A Review of Defected Ground Structure (DGS) in Microwave Design

Chirag Garg[1], Magandeep Kaur[2]

M.Tech. Student ECE, Lingaya's University, Faridabad[1]

Assistant Prof. ECE, Lingaya's University, Faridabad[2]

Abstract: Electromagnetic bandgap (EBG) or alternatively called photonic band gap (PBG) structures have been attractive to obtain the function of unwanted frequency rejection and circuit size reduction. Researches on the PBG had been originally carried out in the optical frequency. Recently, there has been an increasing interest in microwave and millimeter wave applications of PBG circuits. This paper presents a tutorial overview of the new approach for designing compact filters like low pass, band stop and band pass having several advantages than Photonic Band Gap (PBG). This technique is termed as Defected Ground Structure (DGS). The basic conceptions and transmission characteristics with equivalent circuit models of varieties of DGS units are presented. Lastly, the main applications of DGS in microwave technology field have been described.

Keywords: EBG, PBG, DGS.

I. INTRODUCTION

Compact sizes, low cost and high performance often meet the stringent requirements of modern microwave communication systems. Some new technologies such as (LTCC) Low-temperature co-fire ceramic technology, (LTCF) Low-temperature co-fire ferrite and structures such as Photonic band gap (PBG), DGS, (SIW) Substrate integrate wave-guide has been evolved to enhance the whole quality of system. Yablonovitch and John proposed PBG in 1987 [1, 2] which implodes and utilizes metallic ground plane that breaks traditional microwave circuit design to surface components and distributions of the medium circuit plane. PBG is a periodic structure known for providing rejection of certain frequency band but, it's difficult to use it for the design of the microwave or millimeter-wave components. Similarly, another technique called ground plane aperture (GPA) incorporates microstrip line with a centered slot at the ground plane and it has attractive applications in 3 dB edge coupler for tight coupling and band pass filters for spurious band suppression and enhanced coupling [3-5]. With the introduction of GPA below the strip, line properties can be changed as characteristic impedance varies with the width of the GPA. Several compact and high performance components have been reported earlier, Electromagnetic band gap (EBG) or alternatively called photonic band gap (PBG) structures have periodic structure. These structures have been attractive to obtain the function of unwanted frequency rejection and circuit size reduction. Researches on the PBG had been originally carried out

in the optical frequency. Recently, there has been an increasing interest in microwave and millimeter wave Applications of PBG circuits. Various shapes of DGS structures have been appeared. Since DGS cells have inherently resonant property, many of them have applied to filter circuits. However, it is difficult to use a PBG structure for the design of the microwave or millimeter wave components due to the difficulties of the modeling. There are many design parameters, which have an effect on the bandgap property, such as the number of lattices, lattice shape and lattice spacing. Furthermore, to improve circuit performance more investigation is carried out. Park et al. [6] proposed DGS designed by connecting two square PBG cells with a thin slot. DGS adds an extra degree of freedom in microwave circuit design and opens the door to a wide range of application.

This paper presents a tutorial overview of the new approach for designing compact filters. The basic conceptions and transmission characteristics with equivalent circuit models of varieties of DGS units are presented. Lastly, the main applications of DGS in microwave technology field have been described.

II. PHOTONIC BAND GAP

Photonic band-gap (PBG) structures are periodic structures with ability to control the propagation of electromagnetic waves. Periodic structures that can influence on the electromagnetic waves have different names and the PBG is a part of it. The PBG also bears the specific property of defects (defined as distributing of the periodicity of the structure). In aspect of propagation of the electromagnetic waves, defects can be treated as a resonant cavity. In the transmission response it forms free mode inside the forbidden band-gap, this can be used to obtain structures with specific response, and So PBG is a periodic structure known for providing rejection of certain frequency band. PBG improves directivity of antennas and mainly incorporates: suppression of the surface waves, reflectors and Harmonics [7].

