Design and realization of microstrip filters with new defected ground structure (DGS)

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Abstract

In this paper, various microstrip filters, such as bandpass (narrow/wideband) filters, dual band bandpass filter and lowpass filters, are designed with new metal strips loaded defected ground structure (DGS). In this proposed DGS, metal strips are introduced in connecting slot of dumbbell shaped DGS (DB-DGS). This new DGS is an improved version of conventional (dumbbell-shaped) DGS with enhanced characteristics of filters. With this new metal strip loaded DB-DGS, a bandpass (narrow-band/wide-band) filters, dual-band bandpass filter and lowpass filters, are designed with improved characteristics. The entire proposed filters are designed and fabricated with the same substrate area using 50\(\Omega\) microstrip line which is very compact to conventional microstrip filters. For validation of proposed designs, all fabricated filters are measured in Rohde and Schwarz Vector Network Analyzer 1127.8500 and also compared with circuit simulated results. All the simulations are carried out in HFSS V10 and ADS2006A.

Keywords:
Metal strip DB-DGS
Microstrip filters and conventional DGS

1. Introduction

A defected ground structure (DGS) is a very popular methodology for reducing the size of microwave components in recent years. Still, a continuous research is going on this methodology for improving the properties of microwave/millimeter wave components. The concept of DGS is originated from photonic band gap structures (PBG) in the optical field [1]. The DGS is realized by etching simple shape in the ground plane of microstrip line [2]. The etched pattern disturbs the current path in the ground plane which changes the performance of microstrip line. The DGS has two main characteristics: one is slow-wave effect and another one is bandstop characteristics [3]. These characteristics can be modified by changing the dimensions and shapes of DGS. In this paper, microstrip bandpass filters (narrow band/ wide band), dual-band bandpass and low pass filters are proposed with new metal loaded DGS. This new metal loaded DGS is compared with the other conventional DGS and this new proposed DGS shows the better performance characteristics among all the conventional DGS [1–10]. On the basis of the performance of proposed DGS, bandpass, dual-band and low pass filters are designed, fabricated and tested with the same substrate area (20 mm \times 19.5 mm) or (0.0065\(k\)/ 0.0064\(k\)).

2. Comparison of various dumbbell-shaped DGS with metal loaded DGS

Fig. 1 shows design configurations of various DB-DGSs with metal loaded DB-DGS. In this new DB-DGS, two metal strips are added in the connecting slot of the square dumbbell shaped DGS as shown in Fig. 1(e). These strips provide better effective parallel capacitance compared to other conventional DB-DGS which improves the sharpness of the filters response [6–10].

In conventional DB-DGS, the effective capacitance could be improved by adjusting the dimensions of the connecting slot between the dumbbells i.e. connecting slot length (d) and slot gap (g). However, these dimensions cannot be adjusted beyond the limitations of the overall dimensions and hence, limits the scope of the use of this DGS configuration. All the design configurations of DB-DGS are etched out with a line width of 3.4 mm and line length of 19.5 mm.

The dielectric constant (\(\varepsilon_r\)) of the substrate Neltec is 3.38 with the loss tangent (\(\tan\delta\)) of 0.0025. The conductor thickness is 0.07 mm and substrate height is 1.524 mm. The dimensions of various DB-DGS structures are given in Table 1.

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2215-0986/© 2016 Karabuk University. Publishing services by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
2.1 Frequency characteristics of various DB-DGS in compared to new DB-DGS

The characteristics of some simulated DB-DGS design configurations have been shown in Fig. 2. All DB-DGS design configurations have been simulated using EM simulator HFSS V10. The 3 dB cutoff is kept same for all the DB-DGS geometries at 4 GHz. From the Fig. 2, it is clearly seen that the sharpness and selectivity of metal loaded DGS is more than the other conventional DB-DGS geometries. The sharpness factor (S.F.) or roll off factor has been calculated using the expression given below [8,9]:

\[
\text{Sharpness Factor} = \frac{f_c}{f_s} \quad (1)
\]

\[
\text{Selectivity} (\zeta) = \frac{\alpha_{(\text{min})} - \alpha_{(\text{max})}}{f_s - f_c} \quad (2)
\]

where \(\alpha_{(\text{min})}\), \(\alpha_{(\text{max})}\), are the 20-dB and 3-dB attenuation respectively, whereas \(f_s\), \(f_c\), and \(f_o\) are the stop frequency at 20-dB attenuation, 3-dB cut-off and resonant frequency in GHz. The unit of selectivity (\(\zeta\)) is dB/GHz.

