

Phased array antenna for millimeter-wave application

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Abstract. Beam-steering antenna is essential and widely used in communication system. The design of 28 GHz beam steering phased array antenna for 5G millimeter-wave application presented in this communication. The objective of this research is to investigate and implement a phase shifter in a linear antenna array for angle scan. The proposed array antenna has four microstrip patch antenna elements, each feed ports are connected to phase shifter. The main mechanism of radiation is due to the excitation of element in sequence with different phase delays. The overall radiated beam can be steered to different directions depending on the initial excitation of elements. In the first, 3-D good radiation by 0° phase. In the second, good scanning performance of a range of $\pm 10^\circ$ to $\pm 40^\circ$, acceptable side lobe level and gain of 12.1 dB are obtained.

Keywords: Linear Array; Phase Shifters; Phased Array; Radiation Pattern; Microstrip Antenna; Beam Direction.

1 Introduction

In this paper, millimeter-wave communication has become a key enabler for 5G application.

Phased array antennas can adopt a number of different configurations, including linear, planar, and circular. Phased array antennas are used mainly to steer the main beam (main lobe, broadside) of the antenna electronically. It operates by delaying signals coming out of antenna elements by using phase shifter on each antenna element. This provides constructive and destructive interference, thus giving the result that the beam is steered away from the nominal (main) direction of an individual antenna element [1],[6].

This work focuses on linear phased array antennas whose unit cell is formed by a radiating elements, each fed by a transmit and receive module that can provide amplitude and phase control. Linear phased arrays use the progressive phase excitation between the elements to scan the antenna beam electronically over one dimension. The main advantages offered by phased arrays over conventional systems are increased scanning speed, high reliability, and multifunction capability. These advantages make the use of this technology the most logical choice for the next generation weather radars. The use of linear active phased arrays as a component of future low-cost weather radars is the major motivator of this work; consequently, this paper is dedicated to explain the basic concepts related to the theory of linear phase arrays and how their characteristics can be used in the antennas [2].

The organization of the paper is as follows: Section II describes the phased array antenna principle. Section III discusses issues related to the proposed patch antenna design and simulation results. Section IV presents phased array antenna proposed structure and finally the conclusion.

2 Phased array antenna

In single element antenna, the radiation pattern is usually very broad and the directivity is relatively low. This problem can be affected by enlarging the size of the element thus increasing the directivity. Another way to enlarge the antenna without changing the size of the individual elements is to assemble the radiating elements in a geometrical configuration known as an “array” [5]. The individual elements forming the array are usually identical and they can be of any form (wire antenna, microstrip patches etc...). Many antenna system applications require that the direction of the beam's main lobe be changed with time, or scanned. This is usually done by mechanically rotating a single antenna or an array with fixed phase to the element. However, mechanical scanning requires a positioning system that can be costly and scan too slowly. For this reason, electronic scanning antennas which are known as phased array antennas are used. It can sweep the direction of the beam by varying electronically the phase of the radiating element, there by producing a moving pattern with no moving parts. Phased array antennas are known for their capability to steer the beam pattern electronically with high effectiveness, managing to get minimum side-lobe level and narrow beamwidth [7]. To achieve performance specifications such as narrow beamwidth or considerable scanning range with high angle resolution, a large number of antenna elements were needed to construct the array. Normally phase shifters are the devices in a phased array antenna that allow the radiated beam to be steered in the direction [4].

