Application of Defected Ground Structures for Size Reduction of Hybrid Junctions

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Abstract: Quantitative investigation of the impedance of defected ground structure (DGS)-based microstrip lines is presented in this paper. Empirical curves and curve-fitted relations of impedances of DGS lines on RT/Duroid 5880 (ε_r=2.2, h=0.7874 mm) are obtained. The effect of the dumbbell slot size on impedance variations and on the operating frequency shifts are established by producing design curves that relate the DGS line and the non-DGS line characteristics and facilitate device designs. As an application, a rat-race ring coupler based on defected ground structure has been designed, realized and measured. The DGS confers size reduction due to the shift of frequency to lower values. The measurements are in a good agreement with the simulated results and emphasize the size reduction and the harmonics suppression of the DGS coupler.

Keywords: Defected ground structures, rat-race coupler, size reduction, harmonic suppression.

1 INTRODUCTION

The periodic structures typically have lowpass characteristics. The widely used periodic structures for microstrip lines are various kinds of photonic bandgap (PBG) [1-3] and defected ground structures (DGS) [2-9]. The microstrip defected ground structures have become one of the most interesting areas of research due to their extensive applicability in microwave circuits. The defected ground structures are realized by etching-off a defected pattern from backside metallic ground plane. The defected ground structure has been known as providing bandgap effects by rejecting certain frequency bands. These etched patterns in the ground plane of the microstrip line may be periodic or non-periodic. The etched slot in ground disturbs the current distribution in the ground, and increases the effective inductance and capacitance of the microstrip line. Therefore, the DGS is usually modeled by a parallel LC resonance circuit using circuit analysis method. Fig.1a shows a dumbbell DGS unit, which consists of two square slots (dumbbell slots) in the ground plane connected with a small slot-gap under the microstrip line. The equivalent circuit of such a cell is shown in Fig.1b where L and C can be calculated as follows [10]:

$$C = \frac{5 f_c}{\pi (f_o^2 - f_c^2)} \tag{1.1}$$

$$L = \frac{250}{C(\pi f_o)^2} \tag{1.2}$$

C is measured in (pF), L in (nH). The frequencies f_o and f_c are the lowpass attenuation and cutoff frequencies in GHz, respectively. The characteristics of a slot of dimensions $a = b = 4.5$ mm and $g = 0.3$ mm cut in the ground plane of 50 Ω microstrip line on Teflon substrate RT/Duroid 5880 (ε_r=2.2, h=0.7874 mm) designed at operating frequency of f=2.5 GHz, are shown in Fig.2. For such case, the frequencies f_c and f_o are equal to 3.91 and 9.01 GHz, respectively. The corresponding LC equivalent circuit will be inductance and capacitance in parallel with values of 3.3039 nH and 0.0944 pF, respectively.

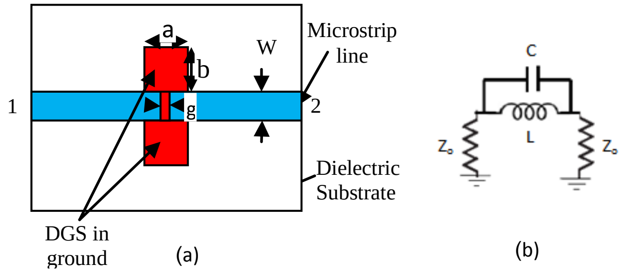


FIGURE 1
(a) The DGS microstrip line (b) The equivalent circuit

In the published literatures, the analysis of the DGS lines relies qualitatively on the equivalent LC circuits of the designed device obtained by optimization through simulation iterations. In the following sections, the impedance of defected ground structure (DGS)-based microstrip lines is quantitatively characterized. The relation between the impedance of the DGS lines and the impedance of regular microstrip lines on RT/Duroid 5880 (ε_r=2.2, *h*=0.7874 mm) is given using empirical curves and curve-fitted equations. The effect of the slots size on impedance variations and frequency shifts are investigated and characterized. Design curves that facilitate the design of DGS microstrip circuits on such substrates are also established. As an application for this method, a ring coupler with defected ground structure is designed and realized. Using DGS-based lines result in a noticeable size-reduction. This is due to the shift of frequency to lower values caused by the ground layer alternation. The measurements of the realized ring coupler are in a good agreement with the simulated results. Measurements emphasize the effect of the frequency shift which results in a considerable size reduction and confirm the harmonics suppression of the realized DGS ring coupler.

