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Omnidirectional circularly polarized antennas – a small antenna perspective

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***Abstract*—The paper discusses recent developments and challenges in the design of small omnidirectional circularly-polarized (CP) antennas. Although omnidirectional CP coverage is easily achievable using antenna arrays, it is just recently that small and low-cost antennas delivered this functionality.**

The paper addresses practical design problems for these antennas, not reported in previous publications. This includes selection of the omnidirectional plane relative to the ground plane and measurement challenges. Future perspectives on how these antennas can provide electronically steerable beams are investigated using simulated results.

***Index Terms*—Circular-polarization, small antennas, 0mnidirectional radiation pattern, adaptive antennas.**

I. INTRODUCTION

The linearly polarized dipole is the oldest and most simple antenna, dating back to the experiments conducted by Heinrich Hertz in 1886. It provides an omnidirectional torus-shaped radiation pattern, with two antipodal nulls.

Surprisingly, comparable designs for circularly-polarized (CP) antennas were missing for a long time. Of course dipole antennas (and similarly loops) were used to generate CP [1], most notably forming the crossed-dipole antenna [2], however the outcome was a pattern, generating right-hand circular-polarization (RHCP) to the front and left-hand circular-polarization (LHCP) to the rear. Another possible approach uses an array of multiple CP antennas [3]. This solution – although able to synthesize almost any desired radiation pattern – is electrically large, with little prospect for successful miniaturization.

Currently, there are two effective approaches to realize dipole-like CP radiation patterns using small antennas, as described in the following section.

II. TWO ANTENNA TYPES

The first one relies on combining two classical antenna shapes: a monopole (or less often a dipole) and a loop, which will be further referred to as monopole-loop antennas. Both antennas exhibit similar radiation patterns but with orthogonal linear polarizations, making them perfect candidates for omnidirectional CP antennas if a 90° phase shift between them can be realized. This is usually done by placing a monopole in the middle and surrounding it with a loop at roughly one quarter-wavelength distance [4]. This basic concept can be transformed into a planar structure, either by embedding the antenna into a dielectric resonator [5] or introducing carefully designed slots and vias [6-7]. The technique is successfully demonstrated to provide triple-band performance [8]. An example antenna of this kind can be seen in Fig 1, as reported in [8].

Fig. 1. Triple-band omnidirectional CP antenna (top view), as reported in [8] (under CC BY 3.0 licence).

Another approach was introduced by Iwasaki in [9] and many years later extended by the authors [10]. It relies on two circularly-polarized patch antennas arranged in a back-to-back configuration (referred in this paper as dual-patch approach). An example of this antenna is shown in Fig. 2. Each patch radiates the same-sense CP. To ensure CP for all directions, the width of the ground plane is reduced, so that the electric field can couple around it.

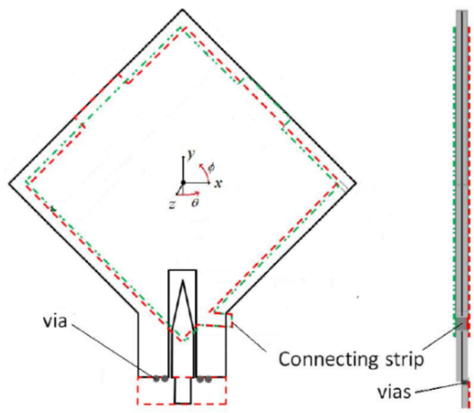

Fig. 2. A back-to-back coupled omnidirectional CP antenna [10]. Red line depicts metalization of the bottom layer patch, green – top layer.

Both approaches have advantages and disadvantages. Most notably, the monopole-loop combination realizes the omnidirectional plane in the same plane as the substrate, whereas the dual-patch approach produces the omnidirectional plane in the plane normal to the substrate (its exact orientation is discussed in Section IV). To ensure the low-profile of the monopole, the monopole-loop antennas often use slots and vias. As this adds some extra capacitance and inductance to the antenna, most reported monopole-loops are electrically smaller than the dual-patch antennas. There is however nothing preventing a similar technique to be incorporated into patch antennas and therefore into a dual-patch antenna, decreasing its electric size. The only limitation here for both types seems to be a tradeoff between size and bandwidth, which is applicable for all electrically small antennas, regardless of the methodology or materials used [11].

