Novel Design of Cavity-Backed Slot Antenna by Reformed Ground Plane (Corner Notch and Stepped) and Elongated Mushroom (EM)-EBG

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Abstract **─** A common problem for the performance of a Cavity-Backed Slot (CBS) antenna could be the heavily effect of ground plane. Travelling surface currents on ground plane could cause destructive effect on the characteristics of CBS antenna. This mainly appears on gain back lobe and also Front to Back Ratio (FBR) of pattern. To resolve this problem, the stepped ground plane and the Extended Mushroom Electromagnetic Band-Gap (EM-EBG) structure was introduced, which could minimize ground plane effects by changing the current distribution. Good agreement was achieved between the simulated and measured results. Experimental results showed that on a frequency range over 14-16 GHz, the gain was better than 11 dB and FBR of pattern in the H-plane reached to 26 dB.

Index Terms **-** Cavity-backed slot antenna, corner notch ground, elongated mushroom EBG, stepped ground, surface currents.

I. INTRODUCTION

In many applications, the antenna should be located in close proximity to earth, be mounted on a platform or be integrated with the rest of the transceiver in a multilayer structure. To improve the adverse effects of the interactions between a slot antenna and the structures behind it, traditionally a shallow cavity is placed behind such an antenna. Therefore, cavity-backed slot antennas extensively have been studied from various views in [1]-[3]. Analyzing CBS antenna characteristics, such as impedance and radiation pattern, has been done by Calejs [3]. CBS antennas are relatively light-weighted, low-profile and relatively high-directivity. One of the significant features of CBS antenna is its capability to mount on the surface of airborne and aircraft applications [4]. Therefore, CBS antenna has been one of most practical antennas in satellite communication, broadcast TV, aircraft and mobile communication [4-5].

Cavity back loading improves some characteristics of antennas, as recent study has been shown its influence on antenna engineering [18]. One of the drawbacks of the finite ground CBS antenna is its high back lobe that reduces the main directive radiation. Unwanted surface currents on ground plane destruct the pattern [6]. When traveling, surface currents on finite ground plane reach edges and they radiate in all directions. Therefore, the antenna gain is reduced and as a result back lobes of the pattern are increased. Also in antenna arrays, surface currents cause mutual coupling [6]. Several methods have been analyzed to compensate destructive surface currents effect, such as using absorber, slits [7] and EBG or high impedance structures [8]. These structures suppress surface currents in their band gap, because EBGs support none of the surface wave propagation modes in their resonance band [9]. EBG structures are periodic patterns created by metallic vias in dielectric or magnetic materials. EBGs have various types, such as mushroom-like and uniplanar that were investigated recently [6]-[11] and [16]-[17]. A compact Elongated Mushroom Electromagnetic Band-Gap (EM-EBG) structure, exploiting the

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thickness of the substrate to achieve higher isolation compared to the case of the Conventional Mushroom EBG (CM-EBG), is proposed in [12].

In this paper, a new technique for reducing the back lobe of CBS antenna is presented. The technique is based on corner notched and stepped ground plane and utilizing EBG (Design 4). Basically, the ground plane of the CBS antenna is initially changed by using corner notched. In order to increase ground plane physical length, ground plane is stepped and reduction in the back lobe of CBSA pattern is observed. By mounting EM-EBG on the antenna, travelling surface wave on the structure is confined and FBR is improved. In the next section, 4 designs of ground plane of CBS antenna is investigated. First, similarities and differences of each design will be discussed and then numerical and measurement results of them will be presented and compared.

II. DESIGNS AND NUMERICAL SIMULATION

The four stage design configuration of the proposed CBS antenna with optimized dimensions is shown in Fig. 1. All designs comprise of three parts: ground plane with slot in center, open end cavity and electrical probe for stimuli antenna. In all stages, we try to design the antenna to work at 15 GHz with return loss less than -10 dB. All designs have the same dimension and the only difference is the shape of ground plane. The first design is a conventional Ku band cavity-back slot similar to antenna that presented in [7], with finite rectangular ground plane that is shown in Fig. 1 as Design 1. Design 2 is a corner notched ground plane and the third design is a CBS antenna with non-flat ground plane, which has step in four directions to suppress currents on edges as shown in Fig. 1.

