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Design of Multilayer and Multiline Microstrip Directional Coupler with Closed Form Relations

Abdullah Eroglu[1, *] and Daniel Rönnow[2]

Abstract—Design, simulation, implementation and measurement results of multiline and multilayer microstrip directional couplers are given with closed form relations. Step-by-step design procedure reflecting the design practice of directional couplers, which requires only information on coupling level, port impedances and operational frequency, is presented. The method based on the synthesis technique applied in the design of conventional two-line microstrip symmetrical directional couplers is adapted to design multilayer directional couplers with the aid of electromagnetic simulators using parametric analysis with curve fitting method. The proposed design method is compared with the measurement results and accuracy is verified. It has been also shown that the directivity of the couplers designed using the multilayer structure is improved significantly. A method such as the one presented in this paper can be used to design multilayer two-line and three-line directional couplers which can be integrated to the front end of an RFID systems to provide the required isolation between transmitter and receiver and prevent signal leakage due to use of conventional circulators.

1. INTRODUCTION

Microstrip directional couplers have been widely used in variety of RF/Microwave applications. The ease of manufacturing and implementation of microstrip type directional couplers make them a good component to detect and transmit desired signals without impacting the performance of the system. The cost effectiveness of the microstrip type directional couplers also make them a viable option for volume manufacturing in the RF industry. The design of conventional microstrip type directional couplers has been well investigated and reported by several researchers [1–5]. The common design method relies on prior knowledge of the physical geometry of the coupler, which requires the use of design charts for the even and odd mode impedances of the structure. The design method that only uses the knowledge of port impedances, coupling level and operation frequency with closed formulation is given in [6, 7]. The three step design procedure and formulation outlined in [6, 7] is also what would be used by designers in practice.

One of the challenges in microstrip type directional couplers is their poor directivity, which usually becomes a problem during sampling of the signals when they are used as power monitoring devices. The poor directivity in essence is due to a discrepancy in phase velocities between the odd and even mode impedances. There have been several compensation methods introduced to improve the directivity of the couplers and enhance the accuracy of the signal sampling. One of the commonly used methods includes using a dielectric overlay on top of the coupled lines [8–11] or implementing wiggling coupled edges of the coupled lines [12–14]. Alternatively, one of the other widely proposed compensation methods includes connecting lumped components at the ends or center of the coupled lines [15, 16]. The discussion of impedance mismatch via additional coupled line and epsilon negative transmission line are presented

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* Corresponding author: Abdullah Eroglu (eroglua@ipfw.edu).
[1] Department of Electrical and Computer Engineering, Purdue University Fort Wayne, 2101 E. Coliseum. Blvd, Fort Wayne, IN, USA. [2] Department of Electronics, Mathematics and Natural Sciences, University of Gavle, Sweden.

in [17, 18]. It has been shown that high directivity for directional couplers can also be obtained using multilayer configuration [19–21]. The design of the two-line multilayer coupler in [20] is similar to the ones presented in [22, 23] which were conducted with static electric field analysis and full wave analysis based on Green's functions, respectively. Although there is an extensive literature on the design of multilayer directional couplers [24–26], the design procedure relies on either design charts with the prior knowledge of geometry or numerical analysis. These methods are not practical and hence, there are no closed form relations available yet to design multilayer couplers that would reflect the practice which requires only the knowledge of port impedances, coupling level and operational frequency as outlined in [6, 7]. It is to be noted that the improved directivity, and hence isolation, in microstrip couplers will extend their application and make them a viable alternative to replace the circulators that are widely used in RFID systems and reduce the inherent leakage problem [27, 28].

Conventional microstrip couplers are practical sampling devices and can be used to detect either forward or reverse power in practice because one of the coupled ports is usually terminated with lumped element for compensation to improve the directivity. This problem can be overcome by using three-line microstrip couplers and having one of the ports of the coupled lines as forward signal detection while terminating the other port of the same-coupled line with a lumped element for compensation of the mismatch for directivity improvement. Then, other coupled line can be used for reverse signal detection and same technique can be applied to improve the directivity. The use of three-line microstrip couplers as reflectometers are discussed in [29, 30]. However, the design of three-line microstrip directional couplers in the literature again is based on the use of odd and even mode impedance design charts or numerical analysis techniques as outlined in [31–33].

