Mutual Coupling Reduction Using Defected Ground Structure (DGS) for Array Applications

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Abstract — **In this paper, a compact dumbbell shaped defected ground structure (DGS) is applied to reduce the mutual coupling between array elements with 0.47 λ_0 elements spacing. The dumbbell DGS is inserted in the E-plane between the adjacent array coupled elements to suppress the pronounced surface waves. A four-element array with dumbbell shaped DGS is designed, fabricated on a substrate with dielectric constant of 10.2 and thickness of 1.27mm and measured. The results show that a reduction in mutual coupling of 35.6 dB is obtained between elements at the operation frequency of the array. The microstrip arrays with and without DGS are studied by the waveguide simulator method and fabricated by photolithographic technique. The analysis indicates that increasing number of dumbbells reduces the mutual coupling between elements. However, the gain and bandwidth are reduced. The results agree with those obtained by the waveguide simulator method.**

Keywords-mutual coupling; defected ground structures; microstrip antenna array.

I. INTRODUCTION

Mutual coupling is a well-known effect in multi-element array antennas. Generally, mutual coupling is an unwanted phenomenon that distorts the behavior of the radiating elements in an antenna array. Every element in an antenna array affects every other element by radiating over the air or by propagating surface currents through the ground plane. Surface currents can be a bigger problem, especially when antenna elements are closely packed. Microstrip patch antennas are well-known antenna types in different kinds of applications, like mobile, airborne and satellite communications. In general, the structure has a thin metallic patch, usually copper, printed on a microwave substrate. The characteristics of microstrip patch antennas are a low profile, light weight, and easy fabrication and design for 50 Ω transmission lines. On the other hand, the antennas have narrow bandwidth and low gain. In practice, an array of several antenna elements is used for applications requiring high gain and/or high directivity. However, the performance of such antennas tends to drop due to the strong mutual interaction between the antenna elements.

Several coupling mechanisms exist in microstrip patch antennas. These coupling mechanisms can be categorized into three main types: surface waves, near-field, and space waves coupling as shown in Fig. 1. In practice, any of those coupling mechanisms can dominate over others depending on many factors: ground plane size, substrate material and its thickness, and type of modes that are excited by the patch antenna and the grounded dielectric slab. Surface waves coupling dominate in situations where patch antennas are printed on a very thick dielectric slab with high permittivity [1]-[2]. These waves are supported by the dielectric slab, propagate and diffract once reaching the edges of the grounded dielectric slab as shown in Fig. 1. The near-field coupling arises when an antenna is placed in the near-field zone of another antenna. This coupling mechanism is strong in situations where the antennas are printed on dielectric substrates with very low permittivity [3]. In such scenarios, the coupling can result in severe degradation to the antenna's radiation characteristics. While surface wave is weakly excited in very thin grounded dielectric substrates, another mechanism of coupling, known as space-wave coupling, dominate and show strong coupling when antennas are in close-proximity.

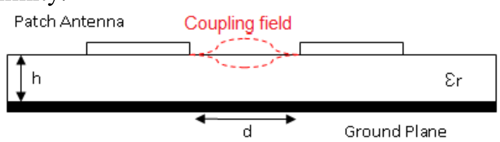


Figure 1. Coupling source between adjacent microstrip antenna elements

This space-wave coupling has a dominant electric field component that is normal to the grounded slab.

There are many methods for reducing the effects of mutual coupling, which include optimizing antenna dimensions [4], grooving the dielectric [5], covering the patch by additional dielectric layers [6], using shorting pins to cancel the capacitive polarization currents of the substrate [3], adding parasitic conducting tape to the middle of two antennas [7, 8], using the dielectric as a band gap structure between elements in the array [9, 10], or using defected ground structures (DGSs) technique which are widely used in microwave circuit and antenna design because they produce the band rejection characteristics similar to EBG structures but with a more compact size [11-18]. However, few researches focus on suppressing element mutual coupling based on DGS techniques.

In this paper, a compact dumbbell shaped defected ground structure (DGS) is applied to reduce the mutual coupling between array elements and reduce the array elements spacing to 0.47 λ_0. The dumbbell DGS is inserted between the adjacent E-plane coupled elements in the array to suppress the pronounced surface waves. A linear and planar four-element array with and without dumbbell shaped DGS are studied. The results show that a reduction in mutual coupling of 35.6 dB is obtained between elements at the operation frequency of the array.

II. ANTENNA DESIGN AND SIMULATIONS

This section is divided into three parts. The first part discusses the geometry of the two elements microstrip patch array arranged on substrate with and without DGS in ground plane. The second part presents the mutual coupling reduction for linear four elements microstrip antenna arrays. The last part of this section shows planar four elements microstrip antenna arrays in E- and H-plane. Each antenna structure is modeled in CST Design Suite 2010 in which extensive full-wave analysis is performed.

