Single-Feed Slotted Equilateral-Triangular Microstrip Antenna for Circular Polarization

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***Abstract*— Novel designs of single-feed equilateral-triangular microstrip antennas for circular polarization (CP) are proposed and studied experimentally. It is demonstrated that by embedding a narrow slot or a cross slot of unequal slot lengths in the triangular patch, circularly polarized radiation of microstrip antennas can easily be achieved using a single probe feed. Furthermore, results show that for the design with a cross slot, the proposed antenna can perform CP radiation with a reduced antenna size at a given frequency (denoted as compact CP operation here); that is, the required antenna size is smaller for the proposed antenna for performing CP radiation as compared to a conventional circularly polarized triangular microstrip antenna at a fixed operating frequency. Details of the proposed CP designs are described, and typical experimental results are presented and discussed.**

***Index Terms*— Circular polarization, microstrip antenna, printed antennas.**

I. Introduction

THE main advantage of single-feed circularly polarized microstrip antennas is their simple structures that do not require an external polarizer. They can, therefore, be realized more compactly by using less board space than the dual-feed circularly polarized antennas. Many designs of single-feed circularly polarized microstrip antennas with square or circular patches have also been reported [1]. To obtain compact circular polarization (CP) operation, some designs by embedding a cross slot of unequal slot lengths in the circular patch [2] or inserting slits of different lengths at the edges of a square patch [3] have been proposed recently. It is also found that for both regular-size and compact circularly polarized microstrip antennas, the related designs are largely on square and circular patches. Relatively very few designs for achieving CP operation using triangular microstrip antennas are available in the open literature, although it is well known that the triangular microstrip antenna has the advantage of being physically smaller at a fixed frequency, as compared to square or circular microstrip antennas. This motivates the present study of novel designs of both regular-size and compact CP operations of triangular microstrip antennas. The compact CP operation is defined here as the circularly polarized radiation of a reduced size or compact triangular microstrip antenna. Conversely, for the regular-size CP operation, it refers to the circularly polarized radiation of triangular microstrip antennas without antenna-size reduction at a fixed operating frequency.

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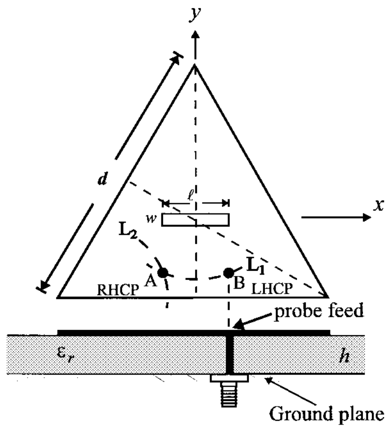
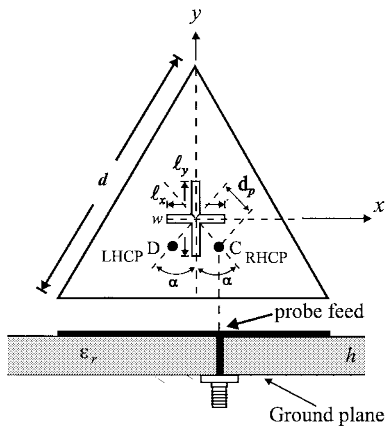
Presently, typical designs of circularly polarized triangular microstrip antennas are using a nearly equilateral-triangular patch [4] or an equilateral-triangular patch with a slit inserted at the patch edge [5]. These CP designs are only applicable for regular-size CP operation of triangular microstrip antennas. In this paper, we demonstrate another promising regular-size CP design of triangular microstrip antennas with an embedded narrow horizontal slot [see Fig. 1(a)]. And it is then shown that by using a cross slot of unequal slot lengths [see Fig. 1(b)] in place of the embedded horizontal slot, the circularly polarized radiation of the slotted triangular microstrip antenna can occur at a lower operating frequency. This implies that an even smaller antenna size for a fixed CP operation can be achieved, if one uses the present proposed compact circularly polarized triangular microstrip antenna with a cross slot in place of the conventional CP designs of square or circular microstrip antennas [1]. Details of the proposed CP designs of slotted triangular microstrip antennas are described and experimental results of the CP performance are presented and analyzed.

