CHAPTER 5
DESIGN AND ANALYSIS

5.1 ANALYSIS OF DESIGN - I (OUTER RING)

For the analysis, the outer CSRR of multi-ring structure is considered as shown in Figure 5.1. The FEXT value for 4 cases of ground plane with the following structures.

(i) Solid ground

(ii) 1 CSRR at the centre

(ii) 2 CSRR at the two ends

(iii) 3 CSRR – one at the centre and the other two at the ends or Edges

Figure 5.1 CSRR design - I
5.1.1 FEXT Comparison for Design - I

The S-parameters of the FEXT values are shown in Figure 5.2 and the values are compared in the Table 5.1.

![Figure 5.2 Comparison of FEXT for design - I](image)

**Table 5.1 Comparison of FEXT for design - I**

<table>
<thead>
<tr>
<th>Design Freq. in GHz</th>
<th>Solid ground</th>
<th>1 CSRR</th>
<th>2 CSRR</th>
<th>3 CSRR</th>
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<td>-14.66</td>
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<td>6.8</td>
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<td>-12</td>
<td>-16</td>
<td>-24</td>
</tr>
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</table>
The solid ground has an average value of -10dB over 6 to 6.5 GHz and increases to -9dB for other frequencies. When 1 unit cell of CSRR of design I is considered, the maximum FEXT reduction occurs at the frequency 8 GHz with a value of -20dB. From the tabulated values using 1 CSRR at centre the FEXT reduces considerably and is maximum at 8 GHz. When 2 unit cell of CSRRs are designed at the two ends of the board the maximum reduction occurs at the frequency range 7.1 to 7.6 GHz with a maximum of -24dB. For the design of 3 unit cell of CSRRs at the ground plane the FEXT has the maximum value of -24dB at 6.8 GHz where resonance occurs. From the analysis when two unit cell of CSRRs are etched in the ground plane, the FEXT has reduced to a maximum value of -23.56 dB for a frequency value of 7.5 GHz.

5.1.2 NEXT Comparison for Design - I

The S-parameters of the NEXT values are shown in Figure 5.3 and the values are compared in the Table 5.2.

![Figure 5.3 Comparison of NEXT for design - I](image_url)
Table 5.2 Comparison of NEXT for design - I

<table>
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<tr>
<th>Design</th>
<th>Freq. in GHz</th>
<th>Solid Ground</th>
<th>1 CSRR</th>
<th>2 CSRR</th>
<th>3 CSRR</th>
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</table>

From the Table 5.2 at 7 GHz, the NEXT has the closer values with the solid ground. At this frequency, the FEXT has a value of -17 dB. Hence at this range of frequencies, the crosstalk has reduced and the signal output has improved.

5.2 ANALYSIS OF DESIGN - II (INNER RING)

For the analysis, the inner CSRR of multi-ring structure is considered as shown in Figure 5.4. The FEXT value for 4 cases of ground plane with the following structures.

(i) Solid ground

(ii) 1 CSRR at the centre

(ii) 2 CSRR at the two ends

(iii) 3 CSRR – one at the centre and the other two at the ends or edges
5.2.1 FEXT Comparison for Design - II

The S-parameters of the FEXT values are shown in Figure 5.5 and the values are compared in the Table 5.3.
Table 5.3 Comparison of FEXT for design - II

<table>
<thead>
<tr>
<th>Freq. in GHz</th>
<th>Design</th>
<th>Solid Ground S(4,1) in dB</th>
<th>1 CSRR S(4,1) in dB</th>
<th>2 CSRR S(4,1) in dB</th>
<th>3 CSRR S(4,1) in dB</th>
</tr>
</thead>
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<tr>
<td>6</td>
<td>-10</td>
<td>-13.27</td>
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<td>-10</td>
<td>-11</td>
<td>-13</td>
<td>-25</td>
<td></td>
</tr>
</tbody>
</table>

