CHAPTER -3

Design and Simulation of Defected Ground Structures (DGS) Filter

Defected Ground Structures (DGS) filter was first proposed by Park et al [24] and had since found applications in the design of planar circuits and low-pass filters. An important method for designing filters is by using Defected Ground Structures (DGS) which can be categorized as a kind of Electromagnetic Band Gap (EBG) structure [25-27]. The basic idea behind the EBG technology is to create a periodic structure in which the propagation of the electromagnetic waves is not allowed in some frequency band. These structures are usually made with circular or rectangular shaped holes in the ground plane, but more complex shapes may be used. For certain hole geometries, the rejection band becomes a low-pass response [28]. EBG structures realized on metal layers are useful for constructing filters (including band-stop filters, low-pass filter and band-pass filter), phase shifters, and antennas. An example of EBG structure patterned on metal layers is the microstrip transmission line with EBG etched holes in the ground plane or on the signal line.

A Defected Ground Structure (DGS) is realized by etching a definite pattern in the ground plane of the micro-strip line, which disturbs the shield current distribution in the ground plane. This changes the characteristics of the transmission line such as equivalent capacitance and inductance, to obtain the slow-wave effect and band-stop property [29]. Compared with the conventional EBG structures, DGS requires only one
defected unit to obtain the forbidden-gap property, and the center frequency of the gap is fully determined by the configuration of the defected unit. Hence, DGS has the advantages of small size and tends itself to the facility of equivalent-circuit analysis and filter design [30-31].

3.1 Basic Theory of Defected Ground Structure
Dumb-bell shaped is the most frequently used Defected Ground Structures (DGS) proposed by Dal et al. This DGS has been used for control of an active microstrip antenna, bandwidth enhancement technique in patch antenna, improved power efficiency of power amplifiers, performance enhancement of filters, power dividers, branch line couplers etc. More recently, to reduce the planar circuit size, the slow wave effect has been used.

When a microstrip line is incorporated with Defected Ground Structures (DGS), the surface impedance of the microstrip line changes and yields low-pass characteristics. This change in the surface impedance is because of the etched out aperture in the ground plane, which in turn disturbs the shielded current distribution in the ground plane. The change in surface impedance changes the phase velocity of the current, which changes the apparent effective permittivity.

In recent times, periodic structures such as Defected Ground Structure (DGS), Electromagnetic Band Gap (EBG) structures have drawn wide interest for use in various microwave applications. DGS is realized by etching off a defected pattern from the ground plane. An etched defect disturbs the shield current distribution in the ground plane. This disturbance can change the characteristics of a transmission line resulting in the change in the effective capacitance and inductance [32-34]. An L,C equivalent circuit
can be used to model the proposed DGS circuit as shown in figure 3.1. The equivalent circuit parameters of the DGS cell can be extracted from its simulation response. Some simple relations are used to obtain the equivalent circuit parameters [39].

\[ C = \frac{5f_c}{\pi \left[ f_0^2 - f_c^2 \right]} \text{ pF} \quad 3.1 \]

Where, \( f_c \) is the cut-off frequency and \( f_0 \) is the resonating frequency.

\[ L = \frac{250}{C \left( \pi f_0 \right)^2} \text{ nH} \quad 3.2 \]

Quality Factor \( Q = \frac{f_0}{f_CU - f_CL} \quad 3.3 \)

Bandwidth \( BW = \frac{f_0}{Q} \quad 3.4 \)

Sharpness Factor \( = \frac{f_c}{f_0} \quad 3.5 \)

In figure 3.2, a DGS is created by etching two identical rectangular cells having length and breadth of \( a \) and \( b \) respectively from the ground plane of microstrip line. These two cells are connected with a slot with a gap of \( g \). Here, \( L \) is the physical length and \( \theta \) is the electrical length, \( W \) is the width of the microstrip line and \( h \) is the thickness of substrate. By changing the dimension of the DGS cell, frequency of operation can be changed. A
quasi TEM mode propagates in a conventional microstrip line. For this mode most of the electric and magnetic fields are confined within the microstrip structures. The return current on the ground plane is the negative image of the current on the microstrip line.

