Offset Cross-Slot-Coupled Dielectric Resonator Antenna for Circular Polarization

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Abstract—A cross-slot-coupled cylindrical dielectric resonator antenna (DRA) is studied theoretically and experimentally. In previous papers, a cross-slot of unequal slot lengths was centered under the dielectric resonator (DR), resulting in circular polarized operation of the antenna. In the present study, the design is enhanced by setting the centers of the two slots at different positions and taking into consideration the partial independence of the slot modes from the DRA mode. Thus, circular polarization (CP) bandwidth of up to 4.7% is attained experimentally in the broadside direction. It is also shown that a largely asymmetrical structure results in a very high bandwidth, but with the tradeoff of distorted CP operation off-broadside.

Index Terms—Circular polarization (CP), cross-slot, dielectric resonator antenna (DRA), slot coupling.

I. INTRODUCTION

THE dielectric resonator antenna (DRA) was first introduced by Long *et al.* [1] in 1983 and since then it has been extensively studied. The features that make DRAs such an attractive candidate for a number of applications include their high radiation efficiency, compact size, low cost, light weight, and versatility in their shape and feeding mechanism.

The operation of circular polarized DRAs has been the focus of a number of papers in the recent past [2]–[7]. Circular polarization (CP) operation was achieved through complex geometries of the DRA [2], [3] or through the attachment of parasitic patches [4], [5]. In these cases, the complicated shapes of the DRAs, the metallic strips or even the arrays of simple-shaped DRAs increased their manufacturing difficulty and thus their cost and in some cases also their size and weight. In [6], another design was proposed, in which CP operation was accomplished by using two crossed slots of unequal lengths to couple energy from a microstrip line to a simple cylindrical DRA. Both slots were angled at 45° with respect to the feeding microstrip line and their centers were at the same position, centered underneath the dielectric resonator (DR), as depicted in the inset of Fig. 1. Their lengths were unequal, so that two near-degenerate orthogonal modes of equal amplitude and 90° phase difference were excited at frequencies close to that of the fundamental $HEM_{11\delta}$ [8] mode of the DRA. The resulting CP bandwidth was 3.91%.

This letter proposes a new design of a cross-slot coupled DRA, taking into consideration that the slot and the DRA resonances are two partially independent mechanisms [9]. The new design is illustrated in Fig. 1. Each slot is resonant at a particular
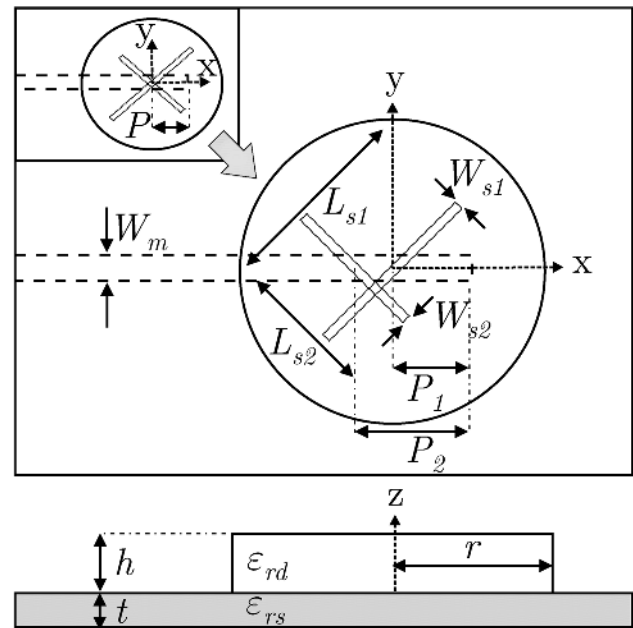
Fig. 1. Schematic of the new cross-slot-coupled DRA. Inset: centered design in [6].

frequency, which depends on its length as well as the permittivity of sub- and superstrate (DRA). The 90° angle crossing of the slots prevents the coupling between the two excited orthogonal modes and therefore, the investigation for each slot resonance may even be conducted separately. CP operation for the DRA is obtained when the two modes have equal amplitudes and ±90° phase difference (for right-handed or left-handed circular polarization). The amplitude of the orthogonal modes is affected by the matching of each slot and consequently also by the stub length (distance between the center of the slot and the open-end of the microstrip line as depicted by P_1, P_2 in Fig. 1). Therefore, excitation by two crossed slots may provide CP operation over a significantly expanded bandwidth, provided the following requirements are satisfied. First, the length of one slot must be adequately larger than that of the other in order to excite modes at different frequencies. Second, a different stub length of the feeding microstrip line must be chosen for every slot so that better matching can be ensured and thus near-degenerate modes will be excited.

