Directive Beam-Steering Patch Array Antenna Using Simple Phase Shifter

Hayat Errifi, Abdennaceur Baghdad, Abdelmajid Badri and Aicha Sahel

Abstract Beam-steering antennas are the ideal solution for a variety of system applications, it is most commonly achieved through using phased arrays, where phase shifters are used to control the relative of the main-beam. In this paper, a low-cost directive beam-steering phased array (DBS-PA) antenna using switched line phase shifters is demonstrated. The proposed DBS-PA antenna has four micro-strip patch antennas, three power dividers and four phase shifters printed on the same Rogers RT-Durroid substrate with a dielectric constant of 2.2 with dimensions of 8 × 3.5 cm. The phased array antenna has a directivity of 11.92 dBi and the main beam direction can be switched between the angles of ±25° with a 3 dB beam-width of 23°. All design and simulations have been carried out using Ansoft HFSS software tool. The frequency considered for the operation is 10 GHz.

Keywords Phase shifters · Switched line · Beam steering · Patch antenna · Phased arrays · Return loss · Directivity

1 Introduction

The phase of an electromagnetic wave of a given frequency can be shifted when propagating through a transmission line by the use of Phase Shifters [1]. They have many applications in various equipment such as beam forming networks, power dividers and phased array antennas or reconfigurable antennas [2].

Reconfigurable antenna has gain a lot of attentions in wireless communication system recently. It can be classified into three major fields which are reconfigurable frequency, polarization and radiation pattern [1]. The reconfigurable antenna can be realized via RF switches such as PIN diodes, MEMs and GaAs FETs. By changing

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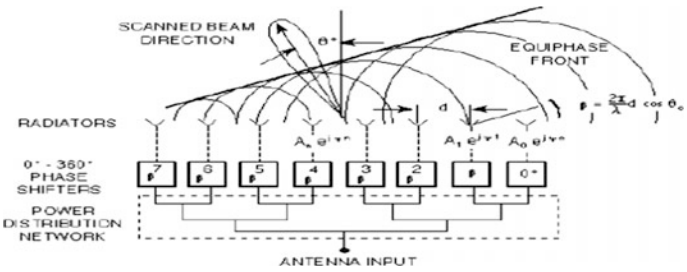


Fig. 1 Phased array antenna system [1]

the switch state to either 'ON' or 'OFF' mode, this determined either feed line would receive or not the radio frequency (RF) signal [3].

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, thereby producing a moving pattern with no moving parts, as shown in Fig. 1.

In this paper, the investigation on amount of beam-steering of main beam by using microstrip switched line phase shifters is presented. The switched line phase shifter is dependent only on the length of line used. An important advantage of this circuit is that the phase shift will be approximately a linear function of frequency. This enables the circuit to operate at a broader frequency range [4].

This research is focuses on the beam-steering patch antenna radiation pattern which suitable for point-to-point communication system that requires high gain and directivity characteristics. All designs and simulations have been carried out using High Frequency Structure Simulator tool (HFSS). The rest of the paper is organized as follow: Sect. 2 presents the design specifications of microstrip phased array antenna. The simulated results are discussed in Sect. 3 and finally Sect. 4 provides the conclusion and future works.

2 Design of Microstrip Phased Array Antenna

Microstrip patch antennas are important as single radiating elements but their major advantages are realized in application requiring moderate size arrays. The primary radiator microstrip antenna is designed at frequency of 10 GHz which gives single patch antenna (SPA) as shown in Fig. 2. The dimensions of the patch are calculated using formulae found in [5, 6] and their values are stored in Table 1.

