Cross-Slot-Coupled Microstrip Antenna and Dielectric Resonator Antenna for Circular Polarization

Chih-Yu Huang, *Member, IEEE,* Jian-Yi Wu, and Kin-Lu Wong, *Senior Member, IEEE*

***Abstract*—Circular polarization (CP) design of microstrip antennas and dielectric resonator (DR) antennas through a cross slot of unequal slot lengths in the ground plane of a microstrip line is demonstrated. The proposed CP design is achieved by choosing a suitable size of the coupling cross slot, which results in the excitation of two near-degenerate orthogonal modes of near-equal amplitudes and 90° phase difference. This CP design can be applied to both configurations of microstrip antennas and DR antennas and has the advantages of easy fine-tuning and less sensitive to the manufacturing tolerances, as compared to their respective conventional single-feed CP designs. For the proposed design applied to a low-profile circular disk DR antenna of very high permittivity studied here, a large CP bandwidth, determined from 3-dB axial ratio, as high as 3.91% is also obtained. Details of the proposed antenna designs are described, and experimental results of the CP performance are presented and discussed.**

***Index Terms*— Circular polarization, dielectric resonator antenna, microstrip antenna, slot coupling.**

I. Introduction

EXCITATION of the microstrip antennas and dielectric resonator (DR) antennas through a coupling slot in the ground plane of a microstrip line offers several advantages. For example, no spurious radiation from the feed network can interfere with the radiation pattern and polarization purity of the antenna, since a ground plane separates the feed network and the radiating elements, and no direct contact to the radiating elements for the excitation is required, which eliminates the problem of large self-reactance for a probe feed. Also, the slot-coupling feed can provide more degrees of freedom in the feed design. For these reasons, many antenna designs with the slot-coupling feed mechanism have been reported. For the case of achieving single-feed circular polarization (CP) operation, the method of using an inclined coupling slot at 45° [1]–[3] has been shown. Recently, the method of using a cross slot of equal slot lengths for CP operation has also been proposed [4]. However, it is noted that, for the microstrip-antenna case, these methods require the designs of nearly square or nearly circular patches or square patches with truncated corners *et cetera* to achieve the excitation of two near-degenerate orthogonal modes for CP operation. Since the resulting CP operation is found to be very sensitive to the small variations in the dimensions of these modified patches, there usually exist strict manufacturing tolerances for the implementation of these CP designs. Similarly, for the DR-antenna case, the designs of the DR with special configurations such as the nearly-cubic DR [2] or the rectangular DR with a specific length-to-width ratio [3] or the cross-shaped DR [5] are required for the CP operation. These requirements for special DR configurations make the CP operation of DR antennas more difficult and inconvenient than that of the microstrip antenna. This is because it is relatively uneasy to form a DR with special configurations and almost impossible to make slight geometrical modifications of the constructed DR, due to its hardness in nature, to compensate the manufacturing tolerances or the fabrication errors.

In this paper, we demonstrate that, by using a cross slot of unequal slot lengths for coupling the electromagnetic energy from the microstrip feed line to the radiating microstrip or DR elements, a circularly polarized radiation can be easily obtained. This CP design method requires no slight geometrical modifications or special configurations of the radiating elements, as usually required for the conventional single-feed CP designs described above. The occurrence of the two near-degenerate resonant modes is mainly controlled by adjusting the two arm-lengths of the cross slot. The radiating microstrip patch can be of a simple square shape or a simple circular shape, while for the DR antenna, any DR with square or circular cross sections can be used in this design for the excitation of circularly polarized waves. To verify the proposed CP design method of using a cross slot of unequal slot lengths, the cases of a square microstrip antenna and a low-profile circular disk DR antenna with very high permittivity [6] are demonstrated. The antenna designs for both cases are described and implemented, and details of the experimental results of the resulting CP radiation are presented and analyzed.