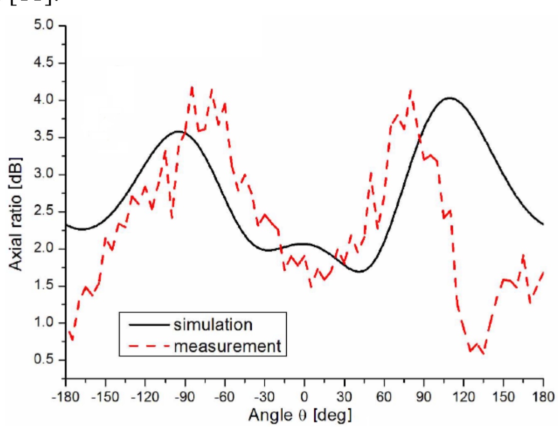

Fig. 3. Axial-ratio of the dual-patch antenna in the *xz*-plane [9].

The main disadvantage of the dual-patch antenna is a increased axial-ratio (AR) for the directions $\pm x$ (i.e. directions located in the plane of the substrate). This can be seen in Fig. 3, where for $\theta = \pm 90°$ the AR slightly exceeds the commonly accepted 3 dB limits. By comparison the monopole-loop exhibit very low AR, as low as 1 dB within the full omnidirectional plane.

On the other hand with dual-patch antennas one can easily change the plane in which the omnidirectional pattern is realised. This property is discussed in Section IV and is employed to prototype a beam-reconfigurable antenna in [12]. On the contrary, for a monopole-loop, the design dictates that the omnidirectional plane must be in the same plane as the substrate.

Due to our expertise and limited space, for the remainder of the paper we will focus more on the dual-patch antenna type. However a complementary contribution discussing details of the monopole-loop antennas would be greatly welcomed to provide the comprehensive and full picture.

III. Ground Plane Effect

It is commonly accepted, that classical CP antennas cannot radiate energy along the ground plane. This is due to the attenuation of the tangential component of the electric field as it travels along a conducting surface. For the small omnidirectional CP antennas (both dual-patch and monopole-loop types) this problem is solved simply by reducing the size of the ground plane. Many monopole-loop antennas place the elements radiating horizontal polarization on the outer perimeter of the structure to avoid this problem. This however still necessitates the reduced ground plane size, as the distance between radiating elements is critical for CP generation.

Reduced ground plane size solves one problem only by creating another one. As the antenna ground plane is substantially reduced, its size becomes comparable to the size of the radiator. This in turn introduces problems with the current flowing on the outside of the feed cable. The issue is reported to cause problems with measurements of other electrically small antennas, most notably reducing the efficiency of UWB monopoles at lower frequencies [13]. For CP antennas the problem is even greater, as – in addition to the decreased efficiency - the current flowing on the outside of the cable generates an electric field with a polarization tangential to the cable (i.e. polarization along *y*-axis for antenna described in Fig. 2). This interferes with the AR measurement. To combat this problem, ferrite can be placed around the feed cable, just below the SMA interface.

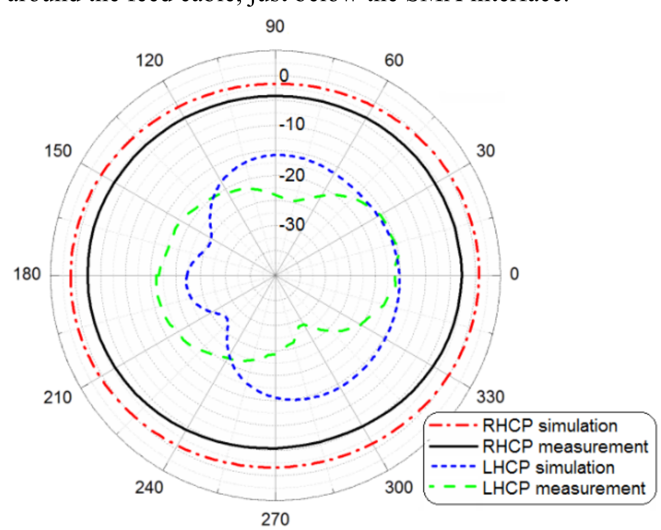

Fig. 4. Measured realized gains of a dual-patch omnidirectional antenna [14]. A discrepancy between simulation and measurement can be seen due to small ground plane effect (i.e. simulation does not include cable).

This improved the measurement, however the antenna in [14] reports measured RHCP realized gain at lower band being 2 dB below the expected simulated results, as seen in Fig. 4. This necessitates the development of a better solution.