In this design, the cross section lengths of waveguide with dominate mode of TE_{10} at 15 GHz is calculated by 11.5 mm to excite the antenna [13]. The dimension of the slot is equal to waveguide's cross section. Also, the waveguide's height's is 3 cm and excitation probe is placed 2.782 cm below ground plane middle of waveguide's length. The slot's width is 5 mm ($\lambda/4$) and probe length is 4 mm ($\lambda/5$), where λ is wave length of resonance frequency at 15 GHz. Length and width of reference ground plane are 44 mm and 37 mm, as shown in Fig. 1.

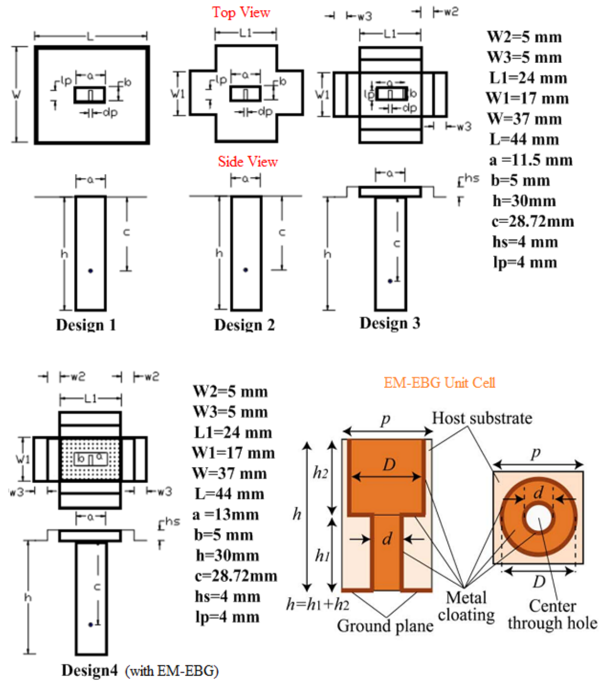

Fig. 1. Schematic diagram of top and side view of four designs of CBS antenna: Design 1: conventional CBS antenna [14]-[15]; Design 2: conventional CBS antenna with corner notched ground plane; Design 3: conventional CBS antenna with corner notched and stepped ground plane (W2=5, W3=5, L1=24, W1=17, W=37, L=44, a=11.5, b=5, h=30, c=28.72, hs=4, lp=4); Design 4: conventional CBS antenna with corner notched and stepped ground plane and EM-EBG [12] (W2=5, W3=5, L1=24, W1=17, W=37, L=44, a=13, b=5, h=30, c=28.72, hs=4, lp=4, P =1.7, D=1.5, d=0.4, $2\times h_1=2\times h_2=h=1.52$); (unit: mm).

As mentioned above, the difference of three antenna designs is the ground plane shape. In Design 1 (D-1), the ground plane is set to reference plane. This design is similar to CBS antennas, which was presented by Georgakopoulos [14]-[15]. To compensate the current flow on the edges, corner notch on ground is used. Therefore, the ground plane divided into two main parts: internal ground plane (which dimension are $L_1\times W_1$) with slot and edges (Design 2 or D-2). For more compensation of currents on edges, non-planar ground plane is presented (D-3). In the third design, the ground plane includes three parts: internal ground plane with slot, steps and edges; which internal ground and edge are planar and steps are elevated. The dimension of internal ground for Design 2 and 3 is 24 mm×17 mm. For comparison, the simulation results of Designs 1, 2 and 3 are presented in Fig. 2. Figure 2 (a) shows H-plane radiation pattern of Design 1-3 at 15 GHz. From Fig. 2, we figure out that Design 3 has better directivity compared to Designs 1 and 2. Also, comparison between Designs 1 and 2 show that corner notched ground plane improved FBR from 10.2 to 10.6 dB at 15 GHz. Also, the results show that applying steps in D-3 improved FBR more than 20 dB (Fig. 2 (a)). Designs 1 and 2 have similar impedance bandwidth. Figure 2 (b) presents the return loss of all designs, which have good impedance bandwidth at 15 GHz. It can be seen that Design 3 has the best return loss at 15 GHz (less than -27 dB) and its bandwidth is 700 MHz.

