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Highly Directive and High Gain Multiple Beam Reconfigurable Antenna for Base Stations

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ABSTRACT- A directional pattern reconfigurable array with high gain is proposed in this paper in which each antenna element is an array of driven and parasitic arc dipoles. The elements can be selectively excited using RF switches and power dividers to produce high gain patterns in desired single or multiple directions. By providing optimum spacing to array elements via stacking, gain can be further improved by exciting multiple elements simultaneously. The array resonates at 5.8 GHz, which is an ISM frequency. The directivity and realized gain of the unit element are 12 dB and 10.2 dB respectively. We hereby present a configuration of stacked antennas suitably arranged on a mast, which can find application as a base station antenna for next-generation wireless communication systems to switch patterns having directivity 14.3 dB and realized gain 12.1 dB in multiple directions with a reasonable bandwidth of 500 MHz and efficiency of 70%.

Keywords: Directional, reconfigurable, base-station, stacking, dipole, array.

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1. INTRODUCTION AND BACKGROUND

Directional base station antennas with enhanced gain [1] can improve the range, coverage and signal quality of the wireless communication system and have great significance in the current scenario. Beamforming is the backbone of future 5G and 6G communication technologies which mainly relies on highly directional and high gain antennas for increased signal strength, reduction of interference from undesired signals and to overcome propagation challenges [2-5]. Different techniques [6-9] have been explored by researchers to attain very high directivity in antenna arrays. But majority of the compact super-directive arrays existing in literature reported poor efficiency, low gain, narrow bandwidth, and impedance mismatch [10-12]. Here in this work, by optimizing various geometrical parameters of an arc dipole array such as arc length, radius and spacing, higher directivity is attained compared to existing structures without compromising much on gain, bandwidth, and efficiency.

To enhance antenna, gain also along with directivity, stacking techniques are adopted by researchers [13-15]. Some of the realizations suffered from poor efficiency and attempts at size reduction led to not so high gain.
Haskou et.al [16] in 2015 had designed a super-directive broadside array by stacking four elements, a pair at top and another pair at bottom to improve gain and directivity. They also studied how offset between the stacked elements affects their performance. But the reported radiation efficiency was only 8.3%. Hossain et.al [17] did a comparison study on bandwidth, gain, directivity and return loss of conventional and stacked antennas. It was concluded that stacked structure produced better gain but as they were trying to reduce the size of the structure, they could achieve a gain of 6.2 dB only.

In this work, a highly directive and high gain stacked antenna of directivity 14.3 dB, gain 12.1 dB and efficiency 70% is realized by stacking two directive elements. The attained gain is higher when compared to structures with similar dimensions realized earlier. A comparison study is presented in *table 1*.

The structure is capable of switching highly directive patterns in multiple directions and gain of the pattern is enhanced via stacking. The resonant frequency has been chosen as 5.8 GHz as it is an open ISM frequency which offers faster network with higher bandwidth and has less congestion when compared to 2.4 GHz. Due to the smaller wavelength, the size of antenna gets reduced and propagation characteristics of the signal is much better at 5.8 GHz. Besides, the frequency falls within the 5G network band.

2. UNIT ELEMENT DESIGN

A microstrip arc dipole-based end-fire array acts as the unit element comprising of a driven element and remaining parasitic elements, namely a reflector and four arc directors as illustrated in *figure 1*. Arc dipole gives higher directivity than a straight dipole as obtained from parametric analysis. Lengths and radii of arcs and spacing between driven element and

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reflector are optimised initially on a trapezoidal FR4 substrate of thickness 1.6 mm and dielectric constant 4.4.

The trapezoidal shape or the flaring boosts the directivity which is enhanced by adding arc directors on the substrate. The authors have elaborated the parametric studies on trapezoidal edge lengths, arc length, arc radii, spacing between the elements and their influence on the directivity of unit element in an earlier work [18].