In this paper, the design, simulation, implementation methods and measurement results for multiline and multilayer microstrip directional couplers with closed form relations are presented. The design procedure for the two-line multilayer coupler shown in Fig. 1 is based on the design method for a two-line conventional microstrip coupler outlined in [6, 7] and requires information for coupling level, port impedances, and operational frequency. The design procedure then requires parametric analysis with the curve fitting method to obtain the closed form relations. The closed form relations are obtained for widely used microwave materials such as TMM10, FR4, RF60, RO4003, and Teflon. The design of a three-line microstrip coupler is accomplished using the design of conventional microstrip two-line coupler by placing the second coupled line on the other side of the main line symmetrically. The analytical method using the techniques presented in [32–34] has been developed to confirm the results obtained in simulation and measurement results for three-line microstrip couplers. The design of multilayer three-line microstrip couplers have then been developed using the technique applied to two-line multilayer microstrip couplers. The analytical results for both two-line and three-line multilayer microstrip directional couplers have been verified by simulation. Several prototypes have been built and measurements results have been obtained. The agreement between analytical, simulation and experimental results were confirmed. It has been shown that the design techniques presented in this paper can be used to implement high performance multiline and multilayer microstrip directional couplers for several RF and microwave applications including RFID systems and energy harvesting applications.

2. FORMULATION

In this section, the formulation and design steps for a conventional two-line microstrip coupler and for three-line couplers, and then multilayer two-line and three-line couplers have been discussed and detailed.

2.1. Two-Line Microstrip Coupler

The design method for a conventional symmetrical two-line microstrip coupler that reflects the practice was presented in [6]. The corrections in [6] for (3) and (22) due to typographical errors are then reported in [7]. The design process in [6] requires only information about coupling level, port impedances and operational frequency. It eliminates the use of design charts for odd and even mode impedances and provides a practical way to design microstrip type couplers. The design procedure for the two-line

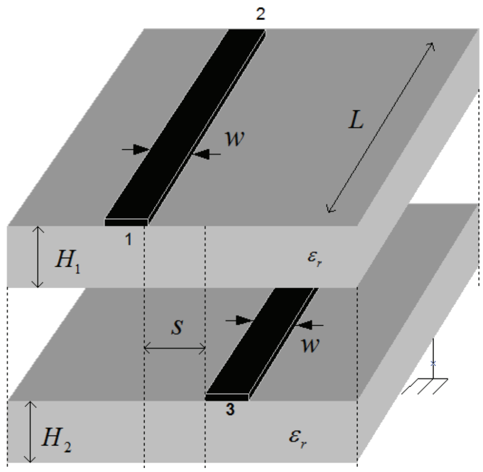


Figure 1. Two-line multilayer microstrip directional coupler with L-length of the coupler, H_2-distance of the coupled line from ground plane, $H = H_1 + H_2$-thickness of the dielectric substrate.

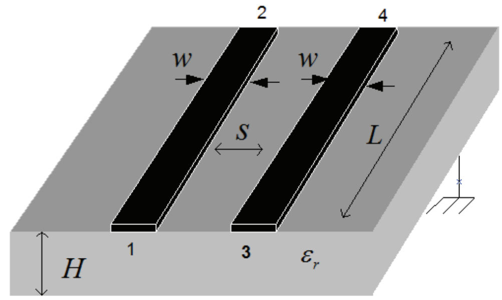


Figure 2. Two-line symmetrical microstrip coupler.

microstrip coupler shown in Fig. 2 is based on three steps as outlined in [6, 7]. The first step involves finding the even and odd mode impedances from

$$Z_{oe} = Z_0\sqrt{\frac{1+10^{C/20}}{1-10^{C/20}}} \tag{1}$$

$$Z_{oo} = Z_0\sqrt{\frac{1-10^{C/20}}{1+10^{C/20}}} \tag{2}$$

the desired coupling value. In Eqs. (1) and (2), C is the desired coupling value in dB. Then, spacing and shape ratios are found from

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

and

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

where

$$R = \frac{Z_{oe}}{2} \quad \text{or} \quad R = \frac{Z_{oo}}{2} \tag{5}$$

$(w/h)_{se}$ and $(w/h)_{so}$ are the shape ratios for the equivalent single case corresponding to even-mode and odd-mode geometry, respectively. $(w/h)'_{so}$ is the modified term for the shape ratio. The length of the coupler is the found from

$$l = \frac{\lambda}{4} = \frac{c}{4f\sqrt{\varepsilon_{eff}}} \tag{6}$$

where ε_{eff} is the effective permittivity constant of the coupled structure and defined as

$$\varepsilon_{eff} = \left[\frac{\sqrt{\varepsilon_{effe}}+\sqrt{\varepsilon_{effo}}}{2}\right]^2 \tag{7}$$

ε_{effe} and ε_{effo} are odd and even mode effective permittivity constants. All terms and their related equations are defined in [7].

