4.1 INTRODUCTION

A coupled section, in general, should offer high isolation, high coupling factors, and large bandwidth. High isolation is achieved if the ratio of phase velocities of dominant even and odd modes is close to unity. The coupling factor is defined as the ratio of difference of even and odd mode characteristic impedances to the sum of even and odd mode characteristic impedances. The coupling factor plays an important role in the design of filters and couplers. Next, the bandwidth of a coupled section depends on the variation of both isolation and coupling factor with frequency. In general, the range of frequencies over which both coupling factor and isolation remain within specified limits gives the bandwidth of the coupled section. Bandwidth also depends on the frequency variation of input impedance, defined as the square root of the product of even and odd mode characteristic impedances. In addition, for broadband applications, e.g. those involving pulsed signals, it is desirable that both even and odd modes do not suffer mode-coupling/mode conversion over a wide range of frequencies [127].

The importance and applications of edge-coupled coplanar waveguides have already been described in Chapter 1. In Chapter III, dispersion characteristics and characteristic impedances have been presented for edge-coupled coplanar waveguides. This chapter deals with the improvement of various characteristics of enclosed edge-coupled suspended CVPW shown in Fig. 4.1a.

In suspended edge-coupled coplanar waveguides, unlike in coupled microstrip lines, the phase velocities of the fundamental even and odd modes do not coincide because of mode coupling [70]. Here an attempt has been made to improve the isolation characteristics of edge-coupled SCPW by reducing the difference in even and odd mode phase velocities using dielectric loading.
The main objective of this chapter is to present a detailed study on characteristics of enclosed edge-coupled SCPW structures for various types of dielectric loading mentioned below:

(i) Dielectric loading of outer slots (Fig. 4.1b).

(ii) Dielectric loading of conductors (Fig. 4.1c).

(iii) Dielectric loading of centre slot (Fig. 4.1d).

(iv) Partial and complete overlay (Fig. 4.1e and f).

For all the above types of dielectric loading the frequency dependent phase velocity ratio and
coupling factor have been evaluated to identify the best configuration with respect to isolation, coupling factor and bandwidth. For the configuration so identified the variation in width of dielectric loading has been carried out to improve the isolation.

This chapter is divided into five sections as described below. Section 4.2 gives the derivation of system equation using Method of Lines for the enclosed dielectric loaded edge-coupled SCPW structures shown in Figs. 4.1a-f. Next, section 4.3 on dielectric loaded edge-coupled SCPW structures contains four subsections on various types dielectric loading. Section 4.4 gives the results on the effect of width of dielectric loading for the best configuration with respect to isolation and coupling factor identify in section 4.3. Finally, section 4.5 presents the conclusion.

### 4.2 DERIVATION OF SYSTEM EQUATION

Figure 4.1 shows the cross section of the enclosed dielectric-loaded edge-coupling suspended CPW (SCPW) structures with layers I, II, III & IV. The layer II, comprised of dielectric loading, may contain various regions with different dielectric constants. Into the symmetry of the structured with respect ot the centre plane. To analyze such structures one follows the analysis given in section 2.2. To obtain the system equation one considers eqn. (2.3.5), which gives the relation between tangential electric and magnetic field in the transformed domain at the upper and lower interfaces of layout. Repeating equation (2.3.5):

\[
\begin{bmatrix}
\tilde{H}_A \\
\tilde{H}_B
\end{bmatrix} =
\begin{bmatrix}
\tilde{y}_1 & \tilde{y}_2 \\
\tilde{y}_2 & \tilde{y}_1
\end{bmatrix}
\begin{bmatrix}
\tilde{E}_A \\
\tilde{E}_B
\end{bmatrix}
\]

(4.1)

where various symbols have been described in Section 2.2.

