A FREQUENCY RECONFIGURABLE FAN BEAM ANTENNA ARRAY FOR C-BAND APPLICATIONS

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Abstract - This paper proposed a frequency reconfigurable fan beam antenna array for C-band applications. The 1×4 antenna array is designed on a Roger 4003C substrate with a size of 60×130×0.8 mm^3. The antenna can automatically switch between two frequency bands at the center frequencies of 4.2 GHz and 4.5 GHz by utilizing PIN diodes. The antenna obtains high peak gains in two states, 7.89 dBi at 4.2 GHz and 7.19 dBi at 4.5 GHz. The radiation efficiency of the antenna is 87 % and 89 % in states 1 and 2, respectively. Moreover, the antenna produces a narrow fan beam in the azimuth plane with 3 dB angular widths of 24^o and 24.8^o, and a broad fan beam in the elevation plane with a 3 dB angular width of 228^o in two different states. With this fan beam characteristic, the antenna can be a suitable candidate for mobile networks and fixed mobile, radar, and monitoring applications in the C-band.

Key words - Frequency reconfigurable antenna; PIN diodes; fan beam antenna

1. Introduction

Recently, transceivers have utilized multiple-band antennas, or ultra-wideband antennas, to meet various standards of different applications. One antenna can operate at various frequency bands to save costs and reduce device size. Nevertheless, the drawback of these antenna types is that interference between adjacent frequency bands could be increased. To address this issue, the filter requirements for the devices become more complex. Frequency-reconfigurable antennas can automatically switch between their configurations to meet different frequency standards [1]. The antenna only operates in one state simultaneously, minimizing interference between bands. Therefore, reconfigurable antennas have received significant attention from researchers. There are a lot of works on frequency reconfigurable antennas for various applications with many advantages, such as small size, high efficiency, and flexible configuration [2]–[5]. However, improving their performance, including antenna gain, is a requirement of wireless communication systems. The reconfigurable antenna array is one of the solutions for enhancing gain. In [6], a frequency-reconfigurable antenna array with two elements can switch between two states by using copper tracks, which are considered RF switches. The operating frequency range covers the 7.1-7.6 GHz and 6.9-7.5 GHz bands with simulated gains of 9 and 8.4 dBi, respectively. Similarly, a proposed array antenna in [7] can work in multi-bands ranging from 5.1 to 7.3 GHz using copper tapes as diodes on the bottom layer. The suggested array in [8] has two states at 27 and 35 GHz by switching diodes. The ON and OFF states are achieved by connecting or disconnecting the slots with a line, which is not done automatically. Another dual-band reconfigurable antenna array is present in [9]. By switching four PIN diodes, the center resonant frequency changes between 12.2 and 13.5 GHz. However, it is impossible to design bias circuits of these antenna structures in [6]–[8] to supply DC voltage to RF switches. The 2×2 antenna array in [10] obtains a continuous adjusting frequency band from 3.6 to 4 GHz with high gain from 6 to 10 dBi. The authors in [11] propose a reconfigurable dual-band antenna array covering bands from 1.9 to 3.1 GHz and 13.6 to 18.6 GHz. The antenna in [10], [11] integrates four varactors for frequency tunability, which requires a complicated DC bias voltage supply. Several frequency reconfigurable antenna arrays in [12], [13] obtain high performance, but they integrate many RF switches, leading to complicated structures. Besides the reconfigurable characteristic of the antenna, handheld devices use fan beam antennas for sector coverage in applications such as positioning [15], imaging [18], [19], radar systems [20], and 5G mobile systems [21]. A fan beam antenna is a type of directional antenna that produces a narrow beamwidth in one plane while maintaining a broader beamwidth in the perpendicular plane [14]. There have been works on fan beam antennas with a narrow 3 dB angular width [15], [20], [22]–[27] but reconfigurable fan beam antennas have not been extensively researched.