II. Antenna Configurations

The proposed antenna designs for regular-size and compact CP operations are, respectively, depicted in Fig. 1(a) and (b), respectively. The equilateral-triangular patch has a side length of d and is printed on a substrate of thickness h and relative permittivity E_r. For the regular-size CP design in Fig. 1(a), a narrow slot of dimensions $\ell \times w(\ell \gg w)$ is embedded in the patch, with the slot oriented in parallel to the bottom side of the triangular patch and the slot center at the null voltage point of the fundamental TM_{10} mode of the simple triangular microstrip antenna without a slot. It is then expected that due to the slot perturbation, the equivalent excited patch surface current path of the TM_{10} mode along the direction perpendicular to the narrow slot is lengthened, while the one in parallel to the slot orientation is slightly affected. This behavior can result in the splitting of the TM_{10} mode into two near-degenerate orthogonal resonant modes. And by further selecting a proper slot length and feeding the patch at a suitable position, the two near-degenerate orthogonal resonant modes can be of equal amplitudes and 90° phase difference, and a CP operation can thus be obtained. As referred to the geometry in Fig. 1(a), the feed position can be determined from the 50-Ω feed-location loci, L_1 and L_2 of the two orthogonal modes,



(a)



(b)

Fig. 1. (a) Geometry of a single-feed equilateral-triangular microstrip antenna with a horizontal narrow slot for CP radiation; feed at point A is for right-hand CP operation and point B is for left-hand CP operation. (b) Geometry of a single-feed compact equilateral-triangular microstrip antenna with a cross slot of unequal slot lengths ($\ell_x < l_y$) for CP radiation; feed at point C is for right-hand CP operation and point D is for left-hand CP operation.

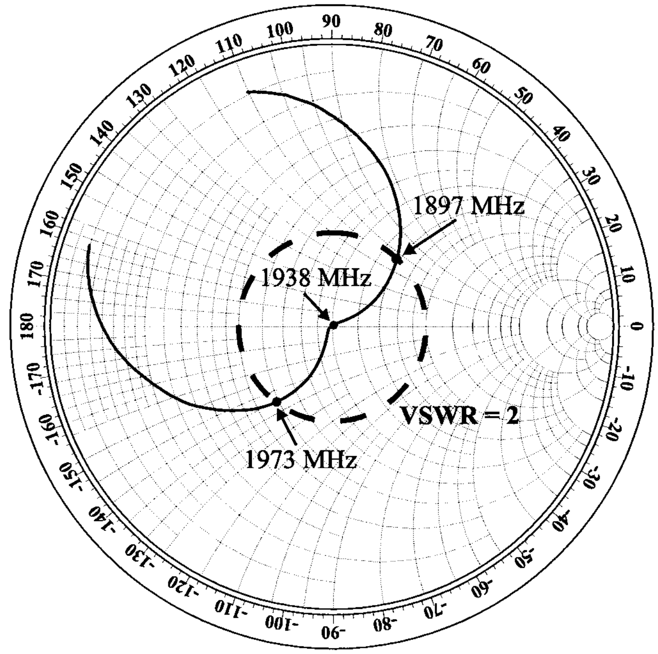


Fig. 2. Measured input impedance for the proposed CP design shown in Fig. 1(a) with feed at point A; $\epsilon_r = 4.4, h = 1.6$ mm, $\ell = 11.9$ mm, $w = 1$ mm, $d = 48$ mm, $(x_p, y_p) = (6.0$ mm, -8.5 mm).

