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Cross-Polarization Reduction of Linear-to-Circular Polarizing Reflective Surfaces

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Abstract—This letter proposes an efficient design process to reduce the cross-polarization of linear-to-circular reflection polarizers illuminated by practical feeds. In particular, we propose a two-step process, where firstly a geometrical optimization of the unit-cell is applied along one plane of the reflector, followed by a progressive rotation of the unit-cell in the orthogonal plane. An offset flat polarizer comprised of dipole unit-cells fed by a standard gain horn has been used to illustrate the process. Significant improvements in cross-polarization discrimination are demonstrated by simulation. Two breadboards have been manufactured and their response is compared in order to demonstrate the validity of the design process. Good agreement with measurements is observed corroborating the proposed technique.

Index Terms—linear-to-circular polarizers, frequency selective surfaces, reflector antennas, reflectarrays

I. INTRODUCTION

Periodic and quasi-periodic arrays of metallic elements printed on grounded dielectric substrates have attracted over the past years significant attention as linear-to-circular polarization converters [1]–[5]. In mm-wave imaging, they offer opportunities to simplify the system optics since they can combine the reflector and the polarization converter in a single component [2]. They can also enable reflectarrays to radiate in circular polarization (CP) with a simple linearly polarized feed [6]–[8]. More recently, this class of surfaces has been considered for multiple beam satellite communications, where they can be exploited to provide CP while keeping the antenna optics in linear polarization (LP) [4], [5], [9].

While these designs present attractive solutions for the aforementioned applications, their performance is often presented for plane wave incidence such that all unit-cells are illuminated at a fixed angle [1]–[5], [9]. In several practical applications the feed is placed at a finite distance from the polarizing surface, thereby producing a large range of angles of incidence across the surface. This in turn can negatively impact the polarization purity of the reflected far-field [10]. Some approaches to address this degradation rely on optimizing each element geometry for the angle of incidence experienced at a given location in the array. This method is computationally costly, particularly for large arrays comprising a large number of unit-cells. Moreover, the optimization of the polarization purity of the reflected field locally does not necessarily guarantee the optimum polarization purity of the far-field reflected by the entire array.

Motivated by the aforementioned challenges, this work proposes an efficient design process to improve the far-field cross-polarization level of linear-to-circular reflection polarizers illuminated by practical feeds at finite distances. The proposed methodology relies on a two-step process that provides an advantageous trade-off between computational complexity and cross-polarization performance of the entire array. The design process is demonstrated by means of an example involving a single offset flat reflector architecture and is validated by means of numerical and experimental results.

II. DESIGN PROCESS

A. Architecture and analysis of the polarizing surface

The design process is demonstrated by means of an example, consisting on a square flat polarizing reflector of side length \( d = 270 \) mm. The polarizer is illuminated by a standard Flann’s gain horn model 19240 polarized at 45° [11], as shown in Fig. 1a. The reflector, with an offset angle of \( \theta_f = 35° \), is placed at a distance \( z_f = 250 \) mm from the feed. In this example, the polarizer exploits the dipole design from [1], [2], and is shown in Fig. 1b. Previous similar designs report for plane wave incidence axial ratios (ARs) below 3 dB for fractional bandwidths in the range 60% and 68% [1], [2]. However, while the AR at boresight follows closely the unit-cell response (i.e. the reflection of a true plane wave by an infinite periodic array), as will be shown later, for finite arrays and practical feeds the AR deteriorates within a finite beamwidth.

We commence with the optimization of the geometry for the unit-cell at the center of the reflector, which for an ideal feed will experience angles of incidence elevation and azimuth of \( \theta_l = 35° \) and \( \phi_l = 180° \) respectively (as defined in Fig. 1a). The selected substrate is Taconic TLY-5, with a thickness of 1.5748 mm, relative permittivity of 2.2 and loss tangent of 0.0009. Since for the finite array the AR degrades away from...
Fig. 1: (a) Example architecture comprising a square flat polarizing reflector with dimensions $d = 270$ mm, distance between feed and reflector $z_f = 250$ mm and offset angle $\theta_f = 35^\circ$, fed by a standard gain horn polarized at slant $45^\circ$, and (b) geometry of the selected linear-to-circular polarizing dipole unit-cell (in semi-transparent the rotated dipole by an angle $\Delta \phi$ is depicted).