Effect of the spacing between reflector and driven element on S_{11} and directivity is plotted in *figure 2a*. When arc directors are added at equal spacing from driven element, impedance matching deteriorates. Thus, to ensure impedance matching and maximum directivity, parametric analysis was done on the spacing between driven element and directors and is plotted in *Figure 2b*.

After optimization, first director is placed 0.1λ from driven element. Second, third and fourth directors are spaced 0.2λ, 0.3λ and 0.75λ from the subsequent directors. The realized gain and directivity of the unit element are 10.2 dB and 12 dB respectively at the resonant frequency. 2:1 VSWR bandwidth of the prototype is 500 MHz ranging from 5.6 to 6.1 GHz with 70% radiation efficiency. Half power beamwidths in E-plane and H-plane are 40o and 52o respectively.

Figures 3a and 3b show the comparison between the simulated and measured VSWR and gain respectively. Figures 4a and 4b show the simulated and measured radiation patterns in E-plane and H-plane respectively. By arranging the unit elements in appropriate configuration, beam switching can be realized. Two such realizations, a circular array and an umbrella structure are shown in *figures 5a and 5b* respectively. They have already been detailed in our previous work [19] and demonstrate beam switching in azimuthal plane and at any desired tilt.

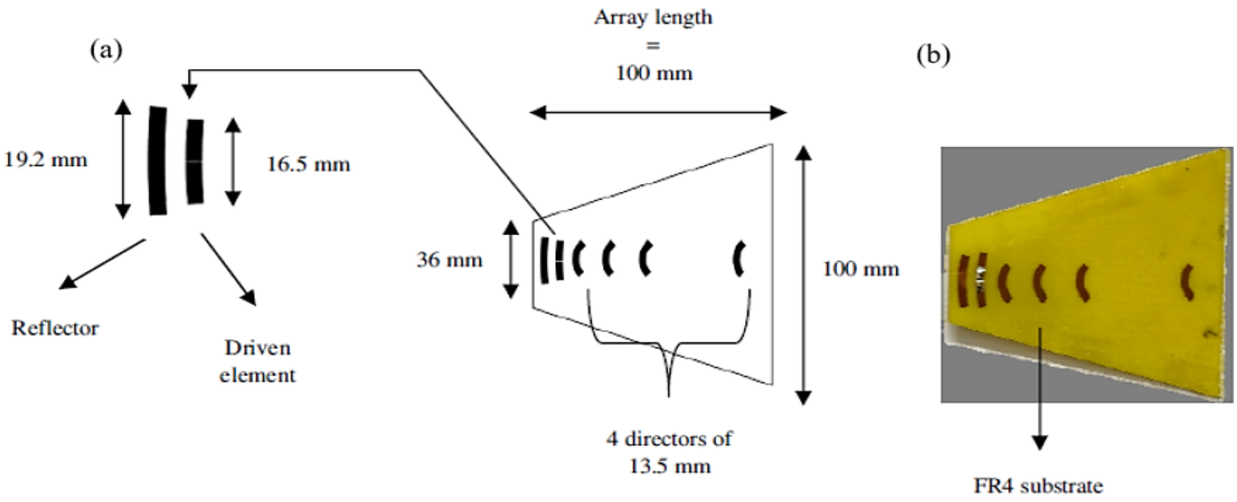

Figure 1. (a) Unit element schematic (b) Fabricated prototype on FR4

(a) (b)

