The Design of Broadband Stripline Directional Coupler

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Abstract—**The main method of analyzing coupled stripline is using odd and even mode characteristics of stripline. Calculation of even and odd mode impedances for the stripline is the most important issues, and it is the key in the design of broadband coupler.In this paper, using coupled transmission line with Chebyshev form, I designed a broadband stripline directional coupler with 2~18 GHz bandwidth, 10 ± 1dB coupling, VSWR<1.4, directivity >15dB, and the insertion loss is less than 1dB.**

Keywords—Coupled stripline, multi-element coupled line, odd and even mode impedance, stripline.

I. Introduction

When two unshielded transmission lines close together, as the result of each transmission line's electromagnetic interactions, there must be electric and magnetic energy coupled with each other. Such lines are referred to as coupled transmission line.

Usually there are three types of coupled stripline, parallel edge-coupled and parallel broadside-coupled strip line posted by Cohn, and offset coupled strip line posted by J. P. Shelton, as shown in Fig.1.

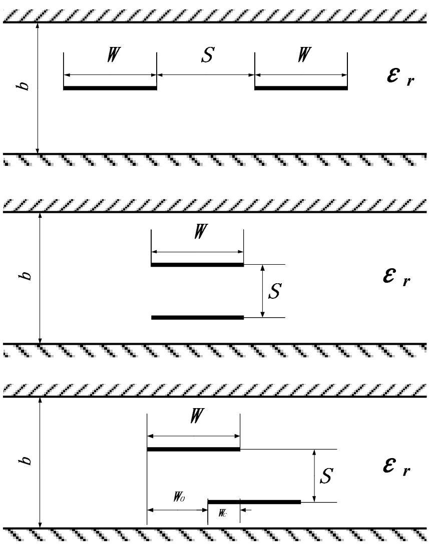


Figure 1. Three kinds of coupled stripline (edge coupled, broad-side-coupled and offset coupled)

II. CoupledLine Theory

The coupled lines of Fig.1, or any other three-wired line, can be presented by the structure shown in Fig. 2. If we assume TEM propagation (stripline), the conductor and the ground are non-magnetizer, so the effect of importing another conductor is small on the distribution of the magnetic field, but greater on the electric field. That is, distributed inductance almost stays the same, but distributed capacitance changes greatly. So the electrical characteristics of the coupled lines can be completely determined from the effective capacitances between the lines and the velocity of propagation on the line. As depicted in Fig. 2, C_{12} represents the capacitance between the two strip conductors, while C_{11} and C_{22} represents the capacitance between the one strip conductor and the ground. If the strip conductors are identical in size and location relative to the ground conductor, then$C_{11} = C_{22}$.

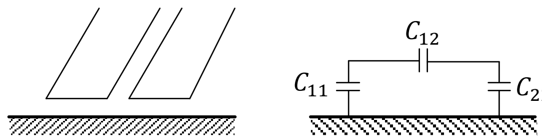


Figure 2. A three-wire coupled transmission line and its equivalent capacitance network

Suppose the coupled lineoperate in TEM mode, the electromagnetic coupling between two lines can be equivalent to the coupling of mutual inductance and mutual capacitance between twolines, and the line element d_z of the equivalent-circuit of lumped parameter can be shown in Fig. 3. $L_m$andC_m represents the coupling inductance and the coupling capacitance in unit length between lines, L_1 and C_1 represents distributed inductance and distributed capacitance of a single line which is under the effect of the other line. Based on Kirchhoff's law, the equation can be expressed as:

$$\begin{cases} -\frac{dV_1}{dz} = j\omega L I_1 + j\omega L_m I_2 \\ -\frac{dV_2}{dz} = j\omega L I_2 + j\omega L_m I_1 \\ -\frac{dI_1}{dz} = j\omega C V_1 - j\omega C_m V_2 \\ -\frac{dI_2}{dz} = j\omega C V_2 - j\omega C_m V_1 \end{cases} \tag{1}$$

Equation (1) is the basic equations of coupled transmission lines. $L = L_1, C = C_1 + C_m$, which represents the totalinductance andcapacitance of unit length in single line of the coupled line.