At the metallization interface, the tangential magnetic field and current density are related by

\[
\tilde{H}_m^* - \tilde{H}_m = -\tilde{J}_m
\]

(4.2)

where \(\tilde{H}_m^*\) and \(\tilde{H}_m\) are the transformed tangential magnetic fields above and below the metallization interface. Applying eqn. (4.1) to layer 1 of the structures (Fig. 4.1b-f) and equating
\( \hat{E}_B^I = 0 \) (because of the top conducting wall), one gets

\[
\hat{H}_A^I = \tilde{y}_I^1 \hat{E}_A^I
\]  \hfill (4.3)

For the layer II, eqn. (4.1) yields,

\[
\hat{H}_A^I = \tilde{y}_I^1 \hat{E}_A^I - \tilde{y}_2^2 \hat{E}_B^I
\]  \hfill (4.4)

Applying the boundary condition, i.e. continuity of tangential electric and magnetic fields at the dielectric interface between the layers I and III, one writes

\[
\hat{E}_A^I = \hat{E}_B^I = \hat{H}_A^I = \hat{H}_B^I
\]  \hfill (4.5)

With the above conditions, eqn. (4.3) can be written as

\[
\hat{H}_B^I = \tilde{y}_I^1 \hat{E}_B^I
\]  \hfill (4.6)

Substituting of eqn. (4.6) in (4.4b) and simplifying, one gets

\[
\hat{E}_B^I = \left[ \tilde{y}_I^1 + \tilde{y}_I^2 \right]^{-1} \tilde{y}_2^2 \hat{E}_A^I
\]  \hfill (4.7)

Replacing \( \hat{E}_B^I \) in equation (4.4a) using equation (4.7), one gets

\[
\hat{H}_B^I = \tilde{H}_m^{-} = \left[ \tilde{y}_2^2 - \tilde{y}_1^2 \left( \tilde{y}_I^1 + \tilde{y}_I^2 \right)^{-1} \tilde{y}_2^2 \right] \hat{E}_A^I
\]  \hfill (4.8)

To obtain \( \hat{H}_m^{-} \), one has to apply eqn. (4.1) to layers IV and III as described in Chapter III, Section 3.2. Following the same procedure, one obtains

\[
\hat{H}_B^I = \tilde{H}_m^{-} = \left[ \tilde{y}_2^2 \left( \tilde{y}_1^1 + \tilde{y}_1^3 \right)^{-1} \tilde{y}_2^3 \right] \hat{E}_B^I
\]  \hfill (4.9)

Application of the continuity condition for the tangential electric field at the metallization interface \( \hat{E}_A^I = \hat{E}_B^I = \hat{E} \) and substitution of eqns. (4.8) and (4.9) in eqn. (4.2) yields
Finally, transforming the eqns. (4.10) into the spatial domain and equating to zero the current on the lines which are in slots, one gets the required eigen value equation:

\[ [\tilde{Y}]\tilde{E} = -\tilde{J}_m \]  
(4.10)

As in Chapter III, for the symmetric structure considered here, the characteristic impedance of the dominant even and odd modes are defined as

\[ Z_0 = \frac{V}{I} \]  
(4.12)

where \( V \) is the voltage across the strip conductor and ground plane, and \( I \) is the total current on the one of the strips.

### 4.3 CHARACTERISTIC OF DIELECTRIC-LOADED ENCLOSED EDGE-COUPLED SCPW

A study of enclosed edge-coupled SCPW for various types of dielectric loading mentioned in section 4.1 has been carried out from the point of view of improving the isolation and coupling characteristics. For the purpose, first the results of unloaded edge-coupled SCPW (Fig. 4.1a) are presented in Fig. 4.2. The results include the dispersion characteristics with higher order modes up to 100 GHz and characteristic impedance for the dimensions \( a = 4 \) mm, \( w = 0.5 \) mm, \( s_1 = s_2 = 0.3 \) mm, \( h_1 = h_2 = 1.0 \) mm, \( h_2 = 0.254 \) mm and \( \varepsilon_1 = 2.22 \), Mode I, the dominant odd mode, which corresponds to an electric wall at the centre \( x = a/2 \), has a higher effective dielectric constant compared to the dominant even mode, mode 2. This is because of greater confinement of field to the slots backed by dielectric slab in the former case. The first two higher modes, modes 3 and 4, correspond to the fine-line like mode and LSE/LSM mode of partially filled dielectric waveguide. The characteristic impedance of the dominant odd mode is less due to higher concentration of field in the centre slot; this leads to a reduction in voltage at the outer slots compared to that for the dominant even mode, which has the field concentrated in the outer slots.
Various types of dielectric loading are studied next. The results are presented in the following subsections.

