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GUIDED AND LEAKY WAVE CHARACTERISTICS OF PERIODIC DEFECTED GROUND STRUCTURES

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Abstract—In recent years, there has been significant research interest in microwave applications of defected ground structures. In this paper, three kinds of Periodic Defected Ground Structures are analyzed to assess their effects on surface and leaky waves. To achieve this purpose, the finite element method accompanied by Periodic boundary conditions is used to show the propagation characteristics of these periodic structures. Also, the existence of surface wave reduction property is investigated and finally the simulation Results are compared to the experimental results with reasonable agreement.

1. INTRODUCTION

Recently, there has been much interest in various kinds of defected ground structures (DGS), realized by etching a defected pattern on the ground plane. Different shapes of DGS structures, such as rectangular [1, 2], square [3], circular [4, 5], dumbbell [6–9], spiral [10], L-shaped [11] and combined structures [12, 13] have been appeared in the literature. These structures that are used in periodic [14, 15] and non-periodic [1–13] states, have two main properties [16]:

1- Slow wave propagation in pass band.

2- Band stop characteristic.

Slow wave propagation phenomenon in pass band is used for compacting microwave structures, whereas the stop band is useful to suppress the unwanted surface waves. Because of these two properties, these structures have found many applications in microwave circuits such as filters [1, 2, 5, 6], power amplifiers [17], dividers [18], microwave oscillator [19] and harmonic control in microstrip antennas [20].

Surface waves on a grounded dielectric substrate have two major effects in microwave integrated circuits [21]. The first one is power dissipation in the integrated circuit it self and the second one is cross-talk between devices on substrates. The surface waves also are a serious problem in microstrip antennas. Surface waves reduce antenna efficiency and gain, limit bandwidth, increase end-fire radiation, increase cross-polarization levels, and limit the applicable frequency range of microstrip antennas. Further more, surface waves cause scan blindness in phase array antennas [22].

Two solutions to surface wave problem are suggested in the literature. One approach is based on the micromachining technology [23] in which some parts of the substrate beneath the radiating element are removed to realize a low effective dielectric constant environment for the antenna. With this technique the power loss through surface wave excitation is reduced and the radiated power is enhanced.

The second method is relied on periodic structures. The original idea of the periodic structures was proposed at optical frequencies [24, 25] and the structures were known as photonic band gap (PBG) structures. The PBG is a periodic structure which suppresses the propagation of all electromagnetic waves in a particular frequency band, called band gap [26]. For the past few years, the PBG concept has been widely applied to microwave and millimeter-wave circuits applications [26–28].

In this paper, we investigate the feasibility of surface-wave elimination by using Periodic Defected Ground Structures (PDGS). For this purpose a full wave method is applied to determine the dispersion diagram for periodic defected ground structures. Dispersion diagrams show the relationship between wave number and frequency and can show bounded and leaky modes and possible band gaps that can exist between such modes. It can be calculated from a unit cell by using periodic boundary condition. Algorithms for solving Maxwell equations under periodic boundary conditions have been implemented using both the Green's function based method of moments [21, 29, 30] and the finite element method. In this work, the dispersion diagram is extracted by using the commercial finite element full wave solver HFSS, by considering only one DGS (or a unit cell) [31].

For experimental verification, the periodic DGS are inserted between two ports and transition (S_{21}) coefficient is measured. A weak reception is assumed to indicate the existence of a surface band gap. However, it is shown in this paper that there may exist leaky — mode excitation at frequencies inside the surface wave band gap.

2. RECTANGULAR PDGS

Here, three types of PDGS are considered. The first one is a simple rectangular PDGS as shown in Figure 1. In this case, the array spacing is 8 mm in both principal directions, the rectangular PDGS is 6-mm long and 1-mm wide and the Substrate is 2.5 mm thick with relative permittivity of $\varepsilon_r = 10.2$.

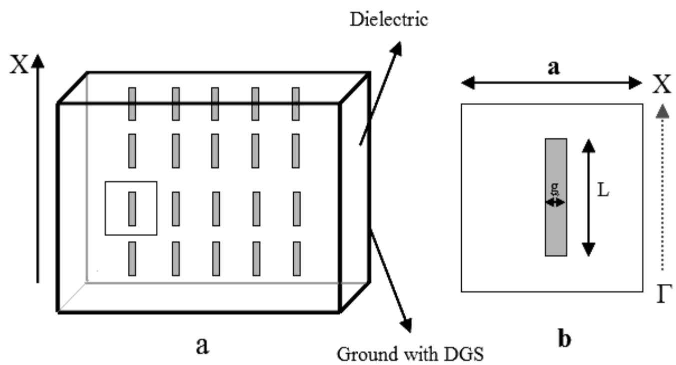


Figure 1. Rectangular slot periodic defected ground structure (a) and its unit cell (b).

