A Four-arm Circularly Polarized High-gain High-tilt Beam Curl Antenna for Beam Steering Applications

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***Abstract*— A novel circularly polarized beam steering four-arm curl antenna with four feed points is presented. The antenna provides steerable high-gain high-tilt right-handed circularly polarized (RHCP) beams for satellite communications. The antenna operates over a test frequency band of 1500 MHz to 1670 MHz and covers the entire L1 band. The four arms are arranged symmetrically with respect to the center of the antenna and each arm is fed by a coaxial line. When one of the four feed points is excited and the remaining feed points either open-circuited or terminated to 50 Ω impedance, the antenna generates an RHCP tilted beam of 49° in the elevation plane. At a test frequency of 1575 MHz, the antenna provides a gain of 8.12 dBic. The antenna can switch the tilted beam in the four different space quadrants in the azimuth plane by exciting one feed point at a time. It is found that over the test band, the antenna provides a total efficiency of more than 89% and a gain of greater than 8 dBic.**

***Index Terms*— Curl antenna, tilted beam, circular polarization, beam steering.**

I. Introduction

BEAM switchable antennas have been receiving special attention in various civil and military applications, such as satellite communications, radar systems, tracking systems, and satellite communication systems [1] [2]. These antennas are capable of directing the beam only toward the intended direction avoiding the interference/noise sources [3] [4]. Consequently, these antennas provide better signal to interference ratio (SIR) enabling the communication system to support high-rate data-transmission.

Traditionally, phased array antennas have been used for applications requiring beam steering [5] [6]. However, the main disadvantage with the array antennas is that they require multiple radiation elements, phase shifters and complex signal processing circuits for beamforming. The size and weight of these antennas prohibit their use in low cost modern portable transceivers.

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One possible solution to these limitations is to use a single element beam switchable antenna with compact structure. Various configurations of single element beam switchable antennas have been investigated, such as, square loop [7]-[9], microstrip patch antennas with a row of shorting vias [10] and *pin* diodes [11] [12]. However, these antennas provide linearly polarized radiation beams and are not suitable for the satellite, radar and other modern wireless communication applications which require or prefer a circularly polarized (CP) radiation beam.

The spiral antenna is known for its ability for generating a circularly polarized radiation beam over a wider frequency bandwidth [13]. During the last decades, several configurations of a planar spiral antenna have been investigated for CP signal generations, such as conical-shaped spiral [14], Archimedean spirals [15] [16] and equiangular spirals [17] [18]. In most cases, two-arm spirals [19] [20] are selected as the preferred configuration providing a CP conical beam or a CP axial beam. Four-arm spiral antennas with a single feeding port are investigated for CP axial beam generation [21] [22]. Four-arm spiral antennas with multiple feed points have also been investigated for CP beam steering applications [23]-[25]. However, these antennas require multi-arm excitation with phase shifters for achieving CP beam steering function.

In this paper, for the first time a four-arm curl antenna with four feed points is presented for high gain, high tilted CP beam-steering operation without any phase shifters. The antenna operates across a test frequency band of 1500 MHz to 1670 MHz. This includes L1 band applications. When only one feed point is excited, and the three remaining feed points are open-circuited or terminated to a 50 Ω load impedance, the antenna radiates a 49° RHCP tilted beam in the elevation plane. The antenna provides a gain of 8.12 dBic at the test frequency of 1575 MHz. Thus, by switching the excitation among the four feed points utilizing a single pole four throw (SP4T) RF switch [26], the antenna can manoeuvre the RHCP tilted beam in the four different quadrants in the azimuth plane. Note that, since the antenna exhibits similar performance irrespective of the terminations (open-circuited or terminated to 50 Ω) of passive ports, the antenna is compatible with both reflective and absorptive RF switches. An absorptive RF switch is used in the experiment. Therefore, all the results in this paper are obtained when the passive ports are terminated to 50 Ω load impedances.

II. Antenna configuration

The geometry of the four-arm curl antenna is shown in Fig.