This paper proposes a frequency-reconfigurable fan beam antenna array for the C-band. The antenna array comprises four elements with PIN diodes for switching antenna states. By switching the diodes, the antenna can operate at two frequency configurations, at the center frequencies of 4.2 and 4.5 GHz, with high gains of 7.89 and 7.19 dBi, respectively. In two states, the antenna obtains a narrow fan beam with a 3 dB angular width of 24^0 and 24.8^0 in the azimuth plane and a wide 3 dB angular width of approximately 228^0 in the elevation plane. The main strengths of the proposed antenna include its compact size, high gain, and a fan-shaped beam that has a widespread and narrow-angle at the perpendicular in both configurations.

2. Antenna Design

2.1. Antenna Element structure

Firstly, a microstrip dipole antenna element based on our previous work [15] is designed on a Roger 4003C substrate with an electric constant of 3.55 and a thickness h_s of 0.8 mm, as shown in Fig.1. The antenna operates as a full-wave microstrip dipole. The length of the arm, L_{arm}, is calculated according to the equation below [16].

$$L_{arm} = \frac{c}{2f\sqrt{\varepsilon_r}} \quad (1)$$

where c is light velocity, f is the operating frequency (Hz), and ε_r is relative permittivity. The single dipole antenna is fed by a U-shaped integrated-balun at the bottom side opposite the radiator. This solution is designed for wideband impedance matching, making it suitable for two nearly identical frequency configurations. Specifically, the resonant frequencies of the two states discussed in this work are closely aligned. The U-shaped balun design is similar to a quarter-waveguide wavelength coaxial balun, so the electric length of the balun is approximately a quarter wavelength at 4.2 GHz. The technique to calculate the width of the transmission line with an input impedance Zin of 50 W and detailed dimensions of the balun is presented in [17]. The width of the transmission line is also calculated approximately according to equation (2) [16].

$$Z_{in} = \frac{120\pi}{\sqrt{\epsilon_e}\left[\frac{W_f}{h_s}+1.393+0.667\,ln\left(\frac{W_f}{h_s}+1.444\right)\right]} \tag{2}$$

ε_e effective permittivity of transmission line given approximately by:

$$\varepsilon_e = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+\frac{12h_s}{w_f}\right)^{-\frac{1}{2}} \tag{3}$$

The detailed dimensions of the element are then optimized by CST Studio software and presented in Table 1. The antenna operates at the center resonant frequency of 4.2 GHz with a bandwidth of 39 MHz, a peak gain of 5.97 dBi, and an efficiency of 94 %. The antenna achieves a narrow 3 dB angular width of 69.9^0 in the XY plane. Figs. 2 and 3 show the antenna element's simulated S-parameter and simulated radiation pattern.

***Table 1**. Antenna dimensions of the antenna element*

Dimension	Value (mm)	Dimension	Value (mm)
W	37	*L*	33.3
l p	6.8	*Wp*	16.4
h p	3.2	*g*	0.6
h	10	*u*	2
h g	8.2	*Wf*	2.2