2.2. Three-Line Microstrip Coupler

Symmetrical three-line microstrip couplers, which are also known as six port couplers, are shown in Fig. 3 and can be used for several applications including detection of forward and reverse power simultaneously and accurately using phase velocity equalization technique with lumped elements terminated at the ports of the coupling lines.

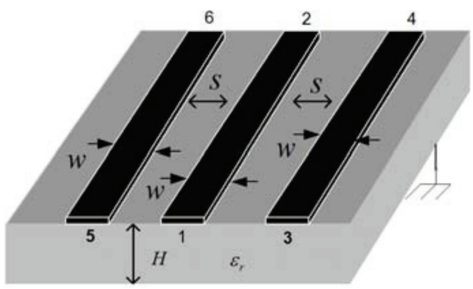


Figure 3. Three-line symmetrical microstrip coupler.

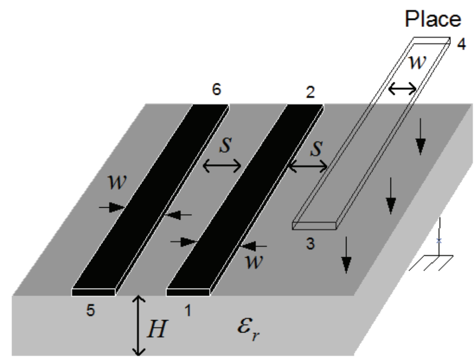


Figure 4. Generation of three-line coupler from design parameters of two-line coupler.

2.2.1. Step 1: Generate the Design Specifications for a Two-line Coupler Using Equations in Section 2.1

In this step, the required design parameters: coupling level, operational frequency and port impedance, are used to create the design for the two-line symmetrical coupler shown in Fig. 2. Spacing ratio, shape ratio and length of the two-line coupler are then found using Equations (3), (4) and (6).

2.2.2. Step 2: Implementation of Three-Line Couplers

A symmetrical three-line coupler, having the same coupling characteristics of two-line couplers, is then obtained by placing the second coupling line on the other side of the main line by keeping the same spacing with the main line as shown in Fig. 4.

2.2.3. Step 3: Verification of Coupling Levels via Semi-empirical Formulation

The coupling levels of a three-line microstrip coupler are given by the following equations [34]:

$$K_{13} = K_{15} = \frac{Z_{ee} - Z_{oo}}{Z_{ee} + Z_{oo}} \tag{8}$$

$$K_{53} = \frac{\sqrt{Z_{ee} Z_{oo}} - Z_{oe}}{\sqrt{Z_{ee} Z_{oo}} + Z_{oe}} \tag{9}$$

where $K_{13} = K_{15}$ (not in dB) represents the coupling from the side lines into the main line. K_{53} is the coupling level between the two-coupled lines.

$K_{13} = K_{15}$ is equal to C, which is the coupling between main line and coupling line for two-line microstrip couplers [6, 7]. Semi-empirical formulation derived in this paper for K_{53} represents the coupling level between the two coupled lines through center line and is found using the analysis given in [6, 7]. The formulation is obtained by finding the coupling between the two-coupled lines without the presence of the main line as shown in Fig. 5 with an introduced error by its removal. The error is

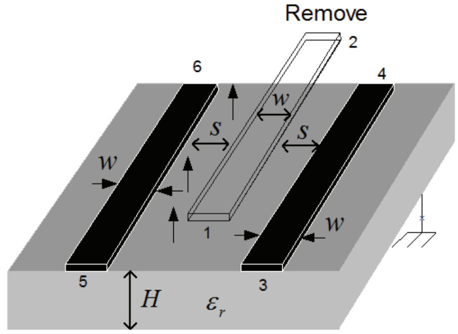


Figure 5. Removal of the main line in three-line coupler for formulation for K_{13}.

found through simulations and integrated to the formulation obtained. After the formulation for K_{53} is obtained, the relations given in [34] can be used to find three-line mode impedances as

$$Z_{oo} = Z_o \left(\frac{1+K_{53}}{1-K_{53}}\right)\sqrt{\frac{1-K_{13}}{1+K_{13}}} \tag{10}$$

$$Z_{ee} = Z_o \left(\frac{1+K_{53}}{1-K_{53}}\right)\sqrt{\frac{1+K_{13}}{1-K_{13}}} \tag{11}$$

with $Z_{oe} = Z_0$ as shown in [32]. The calculated values using the formulation introduced in this paper are substituted back into Eqs. (8) and (9) to confirm the coupling values between the coupled lines and main line.

