CHAPTER 2

MULTILAYERED MICROSTRIP TRANSMISSION-LINE

2.1 INTRODUCTION

In Chapter 1, the growing importance of the terahertz spectrum in the various industrial and scientific areas has been described. In addition to the traditional application, the terahertz wireless communication is the emerging area in which an intensive research is needed. Further, for the successful wireless communication, several components like sources, detectors and radiators are required. Moreover, among various radiators, the microstrip antenna has gained popularity and they can be developed on the single layer well as the multi-layer substrates material to meet the potential requirement of the high directivity at the terahertz frequency described in [109]. For the improvement in performance of the antenna, various techniques for single layer as well as the multi layer substrate have been discussed in detail in [110-118]. In general, microstrip-line is used as the feed of radiator at low frequency. However, its use beyond 60 GHz is restricted due to the heavy loss of the line. On this way, in general, it is thought that the use of microstrip transmission-line at terahertz frequency is impractical. However, on the other side, the microstrip transmission-line has successfully been used for the transmission of terahertz wave [108]. These contradictions motivate the study of the microstrip transmission-line at terahertz frequency which is a frequency dependent quantity. In this Chapter, a generalized novel expression to study the frequency dependent behavior of the effective dielectric permittivity of multilayered substrate transmission-line at terahertz frequency has been developed. Further, the result obtained from the novel approach has been used in the calculation of various losses, which have been found to be tolerable due to the micrometer scale of the terahertz devices.

2.2 ANALYSIS OF MICROSTRIP TRANSMISSION LINE

On the way to explore the propagation characteristics of a narrow microstrip transmission-line, this section is motivated to develop a Quasi-TEM formula which is used to analyze the narrow microstrip transmission-line on the multi-layer substrates at the submillimeter wavelength.

2.2.1 Effective permittivity

The schematic diagram of a multilayered-substrate material microstrip transmission-line is
shown in Figure 2.1.

Figure 2.1: Schematic of the multi-layered transmission line at terahertz frequency.

In the case of multi-layered substrate microstrip transmission-line, the individual layers have different relative dielectric permittivity and overall relative dielectric permittivity of the substrate is presented by \( \varepsilon_{re} \) and to extend the analysis of two-layered-substrate material microstrip transmission-line to the multilayered-substrate material microstrip transmission-line, the formula presented in [119, 120] is modified as:

\[
\varepsilon_{re} = \frac{d_1 + d_2 + \ldots + d_n}{d_1 + d_2 + \ldots + d_n} = \frac{\varepsilon_1 + \varepsilon_2 + \ldots + \varepsilon_n}{\varepsilon_1 + \varepsilon_2 + \ldots + \varepsilon_n}
\]

for \( h_n + h_{n-1} + \ldots + h_1 \equiv \lambda / 10 \) \hspace{1cm} (2.1)

where \( d_1 = \frac{K(k_1)}{K'(k_1)} \) \hspace{1cm} (2.2)

\[
d_2 = \frac{K(k_2)}{K(k_2)} - \frac{K(k_1)}{K'(k_1)}
\]

(2.3)

\[
d_3 = \frac{K(k_3)}{K(k_3)} - \frac{K(k_2)}{K'(k_2)} - \frac{K(k_1)}{K'(k_1)}
\]

(2.4)

\[
d_n = \frac{K(k_n)}{K(k_n)} - \frac{K(k_{n-1})}{K'(k_{n-1})} - \ldots - \frac{K(k_1)}{K'(k_1)}
\]

(2.5)

and in general,

\[
\kappa_n = \frac{1}{\cosh \left( \frac{\pi \omega}{4(h_n + h_{n-1} + h_{n-2} + \ldots + h_1)} \right)}
\]

for \( n = 1, 2, 3, \ldots \) \hspace{1cm} (2.6)

