Dice-Five Polarization-Agile Corner-Fed Patch Array Antenna

Andrea Vallecchi

A novel planar polarization-agile microstrip subarray is proposed and its performance assessed by a thorough numerical investigation. The subarray consists of five square patches with a central element, directly coupled to a pair of microstrip feed lines by a cross-shaped aperture, which spreads the power outwards to the other patches through a network of suitable connections. By properly exciting the antenna at its input ports, any kind of polarization of the radiated field can be accomplished with fairly low cross-polarization levels. Moreover, since only two feed lines are required to drive the whole subarray, polarization agility is simply and attractively achieved by a single phase-shift circuit. The design concept is described and the results of the analyses and simulations performed by two completely independent full-wave approaches are presented and discussed.

Keywords: Polarization agility, microstrip antennas, planar arrays, aperture-coupled patch.

I. Introduction

In wireless communication systems, polarization-agile antennas and associated polarization-diversity techniques provide a significant enhancement in the capacity and reliability of the radio channel by mitigating the effects of multipath fading, polarization mismatch, and interference. Moreover, fully polarimetric sensors can greatly increase the information content of microwave reflectometry measurements by allowing the retrieval of the complete scattering matrix of the surfaces under observation.

As far as the compactness and easiness of manufacturing of the radiating structure are issues of primary concern, multi-polarized operation can be achieved by aperture-coupled microstrip patch antennas, whose many desirable features are well surveyed in the literature [1]. However, the direct feeding of individual elements in planar multi-polarization antenna arrays is an involved matter and implies complex feed networks, crowded with phase-switching circuits and suffering from unwanted mutual coupling between the various sections pertinent to different polarizations, and reduced antenna efficiency. To overcome these difficulties it is convenient to arrange the radiating elements into subarrays, so as to streamline the array design, decrease losses, and simplify RF control circuitry. Particularly, planar cells with a central patch could be very advantageous since they can provide pencil beam radiation patterns with low side lobes. Indeed, single-polarized two-dimensional microstrip patch subarrays have been demonstrated in [2] and [3], where two similar designs with probe and slot feed, respectively, are described. Furthermore, an attempt at developing circularly polarized planar antennas has been also reported [4].

In this paper, a novel typology of multi-polarized aperture-

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coupled microstrip subarrays is proposed for use as the basic element of large polarization-agile array antennas with reduced complexity feeding networks and comprising a limited number of phase-shift circuits. The geometry and design approach of the antenna are outlined in section II. Then, the radiation characteristics of the antenna are numerically investigated in section III, where the results obtained by two completely independent simulation tools are presented and compared. Indeed, the proposed antenna element shows quite good performances, in terms of gain and cross-polarization level, so that it could be conveniently employed, even in a stand-alone configuration, in several short-range wireless applications as well as in a polarimetric sensor.

