The Complete Design of Microstrip Directional Couplers Using the Synthesis Technique

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Abstract—A symmetrical microstrip directional coupler design using the synthesis technique without prior knowledge of the physical geometry of the directional coupler is analytically given. The introduced design method requires only the information of the port impedances, the coupling level, and the operational frequency. The analytical results are first validated by using a planar electromagnetic simulation tool and then experimentally verified. The error between the experimental and analytical results is found to be within 3% for the worst case. 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. The complete design of symmetrical two-line microstrip directional couplers can be obtained for the first time using our results in this paper.

Index Terms—Coupled lines, directional couplers, microstrip, microwave, synthesis, two-line.

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, 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 directional 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 charts with no prior knowledge of the geometry of the directional coupler. This requires several iterations to finalize the design. The geometry of a symmetrical microstrip 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 microstrip 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 the directional couplers. This is a quite tedious and inefficient way of designing any RF/microwave device. Akhtarzad et al. [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 microstrip 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 et al. [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 corrections 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.

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In this paper, a three-step design 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 are obtained for the five most popular materials used in microwave applications: alumina, Teflon, RO4003, FR4, and 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 the 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 50 \( \Omega \) at the desired operational frequency. In this paper, we use the method proposed by Akhtarzad et al. [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 I, we assume that the port impedances, which are equal and referred to as \( Z_o \), 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

\[
Z_{oe} = Z_o \sqrt{\frac{1 + 10C/20}{1 - 10C/20}} \quad (1)
\]

\[
Z_{oo} = Z_o \sqrt{\frac{1 - 10C/20}{1 + 10C/20}} \quad (2)
\]

where \( C \) is the forward coupling requirement and is given in decibels.

Step 2—Find Physical Dimensions \( s/h \) and \( w/h \)

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:

\[
s/h = \frac{2}{\pi} \cosh^{-1} \left[ \cosh \left( \frac{\pi}{2} \frac{w}{h} \right) \right] - 2 \quad (3)
\]

Where \((w/h)_se \) and \((w/h)_so \) are the shape ratios for the equivalent single case that corresponds to even-mode and odd-mode geometry, respectively. \((w/h)_se \) is the modified term for the shape ratio and is different from the one that is given in [3, eq. (4)]. The modifications are based on the corrections given in [4] and [5] and are detailed below.

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

where

\[
R = \frac{Z_{oe}}{2} \quad \text{or} \quad R = \frac{Z_{oo}}{2} \quad (5)
\]

\( Z_{oes} \) and \( Z_{oso} \) are the characteristic impedances that correspond to single microstrip shape ratios \((w/h)_se \) and \((w/h)_so \), respectively. They are given as

\[
Z_{oes} = \frac{Z_{oe}}{2} \quad (6)
\]

\[
Z_{oso} = \frac{Z_{oo}}{2} \quad (7)
\]

\[
(w/h)_se = \frac{(w/h)}{R=Z_{oes}} \quad (8)
\]

\[
(w/h)_so = \frac{(w/h)}{R=Z_{oso}} \quad (9)
\]
The corrected term \((w/h)_{so}^{'}\) in (3) is given as [5]
\[
\left(\frac{w}{h}\right)_{so}^{'} = 0.78 \left(\frac{w}{h}\right)_{so} + 0.1 \left(\frac{w}{h}\right)_{sc}.
\] (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
\[
\left(\frac{w}{h}\right) = \frac{1}{\pi} \cosh^{-1}(d) - \frac{1}{2} \left(\frac{s}{h}\right)
\] (11)
where
\[
d = \cosh \left[\frac{\pi}{2} \left(\frac{s}{h}\right)_{sc}\right] (g + 1) + g - 1
\] (12)
\[
g = \cosh \left[\frac{\pi}{2} \left(\frac{s}{h}\right)\right].
\] (13)

**Step 3—Find the Physical Length of the Directional Coupler**

The physical length of the directional coupler is obtained using
\[
l = \lambda = \frac{c}{4f\sqrt{\varepsilon_{eff}}}
\] (14)
where \(c = 3\times10^8\) m/s, and \(f\) is operational frequency in hertz. Hence, the length of the directional coupler can be found if the effective permittivity constant \(\varepsilon_{eff}\) of the coupled structure shown in Fig. 1 is known. \(\varepsilon_{eff}\) can be found using the method described in [8] as follows:
\[
\varepsilon_{eff} = \sqrt{\varepsilon_{eff} + \varepsilon_{effo}}
\] (15)

\(\varepsilon_{effo}\) and \(\varepsilon_{effo}\) are the effective permittivity constants of the coupled structure for odd and even modes, respectively. \(\varepsilon_{eff}\) and \(\varepsilon_{effo}\) depend on even- and odd-mode capacitances \(C_e\) and \(C_o\) as
\[
\varepsilon_{eff} = \frac{C_e}{C_{e1}}
\] (16a)
\[
\varepsilon_{effo} = \frac{C_o}{C_{o1}}
\] (16b)

