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DRA Reflectarray Unit Elements with Thin Under-Loading Parallel Slots

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Abstract—This paper presents three dielectric resonator (DR) unit elements loaded with one, two, and three narrow slots underneath for designing reflectarrays. The slots are aligned in parallel, and the lengths are varied to function as phase shifter for changing reflection phase. It is found that the dominant TE mode of the square DR element can be easily excited by placing multiple parallel slots beneath a DR element. Study shows that the number and width of the slots can be used as additional design parameters for tuning the reflection loss and phase range of the reflectarray. Rectangular waveguide method has been deployed, showing reasonable agreement between simulation and measurement. It is found that a reasonable reflection phase range of 313° with slow slope is obtainable when the DRA is loaded with two slots beneath, which can be used for designing a small-size reflectarray. The reflection characteristics of the unit elements are studied, along with a complete parametric analysis.

1. INTRODUCTION

Reflectarray antenna was first introduced by Berry et al. [1] in 1963. However, the structure was constructed using matrices of open-ended apertures made of bulky truncated waveguides. This serious drawback had limited the applications of the reflectarrays in many places. Not until the late 1980s, has the introduction of printed microstrip reflectarrays [2, 3] shed light on the possibility of making such reflector structure planar and light. Since then, a myriad of planar reflectarrays have been proposed because they can provide the good features of both of the reflector antenna and phased array. Reflectarray is also well received by space-related applications because of its light weight, low profile, and low cost. However, the antenna bandwidth of a microstrip reflectarray is somehow tied up with its resonator bandwidth, which is usually narrow. Over the past decades, much effort has been dedicated to broadening the bandwidth of microtrip reflectarrays. Among those suggested, multilayer structures [4] and multiple resonators [5] are the popular ways that have been used for extending bandwidth.

Microstrip elements can introduce significant conductive loss at high frequencies. And it can be translated into reflection loss for a reflectarray. As a result, dielectric resonator antenna (DRA) has attracted much attention because it is made of dielectric material [6]. DRA can appear in different shapes such as cylindrical, rectangular, square, conical, and triangular [7]. Due to low loss and the ability to generate efficient radiation, DRA has been explored for designing various reflectarray antennas to achieve large reflection phase range, slow gradient of reflection phase slope, as well as low reflection loss. In [8, 9], the length of the DRA element is varied so that a reflection phase range of 360° is obtainable. However, this can cause many problems in the manufacturing process as different sizes of DRAs are needed. Cutting the super-hard dielectric resonators into different sizes is always very tough. Etching slots onto the ground surface beneath a DRA unit element was also demonstrated to be a possible way to introduce reflection phase shift to an incoming wave [10, 11]. However for both cases, very little design freedom is available as slot width is the only parameter to tune. Later, in [12],

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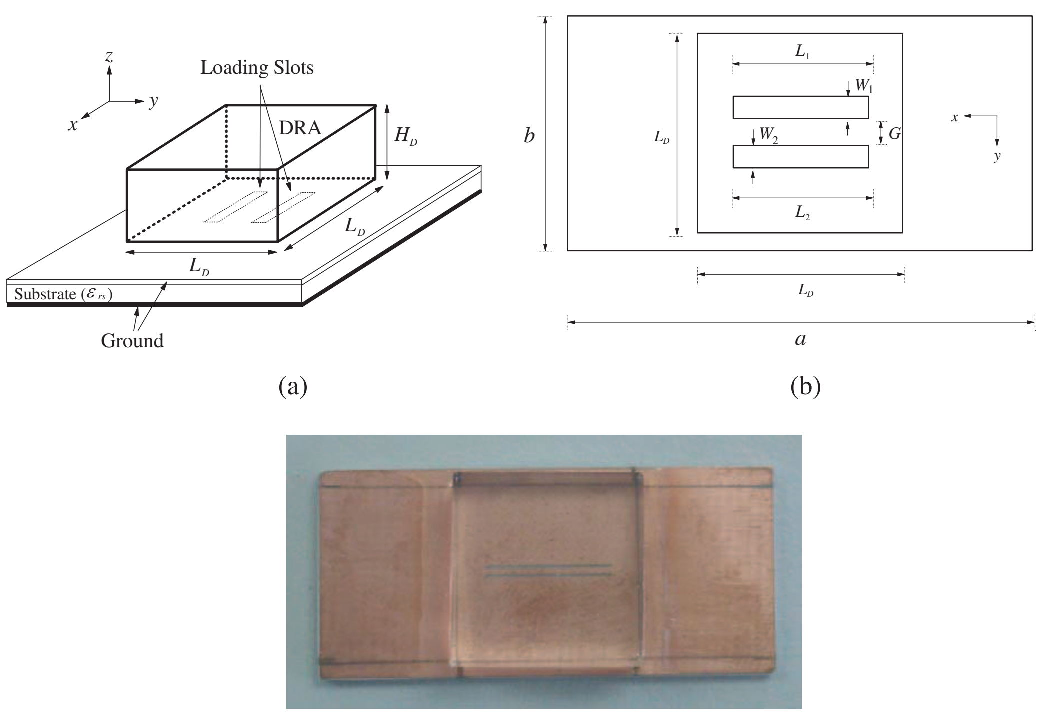
the under-loading slot is combined with a metal stub tuner in a multilayer structure where the stub length is varied for changing reflection phase. The involvement of multilayer structure, unfortunately, has made the implementation extremely tedious.