![Diagram of quasi TEM mode in microstrip line]

**Figure 3.2: Dumb-bell shaped DGS in microstrip line**

This return path of the current is fully disturbed and this current is confined to the periphery of perturbation along DGS side arms. Hence delay occurs due to increased path and also due to perturbation, and the phase velocity is reduced. This reduced phase velocity leads to the slow wave propagation. Since, microwave device size is proportional to the guided wavelength $\lambda_g$, at which it operates, and the guided wavelength is proportional to the phase velocity $v_p$. This reduced $v_p$, increases the phase constant $\beta$ which increases the slow-wave propagation as shown in figure 3.3. This slow wave factor is used to reduce the circuit size [35].
3.2 Design and Simulation of Microstrip line with DGS

Figure 3.4 shows the top view of the microstrip line. This is designed on FR-4 epoxy substrate (dielectric constant 4.4). This microstrip line is simulated on HFSS software. A square dumb-bell shape is etched out from the ground plane (bottom view of microstrip line with DGS) is shown in figure 3.5. The frequency response curve (insertion loss and transmission loss) of this structure is shown in figure 3.6. This microstrip line with DGS unit cell is a good guiding structure with small distortion due to the linear phase variation of transmission loss with frequency. A phase variation of transmission loss versus frequency is shown in figure 3.7. A jumping phenomenon occurs at resonant frequency $\omega_0$. 

![Diagram of Slow Wave Factor](image)
Figure 3.4: Schematic model of top view of square dumb-bell shaped DGS

Figure 3.5: Schematic model of bottom view of square dumb-bell shaped DGS
Figure 3.6: Frequency response curve of square shaped DGS

Figure 3.7: Phase variation of square shaped DGS

Figure 3.7 shows the jumping phenomenon (phase variation) of DGS. Phase variation in microstrip line with DGS is faster as compared to phase variation in microstrip line.
without DGS. Below resonating frequency ($\omega_0$), the DGS exhibits slow-wave behavior, while above resonating frequency ($\omega_0$), it exhibits a fast-wave behavior. This can be explained as follows.

Case 1: (slow wave, inductive microstrip line) $\omega < \omega_0$.

$$\omega L < \frac{1}{\omega C}$$

Case 2: (fast wave, capacitive microstrip line) $\omega > \omega_0$.

$$\omega L > \frac{1}{\omega C}$$

Case 3: (jumping phenomenon) $\omega = \omega_0$.

$$\omega L = \frac{1}{\omega C}$$

Generally, the slow-wave factor (SWF) is defined by the ratio of free space wavelength to the guided wavelength ($\lambda_0 / \lambda_g$).

Where, $\lambda_g = \text{guided wavelength}$ and $\lambda_0 = \text{free space wavelength}$.

The comparison of slow wave behavior of the microstrip lines with DGS and without DGS reveals:

- By increasing the frequency, slow wave factor of the microstrip structures with DGS cells can be improved.
- At resonant frequency $f_0$, jumping phenomenon occurs.
- Below $f_0$, DGS cells exhibit a slow-wave behavior and beyond $f_0$, a fast-wave behavior.
3.3 Size Reduction Techniques in Microstrip Line

A simplified and accurate mathematical model is available to predict the reduced dimensions of the microstrip circuits by using planes with discontinuities such as Defected Ground Structures (DGS). The model is based on the changed in its surface impedance capacitance and inductance in microstrip structure with slotted planes. Due to this change, we calculate the change in slow wave factor or other parameters like operating frequency, phase constant and phase delay. The use of DGS consequently allows an increase in the Slow Wave Factor (SWF) in transmission lines in which they are introduced. This phenomenon can be used to reduce the size of passive planar circuits like microstrip line length, coupling lines, and microstrip antennas, among other microstrip structures. The slow wave factor (SWF) is the relation between the wave number in free space $k_0$ and the propagation constant $\beta$ of the transmission line. For loss less microstrip line,

$$SWF = \frac{\lambda_0}{\lambda_g} = \sqrt{\varepsilon_{eff}} = \frac{\beta}{k_0}$$ \hspace{1cm} 3.6

Where, $\lambda_0$ is free space wavelength and $\varepsilon_{eff}$ is the effective permittivity.

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2} \left(1 + \frac{12h}{W}\right)^{-0.5}$$ \hspace{1cm} 3.7

Where, $\varepsilon_r$ is the relative permittivity, $h$ is the thickness of the substrate and $W$ is the width of strip of microstrip line.

Therefore, phase constant $\beta$ can be written as
\[ \beta = \sqrt{\varepsilon_{\text{eff}}} \cdot k_0 = \frac{\omega}{v_p} = \frac{\omega}{c} \sqrt{\varepsilon_{\text{eff}}} \]  \hspace{1cm} (3.8)

Where, \( \omega \) is the angular frequency, \( c \) is the velocity of light in free space and \( v_p \) is the phase velocity.

The SWF of the microstrip line can be increased by introducing the discontinuity in the path of electromagnetic wave.

The electrical length of microstrip line is given by

\[ \theta = \beta l = \sqrt{\varepsilon_{\text{eff}}} K_0 l \]  \hspace{1cm} (3.9)

Where, \( l \) is the physical length of microstrip line.

Thus, by inserting discontinuities in microstrip line, electrical length \( \theta \) increases, while physical length of microstrip line remains the same. This increased electrical length, shifts the resonating frequency towards left of it. Thus, by reducing the length of the microstrip line, we can retain the original electrical length and also resonating frequency shifted to its original position [36].

