of this paper to introduce this novel optimization technique to electromagnetic community. BBO has been able to achieve superior results and has been in conversant with the available literature. The findings address that they are better or in equality with the GA and CLPSO. As compared to SA, BBO has been proved to be a faster and leads for better results. Further, it is easy to implement and has been consistent in giving solutions i.e. deviation in results obtained after multiple runs has been found to be lesser. Conclusively, BBO has been a good choice for optimizing Yagi antenna and can be tried on other antennas like antenna arrays as well.

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A Wideband Circularly Polarized H-Shaped Patch Antenna

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***Abstract*—A wideband H-shaped patch antenna for circular polarization is described. By incorporating a long probe inside a substantial high cavity ($\sim 0.26\lambda$), a circularly polarized (CP) antenna in broadside direction is achieved. The horizontal arm of the probe is implemented by means of a printed monopole that is diagonally coupled to a small H-shaped copper plate. The CP antenna features a wide operational bandwidth of 19.4%. The maximum gain and the efficiency of this small antenna are recorded as >5 dBic and >80%, respectively, across the bandwidth. The dimension of the H-shaped patch is $0.3\lambda \times 0.3\lambda$ whereas the ground plane size is $1.8\lambda \times 1.8\lambda$.**

***Index Terms*—Axial-ratio bandwidth, H-shaped patch antenna, return-loss bandwidth, singly-fed circularly polarized antenna.**

I. Introduction

With the rapid development of wireless communication systems, circularly polarized (CP) wideband antennas using single-patch have received considerable attention within the antenna community. Suspended plate/patch antenna (SPA) is one of the simple yet cost-effective approaches. A copper or aluminum plate directly suspended over a ground plane at a large fractional height of the free-space wavelength, which not only just minimizes the fabrication cost but also eradicates the dielectric loss [1], [2]. In general, SPA uses air as the dielectric substrate so that the cavity height can be easily adjusted for obtaining an optimal impedance matching. The H-shaped patch antenna is advantageously small compared to the conventional rectangular patch for a given resonant frequency [3], [4]. Recently, a conventional probe-fed CP antenna using a square patch with a perturbation in form of dual slits was proposed. It was named as H-shaped microstrip antenna [5]. It is well-known that a linearly polarized rectangular patch antenna laid in xy-plane, can be excited at the fundamental resonant mode TM_{01} if a feed is located along the y-axis, or operated in the TM_{10} mode if the feed is moved to a point along the x-axis. However, when a square patch is fed at its diagonal line, either 45° or 135° with respect to the x-axis, the two near degenerative orthogonal modes TM_{01} and TM_{10} are excited simultaneously. Therefore, a circularly polarized patch antenna using a single-feed point can be produced, whilst its sense of CP radiation (left-hand or right-hand) in the broadside direction is determined by the feed location as well as the sign of perturbation. The near-square patch is understood as a square patch with a strip (positive perturbation) added on one side whereas the H-shaped patch can be regarded as two rectangles subtracted from a square patch (negative perturbation). However, the operational bandwidth of the singly-fed CP patch antennas is usually constrained by its narrow axial-ratio bandwidth. The 2.45-GHz CP square patch with dual slits reported in [5] has a small operating frequency range of 1.3%, which is the overlapped

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bandwidth between the return-loss bandwidth (RLBW) and the boresight axial-ratio bandwidth (ARBW) of CP antenna. This narrow bandwidth is attributed to a high unloaded Q-factor of the parallel-plate cavity when a high dielectric constant material is used. This can be verified by using the closed-form expressions for the ARBW and RLBW, respectively, as given by [6]

$$ARBW = \frac{AR-1}{\sqrt{AR}Q} \tag{1}$$

and

$$RLBW = \frac{\sqrt{2(VSWR-1)}}{Q}. \tag{2}$$

Here, we define the maximum achievable bandwidths ratio with specific criteria for a CP patch antenna as