For this periodic structure, dispersion diagram is calculated from its unit cell by applying periodic boundary condition on the sides of the cell and a perfectly matched layer (PML) on the top and bottom open walls. Then the phase constant between the two sides of the unit cell (which is parallel to the Γ-X vector) is fixed to 0 and the phase between two other sides of the unit cell (which is perpendicular to the Γ-X vector) is varied from 0 to 180 degrees. The eigenvalue corresponding to each phase difference is calculated by eigenmode solving Maxwell equations. It should be noted that according to Floquet's theorem [32] for the periodic boundary condition, variation of the phase corresponds to the change in the propagation constant. This concept allows the derivation of dispersion diagram using eigenmode solver in HFSS simulator [31].

Simulated β-f diagram for rectangular DGS is shown in Figure 2 for wave propagation along X axis.

It can be seen from Figure 2 that β/K_0 is close to 1 at low frequencies, where the length of slot is much less than a wavelength (similar to dielectric substrate without DGS and the other periodic structures such as PBG [21]). By increasing the frequency, the phase constant increases and tends to the Brillouin zone boundary ($\beta.a = \pi$).

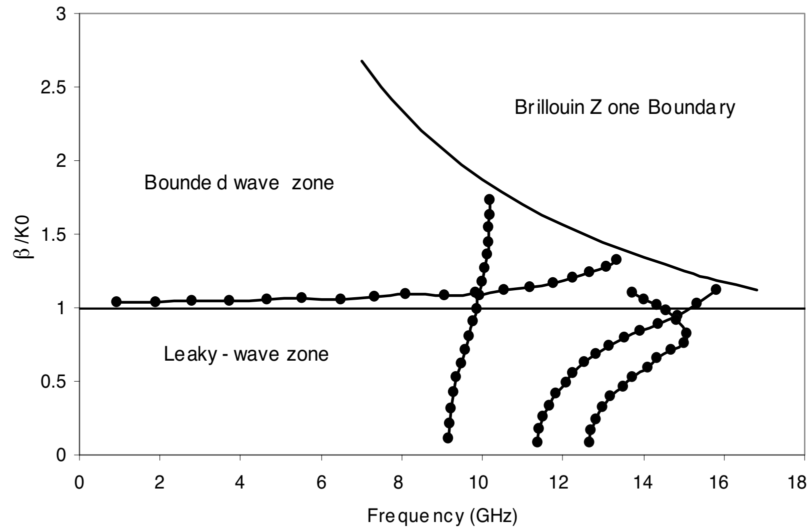
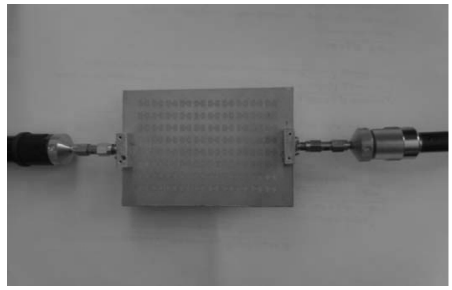


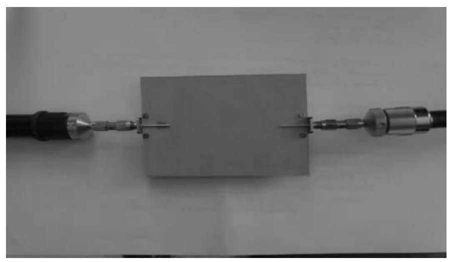
Figure 2. Dispersion diagram for waves on the rectangular slot periodic Defected ground structure. Propagation is in the X direction.

In this zone, the bounded mode changes to a highly attenuating wave with a complex wavenumber (band gap zone). A little higher than 9 GHz, there exists a second mode. In contrast to the first bounded mode that has no cut-off, the second bounded mode becomes fast leaky wave below its cut-off. After these modes, two other modes are excited at about 12 GHz and 13 GHz, respectively which begin with leaky-wave state and turn into the surface wave state as the frequency increase. It can be seen from Figure 2 that total excited leaky–waves in this structure are improper waves which radiate in the forward direction (phase and group velocities are directed in the same direction). These waves have important role in leaky wave antennas [33] and increasing gain in planar antennas. In order to achieve high gain, it is necessary to excite a strong leaky wave [34].

