Circularly Polarized Beam-Scanning Microstrip Antenna Using a Reconfigurable Parasitic Patch of Tunable Electrical Size

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Abstract—A reconfigurable microstrip antenna with a circularly polarized (CP) beam-scanning feature is proposed in this paper. Such feature is attained using a novel methodology that effectively tunes the electrical size of a patch antenna. The proposed antenna is a microstrip Yagi-Uda antenna consisting of two square patches. One patch is driven with two orthogonal feeds for CP operation, whereas the other patch is a parasitic one of tunable electrical size for beam scanning. The parasitic patch is loaded with a narrow square slot and four lumped varactors along with their dc biasing network to effectively tune its electrical size. Because the main beam direction is determined by the electrical size of the parasitic patch, electronic beam scanning is allowed by changing the capacitance value through the applied reverse dc biasing voltage. An antenna prototype has been fabricated for experimental validation. Operating at 2.45 GHz, the antenna performance shows a monotonic CP beam scanning that ranges from $-36^\circ$ to $32^\circ$ with a 0.48–6.64 pF tuning capacitance. The achieved peak value for the realized gain is 8.1 dBi with 2.4-dB variation along the entire scanning range.

Index Terms—Beam scanning, microstrip, reconfigurable, tunable antennas, varactor, Yagi-Uda antenna

I. INTRODUCTION

The recent demand of compact wireless devices propels the development of pattern reconfigurable antennas, which is capable of changing their main beam direction in real time other than conventional antennas of fixed radiation pattern. This capability helps in avoiding noisy environment and strengthening the signal detection from an intended target. Classically, beam steering or switching is realized with phased arrays, but it might be large or complex to meet the demand of compactness and low cost of the antenna terminals.

Some research works proposed the Yagi-Uda-based microstrip antenna with linear polarized (LP) pattern reconfigurable feature [1]–[3]. In a similar fashion, two microstrip Yagi-Uda antennas were placed orthogonally and dual fed with quadrature phase to allow for circularly polarized (CP) beam switching [4]. Other designs have been also utilized to establish beam switching as in [5]–[9]. Recently, instead of discrete beam switching, continuous beam scanning has been achieved by loading the antenna with variable reactive elements [10], [11]. Nevertheless, the radiation beams in these designs are linearly polarized, which is not suitable for some applications, such as the low-orbit vehicular satellites and aircrafts communication systems. In such systems, CP is desired for an adjustable elevation coverage zone, which mitigates fading, or allows for terminal tracking. CP antenna with continuous beam-scanning feature is very challenging, and to the best of the authors’ knowledge, it is found to be very limited in the literature. More research is required for this type of antenna to develop a more practical and efficient system.

As discussed above, many pattern reconfigurable antennas rely on the microstrip Yagi-Uda configuration, because it offers a tilted beam with an excellent efficiency, reduced profile, and less design complexity in comparison with planar phased arrays that require complex feed network and larger areas [12]. Therefore, microstrip Yagi-Uda antenna turns to be a good candidate for attaining scannable CP beam.

This paper presents a reconfigurable microstrip antenna design with a continuous CP beam-scanning feature. The effective tunable patch size method has been used to achieve this feature. The antenna is a microstrip Yagi-Uda antenna consisting of two similar square patches. One patch is driven with two orthogonal feeds for a CP wave excitation. The other patch is a parasitic one of tunable electrical size for beam scanning. Four varactors along with a proper dc biasing network are added to the parasitic patch to tune its electrical size, and hence control the coupling between the driven and parasitic patches. Because the main beam direction is determined by the electrical size of the parasitic patch, electronic beam scanning is attained by changing the applied dc reverse biasing voltage (capacitance value). The 2.45 GHz is selected as the design frequency throughout this paper. The proposed design has been validated through measurements of a fabricated antenna prototype.

