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Performance of Microstrip Directional Coupler Using Synthesis Technique

Vijayan T

Asst. Professor, Dept of E&I, Bharath University, Chennai-600073, India

ABSTRACT: The introduced design method requires only the information of the port impedances, the coupling level, and the operational frequency. The design charts that give all the physical dimensions, including the length of the directional coupler versus frequency and different coupling levels, are given for alumina, Teflon, RO4003, FR4, and RF-60, which are widely used in microwave applications. Further work includes validation of analytical results using a planar electromagnetic simulation tool (IE3D) and experimental verification.

KEYWORDS: Coupled lines, directional couplers, microstrip.

I. INTRODUCTION

Microstrip directional couplers have been commonly used in microwave systems for measuring transmitted and reflected power with accuracy. They have several advantages. Such as manufacturability,

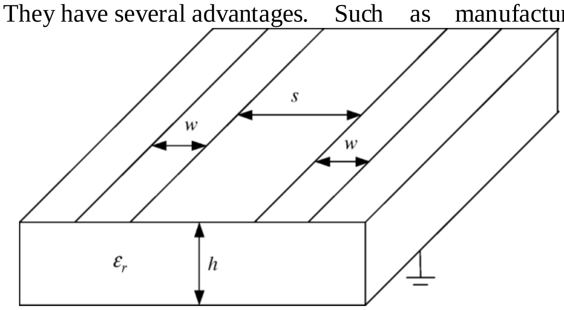

Fig 1. Two-line microstrip directional coupler

repeatability, and low cost. Extensive research has been conducted on the design of microstrip directional couplers due to their widespread application. The existing design procedures in the literature depend on knowledge of the physical geometry of the directional coupler. As a result, available design charts give physical dimensions of the direction al coupler versus even-and odd-mode impedances of the directional coupler. However, in practice, the physical length of the directional coupler is initially unknown to the designer. Designers have only information about the port impedances, the required coupling level, and the operational frequency at the initial stage of their design. Because of this, it is quite cumbersome to use existing design chats with no prior knowledgeof the geometry of the directional coupler. This requires several iterations to finalize the design.The geometry of a symmetrical micro strip directional coupler is shown in fig. 1.

The methods given by Bryant and Weiss [1] and Kirschning and Jansen [2] are among the first reliable and accurate methods to obtain information on coupled microstrip transmission lines. Many researchers used techniques similar to the ones presented in [1] and [2] and studied micro strip directional coupler design for more than 30 years. However, design charts in the literature give only the physical parameters of the directional coupler versus the even-and odd-mode impedances and, as a result, are not practically applicable on real applications. One has to use these charts and work backward to obtain the required design parameters for be directional couplers. This is a quite tedious and inefficient way of deigning any RF/microwave device. Akhtarzad *etal*. [3] give a design method that seems to reflect the design procedure that finds an application in practice. In [3], the synthesis technique is used, and it has an intermediate step of calculating the strip width of the single micro strip line that corresponds to even-and odd-mode impedances of the coupled lines. However, some critical corrections have to be applied to the formulations given in [3] to have accurate results. There are two separate corrections reported by Hinton [4] and Gupta etal. [5] for the work in [3]. Although the error seems to be reduced in comparison to the one in the original work [3] with the application of each correction, the error can still be more than 10% for the low-permittivity materials such as Teflon and for small values of shape and spacing ratios if the correction in [4] and [5] are not employed together. We report that when the corrections in [4] and [5] are employed together, the accuracy of the results increases and the error reduces to within

3% with the experimental results, even when using low-permittivity materials such as Teflon and FR4. This is reported by Eroglu [6]. However, in [6], the method has only been applied on Teflon and FR4, and design charts and parameters have not been given or discussed. Design charts are critical in the design process and make it possible to design directional couplers without using any equations. In addition, the method accuracy has not been verified using different dielectric materials before. Furthermore, the application of the corrections on the formulations has not been presented.

In this paper, a three-step deign procedure with accurate closed formulas that give a complete design of symmetrical two-line microstrip directional couplers that include the physical length at the desired operational frequency is introduced. Our design procedure requires knowledge of the port termination impedances, the coupling level, and the operational frequency. We also give the design charts that are most needed by the designer. Our design charts obtained for the five most popular materials used in microwave applications: alumina, Teflon, RO4003, FR4, RF-60. In the design charts, the coupling level is given versus the physical dimensions of the directional coupler. We also provide design charts that show the physical length of the directional coupler l versus the frequency for the given coupling level. We validated our analytical results with the planar electromagnetic (EM) simulation tool [7] and then experimentally verified them. We show that the error between the analytical and the simulation results is reduced to be within 0.2% for high-permittivity materials like alumina. The complete design of a two-line microstrip directional coupler can be obtained for the first time using our results in this paper. A designer can use either the closed-form solutions or the design charts presented here to have a complete design.

