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Slotted Cells as Amplitude-Phase Cells for Reflectarray Antennas

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Abstract—The aim of this paper is to introduce a new kind of reflectarray cell with both amplitude and phase control abilities. A slot is added in the ground of an arbitrary conventional cell for this purpose. A slotted cell having a square patch is investigated to verify the effectiveness of the proposed approach. This cell is used to reduce the side lobe level of a reflectarray antenna.

1. INTRODUCTION

Reflectarray Antennas (RAAs) are widely investigated and used in recent years. In RAAs, the phases of reflection coefficient of their cells are adjusted so that the radiated wave becomes maximum at a specified direction [1–3].

A well-known way to control the shape of radiated beam of an array, in particular reducing its Side Lobe Level (SLL), uses nonuniform amplitude for its elements. However, the amplitudes of radiating elements of RAAs are not adjustable and depend on their distances from the feed antenna. Indeed, only the phases of elements of RAAs are adjustable. Accordingly, the radiation pattern and in particular the SLL of RAAs is out of our control.

One way to reduce SLL of RAAs is controlling the magnitude of reflection of the cells, i.e., $|\Gamma_{mn}|$ for the mnth cell, so as to have nonuniform distribution for the magnitude of electric field over the aperture. On the other hand, almost all introduced cells of any patch design have $|\Gamma_{mn}|$ equal or nearly equal to one. Therefore, we have to use a new type of cells whose reflection can be any arbitrary value less or more than one. This type of cells is called Amplitude-Phase cells.

So far, some different types of amplitude-phase cells have been introduced [4–9]. In [4], an impedance transformation unit is utilized to control both amplitude and phase. In [5], a nonuniform frequency selective surface (FSS) is used as a reflection plane. In [6], resistors are used in the cells to absorb a part of power hitting them. In [7], a cell rotating the polarization of the incident wave is utilized to control the amplitude of reflected wave. In fact, some of the incident wave is ignored as the cross polarized wave. In [8], a double-reflector arrangement along with a polarizing grid is used. A common feature of all these types of cells is that they waste some of the power of incident wave, and consequently the gain of resulted RAA is reduced. However in some type of cells such as in [9], an amplifier is integrated into the cell to achieve power amplification.

All aforesaid amplitude-phase cells are costly and also have some difficulty and thereby are challengeable. In this paper, a general approach is introduced to provide a conventional cell with both amplitude and phase control abilities. To this end, a slot is removed from the ground plane to waste some part of the incident wave. This approach is easy to realize and inexpensive.

2. SLOTTED REFLECTARRAY UNIT CELLS

Here, we introduce an approach to realize amplitude-phase cells (APCs). In this approach we allow some of the incident wave hitting the cell to escape from it in order to reduce its reflectivity, $|\Gamma_{mn}|$. To

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this end, we create a slot in the ground of the cell to pass a part of the incident wave. The slot must be perpendicular to electric field of the incident wave. For circular polarized wave, we can use two crossing slots like a + sign.

Figure 1 shows a simple cell of size L containing a square (or any other types of shapes) metal patch of size L_1 over it. The thickness and relative electric permittivity of the substrate are h and ε_r, respectively. This is a conventional cell, but a rectangular slot of dimensions $w \times L_2$ is removed from its ground to control the amplitude of reflection in addition to the phase. The Perfect Matched Layer (PML) under the slot dissipates the escaped power. This layer can be either an absorber or the free space. In the latter case, the transmitted power will create back lobe radiation. In fact, losing some power is the cost we pay to adjust the amplitude of reflections in RAAs for reducing their SLL.