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1. The curl arms are printed on the top of a two-layered combined substrate. The upper substrate of RO3035 (relative permittivity ε_{r1}=3.5 and loss tangent tanδ=0.0015) has a thickness of B_1=1.52 mm and the bottom substrate of Delrin plastic (ε_{r2}=3.4 and tanδ=0.005) has a thickness of B_2= 36 mm. Hence, the antenna has a total height of 37.52 mm (≈ λ_0/5.1, where λ_0 is the free space wavelength at 1575 MHz). The whole antenna structure is backed by a metal ground plane having a side length of GP =140 mm. The annular region of the Arm 1 is defined as (1)

$$r = Ae^{a\phi} \tag{1}$$

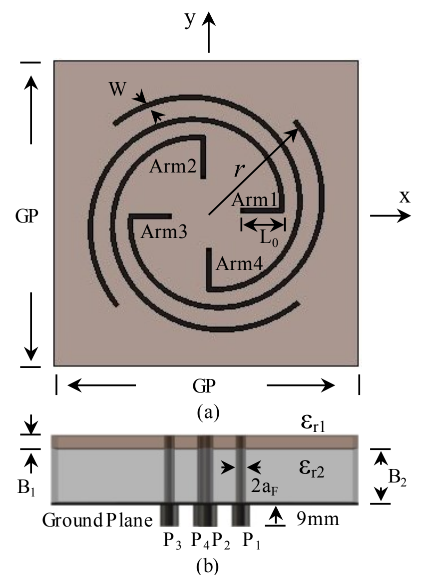

Fig. 1. The structure of four-arm curl antenna. (a) Top view. (b) Side view.

where r is the outer radial distance from the center of the antenna to the central line of the curl arm. A large inner radial distance from the center to the arm starting point is selected to be A = 28 mm for obtaining least mutual coupling between the arms. The curl constant a = 0.135 rad^{-1} and ϕ is the winding angle increasing from 0.5 rad to 1.13 rad. The arms have a track width of W = 2 mm. The annular region of the arm has a total length of 175.7 mm (1.37λ_g). This satisfies the criteria of a curl antenna (λ_g < arm length < 2λ_g) [27]. Note that a straight-line section of length L_0 = 7 mm is added to the arm to increase a horizontal current for attaining a better axial ratio. Arms 2, 3, and 4 are the rotated versions of Arm 1 by π/2, π, and 3π/2 rad, respectively, shown in Fig. 1(a). Each arm is fed by the inner conductor of a coaxial line (inner diameter of $2a_F$ =1.3mm), as shown in Fig. 1(b). The feeding points are defined as port P_1, P_2, P_3 and P_4.

Fig. 2 shows the magnitude and phase of E_θ and E_ϕ components: (a) single arm curl, and (b) four-arm curl with only one feed excited. It is found that one-arm case produces predominantly an E_ϕ component only in the far-field. The magnitude of its E_θ component in the direction of maximum radiation (θ, ϕ) = (40°, 210°) is 7 dB smaller than E_ϕ. Due to such smaller E_θ components, the antenna provides a linearly polarized radiation beam. On the other hand, when three parasitic curl arms are added (Fig. 2(b)), the magnitude of E_θ increases to the same level of E_ϕ and the phase difference between the two components remains unchanged at 90°. As a result, the four-arm curl antenna generates a CP radiation. This means that all the four arms are important for obtaining CP radiation.