In the above Equations, \( h_n, h_{n-1}, \ldots, h_1 \) are positive substrate thicknesses of different layers starting from the top (below the microstrip line). In the above Equations, \( \varepsilon_n, \varepsilon_{n-1}, \ldots, \varepsilon_1 \) are the complex relative dielectric permittivity of the respective substrate layers and \( \lambda_0 \) represents
free-space wavelength. The value of $\frac{K(\ )}{K'(\ )}$ is calculated by using following formula [121].

$$\frac{K(k_n)}{K'(k_n)} = \frac{1}{\pi} \ln \left( \frac{1 + \sqrt{k_n}}{1 - \sqrt{k_n}} \right) \quad \text{for} \quad 0.7 \leq k_n \leq 1$$  \hspace{1cm} (2.7)

By using (2.1) to (2.7), the frequency-independent relative dielectric permittivity of the multilayer-substrate material ($\varepsilon_{rc}$) is obtained. After calculating the frequency-independent relative dielectric permittivity of the multi-layered substrate, the frequency dependent relative dielectric permittivity is obtained by using following expressions [122, 123].

$$\varepsilon_e(f) = \varepsilon_{rc} - \frac{\varepsilon_{rc} - \varepsilon_e(0)}{1 + (f/f_a)^m}$$  \hspace{1cm} (2.8)

where $f_a = \frac{f_b}{0.75 + (0.75 - 0.332 \varepsilon_{rc}^{-1.73}) w/h}$

$$f_b = \frac{47.746}{h \sqrt{\varepsilon_{rc} - \varepsilon_e(0)}} \tan^{-1} \varepsilon_{rc} \sqrt{\frac{\varepsilon_e(0) - 1}{\varepsilon_{rc} - \varepsilon_e(0)}}$$

$$m = m_0 m_e$$

$m_0 = 1 + \frac{1}{1 + \sqrt{\frac{w}{h}}} + 0.32(1 + \sqrt{w/h})^{-3}$

$m_e = \begin{cases} 
1 + \frac{1.4}{1 + w/h} (0.15 - 0.235 e^{-0.45 f/f_a}) & \text{for} \quad w/h \leq 0.7 \\
1 & \text{for} \quad w/h > 0.7
\end{cases}$

$$\varepsilon_e(0) = \frac{\varepsilon_{rc} + 1}{2} + \frac{\varepsilon_{rc} - 1}{2} \left( 1 + \frac{12h}{w} \right)^{1/2} + F(\varepsilon_{rc}, h) - 0.217(\varepsilon_{rc} - 1) \frac{t}{\sqrt{wh}}$$  \hspace{1cm} (2.9)

where $F(\varepsilon_{rc}, h) = \begin{cases} 
0.02(\varepsilon_{rc} - 1)(1 - w/h)^2 & \text{for} \quad w/h < 1 \\
0 & \text{for} \quad w/h \geq 1
\end{cases}$

In the above expressions, $h = h_3 + h_2 + h_1$, $w$, and $t$ are the total substrate thickness, width of the transmission-line, and the thickness of the conductor, respectively. Here, it is important to
mention the reason to consider absolute value of the parameters in (2.1). For three or more substrate layers, the value of \( d_n \) as shown in (2.4) and (2.5) may be negative. However, its value should remain positive to represent the distance between two parallel plates of the equivalent capacitance model of the substrate. To overcome this limitation, absolute value of \( d_n \) has been used in (2.1). In addition to this, to obtain the quasi-TEM characteristics, the substrate thickness must be smaller than the operating wavelength. On this way, we restrict the total substrate thickness to approximately equal to \( \lambda_0/10 \).