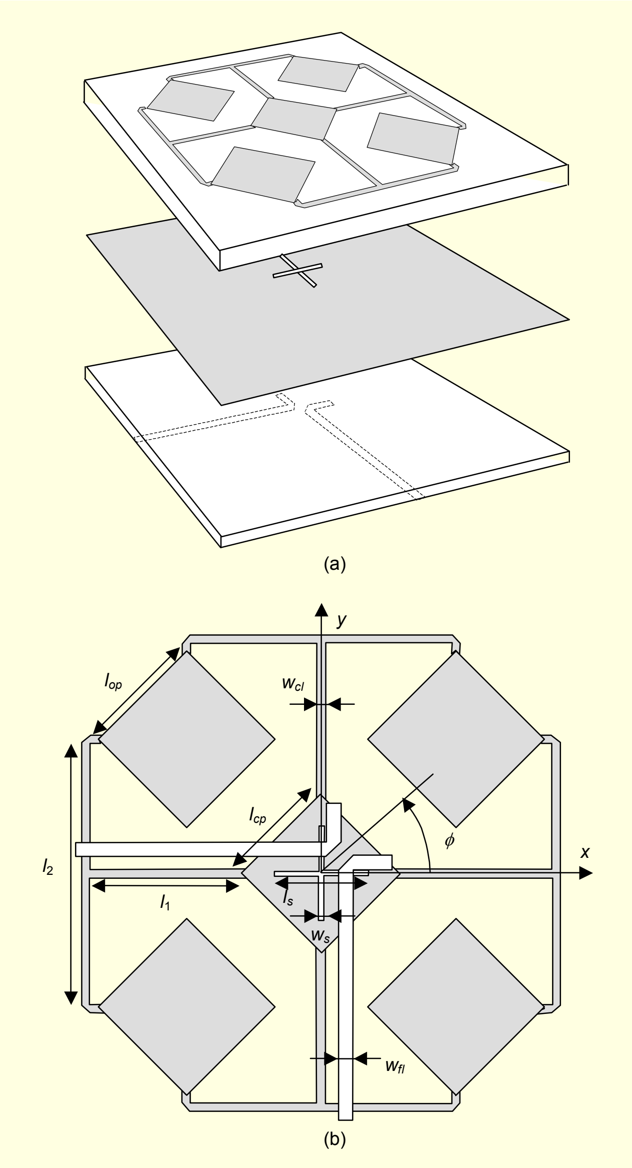

Fig. 1. (a) Multilayered structure and (b) bottom view of the dice-five antenna showing the square patches, the cross-shaped slot and the two feed lines. The central patch side (l_{cp}) is 28.5 mm long, whereas the side length of the outer patches (l_{op}) is 31.75 mm. The other antenna dimensions are as follows: $l_s = 22.8$ mm; $w_s = 1.2$ mm; $l_1 = 38.4$ mm; $l_2 = 66.2$ mm; $w_{fl} = 3.5$ mm; $w_{cl} = 2$ mm.

II. Antenna Topology and Design

The antenna substrate structure consists of two layers of low-loss dielectric material with $\varepsilon_r = 2.2$. The geometry of the antenna is shown in Fig. 1. The radiating part includes five microstrip square patches etched on the upper substrate, whose thickness is 2.286 mm. The central patch is coupled to a pair of 50 ohm microstrip lines, running on the bottom 1.143 mm-thick layer, through two centred crossed slots etched on the middle ground plane and offset-fed. This solution has been demonstrated to yield a more symmetrical excitation and, consequently, improved radiation characteristics of the subarray with respect to a configuration with two off-centre separated orthogonal slots. Microstrip “T” line sections are used to propagate a resonant standing wave to feed the surrounding identical patches. Specifically, these latter elements are connected to the central patch by the pair of their outer corners so that a dual feeding arrangement featuring higher isolation than the standard dual edge feed [5] is obtained.

The functioning of the proposed arrangement can be readily explained. By referring for simplicity to the case of a linear vertical polarization, it is noted that only the upper and lower “T” line sections are travelled through by a significant amount of current. At resonance, this pair of connections is fed with opposite phases. However, this opposite phase of the excitation signal compensates for the opposite position of the patch feed points with respect to the horizontal plane. As a result, equal signals are delivered to the four external patches and a uniform illumination is realized over them.

The excitation amplitude for the outlying patches is controlled by the impedance levels of these elements and the central patch, while the excitation phase is made equal to that of the central patch by tailoring each connecting microstrip line to be one−wavelength long on the whole. The input impedance of the outlying corner-fed patches can be estimated through the closed form expression derived in [6], and the relevant loading effect can then be included in the design and impedance matching of the central patch by using the method of moments (MoM) [7] in conjunction with basic circuit theory [3]. It is pointed out that the central patch turns out to be smaller than the external ones due to the loading of the surrounding elements and aperture coupling, which tend to decrease its resonance frequency. Nonetheless, the resonance input resistance of the outlying patches is similar to that of the unloaded central patch and, as a consequence, equal power is approximately radiated from all the elements. Indeed, since each arm of the "T" connections is about a half-wavelength long at the design centre frequency and a load admittance is transformed to its value by a half-wavelength transmission line section, at resonance the subarray can be roughly modelled as the sum of five equal radiation conductances, which confirms that the power is uniformly distributed over all the patches. To some extent, the distribution of current on the subarray and the corresponding radiation patterns might be controlled by modifying the size of the outlying patches and leaving unchanged that of the central element or vice versa. However, this possibility has not been investigated yet.