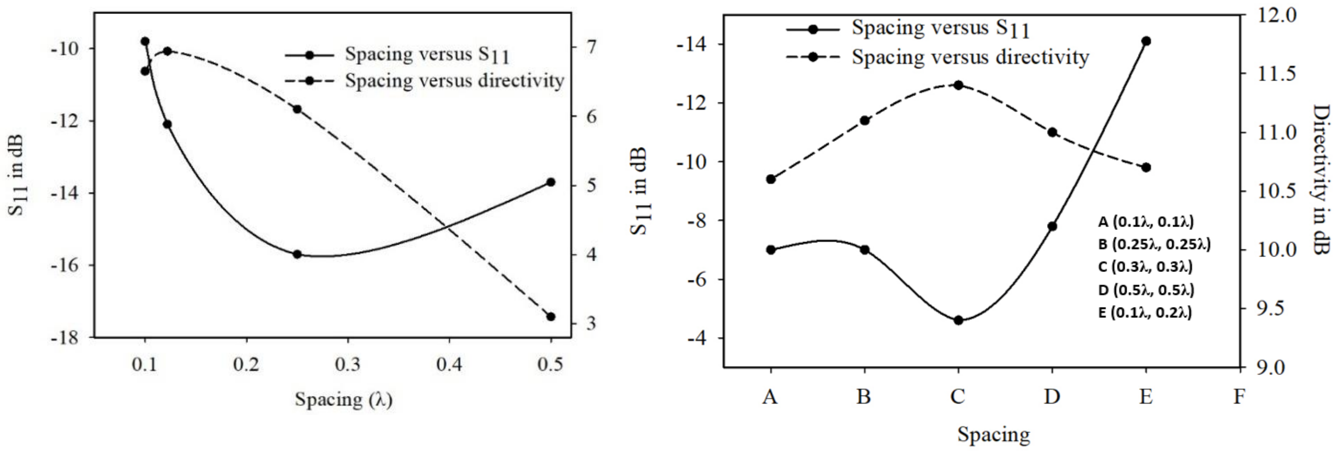

Figure 2. Effect of spacing between driven element and (a) reflector (b) directors

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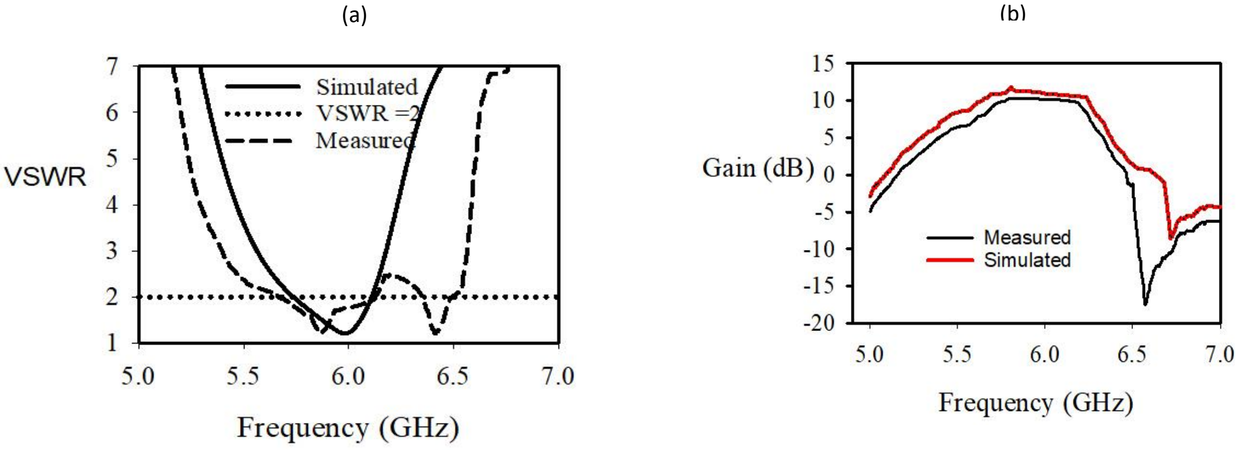