The simulated peak gain of designs at 15 GHz is plotted in Fig. 2 (c). It can be seen that Design 3 has the best gain, approximately 11 dB in bandwidth with flatness less than 1 dB. In Fig. 2 (d), the current distribution of Designs 1, 2 and 3 on ground plane are shown. For D-1, the direction of current distribution is in width alignment. In D-2, the path of current distribution is in both width and length alignment. When current distribution along both sides is similar, back lobe of pattern are decreased.

This electromagnetic phenomenon is probably a result of converting traveling wave to standing wave. In Figs. 3 and 4, effect of slot and waveguide's width *(=b)*, probe length, position of excitation *(=c)* and waveguide's height *(=h)* variations are shown.

Simulation results revealed that slot and waveguide's width is effective on return loss of all three designs, but it does not affect the peak gain and FBR of pattern. Consequently, the best return loss is obtained when probe length reaches 4 mm. Furthermore, the return loss for Designs 1 and 2 are the same as the probe length is changed. In addition, variation of probe's position changes return loss considerably, but it does not have any significant influence on gain and FBR.

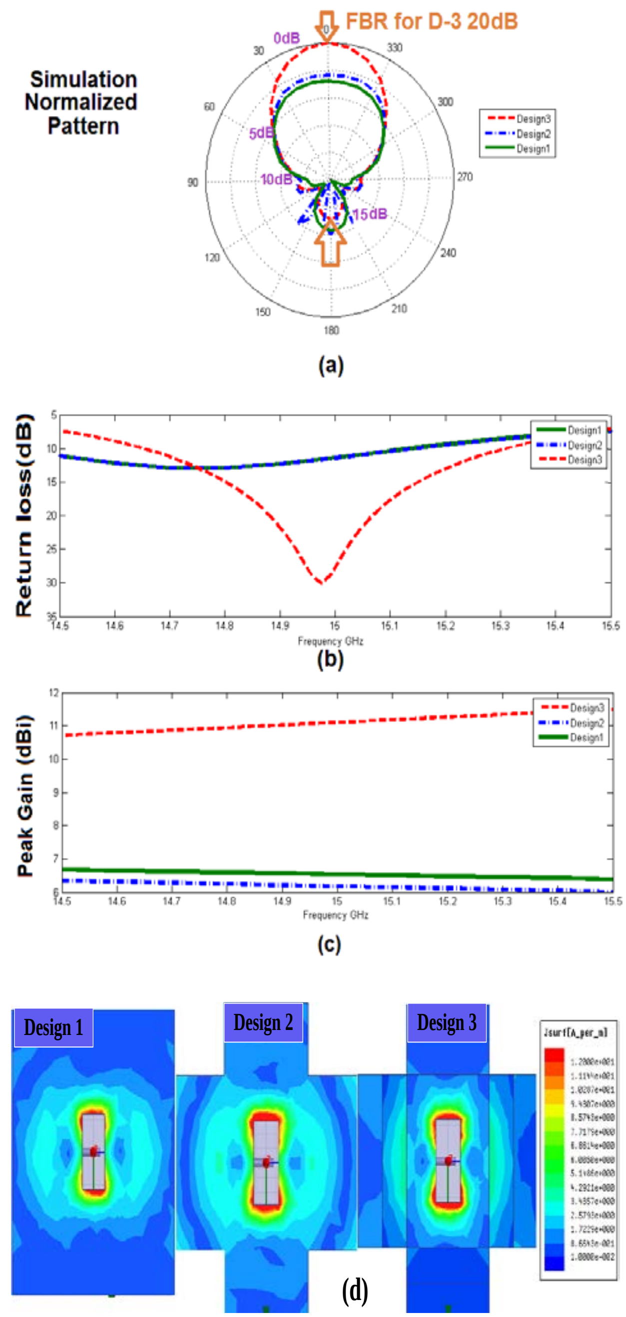

Fig. 2. Comparison of performance of three antenna designs: (a) H-plane pattern, (b) return loss, (c) peak gain and (d) current distribution on ground plane.