The solid ground has an average value of -10 dB over 6 to 6.5 GHz and increases to -9 dB for other frequencies. When 1 unit cell of CSRR of design II is used the maximum FEXT reduction occurs at the frequency 6 GHz with a value of -13.27 dB. When 2 unit cell of CSRRs are designed at the two ends of the circuit board the maximum reduction occurs at the frequency range 6 to 6.2 GHz with a maximum of -16 dB. For the design of 3 unit cell of CSRRs at the ground plane the FEXT has the maximum value of -25 dB at 6.13 GHz where resonance occurs. From the analysis when two unit cell of CSRRs are etched in the ground plane, the FEXT has reduced to a maximum value of -16 dB for a frequency value of 6 GHz. After 7 GHz deviation of FEXT is less due to the fact that this CSRRs contribution is minimum in the high frequency region.

5.2.2 NEXT Comparison for Design - II

The S-parameters of the NEXT values are shown in Figure 5.6 and the values are compared in the Table 5.4.
The NEXT due to the backward crosstalk has the minimum value of -36 dB at 6 GHz when using 2 unit cell of CSRRs in the ground plane achieving 3 dB reduction compared with solid ground. From 6.8 to 7.4 GHz the single unit of CSRR at center gives a reduction of 3 dB average.
5.3 ANALYSIS OF DESIGN - III (MULTI-RING)

Multi-ring CSRR

![Multi-ring CSRR](image)

**Figure 5.7 Multi-ring CSRRs design - III**

For the analysis, the CSRR of multi-ring structure is considered as shown in Figure 5.7. The FEXT value for 4 cases of ground plane with the following structures are considered for analysis.

(i) Solid ground

(ii) 1 CSRR at the centre

(ii) 2 CSRR at the two ends

(iii) 3 CSRR – one at the centre and the other two at the ends or edges

5.3.1 FEXT Comparison for Multi-Ring CSRRs

The S-parameters of the FEXT values are shown in Figure 5.8 and the values are compared in the Table 5.5.
Figure 5.8 Comparison of FEXT for multi-ring CSRRs

Table 5.5  Comparison of FEXT for Multi-ring CSRRs

<table>
<thead>
<tr>
<th>Freq. in GHz</th>
<th>Design</th>
<th>Solid Ground $S(4,1)$ in dB</th>
<th>1 CSRR $S(4,1)$ in dB</th>
<th>2 CSRR $S(4,1)$ in dB</th>
<th>3 CSRR $S(4,1)$ in dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td></td>
<td>-10</td>
<td>-11.28</td>
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<td></td>
<td>-9</td>
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<td>-50</td>
<td>-20</td>
</tr>
</tbody>
</table>

The solid ground has an average value of -10 dB over 6 to 6.5 GHz and increases to -9 dB for other frequencies. When 1 unit cell of multi-ring CSRR is considered at center the maximum FEXT reduction occurs at the
frequency 8 GHz with a value of -20 dB. From the values using 1 multi-ring CSRR at centre the FEXT reduces considerably and is maximum at 8 GHz. When 2 unit cell of CSRRs are designed at the two ends of the board the maximum reduction occurs at the frequency range 7.0 to 7.2 GHz with a maximum of -50 dB. For the design of 3 unit cell of CSRRs at the ground plane the FEXT has the maximum value of -44 dB at 6.81 GHz where resonance occurs. From the analysis when two unit cell of CSRRs are etched in the ground plane, the FEXT has reduced to a maximum value of -50 dB for a frequency value of 7.13 GHz.

5.3.2 NEXT Comparison for Multi-Ring CSRRs

The S-parameters of the NEXT values are shown in Figure 5.9 and the values are compared in the Table 5.6.