III. DEFECTED GROUND STRUCTURE

A. Basic Structure & Transmission Characteristic

The first and the basic DGS is the dumbbell DGS that composes of two $a \times b$ rectangular defected areas, $g \times w$ gaps and a narrow connecting slot wide etched areas in backside metallic ground plane as shown in Fig. 1(b). [6]. Compared with PBG, DGS is more easily to be designed and implemented and has higher precision with regular defect structures. Therefore, it is very extensive to extend

its practical application to microwave circuits. DGS has more competition than PBG in the microwave circuit with high requirement of dimension under certain craftwork condition.
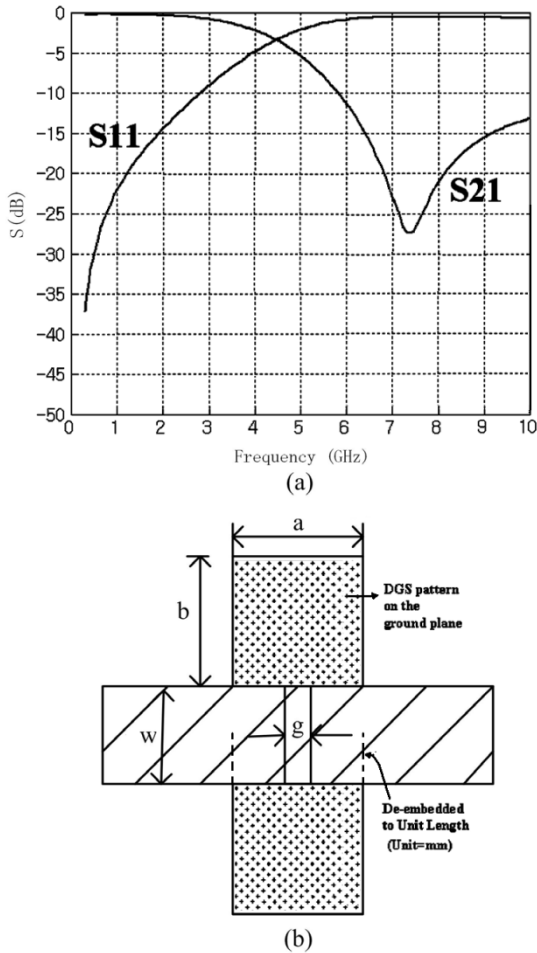

Fig. 1. The first DGS unit: (a) Simulated *S*-parameters for dumbbell DGS unit, (b) Dumbbell DGS unit.

B. DGS Unit

There have been two research aspects for adequately utilizing the unique performance of DGS:

1. DGS unit
2. Periodic DGS.

Different types of geometries etched in the microstrip line ground plane is shown In Fig. 2, including spiral head, arrowhead-slot and "H" shape slots and more complex DGSs to improve the circuit performance are open-loop dumbbell, square open-loop with middle section slot. The newly evolved DGS unit can control the two transmission zeros near the passband edges and easily control the frequency of the slot by changing the length of the metal fingers [11, 12].

Newly proposed DGS unit is having more advantages than dumbbell DGS:

1. A more compact circuit with a higher slow wave factor, like filters using "H" shape slots are much smaller about 26.3% than using dumbbell DGS [19].
2. Deeper rejection and a narrow stopband width.

3. Having external Q slightly larger. We can compare the transfer characteristics of the U-slot DGS with the conventional DGS, spiral-shaped and U-slot DGS are designed to provide same resonance frequency. The Q factor of the spiral DGS is 7.478, while U-slot DGS is having a high-Q factor of 36.05 [13].
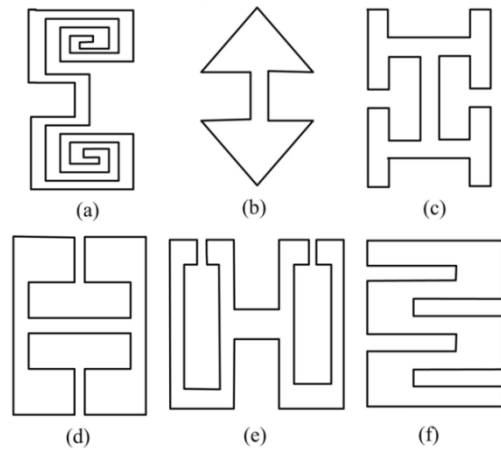

Fig. 2. Various DGSs: (a) Spiral head, (b) Arrowhead-slot, (c) "H" shape slots, (d) A square open-loop with a slot in middle section, (e) Open-loop dumbbell and (f) Interdigital DGS.