II. OPERATIONAL PRINCIPLES OF CP BEAM SCANNING

The antenna geometry shown in Fig. 1 is envisioned based on the CP microstrip Yagi-Uda antenna proposed in [12]. It consists of two square patches: one is driven with two orthogonal coaxial feeds and edge length $L = 38$ mm, whereas the other is parasitic. The substrate is Rogers RT/duroid 5880 of relative...
permittivity $\varepsilon_r = 2.2$, thickness $h = 3.175\text{mm}$, and loss tangent $\tan\delta = 0.0009$. The antenna has a scanned beam whose peak direction $\theta_{\text{max}}$ is determined by the parasitic patch edge size $L_r$ as illustrated in Fig. 2. The beam tilts to the $\pm y$-direction depending on the parasitic patch mode if it is a director ($L_r < L$), or a reflector ($L_r > L$). The curves in Fig. 2 are obtained using the full wave simulator Ansoft HFSS [13]. As can be observed, the maximum tilt angle is $30^\circ$ in both $\pm y$-directions. The maximum tilt occurs when the parasitic patch size is close to the driven patch size. The antenna has high side lobe level (SLL) for beams with large tilt angles, especially in the $-y$-direction (e.g., $L_r = 40\text{ mm}$) in contrast to the typical Yagi-Uda antennas. Indeed, in microstrip Yagi-Uda antenna designs, two parasitic patches—one as reflector and other as director—placed on both sides of the driven patch are typically used to acquire lower SLL. Nonetheless, the shown two Yagi patches are smaller in size and simpler in practice to electronically scan its CP pattern as will be discussed in the rest of this paper. On the other hand, when the parasitic patch is too small or large, it turns to be ineffective because it is off the driven patch resonance (operating frequency), and the coupling between the two patches becomes very weak. Therefore, the beam tilt angle at these cases approaches the broadside direction as the radiation is only due to the driven patch.

According to Huang and Densmore [12], due to the different coupling effect at different values of $L_r$, the differential phase between the orthogonal feeds needs to be adjusted, other than $90^\circ$, to acquire a good CP performance. Moreover, the probes feed positions also need to be moved independently for 50-Ω impedance matching at each port. These adjustments are impractical for a pattern reconfigurable design, and represent a real challenge in achieving scannable CP beam. To overcome this difficulty, the coupling mechanism between both patches has been carefully investigated. There exist two types of coupling between the two patches: $E$-plane coupling due to probe 1 and $H$-plane coupling due to probe 2 [14]. Let’s define the relative phase shifts for the patches surface current (average value) due to the $E$- and $H$-planes coupling as $\beta_e$ and $\beta_h$, respectively, such that

$$\beta_e = \frac{1}{A} \left( \iint \angle J_{1y}(x, y) dx \, dy - \iint \angle J_{2y}(x, y) dx \, dy \right)$$

(1)

$$\beta_h = \frac{1}{A} \left( \iint \angle J_{1x}(x, y) dx \, dy - \iint \angle J_{2x}(x, y) dx \, dy \right)$$

(2)

$$A = L_r^2$$

(3)

where $\angle J_{1x}$, $\angle J_{2x}$, $\angle J_{1y}$, and $\angle J_{2y}$ are the phase of the $x$- and $y$-directed surface currents on patch 1 (driven) and patch 2 (parasitic) surfaces, respectively. Similarly, the current magnitude ratios $\alpha_e$ and $\alpha_h$ are defined by (4) and (5), where $|J_{1x}|$, $|J_{2x}|$, $|J_{1y}|$, and $|J_{2y}|$ are the magnitude of the $x$- and $y$-directed surface currents on patches 1 and 2 surfaces, respectively. The $x$- and $y$-directed surface currents on each patch should be equal in magnitude and $90^\circ$ out of phase to obtain CP radiation. Therefore, (6) and (7) must equal zero, and the CP condition is deduced as $\beta_e = \beta_h$ and $\alpha_e = \alpha_h$. This condition should be always satisfied along the beam-scanning range to acquire a good CP radiation for each scanned beam. Fig. 3 shows the phase shift difference between the $E$- and $H$-plane coupling ($\beta_e - \beta_h$) versus different values of the parasitic patch edge size $L_r$, along with the separation distance $s$ as a parameter. As can be seen when $s = 4\text{ mm}$, the phase shift difference is minimized and is almost constant. Meanwhile, the magnitude ratios ($\alpha_e$)

$$\alpha_e = \frac{\iint |J_{2y}(x, y)| dx \, dy}{\iint |J_{1y}(x, y)| dx \, dy}$$