Fig. 2: AR performance for the unit-cell at the center of the reflector (blue lines) and (a) at oblique angles of incidence across the vertical plane before and after the geometrical optimization (solid and dashed lines respectively) and (b) outside the vertical plane at $\theta_l = 35^\circ$ before and after the element rotation (solid and dashed lines respectively).

Fig. 3: Simulated far-field AR for the 3dB-beamwidth at 14.5 GHz for the (a) uniform and (b) optimized arrays, at 17.7 GHz for the (c) uniform and (d) optimized arrays and at 19 GHz for the (e) uniform and (f) optimized arrays.

**TABLE I:**

<table>
<thead>
<tr>
<th>Freq (GHz)</th>
<th>Unif. array</th>
<th>Opt. array</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.5</td>
<td>1.88</td>
<td>0.86</td>
</tr>
<tr>
<td>17.7</td>
<td>2.47</td>
<td>1.20</td>
</tr>
<tr>
<td>19.0</td>
<td>3.96</td>
<td>2.49</td>
</tr>
</tbody>
</table>

boresight compared to the infinite case (unit-cell response), as a starting point the requirement for the latter is set at AR< 0.5 dB across a frequency band from 14.5 GHz to 19 GHz (fractional bandwidth of about 27%). The dimensions of the optimized geometry with reference to Fig. 1b are $D_x = 7.5$ mm, $D_y = 0.9$ mm, $l = 6.75$ mm and $w = 0.6$ mm. The AR for this design at $\theta_l = 35^\circ$ and $\phi_l = 180^\circ$ as obtained with CST [12] is shown in Fig. 2 with blue line. As shown, the AR is less than 0.5 dB over a frequency range of 14.3 – 19.5 GHz, which corresponds to a fractional bandwidth of 30.77%.

The far-field reflected by a truncated version of the array when illuminated by a feed at a finite distance can be obtained by integrating the equivalent surface currents over the reflector aperture [13]. The equivalent surface currents can, in turn, be obtained from the electric (and magnetic) fields reflected locally at the polarizing surface. Ultimately, the reflected fields can be obtained from the fields incident by the primary feed on the array and upon consideration of the local reflection characteristics. The latter are typically obtained in terms of the S-parameters and upon Floquet modal expansion [14], [15]. It should be noted that since the periodic surface is placed in the Fresnel region of the horn [13], the incident field corresponds to the near-field radiated by the horn [16].

Exploiting the aforementioned procedure, the reflected far-field from the architecture of Fig. 1a is obtained. Fig. 3a, Fig. 3c and Fig. 3e show the far-field AR across a beamwidth within -3 dB from boresight at 14.5 GHz, 17.7 and 19 GHz respectively. The estimated AR at boresight is maintained at values less than 0.5 dB in the frequency range of interest.
However, the peak AR values at these three frequencies are respectively 1.88 dB, 2.47 dB and 3.96 dB. The goal of the optimization process is then to improve the far-field AR across this 3dB-beamwidth.

B. Optimization process

The optimization process exploits the following two observations. On one hand, it is relatively straightforward to re-optimise the unit-cell dimensions (with reference to Fig. 1b it typically suffices adjusting \( l, w \)) for minimising the AR at different angles of incidence along the offset (vertical) plane. On the other hand, as we move away from the main planes, the performance of the unit-cell AR deteriorates, and it is challenging to significantly improve its value by adjusting the unit-cell dimensions (with reference to Fig. 1b, \( l, w, D_x, D_y \)). This is attributed to the increasing misalignment of the element with the polarization of the incoming field. Consequently, a rotation of the element around its center (angle \( \Delta \phi \) in Fig. 1b) is a more efficient way to correct for the AR deterioration at unit-cell level [17].