$$BR|_{RL/AR} = \frac{RLBW}{ARBW}. \tag{3}$$

When the 3-dB axial-ratio ($AR = \sqrt{2}$) and the 10-dB return-loss ($VSWR \approx 2$) are used as the bandwidths criteria in CP antennas, (3) gives a bandwidths ratio as $BR|_{10/3} \approx 4$. That is, the maximum achievable 10-dB RLBW is about 4 times higher than that of the 3-dB ARBW for a given structure of CP patch cavity. Likewise, the bandwidths ratio would reduce to 2.87 for a maximum achievable 14-dB RLBW ($VSWR = 1.5$), viz., $BR|_{14/3} = 2.87$. The above BR values can be justified by the measured bandwidths of the CP patch antennas reported in [5] and [7], respectively. However, these are the maximum achievable values when considering ARBW and RLBW separately. The relation between their mean (referenced) frequencies is not known. Nonetheless, it is known that the total unloaded Q-factor is directly related to the dielectric constant of the medium that made up the cavity, but is inversely proportional to the electrical height of the cavity. For a singly-fed CP patch antenna, the perturbation amount inversely varies with the total unloaded Q-factor [8]. Therefore, a suspended patch structure with an electrically large cavity height gives a small Q-factor, which in turn leads to a wide bandwidth. The art of the CP antenna design is to tailor the mean frequency of its ARBW close to that of the RLBW so that a wide overlapped/operational bandwidth of the CP antenna can be attained. Based on the aforementioned theories, this communication delivers a presentation on the design of a wideband singly-fed CP patch antenna using a printed monopole fed by a long probe. The printed monopole is regarded as the horizontal arm which gives the same effect of the inverted L-probe feeding technique [9]. Because of the large amount of negative perturbation—the rectangle cuttings, the squared patch becomes an H-shaped patch. Numerical simulations are confirmed by experimental results that the proposed singly-fed H-shaped patch antenna features high gain and high efficiency within a wide operational bandwidth.

II. Antenna Configuration

The proposed CP antenna has a simple structure as depicted in Fig. 1: a single H-shaped copper plate of 0.5 mm thick is suspended, by using three nylon bolts, over a very thin dielectric layer: 0.2-mm thick RO4003C ($\varepsilon_r = 3.38$, $tan\delta = 0.0021$). This feed layer is used for the printing of a horizontal stripline (monopole) which diagonally excites the patch. The height of the feed layer, $F_V = 24$ mm, is the length of the vertical probe, whereas the horizontal monopole has a width and a length of $F_w = 2$ mm and $F_H = 5$ mm, respectively. According to the aforementioned singly-fed CP patch theory, the

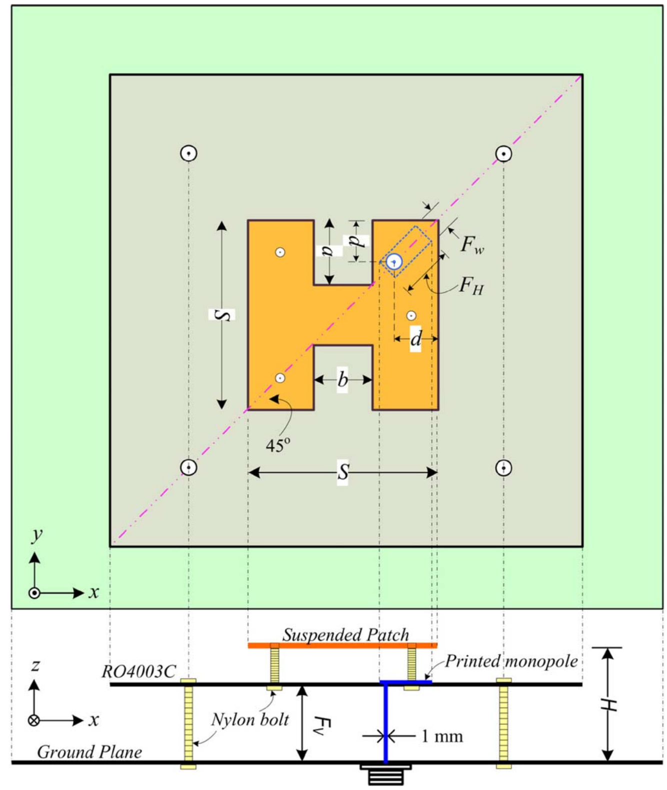

Fig. 1. Geometry of the proposed CP H-shaped patch antenna: $S = 37$, $H = 32$, $a = 13$, $b = 14$, $d = 4$, $F_V = 24$, $F_H = 5.0$, $F_w = 2.0$. Unit: mm.