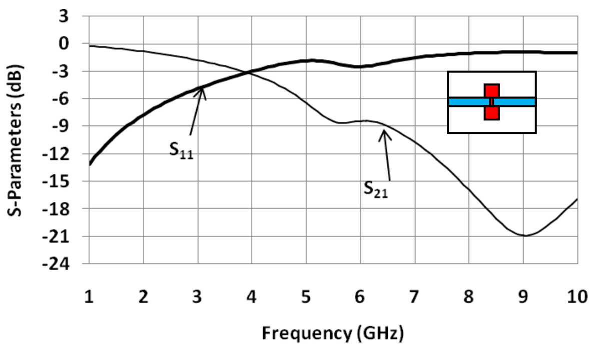


FIGURE 2
The Simulated S-Parameters for DGS dumbbell slots of 4.5mm X 4.5 mm

2 ANALYSIS OF MICROSTRIP LINES WITH DEFECTED GROUND STRUCTURES

For the quarter wave-length 50 Ω microstrip line designed at a frequency of 2.5 GHz on RT/Duroid5880 (ε_r=2.2, *h*=0.7874 mm), the geometric parameters are given by: width (W)=2.378 mm and length (L)=21.9 mm. Using constant gap under the microstrip line with dimension (0.3mm x 2.378 mm), the impedance of the microstrip line will change by changing the dumbbell-slot dimensions (*a*X*b*). The impedance variation when the slot is square (*a*=*b*), is shown in Fig.3. An 80 Ω impedance line can be realized by a 50 Ω regular microstrip line with DGS slot of dimensions (*a*x*b* =

5mmx5mm). The use of suitable DGS slots increases the impedance of the microstrip line. Thus, higher impedance lines can be realized using microstrip lines with moderate widths. The curve of Fig.3 is fitted to the following equation:

$$Z(\Omega) = 0.005L^3 + 0.034L^2 + 5.752L + 51.61 \tag{2}$$

Where L is length of the square slot (*a*=*b*=L). The error in Eq. 2 is within $\pm 3\Omega$. Figure 4 illustrates the variations of the impedance of DGS-based lines against the impedance of regular lines at different values of defected ground slot dimensions. From Fig.4, it is easily noticed that the impedance of the DGS-line increases as the slot dimensions increase and vice versa. As an example, impedance of $50\sqrt{2}\ \Omega$ can be realized using two different DGS dumbbell slots (refer to the available curves in Fig.4). The first is by using a regular 32.8 Ω microstrip line with DGS slots of dimensions (7.5 mm x7.5 mm). The second is by using a regular 43.14 Ω microstrip line with DGS slots of dimension (5X5 mm). The curves in Fig. 4 can be fitted to the following equations:

$Z_{DGS} = 1.008Z + 12.19$ for square slot of 2.5 mm length (3.1)

$Z_{DGS} = 1.157Z + 20.80$ for square slot of 5.0 mm length (3.2)

$Z_{DGS} = 1.246Z + 29.73$ for square slot of 7.5 mm length (3.3)

$Z_{DGS} = 1.368Z + 38.88$ for square slot of 10 mm length (3.4)

The above equations can be combined into one equation of the form:

$$Z_{DGS} = a_x.Z + b_x \tag{3.5}$$

Where $a_x = 0.001L^3 - 0.0221L^2 + 0.172L + 0.694$

$b_x = -0.006L^3 + 0.212L^2 + 2.812L + 4.5$

L is the length of the square slot (L= *a* = *b*), Z is the impedance of the regular microstrip line, and Z_{DGS} is the impedance of the corresponding defected ground structure line. Eqs.3 can be extrapolated to the range of typical regular impedances of (20 Ω - 90 Ω) with error of ±2 Ω.