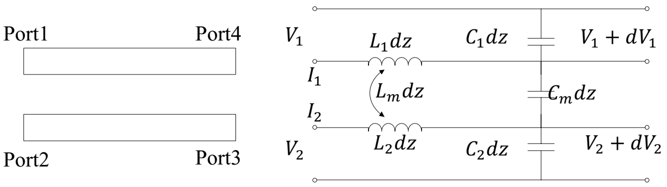


Figure 3. Symmetrical stripline and its equivalent circuit

III. ODD-EVEN MODE METHOD IN COUPLED TRANSMISSION LINE

In odd-even mode excitation, coupled line is dividedinto two halves by the electric and magnetic wall; we just need studya half. That is, the superposition of the single odd mode line and single odd mode line's characteristics is the characteristic of the whole coupled line. In words, under the odd-even mode excitation, the influence of the other conductor is equivalent to boundary condition of electrical wall (odd mode) and magnetic wall (even mode) on the symmetry plane, respectively. Then the original four-port coupled line network is simplifiedto a two-port network, as is shown in Fig4&5.

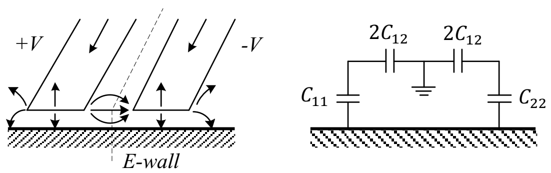


Figure 4. Odd-mode excitation for a coupled line, and the resulting equivalent capacitance network

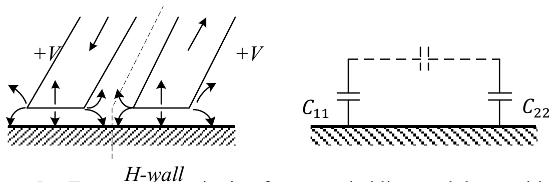


Figure 5. Even-mode excitation for a coupled line, and the resulting equivalent capacitance network

In Fig.6, any excitation voltage V_1 and V_2 on port 1 and 2 of the symmetric coupled line can always be treated as the sum of a pair of odd-even mode excitation voltage V_o and V_e

$$\begin{cases} V_1 = V_e + V_o \\ V_2 = V_e - V_o \end{cases} \tag{2}$$

so that

$$\begin{cases} V_e = \frac{V_1+V_2}{2} \\ V_o = \frac{V_1-V_2}{2} \end{cases} \tag{3}$$

By selectingthe proportion of odd-even mode excitation properly,we can describe different coupling condition. In the actual design of directional coupler,we usually choose excitation on port 1, at this time$V_2 = 0$, we have

$$V_e = V_o = \frac{V_1}{2} \tag{4}$$

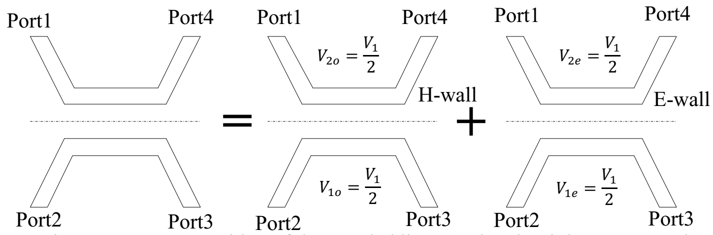


Figure 6. Decomposition of the coupled line coupler circuit into even- and odd-mode excitations

A. Odd-mode impedance

For odd mode excitation,$V_1 = -V_2 = V_o$, $I_1 = -I_2 = I_o$, substitute into (1) ,we can get odd mode transmission line equation:

$$\begin{cases} -\frac{dV_o}{dz} = j\omega L(1-K_L)I_o = j\omega L_o I_o = Z_o I_o \\ -\frac{dI_o}{dz} = j\omega C(1+K_C)V_o = j\omega C_o V_o = Y_o I_o \end{cases} \tag{5}$$

Then we can get phase velocityv_{po} , guide wavelengthλ_{go} , characteristic impedanceZ_{0o} in odd mode as follows

$$v_{po} = \frac{\omega}{\beta_o} = \frac{\omega}{\omega\sqrt{L_o C_o}} = \frac{1}{\sqrt{LC(1-K_L)(1+K_C)}} \tag{6}$$

$$\lambda_{go} = \frac{2\pi}{\beta_o} = \frac{v_{po}}{f} \tag{7}$$

$$Z_{0o} = \sqrt{\frac{L_o}{C_o}} = \sqrt{\frac{L(1-K_L)}{C(1+K_C)}} = Z_0\sqrt{\frac{1-K_L}{1+K_C}} \tag{8}$$

In equation (6) (7) (8), $K_L = L_m/L$ isinductive coupling coefficient, $K_C = C_m/C$ is capacitive coupling coefficient, $Z_0 = \sqrt{L/C}$ is characteristic impedance of single coupled line.