II. DESIGN CONCEPT AND ANTENNA CONFIGURATION

As discussed before, the slot lengths and the permittivity of the sub- and superstrate (DRA) determine the frequencies of the slot resonances, while the DRA modes depend on the DR dimensions, permittivity, as well as the feeding mechanism. For

instance, the fundamental DRA mode $\text{HEM}_{11\delta}$ can be excited by means of a slot at or near the center of the disk or with a probe close to its periphery.

The procedure used to design the circularly polarized cylindrical DRA is based on the concept of partial independence of the resonances. The design for a specified center frequency f_{cp} of CP operation is made in two main steps.

First, the longer of the two slots is assigned to be resonant at a frequency $f_1 = f_{\text{cp}} - f'$, while the shorter one is at a frequency $f_2 = f_{\text{cp}} + f''$, where $f' \approx f'' \ll f_{\text{cp}}$. To that end, the two slots are designed and optimized separately from one another. Each slot forms an angle of $45°$ with respect to the microstrip line and is sandwiched between the substrate and a superstrate of the same height h and permittivity ε_{rd} as the DRA. Infinite lateral dimensions are assumed, in order to avoid resonances resulting from the finite dimensions of the structure. The structure can then be analyzed efficiently by means of Ansoft Designer to obtain optimum slot and stub lengths for the desired resonant frequencies for each slot separately. The first slot, with optimum length L_{s1} and stub length P_1, is resonant at frequency f_1 and is forming an angle of $45°$ with respect to the microstrip line. Similarly, the second slot of length L_{s2} and stub length P_2 is at an angle of $-45°$ with respect to the microstrip line and is resonant at frequency f_2. The two slots are now put together over the microstrip, while retaining the same angle and stub lengths as before. It turns outs that the overall performance of the structure is almost identical to the superposition of the performance of the two slots, since they are crossed at a $90°$ angle and therefore no coupling of energy occurs between them.

In the second step, the design of the two crossed slots is kept unchanged but the superstrate is replaced by a cylinder of the same height and permittivity as before. Additionally, the lateral substrate dimensions are made finite. The following simulations are now performed with Ansoft HFSS to accommodate the finite lateral dimensions. The radius of the cylinder is initially chosen such that the frequency of the fundamental DRA $\text{HEM}_{11\delta}$ mode is f_{cp}. However, in order to obtain optimum CP operation for the DRA, its radius might need to be altered slightly. Further fine-tuning might still be necessary, in order to enhance the CP bandwidth without deteriorating the return loss $(S11)$ or the radiation patterns. This optimization involves mainly the stub lengths and the position of the disc center relative to the center line of the feeding microstrip.

For a CP operation of the DRA at 5.7 GHz, the aforementioned procedure results in an antenna geometry, as illustrated in Fig. 1. The dielectric disc is made from Rogers TMM 10i laminate, with dielectric permittivity $\varepsilon_{\text{rd}} = 9.8$, height $h = 5.1$ mm and radius $r = 15.2$ mm. The DR lies on top of the crossed slots which are etched in the finite ground plane of a carrier substrate ($\varepsilon_{\text{rs}} = 2.2$ and thickness $t = 0.7874$ mm) with dimensions 120 mm $\times$ 120 mm. The center of the DR is exactly on top of the center of the slot with length L_{s1}. This substrate carries on the opposite side the 50 Ω microstrip line with $W_m = 2.4$ mm. The dimensions of the crossed slots are $L_{s1} = 11.4$ mm, $L_{s2} = 8.9$ mm and $W_{s1} = W_{s2} = 0.3$ mm. Slotlines and microstrip line are angled at $45°$ and the stub lengths are $P_1 = 4.2$ mm and $P_2 = 4.7$ mm to ensure good impedance matching of the slots.
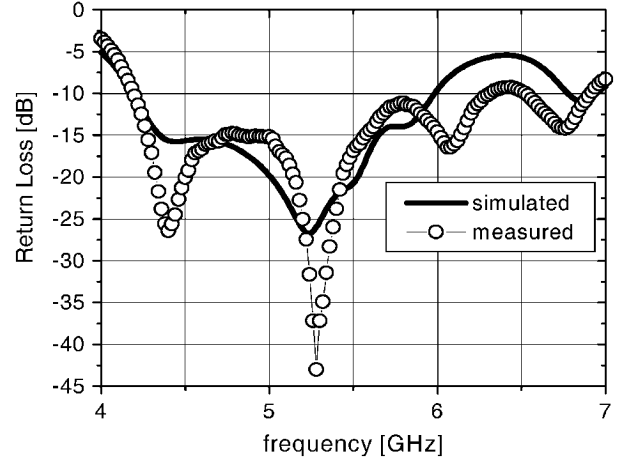