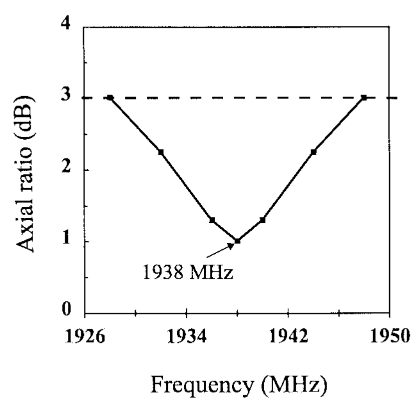


Fig. 3. Measured axial ratio in the broadside direction for the antenna with parameters given in Fig. 2.

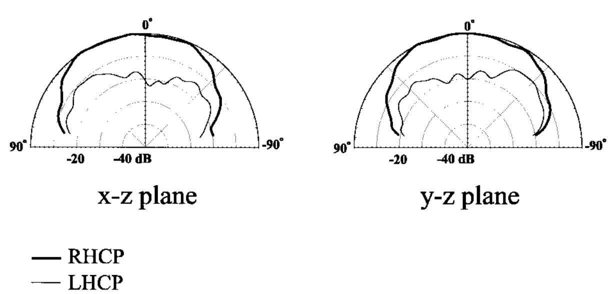


Fig. 4. Measured radiation patterns in two orthogonal planes at 1938 MHz for the antenna with parameters given in Fig. 2.

which are determined experimentally in this study. For the feed position at point A, which is the intersection of loci L_1 and L_2 and is usually located in the left half of the triangular patch, a right-hand CP operation with good matching condition can be obtained. On the other hand, left-hand CP operation can be obtained by feeding the patch at point B (the mirror image of point A with respect to the centerline of the triangular patch).

The proposed antenna in Fig. 1(b) is for compact CP operation. A cross slot of unequal slot lengths are embedded in the triangular patch and centered at the null-voltage position for the TM_{10} mode of the simple triangular microstrip antenna. It is then expected that due to the additional slot perturbation for the horizontal patch surface current path as compared to the design in Fig. 1(a), both the surface current paths of the two orthogonal resonant modes can be lengthened, which lowers their corresponding resonant frequencies. And by adjusting the cross slot to be with unequal slot lengths ℓ_x and ℓ_y and feeding the patch at a position along the lines inclined to the y axis with an angle $\alpha = \tan^{-1}(\ell_x/\ell_y)$ [see Fig. 1(b)], the two orthogonal resonant modes can be of equal amplitudes and 90° phase difference and a compact CP operation can be achieved. The feed postion at point C shown in the figure (with $\ell_y > \ell_x$) is for right-hand CP operation and point D is for left-hand CP operation. And the distance between the feed position and the slot center is denoted as d_p.