From the above circuital interpretation, it also follows that the radiation of the subarray is not much affected by the characteristic impedance of the interconnecting line sections, whose width is thus chosen mainly to balance the conflicting requirements associated with the minimization of radiation and ohmic losses [2]. As a compromise, 100 ohm impedance microstrip connections are adopted, which are sufficiently narrow to also help in reducing the discontinuity effects at the bends and at the corners of the central patch.

The impedance matching of the antenna is quite easily performed by tuning the length of the feed line terminal stubs and the size of the cross-shaped coupling slot.

The above antenna geometry allows one to obtain any kind of linear or circular polarization of the radiated field by appropriately driving the two input ports. Particularly, quadrature excitation of the feed lines results in circularly polarized radiation whose sense is determined by the lead-lag phase relationship between the aperture excitations. Fairly low cross-polarization levels are obtained by virtue of the symmetrical arrangement devised for the antenna, which implements a sort of antiphase feeding technology [8]. In fact, the feed points of symmetrical elements along a vertical or horizontal line are located at opposite corners, and therefore their main-mode radiation fields add up in phase, whereas higher order mode parasitic radiation fields tend to cancel each other. Moreover, the spurious radiation from the currents flowing in the top arm of the "T" connections also cancel each other in the principal planes due to their opposite phases, which further reduces the cross-polarization level.

The proposed subarray concept can be easily generalized to larger antenna configurations. Indeed, planar polarization-agile arrays can be constructed by simply duplicating the dice-five subarray over the aperture and then properly combining the feed lines that drive the various elements by a corporate feed network.

III. Results

The antenna has been developed to work around a test centre frequency of 3 GHz. The design was performed by Ensemble [7], which is based on the mixed potential integral equation formulation in conjunction with the MoM. This full-wave approach is capable of completely accounting for the dielectric layers and the ground plane, with the limitation that they are assumed to be of infinite extent. Moreover, mutual coupling between the patches as well as ohmic and dielectric losses are included in the simulation [9].

The antenna performances as predicted by Ensemble have subsequently undergone validation in a comparative analysis with CST Microwave Studio [10]. This latter program implements the finite integration technique (FIT), a discretization scheme for Maxwell's equations in their integral form, which can be thought of as a generalization of the finite difference time domain (FDTD) method. The effects of finite ground plane and dielectric substrates on the radiation characteristics of the proposed antenna structure are also completely accounted for in the analysis with CST through a fully three-dimensional electromagnetic modelling. Particularly, the size of the ground plane and dielectric layers were chosen to be 160×160 mm. To achieve high accuracy and reliability in the simulations, discretization has been carried out with a resolution of $\lambda/35$ (λ denotes the wavelength at the upper frequency of the analysis range).

The return loss and isolation at the inputs of the antenna element as calculated by Ensemble and CST are plotted in Fig. 2. The impedance response as computed by CST is smoother than that predicted by Ensemble and is shifted towards the lower frequencies, which is not very unexpected since Ensemble was seen to slightly over-estimate the resonance frequency of microstrip antennas [11].