**3.4 Comparison of Stop-band Characteristics of Various Shaped DGS Cell**

The resonance frequency \( f_0 \) of dumb-bell shaped DGS cell depends on its physical structure. For example, resonant frequency \( f_0 \) can be reduced by choosing a smaller gap between the slots, by increasing the area of DGS cell or by increasing the distance between the cells. Due to limitation in PCB fabrication techniques, the gap between the slots cannot be reduced indefinitely. Therefore, increasing the size of DGS cell is the practical approach used to reduce the resonating frequency.
The simulations are performed using High Frequency Structure Simulator (HFSS) software. The substrate used in the simulation is FR4-epoxy ($\varepsilon_r$ is 4.4) with a board
thickness of 0.8 mm, and a loss tangent of 0.0009. All shape of the Defected Ground Structure resonating at same frequency (4 GHz).

The proposed DGS cell can be understood based on the parameters extracted from the equivalent- circuit model proposed by Pramod et al [37]. Figure 3.8 gives the flow chart of design and analysis method of DGS.

3.4.1 Square Dumb-bell Shaped Defected Ground Structure

Here, a square dumb-bell shaped Defected Ground Structure (DGS) is designed and simulated. HFSS design layout of DGS is shown in the figure 3.9. Frequency response curve ($S_{11}$ and $S_{21}$) is shown in the figure 3.4. The 3-dB bandwidth of this structure is 2.45 GHz.

![Figure 3.9: Schematic model of square dumb-bell shaped DGS](image)
Figure 3.10: Frequency response curve of square dumb-bell shaped DGS

3.4.2 Circular Dumb-bell Shaped Defected Ground Structure

Figure 3.11 show the schematic model of circular dumb-bell shaped DGS. This structure is resonating at 4GHz and the 3-dB cut-off frequency of the structure is 2.25 GHz as shown in figure 3.12.

Figure 3.11: Schematic model of circular dumb-bell shaped DGS
Figure 3.12: Frequency response curve of circular shaped DGS

3.4.3 Triangular Dumb-bell Shaped Defected Ground Structure

Here, we design an arrow head DGS resonating at 4GHz. HFSS model of the structure is shown in the figure 3.13. The 3-dB bandwidth of the structure is 2.65 GHz, as can be seen in the figure 3.14.

Figure 3.13: Schematic model of triangular dumb-bell shaped DGS
Figure 3.14: Frequency response curve of triangular shaped DGS

3.4.4 Hexagonal Dumb-bell Shaped Defected Ground Structure

Here, a hexagonal dumb-bell shaped DGS has been designed and simulated on FR-4 epoxy substrate (dielectric constant 4.4). This structure is resonating at 4 GHz. A schematic model of this structure is shown in the figure 3.15. Figure 3.16 shows the transmission and reflection coefficient ($S_{21}$ and $S_{11}$), the 3-dB bandwidth of this structure is 2.35 GHz.

Figure 3.15: Schematic model of hexagonal dumb-bell shaped DGS
3.4.5 Hexagonal Transmetal Dumb-Bell Shaped DGS

In this section, we design a hexagonal dumb-bell shaped DGS with trans-metal (a metallic cut is made inside the hexagonal shaped DGS cell). A HFSS model of DGS is shown in the figure 3.17 and the frequency response curve ($S_{21}$ and $S_{11}$) is shown in the figure 3.18. The 3-dB bandwidth of this structure is 2.95 GHz. Due to the trans-metal, this structure has a sharp transition between 3-dB to 30-dB. It is clear that for the same resonating frequency, any type of DGS cell can be designed. The resonant frequency depends on the shape and size of DGS cell. Figure 3.19 and figure 3.20 show the comparison of the transmission and reflection coefficient of square, circular, triangular, hexagonal and hexagonal with transmetal dumb-bell shaped DGS at 4GHz resonating frequency respectively.
Figure 3.17: Schematic model of hexagonal dumb-bell shaped DGS with trans-metal

Figure 3.18: Frequency response curve of hexagonal shaped DGS with trans-metal
Figure 3.19: Comparison of frequency response curve (S21) of various types of DGS

Figure 3.20: Comparison of frequency response curve (S11) of various types of DGS

With a fixed band stop resonance frequency of 4 GHz, the physical parameters of the five band stop resonators under study were designed and the simulated and their transmission
coefficients and reflection coefficient are plotted in figure 3.19 and figure 3.20. Table 3.1 compares the extracted equivalent-circuit parameters L, C, upper cut-off frequency \( f_{\text{CU}} \), Lower cut-off frequency \( f_{\text{CL}} \) and sharpness factor of the five band stop resonators of all types of DGS cell. From the table it is clear that the occupying is of hexagonal with trans-metal DGS is less among all types of DGS and quality factor as well as the sharpness factor of Hexagonal with trans-metal shaped DGS is more among all as well as the capacitance of the hexagonal with trans-metal cell is much greater than that of the any other shaped cell, while there is little difference in the inductances. Thus, we can conclude that the extended gap length results in increased capacitance, and the increased capacitance leads to \( f_0 \) reduction and size reduction.