To validate the presented expression, we have analyzed the frequency-dependent effective dielectric permittivity of a two- and three-layered-substrate material microstrip transmission-line. We have arbitrarily selected a three-layered microstrip transmission-line whose schematic diagram is shown in Figure 2.1. The width ‘\( w \)’ and length ‘\( l \)’ of the proposed microstrip transmission-line are 20 \( \mu m \) and 1000 \( \mu m \), respectively. The substrate materials of the microstrip transmission-line are arranged in the following manner. The first substrate layer below the strip-line has height \( h_1 = 5 \mu m \), relative dielectric permittivity \( \varepsilon_r = 6.15 \) and \( \tan\delta = 0.0025 \). A substrate material of thickness \( h_2 = 40 \mu m \), relative permittivity \( \varepsilon_r = 2.2 \), and \( \tan\delta = 0.0009 \) follows this layer. The bottom substrate layer that is above the ground plane is made of thickness \( h_1 = 5 \mu m \), the relative dielectric permittivity \( \varepsilon_r = 2.45 \) and \( \tan\delta = 0.0019 \). The surface area of substrate and ground plane is 1000x400 \( \mu m^2 \). The microstrip-line and ground plane are made of copper of thickness \( t = 20 \mu m \) each. To compare this proposed analysis, the structure has been simulated by using CST Microwave Studio and Ansoft HFSS. To maintain the accuracy of simulation in CST Microwave Studio, the computational region has been increased to 500 \( \mu m \) which is 10 times the total substrate thickness. The computation region is filled with vacuum to take in to the account of fringing field. The structure and computational region are surrounded by the perfect electrical boundaries. The number of perfect boundary approximation (PBA) mesh cells have been increased to 12,89,600. The transmission line is excited by the wave-port of 250 \( \mu m \) height and 400 \( \mu m \) width which are \( 5h \) and \( 20w \), respectively.
Figure 2.2: Frequency dependent effective dielectric permittivity of the three-layer-substrate transmission-line.

The structure has been simulated in the time-domain transient solver and effective dielectric permittivity has been obtained from the port information. However, in the Ansoft HFSS, which is based on the finite element method, 13,232 tetrahedral cells have been used. The analytical and simulated value of the effective dielectric permittivity of the three layered substrate material is shown in Figure 2.2.

Figure 2.3: An effective dielectric permittivity of the two-layered substrate material microstrip transmission-line.

To validate the expression, we have considered two-layered-substrate microstrip transmission-line by selecting the value of $n = 2$. On this way, the third substrate layer $h_1$ and relative dielectric permittivity $\varepsilon_r$ as mentioned in (2.1)-(2.7) have been set equal to zero. The total substrate thickness in the present case is equal to 45 $\mu$m and other parameters are unchanged. The analytical value of the frequency-dependent effective dielectric permittivity
of the two-layer-substrate material along with the simulated results is shown in Figure 2.3. From Figure 2.2 and Figure 2.3, it is revealed that the analytical and simulated results are comparable. The maximum deviation occurs in the case of CST Microwave Studio Simulation. However, the maximum relative error for three-layer and two-layer-substrate microstrip transmission-line is 0.98 % and 1.2 %, respectively. It is worthy to mention here that the presented result in this Chapter shows improvement in the accuracy of effective dielectric permittivity in comparison to the previous work [119]. In addition to this, there is significant improvement in the accuracy of the present model in comparison to [124] at 1000 GHz.

2.2.2 Characteristic impedance

Due to the dependency of effective dielectric permittivity on the frequency, the characteristic impedance of the microstrip transmission-line also changes. To examine this effect on the multilayered-substrate microstrip transmission-line, we have analyzed the frequency dependent characteristic impedance of the transmission-line in this section. It is seen that the characteristic impedance of the line also increases with increase in the frequency, which is mainly due to the increase in effective dielectric permittivity of the substrate material. The dispersive behavior of characteristic impedance on the multilayered substrate material can be predicted by following set of formulas [125, 126].

\[
Z_c(f) = Z_c \frac{\varepsilon_e(f) - 1}{\varepsilon_e(0) - 1} \sqrt{\frac{\varepsilon_e(0)}{\varepsilon_e(f)}} \quad (2.10)
\]

where \( Z_c = \frac{120\pi}{2\varepsilon_e(0)} \ln \left( \frac{8h}{w_c} + 0.25 \frac{w_c}{h} \right) \) for \( \frac{w_c}{h} \leq 1 \) \quad (2.11)

and \( w_c = \frac{w}{h} + \frac{1.25r}{\pi h} (1 + \ln \frac{4\pi w}{r}) \) for \( \frac{w}{h} \leq 0.5\pi \) \quad (2.12)