II. Cross-Slot-Coupled Square Microstrip Antenna for CP Operation

The configuration of the proposed circularly polarized microstrip antenna design is depicted in Fig. 1. The square patch has a side length of L and is printed on a substrate of thickness h_2 and relative permittivity ε_{r2}. The microstrip feed line of width W_f is printed on a substrate of thickness h_1 and relative permittivity ε_{r1}. The coupling cross slot of unequal slot lengths, L_{ap1} and L_{ap2}, is centered below the square microstrip patch. And, the cross slot is assumed to be narrow;

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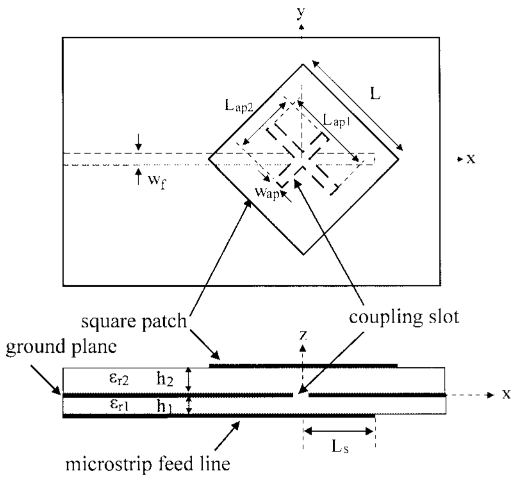

Fig. 1. Geometry of a cross-slot-coupled circularly-polarized square microstrip antenna; $L_{ap1} > L_{ap2}$ is for right-hand CP operation, while $L_{ap1} < L_{ap2}$ is for left-hand CP operation.

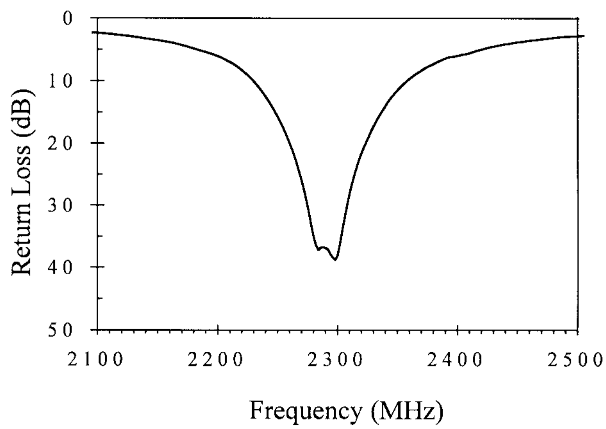

Fig. 2. Measured return loss against frequency for the cross-slot-coupled square microstrip antenna; $h_1 = 0.8$ mm, $\varepsilon_{r1} = 4.4$, $h_2 = 1.6$ mm, $\varepsilon_{r2} = 4.4$, $W_f = 1.5$ mm, $L_s = 15.5$ mm, $L_{ap1} = 14.2$ mm, $L_{ap2} = 11$ mm, $W_{ap} = 1$ mm, $L = 30$ mm.

that is, the slot width $W_{ap} \ll L_{ap1}, L_{ap2}$. Both the two arms of the cross slot are inclined with respect to the microstrip feed line with an angle of 45°. Since it is known that the resonant frequency of the microstrip patch decreases with the increasing of the coupling slot length [7], [8], it is then expected that by carefully adjusting the lengths of the two arms of the cross slot to be different and with a proper length ratio (L_{ap1}/L_{ap2}), the fundamental resonant frequency of the square microstrip patch can be split into two near-degenerate resonant modes with near-equal amplitudes and 90° phase difference. With such an arrangement of the cross slot, the resonant frequency of the resonant mode in the direction perpendicular to the longer slot will be slightly lower than that of the resonant mode in the direction perpendicular to the shorter slot; and when $L_{ap1} > L_{ap2}$, a right-hand CP operation can be obtained. On the other hand, when $L_{ap1} < L_{ap2}$, a left-hand CP operation can be achieved.

