Energy Leakage and Characteristic Analysis of HMSIW and Implement in Multi-layered Structure Equalizer Design

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Abstract. The phase constant and attenuation constant of half mode substrate integrated waveguide (HMSIW) are calculated using an improved quicker multi-line method in this paper. A mathematical method is proposed to analyze the energy leakage of HMSIW theoretically. The radiation and leakage character of electromagnetic field at open face of HMSIW is different with different relative permittivity. An equalizer loaded multi-layered HMSIW resonant cavities is proposed based on the energy leakage excitation without external coupling structure. Compared with the other planar circuits, these structures have superiorities of small size, simple structure, low loss and high Q, suitable for the miniaturization development, and are easily integrated with other circuits. Furthermore, this proposed equalizer has a simpler design procedure than other HMSIW equalizers without resonant frequency deviation.

Introduction

Microwave passive components with planar structure and high performance are in a constant demand for modern wireless communication systems [1]. Substrate integrated waveguide (SIW) proposed in [2] is a new planar structure and has superiorities of the small profile, high Q value and low insertion loss, compared with the traditional microstrip and waveguide type. Half mode substrate integrated waveguide (HMSIW) [3] has a nearly 50% size reduction compared with SIW while it keeps the same propagation properties. They have been used in filters and equalizer [4], [5]. As one of the most important transmission line, the energy leakage property of the HMSIW still has not been studied systematically. The phase constant and attenuation constant are the two important parameters to analyze the performance of HMSIW. However, there is not a simple method to calculate them. Reference [6] and [7] adopt complex methods to calculate the phase constant and attenuation constant with a poor efficiency.

The equalizers are used to compensate the output gain slope fluctuation of traveling wave tube amplifiers (TWTAs) in the radar systems[4]. The function of equalizers and the equalization principle are studied and explained in [4] and [8]. With the rapid development of new materials, new technology, the demand for equalizers with small size, low loss and high Q value grows gradually. In [8] a dual layer equalizer is designed which cannot tune the attenuation and Q value, and the probe excitation plays a poor role in coupling energy into cavities and it is complicated, fabricated with complex process. In [4] a multi-layered HMSIW equalizer is proposed with complex techniques and coupling structure because of the high width-to-height ratio (WHR) and it has a frequency deviation because of coupling structure according to perturbation theory.

This paper proposed an improved method to calculate the phase constant and attenuation constant. The difference between HMSIW structure with high permittivity and HMSIW structure with low permittivity is analyzed. A multi-layered structure equalizer without external coupling structure is designed based on energy leakage of open face of HMSIW with high permittivity. The comparison
between the proposed equalizer and the HMISW equalizer in Ref. [4] is given. The results show that the two equalizer shares the same performance. Furthermore, this equalizer has a simpler design procedure.

Analysis of HMSIW with Different Permittivity

The HMSIW with different permittivity and different height has different radiation and energy leakage quality at the open face. The figure 1 gives the $S_{21}$ of a HMSIW equalizer with high WHR. The permittivity is 2.2 and the height of substrate is 0.254mm. When it is equipped the coupling structure, the $S_{21}$ in red color is satisfied with the goal curve. When without the coupling structure, the $S_{21}$ in black color is nearly an all-pass network, obviously, it is useless.

Without coupling structure, the equalizer cannot work. Whereas, the coupling structure would increase fabrication process complexity and the frequency equations is inaccurate and the resonant frequency would deviate because of the coupling circles. The energy leakage at the open face can solve this problem. The resonant cavities can be excited by the leak energy without external coupling structure. The energy distribution near open face is calculated by the equivalent principle, mirror principle and the Green Function, seen figure 2. The field of dominant mode TE$_{0.5,0}$ inside HMSIW is calculated as follows:

$$E_{x(0,5,0)} = \frac{-j\omega x W}{\pi} H_{10} \sin \frac{\pi x}{2W_h} e^{-j\frac{3}{2}z}$$

$$H_{x(0,5,0)} = \frac{j\beta x W}{\pi} H_{10} \sin \frac{\pi x}{2W_h} e^{-j\frac{3}{2}z}$$

$$H_{z(0,5,0)} = H_{10} \cos \frac{\pi x}{2W_h} e^{-j\frac{3}{2}z}$$

$$E_{x(0,5,0)} = E_{z(0,5,0)} = 0$$

The outer field near the open face is calculated as follows:

$$E = -a_y \int_{\frac{\pi}{2}}^{\frac{\pi}{2}} e^{-j\frac{3}{2}z} x(1 + jk \sqrt{x^2 + l^2}) e^{-jk \sqrt{x^2 + l^2}} dx$$

$$H = j a_x \int_{\frac{\pi}{2}}^{\frac{\pi}{2}} e^{-j\frac{3}{2}z} \frac{\partial A_x}{\partial z} + a_x \frac{\partial A_y}{\partial x} dx$$

(1)

(2)
The E-filed result is shown in figure 3. The electromagnetic field near the open face does not attenuate rapidly. When it attenuates to zero, the distance is near 8mm. The location of energy adopted to excite the resonant cavities is near the open face, the distance is 3.5mm–4mm, and the magnitude of E-field is large enough to excite the resonant cavities.