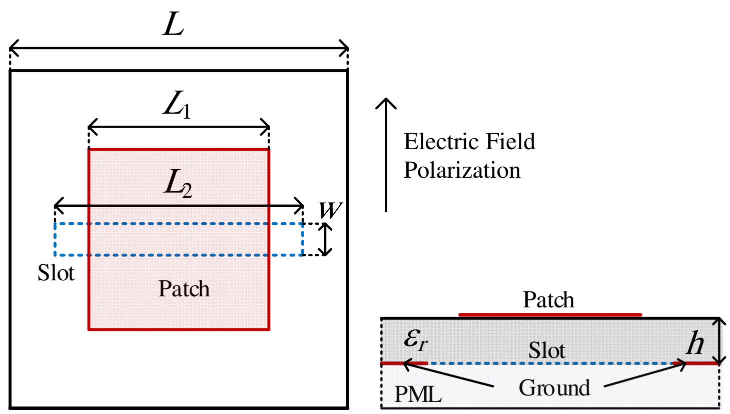

Figure 1. A slotted cell containing a metal square patch over the substrate and a rectangular slot on the ground.

Here, we use a commercial substrate "Rogers RT/duroid 5880" with $\varepsilon_r = 2.2$ and $h = 1.575$ mm. To find the reflection coefficient of the cells, the HFSS software has been used. For this purpose, the unit cell shown in Fig. 2 is utilized which has two opposite electric and magnetic walls.

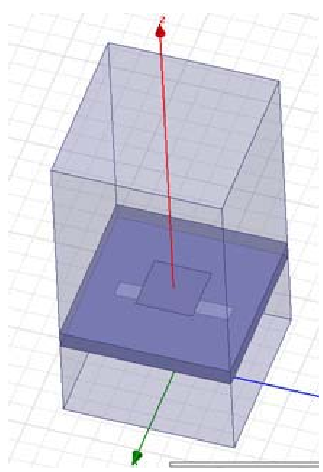

Figure 2. Unit cell used in HFSS to find the reflection coefficient of the slotted cell.

Figures 3 and 4 show the magnitude and phase of reflection coefficient of the slotted cell at frequency of $f_0 = 10$ GHz versus L_1 and L_2, respectively, assuming $L = 15$ mm $= 0.5\lambda_0$ and $w = 1.5$ mm. The accuracy is set about 2%. Fig. 5 depicts the contour of constant magnitude and phase of reflection coefficient. It is seen that each constant magnitude trace intersects nearly all constant phase traces and

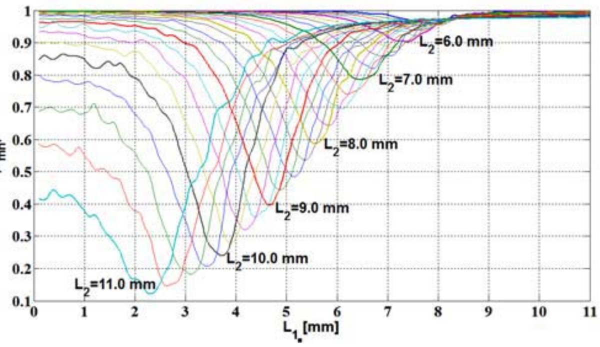

Figure 3. The magnitude of reflection coefficient of the slotted cell versus L_1 and L_2.

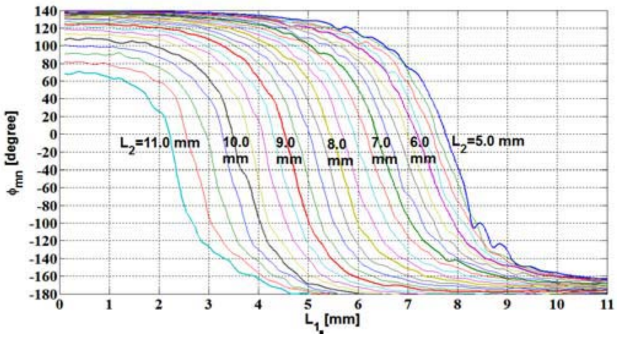

Figure 4. The phase of reflection coefficient of the slotted cell versus L_1 and L_2.