In simple words, new DGSs are proposed that brings great convenience to design microwave circuit for realizing various passive and active device compact structures and to suppress the harmonics.

C. Periodic DGS

As the term clarifies a periodic DGS is the repeated model fixed with DGS's. Periodic means repetition of the physics structure. By cascading DGS resonant cells in the ground plane the depth and bandwidth of the stopband for the proposed DGS circuit are inclined to depend on the number of period. Period DGSs care about parameters including the shape of unit DGS, distance between two DGS units and the distribution of the different DGSs. As shown in Fig. 3, by now there are two types of periodic DGS: one is (a) Horizontally periodic DGS (HPDGS), the other is (b) Vertically periodic DGS (VPDGS) [14][15].
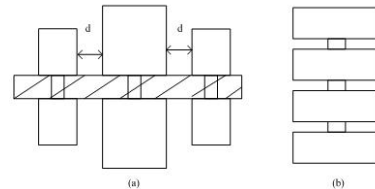

Fig. 3. Periodic DGS: (a) HPDGS, (b) VPDGS.

The proposed structure is having prominent feature to organize the periodicity along the vertical direction as well as the horizontal direction and it is named as VPDGS. Whereas, the conventional DGS for planar transmission lines are having HPDGS only with serially cascading structure along the direction of transmission. HPDGS was initially produced for enlarging the stopband of frequency response curve. A periodic DGS for planar circuit is formed by the uniform square-patterned defects, that provides excellent stopband and slowwave characteristics

that are being used in oscillators and amplifiers [15-18]. Previously nonuniform circular-patterned DGSs using function distribution have been proposed in comparison with the previous periodic DGSs. These have been able to compensate microstrip line and the dimensions of square defects are varied proportionally to relative amplitudes distribution of the exponential function $e1/n$ distribution (where, n denotes the positive integer). The VPDGS produces much higher slowwave factor than HPDGS which means the longer electrical length for the same physical length.

IV. EQUIVALENT CIRCUITS OF DGS

In order to derive the equivalent circuit parameters of DGS unit at the reference plane, the S-parameters vs.frequency should be calculated by full-wave electromagnetic (EM)-simulation to explain the cutoff and attenuation pole characterstics of the DGS section. The circuit parameters can be extracted from the simulation result which can be fit for the one-pole Butterworth-type low-pass response.

The full-wave solver is used to find the S-parameters vs. frequency behavior of the DGS. The disadvantage of this method is that there is no direct correlation between the physical dimensions of DGS and the equivalent LC parameters. The derived performance of DGS is not fully predictable until the optimized solutions are achieved through trial and error iterative process. Hence the conventional methods as reported in the open literature [6, 19-24] are time consuming and may not lead to optimum design.

Presently, DGS can be equivalent by three types of equivalent circuits:

1. LC and RLC equivalent circuits,
2. Π shaped equivalent circuit,
3. Quasi-static equivalent circuit.

A. LC and RLC Equivalent Circuits

The equivalent circuit of the DGS and one-pole Butterworth prototype of the LPF are shown in Fig. 4. The rectangular parts of dumbbell DGS increase the route length of current and the effective inductance. The slot part accumulates charge and increases the effective capacitor of the microstrip line one connecting slot and two rectangular defected areas correspond to equivalently added inductance (L) and capacitance (C) due to parallel L-C circuit the resonance occurs at a certain frequency. The equivalent circuit includes a pair of parallel L-C form the resonant phenomenon in the S-parameter. This means the microstrip line having the DGS (shown in Figure. 1) does not have all-pass characteristics, but restricted passband properties. In addition, slow-wave characteristics are observed due to the added – components of the DGS [9], [24]. The defected areas can be realized by not only rectangle, but also other geometries such as triangle, circle, hexagon, octagon, spiral, and so on. It is clear that the resonant frequency (ω_o) of the DGS and 3-dB cutoff frequency ($\omega_{c, 3dB}$) of the DGS exists. The equivalent L–C circuit of the DGS can evolve because this kind of characteristic is observed from a typical L–C parallel resonant circuit. As the etched area of unit lattice increases, the effective series inductance increase and on

increasing the series inductance it gives rise to a lower cutoff frequencies. When the etched gap distance increases, the effective capacitance decreases in order to move the attenuation pole location to a higher frequency. The equivalent circuit of the DGS circuit and one-pole Butterworth prototype of low-pass filter (LPF) is shown in Figure5. In order to match DGS to Butterworth low-pass filter, the reactance values of both circuits are equal at the cutoff frequency. So L and C are derived as follows:

$$X_{LC} = 1/\omega_0 C(\omega_0/\omega) - (\omega/\omega_0) \tag{1}$$

Where, ω_o is the resonance angular frequency of the parallel LC resonator.

$$X_L = \acute{\omega} Z_0 g_1$$
$$C = (\omega_c/Z_0 . g_1) . (1/(\omega_0^2 - \omega_c^2))$$
$$L = 1/4\pi^2 f_0^2 0C \tag{2}$$

Where f_0 and f_c are resonance (attenuation pole) and cutoff frequency which can be obtained from EM simulation results. The equivalent L-C elements are calculated by X_{LC} and X_L because two reactance values must be equivalent at $\omega_{c,3dB}$ as follows:

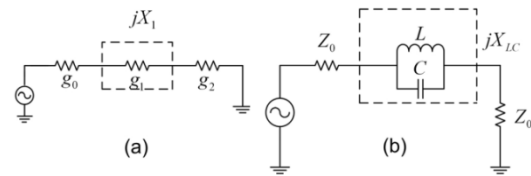$$\mathbf{X_{LC}|_{\omega=\omega_{c/3dB}}} = \mathbf{X_C|_{\acute{\omega}=1}} \tag{3}$$

Fig. 4. LC Equivalent circuit: (a) Butterworth-type one-pole prototype low-pass filters circuit, (b) Equivalent circuit of the dumbbell DGS circuit.

The characteristics of most of DGS are similar to dumbbell DGS, the DGS unit can be modeled most efficiently by a parallel R, L, and C resonant circuit connected to transmission lines at its both sides as shown in Fig. 5.
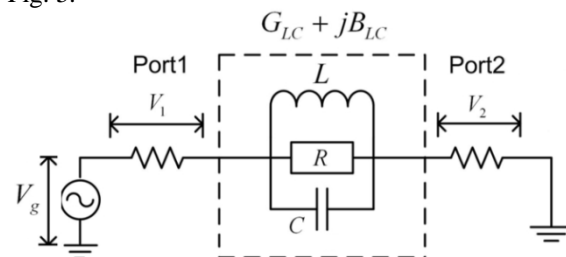
Fig. 5. *RLC* Equivalent circuit for unit DGS.

$$C = \frac{\omega_c}{2Z_0(\omega_0^2 - \omega_c^2)}$$
$$L = 1/4\pi^2 f_0^2 0C \tag{4}$$
$$R(\omega) = 2Z_0 / \sqrt{\frac{1}{|S_{11(\omega)}|^2} - (2Z_0(\omega C - \frac{1}{\omega L}))^2 - 1}$$

The size of DGS is determined by the help of accurate curve-fitting results for equivalent-circuit elements to correspond exactly with the required inductance.