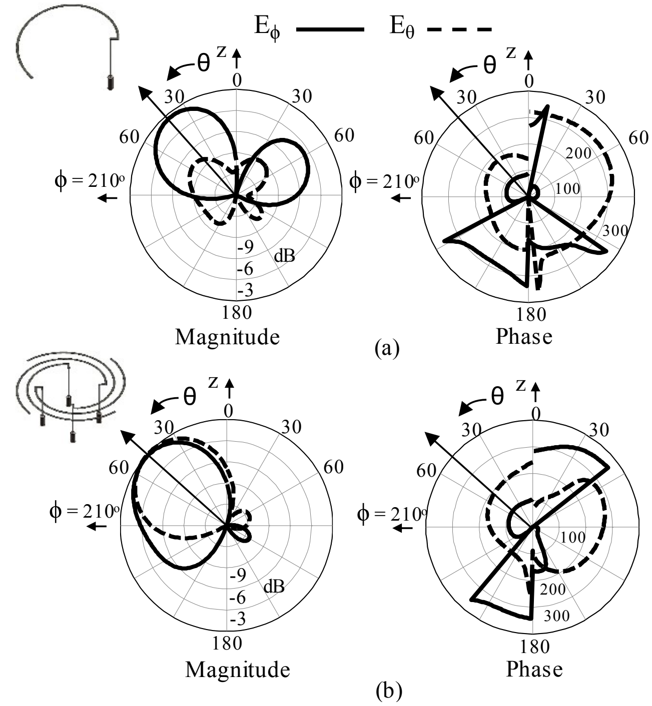

Fig. 2. Magnitude and phase of E_θ and E_ϕ. (a) Single arm curl antenna. (b) Four-arm curl antenna where only one arm is excited and the remaining arms act as parasitic elements.

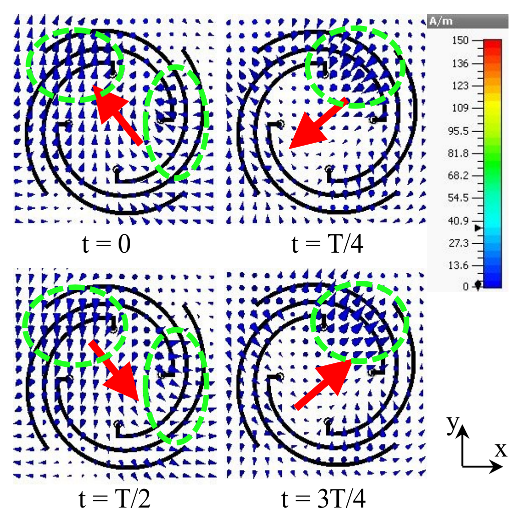

Fig. 3. Magnetic field distribution of four-arm curl antenna.

The generation of CP radiation can also be qualitatively explained from the Magnetic field (H-field) distribution of the four-arm curl antenna. Fig. 3 shows the simulated H-field distribution at 1.575 GHz just above the top surface of the antenna at four stages: t =0, T/4, T/2 and 3T/4, where T is one cycle time period. The dominant H-field components are highlighted with green circles and the effective directions of these field components are highlighted with additional red

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arrows. At t =0, T/4, T/2 and 3T/4 the dominant field makes an angle of 120°, 210°, 300° and 30°, respectively, with the x-axis. Thus, the orientation of the field rotates anti-clockwise by 90°. This satisfies and confirms the RHCP operation of the four-arm curl antenna.

Fig. 4 shows the radiation pattern of the four-arm curl antenna at three frequencies (1500 MHz, 1575 MHz and 1670 MHz). When port P_1 is excited and the other ports are terminated to 50 Ω load impedance the curl antenna provides a tilted RHCP beam across the L1 band. The beam direction at 1575 MHz is (θ, ϕ) = (49º, 210º) as shown in Fig. 4(b). The RHCP radiation provides a half beam width of 68º (θ) × 75º (ϕ) within 15º ≤ θ ≤ 83º and 172.5º ≤ ϕ ≤ 247.5º. Similarly, when port P_2, P_3, and P_4 are excited, the antenna forms tilted RHCP beams in the direction of ϕ = 300º, 30º and 120º, respectively (not shown). All these beams have the same radiation pattern in the elevation plane as that obtained by the P_1 excitation. Therefore, the antenna radiation pattern is reconfigurable when the excitation port is changed by a switching circuit.