The proposed design with right-hand CP operation was implemented. The measured return loss is shown in Figs. 2 and 3 shows the measured input impedance on a Smith chart. The FR4 substrates $(\varepsilon_r = 4.4)$ with thickness 0.8 and 1.6 mm are selected for the feed substrate and patch substrate, respectively. The square patch has a dimension of 30 mm × 30 mm. The microstrip feed line is designed to be with a 50-Ω characteristic impedance and the tuning stub length L_s for impedance matching is adjusted to be 15.5 mm for the case studied here. The lengths of the two arms of the cross slot are chosen to be $L_{ap1} = 14.2$ mm and $L_{ap2} = 11$ mm $(L_{ap1}/L_{ap2} = 1.29)$. From the results obtained, it can be seen that two near-degenerate orthogonal modes are excited for the parameters studied here. Good impedance matching is also seen, with a 2 : 1 VSWR bandwidth to be 135 MHz ($\cong 5.86\%$ with center frequency at 2302 MHz). The axial ratio of the CP radiation was also measured and presented in Fig. 4 in which the CP bandwidth, determined from 3-dB axial ratio, is found to be about 33 MHz or 1.43%. Measured radiation patterns in two orthogonal planes at 2302 MHz

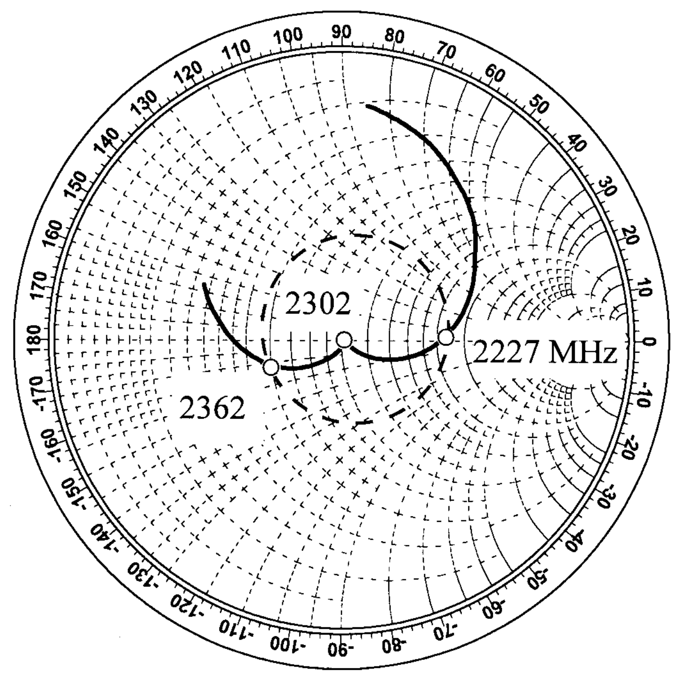

Fig. 3. Measured input impedance on a Smith chart for the antenna shown in Fig. 2.

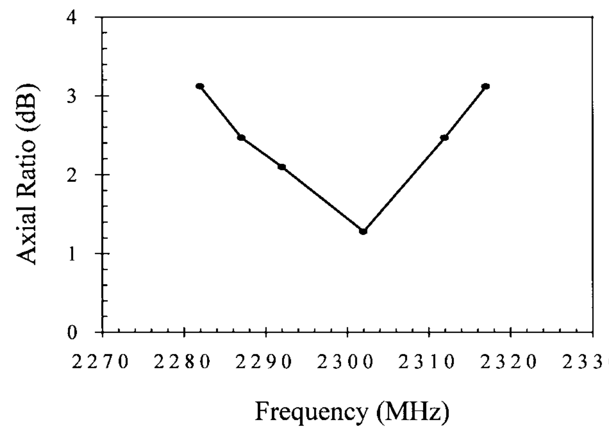

Fig. 4. Measured axial ratio in the broadside direction against frequency for the antenna shown in Fig. 2.