K_{53} given in Eq. (9) depends on the threeline coupler mode impedances Z_{ee}, Z_{oo}, and Z_{oe}. Since the coupling level, port impedance and operational frequency are known, then using the formulation in [6, 7], spacing ratio, s/h, and shape ratio, w/h, are obtained. This leads to

$$d_{new} = \cosh\left(pi\left[(w/h) + \frac{1}{2}(s/h)_{new}\right]\right) \tag{12}$$

where

$$\left(\frac{s}{h}\right)_{new} = 2\left(\frac{s}{h}\right) + \left(\frac{w}{h}\right) \tag{13}$$

In Eq. (13), s/h and w/h are the values that are obtained using the formulation in [6, 7]. $(w/h)_{se}$ is the shape ratio for the even modes for the new coupled system and found from

$$\left(\frac{w}{h}\right)_{se} = \frac{2}{\pi}\cosh^{-1}\left[\frac{(2d_{new} - g + 1)}{g+1}\right] \tag{14}$$

where

$$g = \cosh\left[\frac{\pi}{2}\left(\frac{s}{h}\right)\right] \tag{15}$$

The characteristic impedances corresponding to single microstrip shape ratios $(w/h)_{se}$ can be obtained from

$$Z_{ose} = 42.4\log\left[1 + \frac{1}{2}\left(\frac{64a}{(w/h)_{se}^2} + \Delta\right)\right]\frac{1}{\sqrt{\varepsilon_r + 1}} \tag{16}$$

Then, the characteristic impedance for *oe* propagating mode for the coupled lines is equal to

$$Z_{oe} = 2Z_{ose} \tag{17}$$

In (16),

$$\Delta = \sqrt{\left(\frac{64a}{(w/h)_{se}^2} + \Delta\right)^2 + \left(\frac{256b}{(w/h)_{se}^2}\right)} \tag{18}$$

where

$$a = \left(\frac{7}{11}\right) + \left(\frac{4}{11\varepsilon_r}\right) \tag{19a}$$

and $$b = \left(\frac{1}{0.81}\right) + \left(\frac{1}{0.81\varepsilon_r}\right) \tag{19b}$$

The characteristic impedance of two-line couplers for *oo* mode is then obtained from

$$Z_{oo} = \frac{1}{(2lfC_o)} - \frac{C_e Z_{oe}}{C_o} \tag{20}$$

where C_e and C_o are the capacitances for the even and odd modes, respectively. They are expressed as

$$C_e = C_p + C_f + C'_f \tag{21}$$

$$C_o = C_p + C_f + C_{ga} + C_{gd} \tag{22}$$

The relations for the capacitances in Eqs. (21)–(22) are given in [6, 7]. Then, K_{53} for three-line microstrip coupler can then be found from Eqs. (17), (20) with an error function as

$$K_{53}(\text{dB}) = 20\log\left(\frac{Z_{oe} - Z_{oo}}{Z_{oe} + Z_{oo}}\right) - erf(\varepsilon_r) \tag{23}$$

where $erf(\varepsilon_r) = a\varepsilon_r^2 + b\varepsilon_r + c$ is defined as the error function and obtained from simulations. The error function is approximated to be a polynomial function of dielectric constant at order 2 and is given in Table 1 below at each coupling level.

Table 1. $erf(\varepsilon_r) = a\varepsilon_r^2 + b\varepsilon_r + c$ for different coupling levels.

Coupling Level (dB)	$\boldsymbol{a}$	$\boldsymbol{b}$	$\boldsymbol{c}$
−10	0.0121	−0.6817	12.766
−13	−0.0202	−0.2442	10.265
−15	−0.0941	0.1357	9.725
−18	0.0438	−0.2626	8.9564
−20	0.0543	−0.2873	9.2126

2.2.4. Step 4: Calculation of The Mode Impedances for Three-Line Couplers

Equations (10) and (11) can now be used to calculate the mode impedances of three-line couplers to confirm the results.