(4)
Frequency tuning is usually implemented with the adjustment mechanism that provides changes in the electrical size of a patch resonator. This can be achieved by altering the parasitic patch size, which allows for controlling the mutual coupling and change the scanning characteristics of the antenna radiation beam.

Frequency-agile patch antennas have two topologies regarding the varactor connection. The first topology is the parallel connection of the varactors across the patch radiating edge as in [15] and [16]. The second topology uses the varactors to serially connect two halves of the patch as in [17] and [18]. Both topologies require modification on the patch to support CP operation as shown in Fig. 4. The parallel connection needs two additional varactors at the other two radiating edges of the patch, which is simpler and easier to implement than for the serial connection. However, the serial connection is preferred over parallel connection in terms of the varactors value, because the fringing capacitance at the radiating edge is smaller than at the centered separation gap. Thus, a higher tuning capacitance is allowed for the serial connection than for the parallel one to get the same change in the resonant frequency. This in turn permits the operation at higher frequency as the required tuning capacitance decreases with increasing the frequency, and the small capacitance values are limited by the commercially available varactors. Therefore, serial connection is suggested [19]. On the other hand, the serial connection requires a centered crossed gap (patch divided into four quarters) with at least four varactors placed at the edges. Such configuration imposes a complexity in implementing the dc biasing network to the varactors, which complicates the prototyping process and limits its practicality. Therefore, a new frequency-agile antenna design is necessary for the sake of simplicity and practicality of the proposed beam-scanning antenna.

Fig. 5 shows a newly devised CP frequency-agile patch antenna. It is a double probe-fed square patch antenna with narrow square loop-shape slot carved on its surface. The slot loop is loaded with four capacitors of value $C$ on the middle of its sides. The proposed CP antenna provides dual-resonance behavior, whose resonant frequencies $f_1$ and $f_2$ change with the capacitance value $C$ as shown in Fig. 6(a). It should be noted that the antenna without the square loop slot resonates at $f_0 = 2.45$ GHz, and $f_2 = f_0 = 2.45$ GHz at $C \geq 6 \mu$F. Detailed explanation for such dual-resonance behavior has been recently discussed in [20] and [21]. The proposed CP antenna has equivalently two tunable electrical sizes because of the dual-frequency agility upon changing $C$. Therefore, the relation between the antenna electrical size and $C$ is conceptually deduced from Fig. 6(a), as illustrated in Fig. 6(b). From Fig. 6(b), at small capacitance $C$ (0.5 pF),

$$\alpha_h = \frac{\iint_A |J_{2x}(x,y)| dxdy}{\iint_A |J_{1x}(x,y)| dxdy}$$

$$\alpha_c - \alpha_h = \frac{\iint_A |J_{2y}(x,y)| dxdy}{\iint_A |J_{1y}(x,y)| dxdy} - \frac{\iint_A |J_{2x}(x,y)| dxdy}{\iint_A |J_{1x}(x,y)| dxdy}$$

Fig. 3. Phase difference between the $E$ and $H$-plane couplings versus different $L_r$ and $s$ at 2.45 GHz.

![Fig. 4. Varactor connection topologies for a CP frequency-agile patch antenna. (a) Parallel varactor connection. (b) Serial varactor connection.](image-url)
the patch has two electrical sizes: one is slightly larger than its physical size, denoted as patch 2, and the other is much smaller, denoted as patch 1. Upon increasing $C$, patches 1 and 2 start to increase until $C$ approaches significant large value (6.5 pF), where patch 1 size approaches the physical size (plain patch), and patch 2 size becomes extremely large. Therefore, one can change the capacitance value to effectively tune the patch electrical size. The proposed CP frequency-agile antenna does not impose complications to integrate the biasing circuit for the varactors, as will be presented in Section IV.