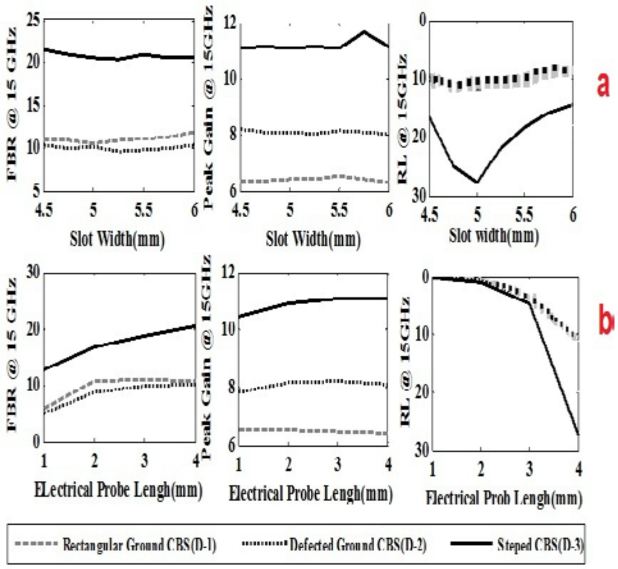

Fig. 3. Return loss and peak gain and FBR of pattern simulation results of Designs 1, 2 and 3 (D-1, 2, 3) of antenna at 15 GHz: (a) slot and waveguide's width effect and (b) probe length.

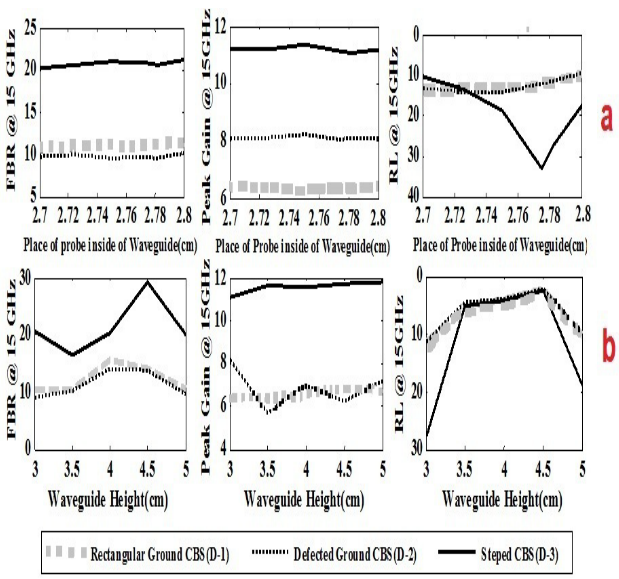

Fig. 4. Return loss and peak gain and FBR of pattern simulation results of Designs 1, 2 and 3 (D-1, 2, 3) of antenna at 15 GHz: (a) position of excitation probe effect (cm) and (b) waveguide's height (cm).

Antenna characteristics are sensitive to height. In order to complete the study of the antenna, we investigate the effect of ground plane dimension on antenna's performance separately. Results of variation of each parameter such as external and internal dimension (W, L, W_1 and L_1), step height (hs), step width (W_2), and edge's width (W_3) for D1, D2 and D3 are presented on Tables 1-5. It is observed that for conventional CBS antenna (D-1, 2) the dimension of ground has no effect on input impedance of the antenna [7]. In D-3, steps increase effective length of current distribution path. Therefore, current flow in both directions is decreased. Also, current distribution along width direction is more effective on FBR. In this work, EM-EBG is designed to suppress current distribution at 15 GHz (for Design 4) and we use RF35 Taconic substrate with permittivity of 3.5 and height of 1.52 mm. The EM-EBG is designed by using standard design equations [12], h_1 and h_2 are equal half of substrate height; via diameters is 1.5 mm for height (=h_1) and 0.4 mm for (=h_2) and distance between two adjacent via is 1.7 mm. Also, the optimized value of P (period of unit cell) and D (diameter of top hole and diameter of bottom hole) are 1.7 mm, 1.5 mm and 0.4 mm, respectively. In the next section, we add EM-EBG structure to D-3 and finalize the design.

Dimension of EM-EBG has adjusted to internal part of ground plane of D-3 with slot in center of structure. The dimensions of antenna using parametric analyzed by HFSS and designers experience, has been shown in Fig. 1.

