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COUPLING REDUCTION OF ANTENNA ARRAY ELEMENTS USING SMALL INTERDIGITAL CAPACITOR LOADED SLOTS

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Abstract—Small size capacitor loaded ground plane slots are used to reduce the mutual coupling between elements in a microstrip antenna array design. The proposed compact slots are inserted between the adjacent E-plane coupled elements in the array to limit the propagation of surface waves between the elements of the array. In order to validate the feasibility of the proposed structure, a two-element array with $0.5\lambda_o$ distance between centers of two patches is designed, fabricated, and measured. The measured results show a reduction in mutual coupling of 17 dB obtained between elements at the operation frequency.

1. INTRODUCTION

In microstrip antenna arrays, mutual coupling is primarily attributed to the fields that exist along the air-dielectric interface. The fields can be decomposed to space waves, surface waves, and leaky waves [1]. To obtain high radiation efficiency and wide bandwidth, a substrate with lower permittivity and a thicker profile has been extensively used in microstrip antenna design. However, a common disadvantage of microstrip antennas are surface waves, which exist whenever the substrate has a dielectric permittivity greater than one ($\varepsilon_r > 1$). Surface waves are guided by the dielectric-air interface and propagate (partially) within the dielectric substrate. Their confinement to the substrate and therefore their excitation is a function of the thickness of the substrate [2]. Surface waves may have some adverse effects on microstrip antennas, such as mutual coupling between elements on an array [3]. In an antenna array, the mutual coupling effect will deteriorate the radiation properties of the array. To avoid mutual coupling and — at the same time — grating lobes, the separation

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between the elements must be in the range between $\lambda_o/2$ and λ_o depending on the angular scan range [4]. To suppress surface waves in a microstrip substrate, several studies have been conducted including electromagnetic bandgap (EBG) structures [5–10].

EBG structures with insertion of vias have been applied to reduce the mutual coupling of the microstrip phased array in [5, 6, 8].

In [11, 12] uniplanar compact EBG structures are used also to reduce the mutual coupling between the elements of the antenna array. These structures are complex to be designed as well as they occupy a comparatively large area.

Defected ground structures (DGSs) are implemented by etching slots of different shapes in the ground plane, which exhibit miniature size compared to EBGs. Slots have been employed to improve the performance in multiple applications such as filters, couplers, as well as to reduce the mutual coupling between elements of antenna arrays [13–21]. In [20], an H-shaped DGS was investigated and applied to reduce mutual coupling, however, the size of DGS slot was large. The researchers have achieved 12 dB isolation between array elements. In [21], narrow and closely spaced three and five rectangular slots were used to mitigate the mutual coupling. The researchers have achieved 9 dB and 11 dB isolation using three and five slots respectively.

In this paper, we propose a new technique to reduce the mutual coupling between elements of an antenna array by placing two interdigital capacitor loaded slots between elements. Each slot can be modeled as a parallel LC bandstop resonator. The presence of the two slots improves the isolation between array elements and increases the stop band. Such structure behaves as a second order bandstop filter.

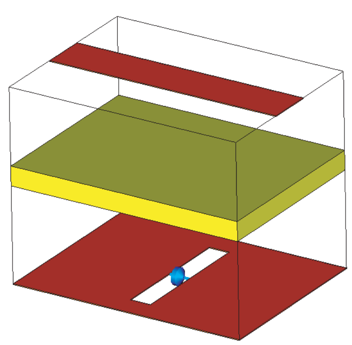


Figure 1. Three dimensional view of the ground-plane slot with capacitance.

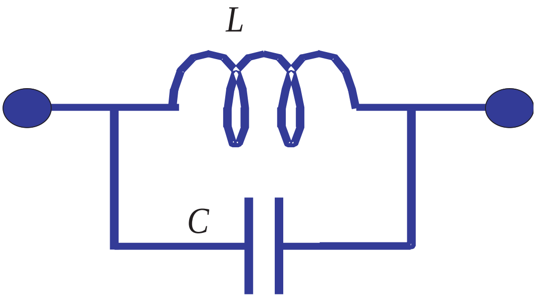


Figure 2. Equivalent circuit of the compact resonator.