Nonetheless, the spread in the estimated resonant frequencies of the two codes is very small, about 1.3%, and the impedance

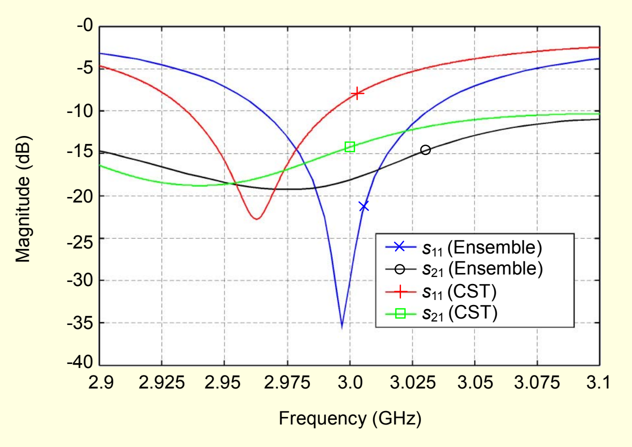

Fig. 2. Return loss and isolation at the input ports of the antenna as calculated by Ensemble and CST around the design centre frequency.

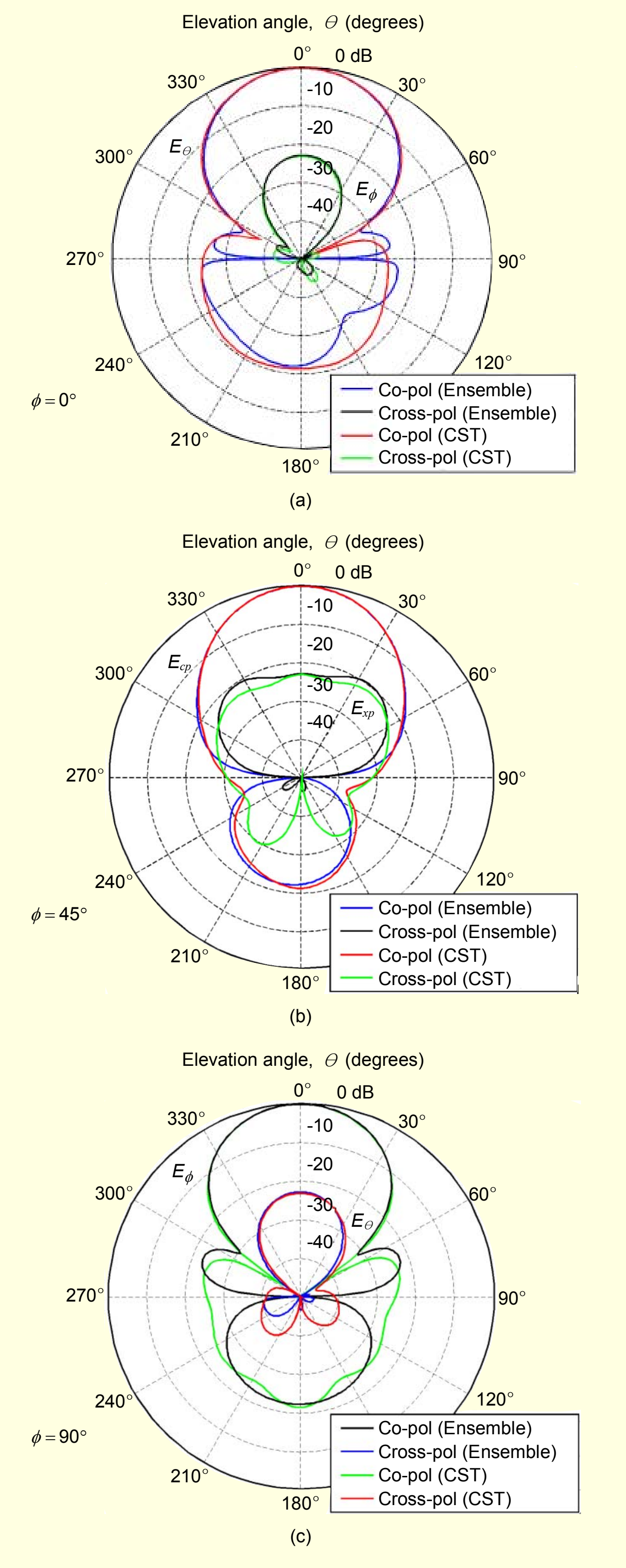

Fig. 3. Co-polar and cross-polar patterns of the dice-five patch array antenna as computed by Ensemble and CST at the relevant resonance frequencies for the horizontal polarization state in the elevation planes: (a) $\phi=0^\circ$; (b) $\phi=45^\circ$; (c) $\phi=90^\circ$.