Figure 3. Simulated and measured (a) VSWR (b) Gain

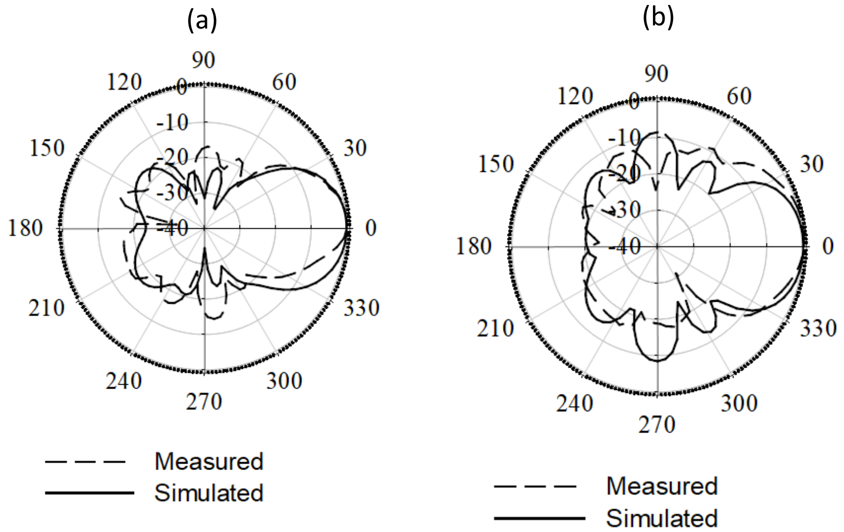

Figure 4. Patterns in (a) E-plane and (b) H-plane

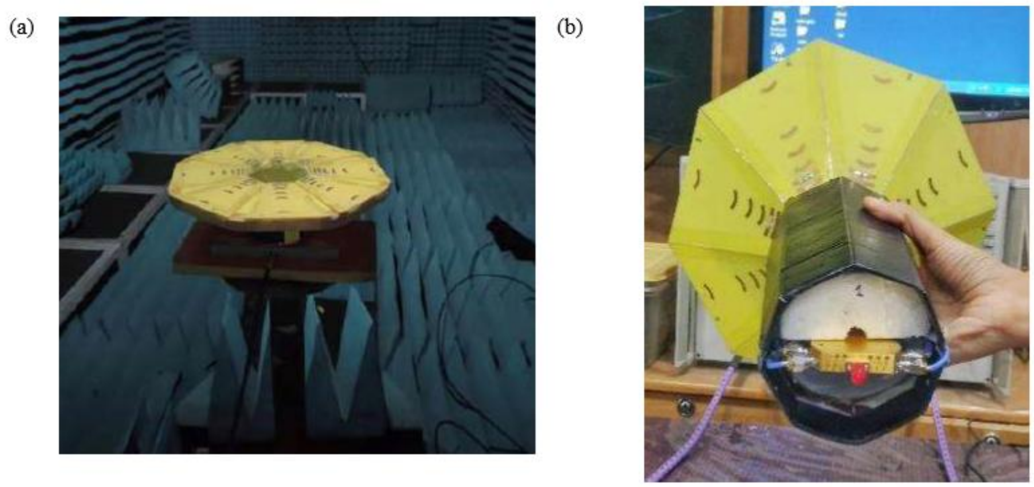

Figure 5. (a) Circular array and (b) Umbrella structure

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3. STACKING OF ELEMENTS

Now, to enhance the gain of highly directive antenna, two such unit elements are stacked one below the other at an optimum spacing d resulting in directive broadside array as shown in *figure 6*. The level of side-lobes in the radiation pattern is determined by the spacing between the elements.

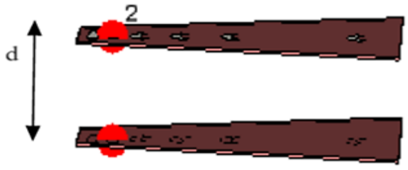

Figure 6. Stacked elements at top and bottom

The stacked elements are excited in phase. Parametric analysis is done to obtain the optimum spacing so that patterns with minimum sidelobes and maximum directivity with proper impedance matching are produced. The impact of spacing on side-lobe level and directivity is graphically plotted in figure 7. It is observed that side-lobe level is minimum at a spacing of 0.6λ, that is, 30mm. At a spacing of 1.54λ, side-lobe level is high. Hence 30mm is selected as the optimum spacing. To avoid grating lobes, spacing between elements must be less than one free-space wavelength for a broadside array.