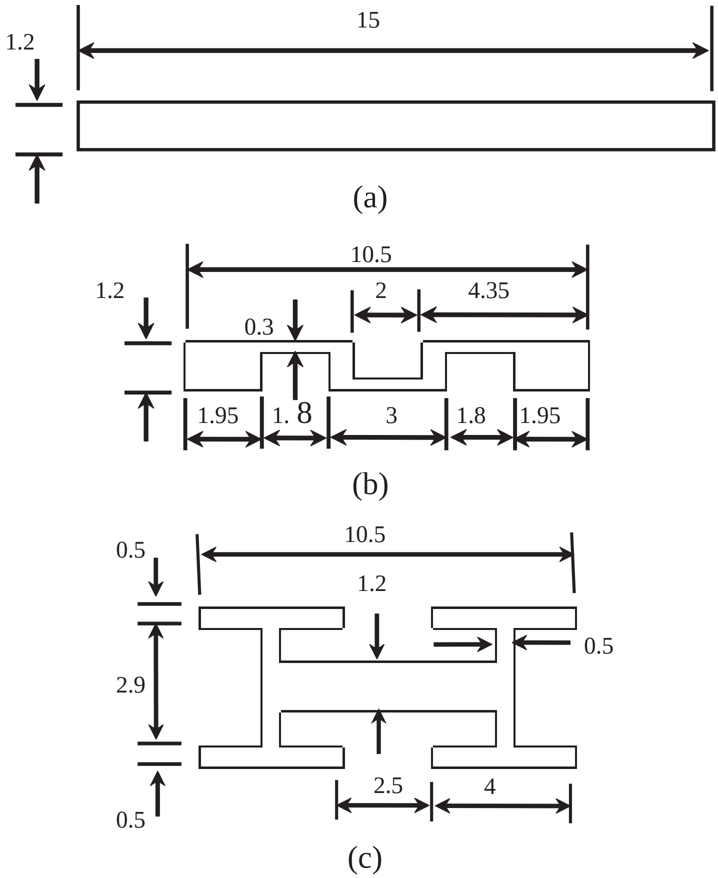


Figure 3. Layout of three different slots. (a) Rectangular slot. (b) Interdigital capacitor loaded slot. (c) *H*-Slot, all dimensions are in mm.

2. CHARACTERISTICS OF THE SLOT

The geometrical configuration of the proposed structure is shown in Figure 1. The structure consists of a 50 Ω microstrip line on the top layer and one slot etched from ground plane on the bottom layer of the substrate. The slot is modelled as a parallel LC resonant circuit as shown in Figure 2 [14, 22]. The structure has been designed on a high frequency printed circuit board RO4003 with a relative dielectric constant of 3.38 and a thickness of 1.524 mm. The strip width of 3.4 mm is chosen for a characteristic impedance of 50 Ω. One pole slot resonator with a rectangular slot shape has been simulated. The resonant frequency of the slot is 8 GHz.

3. EFFECT OF INTERDIGITAL CAPACITOR LOADED SLOTS ON BANDSTOP PERFORMANCE

For the rectangular slot shown in Figure 3(a), the resonant frequency depends basically on the physical dimensions of the slot. We are using in our investigation a rectangular slot with a length of 15 mm and a width of 1.2 mm. The slot resonance frequency is 8 GHz. By adding an interdigital capacitor, the slot resonates at the same frequency but with a small length of 10.5 mm as shown in Figure 3(b). To reduce the coupling between the array elements, one *H*-slot has been used [20]. An H-shaped DGS slot is shown in Figure 3(c). The H-