II. FORMULATION AND SOLUTIONS

In real world engineering applications, the physical parameters of the directional couplers are unknown to the designer at the beginning of the design. The only information available to the designer at the beginning of design is the port termination impedances, the coupling level, and the operational frequency. In practice, the termination impedance for each port of the directional coupler is desired to be 50Ω for most applications. The matched system is accomplished when the characteristic impedance z_o

$$z_o = \sqrt{z_{oe}\, z_{oo}}$$

is equal to the port impedance. The existing design procedure begins with finding the even-and odd-mode impedances z_{oe} and z_{oo} by using the charts given for w/h and s/h.Then, the designer needs to calculate the coupling level and the characteristic impedance z_o . If it does not given the desired coupling level, procedure needs to be repeated until the specifications are met. This procedure is quite cumbersome. Furthermore, there seems to be no design chart available for the physical length of the directional coupler. The physical length of the directional coupler l for coupled lines depends on the effective permittivity constant ε_{eff} of the structure are known. The analytical method that is given by Bahl [8] seems to be accurate and is adapted in this paper to find the physical length of the directional coupler. In this paper, we use the method proposed by Akhtarzad *etal*. [3] to obtain the spacing ratio s/h and the shape ratio w/h of the directional coupler illustrated in Fig. 1. We concurrently apply the corrections given in [4] and [5]. The physical length of the directional coupler is obtained using the method given in [8]. As outlined in section 1. We assume that the port impedances, which are equal and referred to as zoe the forward coupling level, and the operational frequency, are known parameters at the beginning of the design. Based on the known parameters, the proposed design procedure has the following three steps.

Step 1-Find Even- and Odd-Mode Impedances

The even and odd impedances z_{oe} and z_{oo} of the microstrip coupler given in Fig.1 can be found from

$$z_{oe} = z_o\sqrt{\frac{1+10^{C/20}}{1-10^{C/20}}} \quad (1)$$

$$z_{oo} = zo\sqrt{\frac{1-10^{C/20}}{1+10^{C/20}}} \quad (2)$$

Where C forward coupling requirement and is given in decibels.

Step 2 -Find Physical Dimensions w/h and s/h

The physical dimensions of the directional coupler are found using the synthesis method proposed in [3] and applying the corrections given in [4] and [5]. When the corrections are employed, we get the following equation for the spacing ratio s/h of the coupler in Fig.1:

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Vol. 2, Issue 3, March 2013

$$s/h = \frac{2}{\pi}\cosh^{-1}\left[\frac{\cosh\left[\frac{\pi}{2}\left(\frac{w}{h}\right)_{so}^{'}\right]+\cosh\left[\frac{\pi}{2}\left(\frac{w}{h}\right)_{so}\right]-2}{\cosh\left[\frac{\pi}{2}\left(\frac{w}{h}\right)_{so}^{'}\right]-\cosh\left[\frac{\pi}{2}\left(\frac{w}{h}\right)_{se}\right]}\right] \quad (3)$$

$(w/h)_{se}$ and $(w/h)_{so}$ are the shape ratios for the equivalent single case that corresponds to even and odd-mode geometry, respectively. $(w/h)_{so}^{'}$ is modified term for the shape ratio and is different from the one that is given in [4] and [5] and are detailed below. (w/h) is the corrected shape ratio for the single microstrip line, and it is expressed as [4]

$$\frac{w}{h} = \frac{8\sqrt{\left[\exp\left(\frac{R}{42.4}\sqrt{(\varepsilon_r+1)}\right)-1\right]\frac{7+\left(\frac{4}{\varepsilon_r}\right)}{11}+\frac{1+\left(\frac{1}{\varepsilon_r}\right)}{0.81}}}{\left[\exp\left(\frac{R}{42.4}\sqrt{\varepsilon_r+1}\right)-1\right]} \quad (4)$$

where

$$R = \frac{z_{oe}}{2} \text{ or } R = \frac{z_{oo}}{2} \quad (5)$$

z_{ose} and z_{oso} are the characteristic impedances that correspond to single microstrip shape ratios $(w/h)_{se}$ and $(w/h)_{so}$, respectively. They given as

$$z_{ose} = \frac{z_{oe}}{2} \quad (6) \qquad z_{oso} = \frac{z_{oo}}{2} \quad (7)$$

$$\left(\frac{w}{h}\right)_{se} = \left(\frac{w}{h}\right)\Big| z_{ose} \quad (8) \qquad \left(\frac{w}{h}\right)_{so} = \left(\frac{w}{h}\right)\Big| z_{oso} \quad (9)$$