The L-C equivalent circuit model of all DB-DGS configurations is shown in Fig. 3.

\[
C_p = \frac{5f_c}{\pi[f_o^2 - f_c^2]} \quad \text{pF} \quad (3)
\]

\[
L_p = \frac{250}{C_p(\pi f_o)} \quad \text{nH} \quad (4)
\]

Table 1
Dimensions of various DB-DGSs.

<table>
<thead>
<tr>
<th>Dimensions (in mm)</th>
<th>Circular</th>
<th>Hexagonal</th>
<th>Triangular</th>
<th>Square</th>
<th>Metal Loaded</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>–</td>
<td>–</td>
<td>4</td>
<td>3.2</td>
<td>3.5</td>
</tr>
<tr>
<td>g</td>
<td>0.8</td>
<td>1</td>
<td>1.1</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>d</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>r</td>
<td>0.3</td>
<td>3.1</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>r'</td>
<td>0.3</td>
<td>3.1</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>k</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.2</td>
</tr>
<tr>
<td>m</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.2</td>
</tr>
<tr>
<td>t</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>2.2</td>
</tr>
<tr>
<td>s</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Fig. 1. Various DB-DGS pattern: (a) triangular head (b) square head (c) circular head (d) hexagonal head (e) Proposed square head loaded with metal strips [1–6].

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In Table 2, the performances of various DB-DGS configurations are tabulated on the basis of simulated results in Fig. 2. From the Table 2, it is clearly observed that the selectivity ($\xi$) and sharpness of the proposed metal strip loaded DGS microstrip bandstop filters is better than the other conventional DB-DGS. The effective capacitance is increased and the inductance is decreased by inserting the metal strip in connecting slot of proposed DB-DGS. So this improvement in capacitance and inductance of proposed DB-DGS is responsible for high selectivity and sharpness of filter.

### 3. Parametric analysis of proposed DB-DGS

In this section, the effect of various dimensions of proposed DB-DGS on its frequency characteristics have been studied in terms of cut-off and resonant frequency. The critical parameters such as cut-off and resonant frequencies of proposed DB-DGS have been studied with respect to the variation in the dimensions. The main dimensions of proposed DB-DGS are ‘$a$’, ‘$g$’ and ‘$s$’, which effect the cut-off and resonant frequencies in significant manner. By controlling these dimensions, the desired cut-off and resonant frequencies can be achieved for various applications. The effect of various dimensions of proposed DB-DGS on the frequency characteristics have been shown in Figs. 4–6. The parametric analysis is also studied in terms of effective inductance and effective capacitance.

#### 3.1. Effect of dimension ‘$a$’

In Fig. 4, $S_{21}$ parameter is plotted with variation of dimension ‘$a$’. The other dimensions ‘$g$’ = 1.5 mm and ‘$s$’ = 0.3 mm are kept fixed. From the Fig. 4, it is clearly observed that as dimension ‘$a$’ increases the 3-dB cut-off and resonant frequency shifts toward lower frequency side but in this case, 3-dB cut-off is more significantly changed as compared to resonant frequency. This 3-dB cut-off frequency changed significantly due to large current path.

As the dimension ‘$a$’ is varied, the current flow path is also varied; which implies that the effective inductance will change more dominantly as compared to effective capacitance [15,180].

#### 3.2. Effect of dimension ‘$g$’

In this subsection, the effect of dimension ‘$g$’ on frequency characteristics has been plotted in Fig. 5. The dimension ‘$g$’ is slot gap of the square head connecting slot. As the slot gap ‘$g$’ is increased, the resonant frequency shifts toward higher frequency. It means that if the slot gap is less; the fringing field coupling capacitance will be more. As the slot gap minimizes, the coupling of electric field will be better due to fringing effect. From the Fig. 5, it is clear, the 3-dB cut-off is almost same, but only resonant frequency varies significantly as the slot gap ‘$g$’ is varied. This resonant frequency depends on effective capacitance. So by adjusting the slot gap dimension ‘$g$’, the desired resonant frequency can be achieved.