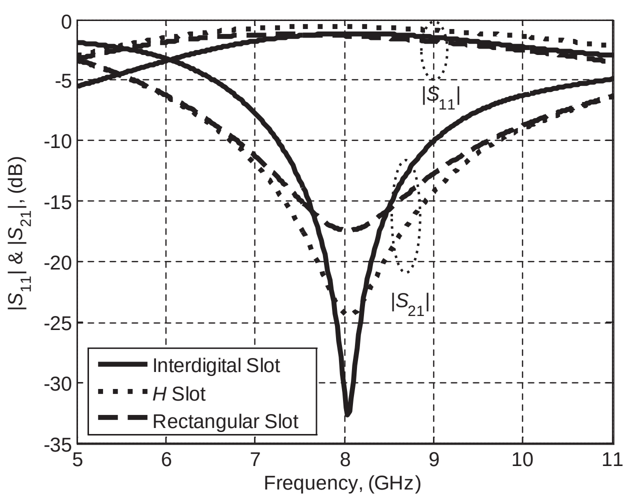


Figure 4. Simulated S-parameters for different slots.

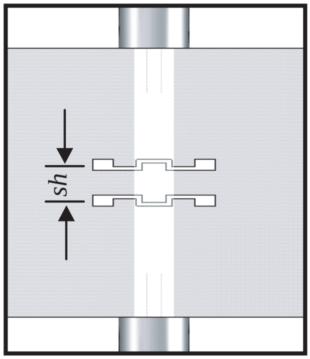


Figure 5. Second order (two slots) bandstop configuration.

shaped and the interdidital capacitor loaded slots have the same length of 10.5 mm. Figure 4 shows the performances of the three different slots The occupied areas are 18, 12.6, and 40.95 mm^2 for the rectangular, the interdigital capacitor loaded, and the H-shaped slots, respectively. It is obvious that the interdigital capacitor loaded slot is compact and suitable for array applications and will be used in our investigation.

Our aim here is to deal with the problem as a second order bandstop filter problem, where the resonating slots are used to reduce the propagating power from one antenna element to the other one. A second order bandstop is shown in Figure 5. The separation between the proposed slots affects the level of isolation between ports, which is an indication of the coupling power between the antenna elements. By increasing the separation sh between slots, the isolation between ports is increased as shown in Figure 6. In case of an antenna array, our limiting separating distance is determined by the separating distance between array elements. In case of $0.5\lambda_o$ center to center distance between two patches, the limit of sh is $0.25\lambda_o$.

4. SIMULATION AND MEASUREMENT ON ARRAY WITH AND WITHOUT SLOTS

Based on the investigations of Section 3, a reduction in mutual coupling in a two-element microstrip array will be achieved using two interdigital capacitor loaded slots. The space between the adjacent elements in an array is typically 0.5–$1.0\lambda_o$ at the operation frequency, where λ_o is the wavelength in free space. Based on the studies in [4, 20], the E-plane coupled two microstrip antennas separated by $0.5\lambda_o$ and constructed on a thick substrate exhibits a stronger mutual coupling compared

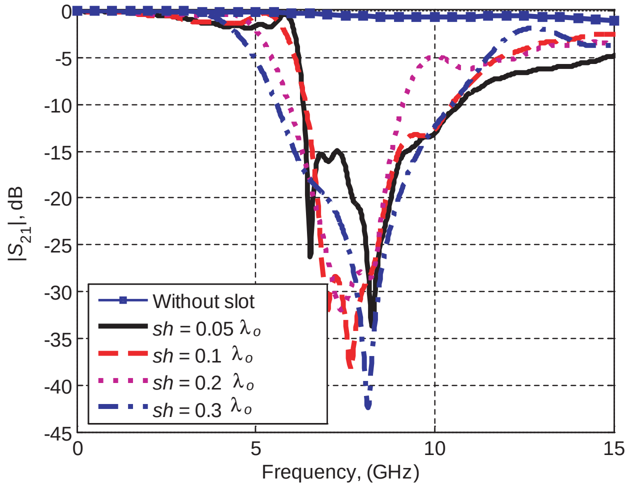


Figure 6. Effect of slots separation *sh* on S_{21}.