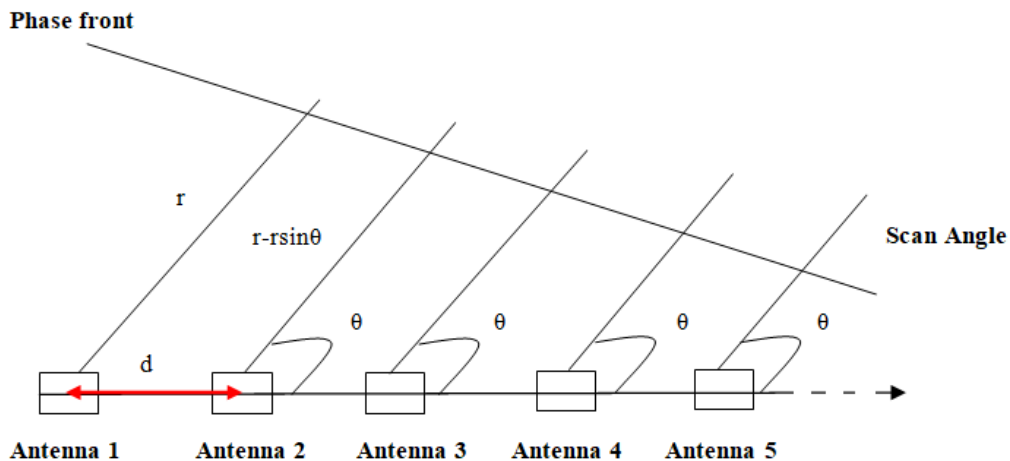


Fig. 1. Uniform linear array of N elements.

In **Figure 1**, shows a uniform linear array of N equally spaced elements having a grating step (separating two adjacent antennas). These sources are fed with the same amplitude and with a phase gradient $\Delta\phi$ with respect to each other. r represents the maximum distance between the reference antenna and the observation plane, and θ is the beam steering angle.

In these conditions, the total electric field radiated by the array antenna is then written as (1):

$$E_{\text{tot}} = E_0 * A(\psi) . \quad (1)$$

Where:

- E_0 represents the electric field radiated by an elementary antenna. It is named "element factor".

- $A(\psi)$ is the "Array factor" independent of the elementary source that makes up the array.

This array factor is given by the relation (2) below:

$$A(\psi) = \frac{1}{N} \exp(j(N-1)\psi/2) \frac{\sin(\frac{N\psi}{2})}{\sin(\frac{\psi}{2})} . \quad (2)$$

Where,

$\Psi = \frac{2\pi d}{\lambda} \sin(\theta) - \Delta\phi$, and λ is the wavelength

The total radiation pattern of the grating antenna is defined by the product of the modulus of the electric field radiated by an elementary antenna by that of the grating factor, the latter being given by the following expression see equation (3):

$$|A(\Psi)| = \frac{1}{N} \left| \frac{\sin(\frac{N\Psi}{2})}{\sin(\frac{\Psi}{2})} \right| . \quad (3)$$

In these conditions, it should be noted that as soon as the number N of elementary antennas becomes large, the total radiation pattern of the array depends essentially on the array factor and very little of the radiation pattern of each antenna. Note that if all the sources are excited in phases (ψ is zero), the radiated field is maximum in the plane normal to the array.

Conversely, if the sources are excited with a non-zero phase gradient, the maximum radiation appears for $\psi = 2m\pi$. The solutions are periodic and show on the same array lobes radiation pattern for values of $m \neq 0$.

Thus, a variation of the phase gradient of the array $\Delta\phi$ to be introduced between the adjacent elementary sources causes the orientation of the radiation pattern in the desired θ_0 direction according to:

$$\Delta\phi = \frac{2\pi d}{\lambda} \sin(\theta_0) . \quad (4)$$

The variation of the phase gradient of the array determines that of the beam steering angle θ_0 of the array antenna: this is the principle of a "phased array antenna"[3].

3 Proposed antenna

The geometry of the proposed single-patch antenna structures is shown in **Figure 2**. consists of a the conventional square patch fed with the transmission line structure printed on a Rogers RT/Duroid5880 substrate, which has permittivity of 2.2, loss tangent of 0.001 and having a thickness of $h = 0.25\text{mm}$. The area of the proposed antenna is $10 \times 15\text{mm}^2$ and the dimensions of the antenna are calculated and optimized so that it resonates at 28GHz

frequency using patch antenna equations, the final dimensions of the proposed antenna are: $L_p=W_p= 3.36\text{mm}$, $L_q= 2\text{mm}$, $W_q= 0.145\text{mm}$, $L_f= 3\text{mm}$ and $W_f = 0.776\text{mm}$.

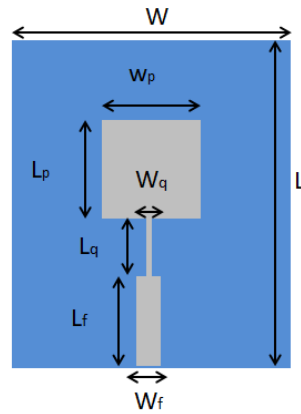


Fig. 2. Geometry of the proposed patch antenna.