H-shaped patch has a side of $S = 37$ mm (0.30λ at 2.45 GHz), and a height of $H = 32$ mm (0.26λ) from the ground plane. In order to excite a circularly polarized wave with a left-hand sense in the broadside direction, two large rectangles perturbation ($a \times b$) were cut away from the top and bottom sides of the square patch whilst the monopole is placed at 45° *w.r.t.* the x-axis. It is worthy of note that the printed monopole is arranged towards the patch corner instead of patch centre. This is in contrast to the conventional L-probe fed patch cases, at which the horizontal arm is placed inwards, e.g. the antennas presented in [9], [10]. The introduction of capacitive effect on the horizontal monopole allows for compensation to the feed inductance due to the long-probe. Hence, this feed technique gives a better impedance matching. The use of printed monopole instead of a 90°-bended copper wire provides extra degrees of freedom on the impedance matching, so that the mean frequencies can be adjusted closely. Moreover, the use of the feed layer (RO4003C) and nylon bolts allows a tight control on the alignment between the feed and the small patch. The use of nylon bolts over the foam also gives an advantage on feasible fine-adjustment of the air-gaps during the measurement phase. The ground plane of this antenna is implemented by using a 1-mm thick aluminum plate having a size of 220 mm × 220 mm.

III. Results and Discussion

To investigate the performance of the proposed antenna configuration in terms of good boresight axial-ratio bandwidth and return-loss bandwidth, the EM simulator Ensemble was used for full-wave simulations in the design and optimization phases. A systematic tuning method [11] has been used to obtain the wideband CP characteristics. The aim is to achieve an overlapped bandwidth by getting the individual mean frequencies close to each other, viz., at 2.45 GHz. A photograph of the assembled small H-shaped CP antenna is shown in Fig. 2. It can

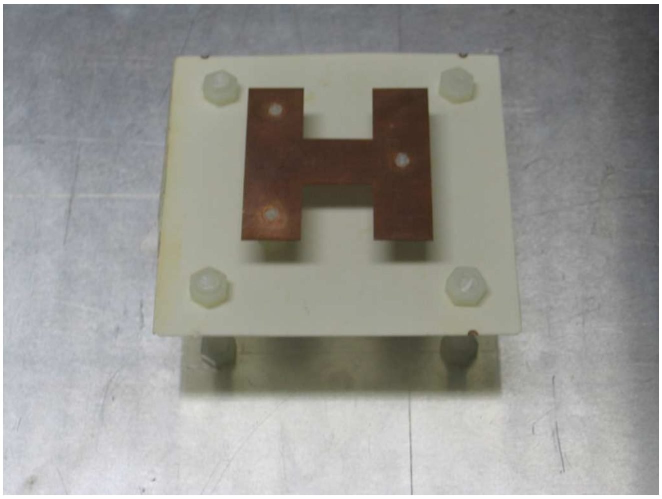

Fig. 2. Photograph of the wideband CP H-shaped patch antenna.