bandwidth, although shifted, is the same (2.2 % for $\text{VSWR} \le 2$). Note that the isolation is a little poor due to the close proximity of the two feed lines, the discontinuity associated with the bends, and the unbalanced feed of the slots. However, the cross-polarization performance benefits from the antenna symmetrical arrangement, and the peripheric patches antiphase feeding scheme and low cross-polar components are observed. Indeed, it appears from Fig. 3, where the copolar and cross-polar radiation patterns calculated for the horizontal polarization at the resonance frequency are plotted, that the maximum cross-polarization level is less than −22 dB in the principal planes ($\phi=0^\circ$ and $\phi=90^\circ$ planes). In the diagonal plane ($\phi=45^\circ$), where the cross-polarization can be expected to be more significant, it is low at broadside and reaches its maximum at around $\theta=\pm40^\circ$, but it always remains 20 dB below the main beam. This result slightly worsens at the upper bound of the impedance bandwidth while it improves at the decreasing of the frequency, in accordance with the trend of S_{21}. At any rate, cross-polar components never surpass −18 dB.

The gain and directivity of the antenna, calculated in the direction of maximum radiation at the varying of the frequency, are shown in Fig. 4. The gain ranges between 12.5 and 12.8 dB in the operating bandwidth. This represents a high radiation efficiency, which in fact is estimated to be more than 90% by both CST and Ensemble. The front-to-back ratio is always better than 20 dB.

As can be noticed in Fig. 3, the radiation patterns computed by the two simulators almost perfectly match, provided that the shift of the predicted resonance frequencies is accounted for by consistently performing the comparison at slightly different frequencies. Furthermore, this circumstance is observed over the whole working bandwidth of the antenna. As a result, the antenna performances as numerically derived can be considered to be cross-validated by this comparative analysis.

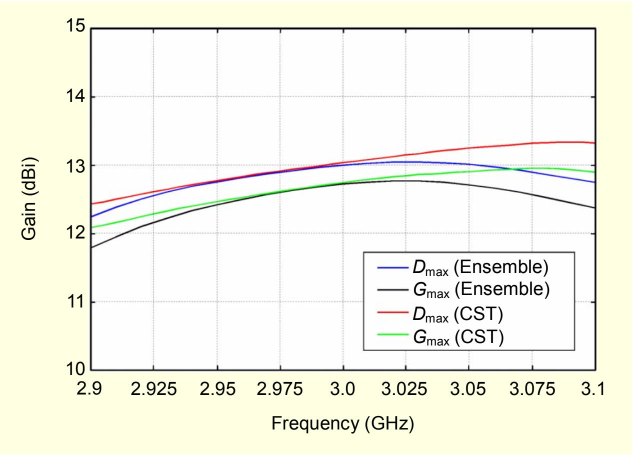

Fig. 4. Boresight directivity and gain calculated by Ensemble and CST as a function of frequency.