4.3.1 Dielectric Loading of Outer Slots

The edge-coupled SCPW with dielectric loading of outer slots is shown in Fig. 4.1b. The dispersion characteristics of the dominant even and odd modes and first two higher order modes are presented in Fig. 4.3. The characteristics have been evaluated for \( a = 4 \) mm, \( b = 0.24 \) mm, \( w = 0.5 \) mm, \( s_1 = s_2 = 0.3 \) mm, \( a = 4.0 \) mm, \( \varepsilon_r = 2.22 \). The characteristic impedances of dominant even and odd modes are also shown in Fig. 4.3. The phase
constants of both dominant even and odd modes increase with the dielectric loading of outer slots compared to the unloaded structure. But the increase in phase constant of dominant even mode is more compared to that for dominant odd mode leading to a reduction in difference between the phase constants. For the dominant odd mode, mode 1, there is only a small change in the phase constant with the dielectric loading of outer slots because of less field in the outer slots. The dominant even mode has a greater change in the phase constants since the entire field is in the outer slots. The cutoff frequency of the fine-line like mode 3, reduces slightly and for mode 4, there is no change. The characteristic impedance of dominant odd mode does not change at low frequencies but it increases higher frequencies due to increased concentration of field in the dielectric loading of the same reason, the dominant odd mode characteristic impedance increases as free from increases.
4.3.2 Dielectric Loading of Strip conductors

For the enclosed edge-coupled SCPW with dielectric loading of strip conduction (Fig. 4.1c), the dispersion characteristics and characteristic impedance with \( b = 0.48 \) mm and other parameters are as in Fig. 4.3. The effective dielectric constants of dielectric loading is high for the dominant odd mode, which has field in all the three compared to the dominant even mode with field only in the outer slots. As in the previous section, the cutoff frequency of mode 3 reduces slightly and there is no characteristic in the cutoff frequency of mode 4. The characteristic impedances of both dominant of electric and odd modes reduce with dielectric loading of strip conductors due to the increase in cure on the strip conductors. Smoother variation of characteristic impedance compared to that in previous section results in better coupling characteristics.
4.3.3 Dielectric Loading of Centre Slot

The dispersion characteristics and characteristic impedance of shielded edge-coupled SCPW with dielectric loading of centre slot (Fig. 4.1d) are given in Fig. 4.5. The parameters of the structure are the same as in section 4.3.1 with $b = 0.254$ mm. The dispersion and impedance characteristics of dominant even and odd modes have been obtained. From Fig. 4.5, the dielectric loading of centre slot increases the phase constant of dominant odd mode, as expected. The phase constant of the dominant even mode does not change much. Correspondingly, the dielectric loading of centre slot increases the difference in the phase constants of the dominant even and odd modes. The behavior of the first two higher order mode, modes 3 and 4, does not change much. The characteristic impedance of dominant odd mode reduces with the dielectric loading of centre slot due to the concentration of more field in the centre which reduces outer slot voltage. For dominant even mode the characteristic impedance has no change in comparison to unloaded case.
4.3.4 Partial and Complete Overlay

For the shielded edge-coupled SCPW with partial dielectric overlay (Fig. 4.1e) with \( b = 1.925 \) mm and with other parameter, as in Section 4.3.1, the dispersion characteristics and characteristic impedance are shown in Fig. 4.6. The dispersion characteristics include the dominant even and odd modes, first two higher order modes, and characteristic impedance for dominant even and odd modes plotted up to 100 GHz. The phase constant of dominant odd mode, mode 1, considerably increases with partial overlay which covers all the strips and slots where most of the field is concentrated. For mode 2, the dominant even mode, also the phase constant increases for the same reason. But the relative change in the phase constant of dominant odd mode is higher compared to that in the dominant even mode. The cutoff frequency of fine-line like mode, mode 3, reduces to 31 GHz due to an appreciable increase in the dielectric loading. The cutoff frequency of mode 4, which corresponds to partially filled waveguide section, has no change. Next, the characteristic impedance behavior with frequency is similar to that for edge-coupled SCPW without loading, but the characteristic impedance value reduces for both dominant even and odd modes because of the partial overlay. It has been seen in Section 4.3.2 that the dielectric loading of the conducting strips leads to reduced and smoother varying characteristic impedance.

