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Metal-Only Reflectarray Unit Cell for Dual-Polarization Control

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Abstract—A metal-only reflectarray unit cell to independently control two polarizations is proposed in this paper. The unit cell is based on a nonresonant cross-shaped geometry backed by a metallic plate. Unlike previous metal-only nonresonant unit cell, the metallic arms of the proposed one are not connected to its neighboring unit cells. This fact enables the propagation of the incident wave along the longitudinal direction of the unit cell more specifically, along parallel-plate waveguides formed between unit cells. Depending on the polarization of the impinging wave, the propagation occurs in the waveguides located at vertical or horizontal directions. The simulated results for a designed unit cell at 60GHz show the independent modification of the phase response for one polarization being unaffected the phase response of orthogonal one. Moreover, phase linearity and a phase shift range over 360° are achieved along a operating frequency range with good phase stability under oblique incidence.

Index Terms—Dual polarization, metal-only, millimeter-waves, polarization control, reflectarray antenna.

I. INTRODUCTION

Reflectarray antennas have gained a lot of interest during the last years since they provide a more versatile and cost-effective design than the traditional parabolic reflectors [1]. When the frequency increases, for example, up to millimeter-wave frequencies, dielectric material in reflectarray can be a source of losses in the antenna because dielectrics with low loss tangent are hard to find at millimeter-waves. Besides, the greater the volume of dielectric used in the unit cell implementation, the greater are the dielectric losses [2], [3]. Thus, metal-only antenna designs are desired to increase the total efficiency of the reflectarrays and avoid outgassing problem for space applications.

In the literature, there exist some reflectarray designs implemented without the use of any dielectric material. The works in [4], [5] present a reflectarray design formed by metal-only unit cells. These unit cells share the same configuration: the reflectarray unit cells are patterned on a metallic plate which is at a certain distance from a metallic ground plane. Other alternatives to design metal-only reflectarrays have been shown in [6]–[8]. In these works, the beam collimation produced by the reflectarray is achieved by means of the depths of 1-D or 2-D perforated grooves. The phase introduced by each unit cell of the reflectarray is determined by the round trip propagation of the wave inside the groove. Alternatively to unit cells based on grooves, nonresonant elements such as squared metallic blocks have been proposed as a reflectarray unit cell [9]. Since

the unit cell is a nonresonant element, the gain bandwidth of the reflectarray can be broadened. In this direction, other nonresonant unit cells have been analyzed for metal-only reflectarray design [10]–[12]. Metallic cylinders or crosses orthogonally connected to surrounding unit cells have been explored in the previous works. Finally, some other complex geometries for the unit cells have been employed for designing reflectarrays. In [13], dual-branch helices are implemented as reflectarray unit cells to obtain a wideband performance keeping unaltered the incident circular polarization. In [14], the considered unit cell is a metallic cylinder etched with a rectangular groove. By the 90° rotation of the unit cell, an out-of-phase response is obtained which is used to implement a mechanically-reconfigurable 1-bit reflectarray.

In addition to the increase of the total efficiency by the use of metal-only reflectarray, another desired characteristic for a reflectarray antenna is the control of the polarization. However, there is a lack in the literature of metal-only unit cells that provide two independent orthogonal polarization control. In this work, a metal-only reflectarray unit cell that controls separately the vertical (V-pol) and horizontal (H-pol) polarizations is proposed. Unlike other works whose unit cells relied on resonant elements in the horizontal and vertical directions to gain the polarization control [15], [16], in this work, the proposed unit cell is a nonresonant element. More precisely, the fundamental element that achieves the phase tuning for each polarization can be seen as a parallel-plate back-shortened waveguide with finite width. The document is organized as follows. Section II presents and analyzes the proposed reflectarray unit cell for V-pol and H-pol. In Section III, the height of parallel plates in the unit cells is studied and its effect in the phase response of each polarization. In addition, the oblique incidence performance is assessed in Section IV. Finally, the conclusions are drawn in Section IV.