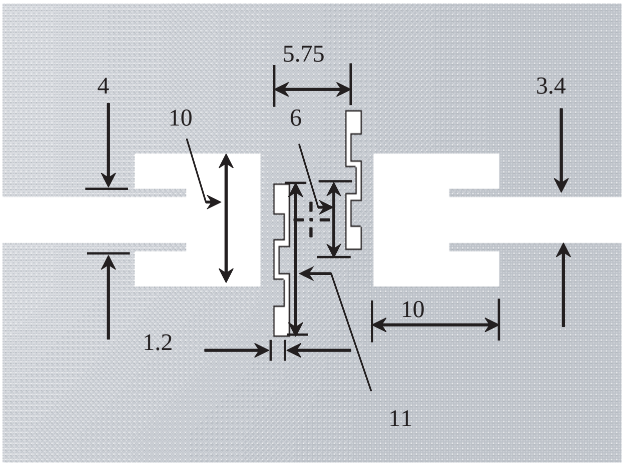
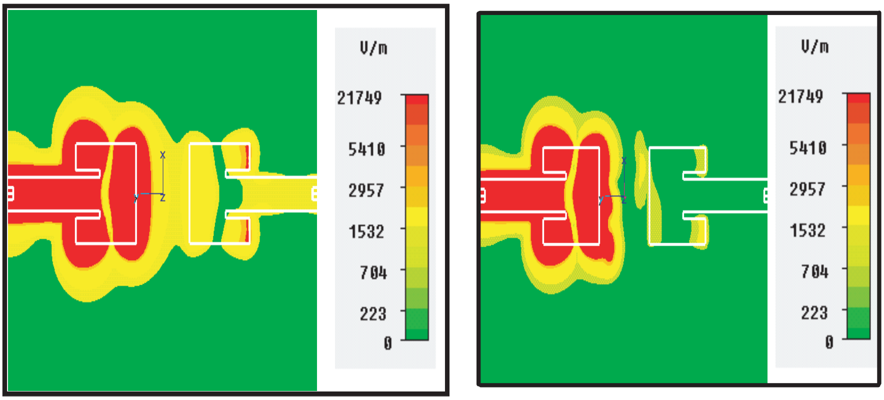


Figure 7. Layout of the proposed array with optimized slots position, all dimensions are in mm.

to the H-plane one. Furthermore, the mutual coupling dominantly results from the pronounced TM surface waves. Figure 7 illustrates the layout of a two-element microstrip antenna array with an operation frequency of 7.8 GHz. The patch size is $L \times W = 10 \times 10$ mm^2, and the space between the two elements is 19 mm corresponding to $0.5\lambda_o$ at the operation frequency. Each patch is excited on its symmetrical axis



(a) (b)

Figure 8. Total electric field inside the substrate for $z = 1\,\mathrm{mm}$ from the ground plane. (a) Without slots. (b) With slots.

by a $50\,\Omega$ microstrip with an inset of 4 mm to match the feed line to the patch. Figure 7 shows the optimum positions to achieve minimum coupling between elements.

To visualize the surface wave propagating inside the dielectric substrate, two identical arrays, with and without slots, were simulated with 3D-EM Simulator, Microwave Studio, 2009 [23]. This surface wave can clearly be observed in the plot of Figure 8(a) and Figure 8(b). In both figures, the array elements have been indicated with white lines. It is obvious from Figure 8(b) that the slots prevent most of the fields from crossing to the other element, which decreases the mutual coupling between array elements.

The effect of the substrate thickness on the coupling has been studied using two high frequency printed circuit boards RO4003 with a relative dielectric constant of 3.38 and thicknesses of 0.813 mm and 1.524 mm. The decoupling method works well. The dimensions of the slot should be optimized due to the change of its resonance with the thickness of the substrate. The simulated E- and H-plane radiation patterns of the array in the presence and absence of the slots is shown in Figure 9. To obtain a main lobe in broadside direction, the ports are fed with 180° phase difference.