IV. BEAM-SCANNING RECONFIGURABLE CP ANTENNA

A. Antenna Design

The geometry of the proposed CP beam-scanning microstrip Yagi-Uda antenna labeled with dimensions is shown in Fig. 7. It is similar to the antenna in Fig. 1 including substrate type and thickness, but with the parasitic patch replaced by the proposed CP frequency-agile patch antenna presented in Fig. 5. Four varactors are placed in the middle of each side of the square slot, and a dc biasing circuit is integrated with the antenna as shown in the figure. The four varactors are biased as unison with one control signal, which is connected to the inner part of the parasitic patch through an RF chock coil for RF/dc isolation. Regarding the completion of the dc path, the outer loop of the parasitic patch is grounded through a shorted $\lambda_g/4$ high-impedance transmission line (TL) of width equal to 0.2 mm. The parameter $\lambda_g$ is the guided wavelength at 2.45 GHz. The $\lambda_g/4$ TL acts as an RF choke at the parasitic patch edge, and hence the RF current on the patch is kept unperturbed. The TL is shorted to the ground through a metallic via. In order to attain the possible widest scanning range, the parasitic patch size is selected to be the same as the driven patch. This selection is according to the results in Fig. 2(b), where $\theta_m$ is maximized when the parasitic patch edge size $L_r$ is close to the driven patch size.

As discussed in Section II, the separation gap $s = 4$ mm is selected to satisfy similar E- and H-plane couplings along the tuning range of the parasitic patch. A custom designed 3-dB quadrature hybrid coupler is used to feed the antenna [22], which will also allow for switching the proposed antenna polarization from left hand to right hand and vice versa. The coupler is printed on FR4 substrate of $\varepsilon_r = 4.4$ and loss tangent $\tan \delta = 0.02$.

Full-wave simulation has been carried out for the proposed antenna, and the results for the main beam direction $\theta_m$ versus the capacitance value $C$ are shown in Fig. 8. As expected, beam scanning is observed upon changing $C$, where $\theta_m$ increases monotonically with $C$. The achieved scan angle ranges from
−28° to 32°. In contrast to Fig. 2(b), the curve monotonicity in Fig. 8 is attributed to the behavior of the utilized CP frequency-agile antenna, which could be explained with the aid of Fig. 6(b) as follows.

1) $0.5 \leq C < 2 \text{ pF}$: According to Fig. 6(b), the parasitic patch has electrically two sizes: patch 1, which is too small to be effective (no effect) and patch 2, which is larger than the driven patch acting as reflector. Therefore, this corresponds to $39 \leq L_r < 60 \text{ mm}$ in Fig. 2(b), and hence the main beam direction is in the $-y$-direction.

2) $2 \leq C < 7 \text{ pF}$: As per Fig. 6(b), patch 2 becomes too large and loses its reflective effect, while patch 1 grows enough to be an effective director and dominates patch 2. Therefore, this corresponds to $30 < L_r \leq 38 \text{ mm}$ in Fig. 2(b), and hence the main beam direction is in the $+y$-direction.

The fact that the parasitic patch functions as a reflector at $0.5 \leq C < 2 \text{ pF}$ and a director at $2 \leq C < 7 \text{ pF}$ is the reason for the abrupt change in Fig. 2(b) to disappear in Fig. 8. With the above explanation, the relation between $\theta_m$ and $C$ in Fig. 8—where the beam direction increases monotonically with $C$ from $-y$ to $+y$ direction—is consistent with the relation between $\theta_m$ and $L_r$ in Fig. 2(b).