The corrected term $(w/h)_{so}^{'}$ in (3) is given as [5]

$$\left(\frac{w}{h}\right)_{so}^{'} = 0.78\left(\frac{w}{h}\right)_{so} + 0.1\left(\frac{w}{h}\right)_{se} \quad (10)$$

The updated formula in (3) gives accurate results for the spacing ratio s/h of the symmetrical two-line microstrip directional coupler when used with (4).

After the spacing ratio s/h for the coupled lines is found, we can proceed to find w/h for the coupled lines, as described in [3]. The shape ratio for the coupled lines is

$$w/h = \frac{1}{\pi}\cosh^{-1}(d) - \frac{1}{2}\left(\frac{s}{h}\right) \quad (11)$$

where

$$d = \frac{\cosh\left[\frac{\pi}{2}\left(\frac{w}{h}\right)_{se}\right](g+1)+g-1}{2} \quad (12)$$

$$g = \cosh\left[\frac{\pi}{2}\left(\frac{s}{h}\right)\right] \quad (13)$$

Step 3-Find the Physical Length of the Directional Coupler:

The physical length of the directional coupler is obtained using

$$l = \frac{\lambda}{4} = \frac{c}{4f\sqrt{\varepsilon_{eff}}} \quad (14)$$

where $c = 3*10^8$ m/s, and f is operational frequency in hertz. Hence, the length of the directional coupler can be found if the effective permittivity constant ε_{eff} can be found using the method described in [8] as follows:

$$\varepsilon_{eff} = \left[\frac{\sqrt{\varepsilon_{effe}}+\sqrt{\varepsilon_{effo}}}{2}\right]^2 \quad (15)$$

ε_{effe} and ε_{effo} are the effective permittivity constants of the coupled structure for odd and even modes, respectively. ε_{effe} and ε_{effo} depends on even- and odd-mode capacitance C_e and C_o as

$$\varepsilon_{effe} = \frac{C_e}{C_{e1}} \quad (16a)$$

$$\varepsilon_{effo} = \frac{Co}{Co1} \quad (16b)$$

$C_{e1,o1}$ is the capacitance with air as dielectric. All the capacitances are given as capacitance per unit length.

1) Even-Mode Capacitance Calculation: The even-mode capacitance C_e is

$$C_e = C_p + C_f + C_f^{'} \quad (17)$$

C_p is the parallel plate capacitance and is defined as

$$C_p = \varepsilon_o \varepsilon_r \frac{w}{h} \quad (18)$$

where w/h is found in Section 2.B. C_f is the fringing capacitance due to the microstrips being taken alone as if they were a single strip, which is equal to

$$C_f = \frac{\sqrt{\varepsilon_{seff}}}{2cz_o} - \frac{C_p}{2} \quad (19)$$

Here, ε_{seff} is the effective permittivity constant of a single strip microstrip, which can be expressed as

$$\varepsilon_{seff} = \frac{\varepsilon_r + 1}{2} - \frac{\varepsilon_r - 1}{2} F(w/h) \quad (20)$$

where

$$F(w/h) = \begin{Bmatrix} (1+12h/w)^{-1/2} + 0.041(1-w/h)^2, \text{ for } \left(\frac{w}{h} \le 1\right) \\ (1+12h/w)^{-1/2}, \qquad \text{for } \left(\frac{w}{h} \ge 1\right) \end{Bmatrix} \quad (21)$$

$C_f^{'}$ is given by the following equation:

$$C_f^{'} = \frac{C_f}{1 + A\left(\frac{h}{s}\right)\tanh\left(\frac{10h}{s}\right)} \left(\frac{\varepsilon_r}{\varepsilon_{seff}}\right)^{1/4} \quad A = \exp\left[-0.1\exp\left(2.33 - 1.5\frac{w}{h}\right)\right] \quad (23)$$