In this paper, three DRA reflectarray elements loaded with multiple under-loading slots on a single layer are studied. It is found that the case loaded with two slots on the ground plane can offer a reflection phase range of larger than 300°. Slots with different dimensions will be studied. Simulation was done using the CST Microwave Studio software, with measurement carried out on a Vector Network Analyzer (VNA) for substantiation. Good agreement is found between the simulation and measurement results.

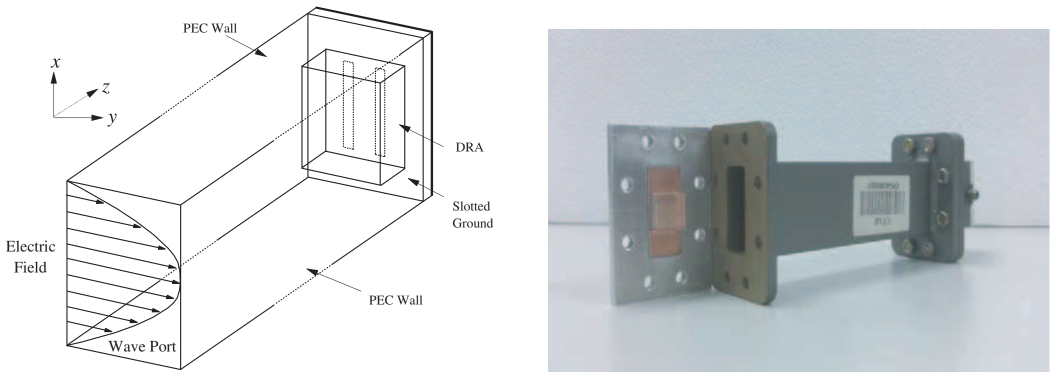
2. REFLECTARRAY UNIT CELL CONFIGURATION

Figure 1(a) shows the perspective view of the proposed reflectarray unit element loaded with two rectangular slots underneath the DRA. Duroid RO4003C (thickness of $h = 1.524\,\mathrm{mm}$ and dielectric constant of $\varepsilon_r = 3.38$) is used as the substrate. With reference to Fig. 1(b), the dimensions of the slots are given by: $W_1 = W_2 = 0.15\,\mathrm{mm}$ and $G = 0.5\,\mathrm{mm}$. In this case, the slot lengths L_1 and L_2 are functioning as phase-shifting parameters. As can be seen from the figure, two rectangular slots are etched on the top metallic surface of the substrate, with its bottom laminated by another layer of metal. A square DRA ($L_D = 14\,\mathrm{mm}$, $H_D = 6\,\mathrm{mm}$, and dielectric constant of $\varepsilon_r = 7$) is then stacked on top of the slots. As can be seen in Fig. 1(b), the slots are symmetrically aligned to the center point of the bottom surface of the DRA. Fig. 1(c) is the photograph of the fabricated prototype. Waveguide method is used to model the reflectarray element. Fig. 2(a) illustrates the simulation model of the DRA reflectarray element. CST Microwave Studio is used for all of the simulations. The slots are aligned orthogonal to the direction of electric fields in a section of C-band (5.8 GHz–8.2 GHz) waveguide ($a = 34.85\,\mathrm{mm} \times b = 15.8\,\mathrm{mm}$) with a length of 154 mm. With reference to Fig. 2(a), a y-polarized wave is generated at the wave port and it propagates to the DRA element, which is placed on another



(c)

Figure 1. Square DRA unit element loaded with 2 slots underneath. (a) Perspective view, (b) top-down view, (c) photograph of the fabricated prototype.