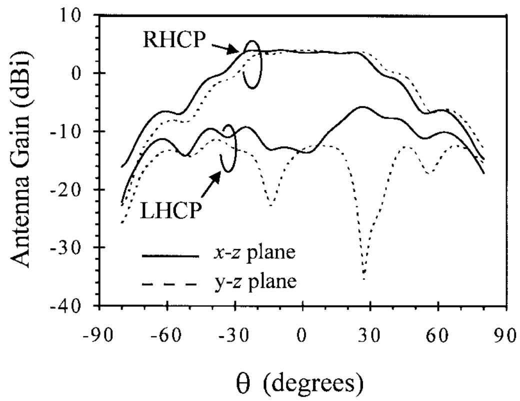

Fig. 5. Measured radiation patterns in two orthogonal planes at 2302 MHz; antenna parameters are given in Fig. 2.

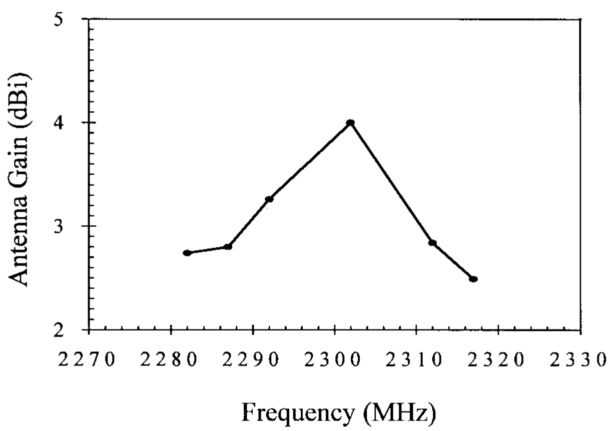

Fig. 6. Measured antenna gain in the broadside direction against frequency; antenna parameters are given in Fig. 2.

are also plotted in Fig. 5. Good right-hand CP radiation is obtained. The antenna gain in the broadside direction ($\theta = 0°$) is about 4 dBi and the front-to-back ratio is 16.6 dB. The antenna gain in the broadside direction against operating frequency is also plotted in Fig. 6. It is seen that, in the 3-dB CP bandwidth, the antenna-gain variation is within 1.5 dB. Finally, it should also be noted that, due to the large arm-length ratio (1.29) of the cross slot, the proposed CP design is much less sensitive to the manufacturing tolerances as compared to the conventional single-feed CP designs [9]. Also, due to the different arm lengths in the coupling cross-slot, the two near-degenerate modes for CP operation will not be excited with equal amplitudes and thus only near-optimal coupling can be obtained in the present configuration. And, although only the case with a square microstrip patch is studied here, the present proposed CP design is also expected to be applicable to a circular microstrip patch antenna.

III. Cross-Slot-Coupled Low-Profile Circular Disk DR Antenna for CP Operation

Fig. 7 shows the configuration of the proposed CP design for a low-profile circular disk DR antenna. It can be seen that this configuration is similar to that shown in Fig. 1, except that the patch substrate and microstrip patch are replaced by a

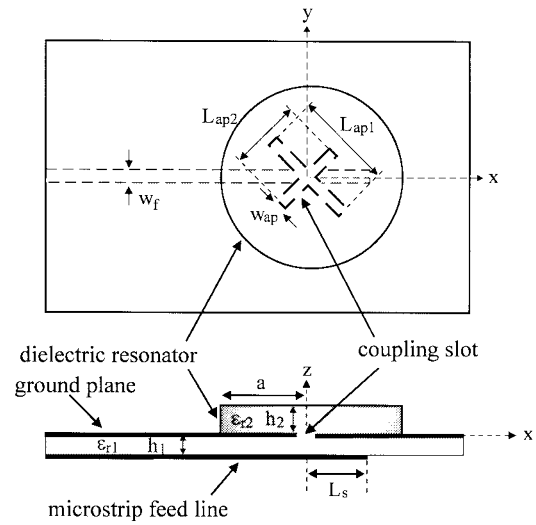

Fig. 7. Geometry of a cross-slot-coupled circularly-polarized circular disk DR antenna; $L_{ap1} > L_{ap2}$ is for right-hand CP operation, while $L_{ap1} < L_{ap2}$ is for left-hand CP operation.

