Reflectarray with Variable-patch-and-slot Size

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Abstract — Reflectarray using a variable-patch-and-slot (VPS) size method is presented. A slot as a new variable is added to the original variable patch (VP) size configuration. The slot plays a role to modify the original phase diagram. In some cases, it optimizes both sensitivity and bandwidth of a reflectarray. Based on this observation, we designed a reflectarray on an FR4 substrate. Experimental results show a maximum gain of 24.5 dB at 11.4 GHz with an aperture size of 19.5 cm × 25 cm. It has a 1.5 dB bandwidth of 19.3% and has an aperture efficiency of 31.48%. The cross-polarization level is below 25 dB.

1. INTRODUCTION

Reflectarray has been extensively studied in the literature. A common step in designing such an array is to adjust phase among elements when it is illuminated by a primary source [1]. Progressive phase shift methods for a microstrip reflectarray have been extensively studied in the literature. The methods include identical microstrip patch elements with variable length delay line [2], variable size microstrip patches [3, 4], and identical microstrip patch elements with angular rotations [5]. In this paper, a modification to the variable size reflectarray of [4] is proposed. A slot as a new variable is added to the conventional design.

Phase adjustment from 0° to 360° in a reflectarray is required. A smoother phase variation versus element change is also important to relax manufacture sensitivity. In [4], a smoother phase variation within a range larger than 360° was obtained by stacking two or more arrays. In [4], a multilayer printed reflectarray based on patches of variable size was built on a low dielectric constant material. In [6, 7], performances of reflectarrays based on variable delay line method were checked by the authors. In this paper, stacked variable patch size reflectarray on FR4 substrate will be investigated with an intention to make an improvement.

Figure 1: The unit cell of a reflectarray with variable patch size (a) top view (b) side view (h₁ = h₂ = 1.6 mm).

The unit cell of the structure, denoted by “VP”, is shown in Fig. 1. In this configuration, the top and bottom layer patches are square. The relative size of the stacked patches is considered fixed in the design process (a₂ = 0.65a₁), the substrate thickness is 3.2 mm (h = h₁ + h₂ = 3.2 mm, h₁ = h₂), and the unit cell occupies an area of 15 × 15 mm. The commonly used substrate materials could be Rohacell (εᵣ = 1.05) [4], Duroid (εᵣ = 2.2), FR4 (εᵣ = 4.4) and Arlon (εᵣ = 6). As a comparison, we adjusted patch size to obtain phase diagram based on a similar approach of [7] for each material. The results are shown in Fig. 2 (at 11 GHz). It shows that relatively lower sensitivity can be obtained using Rohacell and Duroid rather than using FR4 and Arlon. As dielectric constant gets higher, the equivalent wavelength gets shorter. Therefore, the change rate of phase per mini-meter (not in terms of wavelength) is faster. Fig. 3 shows that the sensitivity
value is 166 degrees/mm for FR4 material adopting the definition of [8]. From this study, it is clear that although the “VP” approach of [4] was successfully implemented using low dielectric constant material, it may not work for high dielectric constant material. We also note that a thick (6 mm) substrate was used in [4]. For a thinner substrate, it is expected that the sensitivity will also increase for a fixed dielectric constant.

With a fixed-thickness substrate, it was studied the phase curve also has a high slope near resonance. Therefore, reflectarray with a high dielectric constant or a thin substrate is very sensitive to manufacture tolerances. Our motivation is to present a method to modify the phase curve of “VP” structure when it is applied to the FR4 material with a relative thinner substrate.

2. VARIABLE-PATCH-AND-SLOT SIZE REFLECTARRAY

In this section, we propose a new structure by etching a slot on the bottom-layer patch of the previous “VP” configuration. The new construction unit cell is called by “VPS”. VPS is different from VP by adding a slot of length $L$ as shown in Fig. 4. The width of the slot is $W$. We keep $W = 0.2a_1$ and $a_2 = 0.65a_1$ as we tune the slot length $L$. Four different slot lengths to patch size ratios for each material were studied. In Figures 5 to 8, the curves marked by $s_1$, $s_2$, $s_3$, and $s_4$ refer to $L = 0.2a_1$, $L = 0.4a_1$, $L = 0.6a_1$, and $L = 0.8a_1$ respectively. These curves are all analyzed at 11 GHz.