II. PROPOSED REFLECTARRAY UNIT CELL

The reflectarray unit cell proposed in this work is illustrated in Fig. 1(a). The figure shows a central metallic block of height L surrounded by four metal steps whose heights are L_V in the vertical direction (highlighted in red) and L_H in the horizontal one (highlighted in green). This unit cell allows the propagation along its longitudinal direction (z -direction) for both from V-pol and H-pol. Fig. 1(b) illustrates a planar view of the proposed unit cell indicating the propagating zones

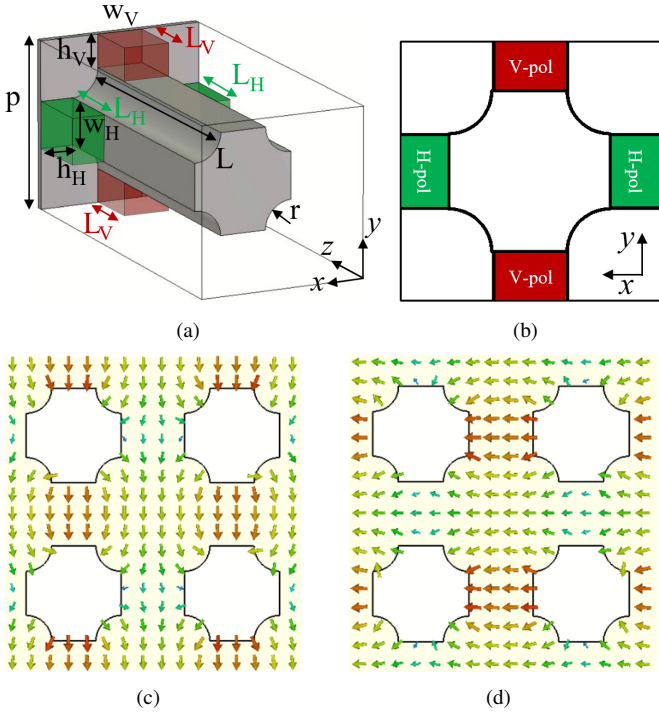


Fig. 1. (a) 3-D view of the proposed reflectarray unit cell. (b) Planar view of the unit cell indicating the propagating zones for V-pol and H-pol. Electric field distribution for a 4-cell unit environment when the excitation is a (c) vertical-polarized plane wave and, (d) a horizontal-polarized plane wave. The dimensions are: $p = 2.5$ mm, $h_V = h_H = 0.5$ mm, $w_V = w_H = 0.7$ mm, $L = 4$ mm and, $r = 0.4$ mm.

and which polarization propagates along these zones. The propagating zones are seen as parallel-plate waveguides with finite width (w_V for V-pol and, w_H for H-pol) and with a short-circuited wall located at their bottom. The short-circuited wall produces the reflection of the wave, which propagates in the parallel-plate waveguide. The reason why each zone only allows a polarization is because parallel-plate waveguides are formed between unit cells in y - and the x -directions as it is illustrated in Figs. 1(c) and 1(d), respectively. For a considered polarization, the wave can propagate in the zones where the metal surfaces are orthogonal to the incident electric field (E-field) since the wave is propagating in a parallel-plate waveguide whose height is $2h_{V,H}$ and its width is $w_{V,H}$. For the orthogonal polarization, these zones cannot support wave propagation because the incident E-field is parallel to the metallic surfaces producing a waveguide condition with a high cutoff frequency as the waveguide width is now $2h_{V,H}$. Figs. 1(c) and 1(d) show the E-field distribution when a vertical-polarized or a horizontal-polarized wave impinges to the unit cells, respectively. For instance, in the V-pol case of Fig. 1(c), the greater E-field amplitude distribution is concentrated between the vertical arms (y -direction) of nonresonant cross-shaped element. The E-field in this case is minimum between the horizontal arms (x -direction) of nonresonant cross-shaped element because the waveguide condition commented above. Additionally, the complementary case occurs in the Fig. 1(d)