### B. Experimental Results

An antenna prototype has been fabricated and measured to validate the performance of the proposed design. A photo of the fabricated antenna prototype is shown in Fig. 9. The antenna substrate (RT/duroid 5880) has four via holes: via 1 and via 2 for the RF signals, via 3 for the dc signal, and via 4 for the dc ground. They are all implemented through plated holes during the PCB manufacturing process. Similarly, the coupler circuit substrate (FR4) has two via holes at the coupler outputs, which are implemented as through plated holes. The two substrates are placed back to back during the antenna assembly, where they are aligned such that two external pins of smaller diameters are allowed to pass through via 1 and via 2 holes across the two substrates. Each of the inserted pin is soldered at the top of the antenna substrate and the bottom of the coupler substrate. The pins are connecting the coupler output to the driven patch surface.

The varactor MHV505-19-1 by Aeroflex Metelics is used as a variable capacitance device. It has a tuning capacitance based on the applied voltage as shown in Fig. 10. The tuning capacitance is sufficient to achieve scanning range in Fig. 8. The antenna is fed from the RHCP port, while the other port (LHCP) is terminated with a 50-Ω matching load. If a LHCP is required, the coupler ports need to be switched.

The simulated and measured results for the CP radiation patterns of the proposed antenna at four different dc voltages
Fig. 11. CP radiation patterns of the proposed antenna at 2.45 GHz and different applied reverse dc biasing voltages. (a) Simulations: solid line (0 V, 31°), dashed line (4 V, 3°), dotted line (8 V, −12°), and dashed–dotted line (20 V, −28°). (b) Measurements: solid line (0 V, 32°), dashed line (4 V, 13°), dotted line (8 V, −17°), and dashed–dotted line (20 V, −36°).

Fig. 12. Simulated and measured results for the main beam direction $\theta_m$ versus the applied reverse dc biasing voltages at 2.45 GHz.

Fig. 13. Simulated and measured realized gain (RHCP) and axial ratio versus the beam scan angles at 2.45 GHz.

are shown in Fig. 11. Good agreement is observed between the simulation and the measured results for the RHCP fields. The main beam direction $\theta_m$ changes with the applied dc voltages as anticipated. Within the 3-dB beamwidths of each beam major lobe, the cross-polarization level (LHCP) is less than −15.34 dB (axial ratio < 3 dB), which ensures the maintenance of the CP performance during the beam scanning. The CP performance is also maintained at all the other dc voltages (scan angles). A variance is noticed between the simulated and measured results for the cross-polarization level (LHCP). These discrepancies are considered due to the following reasons: the existence of the biasing circuit in proximity to the antenna during measurement; the varactors parasitic effect that leads to a tolerance in the capacitance value $C$; the phase error introduced by the hybrid quadrature coupler; and the fabrication tolerance in the antenna prototype that adds additional errors. Even though differences between the simulated and measured results for the cross-polarization level exist, the full-wave simulation model is still a good guiding tool for predicting the antenna scanning performance at different biasing voltages.

The main beam $\theta_m$ direction versus the reverse dc biasing voltages $V$ is shown in Fig. 12. Good agreement can be seen between the simulated and measured curves. The acquired scanning range is from $−36^\circ$ to $32^\circ$. The scan angle is decreasing monotonically with the voltages as expected in correlation with Figs. 8 and 10.