(a) (b)

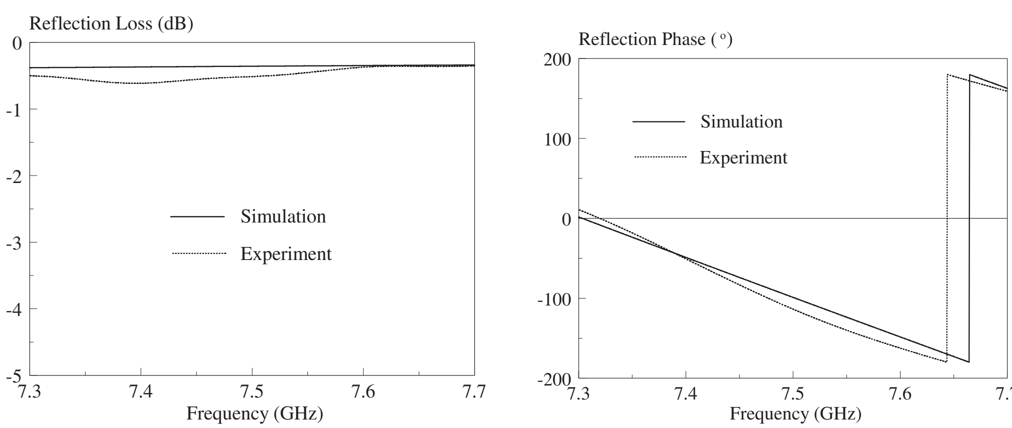
Figure 2. (a) Simulation model for the DRA unit cell, (b) experimental setup for the waveguide method.

end of the waveguide section. All of the lateral walls are defined to be perfect conductors (PEC). Fig. 2(b) shows the measurement setup which composes of a waveguide section which is connected to a coaxial-to-waveguide adaptor. In measurements, with the use of a flat shorting plate, the reference plane is de-embedded flush to the adaptor flange. The substrate is carefully trimmed so that it can fit into the waveguide aperture. A rectangular trench with depth of ~ 1.5 mm is cut on the metal plate to accommodate the substrate, as can be seen in Fig. 2(b).

3. RESULTS AND DISCUSSION

The field characteristics of the DRA unit element are first studied for $L_1 = L_2 = 5.5$ mm. Fig. 3 depicts the simulated and measured reflection losses and reflection phases. Reasonable agreement with low reflection loss (> -0.65 dB) is found across the frequency bandwidth of 7.3–7.7 GHz. Low reflection loss is achievable due to the absence of conductive loss in the dielectric resonator. Fig. 4 shows the electric field vectors in the DRA at the operating frequency of 7.5 GHz. It can be justified from the field distribution that this is the TE^x_{111} mode of the square DRA.

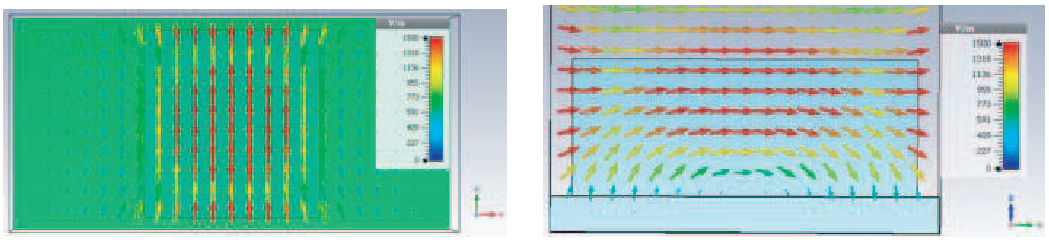
Next, the phase-shifting effect of the unit element is studied by varying the slot lengths L_1 and L_2, both of which are made equal in this case. Fig. 5 shows the simulated and measured reflection loss and phase range of the proposed unit element with two under-loading slots beneath. Reasonable