B. Even-mode impedance

For even mode excitation, $V_1 = V_2 = V_e$, $I_1 = I_2 = I_e$, substitute into (1) ,we can get odd-mode transmission line equation:

$$\begin{cases} -\frac{dV_e}{dz} = j\omega L(1+K_L)I_e = j\omega L_e I_e = Z_e I_e \\ -\frac{dI_o}{dz} = j\omega C(1-K_C)V_e = j\omega C_e V_e = Y_e I_e \end{cases} \tag{9}$$

Then we can get phase velocityv_{pe} , guide wavelengthλ_{ge} , characteristic impedanceZ_{0e} in even mode as follows:

$$v_{pe} = \frac{\omega}{\beta_e} = \frac{\omega}{\omega\sqrt{L_e C_e}} = \frac{1}{\sqrt{LC(1+K_L)(1-K_C)}} \tag{10}$$

$$\lambda_{ge} = \frac{2\pi}{\beta_e} = \frac{v_{pe}}{f} \tag{11}$$

$$Z_{0e} = \sqrt{\frac{L_e}{C_e}} = \sqrt{\frac{L(1+K_L)}{C(1-K_C)}} = Z_0\sqrt{\frac{1+K_L}{1-K_C}} \tag{12}$$

IV. EVEN-ODD MODE IMPEDANCE OF STRIPLINE

For symmetricalstripline with medium filling evenly, it operates in TEM mode, then

$$v_{po} = v_{pe} = v_p = \frac{c}{\sqrt{\varepsilon_r}} \tag{13}$$

Combined with the former formula (6) and (10),we can get$K_L = K_C = K$, and

$$v_{po} = v_{pe} = \frac{1}{\sqrt{LC(1-K^2)}} \tag{14}$$

$$\lambda_{go} = \lambda_{ge} = \frac{2\pi}{\omega\sqrt{LC(1-K^2)}} = \frac{1}{f\sqrt{LC(1-K^2)}} \tag{15}$$

$$Z_{0o} = Z_0\sqrt{\frac{1-K}{1+K}} \tag{16}$$

$$Z_{0e} = Z_0\sqrt{\frac{1+K}{1-K}} \tag{17}$$

Both sides of equation (16) and (17) divided by the characteristic impedanceZ_0, we can get normalized odd-even mode characteristic impedanceZ_{0e} and Z_{0o}

$$z_{0o} = \sqrt{\frac{1-K}{1+K}} \tag{18}$$

$$z_{0e} = \sqrt{\frac{1+K}{1-K}} \tag{19}$$

From (16) and (17), we can reach an important conclusion of stripline directional couplers,

$$Z_0^2 = Z_{0o}Z_{0e} \tag{20}$$

$$K = \frac{Z_{0e}-Z_{0o}}{Z_{0e}+Z_{0o}} \tag{21}$$

Consider (18) and (19), we have

$$Z_{0o}Z_{0e} = 1 \tag{22}$$

$$K = \frac{Z_{0e}^2-1}{Z_{0e}^2+1} = \frac{1-Z_{0o}^2}{1+Z_{0o}^2} \tag{23}$$

J.R Shelton released the method of design an offset stripline coupler completely in 1966, gave explicit expression by using conformal transformation. The formula is divided into loose coupling and tightly coupling, we mainly concern the loose coupled situation.