\(C_{e1,0}\) 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
\[
C_e = C_p + C_f + C^\prime_f.
\] (17)

\(C_p\) is the parallel plate capacitance and is defined as
\[
C_p = \varepsilon_0 \varepsilon_r \frac{w}{h}
\] (18)
where \(w/h\) is found in Section II-B. \(C^\prime_f\) is the fringing capacitance due to the microstrips being taken alone as if they were a single strip, which is equal to
\[
C^\prime_f = \frac{\sqrt{\varepsilon_{eff}}}{2cZ_0} - \frac{C_p}{2}
\] (19)

Here, \(\varepsilon_{eff}\) is the effective permittivity constant of a single-strip microstrip, which can be expressed as
\[
\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} - \frac{\varepsilon_r - 1}{2} F(w/h)
\] (20)
where
\[
F(w/h) = \begin{cases} 
(1+12h/w)^{-1/2} + 0.041(1-w/h)^2, & \text{for } \left(\frac{w}{h}\right) \leq 1 \\
(1+12h/w)^{-1/2}, & \text{for } \left(\frac{w}{h}\right) \geq 1 
\end{cases}
\] (21)

**2) Odd-Mode Capacitance Calculation:** The odd-mode capacitance \(C_o\) is
\[
C_o = C_p + C_f + C_{ga} + C_{gd}.
\] (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
\[
C_{ga} = \varepsilon_0 K(k')
\] (25)

where
\[
\frac{K(k')}{K(k)} = \begin{cases} 
\frac{1}{\pi} \ln \left[\frac{2+\sqrt{2}}{1-\sqrt{2}}\right], & 0 \leq k^2 \leq 0.5 \\
\frac{1}{\pi} \ln \left[\frac{2+\sqrt{2}}{1-\sqrt{2}}\right], & 0.5 \leq k^2 \leq 1 
\end{cases}
\] (26)
\[
k = \frac{(s)}{(h)},
\] (27)
\[
k' = \sqrt{1-k^2}.
\] (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
\[
C_{gd} = \frac{\varepsilon_0 \varepsilon_r}{\pi} \ln \left\{\coth \left(\frac{\pi s}{4 h}\right)\right\} + 0.65 C_f \left[\frac{0.02}{(h)} \sqrt{\varepsilon_r} + \left(1 - \frac{1}{\varepsilon_r}\right)\right].
\] (29)

Since
\[
Z_{oe} = \frac{1}{c \sqrt{C_e C_{e1}}}
\] (30)
\[
Z_{oo} = \frac{1}{c \sqrt{C_o C_{o1}}}
\] (31)

then we can write
\[
C_{e1} = \frac{1}{c^2 C_e Z_{oe}^2}
\] (32)
\[
C_{o1} = \frac{1}{c^2 C_o Z_{oo}^2}.
\] (33)
Substituting (17), (24), (32), and (33) into (16) gives the even- and odd-mode effective permittivities \( \varepsilon_{eff} \) and \( \varepsilon_{effo} \). When (16) is substituted into (15), we can find the effective permittivity constant \( \varepsilon_{eff} \) of the coupled structure. Now, (14) can be used to calculate the physical length of the directional coupler at the operational frequency.

### III. Numerical Results

In this section, the numerical results are obtained for the following five popular microwave materials: 1) alumina; 2) Teflon; 3) RO4003; 4) FR4; and 5) RF-60. In Section III-A, analytical results are obtained using the three-step design procedure outlined in Section II. The analytical results obtained in Section III-A are validated in Section III-B using a planar EM simulation tool [7]. The experimental verification of the results is given in Section III-C. In Section III-D, we introduce design charts for the five materials so that we will have a complete two-line microstrip directional coupler design. In Section III-E, we physically interpret the results.

#### A. Analytical Results

In this section, the complete design of a two-line microstrip directional coupler is obtained using the three-step design procedure given in Section II for five different materials that are widely used in microwave applications, i.e., alumina, Teflon, RO4003, FR4, and RF-60. The list of various dielectric materials and their permittivities can be found in [9]. The results for the five materials that show the final design parameters are tabulated in Table I at the operational frequency of 300 MHz. The physical dimensions of the directional coupler are obtained for the desired level of coupling when the port impedances and the operational frequency are known. This design technique reflects what has been practiced in real-world engineering applications.