2.3. Multilayer Microstrip Couplers

There are several benefits in the use of multilayer directional couplers in RF applications including improvement in directivity, better isolation, and providing better performance against arcing for high power applications as outlined before. The design process that will be given in this section can be used to implement both two-line and three-line multilayer couplers in conjunction with the method given in Section 2.2. The illustration of the two-line and three-line multilayer couplers are given in Fig. 6 and Fig. 7. In Fig. 6 and Fig. 7, the dielectric thickness is H and equal to $H_1 + H_2$.

The step-by-step design procedure to realize two-line and three-line multilayer planar directional couplers are given as follows.

Step 1: Generate Base Design

Generate the design parameters for a two-line coupler using Equations (1)–(7) for the base design and obtain spacing and shape ratios. The thickness and coupling levels can be chosen based on the application.

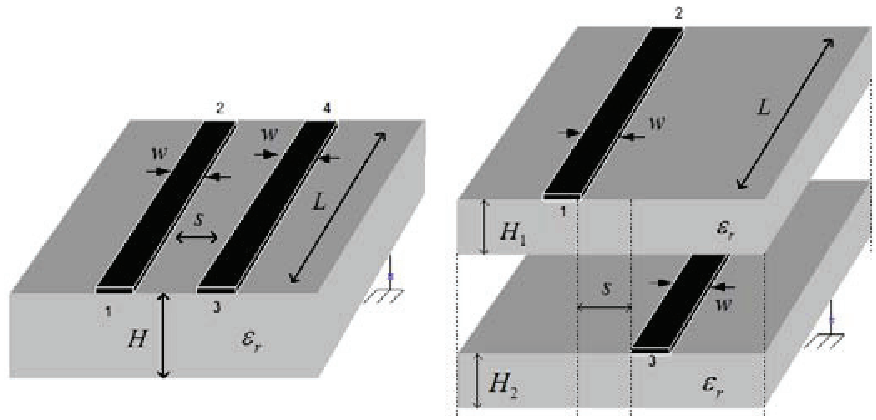


Figure 6. Illustration two-line multilayer directional coupler.

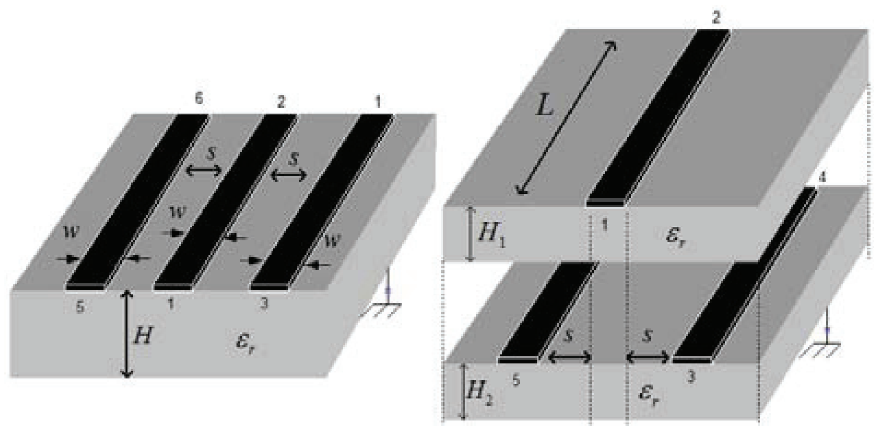


Figure 7. Illustration of three-line multilayer directional coupler.

Step 2: Simulation for Parametric Analysis

Use simulation to conduct parametric analysis by moving the coupled line at a predetermined distance inside dielectric towards ground plane. Obtain the new coupling for the pre-determined distance and repeat this until the full thickness of the dielectric is reached.

Step 3: Curve Fitting for Equation

Use curve fitting method to obtain equation for the material used for the desired the coupling level to calculate the physical dimensions including the height of the coupled line from the ground plane.

This procedure is applied to commonly used RF materials such as TMM10, FR4, RF60, RO4003 and Teflon where the relative dielectric constant ranges from 2.08 to 9.8 to have the design equations for the two-line multilayer configuration shown in Fig. 6. The three-line multilayer structure shown in Fig. 7 is then formed by application of the procedure described in Section 2.2.

The results for each material are obtained such as the one illustrated in Fig. 8 for Teflon. The summary of the equations, which were obtained using curve-fitting technique for each material, is tabulated in Table 2.