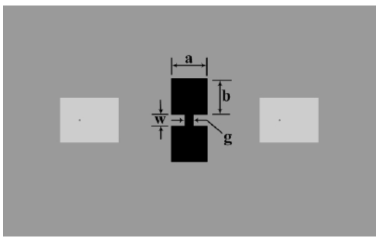


Figure 2. 1 cell Dumbbell shape DGS in between two Elements Array

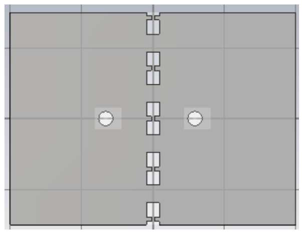


Figure 3. 5 cells Dumbbell shape DGS in between two Elements Array

A. Two Elements Array

The E-plane coupled microstrip patch antenna arrays suffer from strong mutual coupling because of surface waves. Due to the capability of DGS to suppress surface waves, a single dumbbell shape of DGS was inserted between two antenna elements in order to reduce the mutual coupling as shown in Fig. 2, and increased to five cells of dumbbell shape as shown in Fig. 3.

CST numerical simulation was used to simulate the E-plane coupled microstrip antennas on a dielectric substrate with ε_r = 10.2, h = 1.27 mm. To obtain the resonant frequency at 5.64 GHz, the rectangular patch's size was 7.375 mm x 6 mm, and to avoid the grating lobe, the distance between the patches was 25 mm (0.47λ_0). The defected ground plane is 80 mm x 60 mm (1.5λ_0 x 1.2λ_0) at resonant frequency to avoid fringing effect. Each patch is TM_{10} mode excited by a matched coaxial feed 0.7375 mm away from the patch center. The optimum values of the structural parameters of the dumbbell shape DGS are a = 3.6 mm, b = 4 mm, w = 1.24 mm, and g = 0.85 mm. The simulated mutual coupling (S_{21}) and reflection coefficient (S_{11}) in both cases (i.e., with and without DGS) are compared in Table I. It is observed that DGS antenna resonant frequency shifts downward with respect to the conventional antenna. This small frequency shift is due to slow-wave effects of DGS. The conventional antenna shows a very strong coupling of -15.13 dB due to surface waves pronounced in thick, high permittivity substrate. Since the resonant frequency of the antenna falls inside the DGS band gap, surface waves are suppressed and simulations show that mutual coupling drops to -42.24 dB which is 27.11 dB lower than the conventional one, but with reduction in gain and efficiency.

TABLE I. TWO ELEMENTS ARRAY WITHOUT AND WITH DGS CELLS

Parameters	**Without DGS**	**With 1 cell DGS**	**With 5 cells DGS**
F (GHz)	5.646	5.632	5.616
$\lvert S_{11}\rvert$ (dB)	-29.63	-22.6	-24.2
$\lvert S_{21}\rvert$ (dB)	-15.13	-20.4	-42.24
B.W. %	1.29	1.35	1.39
Gain (dB)	8	7.05	6.6
SLL (dB)	-23.3	-7.6	-7.7
Radiation Efficiency	82 %	86 %	64.16 %
Antenna Efficiency	80 %	85 %	64 %

B. *Linear Four Element Arrays*

As shown in Fig. 4, the four elements microstrip patch antennas on a dielectric substrate with ε_r = 10.2, h = 1.27 mm. The distance between the patches is 25 mm (0.47λ_0). The defected ground plane is 130 mm x 60 mm (2.4λ_0 x 1.2λ_0) at resonant frequency. Each patch is TM_{10} mode excited by a matched coaxial feed 0.7375 mm away from the patch center. From Table II, it is noticed that DGS antenna resonant frequency shifts downward with respect to the conventional antenna. This small frequency shift is due to slow-wave effects of DGS. The conventional antenna array in E-plane shows a very strong coupling of -15dB due to surface waves pronounced in thick, high permittivity substrate. Since the resonant frequency of the antenna falls inside the DGS band gap, surface waves are suppressed and simulations show that mutual coupling drops to -35 dB which is 20 dB lower than the conventional one, but with reduction in gain and efficiency as shown in Fig. 6. On the other hand, conventional antenna array in H-plane have mutual coupling increasing with DGS, but the gain and efficiency are slightly increased.