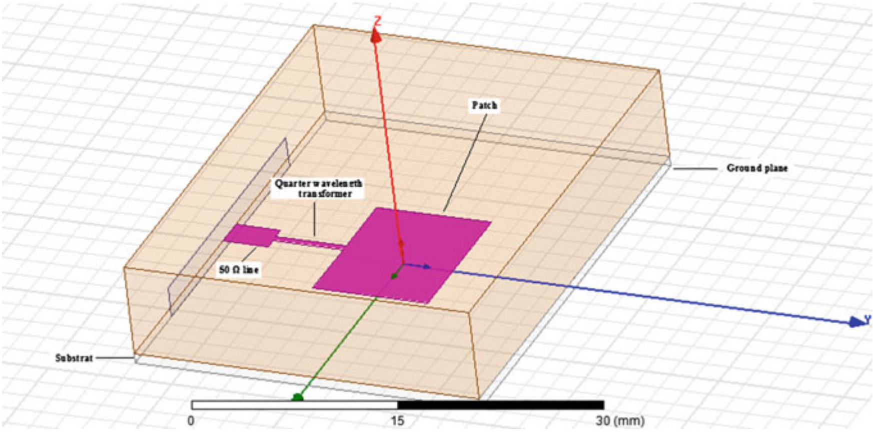


Fig. 2 Geometry of SPA

The proposed directive beam-steering phased array (DBS-PA) antenna is developed from four SPA as shown in Fig. 3. All elements are homogenous which has similar dimensions and characteristics as well [7]. The dimension of the DBS-PA antenna is 3.5 × 8 cm. The inter-element spacing (IES) of radiating elements must be determined precisely in order to get the better antenna performance. The IES is realized to half of wavelength (λ/2) in most array cases. The feed network is composed of three T-junction power dividers and four microstrip switched line phase shifters printed on the same Rogers RT-Durroid substrate with a dielectric constant of 2.2 and thickness of 0.79 mm [8]. The phase shifters are outlined by red circles and there are labelled as S1, S2, S3 and S4.

With in-phase feeding to the patch antennas, the beam direction of the array is perpendicular to the substrate (0°). To achieve beam steering, the microstrip switched line phase shifters are used to reconfigure the delay feeding line between the patches.

The basic schematic of the proposed microstrip switched-line phase shifter is shown in Fig. 4, it is comprised of two microctrip line segments of different length (L_1 and L_2) selectively connected to the transmission line, RF input, RF output, four

Table 1 Dimensions of SPA

Parameter	Value (mm)
Substrate type	Roger RT-Durroid
Substrate length	27.93
Substrate width	35.58
Substrate thickness	0.79
Patch width	11.86
Patch length	9.31
Feed-line width	2.408
Quarter wavelength transformer width	0.5

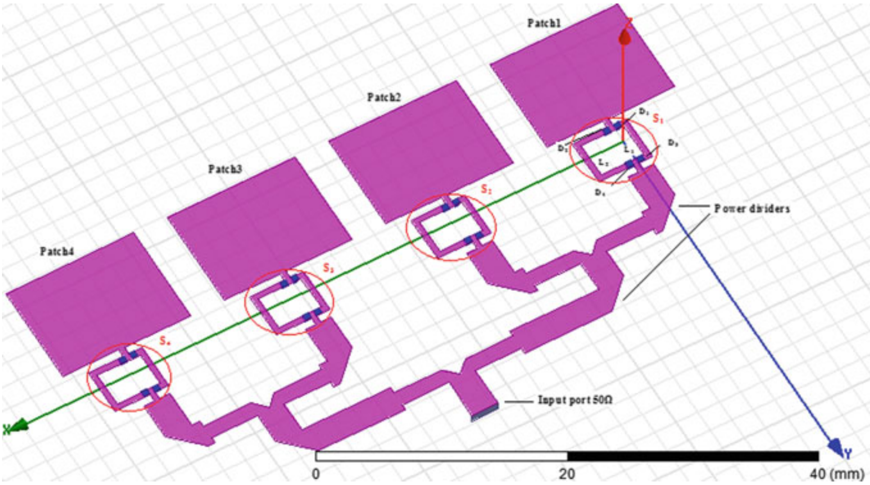
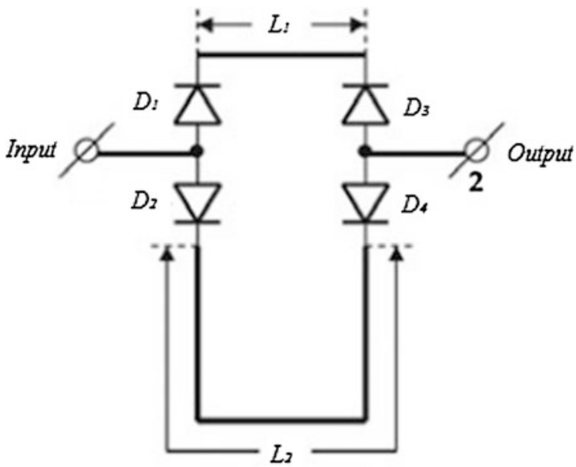