The structure shown in Figure 7 has been designed and fabricated on a high frequency printed circuit board RO4003 with a relative dielectric constant of 3.38 and a thickness of 1.524 mm. A comparison between the simulated and measured mutual coupling between two elements is shown in Figure 10. Figure 11 shows the measured response

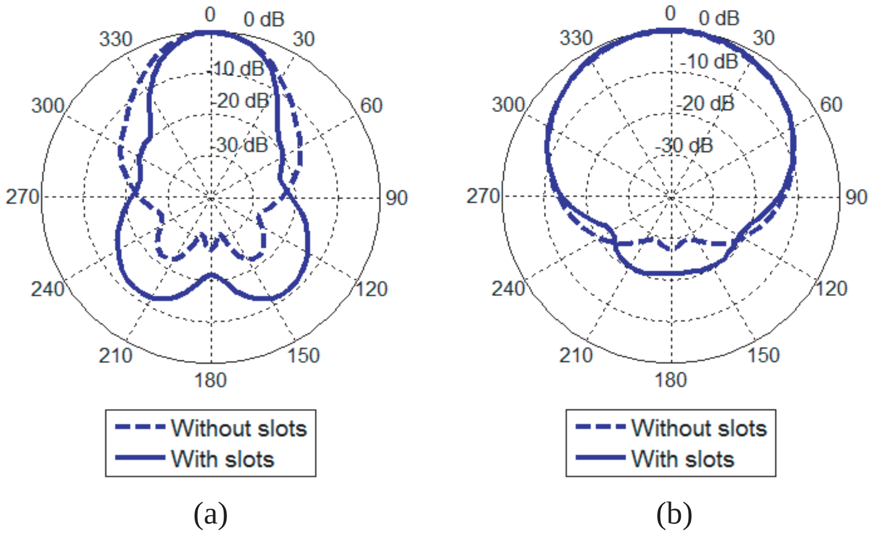


Figure 9. Radiation patterns (simulated) of the two-element array. (a) E-plane, (b) H-plane. Ports are fed 180° out of phase.

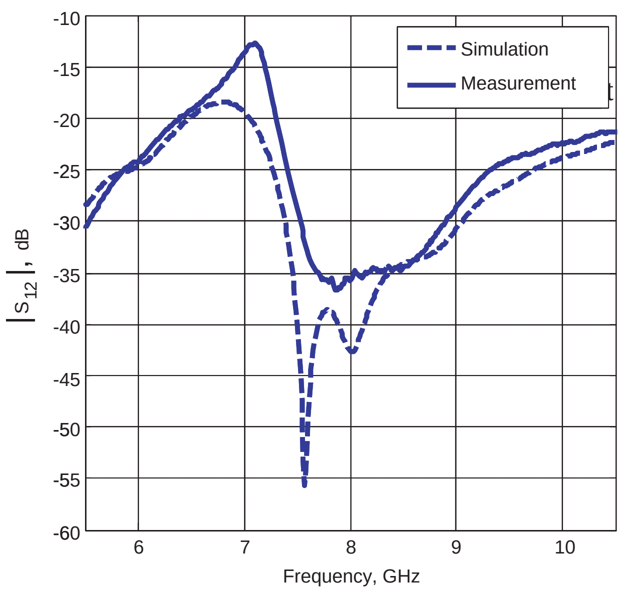


Figure 10. Simulated and measured mutual coupling of the array out of phase.