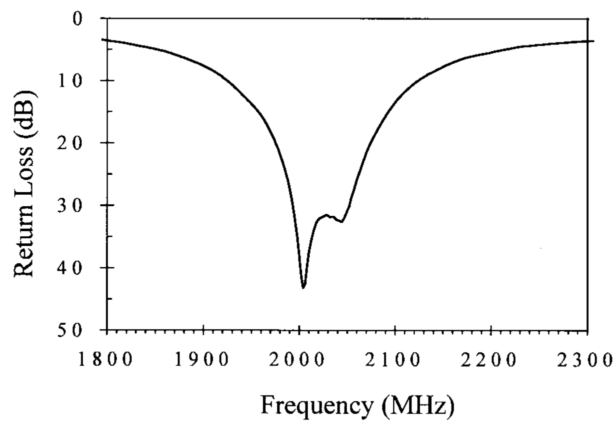

Fig. 8. Measured return loss against frequency for the cross-slot-coupled circular disk DR antenna; $h_1 = 0.8$ mm, $\varepsilon_{r1} = 4.4$, $h_2 = 5.1$ mm, $\varepsilon_{r2} = 79$, $W_f = 1.5$ mm, $L_s = 10$ mm, $L_{ap1} = 13$ mm, $L_{ap2} = 12$ mm, $W_{ap} = 1$ mm, $a = 14.72$ mm.

DR of radius a and height h_2. The DR studied here is with a very high relative permittivity of $\varepsilon_{r2} = 79$. By using a high-permittivity DR, low-profile DR antenna with relatively low resonant frequencies can be achieved [6]. In this study, the DR with a simple shape of circular disk is selected for the analysis. The diameter-to-height ratio of the circular disk DR used here is 5.77 ($h_2 = 5.1$ mm and $a = 14.72$ mm), which is comparable to that used in [3]. And, similar to the case shown in Section II, $L_{ap1} > L_{ap2}$ is for right-hand CP operation and $L_{ap1} < L_{ap2}$ is for left-hand CP operation.

Again, by carefully adjusting the arm lengths of the cross slot, CP operation of the proposed antenna shown in Fig. 7 can be obtained. A typical design with right-hand CP operation has been implemented. The measured return loss and input impedance on a Smith chart are, respectively, shown in Figs. 8 and 9. A wide 2 : 1 VSWR bandwidth of 207 MHz (or about 10.1% with center frequency at 2044 MHz) is obtained. In this design, the two arm-lengths of the cross slot are $L_{ap1} = 13$ mm and $L_{ap2} = 12$ mm. The required arm-

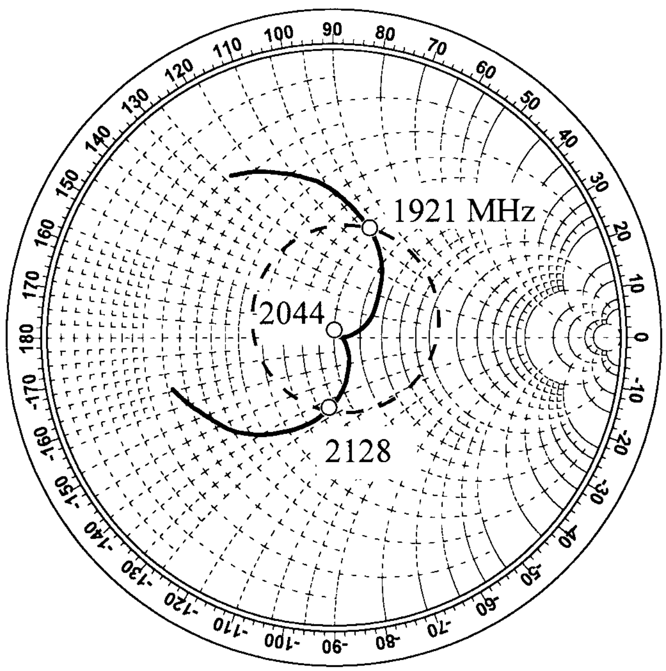

Fig. 9. Measured input impedance on a Smith chart for the antenna shown in Fig. 8.