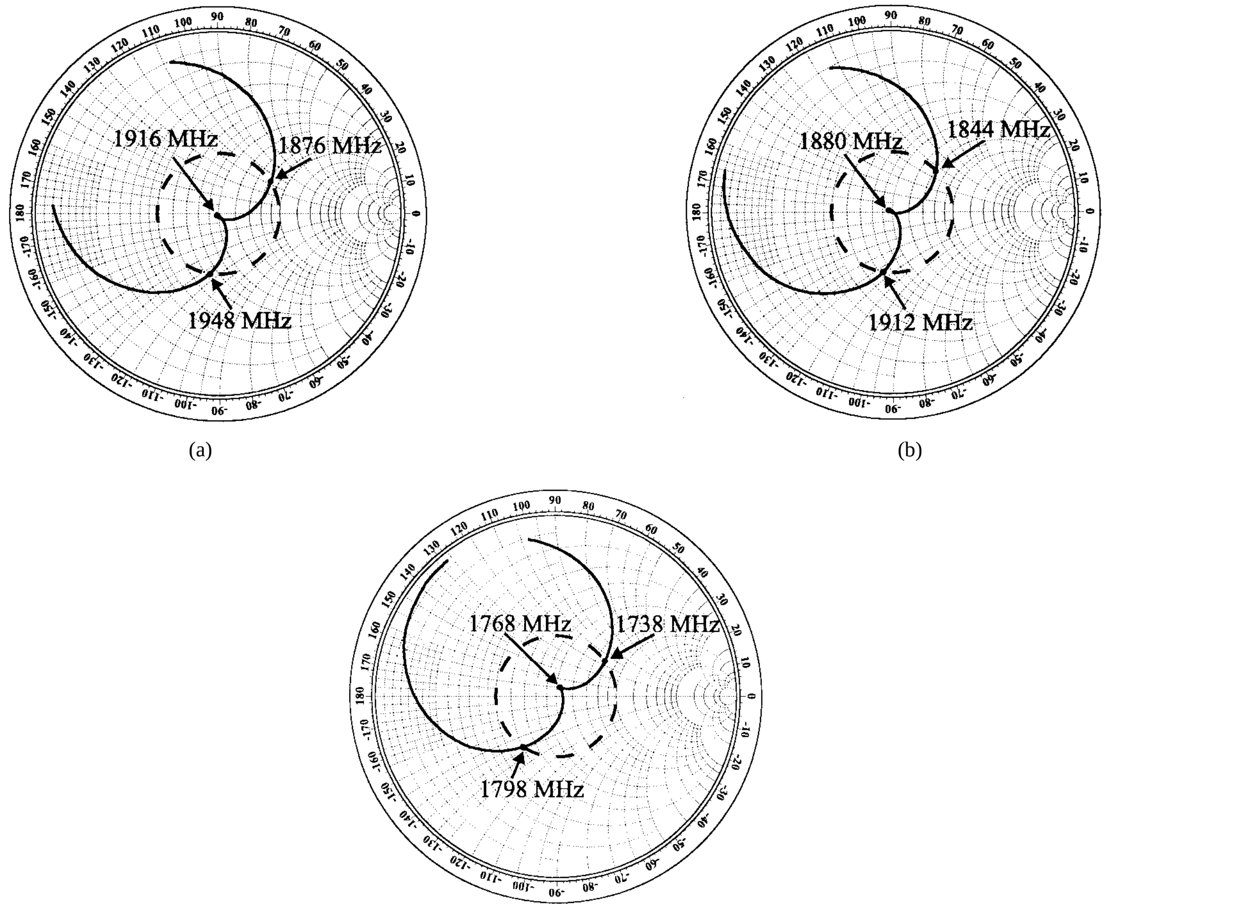


Fig. 5. Measured input impedance for the proposed compact CP design shown in Fig. 1(b) with different cross-slot sizes; feed at point C, $d = 48$ mm, $\epsilon_r = 4.4$, $h = 1.6$ mm, $w = 1$ mm. (a) Antenna 1: $(\ell_x, \ell_y) =$ (6.5 mm, 10.4 mm), $d_p = 9$ mm. (b) Antenna 2: $(\ell_x, \ell_y) =$ (11 mm, 14 mm), $d_p = 7.5$ mm. (c) Antenna 3: $(\ell_x, \ell_y) =$ (17.8 mm, 18 mm), $d_p = 1.5$ mm.