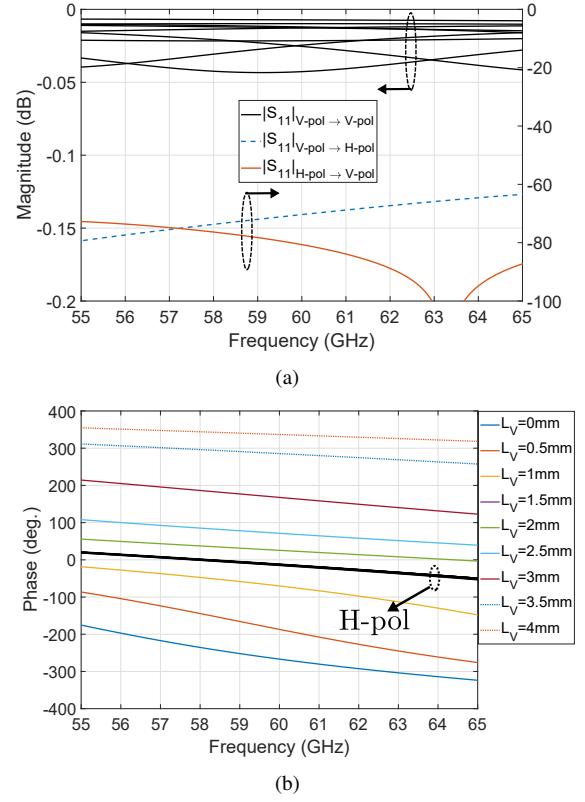


Fig. 2. (a) S-parameters in magnitude of the proposed unit cell. (b) S-parameters in phase of the proposed unit cell when $L_H = 1.5$ mm and L_V is varied.

where the minimum of the E-field is at the vertical arms and the maximum E-field at horizontal arms. In this way, both polarizations can be independently controlled by the position of the short-circuit at the end of the parallel-plate waveguide. The position of the short-circuit for the V-pol and H-pol is determined by the parameter L_V and L_H , respectively.

The electromagnetic (EM) characterization of the proposed unit cell is performed with CST Microwave Studio. Unit cell boundary conditions in the x - and y -directions are imposed for the simulation of the unit cell illustrated in Fig. 1(a) and, the frequency solver of the CST is employed. The magnitude and phase responses of the unit cell for V-pol and H-pol incident waves at normal incidence are shown in Fig. 2. The frequency range is centered at 60 GHz but the unit cell can be designed to work in a different frequency range by size scaling due to its fully-metallic structure. Fig. 2(a) shows the reflection coefficients $|S_{11}|$ of the unit cell when the incident plane wave is V-pol. Black solid lines represent the co-polarized magnitude response for different values of L_V . It can be observed that for all assessed cases, the reflection coefficient is very close to 0 dB being the maximum of losses 0.05 dB. This is because of the ohmic losses of the metal employed in the unit cell, in this case aluminium ($\sigma = 3.56 \cdot 10^7$ S/m). On the other hand, the cross-polarized magnitude response, which accounts the power transmission between the V-pol and H-pol

in the unit cell, is under -60 dB for the worst case in the considered frequency range. Therefore, almost all power is conserved in the same polarization when reflected in the unit cell. The observed performances are preserved on a quite large frequency range.

Fig. 2(b) presents the phase response of each incident polarization, V-pol and H-pol, when the position of the short-circuit L_V for the V-pol is modified keeping L_H fixed. The variation of L_V allows to set different levels of phase shift produced by the unit cell with good phase linearity along the frequency. The variation of the phase shift reaches beyond 360° for all the frequencies under consideration which allows this unit cell to be used for the design of a reflectarray. In addition, due to the independent behavior between the two polarizations explained above, the phase response for the H-pol is practically unchanged when L_V is varied. This demonstrates the expected and desired behavior for polarization-independent control in the unit cell.

III. EFFECT OF THE HEIGHT OF PARALLEL-PLATE WAVEGUIDES

One of the most interesting parameter to be analyzed in the proposed unit cell is the height of the parallel-plate waveguides, say, h_V and h_H for V-pol and H-pol, respectively. Fig. 3 shows the phase responses for V-pol and H-pol for different values of height of the parallel-plates waveguides. Also, in each case, the phase response is assessed for different L_V values. The phase difference shown in Figs. 3(b), 3(d) and 3(f) is defined as the absolute value of the difference in the phase response fixing a reference case. The reference case is the reflected phase produced by the unit cell for H-pol when L_V is 0 mm. The other cases that are compared with the reference case correspond to the phase shift response for the H-pol produced by other L_V value.