To calculate the value of \( Z_c(f) \), the value of \( \varepsilon_e(f) \) and \( \varepsilon_e(0) \) are obtained from (2.8) and (2.9), respectively. The analytical and simulated value of the characteristic impedance of two-layered and three-layered transmission-line is shown in Figure 2.4 (a) and (b), respectively. From Figure 2.4 (a) and (b), it is revealed that the characteristic impedance of the transmission-line increases with the increase in operating frequency. In both the cases, simulation as well as analytical curve follows the same pattern. The maximum relative error which occurs at 1000 GHz is equal to 2.8 % and 6 % in the case of two-layered-substrate and three-layered substrate microstrip transmission-line, respectively. It indicates that with the
increase in number of substrate layers, this error may increase even though for the same overall substrate thickness. The relative error in the characteristic impedance of two-layered-substrate microstrip transmission-line is comparable to the relative error reported in [127].

![Graph showing frequency dependent characteristic impedance](image)

Figure 2.4: Frequency dependent characteristic impedance of the microstrip transmission-line on (a) two layer and (b) three layer substrate material.

2.2.3 Effect of the number of substrate layers on the characteristic impedance

From (2.10), it is seen that the value of $Z_c(f)$ depends on $\varepsilon_r(f)$. Moreover, the accuracy of $Z_c(f)$ is dependent on the degree of the accuracy of $\varepsilon_r(f)$. In order to check the correctness of the proposed numerical model for the multilayered substrate material microstrip-transmission line, we have applied the presented model in this Chapter on the four-layered and five-layered substrate-material microstrip transmission-line while keeping
the overall height of the substrate constant. In both the configurations of the multi-layered substrate material, the heights of the different substrate layers are denoted by \( h_n, h_{n+1}, \) and \( h_j \), respectively where \( h_n \) is the height of the top layer and \( h_{n+1} \) to \( h_j \) are the height of following layers. The substrate layer configuration of the four- and five-layered substrate material microstrip transmission-line is shown in Table 2.1. The total substrate thickness in the both cases is 60 \( \mu \text{m} \). The value of \( Z_c(f) \) has been calculated by using (2.10)-(2.12). To compare the result, multilayered-substrate structure has also been simulated by using CST Microwave Studio and Ansoft HFSS. The results for four-layered and five-layered substrate are shown in Figure 2.5 and Figure 2.6, respectively.

**Table 2.1: Multi-layered substrate material transmission-line.**

<table>
<thead>
<tr>
<th>Layer No.</th>
<th>Thickness (( \mu \text{m} ))</th>
<th>( \varepsilon_r )</th>
<th>( \tan\delta )</th>
<th>Layer No.</th>
<th>Thickness (( \mu \text{m} ))</th>
<th>( \varepsilon_r )</th>
<th>( \tan\delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>h4</td>
<td>10.0</td>
<td>7.0</td>
<td>0.001</td>
<td>h5</td>
<td>10.0</td>
<td>7.0</td>
<td>0.001</td>
</tr>
<tr>
<td>h3</td>
<td>5.0</td>
<td>6.15</td>
<td>0.0025</td>
<td>h4</td>
<td>5.0</td>
<td>6.15</td>
<td>0.0025</td>
</tr>
<tr>
<td>h2</td>
<td>40.0</td>
<td>2.2</td>
<td>0.0009</td>
<td>h3</td>
<td>20.0</td>
<td>4.5</td>
<td>0.0009</td>
</tr>
<tr>
<td>h1</td>
<td>5.0</td>
<td>2.45</td>
<td>0.0019</td>
<td>h2</td>
<td>20.0</td>
<td>2.2</td>
<td>0.0009</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>h1</td>
<td>5.0</td>
<td>2.45</td>
<td>0.0019</td>
</tr>
</tbody>
</table>