3.1 Simulation results and discussions

The proposed antenna is simulated using CST Microwave StudioTM and the calculated S-parameter is shown in **Figure 3**. The proposed structure gives return loss around -19.5 dB at the resonant frequency 28GHz and has a 27.21–28.30 GHz bandwidth for $|S_{11}| < -10$ dB, which is approximately 3.69% bandwidth (1.09 GHz) with a center frequency of 28 GHz.

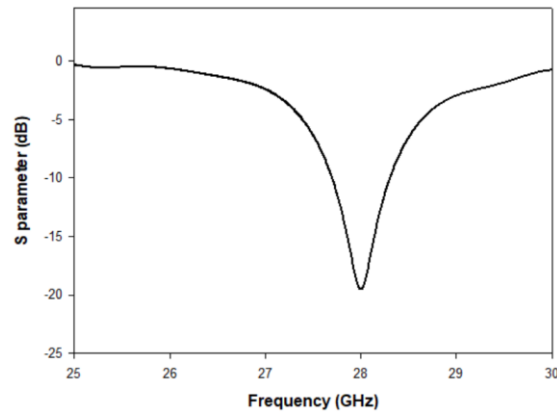


Fig. 3. Simulated result of S parameter of the initial patch.

The **Figure 4** explains the antenna radiation pattern. The antenna exhibits a maximum gain of 7.32 dB. The Side lobe level for the E-plane and H-plane are -20.5 dB and -12.9 dB respectively. Half power beamwidth of 87.3° is obtained H-plane, whereas that of E-plane is 76° .

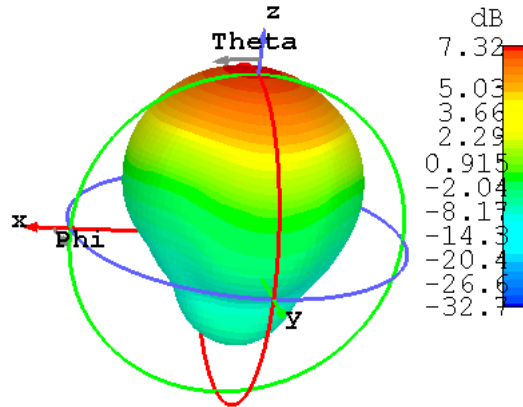


Fig. 4. Simulated 3D Far-field Radiation Pattern at 28 GHz.

3.2 Array of two element microstrip patch

Figure 5. shows an array of two element patch antenna separated by a distance d that varies between 0.5λ and 0.8λ . The goal of this study is to optimize the separation distance between the two elements of the array in order to find a compromise between the side lobe level and the isolation between the two excitation ports. The results found are grouped in the Table 1:

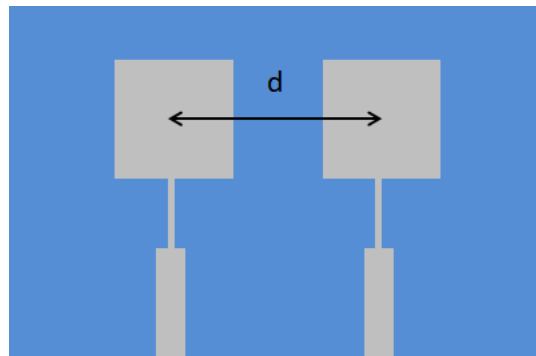


Fig. 5. Array of two element microstrip patch.

Table 1. The effect of separated distance d between the element on the antenna performance.

Separated distance d	S21 (dB)	Gain (dB)	SLL (dB)
0.5λ	-26.7	10.5	-14.7
0.6λ	-28.84	7.58	-18.4
0.7λ	-30.41	7.95	-17.7
0.8λ	-31.6	7.8	-17.5

We can see that the greater the separation distance between these two elements, the better isolation and inferior gain. However, there are a secondary lobes with high gain that are considered parasitic radiation. To reduce the side lobes level, we have to bring closer the antennas as possible. However, the closer they are the closer the field to antenna coupling is important. It was therefore necessary to find a compromise between the separation distance for the reduction of the side lobe level and the coupling between antennas. Based on this analysis, we chose as optimal separations distance 0.5λ because for this the array has good performances at the side lobes level, coupling between antennas and gain of antenna.