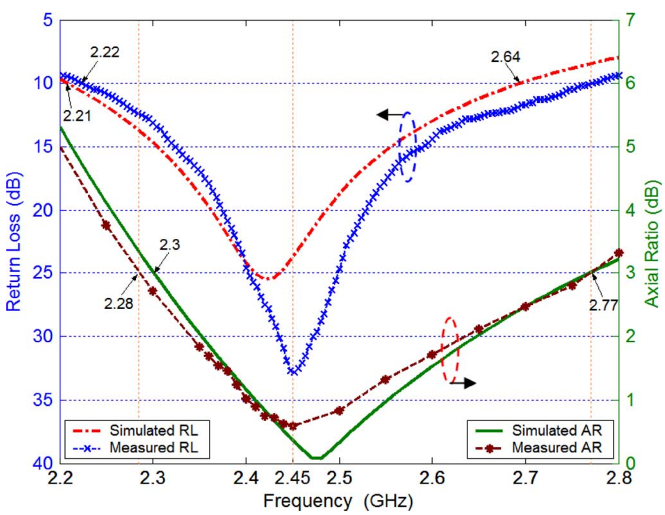

Fig. 3. Measured return-loss and on-axis axial-ratio compared to simulated results.

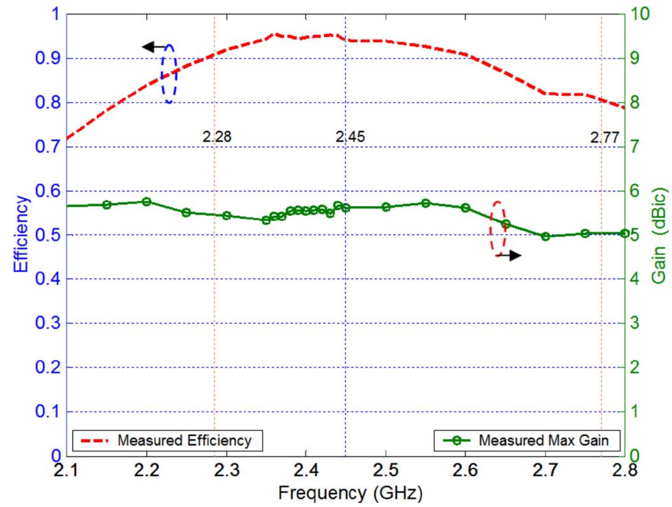

Fig. 4. Measured maximum gain and antenna efficiency versus frequency.

be seen that the copper plate and the dielectric feed layer were mounted together by means of nylon bolts. The simulated and measured return-losses and boresight axial-ratios for the proposed antenna are shown in Fig. 3. As can be seen, the measured results are well corresponded with the theoretical simulations. The small H-shaped antenna has a wide 3-dB axial-ratio bandwidth (ARBW) of 2.3–2.77 GHz (18.5%) in simulation and of 2.28–2.77 GHz (19.4%) from the measurement. From the same figure, a 10-dB return-loss bandwidth of 2.22–2.64 GHz (17.2%) has been obtained in simulation and that of 2.21–2.77 GHz (22.5%) has been measured on a vector network analyzer, Agilent E8363C. These wideband characteristics are attributed to the inclusion of a thick air substrate ($\sim 0.26\lambda$) in the design, which has significantly reduced the Q-factor of the cavity. It is noted that both the measured values on the axial-ratio and return-loss bandwidths are slightly larger than the simulated ones. These are possibly attributed to the nylon bolts and the small holes on the patch that have not been included in the simulation, whereas the fabrication tolerances may also contribute to the discrepancy. Indeed, it is possible to have a wider RLBW by further optimizing the antenna parameters. However, by knowing the operating bandwidth of a CP antenna is limited by the ARBW, we have put the first objective of this design on the maximization of ARBW with an effort on the mean frequencies close to 2.45 GHz. The second objective was set as the impedance matching around 2.45 GHz, rather than a maximization of RLBW. One can see that the measured return-loss has a readable 20-dB RLBW despite the small bandwidths ratio ($BR|_{10/3}$) of 1.16, which is less than the theoretical maximum limit of 4. Moreover, the bandwidths ratio and the ARBW obtained in this design are comparable to the results recently reported by another research team [10], in which a square patch with truncated corners fed by a bent-wire L-probe. Fig. 4 shows the measured maximum gain and efficiency of this small antenna. The use of thick air-substrate and low-loss mechanisms in this design leads to a maximum gain of 5.7 dBic and a high efficiency of 95% at 2.45 GHz. These have been recorded from a near-field SATIMO chamber. Over the CP bandwidth, an efficiency of not less than 80% and a maximum gain of not less than 5 dBic can be warranted.