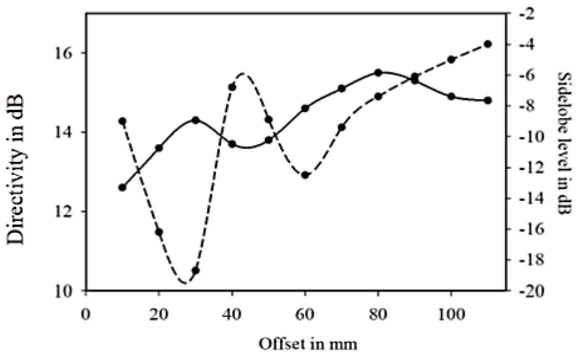

Figure 7. Effect of spacing on dire~~ctivity~~ ( ) and side-lobe level (------)

3.1 Simulated and Measured Results for Stacked Array

3.1.1 Simulated Results

Simulated gain and directivity are 13.3 dB and 14.3 dB respectively in the bandwidth of interest. 3D pattern is shown in *figure 8*.

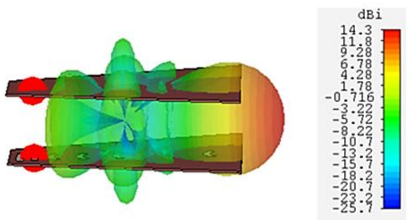

Figure 8. 3D Simulated pattern for stacked array with directivity 14.3 dB

3.1.2 Measured Results

Gain measurement of stacked trapezoidal elements is performed inside anechoic chamber. The elements are spaced 30 mm apart and are excited using 1:2 power divider. RF signal from port 1 of Vector Network Analyzer (VNA) is provided to the input of 3 dB power divider and output ports are connected to the stacked elements. Standard horn antenna is selected as the reference antenna in gain comparison method and is connected to port 2 of VNA.

S_{21} is measured and the gain of the stacked array is graphically plotted in *figure 9*. While a unit element provides measured gain and directivity of 10.2 dB and 12 dB respectively, stacked pair increases the gain and directivity by 2 dB. Simulated and measured gains are 13.3 dB and 12.1 dB respectively in the bandwidth of interest. Two dimensional patterns in E and H-plane are depicted in *Figures 11a* and *11b* respectively.

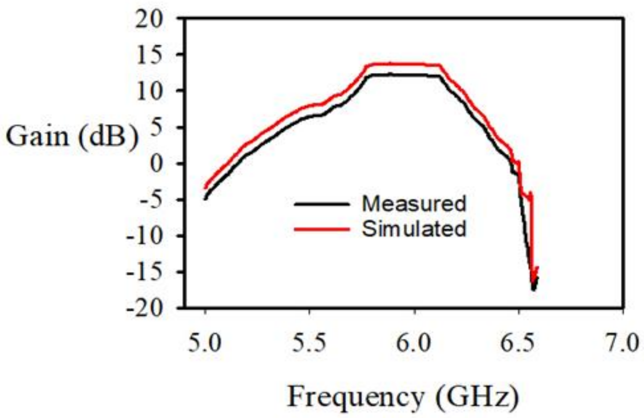

Figure 9. Gain of stacked array

4. MULTIPLE-BEAM RECONFIGURABLE ANTENNA

Multiple beam reconfigurable antenna is realized practically by arranging a group of sixteen-unit elements or eight stacked pairs on a vertical mast as shown in *figure 10*, with switches and power dividers at the bottom of cylindrical mast, emulating the setup of a base station antenna.

High gain patterns can be switched in eight different directions by exciting eight stacked pairs. Adjacent elements are spaced at the optimum offset to obtain stacking effect when required.