A 8×10 DGS array with the same mentioned dimensions is fabricated on the ground of RT-Duroid 6010 LM substrate with $\varepsilon_r = 10.2$ and 1.575 mm thickness and the metal cover of on the other side of substrate is removed. Two wide band connectors with special leg are connected at the opposite substrate edges to construct two-port network. Bottom and top views of the experiment setup are shown in Figures 3(a) and 3(b) respectively. Transmission scattering parameter (S_{21}) is measured by a HP-8722D network analyzer and shown in Figure 4. This parameter specifies relative surface wave power between



(a)



(b)

Figure 3. The experimental setup for surface wave measurement, (a) bottom view, (b) top view.

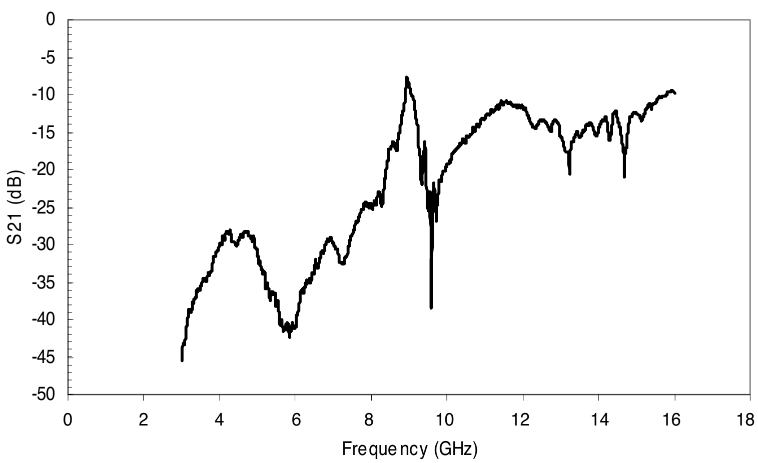


Figure 4. Measured surface-wave power transmission for PDGS in Figure 1.

the two ports. As shown in Figure 4, there is a sudden reduction in transmitted power at around 10 GHz. This reduction is a result of the first band gap predicted in Figure 2. As it is shown in Figure 3, second and third low receptions zones are about 13 GHz and 14.3 GHz respectively. The simulation result in Figure 2 indicates that in these regions only leaky waves were excited.

3. DUMBBELL PDGS

The second periodic structure which is studied in this paper is depicted in Figure 5. This structure is Dumbbell Periodic defected ground structure that is used in many microwave applications [6–9].

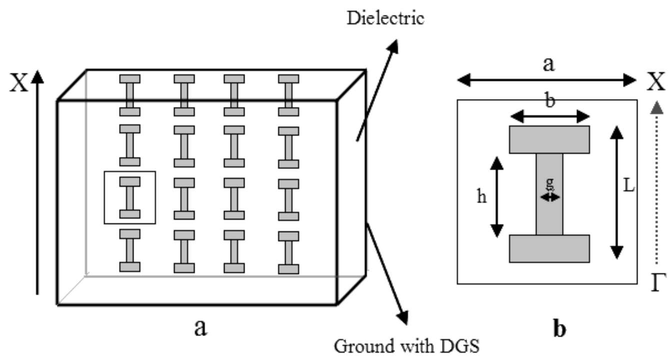


Figure 5. Dumbbell periodic defected ground structure (a) and its unit cell (b).

The substrate is the same as Rectangular PDGS case in Figure 1 and the dimensions of one unit cell are $h = 6$ mm, $g = 1$ mm and $L = 6$ mm and array spacing is $a = 8$ mm. The simulated dispersion diagram for this periodic structure in X direction is illustrated in Figure 6. it can be seen, dispersion diagram of Dumbbell PDGS is similar to the slot PDGS with a frequency shift. By comparing that dispersion diagram (Figure 6) with the experimental results (Figure 7), it can be seen that:

- First surface wave reduction is around 7 GHz. In this frequency band similar to the first surface reduction of previous structure, one of the bounded surface waves is close to brillouin zone and the other one radiates in weakly state ($\beta \approx K_0$)
- Second band gap is around 11 GHz which according to Figure 7, only leaky waves are excited in this frequency.