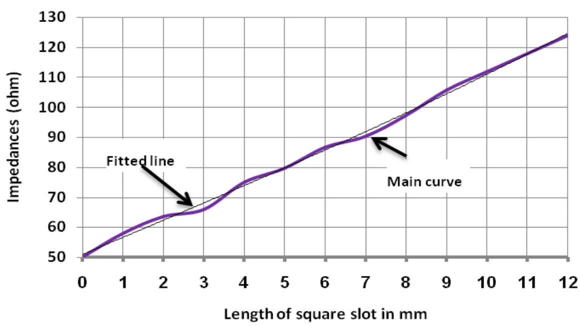


FIGURE 3
Impedance variation of The DGS microstrip line against square DGS slots length

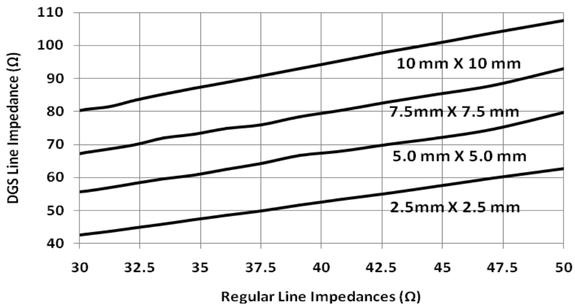


FIGURE 4
Variations of (Z_{DGS}) against regular (Z) at different slot areas (dim. in mm)

It is observed that, by using a constant defected slot, the operating frequency is shifted to lower values when the width of the microstrip line is increased. Similarly, using a constant width line, the operating frequency is shifted to lower values when the dimensions of the DGS slots are increased. These occurrences result in a potential size reduction for microstrip circuits. Fig.5 illustrates the frequency ratio between the new (shifted) frequency and regular frequency (F_{new}/F_{reg}) against the (regular) impedance of the microstrip line. These curves can be fitted to the following equations:

$$F_{new} / F_{\mathrm{Re}\,g} = 0.2148\ln(z) - 0.748 \quad \text{for slot (10 X10 mm)} \qquad (4.1)$$

$$F_{new} / F_{\mathrm{Re}\,g} = 0.3708\exp(0.01z) \quad \text{for slot (7.5 X7.5 mm)} \qquad (4.2)$$

$$F_{new} / F_{\mathrm{Re}\,g} = 0.2156\ln(z) - 0.279 \quad \text{for slot (5 X5 mm)} \qquad (4.3)$$

$$F_{new} / F_{\mathrm{Re}\,g} = 0.3424z^{0.233} \quad \text{for slot (2.5X2.5 mm)} \qquad (4.4)$$

In the above equations, F_{new} is the new operating frequency and z is the impedance of the regular microstrip line designed at the regular frequency F_{reg} (2.5GHz). The above equations can be extrapolated to the impedance range (20Ω-90Ω) with error in frequency less than 0.05 GHz. As an example, for a regular 35.36 Ω ($50/\sqrt{2}$ Ω) line, the resonance frequency will be shifted from 2.5 GHz to 1.9646 GHz, 1.6428 GHz, 1.3202 GHz, or 1.1667 GHz when using DGS slots with dimensions (a X b) equal to (2.5

mm X 2.5 mm), (5.0 mm X 5.0 mm), (7.5 mm X 7.5 mm), or (10 mm X 10 mm), respectively.

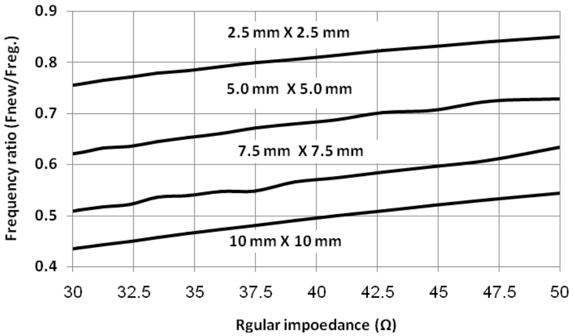


FIGURE 5
The frequency ratio (F_{new}/F_{reg}) against regular impedances at different slot size

3 DESIGN PROCEDURES

The following design procedure will facilitate using DGS-based passive microwave devices. To design any microstrip branch-line with certain impedance:

1. Put the required impedance value of the line-branch as Z_{DGS} in Eqs. (3-1)-(3-4) or (3.5) to have the corresponding regular-line impedance Z at suitable slot dimensions.