2) Odd-Mode Capacitance calculation: The odd-mode capacitance C_o is

$$C_o = C_p + C_f + C_{ga} + C_{gd} \quad (24)$$

C_{ga} is the capacitance term in odd mode for the fringing field across the gap in the air region. It can be written as

$$C_{ga} = \varepsilon_o \frac{K(k^{'})}{K(k)} \quad (25)$$

where

$$\frac{K(k^{'})}{K(k)} = \begin{Bmatrix} \frac{1}{\pi}\ln\left[2\frac{1+\sqrt{k^{'}}}{1-\sqrt{k^{'}}}\right], 0 \le k^2 \le 0.5 \\ \frac{\pi}{\ln\left[2\frac{1+\sqrt{k^{'}}}{1-\sqrt{k^{'}}}\right]}, \quad 0.5 \le k^2 \le 1 \end{Bmatrix} \quad (26)$$

$$k = \frac{\left(\frac{s}{h}\right)}{\left(\frac{s}{h}\right) + \left(\frac{2w}{h}\right)} \quad (27)$$

$$k^{'} = \sqrt{1 - k^2} \quad (28)$$

C_{gd} represents the capacitance in odd mode for the fringing field across the gap in the dielectric region. It can be found using

$$C_{gd} = \frac{\varepsilon_o \varepsilon_r}{\pi} \ln\left\{\coth\left(\frac{\pi}{4}\frac{s}{h}\right)\right\} + 0.65 C_f \left[\frac{0.02}{\frac{s}{h}}\sqrt{\varepsilon_r} + \left(1 - \frac{1}{\varepsilon_r^2}\right)\right] \quad (29)$$

Since

$$z_{oo} = \frac{1}{c\sqrt{C_e\, Ce1}} \quad (30)$$

$$z_{oo} = \frac{1}{c\sqrt{Co\, C_{o1}}} \quad (31)$$

then we can write

$$C_{e1} = \frac{1}{c^2\, C_e\, z_{oe}^2} \quad (32)$$

$$C_{o1} = \frac{1}{c^2\, C_o\, z_{oo}^2} \quad (33)$$

Substituting (17), (24), (32), and (33) in to (16) gives the even and odd-mode effective permittivities ε_{effe} and ε_{effo}. When (16) is substituted into (15), we can find the effective permittivity constant ε_{eff} of the coupled structure. Now, (14) can be used to calculated the physical length of the directional coupler at the operational frequency.

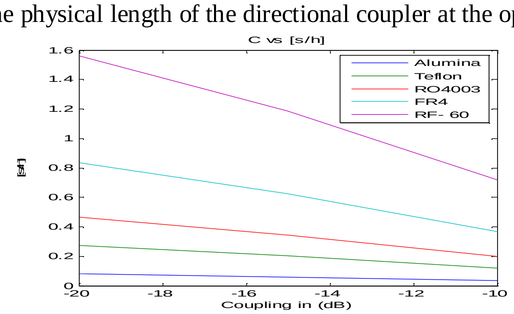

Fig. 2. s/h versus coupling level for alumina, Teflon, RO4003, FR4, and RF-60.

TABLE 1

DESIGN PARAMETERS OF A TWO-LINE MICROSTRIP DIRECTIONAL COUPLER AT 300 MHZ FOR $Z_{O(\Omega)} = 50$

Material	ε_r	Coupling (dB)	w/h	s/h	$l(mils)$
Teflon	2.08	-10	2.6103	0.0352	6782.78
RO4003	3.38	-10	1.9281	0.0771	5846.63
FR4	4.4	-10	1.6117	0.1094	5348.79
RF-60	6.15	-10	1.257	0.1595	4743.29
Alumina	9.8	-10	0.2375	0.8379	3965.26
Teflon	2.08	-15	3.0727	0.2576	7222.39
RO4003	3.38	-15	2.2426	0.3687	6061.05
FR4	4.4	-15	1.8621	0.4343	5508.25
RF-60	6.15	-15	1.4412	0.5202	4868.32
Alumina	9.8	-15	0.9592	0.6359	4076.97
Teflon	2.08	-20	3.243	0.8216	7248.97
RO4003	3.38	-20	2.3522	0.9557	6040.04
FR4	4.4	-20	1.9479	1.0267	5514.46
RF-60	6.15	-20	1.504	1.1129	4876.99
Alumina	9.8	-20	0.9998	1.2184	4071.45

III. DESIGN CHARTS

In this section, we give the design charts to obtain a complete design for a two-line symmetrical microstrip directional coupler for the following five different materials: 1) alumina; 2) Teflon; 3) RO4003; 4) FR4; 5) RF-60. Fig. 2 gives the spacing ratio s/h of the directional coupler versus different coupling levels. Fig. 3 gives the shape ratio of the

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Vol. 2, Issue 3, March 2013

directional coupler w/h versus different coupling levels. Fig. 4-8 give the physical length l of the directional coupler versus frequency at different coupling levels for -10dB.