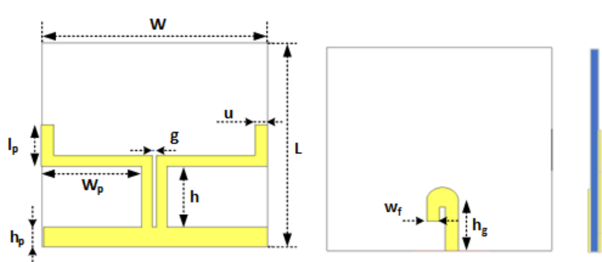


***Figure 1.** Antenna element structure*

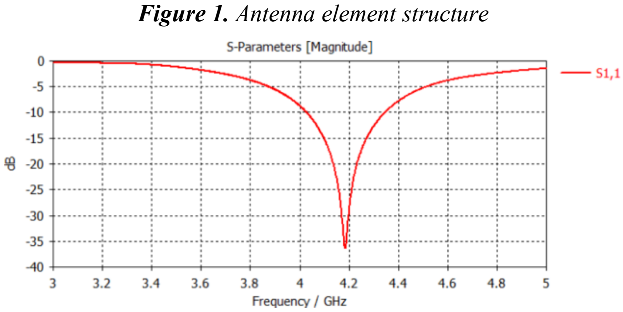
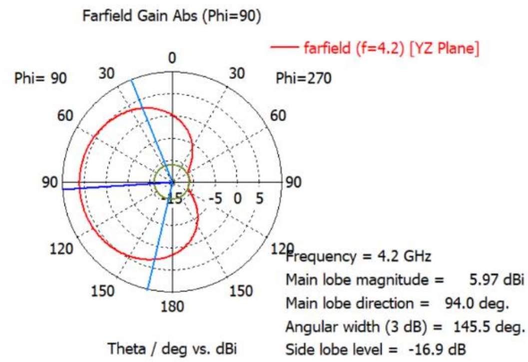
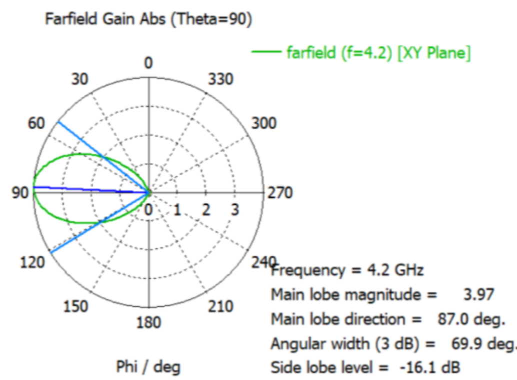


***Figure 2.** Simulated return loss of the antenna element*



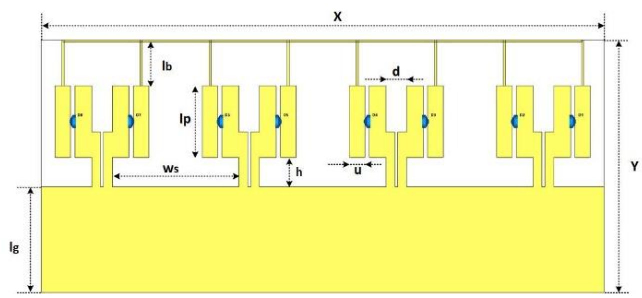
(a) Radiation pattern in YZ plane



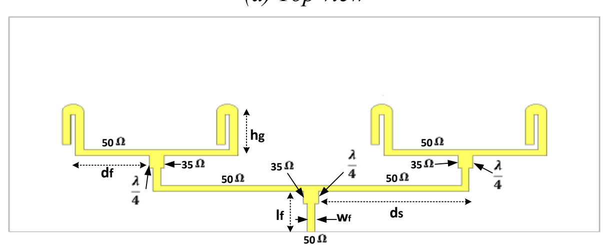
(b) Radiation pattern in XY plane

***Figure 3.** Radiation pattern of the single antenna*

2.2. Reconfiguration antenna array with PIN diode



(a) Top view



(b) Bottom view

***Figure 4.** The structure of reconfigurable antenna array*

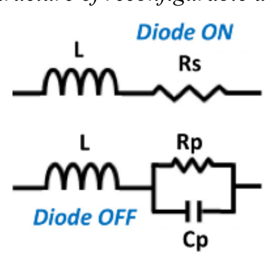


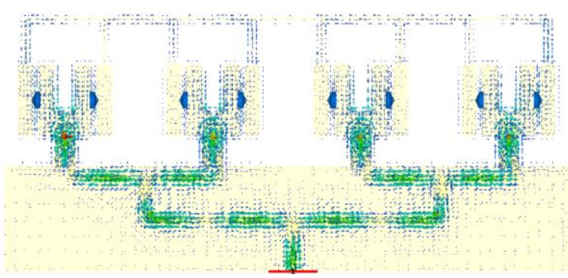
***Figure 5.** Equivalent circuit of PIN diode*