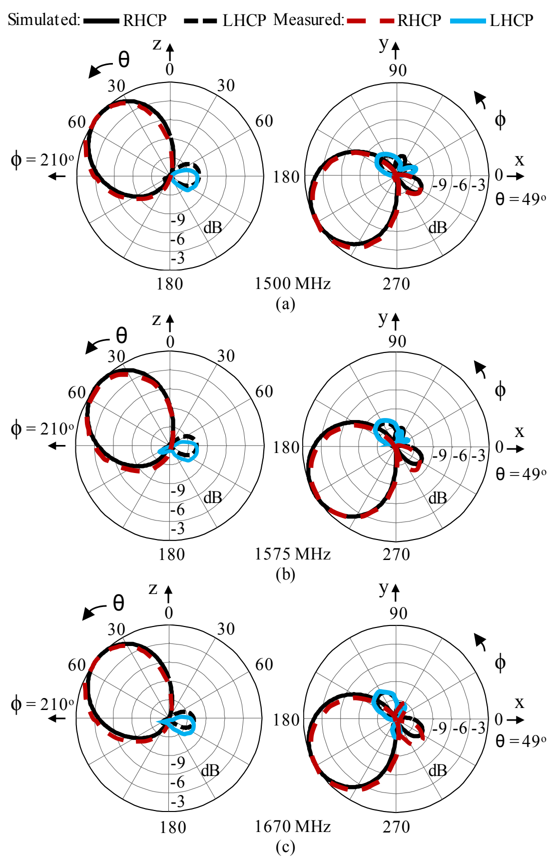

Fig. 4. Radiation patterns for the four-arm curl antenna at (a) 1500 MHz, (b) 1575 MHz and (c) 1670 MHz.

For autonomous operation, an absorptive SP4T RF switch is connected to the antenna by using four 50 Ω coaxial cables (Fig. 5a). Each cable has a length of 100 mm and a loss of 0.2 dB. The SP4T switch has a loss of 0.7 dB [26]. A Raspberry Pi is used to provide a biasing voltage of 5 V and a switching voltage of 3.2 V to the SP4T switch. The switching mechanism in detail has been described in [29]. It is found that the SP4T switch and cables bring negligible effect for antenna radiation pattern. A demonstration of beam switching is shown in Fig. 5(b).

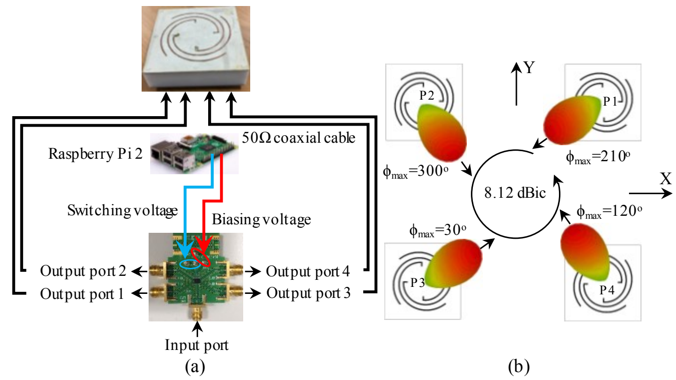

Fig. 5. (a). SP4T switch connection. (b). Demonstration of beam steering at 1575 MHz.

Fig. 6(a) shows the variation of the radiation beam direction across the test frequency band. The beam maintains the direction across the test band. Fig. 6(b) shows the gain and axial ratio for the radiation beam. Without the switch, the antenna provides a gain of more than 8.1 dBic with a total efficiency of more than 89%, across 1500 MHz to 1670. After connecting with the SP4T switch and coaxial cables, the measurement shows that the antenna total efficiency reduces to 72%. The antenna has a 10.7% bandwidth for the 3 dB axial ratio criterion.