Fig. 3 Simulated geometry of the proposed DBS-PA antenna

PIN diodes D_1, D_2, D_3, and D_4. Only one arm should be ON at a time. When the PIN diodes D_1 and D_3 are ON while PIN diodes D_2 and D_4 are OFF, the reference delay line L_1 is in the circuit. When the PIN diodes D_2 and D_4 are ON while PIN diodes D_1 and D_3 are OFF, the delay line L_2 is in the circuit [9]. By switching the signal between two lines of different lengths L_1 = 5.7 mm and L_2 = 15 mm, it is possible to realize a specific phase shift given by the formula (1).

$$\Delta\varphi = \frac{2\pi(L2 - L1)}{\lambda} \tag{1}$$

Fig. 4 Basic schematic of the proposed microstrip switched line phase shifter



However, since this design is implemented using microstrip technology [10], the physical length, ΔL, is determined by:

$$\Delta L = L2 - L1 = \frac{\beta c}{2\pi f \sqrt{\varepsilon\,\mathrm{eff}}}. \quad (2)$$

where c is the speed of light, β is the propagation constant of the line, f is the operating frequency and ε_{eff} is the effective dielectric constant.

3 Simulation Results and Discussion

In antenna design, firstly, the researcher needs to determine the application of the antenna development in order to fix the antenna's operation frequency. This research focused on the 10 GHz operating frequency of telecommunication satellite and radar systems. The simulation results of the proposed phased-array system are obtained using Ansoft high frequency structure simulator (HFSS).

The presented DBS-PA antenna is competent to perform beam shape ability with sustain frequency operating. This can be done by the RF switches configuration as summarized in Table 2. We can choose from any one of L_1 or L_2 as a reference line and the other is delay line. There are five parametric analysis to be considered which are operating frequency, directivity, beam-width at −3 dB, lobe direction and radiation efficiency.

Table 2 PIN diode switches configuration

Type of phase shifter	Number of phase shifter	Phase shifter status		
		Case 1	Case 2	Case 3
Microstrip switched line phase shifter	S_1	D_1 and D_3 ON (L_1)	D_1 and D_3 ON (L_1)	D_1 and D_3 ON (L_1)
	S_2	D_1 and D_3 ON (L_1)	D_2 and D_4 ON (L_2)	D_1 and D_3 ON (L_1)
	S_3	D_1 and D_3 ON (L_1)	D_1 and D_3 ON (L_1)	D_2 and D_4 ON (L_2)
	S_4	D_1 and D_3 ON (L_1)	D_2 and D_4 ON (L_2)	D_2 and D_4 ON (L_2)
Operating frequency (GHz)		10.00	9.84	9.90
Lobe direction (°)		0°	13°	25°
Directivity (dBi)		11.41	11.51	11.32
HPBW (°)		25°	23°	23°
Radiation efficiency (%)		90	93	89