B. π Shaped Equivalent Circuits

Since, it was difficult to implement the DGS circuits for the harmonics termination to satisfy simultaneously the

excellent pass band and stop band characteristics. The π Shaped Equivalent Circuit is more accurate equivalent circuit models than the *LC* and *RLC* equivalent circuits.
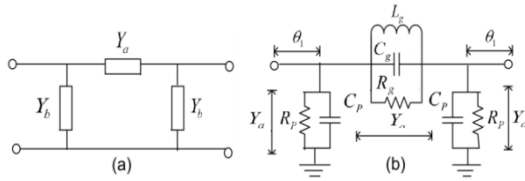

Fig. 6. Π shaped equivalent circuit for unit DGS: (a) π shaped circuit, (b) Equivalent circuit.

Park proposed π shaped equivalent which simulates both amplitude vs. frequency and phase vs. frequency characteristics. The *S*-parameters vs. frequency curve of π shaped equivalent is more anatomized than *LC* and *RLC* equivalents, but its circuit is more complex and the parameters is so many that the equivalent is difficult to extract. Π shaped equivalent circuit is much suitable to the exigent precision of circuit design. The ABCD parameters for the unit cell will be obtained using the expression as follows:

$$\begin{matrix} A & B \\ C & D \end{matrix} = \begin{matrix} 1 + Y_b/Y_a & 1/Y_a \\ 2Y_b + Y_b^2/Y_a & 1 + Y_b/Y_a \end{matrix} \quad (5)$$

$$Y_a = 1/R_r + jB_r$$
$$Y_b = 1/R_b + jB_p$$

$$C_g = \frac{B_r}{\omega_2(\frac{\omega_1}{\omega_2} \frac{\omega_2}{\omega_1})}, L_g = 1/\omega_2\omega_2, C_p = B_p/\omega_1 \quad (6)$$

The full-wave analysis does not give any physical insight of the operating principle of the DGS.

C. Quasi-static Equivalent Circuit

The Equivalent Circuit is different from the L-C and π shaped equivalent circuit that has been elaborated earlier. The Quasi-static Equivalent Circuit model of a dumbbell DGS is developed which is directly derived from the physical dimensions of dumbbell DGS as shown in Fig. 7.

This equivalent circuit overcomes the limitation of report full-wave analysis by developing the equivalent circuit model. This approach helps in understanding the physical principle of DGS including how the DGS creates bandstop and bandpass responses and which dimensions play the most vital role to create the distinct performance.
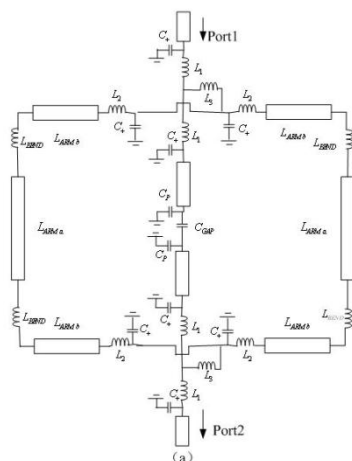

Fig. 7. Equivalent-circuit model of unit cell DGS

V. APPLICATION IN MICROWAVE CIRCUIT

Each DGS provides its own distinctive characteristics depending on the geometries, such circuit functionalities as filtering unwanted signals and tuning high-order harmonics can easily be accomplished by means of placing required DGS patterns, which correspond to the desired circuit operations without increasing circuit complexity. This leads to a wide variety of applications in active and passive devices useful for compact design.

A. Stopband Effects

A Defective Ground Structure (DGS) is an intentionally designed defect on a ground plan, which creates additional effective inductance and capacitance has been known as providing rejection of certain frequency band, namely, bandgap effects. The stopband is useful to suppress the unwanted surface waves, spurious and leakage transmission. Therefore, a direct application of providing rejection to certain frequencies in microwave filters is a topic of research. Considering, the Hilbert curve ring (HCR) DGS lowpass filter achieves a quite steep rejection property, a low in-band insertion less of below 0.5 dB and a high outband suppression of more than 33 dB in a wide frequency range [27][37] shown in Fig. 9. DGS provides excellent performances in terms of ripples in the passband, sharp-selectivity at the cut-off frequency and spurious free wide stopband.
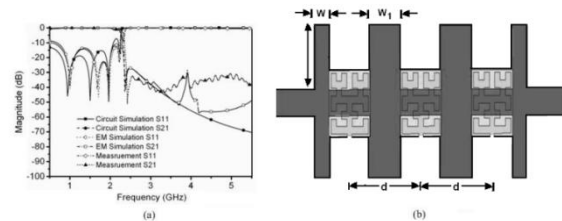