#### B. Validation of Analytical Results With EM Simulation Tools

The analytical results obtained in Section III-A are validated with the planar EM simulation software Ansoft Designer V2.1 [7]. Since Ansoft Designer is a planar 2.5-D EM simulator, the ideal geometry shown in Fig. 1 is used for the simulation. Using planar EM software, we simulated our directional coupler based on the physical dimensions obtained with the analytical method we proposed in Section II. We then compared the value of the simulated coupling level with the value of the specified coupling level for each material. Fig. 2 shows the error in percentage between the simulated coupling level and the specified coupling level versus the relative permittivity (dielectric constant) of each material. The error is calculated as a percentage and is given by

\[
\text{Error}(\%) = \frac{C_{cal}(\text{dB}) - C_{sim}(\text{dB})}{C_{cal}(\text{dB})} \times 100.
\]

where \( C_{cal}(\text{dB}) \) and \( C_{sim}(\text{dB}) \) are the calculated and the simulated coupling levels, respectively. Overall, the worst error is 3.8% and occurs when the lower permittivity material Teflon \( (\varepsilon_r = 2.08) \) is used at a \( -10 \text{-dB} \) coupling. The smallest error is with the high-permittivity material alumina \( (\varepsilon_r = 9.8) \) at \( -20 \text{-dB} \) coupling and is equal to 0.2%. The existing methods [4], [5] give a more than 10% error with the simulation results for Teflon at a \( -10 \text{-dB} \) coupling level.

#### C. Experimental Results

Experimental results are obtained using the analytical results tabulated in Table I for Teflon \( (\varepsilon_r = 2.08) \) and FR4 \( (\varepsilon_r = 4.4) \) at \( -15 \text{-dB} \) coupling levels. The operational frequency is given as 300 MHz. The thickness of Teflon and FR4 are 90 and 120 mils, respectively. The structure is first simulated to confirm the design parameters. The coupling levels using simulation are found to be \(-14.656 \text{ dB} \) and \(-14.671 \text{ dB} \) for Teflon and FR4, respectively. This represents a 2.29% error for Teflon and a 2.19% error for FR4 in comparison with the analytical results. Fig. 3 shows the layout of the two directional couplers that are constructed. Figs. 4 and 5 give the measured result of the forward coupling in decibels for Teflon and FR4 over the frequency range from 1 to 400 MHz. The HP8751A Network Analyzer is used to measure the response of the couplers. The markers in Figs. 4 and 5 show the measured forward coupling level at 300 MHz for Teflon and FR4 as \(-14.562 \text{ dB} \) and \(-14.679 \text{ dB} \), respectively. Based on the measured results, the worst error between the measured results and the analytical results is found to be within 3% for Teflon. This verifies the analytical results and confirms the results of the planar EM software.
D. 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; and 5) RF-60. Fig. 6 gives the spacing ratio \( s/h \) of the directional coupler versus different coupling levels. Fig. 7 gives the shape ratio \( w/h \) versus different coupling levels. Figs. 8–10 give the physical length \( l \) of the directional coupler versus frequency at different coupling levels.

E. Observations

In this section, we physically interpret the numerical results obtained in Section III. The spacing ratio increases as the relative permittivity of the dielectric material increases, as seen in Fig. 6. In Fig. 7, it is seen that this is the opposite of the shape ratio. The loose coupling is a result of a larger spacing ratio, as shown in Fig. 6. The physical length of the directional coupler decreases with the increase of the relative permittivity of the material and the operational frequency. When the forward port is loosely coupled, the physical length of the directional coupler increases. It is also to be noted that the error is reduced as the forward coupling gets looser and the relative permittivity of the material increases. This is shown in Fig. 2. The possible effect of the low relative permittivity on the accuracy of the spacing ratio is mentioned in [3]. However, we note that with the implementation of the corrections that we introduced, an accuracy of around 2% can be obtained for the materials with low relative permittivities when the coupling is loose. The directivity of the directional couplers gets worse as the coupling level gets looser. This is due to the level of isolation between the reverse port and the input port of the directional coupler for different coupling levels. The input impedance of the directional coupler remains within a 1.06 voltage standing-wave ratio circle for all cases.
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. We validated our analytical results with a planar EM simulation tool for five different materials that are widely used in microwave applications. We then experimentally verified the analytical results for Teflon and FR4. 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. The complete design of a symmetrical two-line microstrip directional coupler can be obtained for the first time with minimum error using our results in this paper.

REFERENCES


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套装包含 4 门视频培训课程，培训将 13.56MHz 线圈天线设计原理和仿真设计实践相结合，全面系统地讲解了 13.56MHz 线圈天线的工作原理、设计方法、设计考量以及使用 HFSS 和 CST 仿真分析线圈天线的具体操作，同时还介绍了 13.56MHz 线圈天线匹配电路的设计和调试。通过该套课程的学习，可以帮助您快速学习掌握 13.56MHz 线圈天线及其匹配电路的原理、设计和调试…


我们的课程优势：

※ 成立于 2004 年，10 多年丰富的行业经验，
※ 一直致力并专注于微波射频和天线设计工程师的培养，更了解该行业对人才的要求
※ 经验丰富的一线资深工程师讲授，结合实际工程案例，直观、实用、易学

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