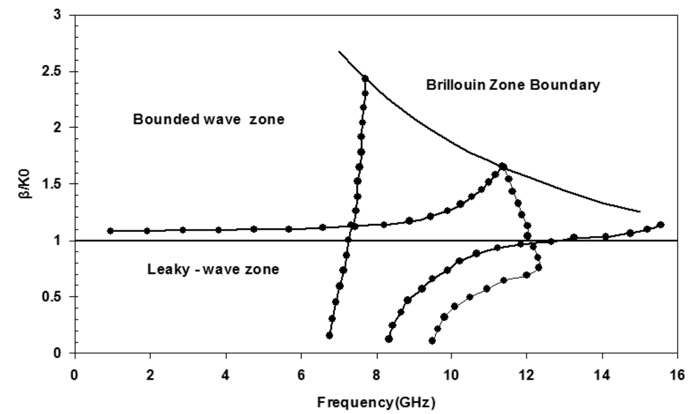


Figure 6. Dispersion diagram for waves on the Dumbbell periodic defected ground structure. Propagation is in the X direction.

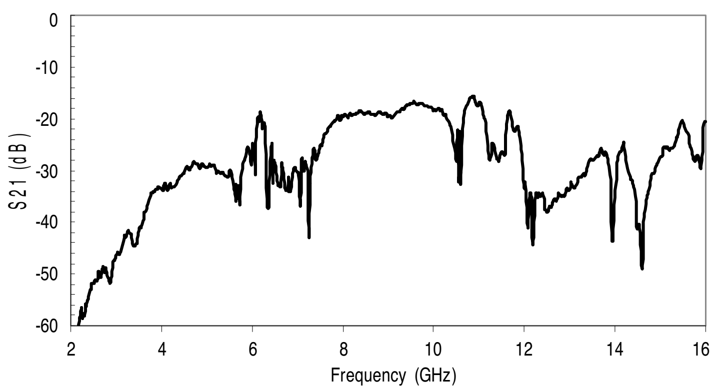


Figure 7. Measured surface-wave transmission for PDGS in Figure 5.

- Third surface wave reduction is occurred about 12 GHz which sudden reduction in transmission is observed (Figure 7).

4. CROSS DUMBBELL PDGS

In many microwave applications, it is necessary to have omnidirectional surface wave reduction. Therefore in this work, propagation characteristic of Cross Dumbbell PDGS is investigated. Figure 8 shows the configuration of Cross dumbbell PDGS and unit cell of it.

The dimensional of unit cell are $h = 6$ mm, $g = 1$ mm, $L = 10$ mm, $b = 4$ mm and the array spacing is 8 mm in both main axis.

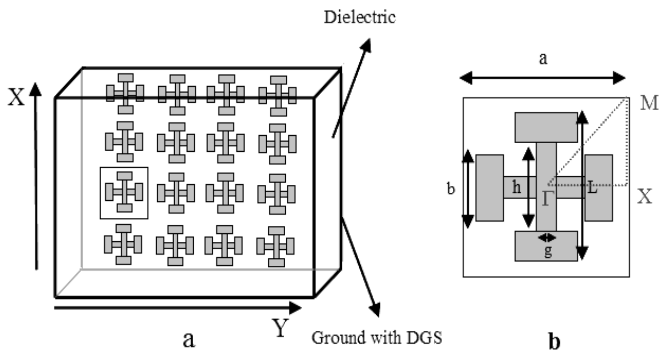


Figure 8. Cross Dumbbell periodic defected ground structure (a) and its unit cell (b).

To derive propagation characteristic of this periodic structure, it is necessary to use Birllouin theory [35]. According to this theory, any periodic structure has certain vectors in its unit cell which derivation of the propagation mode in the directions of these vectors suffices to investigate all possible direction of propagation within the lattice. So, dispersion analysis of periodic structures is reduced to find only propagation modes in the directions of the vectors of the irreducible Birllouin zone. For the periodic structure considered in this section, the irreducible Birllouin zone is illustrated in Figure 9 and it consists of the direction pointing from Γ to X, from X to M, and M back to Γ. Therefore the calculation of the dispersion diagram for this two dimensional periodic structure involves three major steps.

- Step 1: in this step the phase constant between the two sides (of the unit cell) parallel to the vector M-X is fixed to 0 and the phase constant between the two sides (of the unit cell) parallel to the vector Γ-X is varied from 0 to 180 degrees, while Maxwell's equations are being solved for the first N eigenmode frequencies. This step corresponds to one-dimensional wave propagation perpendicular to the vector Γ-X.
- Step 2: in second step phase difference between the two sides parallel to MX vector is fixed to 180 degree and phase difference between two other sides is varied from 0 to 180 degrees and as in the first step, Maxwell equations are being solved for the first N eigenmode frequencies. This step corresponds to one-dimensional

wave propagation in the direction perpendicular to the vector X-M.

- Step 3: In the third step, in the M-X direction, both phase differences between parallel sides of the unit cell are changed from 180 to 0, which corresponds to two-dimensional wave propagation in diagonal direction of the lattice.