III. Results and Discussion

A. The Design with a Narrow Horizontal Slot

Several antennas based on the proposed CP design have been implemented. The experimental results of a typical case with right-hand CP operation are presented in Fig. 2 in which the measured input impedance is shown. It is first noted that without the slot presence, the fundamental resonant frequency (f_{10}) of the triangular microstrip antenna studied here is at about 1.9 GHz. And from the obtained results in Fig. 2, it can be seen that a dip in the impedance locus near 1.9 GHz is obtained, which indicates that two resonant modes are excited at very close frequencies (if the two modes are excited at frequencies far apart, a loop instead of a dip will be observed in the impedance locus; and if only one resonant mode is excited, there will be no dip seen in the impedance locus). This suggests that the fundamental TM_{10} mode in the present design is split into two near-degenerate resonant modes. And this is largely due to the effective excited patch surafce current path in the y direction being slightly lengthened with respect to that in the x direction, which makes the $\hat{y}$-directed resonant mode with a resonant frequency slightly lower than that of the $\hat{x}$-directed resonant mode. It is also found that, when the slot length is adjusted to be about 0.25 times the side length of the triangular patch (11.9 mm for the proposed antenna with a side length of 48 mm studied here), these two resonant modes can be excited with equal amplitudes and 90° phase difference to result in CP radiation. And the single-feed position for 50-Ω impedance matching, determined from the intersection of loci L_1 and L_2 is found to be approximately located in a position along the direction between the left-hand side edge of the narrow slot and the bottom side of the triangular patch [see Fig. 1(a)]. This property makes the determination of the feed position for the present CP design very convenient, as compared to the regular-size designs reported in [4] and [5]. The measured axial ratio in the broadside direction is also presented in Fig. 3. It is observed that the CP bandwidth, determined from 3-dB axial ratio is 18 MHz or about 0.93% with respect to the center frequency (1938 MHz), defined here to be the frequency with minimum axial ratio in the operating bandwidth. The measured radiation patterns of the present design in two orthogonal planes at the center frequency are also plotted in Fig. 4, and good right-hand CP radiation is observed.

B. The Design with a Cross Slot of Unequal Slot Lengths

The proposed compact CP design with the cross slot of various slot lengths was also implemented and studied. The feed position is selected at point C for achieving right-hand

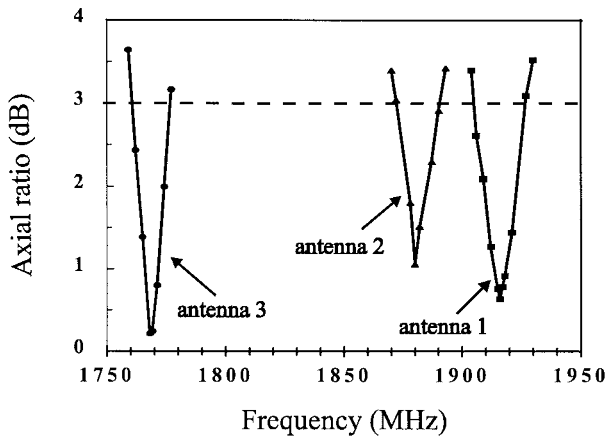


Fig. 6. Measured axial ratio in the broadside direction for antennas 1, 2, and 3 shown in Fig. 5.

TABLE I
CP PERFORMANCE OF THE PROPOSED COMPACT CP DESIGN OF EQUILATERAL-TRIANGULAR MICROSTRIP ANTENNAS; ANTENNA PARAMETERS ARE GIVEN IN FIG. 5

	ℓ_x, ℓ_y (mm)	d_p (mm)	Center Frequency	CP Bandwidth
antenna 1	6.5, 10.4	9.0	1916 MHz	22 MHz (1.15%)
antenna 2	11, 14	7.5	1880 MHz	19 MHz (1.01%)
antenna 3	17.8, 18	1.5	1768 MHz	16 MHz (0.91%)

