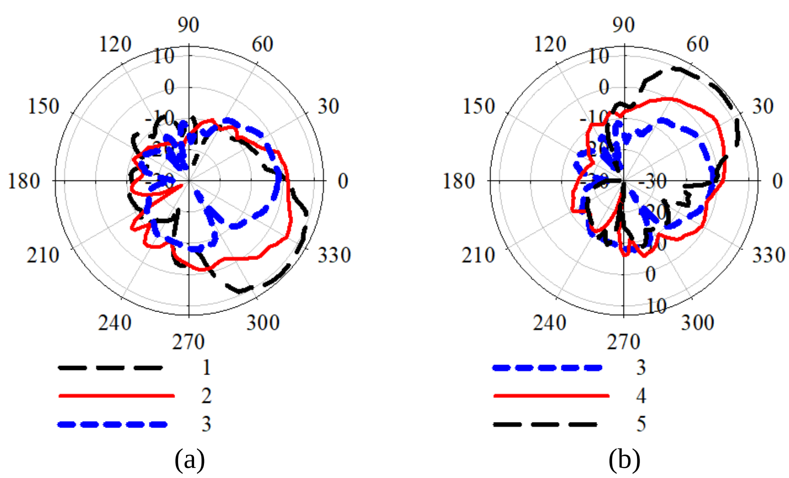

Figure 19. Measured patterns in $\theta = 90°$ plane for antennas (a) 1, 2, 3, (b) 3, 4, 5.

3.2. Measured Results

For the ease of performing radiation pattern measurements at the anechoic chamber, the umbrella structure is arranged as shown in Figure 18 with switch connected at the back of the structure for selectively switching the antenna elements. The structure is rotated anticlockwise in the XY plane.

Measured radiation patterns of antennas 1, 2, and 3 and that of 3, 4, and 5 are plotted together in Figures 19(a) and 19(b), respectively. Due to symmetry of the structure, the patterns of antennas in upper half of the plane with respect to the horn antenna only need to be measured as patterns are similar in the lower plane. Cross polar level is also measured which is found to be less than -25 dB in all cases. The radiation patterns show a distortion and a lesser value in the received amplitude due to the misalignment of the different elements of the umbrella structure with the transmitting horn antenna.

Angular difference between the patterns formed during excitation of eight antennas is 45°. So the umbrella shape can tilt patterns at desired elevation angles, making it a promising candidate for base station applications.

4. CONCLUSION

A highly directive pattern reconfigurable array which can perform azimuthal switching of narrow focussed beams at desired elevation tilt has been designed, fabricated, and experimentally verified. In the proposed structure, any array element can be switched one at a time, to steer highly directive beams or any number of elements can be switched on simultaneously to radiate multiple beams in desired directions. A highly directional planar end-fire array with arc shaped dipoles is used as the array element. The proposed system gives the flexibility to point the directional beams in the azimuth as well as elevation plane making it suitable for base station antennas.

ACKNOWLEDGMENT

The authors would like to acknowledge UGC for providing financial assistance through research fellowship, SERB for VAJRA faculty scheme and CSIR for the support through Emeritus Scientist scheme.

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