![Figure 3. The E-field distribution of HMSIW.](image)

This paper uses the energy leakage as the excitation to excite cavities. The substrate with permittivity 11.9 and height 0.6mm is adopted for a larger energy leakage. The distance between metal holes is 1.6mm, and the diameter of metal hole is 0.8mm. The coupling value can reach -14dB and it meets the design need of the equalizer, whose minimum value of $S_{21}$ is usually less than -10dB.

### Calculation of Phase Constant and Attenuation Constant

This paper uses an improved method compared to the method in Ref.[7] to calculate the attenuation constant $\alpha$ and phase constant $\beta$, and the results are plotted in figure 5. Two different length HMSIW lines are used here. Transfer matrix of the two line is $T_1$ and $T_2$ respectively, shown in figure 4.

The transfer matrices have following equation:

$$T_1 = T_A T_{HMSIW} T_B$$

$$T_2 = T_A T_B$$

On one hand, the transfer matrix and scatter matrix has relation as follows:

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} (-S_{11}S_{22} + S_{12}S_{21})/S_{21} & S_{11}/S_{21} \\ -S_{22}/S_{21} & 1/S_{21} \end{bmatrix}$$

The S-parameter can be gotten easily and the transfer matrix can be calculated by above equation. The S-parameter is calculated by following equation:

$$S = \frac{1}{D_5} \begin{bmatrix} (Z^2 - Z_0^2) \text{sh} \gamma l & 2ZZ_0 \\ 2ZZ_0 & (Z^2 - Z_0^2) \text{ch} \gamma l \end{bmatrix}$$

Where $D_5 = 2ZZ_0 \text{ch}\gamma l + (Z + Z_0) \text{sh} \gamma l$, $\text{sh}$ and $\text{ch}$ is hyperbolic sine function and hyperbolic cosine function respectively.

As $Z$ is equal to $Z_0$ there, so the equation (7) can be rewritten as:
With the equation (6), the transfer matrix is:

\[
S = \begin{bmatrix} 0 & e^{\gamma l} \\ e^{-\gamma l} & 0 \end{bmatrix}
\]

With the equation (6), the transfer matrix is:

\[
T = \begin{bmatrix} e^{-\gamma l} & 0 \\ 0 & e^{\gamma l} \end{bmatrix}
\]

On the other hand, the equation (4) and equation (5) can also be rewritten as:

\[
T_B T_A^{-1} = T_A T_{\text{HMSIW}}
\]

(10)

\[
T_A^{-1} T_2 = T_B^{-1}
\]

(11)

With equation (10) and equation (11), we can get:

\[
T_A^{-1} (T_1 T_2^{-1}) T_A = T_{\text{HMSIW}}
\]

(12)

Obviously, we can know that:

\[
T_{\text{HMSIW}} \sim T_1 T_2^{-1}
\]

(13)

Namely, eigenvalue of \( T_{\text{HMSIW}} \) is the same as eigenvalue of \( T_1 T_2^{-1} \). And the eigenvalue is leading diagonal parameters of transfer matrix, that is \( e^{-\gamma l} \) and \( e^{\gamma l} \), shown in equation (9).

As it illustrates above, the \( T_1 T_2^{-1} \) can be easily calculated by the scatter matrix. Then we calculate the eigenvalue \( \lambda_r \) of \( T_1 T_2^{-1} \), and set \( \lambda_r \) equal to \( e^{\gamma l} \) or \( e^{-\gamma l} \), the \( \beta \) and \( \alpha \) can be calculated by the following equation:

\[
e^{\gamma l} = e^{(\alpha + j\beta)l} = \ln \lambda_r
\]

(14)

Where \( \lambda_r \) is the eigenvalue of \( T_1 T_2^{-1} \). \( l \) is the length difference of two lines. With equation (14), we cannot get the phase constant because of the periodic feature. It should be revised. Due to \( e^{2\pi n} = 1 \),

\[
\alpha = \text{Re} \left( \frac{\ln \lambda_r \pm j2\pi n}{l} \right) \quad \text{or} \quad \text{Re} \left( \frac{\ln \lambda_r}{l} \right)
\]

\[
\beta = \text{Im} \left( \frac{\ln \lambda_r \pm j2\pi n}{l} \right)
\]

(15)

In this case, \( n \) value can be decimal because of the high-order modes. The original phase constant calculated by improved multi-line method \((n=0)\) is shown in figure 5 (a), obviously, the result is false when \( n \) is zero and has a periodic feature. A proper value of \( n \) should be chosen to calculate the precise phase constant. The result of phase constant calculated with different \( n \) value is shown in figure 5 (b).