Table 1: Effect of variation of length (=L) and width (=W) of ground plane on D-1 on antenna characteristic

L(mm)	W(mm)	FBR(dB)	Peak Gain)	RL(dB)
44	35	9.1	8.06	11.09
44	36	9.17	8	11.11
44	37	10.22	8.12	11.36
44	38	12.89	7.74	11.51
44	39	12.48	7.74	11.64
42	37	10.36	8.08	11.42
43	37	10.22	8.1	11.43
44	37	10.22	8.12	11.36

Table 2: Effect of variation of ground plane dimensions on D-2 on antenna characteristic

L	W	L1	W1	FBR	Peak Gain	RL
mm	mm	mm	mm	dB	dB	dB
44	37	22	17	10.9	6.34	11.27
44	37	23	17	10.91	6.42	11.33
44	37	24	17	10.66	6.45	11.36
44	37	25	17	10.78	6.4	11.46
44	37	26	17	11.13	6.46	11.47
44	37	24	13	12.71	6.43	11.42
44	37	24	15	11.63	6.42	11.42
44	37	24	17	10.66	6.43	11.42
44	37	24	19	9.9	6.37	11.4
44	37	24	21	9.34	6.44	11.39
44	31	24	17	8.12	6.91	11.42
44	33	24	17	8.16	6.9	11.43
44	35	24	17	8.71	6.88	11.43
44	37	24	17	10.66	6.43	11.42
44	39	24	17	11.14	6.41	11.34
44	41	24	17	11.3	6.37	11.4
42	37	24	17	11.16	6.54	11.5
43	37	24	17	11.19	6.43	11.42
44	37	24	17	11.51	6.43	11.42
45	37	24	17	10.65	6.44	11.37
46	37	24	17	10.1	6.52	11.6

Table 3: Effect of variation of ground plane dimensions on D-3 on antenna characteristic, which L=44 and W=37

L1	W1	FBR	Peak Gain	RL
mm	mm	dB	dB	dB
20	17	20.89	10.86	23.9
21	17	20.24	10.59	24.1
22	17	20.3	11	25.6
23	17	20.73	11.7	27.4
24	17	20.58	11.1	27.7
24.5	17	20.58	11.1	27.8
25	17	20.79	11.1	31.3
26	17	21.43	11.18	31.3
27	17	22.12	11.15	35.2
24	13	21.31	10.97	13.8
24	14	21.91	10.97	13.8
24	15	21.96	11.06	17.3
24	16	21.01	11.13	23.1
24	17	20.68	11.1	29.8
24	18	20.7	11.06	20.2
24	19	19.93	10.95	15.4
24	20	19.81	10.66	12.4
24	21	19.97	10.57	12.2

Table 4: Effect of variation of step (hs) on D-3 on antenna characteristic

Alignment	Dimension(mm)	FBR(dB)	Peak Gain(dB)	RL(dB)
width	1	14.05	5.518	13.49
width	2	19.51	5.99	16.19
width	3	24.02	8.419	19.91
width	4	24.96	10.05	24.59
width	5	26.24	10.47	22.24
width	6	26.72	9.63	16.01
width	7	28.47	8.42	13.24
width	8	32.05	8.02	12.39
Length	1	10.95	8.1	11.3
Length	2	11.4	8.29	10.93
Length	3	11.65	8.31	10.7
Length	4	11.52	8.43	10.51
Length	5	11.35	8.46	10.33
Length	6	10.32	8.42	10.33
Length	7	10.72	8.38	10.3
Length	8	9.84	8.29	10.33
Both side	1	20.68	7.67	13.3
Both side	2	18.16	8.74	15.95
Both side	3	18.91	10.15	20.17
Both side	4	20.68	11.1	27.7
Both side	5	24.98	11.41	26.54
Both side	6	31.3	11.14	18.8
Both side	7	30.44	10.48	15.05
Both side	8	32.8	9.48	13.52

Table 5: Effect of variation of width of step (w2) and width of edges (w3) on D-3 on antenna characteristic