First we give a series of parameters; S represents the distance between two strip lines

$$\rho = \frac{Z_{0e}}{Z_{0o}} \tag{24}$$

$$C_0 = \frac{120\pi\sqrt{\rho}}{\sqrt{\varepsilon_r}Z_0} \tag{25}$$

$$\Delta C = \frac{120\pi}{\sqrt{\varepsilon_r}Z_0}\frac{\rho-1}{\sqrt{\rho}} \tag{26}$$

$$k = \frac{1}{e^{\frac{\pi\Delta C}{2}}-1} \tag{27}$$

$$a = +\sqrt{\left(\frac{S-k}{S+1}\right)^2 + k} - \frac{S-k}{S+1} \tag{28}$$

$$q = \frac{k}{a} \tag{29}$$

or

$$q = \left(\frac{S+1}{2}\right)\left[\frac{a+\frac{2S}{S+1}}{a+\frac{S+1}{2}}\right] \tag{30}$$

$$C_{f0} = \frac{2}{\pi}\left\{\frac{1}{S+1}ln\left[\frac{1+a}{a(1-q)}\right] - \frac{1}{1-S}ln(q)\right\} \tag{31}$$

$$C_f = -\frac{2}{\pi}\left[\frac{1}{S+1}ln\left(\frac{1-S}{2}\right) + \frac{1}{1-S}ln\left(\frac{1+S}{2}\right)\right] \tag{32}$$

Then we can work out W$W_c$and W_o based on the follow two equations

$$W_c = \frac{1}{\pi}\left[Sln\left(\frac{q}{a}\right) + (1-S)ln\left(\frac{1-q}{1+a}\right)\right] \tag{33}$$

$$W_o = \frac{1-S^2}{4}\left(C_0 - C_{f0} - C_f\right) \tag{34}$$

V. DESIGN OF MULTI-SECTION COUPLED LINECOUPLER

A. *Model and Simulation*

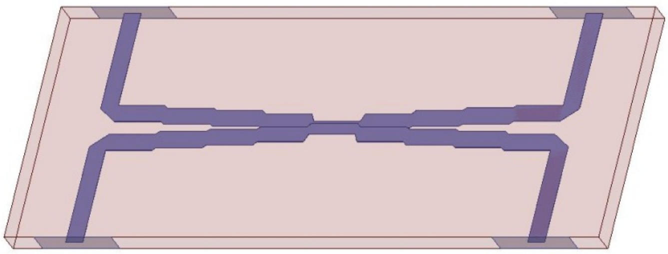


Figure 7. HFSS model

We choose Rogers 5880 as a substrate, itsrelative dielectric constant is 2.2, thickness b=1.828mm.And the distance between two lines is S=0.254mm. Eachcoupled line's length is$L = \lambda_g/4$, and $\lambda_g = \lambda_0/\sqrt{\varepsilon_r}$, so L=5.056 mm.

Given $f_0 = \frac{f_1+f_2}{2}$, $w = \frac{f_2-f_1}{f_0}$, $B = f_2/f_1$, the desire band width is 2-18Ghz, sof_0=10Ghz, B=9, w=1.6, consider table 1,we choose 7-section design, and its ripple is 0.4.But the coupling degree decrease to 20dB, so we choose 9-section, 0.4dB ripple, f_0=13GHz, B=12, w=1.6.

TABLE I. EVEN-MODE IMPEDANCE OF DIFFERENT SECTION AT 10 DB COUPLING DEGREE

Section	ripple	Z_{1e}	Z_{2e}	Z_{3e}	Z_{4e}	Z_{5e}
5	0.8	1.0714	1.2601	1.8194		
7	0.4	1.0360	1.0973	1.2384	1.8672	
9	0.2	1.0189	1.0516	1.1174	1.2639	1.9063
9	0.4	1.0304	1.0701	1.1431	1.2978	1.9607

Then consider equation (22), the odd-mode impedance can also be determined.

$$Z_{1e} = 1.0304, Z_{2e} = 1.0701, Z_{3e} = 1.1431, Z_{4e} = 1.2978,$$

$$Z_{5e} = 1.9607, Z_{6e} = Z_{4e}, Z_{7e} = Z_{3e}, Z_{8e} = Z_{2e}, Z_{9e} = Z_{1e}$$

$$Z_{1o} = 0.9705, Z_{2o} = 0.9345, Z_{3o} = 0.8748, Z_{4o} = 0.7705$$

$$Z_{5o} = 0.5100, Z_{6o} = Z_{4o}, Z_{7o} = Z_{3o}, Z_{8o} = Z_{2o}, Z_{9o} = Z_{1o}$$