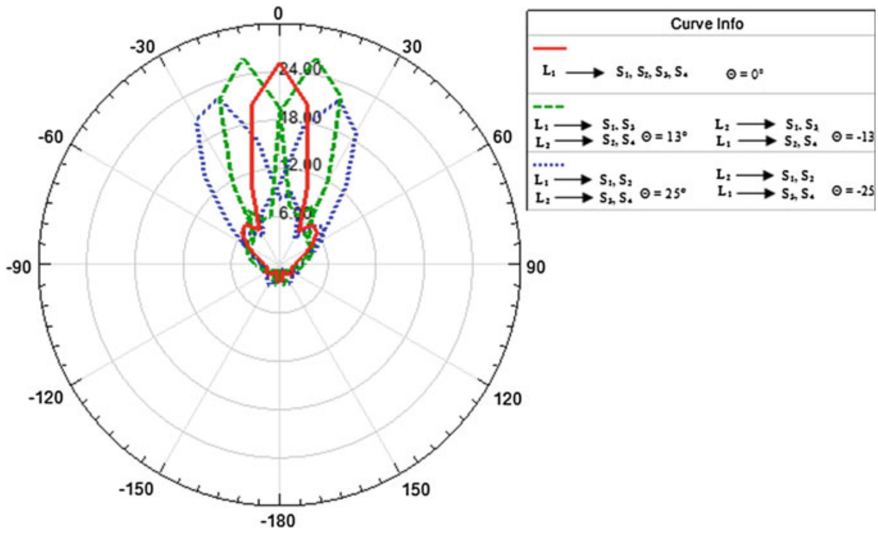


Fig. 5 Comparison of radiation pattern by certain phase shifters configuration in polar plot

Directional beam steering from −25° to 25° has been observed. To illustrate this beam steering, five different beam steering angles at −25°, −13°, 0°, 13°, and 25° are simulated and presented. The E-plane radiation patterns of the DBS-PA antenna are shown in Figs. 5 and 6. The scanning ability is 50° with two delay paths (L_1 and L_2).

There is an improvement in terms of directivity between case 1 and case 2. This has been clearly compared in Fig. 6 which case 2 has high directivity of up to 11.51 dBi while case 1 has directivity of 11.41 dBi. Single patch provide directivity up to 7 dBi, here directivity is increased significantly by 4.5 dBi using array structure. Besides, the half power beam width (HPBW) of case 2 is smaller than case 1, the radiation beam becomes narrow (at 23°) and more directive.

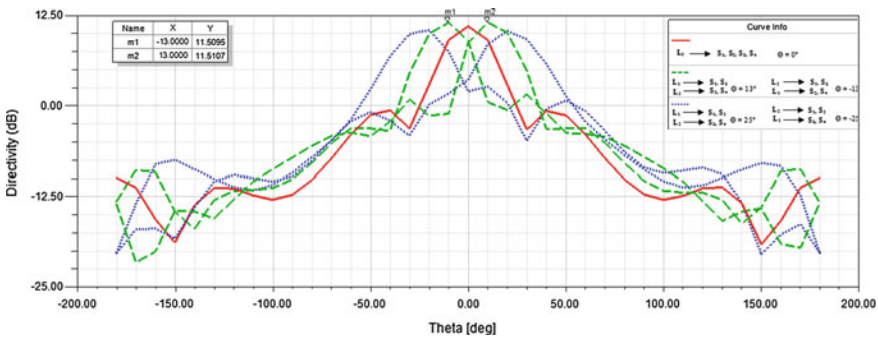


Fig. 6 Comparison of radiation pattern by certain phase shifters configuration in rectangular plot