IV. Omnidirectional Plane

An interesting and useful feature unique to dual-patch antennas is its ability to control the omnidirectional plane. This is due to the interaction between the resonances in both patches. This is explained in Fig. 5, which shows the electric fields excited in the plane of the patch (blue arrows) and around it (green arrows). Two feed configurations are investigated: where both back-to-back oriented patches are fed in-phase (i.e. electric fields at time $t = 0$ are aligned in both patches) and where they are fed out-of-phase (i.e. electric fields at time $t = 0$ are opposing each other). As the electric field in each CP patch rotates counter-clockwise, this alignment is true only for $t = 0$, which is shown in the left column (*a* and *c*). The right column show the fields for the orthogonal mode, i.e. for $t = 0.25 / f$, where f is the frequency of the investigated signal. It is assumed, that the input feeds are located along the *zy* wall of the antenna's substrate.

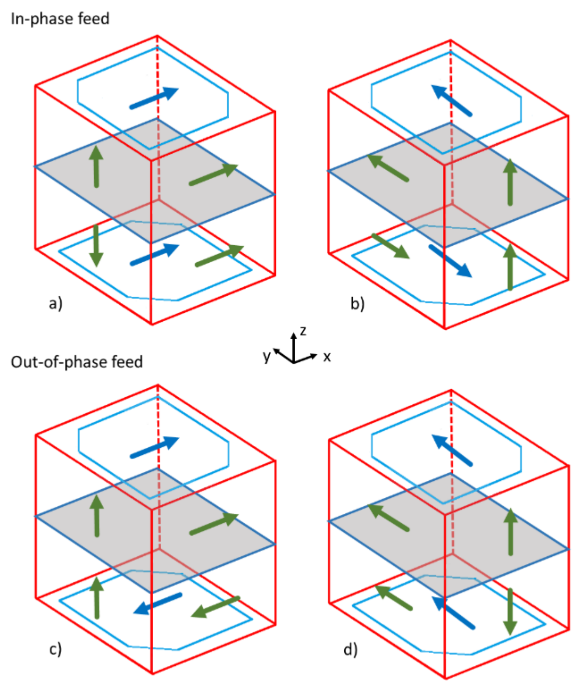

Fig. 5. Electric field for the two orthogonal modes, when the antenna is fed in-phase (*a* and *b*) and out of phase (*c* and *d*).

In Fig. 5a at $t = 0$ the fields produced in the two patches are aligned and oriented along the *x*-axis. This causes the fields generated along the *xz* wall to be aligned in this direction, interfering constructively with each other. However the fields generated along the *yz* wall are opposing, causing destructive interference and producing a null in that direction. In Fig. 5b at $t = 0.25 / f$ the electric field along each patch is rotated by 90°. However due to patch construction (required for same-sense CP), both fields rotate counterclockwise, i.e. in opposite directions as seen from a point located above the patch. Although now the blue vectors are aligned in opposite directions, the fields along the *xz* wall (green arrows) are still aligned, interfering constructively and producing good radiation in this direction. The electric fields along the *yz* wall are still opposing, producing a null. This performance can be observed in [9], where the CPW feed is located parallel to the edge of the patch and the omnidirectional plane is realized in the horizontal plane (i.e. orthogonal to the CPW alignment). However in [10] the CPW feed is placed along a diagonal of the patch and the omnidirectional plane is located along the other diagonal of the patch (i.e. again orthogonal to the CPW alignment).

On the other hand, the differential feed – as presented in Figs. 5c and 5d –reverses that situation. Although for $t = 0$ the fields in the patch are oriented in opposite directions, along the *yz* wall they produce electric fields which are aligned, yielding constructive interference and good radiation. Due to the same mechanism, destructive interference is produced along the *xz* wall, yielding a null in that direction. This can be observed in the differentially-fed antenna in [15].

The phenomena is described here only for two extreme cases, however the basic principles apply for any phase shift between the two patches. This was used in [11] to produce a pattern reconfigurable antenna. It is demonstrated there, that the omnidirectional plane can be tilted by angle:

$$\gamma = \frac{1}{2}\Delta_{PH} \tag{1}$$

where Δ_{PH} is a phase shift between the two patches. This performance allows a single antenna to cover signals from any point on a full sphere.

V. Huygens Sources

The steering introduced in (1) allows only a single degree of freedom, i.e. rotation along a single axis. This functionality can be of course extended by employing an antenna array. An array of two such antennas is discussed within the Huygens Source configuration [16].