Analyzing the results of Fig. 3, a general conclusion can be obtained. As the height of the parallel-plate waveguides increases, the phase linearity improves but the phase difference in the orthogonal polarization (H-pol) worsens. The first effect, the enhancement of the phase linearity as h_V and h_H increase, is because the waveguide impedance is more similar to impedance of free space. This fact improves the phase linearity of the reflectarray unit cell as it has been previously reported for dielectric reflectarray unit cells [17]. The second observed effect is the increase of the phase difference for the H-pol as height of the parallel-plate waveguides increases. With the increase of h_V and h_H , the distance between orthogonal waveguides decreases and also, the cutoff frequency of the waveguides is reduced for the orthogonal polarization. Both factors contribute slightly to amplify the effect of the modification of the short-circuit position governed by the parameter L_V . Besides, it can be appreciated that the greater phase differences are achieved for higher values of L_V . These situations entail a shorter length for the cut-off waveguides and therefore a greater effect of the short-circuit position since the wave has not been fully attenuated. Nevertheless, the phase difference for the worst case is under 9° in the whole operating frequency

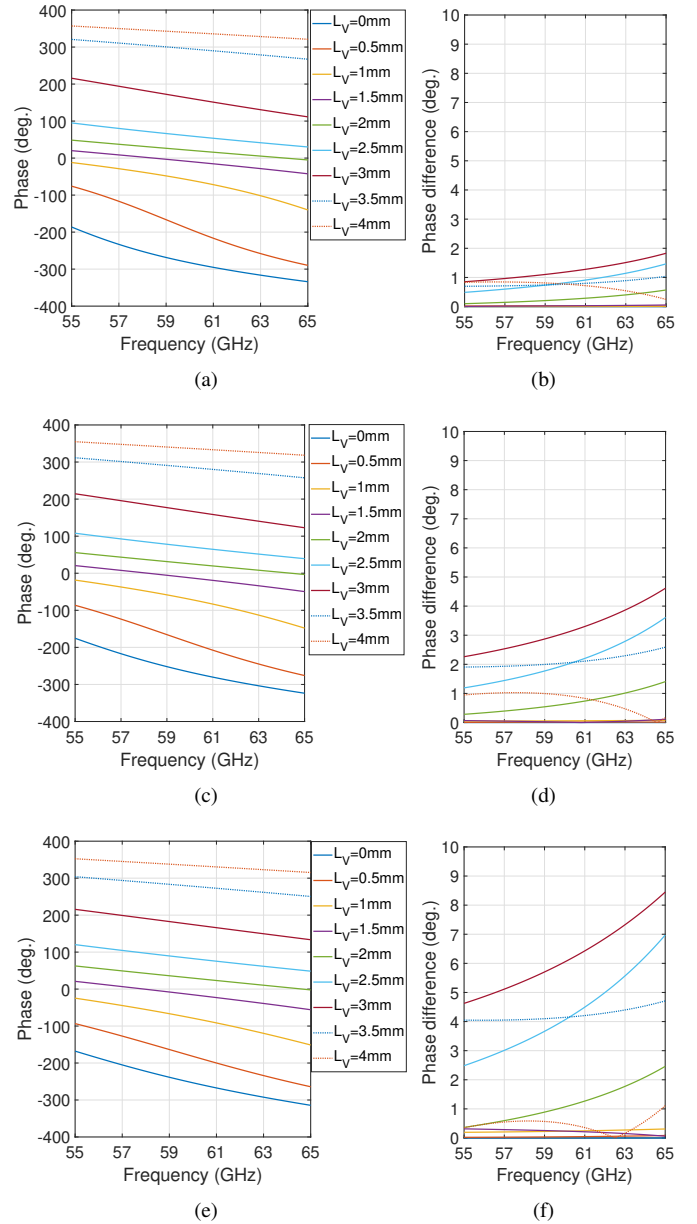


Fig. 3. Phase response for the V-pol when $L_H = 1.5$ mm, L_V is varied and (a) $h_V = h_H = 0.375$ mm, (c) $h_V = h_H = 0.5$ mm, and (e) $h_V = h_H = 0.625$ mm. Difference phase shift response for the H-pol when L_V is varied and (b) $h_V = h_H = 0.375$ mm, (d) $h_V = h_H = 0.5$ mm, and (f) $h_V = h_H = 0.625$ mm.