**Table 3.1: Simulated parameters from frequency response curve of DGS cells**

<table>
<thead>
<tr>
<th>Shape of DGS</th>
<th>DGS area (mm²)</th>
<th>Value of L &amp; C</th>
<th>( f_0 = 4 ) GHz ( f_{\text{CU}} ) &amp; ( f_{\text{CL}} ) (GHz)</th>
<th>Sharpness factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square shaped DGS</td>
<td>28.88</td>
<td>L=2.483 nH</td>
<td>( f_{\text{CU}} =9.7) ( f_{\text{CL}}=2.45 )</td>
<td>0.6125</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C=0.65 pF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circular shaped DGS</td>
<td>42.4528</td>
<td>L=4.9523 nH</td>
<td>( f_{\text{CU}} =12) ( f_{\text{CL}}=2.25 )</td>
<td>0.5625</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C=0.32 pF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Triangular Shaped DGS</td>
<td>21.625</td>
<td>L=3.37 nH</td>
<td>( f_{\text{CU}} =8.8) ( f_{\text{CL}}=2.65 )</td>
<td>0.6625</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C=0.47 pF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hexagonal shaped DGS</td>
<td>32.4375</td>
<td>L=4.4372 nH</td>
<td>( f_{\text{CU}} =10) ( f_{\text{CL}}=2.35 )</td>
<td>0.5875</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C=0.357 pF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hexagonal with trans-metal shaped DGS</td>
<td>27.035</td>
<td>L=2.4646 nH</td>
<td>( f_{\text{CU}} =6.4) ( f_{\text{CL}}=2.95 )</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C=0.643 pF</td>
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</tr>
</tbody>
</table>
3.5 Design of Band-Stop Filter Using Triangular Ring Shaped DGS

The microstrip band-stop filter is designed on FR4 epoxy with loss tangent 0.002 and board thickness of 0.87 mm. The dimension of the filter is 10 mm×6 mm×0.87 mm. To get better response a small patch is placed on the both the triangular DGS. The area of this filter is very small. This filter is simulated up to 15 GHz frequency, this filter passing all the frequency except in stop-band which is 8.6 GHz to 10.7 GHz. Thus stop-bandwidth of this filter is 2.1 GHz. Figure 3.21 and figure 3.22 shows the top and bottom view of the filter. Figure 3.23 plots the transmission coefficient and the reflection coefficient versus frequency. E-field variation and H-field variation of the filter is clearly shown in figure 3.24 and figure 3.25 respectively.

![Figure 3.21: Schematic (top view) model of band-stop filter with small patch on triangular ring DGS](image-url)

...
Figure 3.22: Schematic model (bottom view) of band-stop filter with small patch on triangular DGS

Figure 3.23: Frequency response curve of band-stop filter
Figure 3.24: E-Field variation of band-stop filter

Figure 3.25: H-Field variation of band-stop filter
3.6 Low-Pass Filter with Arrow Head DGS

Here, arrowhead Defected Ground Structures low-pass filter is successfully designed with a very sharp transition from -3dB to -33 dB. This transition is almost approaching unity. Half power cut-off frequency of this filter is 5.8 GHz with a wide stop-band more than 12 GHz. The microstrip band-stop filter is designed on FR4 epoxy with a loss tangent of 0.002 and board thickness of 0.87mm. The dimension of the filter is 12.25 mm ×10. 75mm. Figure 3.26 and figure 3.27 shows the top and bottom view of the filter, S$_{11}$ and S$_{21}$ parameters are clearly seen in figure 3.28, where sharp transitions can be seen. Figure 3.29 and figure 3.01 show the E-field and H-field variations respectively.

![Figure 3.26: Schematic model (top view) of low-pass filter with arrow head DGS](image)
Figure 3.27: Schematic model (bottom view) of low-pass filter with arrow head DGS

Figure 3.28: Frequency response curve of low-pass filter with arrow head DGS
Figure 3.29: E-field variation of low-pass filter with arrow head DGS

Figure 3.30: H-field variation of low-pass filter with arrow head DGS
Here, we have designed and simulated different types of Defected Ground Structure (DGS) filter. Thus, our work shows that it is possible to design various types of filter for any frequency band by using Defected Ground Structure (DGS). These filters are low cost and occupy a very small area and volume because of their planner structure.