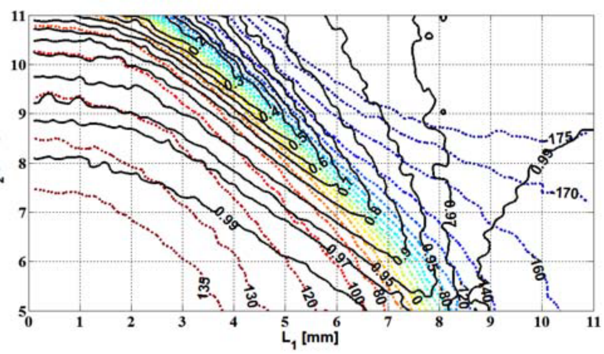

Figure 5. The contour of both constant magnitude (- - -) and constant phase (. . .) of the slotted cell.

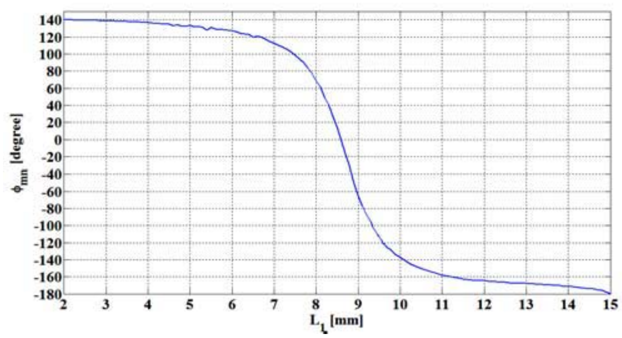

Figure 6. The phase of the slotted cell versus L_1 when the slot is eliminated (conventional cell).

vise versa. Hence, the required magnitude and phase of reflection coefficient of the cell are determined by properly choosing two parameters L_1 and L_2.

It is seen form Figs. 3–5 that the slotted cell introduced in Fig. 1 can act as a partially reflective cell due to resonating its slot. The resonance of the slot depends on its length as well as the length of the metal patch. The longer the slot is, the smaller the patch should be for resonance phenomenon and the less power reflects.

When the slot is eliminated from the introduced cell, i.e., $L_2 = w = 0$, it is reducef to a conventional cell whose reflection coefficient has magnitude equal to 1 and phase as shown in Fig. 6.

It is seen from Figs. 4 and 6 that the total coverage of phase is 320° due to simplicity of the shape of square patch. So, the phase coverage can be simply increased to 360° by choosing metal patch of other well-known shapes.

3. REFLECTARRAY ANTENNAS DESIGN

Here we design two RAAs at frequency of $f_0 = 10\,\text{GHz}$, with conventional and slotted cells introduced in Section 2. First, a square aperture with length of $D = 225\,\text{mm} = 7.5\lambda_0$ consisting of $N \times N = 15 \times 15$ cells is considered. A small antenna such as a microstrip patch is used as feed at the center of aperture and at height of $F = 2D = 450\,\text{mm}$. The maximum radiation angle is supposed $\theta_m = 0°$, i.e., broadside. There is a need to have $\Delta\phi = 286.4°$ phase variation for the cells.

To have SLL as low as possible, we used an optimization procedure for finding the optimum values of $|\Gamma_{mn}|$s. The error function of optimization is defined the same as SLL of the radiation pattern.

$$\text{Error} = \text{SLL} = \frac{|E'_{\max}|}{|E_{\max}|} \tag{1}$$

where $|E_{\max}|$ and $|E'_{\max}|$ are the main and second maximums of the radiation patterns, respectively. Furthermore, the foregoing error function is subject to a constraint that does not allow the 3-dB beamwidth increased substantially, for example not more than 10% increment.

For constrained optimization, the "trust-region-reflective" algorithm existing in "fmincon" of MATLAB software has been used.

It is known that equi-ripple Chebysheve pattern is an optimum array factor in the sense of low SLL. So, we could use the explicit results in some references such as [10] rather than using optimization method, to find the optimum value of $|\Gamma_{mn}|$. To this end, the distance of the mnth cell from the feed must be taken into account, of course.