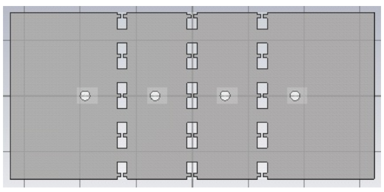


Figure 4. Linear four elements array in E-plane

TABLE II. LINEAR FOUR ELEMENTS ARRAY IN E- AND H-PLANE

Parameters	E-plane		H-Plane	
	Without DGS	*With DGS*	*Without DGS*	*With DGS*
F (GHz)	5.646	5.628	5.64	5.592
$\lvert S_{11}\rvert$ (dB)	-28.5	-17	-34.3	-24.9
$\lvert S_{21}\rvert$ (dB)	-15	-35	-17.7	-15.03
$\lvert S_{32}\rvert$ (dB)	-14.7	-29	-17.1	-14.38
$\lvert S_{41}\rvert$ (dB)	-24.4	-25	-35.2	-32.3
$\lvert S_{43}\rvert$ (dB)	-15	-30.5	-17.5	-14.6
B.W. %	1.3	1.5	1.2	1.1
Gain (dB)	11.07	6.6	9.8	9.99
SLL (dB)	-13.2	-10	-10.6	-10.4
Radiation Efficiency	82 %	65 %	89 %	90 %
Antenna Efficiency	78 %	61 %	87 %	88 %

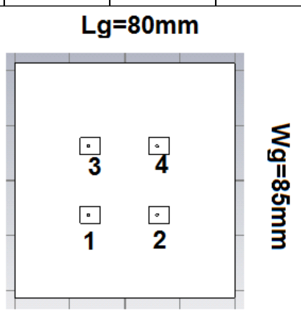


Figure 5. Planar four elements array in E-plane

TABLE III. PLANAR FOUR ELEMENTS ARRAY IN E- AND H-PLANE

Parameters	E-plane		H-Plane	
	Without DGS	*With DGS*	*Without DGS*	*With DGS*
F (GHz)	5.646	5.58	5.646	5.58
$\lvert S_{11}\rvert$ (dB)	-36.32	-23.74	-36.32	-23.74
$\lvert S_{21}\rvert$ (dB)	-14.9	-22.08	-17.6	-22.08
$\lvert S_{31}\rvert$ (dB)	-18.2	-13.4	-14.4	-13.4
$\lvert S_{41}\rvert$ (dB)	-33.72	-25.95	-30.96	-25.95
$\lvert S_{43}\rvert$ (dB)	-14.9	-22.08	-17.3	-22.08
$\lvert S_{42}\rvert$ (dB)	-17.9	-13.6	-14.4	-13.6
B.W. %	1.2	0.9	1.3	0.9
Gain (dB)	10.2	9.54	10.04	9.54
SLL (dB)	-25.2	-6.3	-23.9	-6.3
Radiation Efficiency	87 %	88 %	87 %	88 %
Antenna Efficiency	83 %	87 %	83 %	87 %

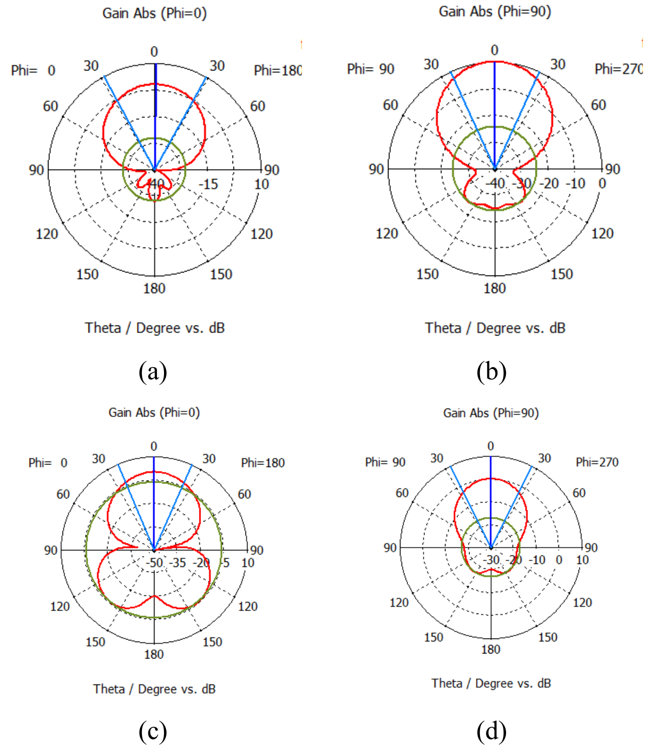


Figure 6. Simulated radiation pattern for E-plane linear four elements antenna array (a) Without DGS Phi= 0^o, (b) Without DGS Phi= 90^o ,(c) With DGS Phi= 0^o, and (d) With DGS Phi= 90^o

C. *Planar Four Element Arrays*

The four elements microstrip patch antennas on a dielectric substrate with ε_r = 10.2, h = 1.27 mm. The distance between the patches is 25 mm (0.47λ_0). The defected ground plane is 80 mm x 85 mm (1.5λ_0 x 1.6λ_0) at resonant frequency. Each patch is TM_{10} mode excited by a matched coaxial feed 0.7375 mm away from the patch center as shown in Fig. 5.