range. Finally, another consequence of decreasing the height of the waveguides is the increase of phase shift range at the expense of deteriorating the phase linearity specially for lower values of L_V .

IV. PERFORMANCE FOR OBLIQUE INCIDENCE

The oblique incidence performance of the unit cell is also analyzed in this work because it is of great importance in the design of reflectarrays with a realistic feed such horn antenna [1]. Fig. 4 presents the simulated results of the proposed unit cell under the oblique incidence of a plane wave. It is sufficient

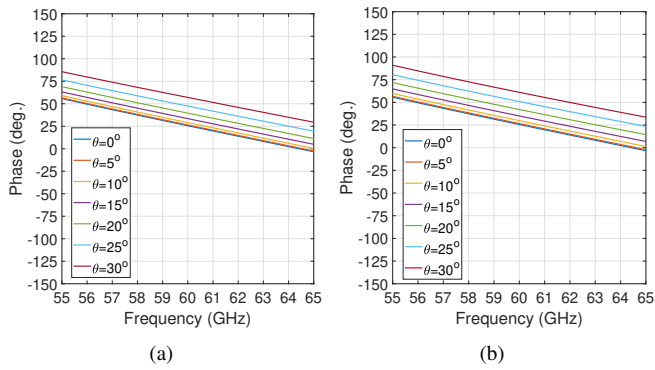


Fig. 4. Phase response for the V-pol under different oblique angles (θ) when $h_V = h_H = 0.5$ mm. L_V and L_H are fixed and equal to 2 mm and 1.5 mm, respectively. (a) Performance in the E-plane (YZ plane). (b) Performance in the H-plane (XZ plane).

to only consider the V-pol due to the symmetry of the unit cell. For the oblique incidence, the E- and H-planes are defined regarding axis of Fig. 1(a) where E- and H-planes correspond to YZ and XZ planes, respectively. The results presented in Figs. 4(a) and 4(b) reveal a modification of the phase response with the variation of the oblique angle. As the value of θ increases, the difference regarding the normal incidence ($\theta = 0^\circ$) also increases. The maximum phase difference at 60 GHz is 31.4° and 35.5° for the E-plane and H-plane, respectively. It is also observed that the phase linearity are preserved along the frequency for both planes even with the increase of the oblique angle. This unit cell behavior provides robustness since the phase curve does not suffer great changes when the angle of incidence is modified and thus, the phase error committed in the reflectarray design is minimized.

V. CONCLUSION

In this paper, a metal-only reflectarray unit cell for independent polarization control is presented. The unit cell is based on a metallic nonresonant cross-shaped that is not physically connected by its arms to the neighboring unit cells. The reflected phase response of each polarization is tuned by the position of a short-circuited wall located at the end of the parallel-plate waveguides formed between unit cells. The proposed unit cell is designed to operate in millimeter-waves centered at 60 GHz but other frequency range can be tuned by an easy size scaling of the unit cell. The electromagnetic performance of the unit cell demonstrates the independent tuning of the phase response for each incident polarization. Additionally, the range of the phase shift produced by the unit cell is beyond 360° in the operating frequency range which is suitable for the design of reflectarray antennas. Besides, the values of the waveguide heights have been swept in order to observe the effects produced in the phase response for each polarization. As the heights increase, the linearity of the phase response along the frequency is enhanced at the cost of increasing the phase variation for the orthogonal mode. Finally, the oblique incidence performance has been assessed revealing

acceptable variation of the phase response up to 30° with a linearity in phase that is preserved over the frequency.

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