Fig. 5 presents a comparison on the surface currents flow on three types of singly-fed CP patch antennas at 2.45 GHz. Fig. 5(a) shows a near-square patch with a positive perturbation included on the bottom edge of a square patch. The one shown in Fig. 5(b) is a square patch with a negative perturbation—the narrow-band H-shaped patch antenna presented in [5]; and the one shown in Fig. 5(c) is the proposed wideband H-shaped patch antenna. All these CP patches are 45° diagonally (*w.r.t.* x-axis) excited with a zero-degree phase. It is worthwhile to note that the current flows of the two near-degenerative modes on the patches of Fig. 5(a) and Fig. 5(b) is opposite due to using the opposite signs of perturbation. Hence these CP patch antennas produce the opposed senses of CP wave (RHCP vs. LHCP) in the broadside direction. As the amount of perturbation is much larger for the wideband H-shaped patch shown in Fig. 5(c), the current flows are constrained into the horizontal (from left to right) and vertical directions. The corresponding measured far-field patterns of the wideband H-shaped patch at 2.45 GHz in two principal (xz and yz) planes are shown in Fig. 6. A left-hand sense of CP as the co-polarization with an offset directive is observed. The on-axis cross-polarization discrimination (XPD) of ~30 dB (corresponds to ~0.5 dB axial-ratio) is verified, nonetheless, the off-axis cross-polarization levels have gone up rapidly due to the effect of radiation from the vertical long-probe.

IV. Conclusion

An H-shaped geometry of suspended patch antenna for circular polarization is presented in this communication. The proposed CP antenna is singly-fed by a long probe in conjunction with a printed monopole. The measured results illustrate a good agreement with the numerical simulations. A wide axial-ratio bandwidth of 19.4% is achieved, which is entirely fallen into the measured 22.5% return-loss