The formulation and analytical results obtained are used to develop Matlab GUI to design multilayer microstrip couplers and to obtain their physical dimensions. The designer is required to only enter the desired coupling level, port impedance, dielectric contact of the material used, and its thickness in the GUI program. The program then calculates all the physical dimensions, including the spacing between coupled and main lines, width, and height of the coupled line from the ground plane. The GUI program results can also be used to design three-line multilayer couplers using the same physical dimensions with an addition of the second coupling line as described in Section 2.2.

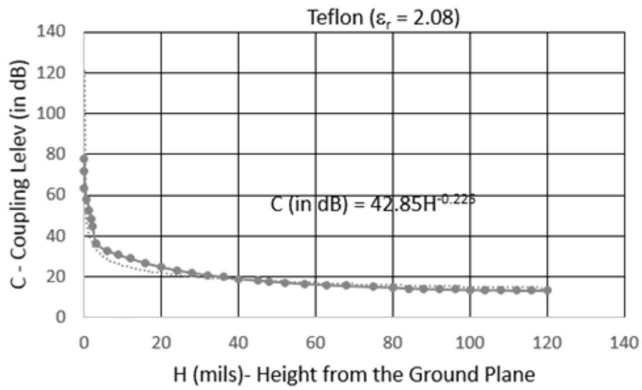


Figure 8. Multilayer coupler parametric analysis results with curve fitting equation for Teflon.

Table 2. Multilayer coupler design equations.

Material	**Dielectric Constant (ε_r)**	**Equation**
Teflon	2.08	$C(\text{dB}) = 42.85H^{-0.225}$
RO 4003	3.38	$C(\text{dB}) = 43.897H^{-0.246}$
FR4	4.4	$C(\text{dB}) = 42.387H^{-0.245}$
RF60	6.15	$C(\text{dB}) = 45.873H^{-0.276}$
TMM10	9.8	$C(\text{dB}) = 44.139H^{-0.282}$

3. SIMULATION AND MEASUREMENT RESULTS

In this section, simulation and measurement results for several cases of two-line, three-line and multilayer couplers are presented. The base design has been considered as -15 dB coupler at 300 MHz using different substrates.

3.1. Simulation and Measurement Results for Three-Line Microstrip Couplers

The design of three-line couplers has been implemented by following the steps outlined in Section 2.2. The design process begins with the creation of two-line couplers at 300 MHz for -15 dB coupling level. The substrate material is chosen to be TMM10, which has relative dielectric constant of 9.8. Matlab GUI shown in Fig. 9 is used to generate the physical dimensions to simulate a two-line coupler. Several other parameters, including spacing and shape ratios versus relative dielectric constant, odd and even mode capacitance variation, length, etc., are calculated and illustrated in this GUI.

Once all the physical dimensions are obtained, simulation can be performed. The simulation is done by choosing the thickness of the material to be 100 mils due to availability of material thickness in practice. This gives the calculated spacing to be 63 mils and width to be 95.9 mils. The tolerance of the milling machine allows having 65 mils and 100 mils spacing and width instead of the calculated values. This small deviation is expected to produce minimal error. The layout of the simulated of two-line microstrip coupler with Ansys Designer is illustrated in Fig. 10.

The simulation results for the two-line coupler illustrated in Fig. 10 are shown in Fig. 11. The results show that the coupling level is -17.266 dB and the isolation level is -27.458 dB.

Now, the design steps described in Section 2.2 are followed, and a three-line coupler is formed using the formulation with Matlab GUI with results shown in Table 3 including mode impedances illustrated.

As expected, the spacing and shape ratios remain the same to produce the same level of coupling level. The layout of the simulated of three-line microstrip coupler with Ansys Designer is illustrated in Fig. 12.

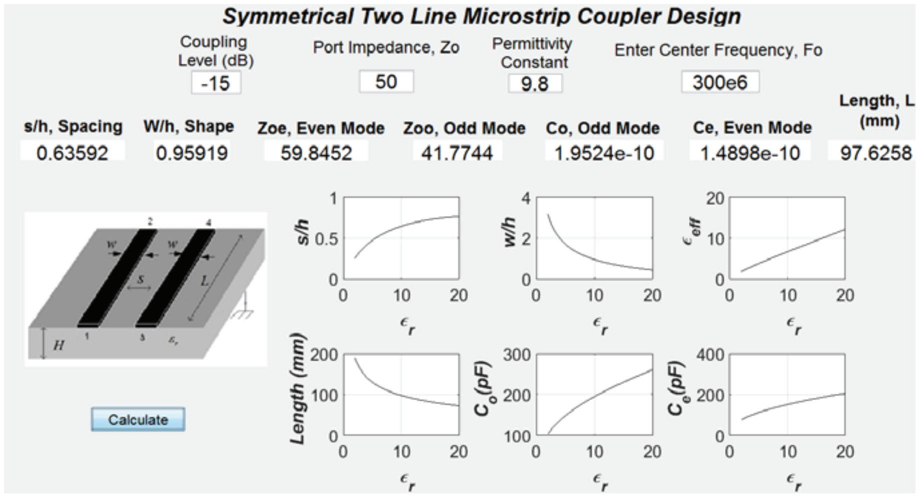


Figure 9. Two-line microstrip coupler design for 15 dB coupling using Alumina as a substrate.