length ratio $(L_{ap1}/L_{ap2} = 1.083)$ of the cross slot is smaller than that of the microstrip-antenna case in Section II, which indicates that the DR antenna is more sensitive to the variation in the arm-length of the coupling cross slot. This cross slot of unequal slot lengths makes the fundamental $\mathrm{HEM}_{11\delta}$ mode of the circular disk DR split into two near-degenerate orthogonal modes for CP operation, while the resonant frequency of the $\mathrm{HEM}_{11\delta}$ mode can be roughly estimated from [10]

$$f = \frac{c}{2\pi a\sqrt{\varepsilon_{r2}}}\sqrt{(1.841)^2 + (\pi a/2h_2)^2} \tag{1}$$

where c is the speed of light in air.

Fig. 10 shows the measured axial ratio of the CP radiation. A large 3-dB CP bandwidth of about 80 MHz or 3.91% is obtained. This large CP bandwidth makes the present design with relaxed manufacturing tolerances. Measured radiation patterns are also plotted in Figs. 11 and 12 shows the antenna gain in the broadside direction against operating frequency. Good right-hand CP radiation is obtained, and at resonance, the antenna gain of 6.4 dBi is observed. The front-to-back ratio is measured to be 14.7 dB, which suggests that the DR element radiates more effectively than the cross-slot element. The antenna-gain variation in the 3-dB CP bandwidth is also seen to be small, within 1.0 dB. Finally, it can also be expected that the present proposed CP design is applicable for the DR with simple square cross sections. This advantage makes the present design much easier to be implemented, as compared to the conventional designs that requires the use of DR with special configurations [2], [3], [5]. Also, the present design allows post-adjustments, by fine-tuning the coupling cross-slot size, to compensate possible manufacturing errors to meet precise frequency specifications.

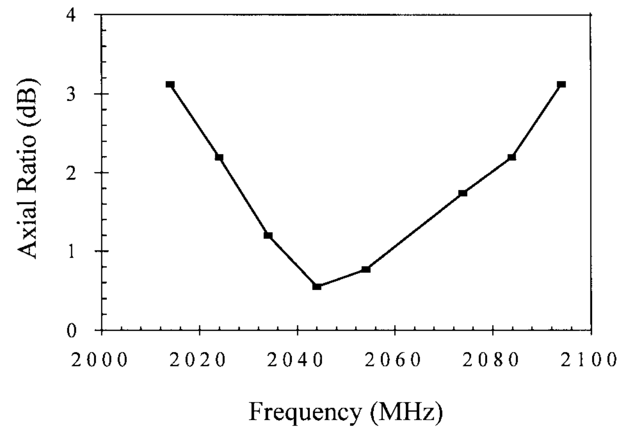

Fig. 10. Measured axial ratio in the broadside direction against frequency for the antenna shown in Fig. 8.

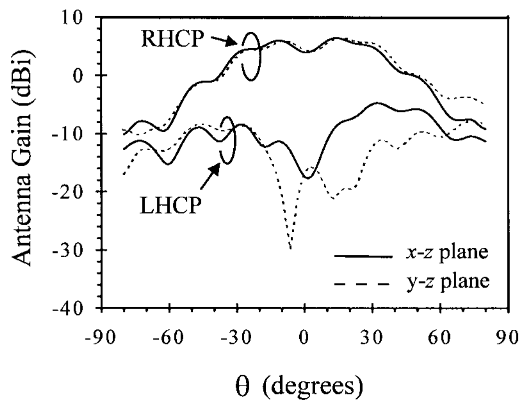

Fig. 11. Measured radiation patterns in two orthogonal planes at 2044 MHz; antenna parameters are given in Fig. 8.