(a) (b)

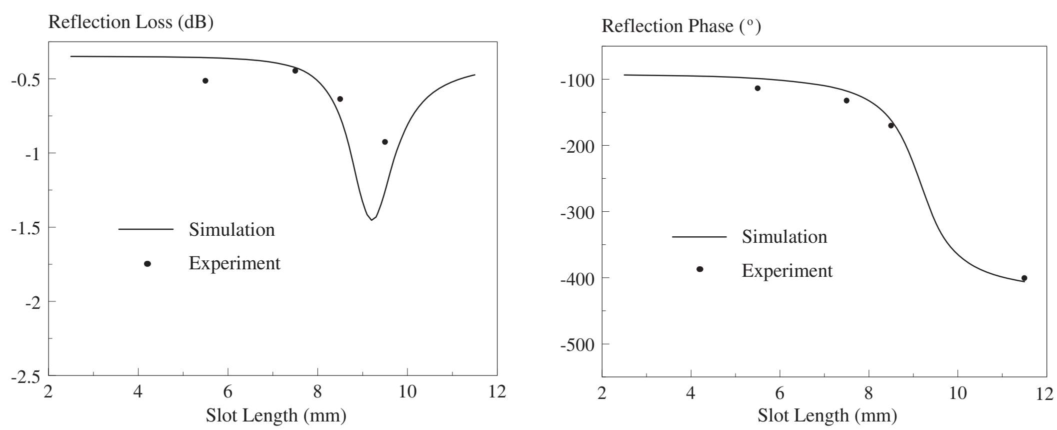
Figure 3. Simulated and measured (a) reflection loss, (b) reflection phase of the DRA reflectarray unit element with two under-loading slots ($L_1 = L_2 = 5.5$ mm, $W_1 = W_2 = 0.15$ mm, $G = 0.5$ mm).

agreement has been observed. With reference to Fig. 5(a), the measured reflection loss maximizes at −0.9 dB (simulation: −1.4 dB) at the slot length of 9.5 mm. This can be caused by the energy loss at resonance which is around 7.5 GHz when the slot length is 9.5 mm. Fig. 5(b) depicts the measured and simulated reflection phases, which are more commonly known as S Curves, where good agreement is observed. By varying slot length, as can be seen from the figure, the reflection phase range is 313°, which is sufficient for designing the small-size reflectarrays.



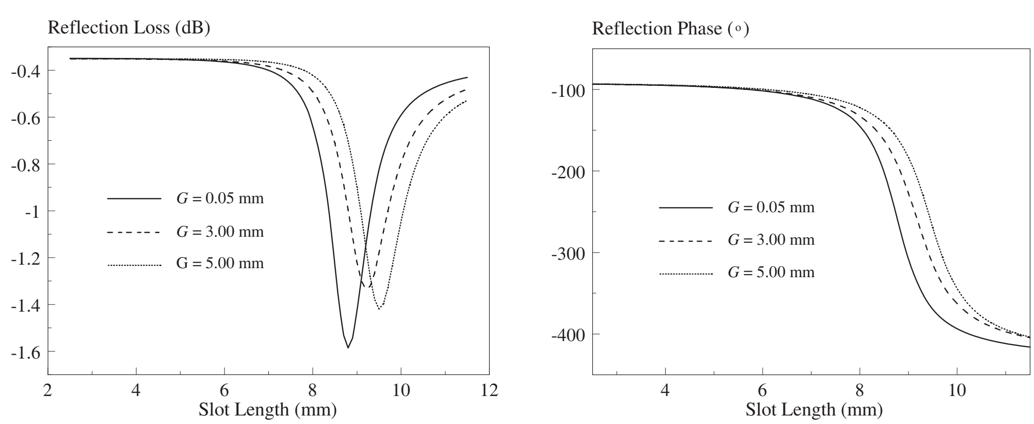
(a) (b)

Figure 4. Electric field distribution of the DRA reflectarray unit element at 7.5 GHz. (a) Top-down view, (b) side view.



(a) (b)

Figure 5. Simulated and measured (a) reflection loss, (b) reflection phase at 7.5 GHz of DRA unit element with two under-loading slots.



(a) (b)

Figure 6. Effect of gap separation between the two slots on (a) reflection loss, (b) reflection phase.