Based on the antenna element mentioned in section 1.1, a reconfigurable array of four elements is designed on a substrate. The T-shaped power divider network is used for the antenna array as shown in Figure 4b. For the antenna array, a T-shaped power divider network is employed. The input impedance Zin of the antenna is chosen as 50 Ω, and the impedance of the quarter-wave impedance transformer is 35 Ω. The widths of the transmission lines, which are 50 Ω and 35 Ω, are calculated according to equation (2). The PIN diodes are integrated into the slots on the top of the antenna to adjust the antenna radiator's electricity length. A biasing circuit is designed to supply DC voltage to control diode states. By switching the PIN diodes, the antenna can operate at two frequency band configurations. These diodes are supplied with a DC voltage via a bias line circuit. Figs. 4 and 5 show the reconfigurable antenna array and the equivalent circuit of the PIN diode, respectively. The component values in the equivalent circuit depend on the diode types used. The diodes used in our design are MACOM-MA4AGBLP912 with L = 0.5 nH, Rs = 4.9 Ω, Rp = 10 kΩ, and Cp = 22 fF. Table 2 presents the detailed dimensions of the antenna.

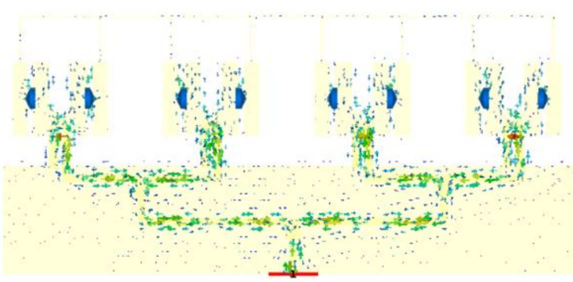
In state 1, when all diodes are biased by a positive DC voltage, they are in the ON state, and the radiators of each antenna element become electrically connected, allowing lengthened radiating elements. Therefore, the antenna can operate at a lower center frequency of 4.2 GHz.

***Table 2**. Detailed dimensions of the reconfigurable antenna array*

Dimension	Value (mm)	Dimension	Value (mm)
X	133.9	Y	60
lg	25.06	lb	10.9
lp	17	h	7
u	3.7	u	4.9
ws	31.1	df	16.77
hg	12.38	lf	11.3
ds	34.15		



(a) State 1 at 4.2 GHz



(b) State 2 at 4.5 GHz

***Figure 6.** The current distribution of the antenna in two states*

Conversely, in state 2, all the diodes are not connected to the positive DC voltage; the diodes are in the OFF state, so the length of the radiators is shorter than in state 1. The antenna resonates at a higher center frequency of 4.5 GHz. This effect is further explained by the current distribution of the antenna in two states, as shown in Figure 6. The figure indicates that the surface current on extra parts connected to the diodes appears when the diodes are in state 1, which makes the electric length of the antenna lengthen. In state 2, the surface current disappears on these extra parts.

3. Results and Discussion

This section presents the simulated results of the reconfigurable antenna's current distribution, return loss, and radiation pattern. Figure 7 shows the return loss parameter of the antenna in two states. It can be seen that in state 1, all the diodes are on, and the antenna achieves a center resonant frequency at 4.2 GHz with a bandwidth from 4.08 to 4.28 GHz. In state 2, all the diodes are off, the center resonant frequency shifts to 4.5 GHz, and the antenna obtains a bandwidth from 4.42 to 4.59 GHz. Figures 8 (a, b) show the radiation patterns of the reconfigurable antenna in two states. The figures show that the radiation patterns are almost unchanged between the two states. The antenna obtains a high gain of 7.89 dBi and 7.19 dBi at 4.2 GHz and 4.5 GHz, respectively. It can be seen that there is a similarity in the radiation pattern in states 1 and 2. Moreover, the antenna obtains a higher gain than a single antenna presented in section 2.1. The radiation efficiency of the antenna is 87 % and 89 % in states 1 and 2, respectively. Besides, the antenna achieves a favorable direction with a narrow angular width of 240 and 24.80 in the XY plane and a wide coverage with a 3 dB angular width of 2280 in the YZ plane in two states. It is an advantage of the proposed antenna for applications that require interference reduction in wireless communication.