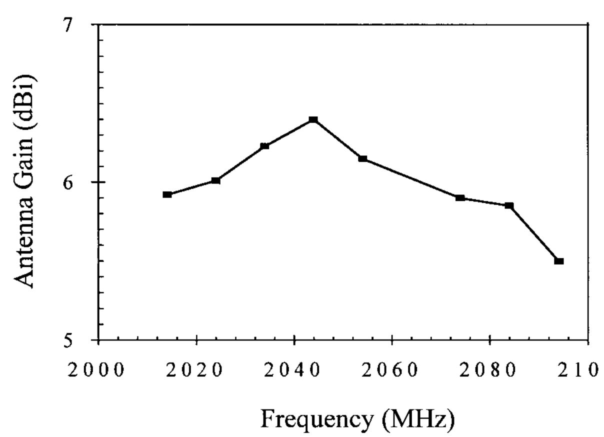

Fig. 12. Measured antenna gain in the broadside direction against frequency; antenna parameters are given in Fig. 8.

IV. Conclusions

By carefully choosing a coupling cross slot of unequal slot lengths, CP operation of the slot-coupled microstrip antennas and DR antennas has been successfully implemented. This CP design method is applicable to the microstrip antennas with square or circular patches and the DR antennas with the DR's of simple circular or square cross sections. From the results obtained, it is also found that the present proposed

CP design has relatively relaxed manufacturing tolerances, as compared to the conventional CP designs that require slight geometrical modifications of the microstrip patch or DR elements. The obtained CP operation also shows good performance, especially for the case with the low-profile circular disk DR antenna in which a large CP bandwidth of 3.91% is obtained.

REFERENCES

[1] M. I. Aksun, S. L. Chuang, and Y. T. Lo, "On slot-coupled microstrip antennas and their applications to CP operation—Theory and experiment," *IEEE Trans. Antennas Propagat.*, vol. 38, pp. 1224–1230, Aug. 1990.

[2] M. B. Oliver, Y. M. M. Antar, R. K. Mongia, and A. Ittipiboon, "Circularly polarized rectangular dielectric resonator antenna," *Electron. Lett.*, vol. 31, pp. 418–419, Mar. 16, 1995.

[3] K. P. Esselle, "Circularly polarized higher-order rectangular dielectric-resonator antenna," *Electron. Lett.*, vol. 32, pp. 150–151, Feb. 1, 1996.

[4] T. Vlasits, E. Korolkiewicz, A. Sambell, and B. Robinson, "Performance of a cross-aperture coupled single feed circularly polarized patch antenna," *Electron. Lett.*, vol. 32, pp. 612–613, Mar. 28, 1996.

[5] A. Ittipiboon, D. Roscoe, R. K. Mongia, and M. Cuhaci, "A circularly polarized dielectric guide antenna with a single slot feed," *ANTEM'94 Dig.*, pp. 427–430.

[6] K. W. Leung, K. M. Luk, E. K. N. Yung, and S. Lai, "Characteristics of a low-profile circular disk DR antenna with very high permittivity," *Electron. Lett.*, vol. 31, pp. 417–418, Mar. 16, 1995.

[7] C. Y. Huang and K. L. Wong, "Analysis of a slot-coupled cylindrical-rectangular microstrip antenna," *Microwave Opt. Technol. Lett.*, vol. 8, pp. 251–253, Apr. 5, 1995.

[8] P. L. Sullivan and D. H. Schaubert, "Analysis of an aperture coupled microstrip antenna," *IEEE Trans. Antennas Propagat.*, vol. 34, pp. 977–984, Aug. 1986.

[9] C. Sharma and K. C. Gupta, "Analysis and optimized design of single feed circularly polarized microstrip antennas," *IEEE Trans. Antennas Propagat.*, vol. 31, pp. 949–955, Nov. 1983.

[10] S. A. Long, M. W. McAllister, and L. C. Shen, "The resonant cylindrical dielectric cavity antenna," *IEEE Trans. Antennas Propagat.*, vol. 31, pp. 406–412, May 1983.

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