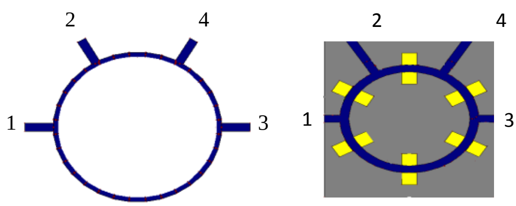
2. Use Eq. 4 to calculate the frequency ratio $(F_{new} / F_{\mathrm{Re}\,g})$ of the new operating frequency F_{new} and the regular-line frequency F_{reg} that corresponds to Z at the chosen slot dimensions.

3. Calculate the microstrip width corresponding to Z using regular microstrip equations. The line-branch electrical length is calculated to the desired operating frequency and then reduced by the frequency ratio $(F_{new} / F_{\mathrm{Re}\,g})$.

The above analysis and procedures are used to design a compact rat-race ring coupler on RT/Duroid 5880 (ε_r=2.2, h=0.7874 mm). In the following section, the conversion of the regular microstrip branches to their corresponding reduced size defected ground structure branches are demonstrated.

4 DESIGN AND SIMULATION OF A DGS RAT-RACE RING COUPLER

The conventional rat-race ring coupler of Fig. 6a consists of four branches. Three branches are of length $\lambda/4$ and the fourth branch has a length of $3\lambda/4$. All branches are with impedances of $50\sqrt{2}\,\Omega$. Fig.7 illustrates the Simulated S-parameters for the conventional rat-race that was designed at resonance frequency 2.5GHz on RT/Duroid 5880 (ε_r=2.2, h=0.7874 mm). It is clear that a better performance appear at 2.5GHz and at its harmonics 7.5GHz. To convert the design into defected ground structures, we need to convert the $50\sqrt{2}\,\Omega$ impedance line to its corresponding DGS line. Using the design procedure described above, when Z_{DGS}=70.71 **Ω**, the corresponding (Z) will be equal to 43.13 **Ω** for slots 5 mm X 5 mm**.** Using Eq.4.3, the frequency ratio if using slots of 5 mm X 5 mm will be 0.7. This indicates that the size of the defected ground ring coupler shown in Fig. 6b represents 49% of the size of the regular ring coupler. The widths corresponding to 43.13 **Ω**, on RT/Duroid 5880 (ε_r=2.2, h=0.7874 mm) at operating frequency of 2.5 GHz will be 2.99 mm, where the electrical length (λ/4) is 21.8 mm. The simulated S-Parameters of a ring coupler designed with DGS with slots of (5.0 mm X 5.0 mm) and the gap under the microstrip line of (0.3 mm X 2.99 mm) is shown in Fig.8. It is clear that, the resonance frequency is moved down to 1.75 GHz if the same branch-lengths were preserved without reduction. It is evident also that this DGS ring coupler has a remarkable harmonics-suppression up to 9.5 GHz.



(a) (b)