Fig. 7 shows the optimum values of $|\Gamma_{mn}|$s, i.e., the reflection magnitude of the mnth cell, which vary between 0.302 and 1. Also, Fig. 8 shows the structure of RAA constructed by slotted cell, obtained by comparing Fig. 7 with Fig. 5. Finally, Fig. 9 shows normalized radiation patterns of two designed RAAs with conventional and slotted cells. It is seen that SLLs of two designed RAAs are -13.8 dB and -21.0 dB, respectively, therefore 7.2 dB SLL reduction, while 3-dB beamwidth is increased from 6.84° to 7.38°, i.e., only 7.9% increment.

As mentioned before, since some part of incident wave is escaped from the proposed cells, the gain of designed RAA is decreased with respect to the conventional cells. It is the intrinsic drawback of

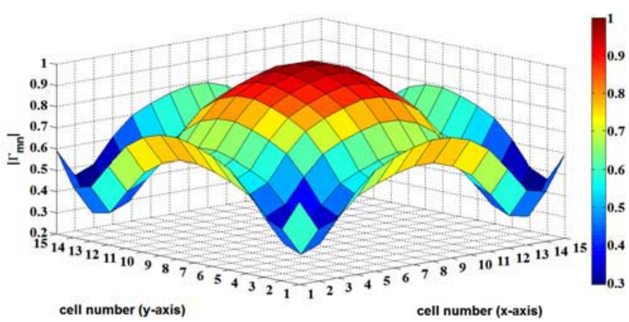

Figure 7. The optimum values of reflection magnitude of the cells.

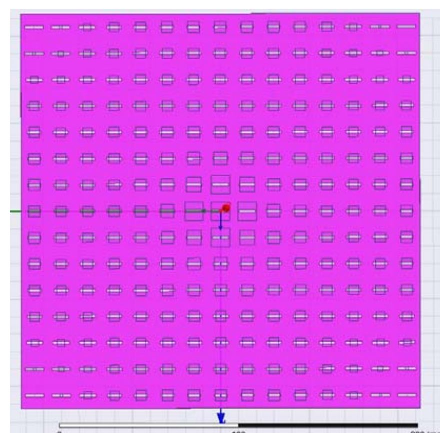

Figure 8. Structure of designed RAA using slotted cells shown in Fig. 1.

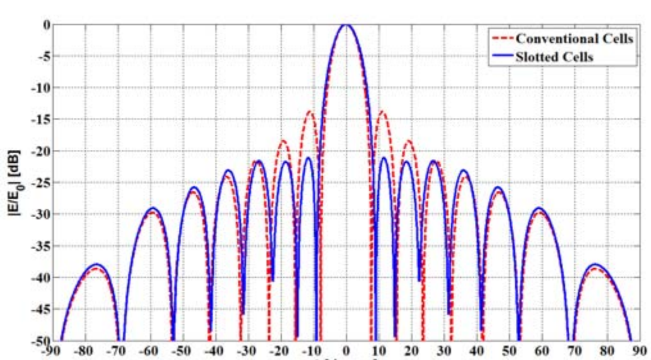

Figure 9. The normalized radiation pattern of two designed RAAs.

almost all other types of amplitude-phase cells, too. The ratio of gain decrement can be obtained as follows.

$$\frac{\Delta G}{G} = 1 - \sum_{m=1}^{N}\sum_{n=1}^{N}\frac{|\Gamma_{mn}|^2}{R_{mn}^2} \Bigg/ \sum_{m=1}^{N}\sum_{n=1}^{N}\frac{1}{R_{mn}^2} \tag{2}$$

where R_{mn} is the distance of the mnth cell from the feed. Eq. (2) is the ratio of the total reflected power from the amplitude-phase cells to the total incident power from the feed to them. In the designed RAA, $\Delta G/G$ is 52.3%.

4. CONCLUSION

This paper introduces a new kind of reflectarray cell with both amplitude and phase control abilities. A slot is added in the ground of an arbitrary conventional cell for this purpose. A slotted cell having a square patch is investigated to verify the effectiveness of the proposed approach. This cell is used to reduce the side lobe level of a reflectarray antenna. This approach is easy to realize and inexpensive.

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