![Figure 5.9 Comparison of NEXT for multi-ring CSRRs](image-url)

Figure 5.9 Comparison of NEXT for multi-ring CSRRs
Table 5.6  Comparison of NEXT for Multi-ring CSRRs

<table>
<thead>
<tr>
<th>Freq. in GHz</th>
<th>Design</th>
<th>Solid Ground S(3,1)in dB</th>
<th>1 CSRR S(3,1)in dB</th>
<th>2 CSRR S(3,1)in dB</th>
<th>3 CSRR S(3,1)in dB</th>
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<td>6</td>
<td>-33.77</td>
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<td>6.5</td>
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<tr>
<td>7</td>
<td>-21.9</td>
<td>-15.20</td>
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<td>7.5</td>
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<td>-16</td>
<td>-23</td>
<td>-18.36</td>
<td></td>
</tr>
</tbody>
</table>

From the NEXT Figure 5.9 the backward crosstalk varies with the frequency. For the two multiring CSRR configuration the NEXT has reduced -27 dB at 7.5 GHz. The FEXT at this frequency is reduced by 12 dB. Hence at this frequency, the FEXT and NEXT has reduced to achieve better signal integrity.

5.4 SUMMARY OF CROSSTALK SUPPRESSION IN PRINTED CIRCUIT BOARDS

A simple way to get negative values for the left handed operation is to load the coupled transmission lines with the CSRR designs. At a certain frequency range, the loading of CSRR gives rise to a left handed transmission bands. The design features of CSRR themselves operate as negative permittivity region for the cancellation of fields at resonance. The addition of CSRR to the ground plane enhances the crosstalk suppression but also increases the inductance and capacitance values. Three types of CSRR structures are designed in the ground plane to control the electromagnetic fields.
5.4.1 Geometrical Parameters

The inclusion of CSRR structure in the design makes the effective suppression of mutual coupling between the traces. The presence of inductance and capacitance in the CSRR structure gives rise to resonant frequency pulling the characteristic curve either upwards or downwards depending upon the respective designs. The variable geometric parameters include capacitances, gap distance, split gap and ring width size. From the designs by varying the capacitance gap of the CSRR, a relative shift occurs in the resonant frequency from higher to lower region.

When one unit cell of Multi-ring CSRR is used at the center the maximum value of suppression for $S_{41}$ exist at value of -20 dB at a frequency of 8 GHz. When two unit cell of CSRRs is used in the two ends of the coupled lines, the maximum value of suppression occurs at 7.13 GHz at a value of -50 dB. When unit cell of 3 CSRRs is used to suppress the mutual coupling, a maximum of crosstalk suppression exists to a value of -44 dB at a frequency of 6.81 GHz.

From the above discussion due to the increase in the number of CSRRs in the ground plane, the resonant frequency increases thereby pulling $S(4,1)$ characteristics downwards thus enhancing the suppression. When more number of unit cell of CSRRs is etched in the ground place narrower band of characteristics occurs at the resonance frequency.

5.4.2 Equivalent Circuit of Coupled Lines under CSRRs Loaded Conditions

The small electrical dimensions of CSRR at resonance can be treated as lumped equivalent circuit as shown in Figure 5.10. The L and C are inductance and capacitances of per section and $L_m$ and $C_c$ are the inductance
and capacitance of CSRR magnetically coupled to the transmission lines. The model is developed based on the structure symmetry of the traces with the CSRRs.

A single CSRR itself gives a strong response to an incident field in the resonant behavior. A sharp dip portion in the characteristic curve indicates the resonance. The CSRR structure has the effective capacitance between the rings and slits. This capacitance allows the electric field to circulate within the CSRR and coupling enables current through the rings. Similar procedure is also applicable for inductance where the magnetic field circulates in the CSRRs ring and the mutual coupling effect will reinforce the effects of flux cancellation. By varying the spacing between the CSRRs mutual inductance and capacitance varies making the resonant frequency to change.

![Figure 5.10 Equivalent circuit and resonant frequency of CSRR loaded PCB traces](image)

\[
F_r = \frac{1}{2\pi\sqrt{L_C C_C}}
\]

**Figure 5.10** Equivalent circuit and resonant frequency of CSRR loaded PCB traces
When the CSRRs are placed in a row beneath the coupled lines in
the ground plane the field produced as per the above discussion circulates
surface current in the rings following the Maxwell’s equations. Both the fluxes
penetrate through the rings making the effective permittivity values to change.
The CSRRs structures exhibits cross polarization effects for the applied fields.
When the number of CSRRs are increased in the ground plane along with the
traces the resonant frequency is shifted and reaches a peak value of
suppression with narrow band. The wide band region exists for the multi-ring
configuration of 2 CSRRs giving larger crosstalk suppression. This is due to
the fact that the electromagnetic field implicitly imposes the applied boundary
conditions on the CSRRs.