The dispersion characteristics and characteristic impedance of edge-coupled SCPW with complete overlay (Fig. 4.1f) are shown in Fig. 4.7 for the same dimensions as given above. As expected, from Figs. 4.6 and 4.7 it is clear that the characteristic are very much similar in both cases, i.e., with partial and complete dielectric overlay.
Figure 4.6 Dispersion characteristics and characteristic impedance for edge coupled SCPW with partial dielectric overlay, shown in Fig. 4.1e, with $b = 1.925$ mm and other parameters are as in Fig. 4.3.
4.4 COMPARISON OF PHASE VELOCITY RATIO AND COUPLING FACTOR FOR DIFFERENT TYPES OF DIELECTRIC LOADING

Here, a comparison of phase velocity ratio and coupling factor for various types of dielectric loading (Fig. 4.1b-f) is presented. From the dispersion characteristics and characteristic impedances of dominant even and odd modes for various types of dielectric loading given in section 4.3, the frequency dependent phase velocity ratio and coupling coefficient have been
evaluated and are presented in Figs. 4.8 and 4.9, respectively. For an ideal coupled section the phase velocity ratio should be unity. From Fig. 4.8, the curve 1, belonging to unloaded edge-coupled SCPW, has a phase velocity ratio of greater than 1.03. The phase velocity ratio improves with dielectric loading of outer slots as shown by curve 2. For the remaining configurations, i.e., dielectric loading of strip conductors, centre slots and partial and complete overlay the phase velocity ratio is not much better than that for the unloaded edge-coupled SCPW. Even though curve 3 with dielectric loading of strip conductors has the smoothest variation of phase velocity ratio with frequency, the ratio is greater than that for the unloaded edge-coupled section.
Fig. 4.9 shows the frequency dependent coupling coefficient up to 100 GHz for various dielectric loadings. The coupling coefficient for curves 1 and 2, corresponding to the unloaded and dielectric loading of outer slots cases, have a lower value compared to other configurations. Curve 3 shows a fairly high and smooth coupling coefficient with frequency. The coupling coefficient for partial and complete dielectric overlay (curves 5 and 6) behave similarly but are slightly less than coupling coefficient obtained for dielectric loading of strip conductors.
(curve 3). Curve 4, representing loading of centre-slot, shows considerable frequency variation.

Considering both isolation and coupling coefficient characteristics of various configurations, the dielectric loading of strip conductor and outer slots offer better characteristics. For high coupling coefficient applications, the dielectric loading of strip conductors is the better configurations. But for very high isolation, the dielectric loading of outer slots is the best choice. In the following section the effect of the width of dielectric loading in outer slots for achieving good isolation as well as coupling characteristic is carried out.
For the edge-coupled SCPW with dielectric loading of outer slots (Fig. 4.1b), with $a = 4 \text{ mm}$, $w = 0.5 \text{ mm}$, $s_1 = s_2 = 0.3 \text{ mm}$, $h_1 = h_4 = 1.0 \text{ mm}$, $h_2 = h_3 = 0.254 \text{ mm}$ and $\varepsilon_{r2} = \varepsilon_{r3} = 2.22$ and for different values of $b = 0.16, 0.24, 0.32 \text{ mm}$, the dispersion characteristics of characteristic impedance are presented in Fig. 4.10. The first two higher order modes are also presented for $b = 0.24 \text{ mm}$. The phase constant of dominant even and odd modes increases with the raise in the width “$b$” of the dielectric loading. The relative increase in the phase constant of dominant even modes is high compared to that in odd modes for the same reason as given in section 4.3.1.
variation of characteristic impedance with frequency is smoother for \( b = 0.24 \) mm (curves labeled “2”).

Next, the frequency dependent phase velocity ratio and coupling factor are shown in Fig. 4.11 for different values of \( b = 0.16 \) mm (curve 1) one gets a flat coupling coefficient characteristics but phase velocity ratio is high in comparison with \( b = 0.24 \) and \( 0.32 \) mm. For \( b = 0.234 \) mm, one achieves fairly good isolation and coupling coefficient characteristics. For \( b = 0.32 \) mm, even though isolation is best, the variation in coupling coefficient is considerable. So for broad band applications, the edge-coupled SCPW with dielectric loading of outer slots with \( b \) of the order of \( 0.234 \) mm is the better choice, for the dimensions chosen here.

4.6 CONCLUSION

Here we have carried out a detailed study on enclosed edge-coupled SCPW with various types of dielectric loading to improve the isolation and coupling characteristics. The edge-coupled SCPW with dielectric loading of strip conductors is the choice for high coupling factor applications, whereas dielectric loading of outer slots is the best choice for high isolation requirements. Also, the effect of variation in width of dielectric loading in outer slots is carried out to further improve the overall characteristics.