Fig. 9. (a) Simulation and measurement results of HCR DGS lowpass filter, (b) Layout of the HCR DGS lowpass filter (3-cell).

There have two types of filter design using DGS: one is directly using the frequency-selectivity chrematistic of DGS to design filters [23][25–27], the other is using DGS on the conventional microstrip filters so as to improve performance [24][28-31][37]. After using DGS in metallic ground plane for the response of filter there have been a lot of improvements such as: (1) Higher harmonic suppression, (2) Broader stopband responses, (3) More transition sharpness, (4) Improvement of stopband and passband characteristics.

B. Slow-Wave Effect

Slow-wave effect caused by the equivalent *LC* components is one of the advantages of DGS. In contrast to the conventional lines the transmission lines with DGS are having much higher impedance and increased slow-wave factor due to the help of which the circuit size can be reduced such as microwave amplifiers and Rat-race hybrid couplers [32]. Comparing DGS Doherty power amplifier (DDA) with conventional Doherty power amplifier (CDA) we can conclude that DGS Doherty power amplifier (DDA) could reduce the circuit size effectively by the negligible insertion loss, excellent harmonic termination

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characteristic and slow-wave effect [33]. DGSs can be used in the beam steering of a phased array antenna it also restrains harmonious and reduce the mutual coupling of antenna array by suppressing the surface waves and increases the antenna performance [34] [35][37].

C.   High Characteristic Impedance

Generally the accepted impedance is limited to around 100~ 130 Ω in case of conventional microstrip line which is an obstacle that can be overcome by the adoption of DGS technique. It is possible to increase the equivalent inductance L highly and to decrease the equivalent C at the same time by designing DGS on ground plane; this will also raise the impedance of the microstrip line more than 200 Ω.

The high characteristic impedance of DGS may also be used in digital systems [37].

D.   Additional Applications of DGS

Delay lines— Changes in propagation of wave along the line can be introduced by placing DGS resonators along a transmission line. In this manner, the DGS elements don't affect the odd mode transmission, but it slows down the even mode, which should propagate around the edges of the DGS slot. With this change in the phase velocity of the wave, the effective dielectric constant is effectively altered [36].

Antennas—The filtering characteristics of DGS can be applied to antennas, reducing mutual coupling between antenna array elements, or reducing unwanted responses. This is the most common application of DGS for antennas, as it can reduce side lobes in phased arrays, improve the performance of couplers and power dividers, and reduce the response to out-of-band signals for both transmit and receive. An interesting application combines the slot antenna and phase shift behaviors of DGS [36].

V.   CONCLUSIONS

The tutorial overview of DGS has been carried out, which provides evolutions of DGS from conventional PBGs are reported. The basic conceptions and transmission characteristics of DGS are introduced and the equivalent circuit models of varieties of DGS units are also presented. A (DGS) is an *intentionally* designed defect on a ground plane, which creates additional effective inductance and capacitance. Designing of DGS structures is a tough, so EM simulation having both domain and frequency-domain EM simulation can be used. Finite Difference Time Domain (FDTD) is needed to analyze and optimize these structures, so that it can provide insightful TDR results for Time-domain and in case of Finite Element Method (FEM), can very quickly find the resonant frequencies for Frequency-domain. In comparison to PBG, DGS has simple structure, equivalent LC circuit model, and potentially great applicability to design microwave components. Various designs of DGS have been evolved to yield better performance in terms of pass band width, ripple free transmission and wider stop band. DGS added an extra degree of freedom in microwave design and application.

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