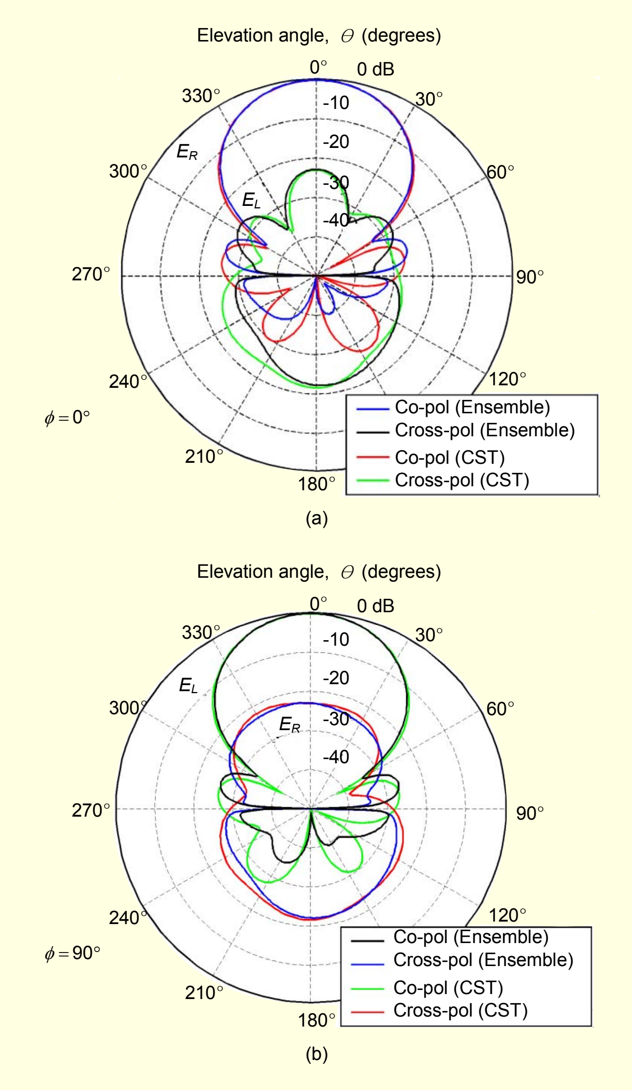

Fig. 5. Co-polar and cross-polar patterns for quadrature excitation of the dice-five subarray as computed by Ensemble and CST at the relevant resonance frequencies in the $\phi=0^\circ$ elevation plane: (a) right-hand circular polarization and (b) left-hand circular polarization.

Due to the symmetry of the antenna, exactly the same results are obtained for the patterns relative to the vertical polarization state, apart from being exchanged with respect to the observation angle of 90°. In spite of the fact that the ground plane was moderately larger than the microstrip patch subarray (about a factor of 1.35), it is also seen that the boundary does not produce any noticeable disturbing influence on the radiation of the antenna, apart from a slight increment of the field in the backward and lateral directions. Thus, on condition that the ground plane is not very narrow, its finite size can conveniently be disregarded in the design.

As far as the case of circular polarization is considered, almost the same performances in terms of gain and cross-polarization level are found. It can be deduced from Fig. 5, where the right-hand and left-hand circular field components calculated at the respective resonance frequencies by the two codes are plotted, that the axial ratio slowly deteriorates away from the boresight and is indeed maintained below 3 dB over a wide angular range. This is better illustrated in Fig. 6, which reports the axial ratio against the angle of observation in the principal and $\phi=45^\circ$ diagonal planes. These graphs highlight that the radiated field exhibits good circular polarization characteristics up to $\pm 35^\circ$ from the boresight. The axial ratio behaves similarly in the $\phi=45^\circ$ and $\phi=135^\circ$ diagonal planes, and thus its plot in the $\phi=135^\circ$ plane is not shown.