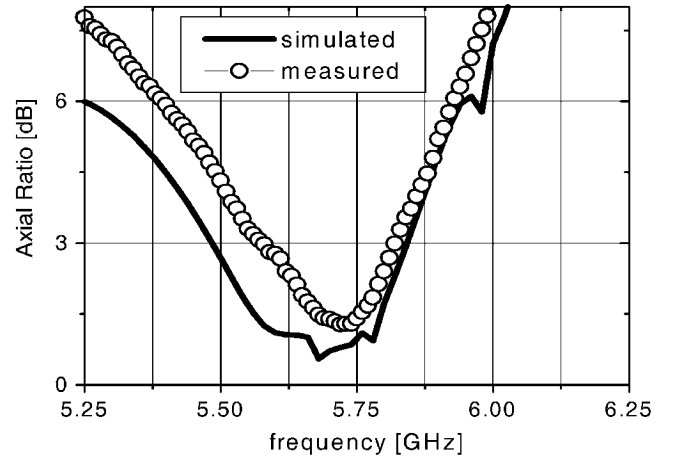Fig. 2.   Measured and simulated return Loss as a function of frequency.

Fig. 3.   Measured and simulated axial ratio in broadside direction as a function of frequency.

III. RESULTS AND DISCUSSION

According to the specifications given above, an antenna prototype was manufactured. In Fig. 2, the measured and simulated return loss of the cross-slot-coupled DRA is illustrated. The wide impedance bandwidth obtained is due to the slot and DRA resonances. More specifically, the two slots are designed to be resonant at about 4.4 GHz and 5.9 GHz while the $\text{HEM}_{11\delta}$ mode of the DRA occurs at 5.25 GHz.

The axial ratio of the CP operation in the broadside direction (z axis) was also measured and compared with the simulation (Fig. 3). The measured and simulated CP bandwidth, as determined from the 3-dB axial ratio, was found to be around 4.7% and 6.3%, respectively. The polarization obtained was left-handed CP since $L_{s1} > L_{s2}$.

The simulated data presented in Fig. 4 illustrates the effect of the asymmetric design on the CP bandwidth of the DRA. In the previously proposed DRA geometry, the ratio L_{s1}/L_{s2} is 1.28. For this ratio, Fig. 4 depicts how the asymmetry of the design (x-axis is the distance P_2–P_1 of the stub lengths) affects the CP bandwidth of the DRA. The effect of the asymmetry on the angle θ_{cp} is also shown, where θ_{cp} is the angle off broadside direction for which CP operation is actually obtained (at the center frequency). It is clear that up to a certain point, by increasing the
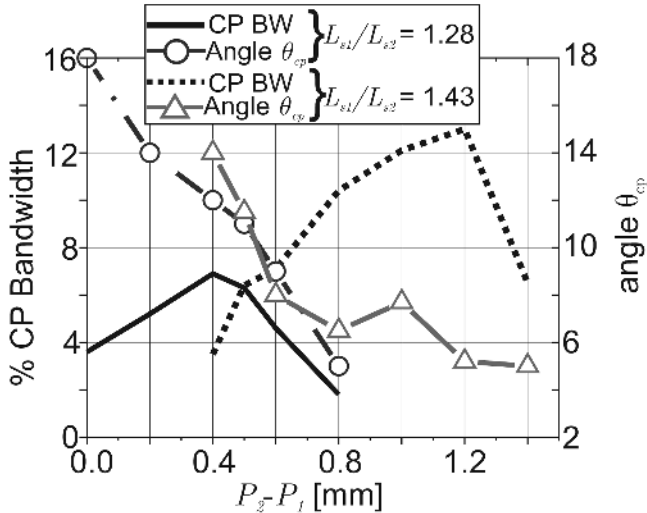
Fig. 4. Simulated CP Bandwidth and angle $\theta_{\rm cp}$ versus the distance of the centers of the two slots, for two different ratios of slot lengths. $P_1 = 4.2$ mm for $L_{s1}/L_{s2} = 1.28$, $P_1 = 3.1$ mm for $L_{s1}/L_{s2} = 1.43$.