The resulting full dispersion diagram for the unit cell of Figure 8 is shown in Figure 9. As illustrated in the figure, this dispersion diagram is divided into three regions by two light lines that includes two leaky wave zones and a bounded wave zone which are located above and below the light lines, respectively. By studying the obtained dispersion diagram, it is observed that the cross dumbbell PDGS with mentioned dimensions, possesses an omnidirectional surface wave band gap in the rang of 5 to 6 GHz. Also it is worth mentioning that a leaky wave mode is excited in this frequency band.

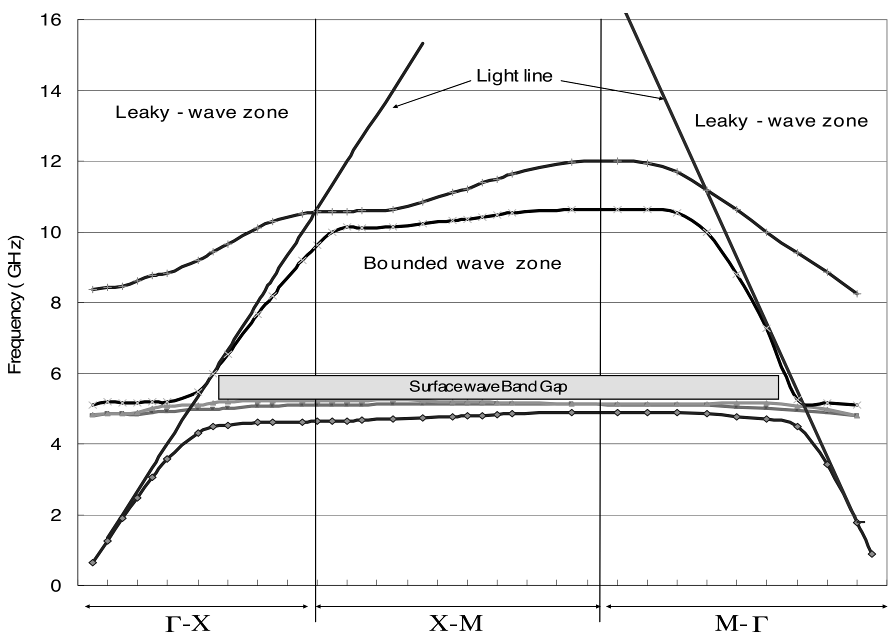


Figure 9. Full dispersion diagram of Cross Dumbbell periodic defected ground structure. Γ, X, M are symmetric points in the Brillouin zone of the unit cell

Experimental results of this structure, obtained by measuring the surface wave propagation only in X direction, are shown in

Figure 10. It is observed from this figure that like that simulation results (dispersion diagram), a surface wave reduction has occurred in the range of 5 to 6.5 GHz.

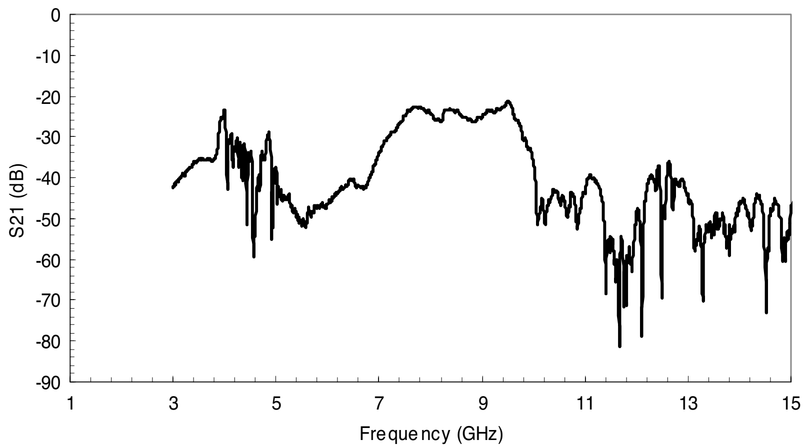


Figure 10. Measured surface-wave power reception for PDGS in Figure 8 (only X direction).

5. CONCLUSION

Three types of periodic Defected Ground structures have been studied. The propagation characteristics have been numerically simulated and discussed. It is shown that a surface wave reduction phenomenon can be achieved with in a certain frequency band. It was also shown that leaky modes that are fast wave (with respect to free space) may exist. It should be noted that this structure in comparison with other periodic structures such as EBG, has an important advantage witch doesn't cause disturbance in microwave element operation on the substrate surface due to its position on ground of substrate. Measured results are also given to confirm the simulation results.

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