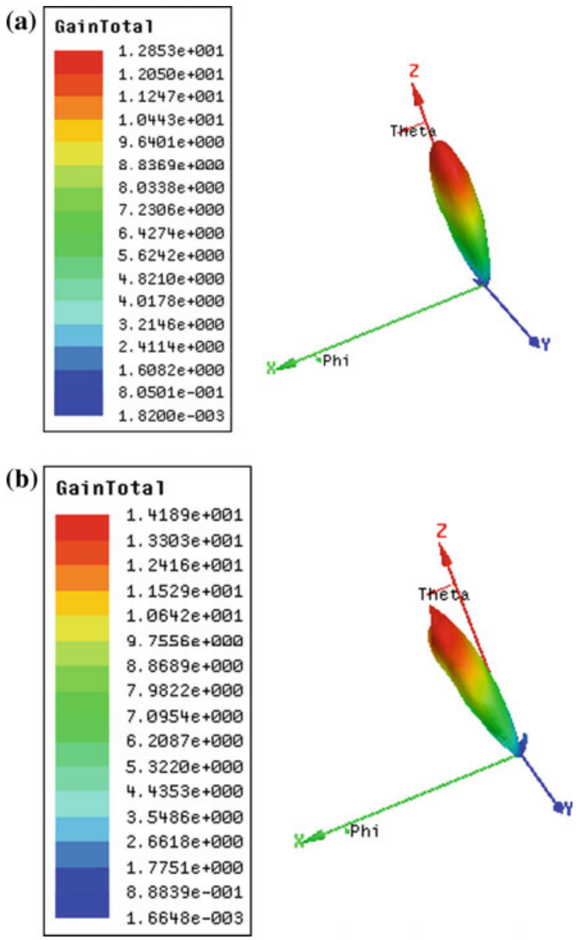


Fig. 7 **a** 3D radiation plot at 10 GHz for 0° beam steering. **b** 3D radiation plot 10 GHz for 13° beam steering

Our goal is to maximize the antenna gain at the specified angle. As an example, Fig. 7 shows the 3D radiation pattern obtained at 0° direction and when steering the radiation beam at 13°, we obtained a maximum gain at the desired angle, it is about 14 dB.

It is important for the phased array to have good impedance matching at all beam steering angles. To verify this impedance matching, return losses for the proposed DBS-PA antenna at beam steering angles of 0°, 13° and 25° are plotted in Fig. 8.

This figure illustrates the reflection coefficient result under the tolerable S_{11} of less than −10 dB for certain phase shifters configuration. It is observed that very good impedance matching is maintained across all the beam steering angles with small discrepancy in frequency due to the shift line lengths.

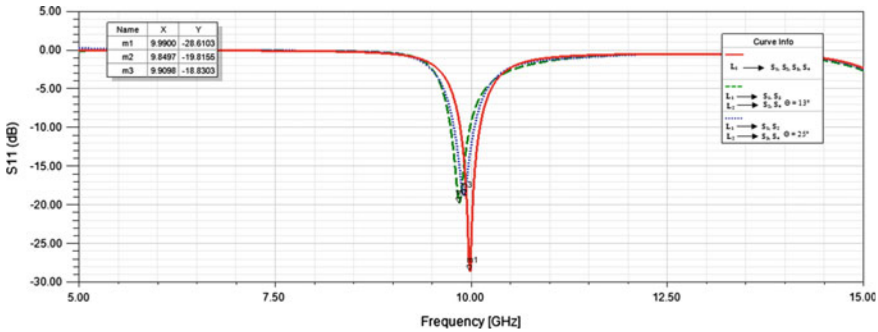


Fig. 8 Comparison of reflection coefficient by certain phase shifters configuration

4 Conclusion

The paper presented the design and simulation of the DBS-PA antenna using microstrip switched line phase shifters for the X band frequency. A patch antenna is selected due to the easiness to feed each element via feed network. The proposed antenna which is rectangular in shape and has a dimension of 8 × 3.5 cm can be considered small in size. Besides, the simulation results show that the proposed antenna has successfully achieved the scanning ability of 50° including beam steering angles of 0°, 13° and 25° in the right and left as well as improved directivity and good impedance matching are maintained across all the beam steering angles. With all capability demonstrated, the presented DBS-PA antenna has a potential to be implemented in smart antenna system and also for military applications. Future research on implementing this antenna and achieving larger beam steering angles is being conducted by the authors.

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