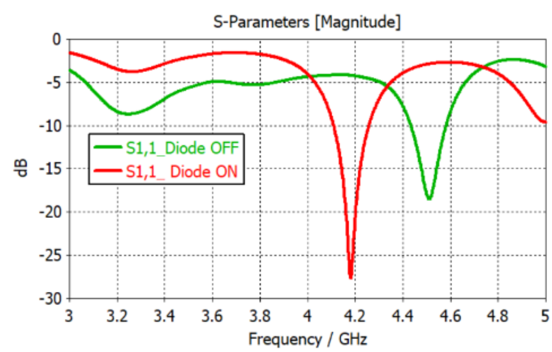
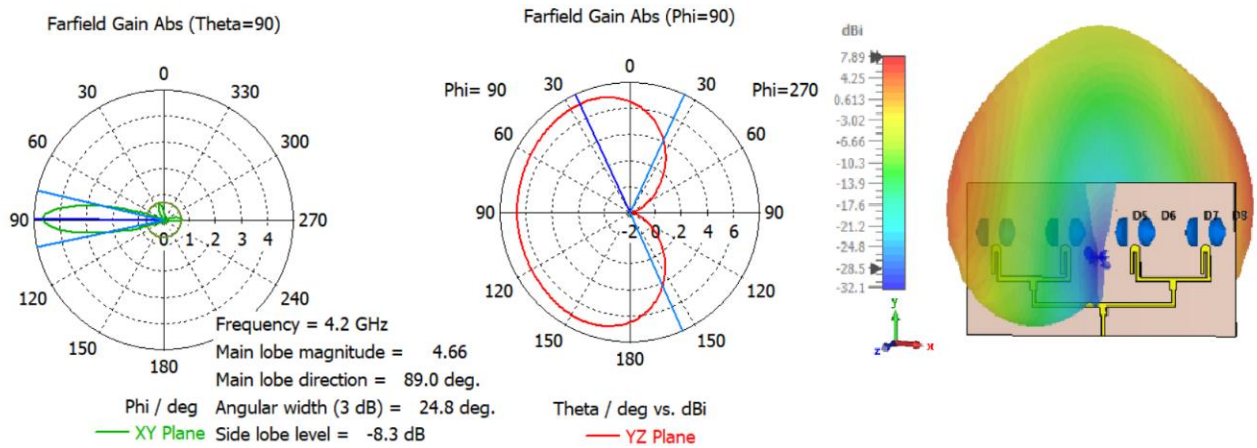