FIGURE 6
(a) conventional rat-race (b) DGS rat-race

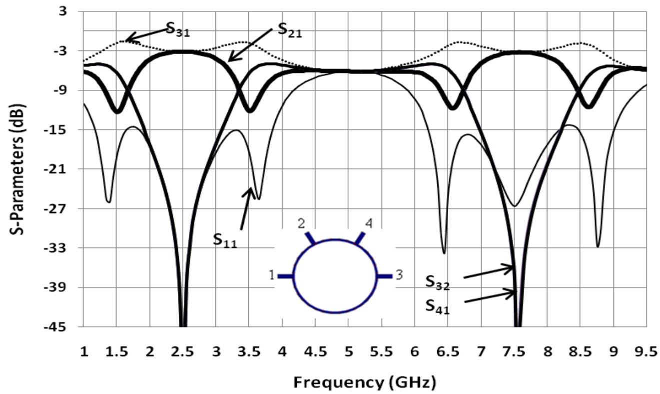


FIGURE 7
The Simulated S-Parameters for the conventional rat-race coupler

5 FABRICATION AND MEASUREMENTS

The DGS rat-race coupler is realized on RT/Duroid 5880 (ε_r=2.2, *h*=0.7874 mm). The measured S-parameters for the rat-race ring coupler are shown in Fig.9. The return loss (S_{11}) is less than -15 dB in the band 1.5 GHz to 2.1 GHz while the insertion losses (S_{21}, S_{31}) are equal to 3±0.25dB. The isolation (S_{41}) and the output isolation (S_{32}) are less than -15 dB in the same band. Such DGS ring coupler achieved bandwidth of 33.33% at a resonance frequency of 1.8 GHz. The harmonics are suppressed up to 9.5 GHz.

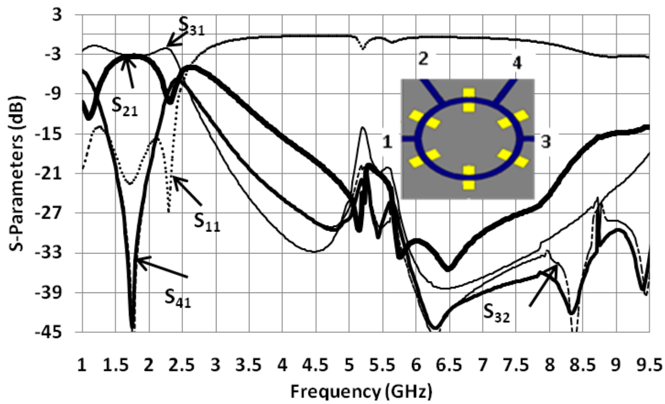


FIGURE 8
The Simulated S-Parameters for the defected ground rat-race coupler

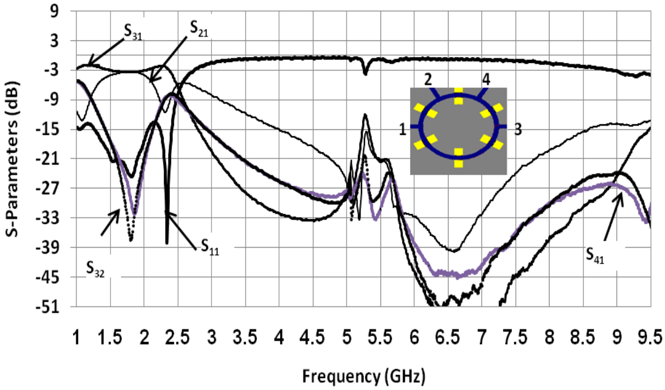


FIGURE 9
The measured S-Parameters for the dfected ground rat- race coupler

6 CONCLUSION

In this paper, a quantitative analysis of the impedance of defected ground structure (DGS)-based microstrip lines is presented. Empirical curves and curve-fitted relations of impedances of DGS lines on RT/Duroid 5880 (ε_r=2.2, *h*=0.7874 mm) are obtained. The effect of the dumbbell slot size on impedance variations and on the operating frequency shifts are established by producing design curves that relates the DGS line and the non-DGS line characteristics and facilitates design procedures. Based on that procedure, a ring coupler has been designed, then simulated and realized. The measurements of S-parameters gave good agreement with the simulated results. The realized DGS rat-race coupler gives a size reduction of 55% as compared to the conventional ring coupler and suppressed the harmonics up to 9.5GHz. The DGS ring coupler achieves a coupling of to 3±0.25dB in the range 1.5 GHz to 2.1 GHz. The analysis method of this paper can be easily extended to other microstrip substrates and DGS geometries as well.

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