Parametric analysis has been performed to visualize the effects of the slots on reflection loss and phase range. First, the effect of the separation distance between the two gaps is studied. Referring to Fig. 6, it can be seen that reflection loss maximizes at a shorter slot length when the gap distance becomes closer, which can be caused by additional capacitive coupling between the two slots. For all cases, the phase ranges are greater than 300°.

Next, the effects of changing slot width and slot length are studied. In the first study, the width (W_1, W_2) of both of the slots are varied at the same time. With reference to Fig. 7(a), the maximum reflection loss reduces from -1.45 dB to -0.77 dB when both of the slots are increased from 0.15 mm to 0.75 mm. On the other hand, narrow slot is good for a larger phase range, as can be seen in Fig. 7(b). In the second study, with reference to Fig. 8, only one slot is varied while another is kept unchanged ($W_1 = 0.15$ mm). For the cases $W_2 = 0.5$ mm and 0.75 mm in Fig. 8(a), the reflection losses become slightly greater than those in Fig. 7(a) when only one of the slots is trimmed narrower. It can be seen from Fig. 8(b) that the phase range for each parameter is close to its counterpart in Fig. 7(b). Finally, by fixing the slot length L_2 at 2.5 mm, 5.5 mm, or 8.5 mm, the reflection loss and reflection phase obtained in each case by varying L_1 (shown in the x-axis) are shown in Fig. 9. It is obvious that varying the length of one of the slots does not affect the reflection performance much. It was also found from simulation that the reflection loss and phase range are not affected much if the slots are intentionally misaligned with a displacement of 4 mm with respect to the center point of the DRA. This is very promising as it shows that the proposed DRA unit element has good tolerance to the DRA misplacement.

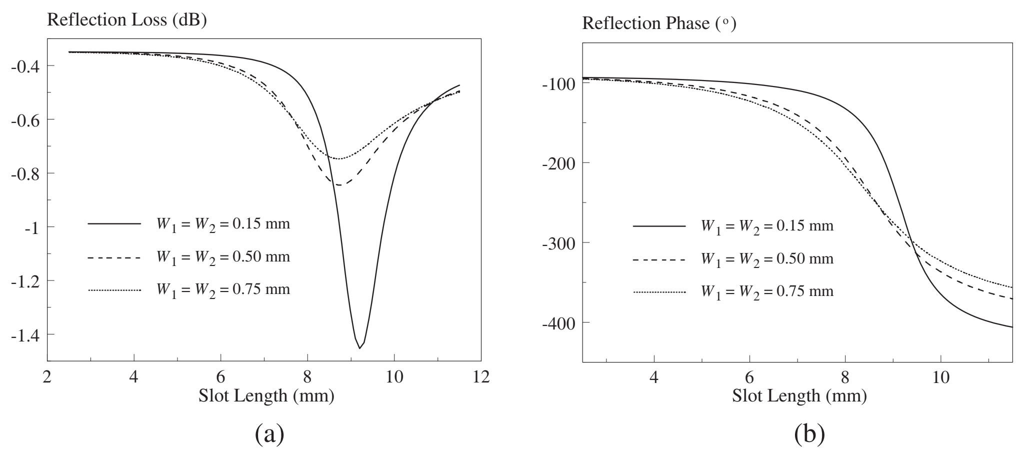


Figure 7. Effect of varying the widths of the two slots on the (a) reflection loss, (b) reflection phase.

Similar DRAs loaded with one and three slots are also simulated for comparison. The configurations are given in Fig. 10. The slot dimensions of the single slot case are given by: $W = 0.15$ mm and $L_D = 14$ mm. For the triple slots, the design parameters are $W_1 = W_2 = W_3 = 0.15$ mm, $G_1 = G_2 = 0.5$ mm. Other parameters are identical to those for the two slots case in Fig. 1. In both cases, the lengths of all the slots are made equal and they are varied simultaneously for introducing phase change to the reflection phase. Also, their gap widths are made to be equal with that of the two-slot case (Fig. 1) for ease of comparison. Fig. 11 shows reflection losses and reflection phase ranges of the unit cells with one, two, and three under-loading slots. It can be seen from Fig. 11(a) that the reflectarray element with two slots has the lowest reflection loss (-1.45 dB) at resonance. The under-loading single and triple slots have higher reflection loss of -2.4 dB and -7 dB, respectively. Fig. 11(b) shows the reflection phase ranges for the three cases. The DRA reflectarray with a single under-loading slot has the broadest phase range but the steepest gradient. This may compromise the available design choices. The phase change becomes slower with increasing the number of slots, but it comes at the price of a smaller phase range.