To improve array gain, two adjacent elements are excited together. One such pattern formed by exciting a stacked pair of antennas 1 and 2 is shown in *figure 12a*. The pattern is oriented along an angle between the individual excitation patterns of antennas 1 and 2. Hence patterns of enhanced gain 12.1 dB and directivity 14.3 dB are obtained in all eight directions by selectively switching the elements. Multiple stacked pairs can be excited at the same time to produce multiple beams. One such pattern formed by simultaneously exciting stacked pairs 1 and 7 is depicted in *figure 12b*. Value of directivity is indicated by the colour bar graph, that is, 12 dB.

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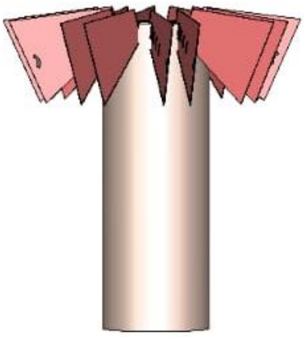

Figure 10. Multiple beam reconfigurable antenna array excited using switches / power dividers

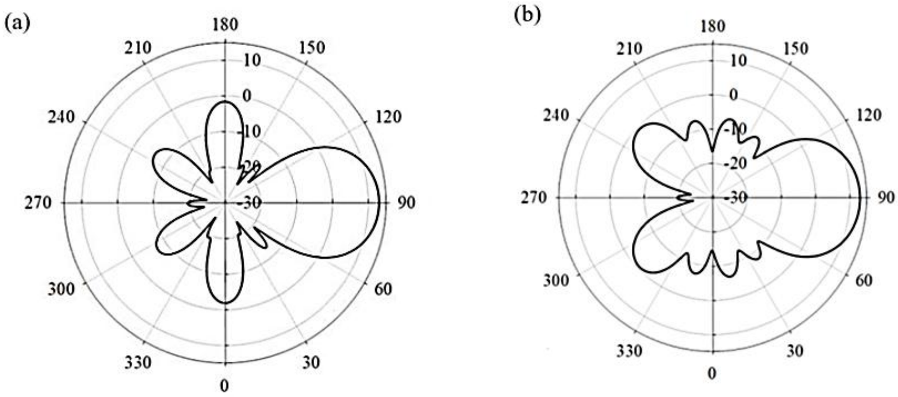

Figure 11. Polar patterns of stacked array in (a) E-plane (b) H-plane

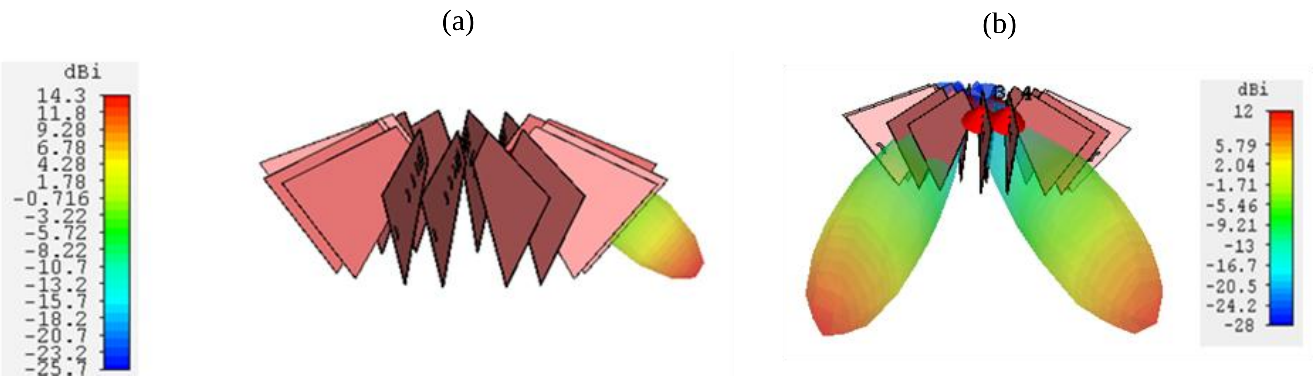

Figure 12. Patterns formed by excitation of (a) one stacked pair (b) multiple stacked pairs