The simulations are done to show a reduction in the crosstalk over
the range of frequency 6 to 8 GHz. From the diagram it is observed that whole
structure of the CSRR resonates to the incident electromagnetic field. The
induced fields in the CSRRs structure gives uniform rise to resonant behavior
as can be seen from the plot of S (4,1) for all the three designs.

5.4.3 Modeling of CSRRs using L and C parameters

Figure 5.11 Coupled CSRR
For the Figure 5.11, CSRR configuration the value of inductance and capacitance for the resonant frequency is calculated by the expressions.

The resonant frequency is given by

$$\omega_0 = \frac{1}{\sqrt{LC}}$$  \hspace{1cm} (5.1)

and Inductance ($L$) is given as

$$L = \left( \frac{\mu_0}{4\varepsilon_0} \right) C_1$$  \hspace{1cm} (5.2)

Where

$$C_1 = \left( L - \frac{3}{2} (w + b) \right) C_{pal}$$  \hspace{1cm} (5.3)

and the capacitance ($C$) is given by

$$C = 4 \left( \frac{\varepsilon_0}{\mu_0} \right) L_1$$  \hspace{1cm} (5.4)

Where

$$L_1 = 4.86 \frac{\mu_0}{2} \left( L - w - b \right) \ln \left( \frac{0.98}{\rho} \right) + 1.84 \rho$$  \hspace{1cm} (5.5)

and

$$\rho = \left( \frac{w + b}{L - w - b} \right)$$  \hspace{1cm} (5.6)
For Figure 5.12, multi-ring CSRR configuration the value $L_{mcsrr}$ and $C_{mcsrr}$ is calculated from the following expressions.

\[
L_{MCSRR} = 4\mu_0 \left[ L - (N-1)(w+b) \right] \left[ \ln \left( \frac{0.98}{\rho} \right) + 1.84 \rho \right] \tag{5.7}
\]

\[
C_{MCSRR} = \frac{(N-1)}{2} \left[ 2L - (2N-1)(w+b) \right] C_{pul} \tag{5.8}
\]

Where,

- $L$ - overall length of square CSRR
- $w$ - width
- $b$ - dielectric gap
- $\rho$ - filling factor
N-number of rings

\( C_{\text{pu}} \) – per unit length capacitance

5.5 CONCEPT OF FLUX CANCELLATIONS

5.5.1 For Electric Fields

![Figure 5.13 Electric field for PCB traces only](image)

The Figure 5.13 shows the circulated electric field considering the PCB traces only. The time changing electric field causes polarization \( \text{`P'} \) is entirely concentrated under the traces as discussed in the Section 4.4. The Figure 5.14 shows the electric field around the CSRR ring considered separately due to the applied electric field in the PCB traces. This field causes electric polarization opposite to the previous one. As it goes along its path the field caused by the CSRR as depicted in Figure 5.14 nullifies the field generated at traces. Once this happens the effective value has decreased and the reduction of crosstalk is achieved. The cancellation of field from the lines with the CSRR is shown in Figure 5.15 for the frequency from the design I.
5.5.2 For Magnetic Fields

The Figure 5.16 shows the magnetic field generated by the trace of the PCB under high frequency condition. Around the conductor magnetic flux...
lines circulated causes magnetic polarization towards the ground plane. The Figure 5.17 shows the field loop generated within the rings of the CSRR for the same condition and causes magnetic polarization opposite to the previous one as discussed in the section (4.4). Once the condition given by the Equation (5.9) arises, the two magnetic fluxes cancel where the minimum crosstalk exists. This process is explained in the Figure 5.18.

\[ \chi_m = \frac{1}{\mu_0 \alpha^2 Chd} \] (5.9)

Figure 5.16 Magnetic field for PCB traces only

Figure 5.17 Magnetic field vectors for CSRRs
5.6 CROSSTALK ANALYSIS USING S-PARAMETERS