The effect of oblique incidence is now studied. In a rectangular waveguide, the incident angle (α) can be calculated using $\alpha = 90° - \cos^{-1}\sqrt{1-(\frac{f_c}{f})^2}$, where f_c (4.3 GHz) is the cutoff frequency of the waveguide and f is the operating frequency. For the C-band waveguide working in the frequency

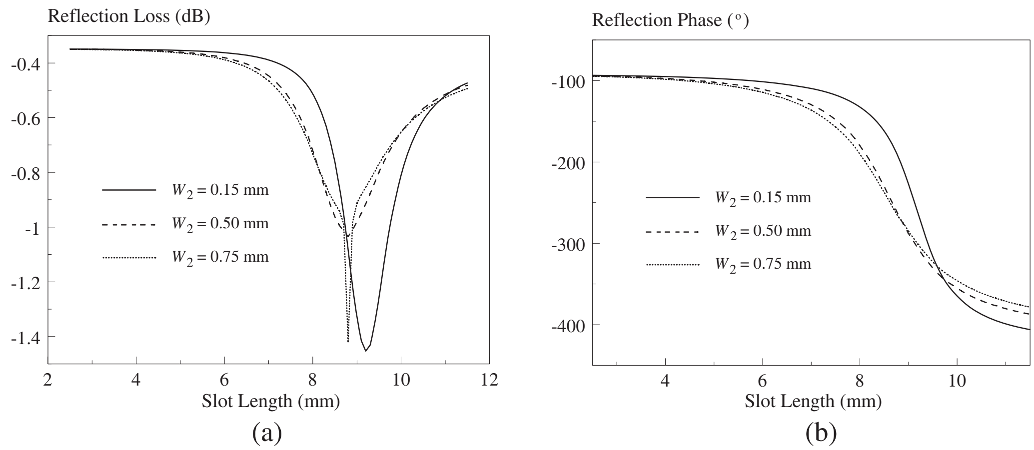


Figure 8. Effect of changing the slot width W_2 on the (a) reflection loss, (b) reflection phase.

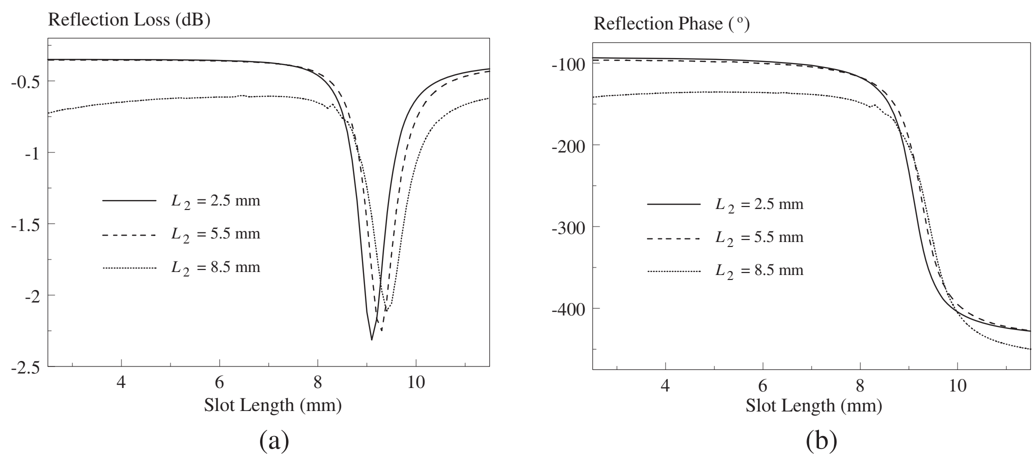


Figure 9. Effect of the slot length L_1 on the (a) reflection loss, (b) reflection phase.