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**Table 2**

Comparative performance of microstrip bandstop filter with DGSs.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Circular</th>
<th>Hexagonal</th>
<th>Triangular</th>
<th>Square</th>
<th>Metal Loaded</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_c$ (GHz)</td>
<td>6</td>
<td>5.7</td>
<td>5.6</td>
<td>5.4</td>
<td>4.91</td>
</tr>
<tr>
<td>S.F.</td>
<td>0.66</td>
<td>0.7</td>
<td>0.71</td>
<td>0.74</td>
<td>0.81</td>
</tr>
<tr>
<td>$C_p$ (pF)</td>
<td>0.318</td>
<td>0.386</td>
<td>0.414</td>
<td>0.484</td>
<td>0.785</td>
</tr>
<tr>
<td>$L_p$ (nH)</td>
<td>2.214</td>
<td>2.021</td>
<td>1.953</td>
<td>2.1</td>
<td>1.339</td>
</tr>
<tr>
<td>$f_s$ (GHz)</td>
<td>5.7</td>
<td>5.5</td>
<td>5.4</td>
<td>5.3</td>
<td>4.8</td>
</tr>
<tr>
<td>$\xi$ (dB/GHz)</td>
<td>10</td>
<td>11.3</td>
<td>12.1</td>
<td>13</td>
<td>21.3</td>
</tr>
</tbody>
</table>

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3.3. Effect of dimension ‘s’

The effect of dimension ‘s’ on the frequency characteristics is shown in Fig. 6. As the dimension ‘s’ is increased, the resonant frequency is shifted toward the lower frequency. The shift in the frequency to lower side is due to reduction in gap between the metal strips of connecting slot. If the gap between metal strips of the connecting slot is less, the coupling will be better due to fringing field. In this case, 3-dB cut-off frequency varies little bit but the resonant frequency significantly changes with the variation of dimension ‘s’.

4. Design and realization of bandpass filters with narrow and wide bandwidth

In this section, narrow band, wide band and dual-band microstrip bandpass filters are designed with new metal strip DGS for wireless applications. All the bandpass filters are designed using 50 Ω, \( \lambda_g/4 \) microstrip line. The size of these bandpass filters are kept fixed which is 20 mm \( \times \) 19.5 mm \( (0.0065 \lambda_g \times 0.0064 \lambda_g) \). The dielectric constant \( (\varepsilon_r) \) of substrate = 3.38, height of substrate (h) = 1.524 mm, thickness of conductor (t) = 0.07 mm and loss tangent \( (\tan \delta) = 0.0025 \) are used in all design configurations. The design configurations of all bandpass filters have been explained with fabrication and measurement results in the subsection ‘A’, ‘B’ and ‘C’.

4.1. Narrow band microstrip bandpass filter (NBMBF)

The specifications for designing narrow band bandpass filter are the center-frequency \( (f_0) = 5.4 \text{ GHz} \), bandwidth \( (BW) \approx 300 \text{ MHz} \), 10-dB attenuation bandwidth \( \approx 900 \text{ MHz} \), insertion loss in pass band <1.0 dB and 20-dB attenuation in stopband. These specifications are suitable for WLAN applications.

Fig. 7 shows the design configuration of narrow band bandpass filter along with fabricated components using proposed DB-DGS. The dimension of proposed filter is shown in Fig. 7. In this design configuration two U-shaped slots are introduced in the strip of microstrip line in alternate fashion [12].

These two slots in conducting strip add capacitance in series with inductance and in turn parallel to the capacitance of L-C resonator of proposed DB-DGS [13–15]. The L-C equivalent circuit of this proposed design is shown in Fig. 8. This type of prototype circuit model will provide the narrow band effect. This circuit model has two resonant frequency characteristics with resonance and anti-resonance. There are two resonant circuits in Fig. 8, one is series resonant and second one is parallel resonant. For these resonant circuits, the circuit parameters can be calculated using the following equations [13]:

For series resonant circuit

\[
C_k = C_0 \left[ \frac{f^2_0}{f^2 - f^2_k} \right] \quad (1)
\]

\[
L_k = \frac{1}{4\pi^2 f^2_C C_k} \quad (2)
\]

\[
f_0 = \frac{1}{2\pi \sqrt{L_k C_k}} \quad (3)
\]

For parallel resonant circuit

\[
C_k = C_0 \left[ \frac{f^2}{f^2 - f^2_k} \right] \quad (4)
\]
Here $f_o$, $f_a$ and $f_i$ are the resonant, anti-resonant frequencies. $C_p$ and $C_o$ can be determined using the same modeling method as presented in [13,14]. The extracted values of circuit parameters are: $L_k = 8.03\,\text{nH}$, $C_k = 0.118\,\text{pF}$, $C_p = 0.659\,\text{pF}$ and $C_o = 0.365\,\text{pF}$. If the number of slots increases in the conducting strip, it will increase the series capacitance which will make the response narrower. The effect of increased slots has not been shown here. This proposed filter has been tested after fabrication. The measured results of proposed narrow band bandpass filter are shown in Fig. 9. These measured result are compared with circuit simulated and HFSS simulated results. The measured results are in good agreement with simulated results. In Fig. 9, it can be clearly seen that the center frequency is 5.4 GHz, 3-dB upper and lower cut-off frequencies are 5.5 GHz and 5.2 GHz, respectively, bandwidth (BW) is 300 MHz, insertion loss in passband is 0.6 dB and 10-dB attenuation bandwidth is 1 GHz. It can be observed that the measured values are in good agreement with simulated results.