**Figure 2.5:** Characteristic impedance of four-layered substrate material transmission-line.

**Figure 2.6:** Characteristic impedance of five-layered substrate material transmission-line.
From Figure 2.5 and Figure 2.6, it is seen that the analytical model closely follows the simulated results achieved by the simulating structure in CST Microwave Studio as well as in Ansoft HFSS simulator. The maximum deviation in analytical and simulated model occurs in the lower frequency band. The relative maximum deviation of the analytical result in comparison to the simulated results in the four-layered and five-layered substrate structure is 3.16 % and 10.7 %, respectively. The comparison of characteristic impedance for two-layer, three-layer, four-layer and five-layer substrate material microstrip transmission-line as shown in Figure 2.4 (a), Figure 2.4 (b), Figure 2.5 and Figure 2.6, respectively, which depicts that model can predict the behavior of transmission-line correctly up to the four-layered substrate material. With an increase in the number of layers above four, the relative error increases to a significant value. However, the error is reduced with the increase in the operating frequency and it indicates the potential application of the presented model at higher frequency. It is also important to mention that the practical application of the five- and more-layered substrate material is reduced due to the fabrication complexity. In the view of this fact, the proposed model finds a practical application in the analysis and design of the multi-layered substrate material microstrip transmission-line.

2.2.4 Losses in microstrip transmission-line

In this section, we have computed two types of losses: a) dielectric loss and b) conductor loss. The analysis has been compared with the simulated results obtained by using CST Microwave Studio and Ansoft HFSS simulation.

2.2.4.1 Dielectric loss

Here, it is important to note that the effective dielectric permittivity is frequency dependent complex quantity. In the case of multilayer substrate, the loss tangent of composite material is also modified in accordance with the position of substrate layers. The frequency-independent loss tangent of the multilayer transmission-line can be obtained by a simple series-capacitance-method in which the relative dielectric permittivity of each layer is replaced by its complex value and the equivalent complex relative dielectric permittivity of the substrate layers is calculated. After calculating the value of frequency independent loss tangent, it is substituted in the following formula to obtain the frequency dependent dielectric attenuation constant \( \alpha_d(f) \) of the multilayer substrate material [128, 129].

\[
\alpha_d(f) = 8.686 \pi \frac{\varepsilon_r(f) - 1}{\varepsilon_r - 1} \frac{\varepsilon_r}{\lambda_g} \frac{\tan \delta}{\lambda_g} \text{dB/unit-length}
\]  

(2.13)
In (2.13), the value of $\varepsilon_{rc}$ and $\varepsilon_e(f)$ are obtained from (2.1) and (2.8), respectively. Other variables, $\lambda_g$ is the guided wavelength and $\tan\delta$ is obtained from a simple series capacitance model of the multilayered substrate material.

To simulate the dielectric loss in the CST Microwave Studio, we have activated E-field and H-field monitor at each frequency point of the interest and calculated the dielectric quality factor of the multilayered-substrate microstrip transmission-line by using the loss and quality factor ‘Q’ calculation macro. The calculated value of quality factor can be placed in the following formula to obtain the frequency dependent attenuation constant [130].

$$\alpha_d(f) = \frac{8.686\beta}{2Q_d} \text{ dB/unit length} \quad (2.14)$$

![Figure 2.7: Frequency dependent dielectric attenuation constant.](image)

In (2.14) $\beta$ and $Q_d$ are phase constant and dielectric quality factor, respectively. Based on (2.13) and (2.14), we have calculated the frequency dependent dielectric attenuation constant for the three-layered-substrate microstrip transmission-line which was analyzed in previous section and the result is presented in Figure 2.7. From this figure, it is revealed that, the dielectric loss also increases with the increase in frequency. Further, it is noticed that the two curves are close to each other at each frequency point.