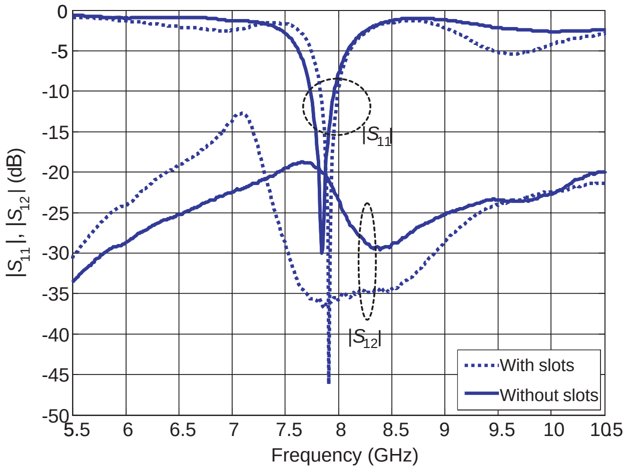
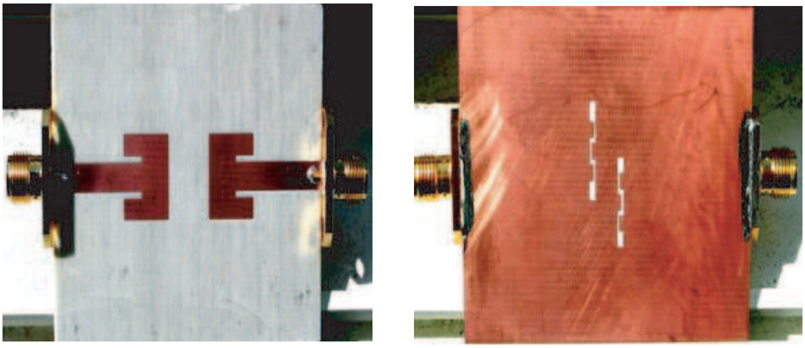


Figure 11. Measured S-parameters of the array with and without slots.



(a) (b)

Figure 12. Photograph of the fabricated array. (a) Top view. (b) Bottom view.

for the conventional structure without slots and proposed array with slots. Looking at the measured return loss of the element in array with and without the interdigital slots, it is observed that the antenna resonant frequency shifts from 7.8 GHz to 7.9 GHz due to the presence of the slots. The input ports have a good match. A significant mutual coupling of -19 dB is observed in the conventional microstrip array at the operating frequency. Employing the proposed interdigital slots in the array, the surface wave is suppressed remarkably and the mutual coupling between two elements drops to −36 dB. Therefore, a reduction in mutual coupling of 17 dB is obtained by applying the proposed interdigital slots technique. Figure 12 shows a photograph of the fabricated array. The results demonstrate the validity of the DGS in improving the performance of the microstrip phased array.

5. CONCLUSION

In this paper, we have introduced compact interdigital capacitor loaded ground plane slots to reduce significantly the mutual coupling between the elements of a microstrip antenna array. The coupling reduction has been achieved based on optimally positioning two bandstop resonators between the array elements. Two-element arrays with and without slots were presented. The antenna was designed, fabricated and measured. An improvement of isolation between array elements by 17 dB for the center to center distance of $0.5\lambda_o$ between the two patches at the operation frequency has been achieved due to the presence of the slots in the ground plane. The back lobe radiation has been increased because of the existence of the slots. Good agreement between simulated and measured results was achieved.

REFERENCES

1. Alexopoulos, N. G. and I. E. Rana, "Mutual impedance computation between printed dipoles," *IEEE Trans. Antennas Propag.*, Vol. 29, No. 1, 124–128, Jan. 1981.
2. Balanis, C. A., *Advanced Engineering Electromagnetics,* John Willy & Sons, New York, 1989.
3. Pozar, D. M. and D. H. Schaubert, "Scan blindness in infinite phased arrays of printed dipoles," *IEEE Trans. Antennas Propag.*, Vol. 32, 602–610, 1984.
4. Balanis, C. A., *Antenna Theory Analysis and Design,* 2nd edition, John Willy & Sons, 1997.
5. Yang, F. and Y. Rahmat-Sami, "Microstrip antennas integrated with electromagnetic band-gap (EBG) structures: A low mutual coupling design for array applications," *IEEE Trans. Antennas Propag.*, Vol. 51, No. 10, 2936–2946, 2003.
6. Zhang, L., J. A. Castaneda, and N. G. Alexopoulos, "Scan blindness free phased array design using PBG materials," *IEEE Trans. Antennas Propag.*, Vol. 52, No. 8, 2000–2007, 2004.
7. Iluz, Z. and R. Shavit, "Microstrip antenna phased array

with electromagnetic bandgap substrate," *IEEE Trans. Antennas Propag.*, Vol. 52, No. 6, 1446–1453, 2004.