The roles played by the slot depend on the employed material. In [4], thick substrate (thickness
is 6 mm) with low dielectric constant (\(\varepsilon_r = 1.05\)) was used. In this case, we found from Fig. 5 that it is not necessary to introduce the slot. In fact, the slot makes a steeper slope than the original design for a low dielectric constant material. However, it is clear that the slot introduces additional phase delay. For an original less smooth VP-based phase diagram, we may use the slot to modify the high-slope region. For example, we may use the \(s_4\) curve in Fig. 8 or use the \(s_3\) or \(s_4\) curve in Fig. 7 to replace the conventional design. As for Fig. 6, no apparent advantage can be obtained from VPS design. In experiment, we use the “layout curve” which is a straight line in Fig. 9 to approximate the \(s_3\) curve in Fig. 7 to design a reflectarray on an FR4 substrate.

Figure 5: Phase diagram of VP (with no slot) and VPS in Rohacell material (\(\varepsilon_r = 1.05\)).

Figure 6: Phase diagram of VP (with no slot) and VPS in Duroid material (\(\varepsilon_r = 2.2\)).

Figure 7: Phase diagram of VP (with no slot) and VPS in FR4 material (\(\varepsilon_r = 4.4\)).

Figure 8: Phase diagram of VP (with no slot) and VPS in Arlon material (\(\varepsilon_r = 6\)).

Figure 9: Phase diagram of VPS at different frequencies in FR4 material.
3. EXPERIMENTS

The reflectarray is composed of 320 elements with an area of 19.5 cm × 25 cm. It is a center-fed array with a feed horn at a distance of 20 cm away from the reflecting board. In [4], the substrate thickness is 6 mm. In this design, only 3.2 mm thickness is needed. Low efficiency of the present array is due to the losses of the FR4 substrate. It has been checked in [6] that the FR4 material may cause 2.5 dB loss in this frequency range. Besides this unavoidable loss, other performances such as bandwidth and cross polarization level are all comparable to each other. A measured H-plane pattern at 11 GHz is shown in Fig. 11.

![Figure 10: Measured gain of a VPS reflectarray.](image1)

![Figure 11: Measured H-plane pattern of a VPS reflectarray at 11 GHz.](image2)

4. CONCLUSION

In this paper, we first investigate a conventional stacked variable patch size reflectarray. The phase diagram shows that the configuration can lead to a phase change greater than 360°. Therefore, thick substrate with low dielectric constant can be used in order to optimize both sensitivity and bandwidth. To further extend application of the stacked variable patch size method to a relatively thin substrate with high dielectric constant, we propose a VPS structure. It is obtained by etching rectangular slot on bottom-layer patch of the original array. The slot introduces additional phase delay to modify the high slope region which is commonly seen on a reflectarray built on a high dielectric constant material. Therefore, more design flexibilities can be obtained. However, we should know that as dielectric constant gets higher, the equivalent wavelength gets shorter. Therefore, the change of phase per mini-meter (not in terms of wavelength) is faster. This should be a general restriction for any phase-changing scheme in design of a reflectarray. What we present here is to show that we may possibly lower down the changing rate at least to some degrees. The method is demonstrated using FR4 as the substrate. Experiments show that we can account on the new modified phase diagram to design a reflectarray. Without this modification, the original curve shown in Fig. 7 suggests that as bottom-layer patch size ranges from 8 mm to 9 mm, only 200° phase shift yields. It is easy to see that the proposed VPS method can relax manufacture sensitivity in this example.

Reflectarray on high dielectric constant substrates can be made more compact. The disadvantage of doing so is sensitivity limitations even for a VP array. The use of a variable-patch-and-slot size (VPS) element can potentially solve this problem. For a reflectarray built on FR4 substrate, experiment showed that we can get 1.5 dB gain bandwidth of 19.3% with an aperture efficiency of 31.48%.

REFERENCES