The proposed printed circuit board design with measurement set up is shown in Figure 5.21. The FEXT and NEXT comparison is made for the simulated and fabricated structure with two CSRRs etched on the ground. The design values are as follows: width $W = 2.35\text{mm}$, length $L = 40\text{mm}$, spacing $s = 2\text{mm}$, $\varepsilon_r = 4.7$, $\tan\delta = 0.02$, height of the substrate $h = 1.2\text{mm}$, $Z_{\text{odd}} = 45.2\Omega$, $Z_{\text{even}} = 55\Omega$ and thickness of the conductor $t = 1.35\text{mil}$. The CSRR unit is used to reduce the crosstalk.

For the analysis of crosstalk the momentum software from Agilent ADS tool is used for developing the S-parameters. The fabricated structure is measured with Agilent VNA. The trace is loaded at single end at port 1 and the operating range frequency is selected as 6 to 8 GHz based on the resonance behavior of the design.
Figure 5.19 FEXT comparisons with simulated and fabricated structures

The Figure 5.19 shows the simulated and measured values of the proposed design of two unit cell of multi-ring CSRR as shown in Figure 5.20 in the ground plane. The Table 5.7 shows the reading taken from the measurement setup Figure 5.21. The difference in the two readings of FEXT and NEXT is due to the loss parameters.
Table 5.7 Comparison of FEXT and NEXT

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<tr>
<th>Freq. in GHz</th>
<th>FEXT in dB</th>
<th>NEXT in dB</th>
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<td>Measured</td>
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<td>7.13</td>
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</table>
5.7 SIGNAL INTEGRITY ANALYSIS OF THE DESIGN

In this section the signal integrity of the CSRR loaded structure is investigated using eye diagrams, compared with solid ground plane. A pseudorandom bit sequence of 1 Gbps with a step size 0-1V launched at port 1 and signal output transmitted is measured at port 2. The coupled signal at the Near-end is measured at port 3 and far-end is measured at the port 4. The distorted eye diagram at the port 2 as shown in Figure 5.22 indicates the effect of crosstalk on the transmission lines. The effect of near-end crosstalk produces changes in the eye height and the far-end crosstalk causes timing jitter. The cross talk suppression achieved by CSRR should meet the signal integrity requirements for the effective transmission for a wide range of frequency. The input at port 1 is NRZ coded with a rise time of 100 psec with a data rate of 1 Gbps and the output is measured at the port 2.

Two streams of eye patterns are discussed for SI analysis. In the first case eye parameter with solid ground Figure 5.22 and in the second case with the CSRR etched ground Figure 5.23. It is seen that for the solid ground plane the eye width is measured as 7.63E-10 and eye opening factor of 0.912. For the 2 CSRR etched ground eye width is measured as 8.69E-10 with eye opening factor of 0.944.

Hence in order to ensure the received signal can be recovered sufficiently the value of the jitter must be small for the required threshold level. For the solid ground plane the peak to peak jitter is 2.388E-10 and for the CSRR etched ground is 1.30E-10. Hence the CSRR designed ground enables better jitter performance compared with the solid ground and without affecting the bit rate.
The total jitter is captured to a clock cycles of 10000 samples crossing at the specific region for a $3\sigma$ Gaussian PDF function. For a crosstalk affected ground a value of 4000 samples crossing with 7 ns earlier but the CSRR ground allows 8000 samples with zero time difference. The rising edge peak-to-peak jitter for the solid ground is measured as $2.4E-10$ and the CSRR based ground is $1.257E-10$. So the jitter peak to peak value gets reduced by a factor of 0.5.
5.8 CONCLUSION

From this chapter it is clear that the design of high speed PCBs with reduced NEXT and FEXT is possible by designing the complementary splitting structures in the ground plane. The etching of these structures is possible by simple conventional etching methods. To analyze the crosstalk in frequency domain, the S-parameters are used and to analyze the crosstalk in time domain, eye diagrams are used. Both the analyses are implemented and the results are compared with the design.