4.2. Wide band microstrip bandpass filter (WBMBF)

In Fig. 10, a wide band microstrip band pass filter is shown. The design specifications are chosen like center frequency ($f_a$) is 4 GHz, 3-dB upper and lower cut-off frequencies are 6.4 GHz and 1.4 GHz, respectively, bandwidth (BW) is 5 GHz, insertion loss in passband $\leq 0.5\,\text{dB}$ and 10-dB attenuation bandwidth is 6.3 GHz. The dimensions are shown in Fig. 10. This filter is also designed using 50 $\Omega$, $\lambda_g/4$ microstrip line. In this bandpass filter a new metal loaded DBDGS array is used with U-slot in conducting strip. This DB-DGS array gives a wide stopband because it suppresses the other frequency bands [1,14–17]. U-slot in the conducting strip gives a series capacitance due to fringe field coupling. This U-slot will also produce inductance effect in parallel with line capacitance. This whole combinations of L-C circuit model behave as a wide band bandpass filter. The L-C circuit model for this proposed filter is shown in Fig. 11. The values of circuit parameters as shown in Fig. 11, can be determined as in case of narrow-band bandpass filter in subsection ‘A’.

The values of these circuit parameters are: $L_k = 2.1667\,\text{nH}$, $C_k = 0.342\,\text{pF}$, $C_p = 0.620\,\text{pF}$, $L_p = 4.186\,\text{nH}$, and $C_o = 0.1.199\,\text{pF}$. The fabricated bandpass filter is measured in Vector Network Analyzer. Fig. 12 shows the measured result along with HFSS simulated and circuit simulated results. The simulated and circuit simulated results are similar but the measured results differ a little bit. The difference in results is due to fabrication error.

4.3. Dual-band microstrip bandpass filter (DBMBF)

In this section, a dual band bandpass filter is designed. Fig. 13 shows the design configuration of proposed dual band bandpass
filter with same new metal strip DB-DGS topology. In this proposed
design, two via is used for getting dual band properties
In this proposed dual band bandpass filter, a slot is introduced
in the conducting strip with the two via with different dimensions
as 1.2 mm and 1 mm respectively [18]. This slot adds the series
capitance due to fringing field convergence or coupling. This series
capitance behaves like a high pass filter for particular fre-
quency that characteristics applied to design bandpass filter. The
proposed DB-DGS gives one pole low pass characteristics [7]. So
the combination of low-pass and high-pass will give the bandpass
characteristics. That is why series capacitance is included in series
with the line. The two via which make the microstrip line shorted
with ground which will give two inductances in parallel with
capacitances. The L-C equivalent circuit model for this proposed
dual-band bandpass filter is shown in Fig. 14.

The extracted values of equivalent circuit parameters are:

\[
L_1 = 2.2575 \, \text{nH}, \quad C_1 = 2.63039 \, \text{pF}, \quad L_2 = 1.9276 \, \text{nH}, \quad C_2 = 0.06294 \, \text{pF}, \quad L_3 = 1.0487 \, \text{nH}, \quad C_3 = 0.62237 \, \text{pF}, \quad L_4 = 2.4869 \, \text{nH}, \quad C_4 = 1.71129 \, \text{pF},
\]

\[
L_5 = 1.2085 \, \text{nH}, \quad C_5 = 0.45255 \, \text{pF} \quad \text{and} \quad C_0 = 0.6024 \, \text{pF}.
\]

In this proposed dual-band band filter, the center frequencies are 4.2 GHz
and 7.7 GHz. The bandwidths of this dual band are 400 MHz and
500 MHz. The other design specifications such as dielectric con-
stant, loss tangent, height of substrate and thickness of conductors
are same as in Fig. 1. This proposed design is fabricated and the lay-
out of fabricated design is also shown in Fig. 13.