Table 3. Three-line microstrip coupler design parameters for TMM10.

Coupling Level (dB)	F **(MHz)**	**Material**	ε_r	s/h	w/h
-15	300	TMM10	9.8	0.63592	0.95919
K_{12} **(dB)**	K_{13} **(dB)**	Z_{oe} **(Ω)**	Z_{oo} **(Ω)**	Z_{ee} **(Ω)**	L **(mils)**
-15	-33.3976	50	43.6002	62.4608	3843.5433

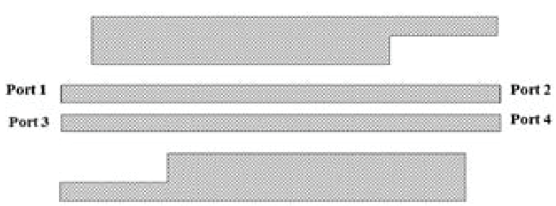


Figure 10. Two-line microstrip coupler with 2D view.

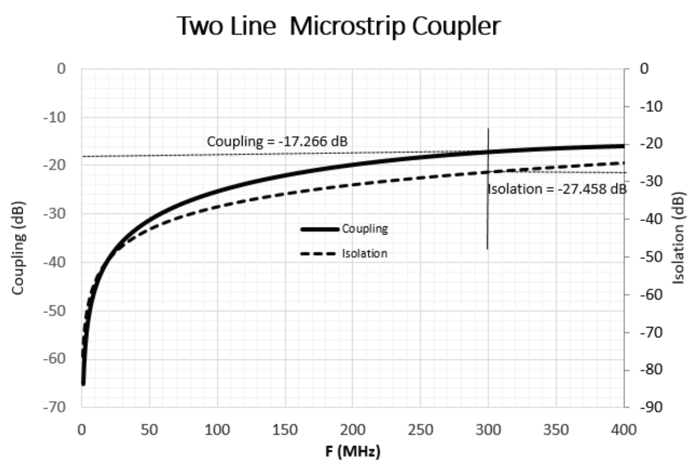


Figure 11. Simulation results of two-line microstrip coupler at 300 MHz for Coupling Level = S_{13} = -17.266 dB and Isolation Level = $S_{14} = -27.458$ dB.

The simulation results showing coupling and isolation levels at 300 MHz are given in Fig. 13. The simulation results give almost identical coupling and isolation levels as -17.31 dB and -27.52 dB, respectively.

Since the analytical results and simulation results are in agreement, one can proceed to build prototype three-line directional couplers using the physical dimensions in the simulation based on the calculated values where width of the main and coupling traces are 100 mils, the thickness of the material

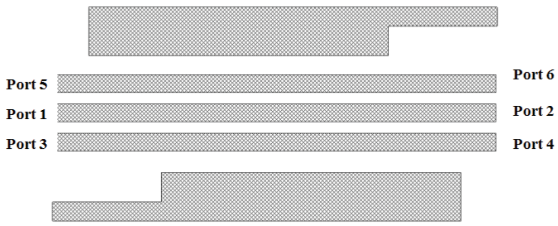


Figure 12. 3 line microstrip coupler with 2D view.

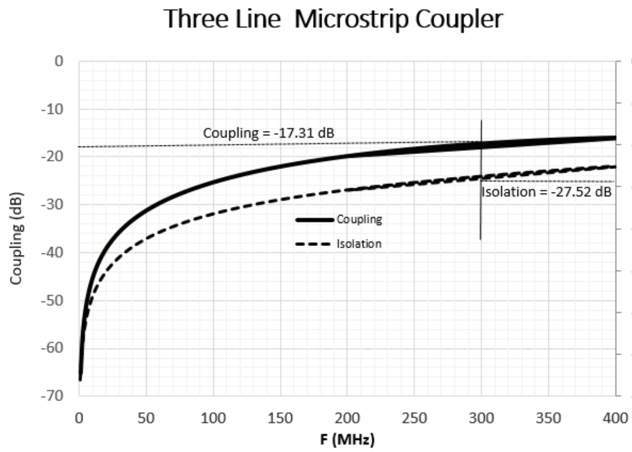


Figure 13. Simulation results of three-line microstrip coupler at 300 MHz for Coupling Level = −17.31 dB and Isolation Level = −27.52 dB.