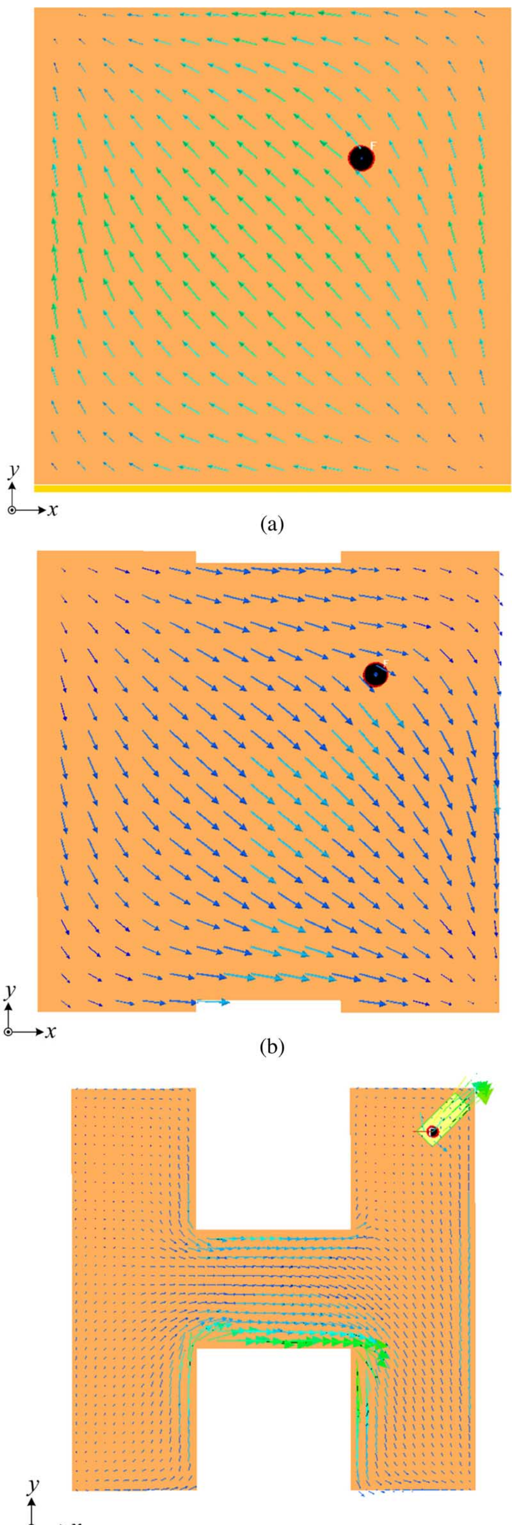

Fig. 5. A comparison of surface current plots on three types of CP radiators: (a) near-square patch antenna with RHCP, (b) narrow-band H-shaped patch with LHCP [5], (c) wideband H-shaped patch antenna with LHCP operation.

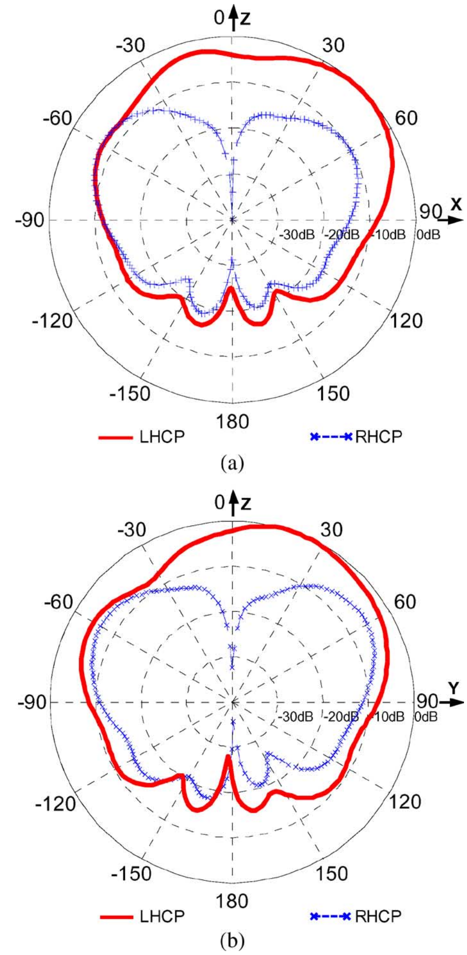

Fig. 6. Measured far-field radiation patterns at 2.45 GHz: (a) xz-plane, (b) yz-plane.

bandwidth. In spite of the small bandwidths ratio, it has demonstrated the essence on the design of a wideband CP antenna: the mean frequencies of axial-ratio and return-loss bandwidths are tailored at the desired frequency of 2.45 GHz. Moreover, the present H-shaped patch antenna attained a maximum gain of 5–6 dBic and over 80% efficiency across the operational bandwidth.

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Polarization Reconfigurable U-Slot Patch Antenna

Pei-Yuan Qin, Andrew R. Weily, Y. Jay Guo, and Chang-Hong Liang

***Abstract*—A compact U-slot microstrip patch antenna with reconfigurable polarization is proposed for wireless local area network (WLAN) applications. PIN diodes are appropriately positioned to change the length of the U-slot arms, which alters the antenna's polarization state. Two antenna prototypes with identical dimensions are designed, fabricated and measured. The first antenna prototype enables switching between linear and circular polarization by using a PIN diode and a capacitor located on the U-slot. The second antenna prototype uses two PIN diodes to switch between the two circular polarization senses. A good impedance match ($S_{11} \leq -10$ dB) for both linear and circular polarization is achieved from 5.725 to 5.85 GHz, a band typically used for WLAN applications, and the 3 dB axial ratio bandwidth is greater than 2.8%. Details of the simulated and measured reflection coefficient, axial ratio, gain and radiation patterns are presented.**