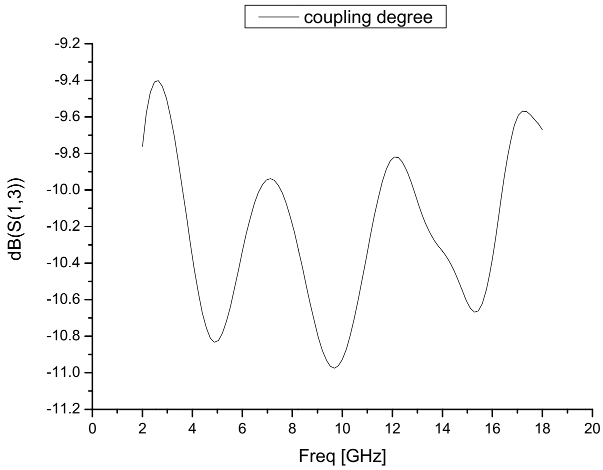
substituteinto equation (33) and (34), we can get the detail parameters, listed in table 2.

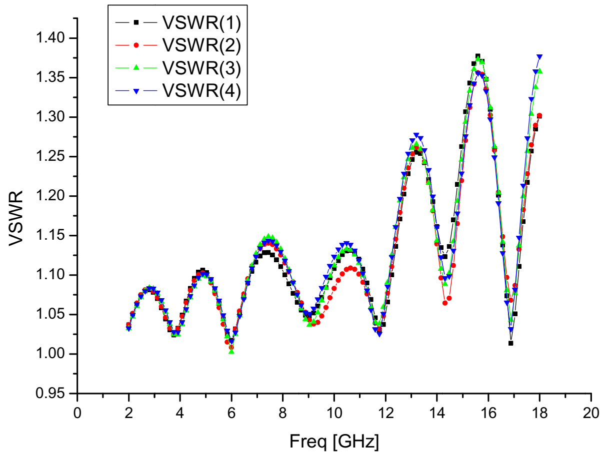
TABLE II. LINE WIDTH AND OFFSETPARAMETERS.

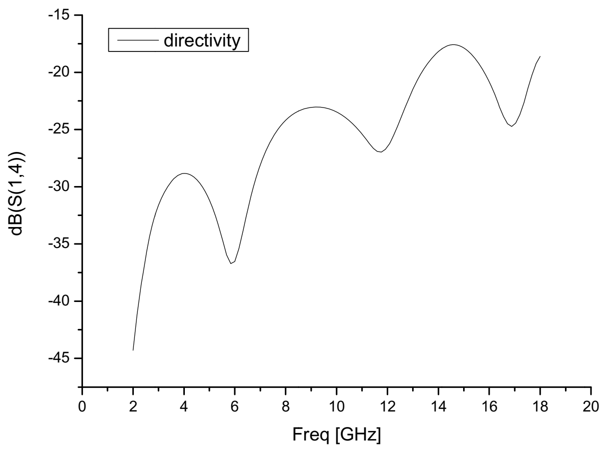
Section	$Z_e(\Omega)$	$Z_o(\Omega)$	Line width	Offset
1	51.5205	48.5244	1.42373	2.65597

2	53.502	46.7272	1.41195	2.17773
3	57.1565	43.7396	1.37331	1.76423
4	64.8885	38.5276	1.25818	1.32059
5	98.037	25.5006	0.93923	0.305614

Simulationresults







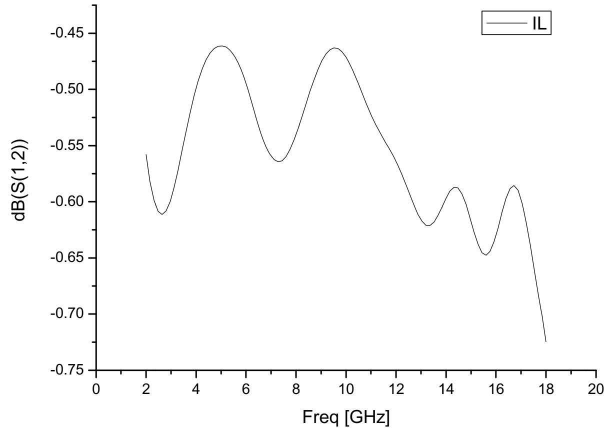


Figure 8. simulation results

B. *Measured Performance Curve*

Figure 9. Photo

Figure 10. VWSR 1

Figure 11. Insertion Loss

Figure 12. Coupling degree

Figure 13. Directivity

VI. CONCLUSION

The edge connection between two lines has a great effect on the coupler; the edge must be cut to decrease the uncontinuity. Choosing a proper size of the cut is very important.

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