5. PRACTICAL IMPLEMENTATION OF INDIVIDUAL AND MULTIPLE EXCITATION

Practically, for individual and multiple excitations of stacked pairs, switches and power dividers are used. They are mounted at the base of the cylindrical structure depicted in *figure 10.*

For exciting each stacked pair, SP8T switch is employed. To each output port of this switch, 1:2 power dividers are connected. Outputs of these 1:2 power dividers are connected to each stacked pair so that both elements of the pair get excited simultaneously. The control pins of SP8T switch are provided with appropriate control logic to excite desired stacked pair.

To excite all 8 stacks together, 1:8 power divider is mounted. RF signal is provided to input port of this power divider. SPDT switch is connected to each output of 1:8 power divider. One output port of SPDT switch is connected to 1: 2 power divider and the other output port is connected to matched load. Output ports of 1:2 power divider is connected to the stacked elements. Now multiple stacked pairs can be excited simultaneously. For example, to excite stacked pairs 1, 3 and 5 simultaneously, control logic is provided to first, third and fifth SPDT switches to excite 1:2 power dividers connected to their output ports.

Hence by employing stacking technique and by switching the elements selectively, patterns of enhanced gain and directivity can be produced in single or multiple directions, making this structure an ideal candidate for application as base station antenna. *Table 1* shows the comparison of proposed structure with some related works in literature.

Table 1. Comparison of the structure with previous related works

Work	Structure, array length	Gain (dB)
[20]	Reconfigurable directive patch array,4 beams, 0.5 λ	-4 to -12
[21]	Reconfigurable rhombic patch array, 2 beams, 1.66 λ	2.3 to 3
[22]	Log-periodic array, 1.93 λ	7.5 to 9
[23]	Printed dipole array, 3,41 λ	10.9
[24]	Switched beam Yagi array ,2.32 λ	10.9
[25]	Log-periodic dipole array,2.5 λ	8.4 to 9.8
[26]	Yagi-Uda array, 4.6 λ	11.3
[27]	Stacked patch array, λ	8
[28]	Stacked patch and dipole array, λ	6.38
Our work	Multiple pattern reconfigurable stacked arc dipole array, 1.9 λ	12.1

6. CONCLUSION AND FUTURE SCOPE

The novelty of the designed antenna lies in the fact that it overcomes the major limitations of conventional highly directional antennas, namely poor impedance matching, low gain, bandwidth and efficiency. By adjusting parameters such as shape, length, spacing between elements and substrate shape, high directivity can be realized in antenna arrays without comprising much on gain, efficiency and bandwidth. Arrays can be designed to switch highly directive patterns in azimuthal plane or at any desired tilt.

Gain of directive antennas can be enhanced by 2 to 2.5 dB by adopting stacking technique. When stacked arrays are used as base station antennas, patterns of enhanced directivity and gain can be switched in multiple directions. Besides, multiple elements can be excited simultaneously to produce multiple patterns of high directivity and gain. The stacked structure offers high directivity of 14.3 dB and gain 12.1 dB with a reasonable bandwidth of 500 MHz and efficiency of 70%. Hence the designed antenna is a promising candidate as base station antenna for next-gen wireless systems.

In future, adaptive beamforming techniques can be explored in directional arrays to dynamically switch patterns. To optimize beamforming, AI driven algorithms can be employed. Also, metamaterial integration can be attempted in these antennas to achieve miniaturization as metamaterials can manipulate the phase of electromagnetic waves passing through them to create highly directional beams and can create effective inductive and capacitive responses in a compact form, enabling size reduction.

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