	W_2	W_3	FBR	Peak Gain	RL
Alignment	mm	mm	dB	dB	dB
Width	9	1	22.64	10.52	34.63
Width	8	2	24.31	19.42	30.61
Width	7	3	24.06	10.7	27.82
Width	6	4	25.06	11.05	27.5
Width	5	5	20.57	11.1	27.73
Width	4	6	19.6	11.17	30.66
Width	3	7	18.14	11.18	36.83
Width	2	8	17.17	10.91	34.84
Width	1	9	16.79	10.26	25.2
Both side	9	1	22.7	10.35	28.58
Both side	8	2	21.71	10.59	28.39
Both side	7	3	21.11	10.82	27.43
Both side	6	4	22.06	11.1	26.44
Both side	5	5	20.57	11.1	27.73
Both side	4	6	19.82	11.23	32.06
Both side	3	7	19.74	10.94	42.62
Both side	2	8	18.76	10.64	35.76
Both side	1	9	18.29	10.03	26.86
Length	9	1	19.48	11.33	26.87
Length	8	2	19.49	11.27	27.38
Length	7	3	19.46	11.23	27.46
Length	6	4	20.07	11.12	28.03
Length	5	5	20.57	11.1	27.73
Length	4	6	23.65	11.14	30.25
Length	3	7	24.24	11.05	30.46
Length	2	8	22.92	10.92	33.67
Length	1	9	23.7	10.83	33.66

III. FORMATTING OF EQUATION, FIGURE AND REFERENCE

By adding EM-EBG to Design 3, input impedance is changed and return loss is destructed. In order to have better input impedance in 14-16 GHz, we change the slot and waveguide length *(=a)* from 11.5 mm to 13 mm. Figure 5 shows the photo of a CBS antenna with and without EBG. Geometry parameters of the fabricated antennas are chosen to achieve the optimum performance as predicted from the parametric analysis described in Section 2. Figures 6 and 7 show the measured and simulated return loss and peak gain and FBR of the fabricated prototype. From simulation results in Figs. 6 and 7, it can be seen that by adding EM-EBG and adjusting slot or waveguide length *(=a)* (from 11.5 mm to 13 mm), the FBR and return loss at 15 GHz are improved. The gain and radiation pattern were measured using the ETS 3115 system. It is clearly distinct that results of these two investigations closely meet each other and sometimes the measurement results are dominant. This may be due to little differences of the substrate between the practical and simulated models. In addition, the dielectric constant and dissipation factor are not stable when the frequency increases. In order to more discuss the principle of EM-EBG on antenna performance, the simulated electric field distribution of the antenna is shown in Fig. 8.

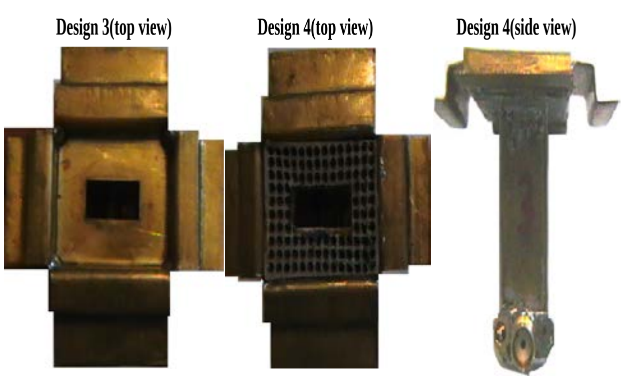

Fig. 5. Photograph of fabricated prototypes with and without EM-EBG structure.