After the fabrication, the fabricated design is measured in VNA.
The simulated, circuit simulated and measured results are shown
in Fig. 15. The resonant frequencies are almost same in all the sim-
ulated and measured results. It is clearly observed in the Fig. 15,
the insertion loss is more in measurement as compared HFSS sim-
ulated and circuit simulated results. Insertion loss is 0.7 dB in both
the passband but in measurement it is 0.9 dB. This additional loss
is due to attenuation in VNA cable. This additional loss is very less.
The measured and simulated results are almost good in agreement.

5. Design and realization of low pass filter

In Fig. 16, a microstrip low pass filter is shown. This low pass fil-
ter is also designed using 50 $\Omega$, $\lambda_s/4$ microstrip line. In this design
configuration the specifications are dielectric constant ($\varepsilon_r$) = 3.38,
height of substrate ($h$) = 1.524 mm, thickness of conductor ($t$) = 0.07 mm
and loss tangent ($\tan \delta$) = 0.0025. The design goals for designing this low pass filter are 3-dB cutoff frequency = 6.6 GHz,
insertion loss in passband 0.5 dB, 20-dB attenuation from
7.4 GHz to 10 GHz. The proposed DB-DGS is used in the ground
plane of 50 $\Omega$ microstrip line. The size of filter is

![Fig. 12. S-parameter results of wide band bandpass filter with proposed DB-DGS.](image1)

![Fig. 13. Design configuration for dual-band bandpass filter with fabricated design (top view and bottom view).](image2)

![Fig. 14. L-C equivalent circuit model for proposed dual-band bandpass filter.](image3)

![Fig. 15. S-parameter results of dual-band bandpass filter with proposed DB-DGS.](image4)
20 mm × 19.5 mm. The dimensions of this proposed filter is shown in Fig. 16 with fabrication. In this low pass filter, there is no use of stub or hi-lo impedance. Various DB-DGS low pass filter is reported [11,19] but in this low pass filter metal strip is inserted in the connecting slot of DB-DGS which gives the high sharpness as well as high selectivity. The DB-DGS array suppressed the higher order mode of frequency due to this high rejection is achieved in stopband [17]. The L-C equivalent circuit model of this proposed low pass filter is shown in Fig. 17.

There three resonator circuits each for three DGS. Extreme left and extreme right DGS are symmetrical so due to this the values of these resonators are same. Only center DGS is different in dimension so the values of circuit parameters are more as compare to small DGS resonators. The mathematical derivations for calculating extracted parameters are described in [1]. After the fabrication, the filter is measured in terms of S- parameter. The simulated, circuit simulated and measured results are shown in Fig. 18.

It is clearly observed that 3-dB cut-off frequency is same in both simulation and in measurement. In measurement insertion loss in passband is 0.7 dB which is quite comparable with insertion loss in simulation and in measurement. In measurement insertion loss in circuit simulated and measured results are shown in Fig. 18.

5.1. Comparison of recently reported work

Here, in this section, recently reported works have been compared with the proposed work, shown in Table 3.

In the Table 3, it is clearly observed that the proposed design has the lesser size as compare to other recently reported work.

### Table 3
Comparison of recently reported work with proposed work.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Effective size of filter ($a \times b$)</th>
<th>IL (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[20]</td>
<td>0.06a x 0.055b</td>
<td>1.0 dB</td>
</tr>
<tr>
<td>[21]</td>
<td>0.106a x 0.055b</td>
<td>0.3 dB</td>
</tr>
<tr>
<td>[22]</td>
<td>0.17a x 0.152b</td>
<td>1.49 dB</td>
</tr>
<tr>
<td>[23]</td>
<td>1.1a x 0.45b</td>
<td>1.5 dB</td>
</tr>
<tr>
<td>[24]</td>
<td>0.37a x 0.182b</td>
<td>0.32 dB</td>
</tr>
<tr>
<td>[25]</td>
<td>0.489a x 0.278b</td>
<td>0.5 dB</td>
</tr>
<tr>
<td><strong>In this work</strong></td>
<td><strong>0.0065a x 0.0064b</strong></td>
<td><strong>&lt;1dB</strong> (in all the filter type)</td>
</tr>
</tbody>
</table>

6. Conclusions

All type filters are investigated with new metal loaded DB-DGS which shows the high selectivity and high sharpness factor. All the filters designed on a same substrate with same area 20 mm × 19.5 mm = 390 mm². No stubs, hi-lo impedance are used in the designing of bandpass and low pass filter designing. In this paper, all filters are designed using metal loaded DB-DGS. All filters show measured and simulated results in good agreement. So far no detailed work is reported for designing all filters such bandpass filters with narrow/wide band, dual band and low pass filter by using same design configuration with same area.

### References