4 Linear array antenna

Phased array antennas are known for their capability to steer the beam pattern electronically with high effectiveness, managing to get minimum side-lobe levels and narrow beamwidths. Normally phase shifters are the devices in a phased array antenna that allow the radiated beam to be steered in the direction [4]. The objective of this part is to investigate a phase shifter in a linear antenna array for angle scan. **Figure 6.** depicts a linear array of 4 elements; all elements are excited with equal amplitude and with a progressive phase shift $\Delta\phi$ determined by the location of the element in the array.

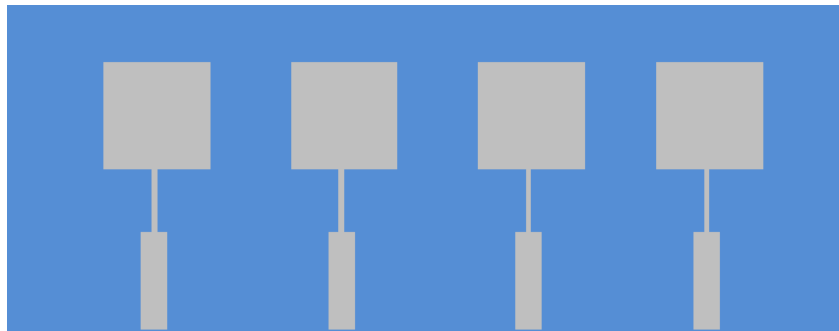


Fig. 6. Array of four element microstrip patch.

The return loss of the antenna is shown in **Figure 7.** From the result the resonance frequency of the antenna is at 28.03 GHz and $S_{11}=S_{22}= -16.17$ dB and $S_{33}=S_{44}= -14.78$ dB. The bandwidth of the antenna is 2.03 %.

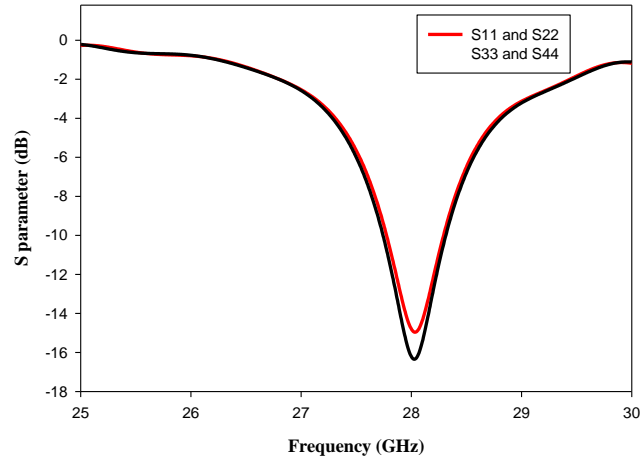


Fig. 7. Array of four element microstrip patch.

In the first, all the ports are excited by 0 phase and equal amplitude, the results of the radiation patterns in (XY) E-plane and properties such as beam position, maximum gain and SLL are shown in **Figure 8**. The maximum gain equal to 12 dB in broadside ($\theta=0^\circ$). Here, the SLL is equal to -13.5 dB at E-plane. In the second, to study the beam scanning capability of the array antenna all the ports are excited by a scanning over $\pm 40^\circ$ and equal amplitude. In **Figure 9**, the radiation pattern for (XY) E-plane for different values of phase from -40° to 40° at resonance frequency 28 GHz are shown. The gain for all the scanning is 12 dB, but the side lobe level is -10.8 dB when the beam is tilted by $\pm 30^\circ$ and $\pm 40^\circ$, and its gain remains constant 12 dB. When we have the beam tilting of $\pm 20^\circ$ gets a SLL of -11.5 dB at 28 GHz and beamwidth of 26.3° .

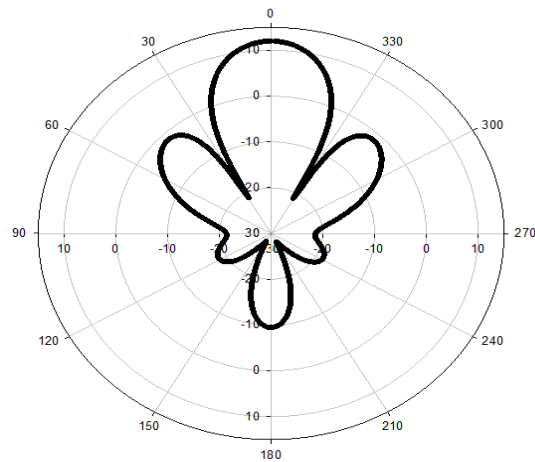


Fig. 8. Simulated radiation pattern For (XY) E-plane $\Phi=0$ Phase 0° .