***Index Terms*—Circular and linear polarization, microstrip antennas, reconfigurable antennas, slot antennas.**

I. INTRODUCTION

Circularly polarized (CP) antennas have been widely used in wireless and satellite communication systems to reduce multipath effects and the need for accurate polarization alignment between transmitting and receiving antennas [1]. In contrast to the traditional techniques including extra stubs and chamfering corners of the square patch, which have the drawback of limited 3 dB axial ratio bandwidth, printed slot antennas are gaining popularity for CP radiation design since they have the potential to improve the CP bandwidth without increasing the antenna size. Recently, a single-layer probe-fed U-slot patch antenna with circular polarization was presented, which significantly increases both the impedance and the 3 dB axial ratio bandwidth [2]. Polarization reconfigurable antennas, also known as polarization agile antennas, have attracted considerable attention due to their ability to improve the performance of the communication systems through polarization diversity and frequency reuse. Polarization reconfigurable antennas also have applications in multiple-input multiple-output (MIMO) systems. Most of the previous work for polarization reconfigurability concentrates on switching between right hand circular polarization (RHCP) and left hand circular polarization (LHCP) [3]–[8]. Relatively few antennas have been presented that can switch between linear and circular polarization because it is difficult to simultaneously realize a good impedance match for circular and linear polarization [4]. The reason is that CP radiation is generated by two degenerate orthogonal linear modes, the input impedance of which is different from that of one resonant mode used to generate linearly polarized (LP) radiation. However, it will make the antenna more versatile if switching between linear and circular polarization can be achieved [9]. Several interesting designs have been proposed to solve this problem [9]–[11]. In [9], four pin-diodes were used on a corner-truncated square patch to produce LP and CP radiation with a small impedance bandwidth (2.5%). In [10], a perturbed square-ring slot antenna using four pin diodes was designed that allows operation in both CP and LP modes. Unfortunately, the biasing and control circuits were not physically implemented. In [11], a ring-slot-coupled microstrip circular patch antenna, fabricated on two single FR4 substrates separated by a piece of foam, was proposed that can switch between LP and CP modes. However, the overlapped operating frequency bandwidth is 2.2% and it is difficult to integrate such an antenna in a compact wireless device due to its large volume. A good summary of research on polarization reconfigurable antennas can be found in [12].

In this communication, a microstrip U-slot patch antenna is proposed to allow switching either between linear and circular polarization or between two circular polarization senses. The antenna is compact and can cover the WLAN frequency band with good impedance bandwidths for both CP (11.8%) and LP (6.1%) modes and 3 dB axial ratio bandwidth (>2.8%) for CP mode. The design is based on the circularly polarized U-slot antenna [2]. Compared to [2], [11], however, a single layer microwave substrate is used for ease of fabrication. Two beam-lead PIN diodes embedded into the slot at specific positions enable the length of the U-slot arms to be varied. Two orthogonal modes with quadrature phase can be excited by the asymmetrical U-slot to generate circular polarization. By turning the diodes on or off, the U-slot becomes either symmetrical or asymmetrical, which allows the patch antenna to switch between linear and circular polarization states. The validity of this concept is demonstrated by two identical antennas that achieve good agreement between the simulated and measured results. The complete dc bias network and equivalent circuits of the PIN diodes have been included in the antenna design. A bias-tee is used to superimpose the bias voltage on the RF signal; hence, the dc-bias circuit for the PIN diodes is relatively simple.

II. RECONFIGURABLE U-SLOT ANTENNA DESIGN

The configuration of the proposed reconfigurable U-slot patch antenna is shown in Fig. 1. The parameters and dimensions of the antenna are given in Table I. The length of the patch, denoted as L4, is $\sim 0.35\ \lambda_g$ (14.2 mm), where λ_g is the guided wavelength. This value has been obtained from the parametric analysis in Section III. λ_g is given by $\lambda_0/\sqrt{\varepsilon_{\mathrm{eff}}}$, where λ_0 is the wavelength in free-space, $\varepsilon_{\mathrm{eff}} \approx (\varepsilon_r + 1)/2$ is the effective dielectric constant of the microstrip patch, and $\varepsilon_r = 2.2$ is the dielectric constant of the substrate. A U-slot

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