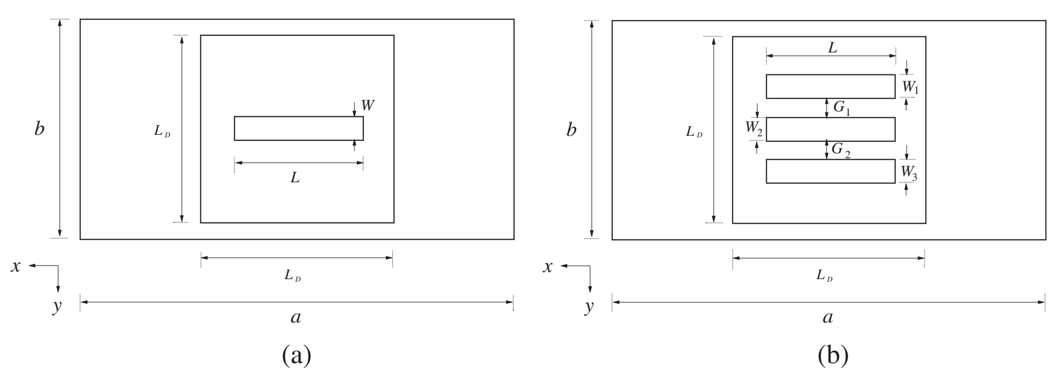
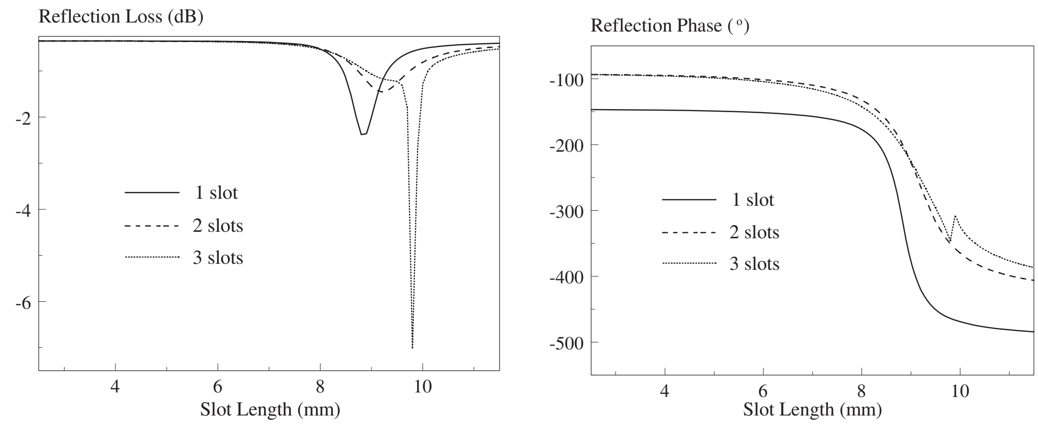


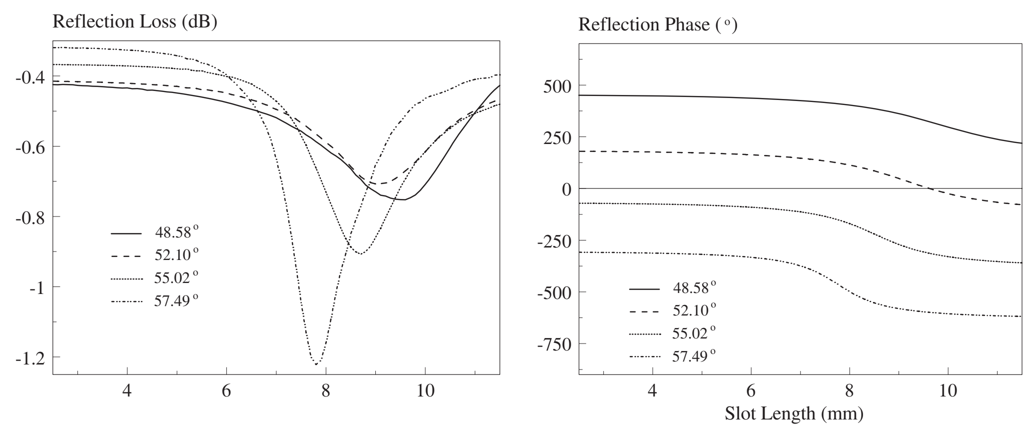
Figure 10. Square DRA unit element loaded with (a) 1 slot and (b) 3 slots underneath.

range of 5.8 GHz–8.2 GHz, oblique incident angles of 48.58° (at 6.5 GHz), 52.1° (at 7 GHz), 55.02° (at 7.5 GHz), and 57.49° (at 8 GHz) can be used to simulate the reflection losses and phase ranges shown in Fig. 12. With reference to Fig. 12(a), it can be seen that reflection loss increases proportionally with the incident angle. Fig. 12(b) shows that the reflection phase range is not affected so much by the incident angle.