**2.2.4.2 Conductor loss**

The conductor loss of narrow microstrip line is influenced by the width of metallization and characteristic impedance of the line. However, the characteristic impedance of the line itself is an inconsistent parameter at terahertz frequency, which makes the analysis of conductor loss a challenging task. We have successfully used the formula proposed in [131] to calculate the conductor attenuation constant of a narrow microstrip transmission-line at terahertz
frequency.

\[ \alpha_c(f) = \frac{8.68}{2\pi} \frac{R_s}{Z_c(f) h} \left[ 1 - \left( \frac{w_c}{4h} \right)^2 \right] \times \left[ 1 + \frac{h}{w_c} + \frac{h}{w_c} \left( \ln \frac{2h}{t} - 1 \right) \right] \quad \text{for} \quad \frac{1}{2\pi} \leq \frac{w}{h} \leq 2 \quad (2.15) \]

where \( R_s = \sqrt{\frac{\pi f \mu}{\sigma}} \)

In (2.15), the value of \( Z_c(f) \) and \( w_c \) have been calculated by using (2.10) and (2.12), respectively. To compare the analysis, the conductor attenuation constant has also been simulated by using the CST Microwave Studio. In this case conductor quality factor \( (Q_c) \) has been extracted from the simulation and it has been substituted in (2.14) in place of \( Q_d \) as:

\[ \alpha_c(f) = 8.686\beta / 2Q_c \quad \text{dB/ unit length} \quad (2.16) \]

The resultant conductor attenuation constant obtained by analysis and simulation is shown in Figure 2.8.

![Figure 2.8](image)

**Figure 2.8:** Frequency dependent conductor attenuation constant of the transmission-line at terahertz frequency.

From Figure 2.8, it is seen that simulated as well as analytical attenuation constant curves follow almost all same pattern except a deviation near 750 GHz. The maximum relative error of analysis and simulation is about 7% at this frequency. Next to this, total attenuation constant due to the conductor and dielectric loss is shown in Figure 2.9. In Figure 2.9, the first curve from the bottom shows the sum of dielectric and attenuation loss constant obtained
by extracting the quality factors by using CST Microwave Studio. The next curve to this shows the sum of dielectric and attenuation constant obtained from the numerical analysis. The first curve from the top shows the total attenuation when the proposed three-layered-substrate microstrip line is simulated in the Ansoft HFSS.

![Graph showing total attenuation constant compared to calculated values](image)

**Figure 2.9:** Total, conductor, and dielectric attenuation constant for three layered line.

From Figure 2.9, it is seen that the sum of conductor and dielectric attenuation constant obtained from analysis and CST Microwave Studio simulation are comparable in the 0.5-1.0 THz frequency range. However, the radiation loss has not been considered in these calculations. The Ansoft HFSS simulation (first line from the top) shows the total loss in the transmission line. From the above analysis, it is clear that the difference between the first curve and second curve from the top indicates other losses. However, the radiation loss is dominant at the high frequency and this difference is due to the radiation loss. Further, with an increase in the frequency, the difference between these curves increases and it indicates that the radiation loss increases with the increase in the operating frequency. The total loss at 1 THz is 455 dB/m (an onerous figure indeed). However, the predicted loss in multilayer transmission line in this Chapter is smaller than the figure predicted by Yeh et. al. [107]. According to them, for the conventional microstrip transmission line, the total attenuation is 150 dB/m at 300 GHz and it increases at the rate of $f^{3/2}$ with the increase in the operating frequency. On this way, the expected attenuation in a conventional microstrip transmission-line at 1 THz is 912 dB/m. However, three-layer transmission-line as presented in this Chapter shows quite smaller value of the total loss. Further, it is required to mention that the size of the terahertz devices are in the order of micrometer and multilayered-transmission line can serve the purpose of interconnects.
2.3 SUMMARY

In this Chapter, a microstrip transmission-line has been analyzed and simulated in detail and the analysis shows that the losses in line are insignificant in the case of multi-layered substrate materials. The result of the analysis of multilayered transmission line motivates the study of the different configuration of the microstrip antenna at the terahertz frequency and to enhance the directivity of these antennas with the help of novel concepts.