As shown in Table III, it is observed that DGS antenna resonant frequency shifts downward with respect to the conventional antenna. This small frequency shift is due to slow-wave effects of DGS. The conventional antenna array in E-plane shows a very strong coupling of -14.9 dB due to surface waves pronounced in thick, high permittivity substrate. Since the resonant frequency of the antenna falls inside the DGS band gap, surface waves are suppressed and simulations show that mutual coupling drops to -22.08 dB which is 7.18 dB lower than the conventional one, but with slightly reduction in gain and small increase in efficiency. Also, in the H-plane array there is a little reduction in the mutual coupling, slightly reduction in gain and small increase in efficiency.

III. EXPERIMENTAL RESULTS AND DISCUSSION

To verify the conclusions drawn from the simulation, two microstrip antennas are fabricated on Roger RT/Duroid 6010 substrates. The permittivity of the substrate is 10.2, and the substrate thickness is 1.27 mm (50 mil). Fig. 7 shows a photograph of the fabricated two elements antennas with and without the DGS. The antenna's size is 7.375 mm x 6 mm, and the distance between the antennas' center is 25 mm ($0.47\lambda_0$). The antennas are fabricated on a ground plane of 80 mm x 60 mm ($1.5\lambda_0$ x $1.2\lambda_0$). Comparison between measured values without and with DGS are reported in Table IV. Linear four elements Array are fabricated on the previous substrate parameters as shown in Fig. 8. The measured results without and with DGS are compared in Fig. 9. Comparison between measured values without and with DGS are reported in Table V. It is observed that both antennas resonate at 5.646 GHz with return loss better than 10 dB. For the antennas without the DGS structure, the mutual coupling at 5.86 GHz is -15 dB. In comparison, the mutual coupling of the antennas with the DGS structure is 35 dB. An approximately 20 dB reduction of mutual coupling is achieved at the resonant frequency of 5.646 GHz. This result agrees well with the simulated results. From this experimental demonstration, it can be concluded that the DGS can be utilized to reduce the antenna mutual coupling between array elements.

(a)

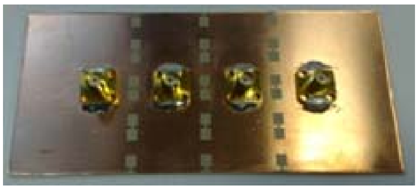
(b)

Figure 7. Fabricated E-plane two elements antenna array (a) Without DGS, (b) With DGS

TABLE IV. MEASURED VALUES OF TWO ELEMENTS ARRAY IN E-PLANE WITHOUT AND WITH DGS

Parameters	Without DGS	With DGS
F (GHz)	5.646	5.628
$\lvert S_{11}\rvert$ (dB)	-28.5	-17
$\lvert S_{21}\rvert$ (dB)	-15	-35
B.W. %	1.3	1.5

(a)



(b)

Figure 8. Fabricated E-plane four elements antenna array (a) Without DGS, (b) With DGS

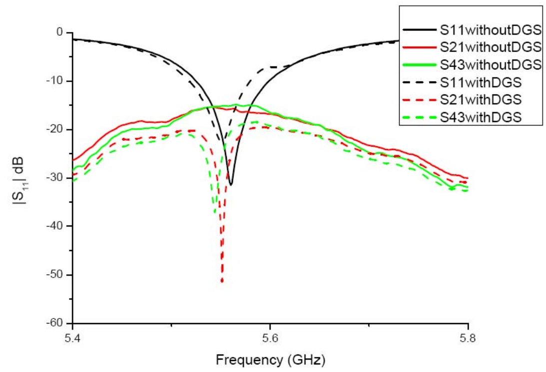


Figure 9. Measured values of four elements array(a) Without DGS, (b) With DGS.

TABLE V. MEASURED VALUES OF LINEAR FOUR ELEMENTS ARRAY IN E-PLANE WITHOUT AND WITH DGS

Parameters	Without DGS	With DGS
F (GHz)	5.646	5.628
$\lvert S_{11}\rvert$ (dB)	-28.5	-17
$\lvert S_{21}\rvert$ (dB)	-15	-35
$\lvert S_{32}\rvert$ (dB)	-14.7	-29
$\lvert S_{41}\rvert$ (dB)	-24.4	-25
$\lvert S_{43}\rvert$ (dB)	-15	-30.5
B.W. %	1.3	1.5

IV. CONCLUSION

In this paper, a low mutual coupling design for a two-element microstrip antenna array was proposed. A dumb-bell shaped defect on the ground plane of the antenna is inserted between the patches creating a band gap in the operation frequency band of the antenna. By suppressing the surface waves, it provides a very low mutual coupling between array elements. The DGS antenna was analyzed using a finite integration technique (FIT) and a mutual coupling reduction of 20 dB was achieved. Radiation patterns have minimal change in the broadside direction but back lobe level is increased. However, the gain and the efficiency are decreased.

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