8. Fu, Y., and N. Yuan, "Elimination of scan blindness in phased array of microstrip patches using electromagnetic bandgap materials," *IEEE Antennas Wirel. Propag. Lett.*, Vol. 3, 63–65, 2004.
9. Yang, H. Y. D. and J. Wang, "Surface waves of printed antennas on planar artificial periodic dielectric structures," *IEEE Trans. Antennas Propag.*, Vol. 49, No. 3, 444–450, 2001.
10. Yang, L., M. Fan, F. Chen, J. She, and Z. Feng, "A novel compact electromagnetic-bandgap (EBG) structure and its applications for microwave circuits," *IEEE Trans. Microw. Theory Tech.*, Vol. 53, No. 1, 183–190, 2005.
11. Farahani, H., M. Veysi, M. Kamyab, and A. Tadjalli, "Mutual coupling reduction in patch antenna arrays using a UC-EBG superstrate," *IEEE Antennas Wirel. Propag. Lett.*, Vol. 9, 57–59, 2010.
12. Werth, T. and J. Schoebel, "An electromagnetic bandgap enhanced active antenna design for microwave-based motion sensing," *European Microwave Conference 2007*, 980–982, Munich, Germany, Oct. 8–12, 2007.
13. Mandal, M. K. and S. Sanyal, "A novel defected ground structure for planar circuits," *IEEE Microw. Wirel. Compon. Lett.*, Vol. 16, No. 2, 93–95, 2006.
14. Abdel-Rahman, A., A. K. Verma, A. Boutejdar, and A. S. Omar, "Control of band stop response of Hi-Lo microstrip lowpass filter using slot in ground plane," *IEEE Trans. Microw. Theory Tech.*, Vol. 52, No. 3, 1008–1013, Mar. 2004.
15. Ahn, D., J. S. Park, C. S. Kim, J. Kim, Y. Qian, and T. Itoh, "A design of the low-pass filter using the novel microstrip defected ground structure," *IEEE Trans. Microw. Theory Tech.*, Vol. 49, No. 1, 86–93, Jan. 2001.
16. Kim, C. S., J. S. Lim, S. Nam, K. Y. Ang, and D. Ahn, "Equivalent circuit modeling of spiral defected ground structure for microstrip line," *Electron. Lett.,* Vol. 38, 1109–1111, 2002.
17. Lim, C. S., C. S. Kim, D. Ahn, Y. C. Jeong, and S. Nam, "Design of the low-pass filters using defected ground structure," *IEEE Trans. Microw. Theory Tech.,* Vol. 53, No. 8, 2539–2545, 2005.
18. Park, J. S., J. S. Yun, and D. Ahn, "A design of the novel coupled line bandpass filter using defected ground structure with wide stopband performance," *IEEE Trans. Microw. Theory Tech.*,

Vol. 50, No. 9, 2037–2043, 2002.

19. Salehi, M., A. Motevasselian, A. Tavakoli, and T. Heidari, "Mutual coupling reduction of microstrip antennas using defected ground structure," *10th IEEE Singapore Int. Conf. Communication Systems, ICCS 2006*, 1–5, Oct. 2006.
20. Hou, D.-B., S. Xiao, B.-Z. Wang, L. Jiang, J. Wang, and W. Hong, "Elimination of scan blindness with compact defected ground structures in microstrip phased array," *IET Microw. Antennas Propag.*, Vol. 3, No. 2, 269–275, 2009.
21. Vazquez, C., G. Hotopan, S. Ver Hoeye, M. Fernandez, L. F. Herran, and F. Las-Heras "Defected ground structure for coupling reduction between probe Fed microstrip antenna elements" *PIERS Proceedings*, 640–644, Cambridge, USA, Jul. 5–8, 2010.
22. Woo, D. J., T. K. Lee, J. W. Lee, C. S. Pyo, and W. K. Choi, "Novel U-slot and V-slot DGSs for bandstop filter with improved Q factor," *IEEE Trans. Microw. Theory Tech.*, Vol. 54, No. 6, 2840–2847, Jun. 2006.
23. Computer Simulation Technology Microwave StudioTM, 2009.