Fig. 5. Measured radiation patterns in the x–z and y–z planes.

asymmetry, the CP bandwidth becomes broader. On the other side, however, the increasing asymmetry results in a reduction of angle $\theta_{\rm cp}$ of the CP operation. As an example, for the case of our manufactured prototype, the stub lengths difference P_2–P_1 is 0.5 mm and the resulting simulated CP bandwidth is 6.3% for an angle $\theta_{\rm cp}$ of about 11°.

If the ratio of the long to the short slot length becomes larger, an even larger broadside CP bandwidth can be obtained, provided that the asymmetry is increased correspondingly. This argument can be further substantiated considering a second set of curves in Fig. 4. The dependence of the design asymmetry on the CP bandwidth and the angle $\theta_{\rm cp}$ is also shown for the ratio L_{s1}/L_{s2} being 1.43. It is observed that in this case and for $P_2 = P_1$ an axial ratio below 3 dB cannot be obtained. As the two slot centers are moved apart, CP bandwidth increases and for a value of $P_2 - P_1$ being about 1.2 mm, the bandwidth becomes maximum. It is important to observe here that the maximum value of CP bandwidth for $L_{s1}/L_{s2} = 1.43$ is larger than the one for $L_{s1}/L_{s2} = 1.28$. With respect to the sensitivity on the angle $\theta_{\rm cp}$, it is obvious that in this case, because of the larger design asymmetry, the angle θ_{cp} will also be smaller. To test the above, a DRA was designed and manufactured, for which $L_{s1} = 11.7$ mm, $L_{s2} = 8.2$ mm and $P_1 = 3.1$ mm, $P_2 = 4.3$ mm. A 6.8% broadside CP bandwidth was measured, but the angle $\theta_{\rm cp}$ was reduced to less than 5°.

Finally, the radiation pattern for the first DRA was extracted at 5.75 GHz, at which frequency the antenna is circularly polarized. The measured radiation patterns are depicted in Fig. 5 in the orthogonal planes x–z ($\phi = 90°$) and y–z ($\phi = 90°$), respectively. It is apparent that satisfactory left-handed CP (LHCP) is obtained, with cross polarization down by -15 dB. At 5.75 GHz the gain in the broadside direction was found to be around 3.5 dBi.
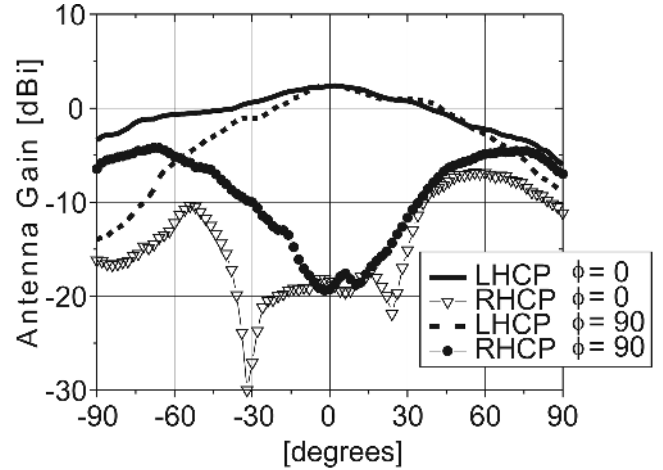
IV. CONCLUSION

A cross-slot-coupled cylindrical dielectric DRA has been described. It was shown that an asymmetric feed structure has a strong influence on the CP bandwidth without affecting the radiation pattern. By optimizing the slot lengths and the distance of each slot to the open-end of the feeding microstrip line separately, a wide CP bandwidth of 4.7% is possible. Measurements and simulations are in good agreement.

ACKNOWLEDGMENT

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