The above is illustrated in Fig. 2, where the AR obtained with CST for an infinite array under plane wave incidence for various scenarios is plotted. Fig. 2a shows in solid red and black lines the response of the unit-cell at \( \theta_1 = 20^\circ \) and \( \theta_1 = 45^\circ \) respectively. These correspond to the angles of incidence experienced by unit-cells close to the lower and upper rims of the polarizing reflector respectively. The same figure plots optimized designs for the same angles in dashed lines. As shown, at lower elevation angles the original performance can approximately be recovered, although the improvement obtained at large elevation angles is more limited. The off-plane (\( \phi_1 \neq 180^\circ \)) AR response is plotted in Fig. 2b and reveals notable degradation for low (\( \phi_1 = 177^\circ \) and \( \phi_1 = 170^\circ \)) azimuthal deviations. It is noted that the azimuthal range for this reflector is \( \pm 30^\circ \). Numerical simulations (not shown here for brevity) indicate that there is little margin to improve this response by adjusting the dipole length and width (\( l, w \)). However, as also shown in Fig. 2b, if the element is rotated by an angle approximately equal to the azimuthal deviation, the performance of the original unit-cell is overall restored. This has indeed been confirmed for rotation angles up to \( 10^\circ \).

Based on the above observations, the proposed optimization process entails two steps. First a geometrical optimization of the unit-cell geometry to minimise the AR for each elevation angle, \( \theta_1 \), along the offset plane, i.e. \( \phi_1 = 180^\circ \) is performed. Then each optimized element is repeated along contours of constant \( \theta_1 \) but imposing a rotation of the element by an angle (with reference to Fig. 1b), \( \Delta \phi \), that depends on \( \phi_1 \). It is noted that minimizing the AR locally for each unit-cell does not necessarily guarantee the best AR performance in the far-field. Consequently, the second step is directly applied targeting to minimise the far-field AR within the 3dB-beamwidth region at three frequencies (extremes of the band and middle point). The Nelder-Mead algorithm [18] has been chosen for the optimization, since it is a gradient-free local search method. The rotation \( \Delta \phi \) of the unit-cell \((i, j)\) experiencing angle of incidence \((\theta_1^i, \phi_1^j)\) is expressed as a polynomial function

\[
\Delta \phi(\theta_1^i, \phi_1^j) = \sum_{i=0}^{n} \sum_{j=1}^{n-i} c_{ij} \theta_1^i \phi_1^j
\]

where \( n \) is the order of the polynomial, \( c_{ij} \) are the coefficients to be obtained and \( j = 1 \) means that \( c_{00} = 0 \) since no rotation is needed for the vertical plane.

It can be shown that the two steps have an almost independent impact on the vertical and the horizontal planes [10]. The combination of the two steps delivers a global improvement of the far-field cross-polarization (or AR) throughout the far-field beam. It is noted that significant computational benefits can be obtained by exploiting a close observation of Fig. 2b; if the impact of the relative rotation of the dipole with respect to the rectangular unit-cell is neglected (which is reasonably accurate for low values of \( \Delta \phi \)), such a rotation will otherwise change the plane of incidence with respect to the element. This is shown in Fig. 2b, where for \( \phi_1 = 177^\circ \) the original response is almost identically recovered by rotating the dipole by \( \Delta \phi = -3^\circ \). This approximation holds to a good extend also for \( \Delta \phi = -10^\circ \). Consequently, if for a given \( \phi_1 \) a rotation of \( \Delta \phi_1 \) is needed, there is no requirement (to a first approximation) for obtaining full wave simulation results for the rotated element; instead with this observation, the S-parameters of the unit-cell with \( \phi_1^2 = \phi_1^1 - \Delta \phi_1 \) can be assumed. This statement is true for small rotations, where the array lattice can still be considered rectangular. With this observation, the unit-cell database is limited to the different dipole geometries (i.e. the elements along the offset plane) modelled for a range of incident angles. It is further noted that the proposed design process can be applied to other geometrical shapes [10], [19].