The antenna realized gain (RHCP) and axial ratio at each scan angle are shown in Fig. 13. The figure reveals good agreements between the simulated and measured curves. The peak gain is 8.1 dBiC with 2.4-dB variation along the scanning range. The axial ratio is < 3 dB at each scan angle as previously shown in Fig. 11, which indicates good CP performance along the beam scanning. The antenna efficiency is measured inside a far-field range, where it is mounted on a post of two axis of rotation: azimuth and elevation. The dual-axial motion allows to capture the antenna three-dimensional (3-D) pattern. The 3-D gain is first measured for both the theta and phi components, then the efficiency is computed using (6). It is found to be bounded between 83% and 57% along the scan range. The efficiency drops due to the varactor inherent $I^2R$ loss. The varactor $I^2R$ loss varies with the capacitance value (scan range) due to: higher current due to the lower impedance (larger capacitance); and higher current induced on the parasitic patch surface at its high Q-resonance. Better efficiency could be attained by using higher quality varactors, where the $I^2R$ losses are minimized. Newly emerged technologies are needed to enable higher quality varactors [18].
Fig. 14 shows the reflection coefficient of the proposed antenna at different biasing voltage. The reflection coefficient is from the RHCP port 1 of the 3-dB hybrid coupler, while port 2 (LHCP) is terminated with 50 Ω. From the figure, it is observed that the reflection coefficient is below −10 dB over a broadband of frequencies. In fact, the antenna radiates efficiently within 2.4–2.5 GHz. Outside this frequency range

\[ \eta_{eff} (\%) = \left[ \frac{1}{4\pi} \int_0^{2\pi} \int_0^\pi (Gain_\theta (\theta, \varphi) + Gain_\varphi (\theta, \varphi)) \sin \theta d\theta d\varphi \right] \times 100\% \quad (8) \]

two antenna ports add up out of phase or absorbed at the coupler input ports. The coupling between the two antenna ports at different biasing voltage is shown in Fig. 15. It is minimized at the design frequency (2.45 GHz) with the worst case equals—21 dB at 4-V biasing voltage. In 2.4–2.5 GHz band, the coupling is below −7 dB along the biasing voltage range, whereas in 2.425–2.475 GHz, it is ≤−12.5 dB.

Fig. 16. Measured axial ratio versus frequency at different biasing voltage, observed at the peak gain direction of the scanned beams: solid line (\(\theta_m = 32^\circ\)); dashed line (\(\theta_m = 13^\circ\)); dotted line (\(\theta_m = -17^\circ\)); and dashed–dotted line (\(\theta_m = -36^\circ\)).

The axial ratio versus frequency of the proposed antenna observed at the peak gain direction of the scanned beams is presented in Fig. 16. It is observed from the figure that the axial ratio level is below 3 dB in 2.38–2.63 GHz along the beam-scanning range. Although a CP antenna bandwidth is usually defined by the overlapped 10-dB return loss and 3-dB axial ratio bandwidths, the practical bandwidth for the proposed design is limited by the beam squint. The beam squint is the fact that the beam shifts with frequency because the main beam direction depends on the electrical size of the parasitic patch, which is frequency dependent. Given that the proposed antenna beamwidth is larger than 40°, a 5° beam squint is quite acceptable and the antenna overall bandwidth could be defined accordingly. The 5° beam squint occurs within 2.425–2.475 GHz, hence the achieved practical bandwidth for the proposed antenna design is 2%.

V. CONCLUSION

A new reconfigurable microstrip Yagi-Uda antenna for CP beam scanning is proposed. The novel effective tunable parasitic patch size method is introduced and used to achieve the challenging CP beam-scanning feature. Four varactors along with a simple biasing circuit integrated with the antenna are utilized to realize the tuning. The tuning capacitance values of the varactors range from 0.48 to 6.642 pF, which correspond to 0–20 V dc voltages range. The measured scanning range is from −36° to 32°, and the attained peak gain value is 8.1 dBiC with 2.4-dB gain variation along the entire scanning range. The antenna efficiency varies from 83% to 57%. A better efficiency could be obtained with advanced enabled technologies for varactors of higher quality factor. Low orbit vehicular satellites, aircrafts, tracking terminals, and remote-sensing receiving systems are potential applications for the proposed antenna.

The proposed design is the simplest form of the CP beam-scanning Yagi-Uda antenna. Further improvement for symmetrical scanning and lower SLL along positive/negative angles
could be achieved with two parasitic patches on each side of the driven patch operating in director/reflector modes, respectively. However, the expenses are bigger antenna size, four additional varactors, and two independent control signals that complicate the logic control. A tradeoff should be encountered in actual system implementation depending on target specifications.

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