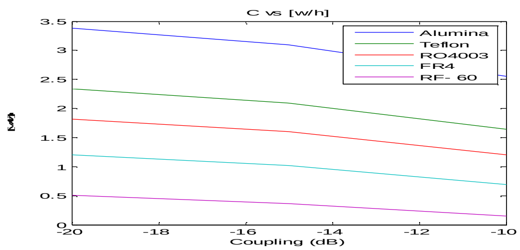

Fig. 3. w/h versus coupling level for alumina, Teflon, RO4003, FR4, and RF-60.

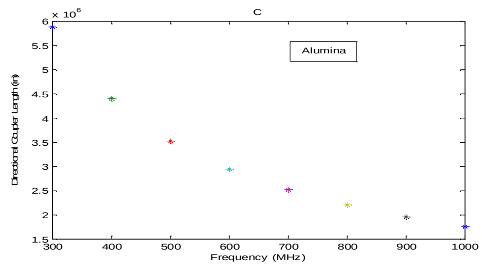

Fig. 4. Directional coupler length l versus frequency for alumina at -10(dB), coupling.

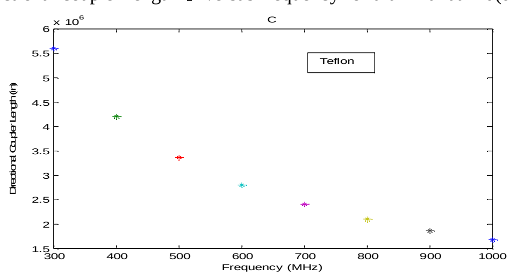

Fig. 5. Directional coupler length l versus frequency for Teflon at -10(dB), coupling.

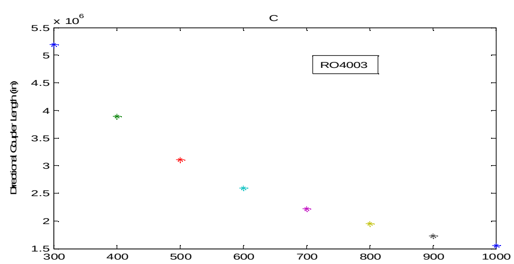

Fig. 6. Directional coupler length l versus frequency for RO4003 at -10(dB), coupling.

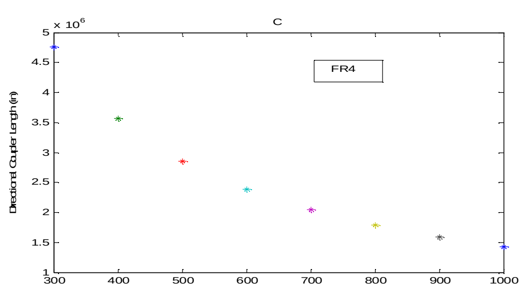

Fig. 7. Directional coupler length l versus frequency for FR4 at -10(dB), coupling.

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International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering
Vol. 2, Issue 3, March 2013

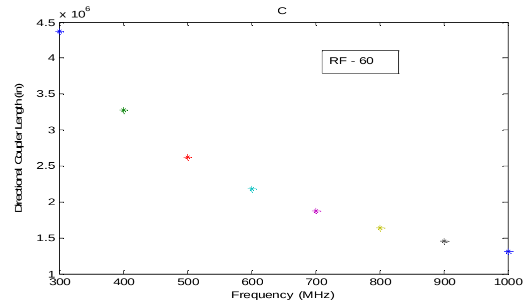

Fig. 8. Directional coupler length l versus frequency for RF-60 at -10(dB), coupling.

IV.CONCLUSION

In this paper, a practical and complete method to have a symmetrical two-line microstrip directional coupler has been presented by analytically introducing a three-step design procedure. Our design procedure requires knowledge of the port termination impedances, the coupling level, and the operational frequency, which are the three parameters that are known at the beginning of the design in practice. The design charts that give the shape and spacing ratios versus different coupling levels for five different materials that have relative permittivities between $2.08 \leq \varepsilon_r \leq 9.8$ are presented. We also give design charts that show the physical length of the directional coupler versus frequency at different coupling levels for the five materials.

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