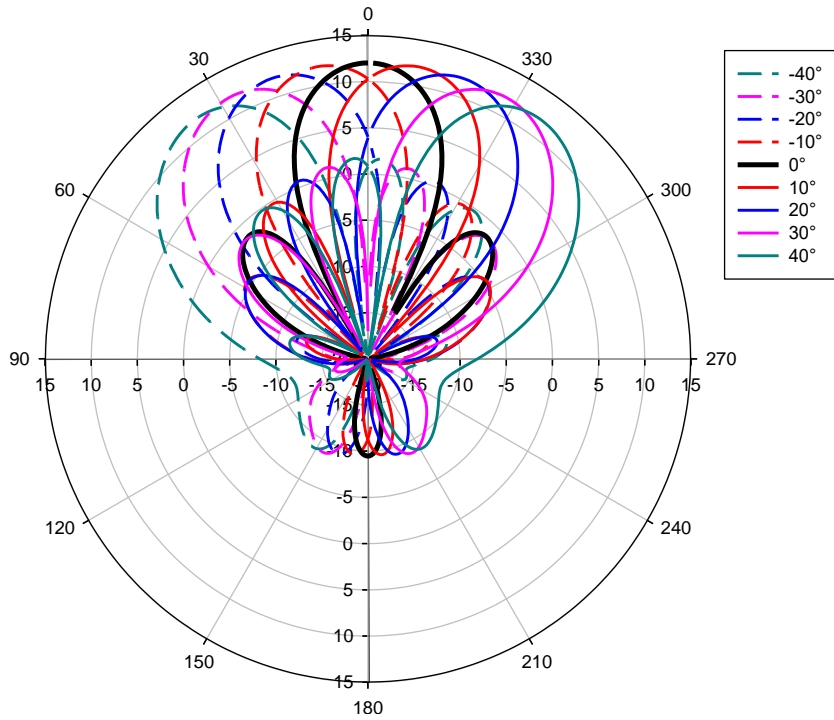


Fig. 9. Simulated radiation pattern For (XY) E-plane $\Phi=0$
Phase ± 10 to ± 40 .

5 Comparison with literature

As indicated at the onset of the paper, a number of techniques have been proposed in the literature for the beam steering. Table 2 presents a comparison of the scanning angular range of the proposed antenna and the beam steering antennas in [6], [8] and [9]. We can see that the proposed antenna realizes a larger beam tilted angle.

Table 2. Comparison of techniques reported in literature for beam steering.

Antenna Model	Fr (GHz)	Beam Tilt ($^{\circ}$)	Technology
Antenna in [6]	28	± 25	Series-Fed Pach Antennas
Antenna in [8]	34.25	± 30	Antenna Using a Metasurface
Antenna in [9]	9	± 30	Design Of Phase-Modulated Metasurfaces
Antenna in this paper	28	± 40	Uniform linear array

6 Conclusion

In this paper, a phased array structure has been proposed and analyzed. The structure is formed by uniformly arranged as an 4-element identical, which is able to achieve beam steering with using phase shifters. The phase shift are achieved by changing the phase of the element. The final proposed antenna achieves a 750 MHz bandwidth for $S_{11} < -10$ dB to cover 27.74-28.31 GHz frequency band which is intended for future millimeter wave communications. Moreover, the antenna array achieved a maximum gain of 12 dB in the broadside direction. The antenna array could be utilized as a phased array and hence could be used to steer the radiation beam. The antenna exhibited a very good radiation pattern and stable gain. The structure can have 9 kinds of reflection phase distribution, so the antenna can change its beams among 0° , $\pm 10^\circ$, $\pm 20^\circ$, $\pm 30^\circ$ and $\pm 40^\circ$ in xoy-plane at 28 GHz. Compare to other beam steering antenna, the proposed antenna can realize a larger beam tilted angle (40°). The next step is to fabricate the antenna and verify the simulation results which will be reported at the conference.

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