

3. MICROWAVE NETWORKS

At low frequencies for electrically small circuits, lumped active and passive circuit elements are enough for analyzing the circuit leading a type of a Quasi-Static solution (assumption of negligible phase change in any where of the circuit) of Maxwell's equations and to Kirchhoff Current and Voltage Laws with impedance concept. Moreover fields are considered as TEM type. But this way is not possible to analyze microwave circuits. The circuit concept should modify and apply to microwave network theory developed in MIT in 1940. The reasons of using it are as follow

- Much easier than field theory.
- Calculations are performed at terminals, not everywhere.
- Easy to modify and combine different problems.
- The field solution of Maxwell's equation gives more information at the every time and place of the network, but difficult. At microwave frequencies, although the definition of the terminal pairs for TEM line is relatively easy, the terminal pair for non-TEM line does not strictly exist.

3.1. Voltage, Current and Impedance

The measurements of V and I at microwave frequencies are difficult due to not easily defined terminals for non-TEM waves. Because of that the fields are measured and used as

$$V = \int_a^b \vec{E} d\vec{l} \quad , \quad I = \oint_C \vec{H} d\vec{l}$$

than, the impedance can be defined as $Z = V/I$. Because the fields depend on the coordinates (like in waveguide), special attenuation should be given for extraction of V and I . The way is to do that

$$\vec{E} = \frac{e(x,y)}{a} \frac{(V^+ e^{-jkr} + V^- e^{+jkr})}{v(r)}$$

$$\vec{H} = \frac{h(x,y)}{b} \frac{(I^+ e^{-jkr} + I^- e^{+jkr})}{i(r)}$$

then, the impedance can be defined as $Z = V^+/I^+ = V^-/I^- = a/b$. The impedance concept first used by O. Heaviside, and then after application to transmission lines, to electromagnetics by Schelkunoff. In this manner, types of it

- Intrinsic Impedance, $Z = \sqrt{\mu/\epsilon}$: It depends on only the material parameters.
- Wave Impedance, $Z = \vec{E}_{tang}/\vec{H}_{tang}$: TM, TE, TEM types are present which may depend on type of guide, material and frequency.
- Characteristic Impedance, $Z = \sqrt{L/C}$: For TEM, it is unique, but for TE and TM, not unique because v and i can not be determined, uniquely.

It can be shown that the real parts of $v(\omega)$, $i(\omega)$ and $Z(\omega)$ are even in ω , but the imaginary parts of them are odd in ω . $|\Gamma(\omega)|$ and $|\Gamma(\omega)|^2$ are the even function in ω .

3.2. Impedance & Admittance Matrices

The v and i of a N port microwave network having n 'th terminal

$$v_n = V_n^+ + V_n^- \quad , \quad i_n = I_n^+ + I_n^-$$

The impedance matrix is in the form of $[v] = [Z][i]$

$$\begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_N \end{bmatrix} = \begin{bmatrix} Z_{11} & \cdot & Z_{1N} \\ \cdot & \cdot & \cdot \\ Z_{N1} & \cdot & Z_{NN} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_N \end{bmatrix}$$

Similarly the admittance matrix is in the form of $[i] = [Y][v]$

$$\begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_N \end{bmatrix} = \begin{bmatrix} Y_{11} & \cdot & Y_{1N} \\ \cdot & \cdot & \cdot \\ Y_{N1} & \cdot & Y_{NN} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_N \end{bmatrix}$$

Clear that $[Y] = [Z]^{-1}$. It can be shown that

$$Z_{ij} = \left. \frac{V_i}{I_j} \right|_{\text{Open circuiting all other ports}}$$

$$Y_{ij} = \left. \frac{I_i}{V_j} \right|_{\text{Short circuiting all other ports}}$$

Then Z_{ii} and Z_{ij} are known as *Input Impedance* and *Transfer Impedance*, respectively.

- If the network is reciprocal (no ferrites, plasmas and active devices inside), $Z_{ij} = Z_{ji}$ and $Y_{ij} = Y_{ji}$ are the right relations.
- If the network is lossless, Z_{ij} and Y_{ij} are purely imaginary.

3.2.1. Scattering Matrix

The form $[V^-] = [S][V^+]$ of the scattering matrix gives the complete description of the N port networks with the incident and reflected waves as

$$\begin{bmatrix} V_1^- \\ V_2^- \\ \vdots \\ V_N^- \end{bmatrix} = \begin{bmatrix} S_{11} & \cdot & S_{1N} \\ \cdot & \cdot & \cdot \\ S_{N1} & \cdot & S_{NN} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \\ \vdots \\ V_N^+ \end{bmatrix}$$

Any element of the scattering matrix

$$S_{ij} = \left. \frac{V_i^-}{V_j^+} \right|_{\text{All ports matched with loads}}$$

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