The phase constant is changeable with different \( n \) value. All the curves in figure 5(b) have the same gradient. So an optimum value can be gotten to calculate the phase constant. Different method are used to calculate the phase constant, results are shown in figure 5(c). The method is this paper shares the same precision with the full wave analysis by HFSS software. It verifies that the HMSIW has the same property with the conventional rectangular waveguide theoretically. The attenuation phase is also plotted in figure 5(d).

**Design of Multi-Layered Structure Equalizer**

With the analysis above, a HMSIW equalizer with five HMSIW cavities is simulated and fabricated. As the relative permittivity of substrate is 11.9, the energy leaking from the long side wall without the
metallic via holes is used to excite the upper and bottom HMI SW cavities. Figure 6 shows the configuration of HMI SW equalizer. Figure 6(a) illustrates the upper layers: HMI SW resonant cavities. Figure 6(b) shows the middle layer, it consists of two microstrip lines, two microstrip-to-HMI SW transitions and a HMI SW line, working as transmission line. Figure 6(c) shows the bottom layer and it is resonant cavity. Figure 6(d) shows the side view of this equalizer while Figure 6(e) gives the photo of the fabricated sample. Absorbing pillars are used to tune the attenuation[4]. All the values of parameters labeled in Figure 6 are shown in table 1.

![Image: Fig 5](image-5.png)

(a) The periodic feature of phase constant based on improved multi-line method
(b) The phase constant with different $n$.
(c) The phase constant of different method.  
(d) The attenuation constant of HMI SW.

Figure 5. The phase constant and attenuation constant of HMI SW.

![Image: Fig 6](image-6.png)

Figure 6. Configuration of HMI SW equalizer.

Compared with the HMI SW equalizer designed in Ref. [4], the proposed HMI SW equalizer in this paper has a small size. Because resonant cavities in [4] are excited by circles, and the resonant frequency would deviate to upper band according the perturbation theory. We have to increase the size of cavities to make the resonant frequency move to low band. The proposed equalizer has no external coupling structure and there is no frequency deviation. The calculated resonant frequencies are the same as full wave analysis results.

Table 1. The parameter values of the proposed equalizer.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value(mm)</th>
<th>Parameter</th>
<th>Value(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_1$</td>
<td>0.53</td>
<td>$W_L$</td>
<td>1.5</td>
</tr>
<tr>
<td>$L_1$</td>
<td>22</td>
<td>$W_e$</td>
<td>3.5</td>
</tr>
<tr>
<td>$W_{d1}$</td>
<td>4.83</td>
<td>$W_{34}$</td>
<td>4.83</td>
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<tr>
<td>$W_{d2}$</td>
<td>5.08</td>
<td>$W_{35}$</td>
<td>5.23</td>
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<tr>
<td>$W_{d3}$</td>
<td>5.1</td>
<td>$W_{36}$</td>
<td>5.2</td>
</tr>
</tbody>
</table>

To test it performance, the proposed HMI SW equalizer is compared with the designed HMI SW equalizer in [4]. The two HMI SW equalizers would have nearly the same performance for they are only different in coupling structures. The $S_{21}$ and $S_{11}$ of HMI SW equalizers are plotted in figure 7. Compared with The HMI SW equalizer in Ref. [4], the insertion loss of the proposed equalizer is larger, nearly -2dB while the insertion loss in Ref. [4] is -1.4dB. This is because the proposed equalizer has a small WHR and it leads to a larger energy radiation and leakage, as well as the improvement of $S_{11}$. All the HMI SW equalizers are tested by Agilent N5244A network analyzer.
Conclusion

The phase constant and attenuation constant is calculated with an improved method. And energy leakage of open face is analyzed. With the energy leakage, a HMM SiW equalizer is designed. This equalizer has a simpler structure compared with other HMM SiW equalizer, suitable for the miniaturization of microwave components.

![Figure 7. Method proposed in this paper: simulation and measurement results.](image)

(a) The measured S21 curves of different equalizers. (b) The measured S11 curves of different equalizers.

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