***Figure 7.** Return loss of the reconfigurable antenna in two states*

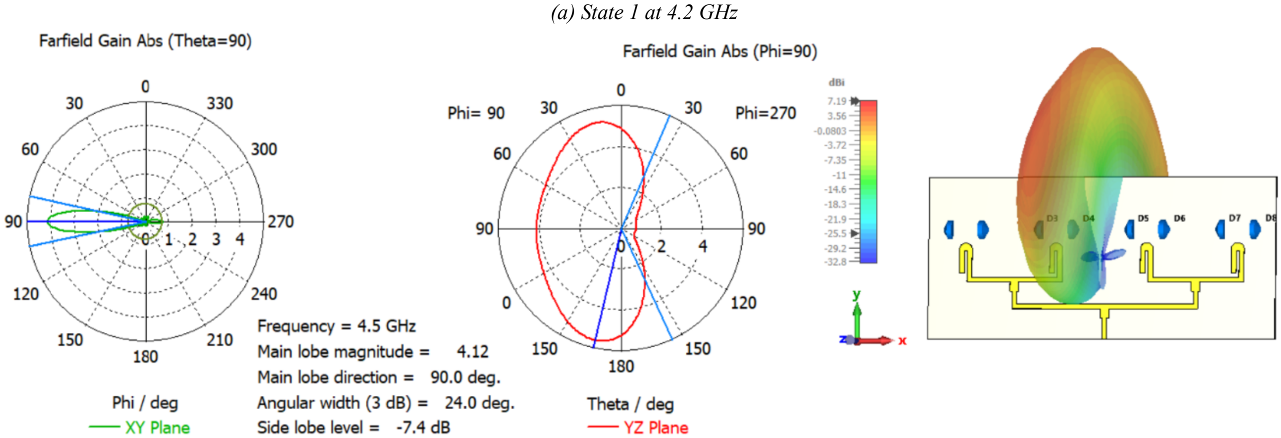
The impact of the PIN diodes and bias circuit on radiation efficiency is evaluated by simulating the antenna with and without the bias circuit and PIN diodes. The antenna without a bias circuit and PIN diodes are simulated at two states. In state 1, when PIN diodes are ON, these diodes are replaced by copper pads. In state 2, PIN diodes are removed from the antenna radiation, as diodes are in the OFF state. Figure 9 shows the result of simulated return loss in the case with and without both diodes and the bias circuit. It can be seen that the bias circuit impacts the resonant frequency of the antenna in two states. The center frequencies shift from 4.2 GHz to 4.12 GHz in state 1 and from 4.5 GHz to 4.55 GHz in state 2. This is because the bias circuit also functions as the radiator. Therefore, removing the bias circuit, which causes changes in the electric length of the antenna radiator, leads to changes in the operating frequency.

Figure 10 presents the impact of diodes and bias circuits on radiation efficiency. When using PIN diodes, antenna gain and efficiency decrease from 8.41 dBi to 7.88 dBi and from 89 % to 87 % in state 1, and from 7.73 dBi to 7.19 dBi and from 91 % to 89 % in state 2. The reason is that diodes are electric components, which lead to energy consumption. This is a trade-off when using electric components to obtain antenna reconfigurations.

Table 3 presents a comparison of the parameters between the proposed antenna and those from existing publications. The table shows that the proposed antenna supports frequency reconfiguration between two bands, which the others do not achieve. Moreover, the antenna has a compact size compared to the other antennas, while it achieves a narrow beamwidth of about 240 in the azimuth plane and a wide beamwidth of 2280 in the elevation plane, significantly enhancing coverage. Therefore, the antenna is suitable for radar and monitoring applications.