(a) (b)

Figure 11. Comparison of the (a) reflection loss, (b) reflection phase of the DRA reflectarray unit element with different under-loading slots.



(a) (b)

Figure 12. Comparison of the (a) reflection loss, (b) reflection phase of the DRA reflectarray unit element at different oblique incident angles.

4. CONCLUSIONS

DRA unit elements loaded with one, two, and three parallel and thin slots beneath have been studied. It is found that narrowing the slot width is good for increasing the phase range of the S Curve. Also, the separation distance and width of multiple parallel thin slots can be used as additional parameters for tuning the reflectarray performance. For the proposed DRA unit element loaded with two slots underneath, a phase range of 313° is attainable for designing a small-size reflectarray. The proposed configuration is very compact as it does not require the use of any active electronic components. Good agreement has been found between the simulated and experimental data.

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REFERENCES

1. Berry, D., R. Malech, and W. Kennedy, "The reflectarray antenna," *IEEE Trans. Antennas Propag.*, Vol. 11, No. 6, 645–651, Nov. 1963.
2. Huang, J. and J. A. Encinar, *Reflectarray Antenna,* John Wiley & Sons, Inc., Hoboken, 2007.
3. Pozar, D. M., S. D. Targonski, and H. D. Syrigos, "Design of millimeter wave microstrip reflectarrays," *IEEE Trans. Antennas Propag.,* Vol. 45, No. 2, 287–296, Feb. 1997.
4. Encinar, J. A., "Design of two-layer printed reflectarrays using patches of variable size," *IEEE Trans. Antennas Propag.*, Vol. 49, No. 10, 1403–1410, Oct. 2001.
5. Bialkowski, M. E. and K. H. Sayidmarie, "Investigations into phase characteristics of a single-layer reflectarray employing patch or ring elements of variable size," *IEEE Trans. Antennas Propag.,* Vol. 56, No. 11, 3366–3372, Nov. 2008.
6. Long, S. A., M. McAllister, and S. Liang, "The resonant cylindrical dielectric cavity antenna," *IEEE Trans. Antennas Propag.,* Vol. 31, No. 3, 406–412, May 1983.
7. Petosa, A. and A. Ittipiboon, "Dielectric resonator antennas: A historical review and the current state of the art," *IEEE Antennas Propag. Mag.,* Vol. 52, No. 5, 91–116, Oct. 2010.
8. Abd-Elhady, M., S. H. Zainud-Deen, A. A. Mitkees, and A. A. Kishk, "Wideband rectangular dielectric resonator elements reflectarray," *Middle East Conference on Antennas and Propagation,* 1–5, Dec. 2012.
9. Zainud-Deen, S. H., S. M. Gaber, A. M. Abd-Elhady, K. H. Awadalla, and A. A. Kishk, "Wideband perforated rectangular dielectric resonator antenna reflectarray," *IEEE International Symposium on Antennas and Propagation*, 113–116, Jul. 2011.
10. Zainud-Deen, S. H., A. M. Abd-Elhady, A. A. Mitkees, and A. A. Kishk, "Dielectric resonator reflectarray with two DRA sizes and varying slot loading," *IEEE Antennas and Propagation Society International Symposium,* 1–4, Jul. 2010.
11. Abd-Elhady, M., S. H. Zainud-Deen, A. A. Mitkees, and A. A. Kishk, "Slot-loading rectangular dielectric resonator elements reflectarray," *Middle East Conference on Antennas and Propagation,* 1–3, Oct. 2010.
12. Abd-Elhady, A. M., S. H. Zainud-Deen, A. A. Mitkees, and A. A. Kishk, "X-band linear polarized aperture-coupled DRA reflectarray," *International Conference on Microwave and Millimeter Wave Technology,* 1042–1044, May 2010.