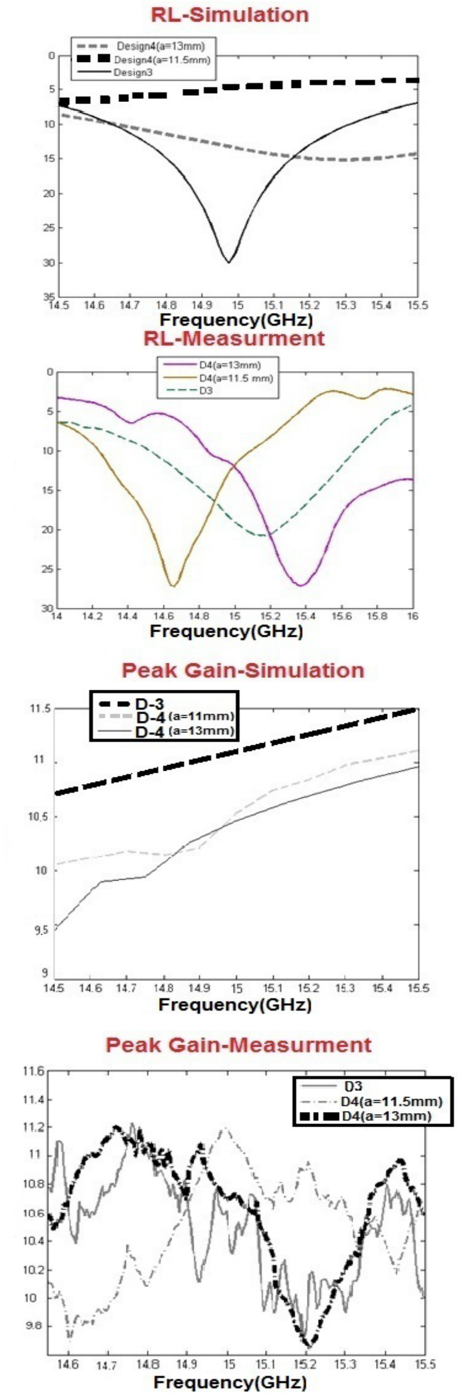

Fig. 6. Simulation and measurement results of D-3, 4 (a=11.5 mm), and D-4 (a=13 mm): (a) return loss and (b) peak gain.

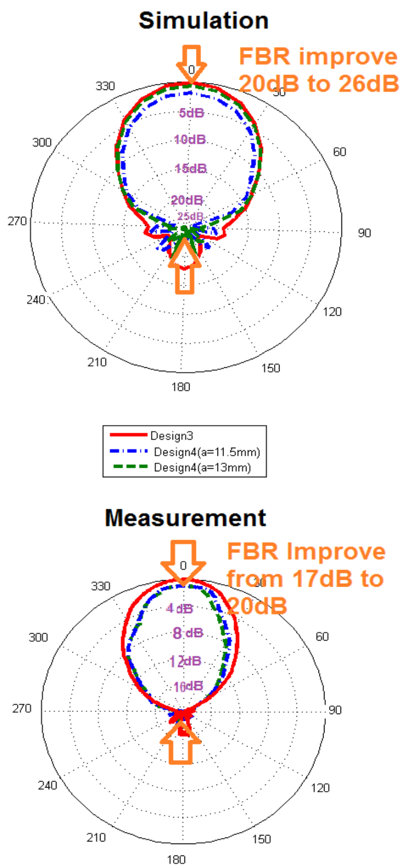

Fig. 7. H-Plane normalized pattern, simulation and measurement show improvement of FBR.

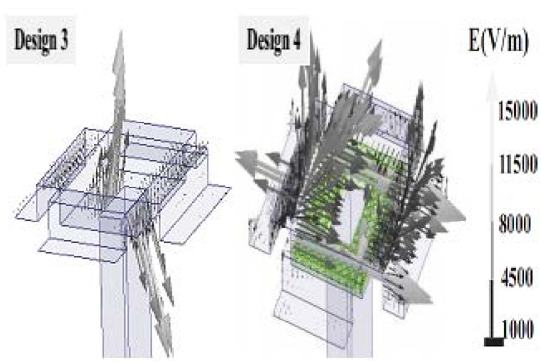

Fig. 8. The simulated electric field distribution of Design 3, 4.

In D-3 the direction of E-field is in both back and front. In D-4, EM-EBG structure neutralizes back fields completely. The return loss was measured using Agilent 8720ES network analyzer. It is clearly distinct that results of these two investigations closely meet each other and sometimes the measurement results are dominant. This may be due to little differences of the substrate between the practical and simulated models. In addition, the dielectric constant and dissipation factor are not stable when the frequency increases.

IV. CONCLUSION

An EM-EBG loaded CBS antenna with a new notched and stepped ground plane was simulated and presented. The results show this could make a better gain and low back lobe in comparison to conventional CBS antenna.

The massive increase in FBR was from 10 dB to 20 dB by using the new notched and stepped plane, which came from the simulation results could prove the advantage of the new system. Mounting EM-EBG on CBS antenna at the same time could improve the FBR to 26 dB. The results were confirmed by measurement result in practice, as FBR was increased to 17 dB and 20 dB after same examination. Also, the further benefit from new ground plane was established as the changes on antenna's gain from 6 dB to 11 dB examined after providing the same applications. Also in this work, effect of surface current on the new ground plane is studied.

As the new developed antenna works in a 15 GHz Ku band, then it could also be an attractive candidate for antenna diversity applications where there is use of higher FBR. This could be the subject for further study in this area.

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