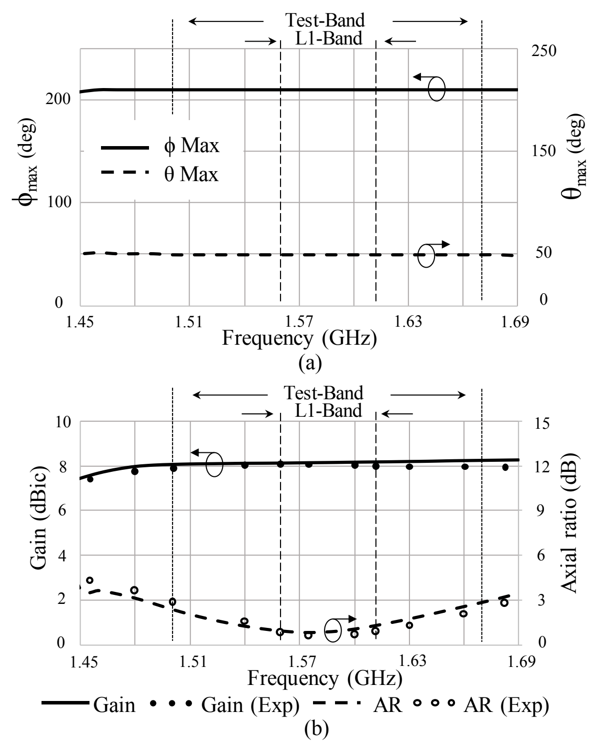

Fig. 6. Four-arm curl antenna radiation characteristics; (a) Beam direction. (b) Gain and axial ratio (AR).

Fig. 7 shows the |S|-parameters for the antenna. The $|S_{11}|$ bandwidth is 16.6% (from 1433 MHz to 1693 MHz) for a −10 dB criterion. It is found that the simulated $|S_{11}|$ is very similar for open-circuited and 50 Ω termination conditions of the

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passive ports. The measured results are in good agreement with the simulated results. As shown in Fig. 7(b), the mutual couplings amongst the ports when P_1 is excited are small: less than −12 dB for the entire antenna test band (1500 MHz to 1670 MHz). Note that, mutual coupling between the ports are obtained from CST (computer simulation technology) when all the passive ports are terminated to port impedance of 50 Ω. Since the antenna arms are symmetrically arranged, similar |S|-parameters are expected for other ports.

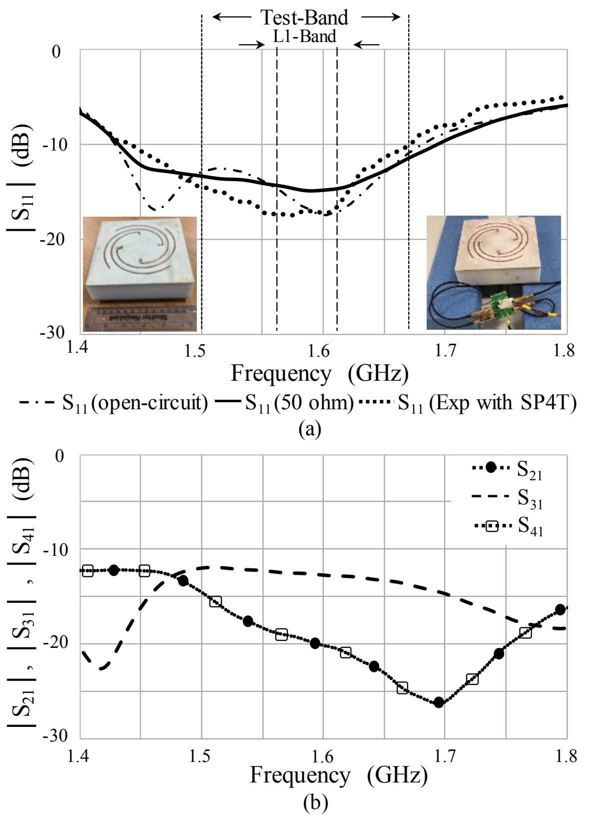

Fig. 7. S-parameters of the four-arm curl antenna; (a) $|S_{11}|$; (b) $|S_{21}|$, $|S_{31}|$ and $|S_{41}|$.