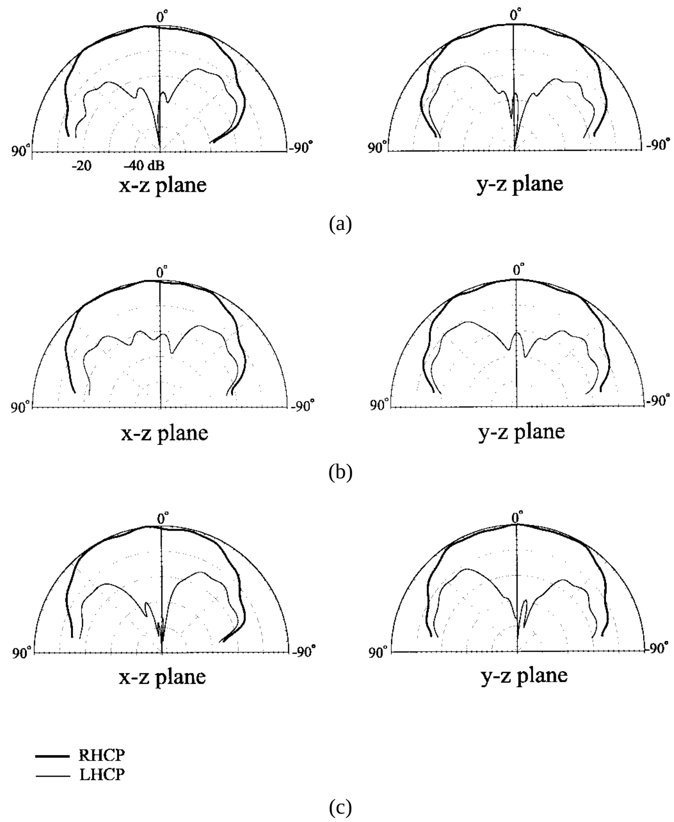


Fig. 7. Measured radiation patterns in two orthogonal planes for the antennas with parameters given in Fig. 5. (a) Antenna 1 at 1916 MHz. (b) Antenna 2 at 1880 MHz. (c) Antenna 3 at 1768 MHz.

CP operation. Fig. 5 shows the measured input impedance of the proposed design with different cross-slot sizes. It is first noted that the antenna parameters are the same as those used in Fig. 2 and antennas 1, 2, and 3 (shown in the figure) denote the designs with different cross-slot sizes. And it is found that by properly adjusting the slot lengths, two near-degenerate orthogonal resonant modes with equal amplitudes and phase difference for CP operation are excited. The measured axial ratio in the broadside direction is presented in Fig. 6, and the corresponding CP performance is listed in Table I. From the experimental results obtained, it is seen that the center frequency for CP operation decreases with increasing cross-slot size, which is expected as discussed in Section II. And for the case of antenna 3, the center frequency is decreased to be 1768 MHz, which is about 0.91 times that (1938 MHz) of the regular-size CP design. This lowering in the center operating frequency can correspond to an antenna size reduction of about 17%, when using the present compact CP design in place of the regular-size CP design shown in part A of this section or the designs reported in [4] and [5]. It is also noted that, with increasing cross-slot size, the feed position needs to be moved closer to the slot center. This behavior limits the use of a larger cross slot for achieving an even greater antenna size reduction using the feed method of a probe feed. However, for such cases with larger cross slots, alternative feed methods such as the slot-coupling feed [6] or the proximity coupled feed [4] can be applied.

Also, it is noted that the CP bandwidth of antenna 3 is about the same as that of the regular-size CP design shown in part A of this section, although the electrical thickness of the substrate of antenna 3 is smaller due to the lowering in the center operating frequency. And, for antennas 1 and 2, the CP bandwidths are even greater than that of the regular-size CP design. This is probably because in this particular case, the use of a cross slot is easier in generating two orthogonal polarizations than the case with a single narrow slot; thus, wider CP bandwidths for antennas 1 and 2 are resulted. Fig. 7 also shows the measured radiation patterns of the compact CP designs in two orthogonal planes, and good right-hand CP operation is seen.

IV. CONCLUSIONS

Novel designs of single-feed circularly polarized microstrip antennas using slotted equilateral-triangular patches have been successfully demonstrated. Both the cases of regular-size and compact CP operations using the designs with, respectively, a narrow horizontal slot and a cross slot of unequal slot lengths embedded in the triangular patch are experimentally investigated. The optimal feed positions for both cases to achieve good impedance matching are found to be easily determined. And for the compact CP design, an antenna-size reduction of about 17% as compared to the regular-size CP design is also obtained. Also, although the electrical thickness of the substrate is reduced due to the lower operating frequency, the CP bandwidth of the compact CP design studied here is about the same as or even greater than that of the regular-size CP design.

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