C. Far-field AR comparison

In order to demonstrate the performance achieved by the proposed design process, Fig. 3 shows the far-field AR over the 3dB-beamwidth for the uniform and the optimized arrays. Both arrays follow the configuration of Fig. 1a. The far-field \( u, v \) coordinates are defined as \( \sin \Theta \cos \Phi \) and \( \sin \Theta \sin \Phi \) respectively, where \( \Theta \) and \( \Phi \) represent the far-field spherical angles. The broadside directions at \( u = 0.57 \) and \( v = 0 \), as shown in Fig. 3.

A significant improvement is obtained at all three frequencies. The AR values at boresight and the peak AR values within the 3dB-beamwidth are summarised in Table 1. In

![Fig. 4: (a) Mask of the breadboard with the two-step optimization process and (b) photograph of the measured configuration.](image-url)
the 3dB-beamwidth for the uniform array the AR degrades to almost 4 dB. Improvements in these values of 1.02 dB, 1.27 dB and 1.47 dB are achieved after the optimization at 14.5 GHz, 17.7 GHz and 19 GHz respectively. The elevated AR value at 19 GHz is attributed to the compromised angular stability of the dipole unit-cell for increased elevation angles (as shown in Fig. 2a, black solid line).

III. EXPERIMENTAL VALIDATION

The two arrays simulated in Section II-C were manufactured at Heriot-Watt University by standard wet etching process. The mask of the optimized array is shown in Fig. 4a. The complete configuration (reflector and feed) has been mounted on a supporting structure, as shown in Fig. 4b. A NSI near-field planar test range has been used to perform the measurements. The whole configuration has been rotated so that the boresight direction of the AUT matches with the boresight direction of the near-field probe. A new set of far-field coordinates aligned with the beam broadside is defined, denoted as \(u', v', \phi', \theta'\).

Fig. 5a and Fig. 5b show the measured far-field AR at the center frequency of 17.7 GHz for the uniform and optimized prototypes respectively across the 3dB-beamwidth region. These results compare well with the simulations presented in Fig 3c and Fig. 3d and hence validate the simulations. The measured results clearly indicate the improvement in AR achieved across the 3dB beamwidth by virtue of the proposed optimization, which improves the worse AR from 2.35 dB to 1.57 dB (simulations shown in Table 1). Fig. 6 shows the far-field cuts associated with the measurements of Fig. 5 along the two principle planes, \(\Phi = 0^\circ\) (vertical plane) and \(\phi = 90^\circ\) (horizontal plane). Simulated results are superimposed. Good agreement is observed down to -22 dB, which again demonstrates the improvements achieved. A second frequency point, 18.95 GHz, was measured. The worse AR improved from 3.99 dB to 1.89 dB (3.98 dB to 1.62 dB in simulation). It has not been possible to include more plots due to space limitations, but these numbers also demonstrate the validity of the proposed optimization process at another frequency.

Some disagreements between simulations and measurements are observed. These disagreements are present both in the co- and cross-polarization components, and are primarily attributed to misalignments in the measurements. A small squint towards negative values on the \(v\)-axis is observed in Fig. 5. As shown in Fig. 6b, this corresponds to a squint of about 0.2 degrees in the horizontal plane, and it is attributed to misalignments in the experimental setup. Mainly, two types of misalignments can be present: between reflector and near-field probe and between horn and reflector. Additional errors may be associated with the rotation of the feed, diffraction effects and the etching of the polarizers. However, it can be stated that overall, the simulated and measured results match well, particularly in light of the accuracies in reported literature for cross-polarization measurements [20]–[23].

IV. CONCLUSION

A two-step design process to reduce the cross-polarization levels of linear-to-circular reflection polarizers has been presented. The proposed design process exploits physical insight and leads to computational efficiencies. This in turn allows the simultaneous optimization of the cross-polarization (or AR) levels across a wide frequency bandwidth. Improvements in the far-field AR across the 3dB-beamwidth in the range 1.02-1.47 dB are obtained. The procedure is validated experimentally. We note that the proposed procedure can be used as a starting point for more computationally intense optimization, the extreme case being a polarizing surface where each element is individually optimized.
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