(a) State 1 at 4.2 GHz



(b) State 2 at 4.5 GHz

Figure 8. *Radiation pattern of the reconfigurable antenna in two states*

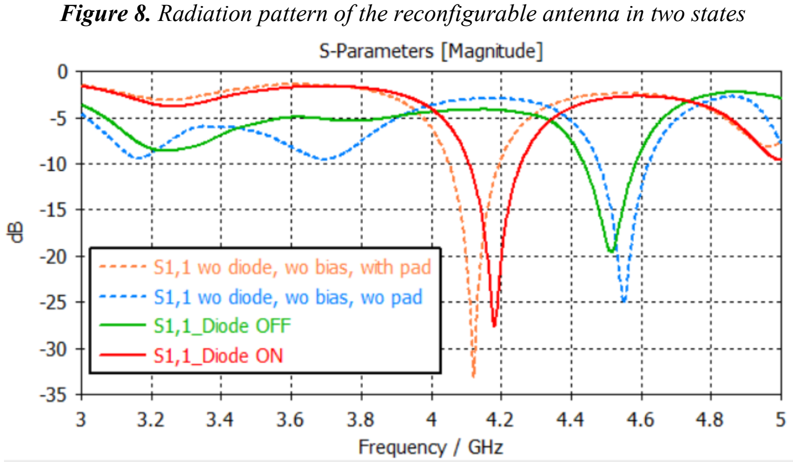


Figure 9. *Evaluating the bias circuit and PIN diodes on return loss*

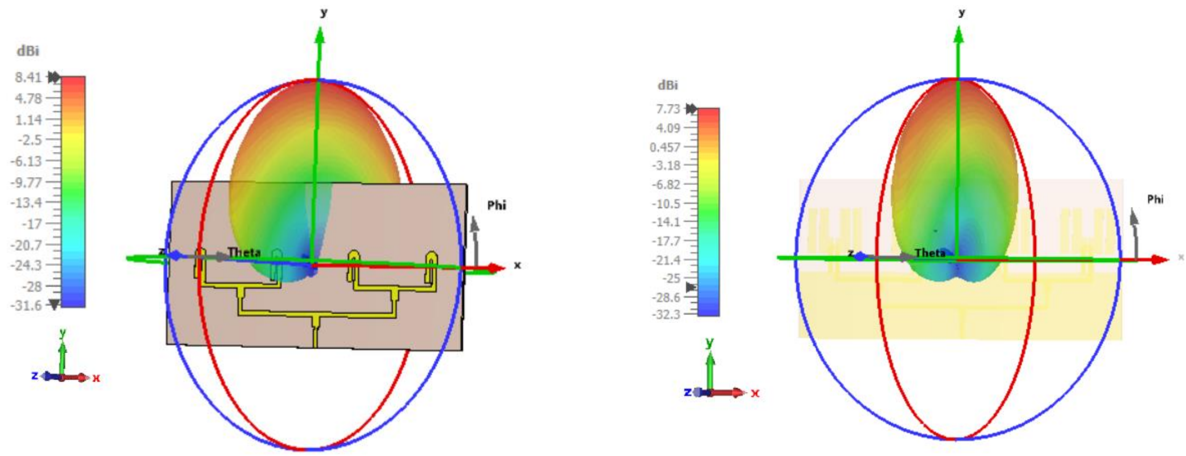


***Figure 10**. Radiation pattern of the reconfigurable antenna without diodes and bias circuit in two states*

***Table 3.** Comparison between the parameters of our antenna and existing antennas*

Ref.	**[15]**	**[20]**	**[23]**	**[24]**	**[25]**	**[26]**	**[27]**	***Our Work***
Operating Frequency [GHz]	2.4	3.3 & 3.5	3.5	5.8	28	3-4	5.8	**4.2, 4.5**
Antenna size (wavelength)	$1.8\lambda\times2.1\lambda$	$1.92\lambda\times0.35\lambda$	$4.59\lambda\times0.71\lambda$	$0.60\lambda\times0.32\lambda$	$15\lambda\times7\lambda$	-	$10\lambda\times10\lambda$	**$0.8\lambda\times1.9\lambda$**
Peak gain (dBi)	9.1 to 9.8	11	10.91	-	7 to 11.16	13.6	10.3	**7.19&7.89**
HPBW Azimuth (^{0})	24.5	26	23.8	85	-	32	20	**24&24.8**
HPBW Elevation (^{0})	90	79	85.4	168	256.7	145	129	**228**
Antenna Type	Planar	Planar	Not Planar	Planar	Planar	Not Planar	Planar	**Planar**
Element Number	4	4	4	1	8	5	1	**4**
Frequency Reconfiguration	No	No	No	No	No	No	No	**Yes**

4. Conclusion

This paper presents a compact frequency reconfigurable fan beam antenna array using PIN diodes for C-band applications with an antenna size of 60×130×0.8 mm3. By switching the PIN diodes, the antenna can operate in two states with the center frequencies of 4.2 GHz and 4.5 GHz. The antenna achieves a high peak gain of 7.89 dBi and 7.19 dBi and radiation efficiency of 87 % and 89 % in states 1 and 2. Additionally, its radiation pattern is a fan shape with a narrow 3 dB angular width of 240 and 24.80 in the azimuth plane and approximately 2280 in the elevation plane in two different states. In future work, a prototype will be fabricated, and its parameters will be measured to verify the simulated results. The proposed antenna is suitable for wireless applications in the C bands, such as mobile networks, fixed-mobile, radar, and monitoring.

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