The formation of tilted beam in the elevation plane can be qualitatively explained by magnetic field phase distribution [30] - [32]. Fig. 8(a) shows a line AB along the beam direction at ϕ = 210º at 1575 MHz. The phase distribution along the line AB, obtained using CST, is presented in Fig. 8(b). It is found that the phase at point A is 179º and phase at point B is –213º. Thus, the phase is delayed at point B by 32º. As a result, the beam in the elevation plane is tilted from the z-axis toward point B. In addition to the four steerable tilted beams, the four-arm curl antenna can also provide a CP axial beam and a CP semi-doughnut beam by using multi-port feeding technology [10].

Table I provides a comparison of the four-arm curl antenna with previously published research works [10], [23], [28]. This clearly demonstrates that the four-arm curl antenna provides highest beam tilt angle, and the greatest gain of the steerable tilted beam. This four-arm curl antenna is the first antenna which offers CP steerable tilted beams with a gain greater than 8 dBic and a beam tilt angle as high as 49° without using any phase shifters. High beam tilt steering is essential to track the low elevation angle satellites.

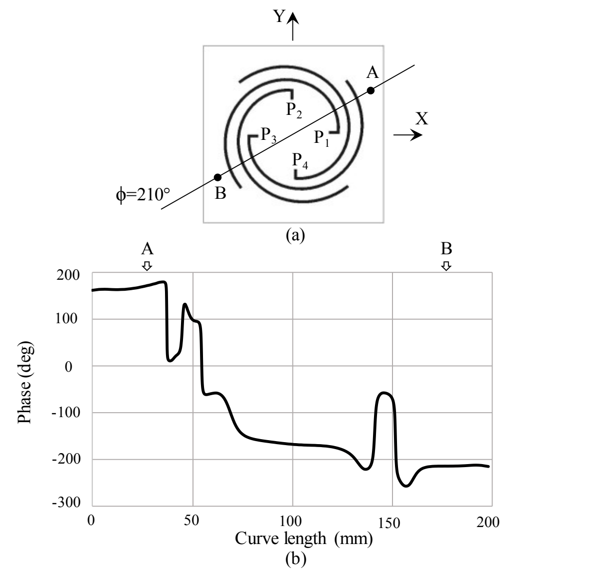

Fig. 8. (a) Line AB follow the beam direction at ϕ=210º. (b) Phase distribution just above the antenna arm along the line AB.

TABLE I. PERFORMANCE COMPARISONS BETWEEN CURRENT MODEL AND PREVIOUS RESEARCH WORKS

	This work	Ref [10]	Ref [23]	Ref [28]
Antenna size (λ_0)	L=W=0.74 H=0.19	L=W=0.8 H=0.12	L=W=0.62 H=0.1	D=0.56 H=0.28
Beam numbers	4 beams	4 beams	4 beams	1 fixed beam
Polarization	CP	LP	CP	CP
Beam tilt angle (θ)	49°	30°	20°	33°
Operating frequency (GHz)	1.575	2.4	1.575	12.225
Peak Gain (dBic/dBi)	8.1	6.1	6	9

L= length, W= width, D= diameter and H= height

III. Conclusions

A four-arm curl antenna has been investigated to realize an RHCP steerable radiation beam with high gain and large tilt angle. The antenna has four feed points and operates over a frequency band of 1500 MHz to 1670 MHz. The antenna provides an RHCP tilted beam of θ=49° in the elevation plane when only one feed point is excited and the remaining feed points are terminated to 50 Ω load. Due to the symmetry of the structure, the antenna produces the similar radiation beams when the excitation port is changed. These beams can be steered in four different space quadrants by using a RF switch. Therefore, this antenna acts as a beam reconfigurable / steerable antenna. Across the test frequency band, the four-arm curl antenna provides a radiation beam with a gain of more than 8 dBic. Note that any phase shifters are not used for obtaining the beam steering function; this results in less complexity and reduced cost of the feeding network.

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