Traditional Huygens Sources consist of two omnidirectional antennas (usually a loop and a dipole or a monopole), rotated so that their omnidirectional planes are orthogonal and intersect at two antipodal points [17]. If the phase and polarization properties are aligned accordingly, they interfere constructively at one point and negatively at the other. This produces a unidirectional radiation pattern with theoretically up to 4.8 dBi gain [18].

Of course unidirectional CP antennas have been known for decades and there is little need to combine two omnidirectional CP antennas for this function. However the reconfigurable antenna proposed in [12] with its property of rotating the omnidirectional plane can be used for a Huygens Source with flexibly reconfigurable steering.

Fig. 6 shows two antennas, oriented in a Huygens Source configuration [16]. Traditionally such sources are realized using electrically small antennas, allowing placement at a distance much less than a wavelength. These distances provide optimum performance of a Huygens Source. Currently, the investigated antennas are too big and need to be placed at a half wavelength distance from each other (i.e.

61 mm, as seen in Fig. 6); such antenna will be called a quasi-Huygens Source. It brings a considerable decrease in performance, most notably increasing sidelobes and decreasing directivity. It is however expected, that future designs will be more compact and therefore solve these issues.

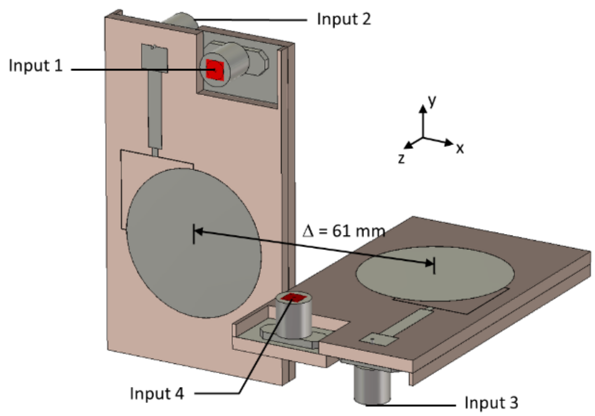

Fig. 6. Two reconfigurable omnidirectional CP antennas forming reconfigurable quasi-Huygens Source.

Fig. 7 shows the simulated radiation patterns in the *xz*-plane for four beam directions, generated by applying various phase shifts between ports. The phases for the discussed configurations are as follows:

-z beam : [0°, 0°, 0°, 180°]

+z beam : [0°, 0°, 180°, 0°]

-x beam : [0°, 0°, 270°, 270°]

+x beam : [0°, 0°, 90°, 90°]

where the values correspond to phases at port 1, 2, 3 and 4 respectively (numbering convention as seen in Fig. 6).

It can be seen, that although the main beam is directed towards the desired direction with a high front-to-back ratio, the sidelobes are reasonably large. This is due to the spacing between antennas along the *x* axis and is expected to improve with implementation of smaller antennas, such as [19].

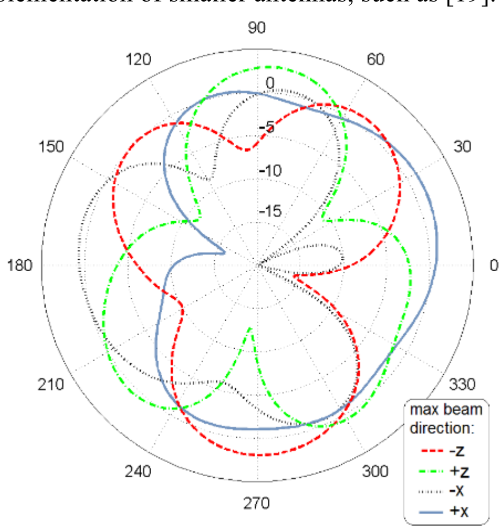

Fig. 7. Simulated RHCP realized gains for the quasi-Huygens Source antenna array. Results shown for the *xz*-plane at 2.46 GHz.

VI. Conclusions

The paper overviewed current state of the art and challenges for planar omnidirectional CP antenna design. The antennas considered are low-cost and easy to manufacture, while offering coverage previously available only with much larger CP arrays.

Currently, two main challenges are related to the improved measurement techniques and miniaturization. In the first case, a possible solution is to measure the antenna pattern with excitation from an integrated source. This would remove the radiation contribution of the current carrying cable and provide a more realistic measurement.

The miniaturization of the antenna can be realized in many ways, as the basic radiating structure is a microstrip patch. It is expected, that most of the miniaturization techniques used for CP patches, such as folding [19] or meshing [20] can be adopted for the omnidirectional back-to-back patches.

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