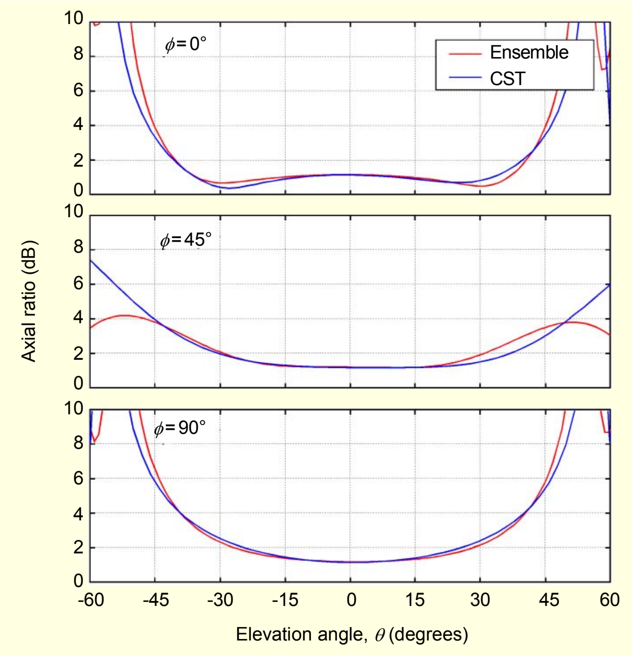

Fig. 6. Axial ratio as calculated by Ensemble and CST at the relevant resonance frequencies in the $\phi=0^\circ$, $\phi=45^\circ$, and $\phi=45^\circ$ elevation planes.

The dependence on frequency of the axial ratio in the broadside direction is displayed in Fig. 7. Again, it is found that the results obtained by Ensemble and CST are in very good agreement, apart from being a little displaced in frequency. It appears that an axial ratio of less than 3 dB is obtained over a 6.6 % bandwidth, which is about three times the bandwidth for a 10 dB return loss. Thereby, the most limiting factor for this kind of subarray turns out to be the impedance bandwidth. This latter performance can be easily enhanced with a thicker substrate for the patches or by replacing the microwave substrate with a foam layer. However, the size of the antenna will be increased this way, with the potential disadvantage of diminishing the allowable scan range when operated into an array configuration; in addition, some cautions have to be taken not to undermine the cross-polarization performance of the

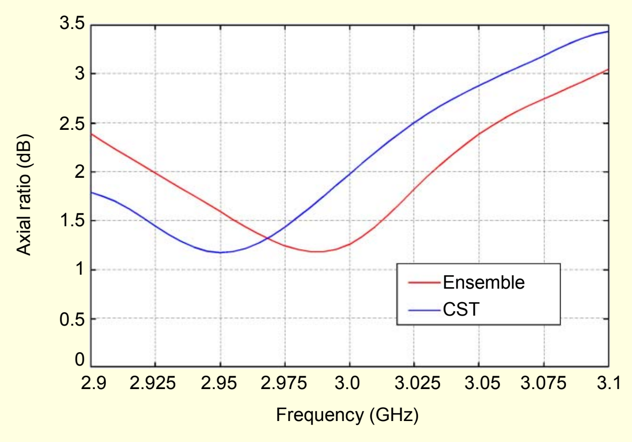

Fig. 7. Axial ratio calculated in the broadside direction as a function of frequency.

antenna. In this connection, it is observed that cross-polarized radiation could possibly be reduced by feeding the slots in a fully balanced configuration, which would imply as a drawback the adoption of a more complicated multi-layered structure for the feed, such as those proposed in [12] and [13] for a single patch. As an alternative, the inductive mutual impedance of the crossed slots could be compensated with capacitive coupling between the terminal stubs of the microstrip feeding lines so as to increase the port isolation and accordingly improve cross-polarization [14].

IV. Conclusions

A new compact and low-cost array antenna exploiting a dice-five symmetric arrangement with a central aperture-coupled patch and four surrounding dual corner-fed patches has been presented. The antenna was proven to be capable of producing dual-linear and circular polarization exhibiting good gain and a low enough cross-polarization level, which make it suitable for being used both in a stand-alone configuration and as the basic component of large planar polarization-agile arrays. In this latter case, a considerable simplification of the feed network could be achieved accompanied by a drastic reduction in the number of required phase-shift circuits and, consequently, in antenna cost. The impedance bandwidth has been found to represent the factor mainly hampering the proposed antenna from fully complying with wireless local area network system requirements; possible means to overcome this limitation are presently being investigated. The demonstration of the use of this subarray in larger array antennas is also underway.

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