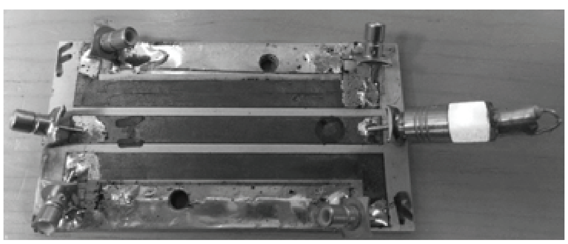


Figure 14. The prototype of three-line directional coupler using TMM10 material.

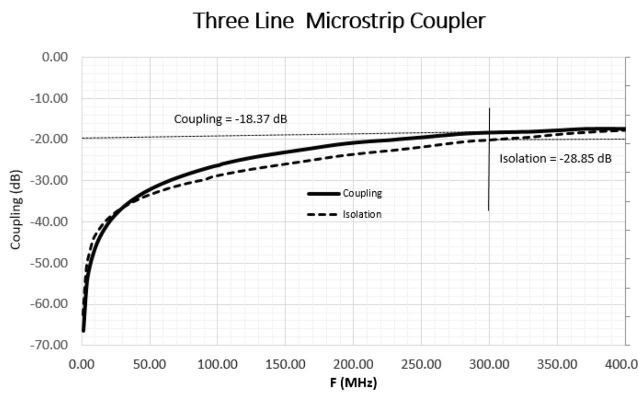


Figure 15. Measurement results for three-line coupler at 300 MHz for Coupling Level = −18.37 dB and Isolation Level = −28.85 dB.

is 100 mils and the spacing of the coupled line from the main line is 65 mils. The substrate used in the prototype is Rogers TMM10 material as illustrated in Fig. 14. The measurement results for coupling and isolation are shown in Fig. 15. Measurement has been done using E5063A Keysight Network Analyzer. The coupling and isolation levels are measured at 300MHz and shown in Fig. 15.

The measured values of coupling and isolation levels are found to be −18.37 dB and −28.85 dB, respectively. These are close to the analytical and simulated values.

3.2. Simulation and Measurement Results for Multilayer Microstrip Couplers

In this section, two-line and three-line multilayer directional coupler designs will be presented. The base design is considered to produce −15 dB coupling using FR4 material as a substrate. Two-line and three-line multilayer coupler configurations were designed and simulated. Several prototypes have been built and measured.

The first step is to design the two-line microstrip coupler for −15 dB coupling level. The substrate thickness is taken to be 120 mils. The calculated values with Matlab GUI are given in Table 4. The design parameters shown in Table 4 are then used to simulate the structure with a planar electromagnetic simulator. The simulation results for coupling and isolation levels are illustrated in Fig. 16.

The coupling and isolation levels are found to be −15.54 dB and −22.50 dB, respectively. The multilayer two-line directional coupler is then designed using the step-by-step procedure outlined in Section 2.3. Matlab GUI program to obtain −15 dB coupling using FR4 material as main substrate is used to calculate the physical dimensions as shown in Table 5. The physical dimensions are then used to simulate the two-line multilayer microstrip structure. The simulated coupling and isolation levels are observed to be −15.58 dB and −28.6 dB as shown in Fig. 17, respectively.

Table 4. Calculated physical dimensions for two-line microstrip coupler design.

Coupling Level (dB)	***F*** **(MHz)**	**Material**	**Dielectric Constant (ε_r)**	***s/h***	***w/h***	***L*** **(mils)**
−15	300	FR4	4.4	0.43435	1.8621	5255.24

Table 5. Calculated physical dimensions for multilayer two-line coupler design.

Coupling Level (dB)	***F*** **(MHz)**	**Material**	ε_r	**Port Imp (Ω)**
−15	300	FR4	4.4	50
s **(mils)**	***w*** **(mils)**	***L*** **(mils)**	H_2 **(mils)**	***H*** **(mils)**
13.1331	193.4027	5071.3009	55.8175	120

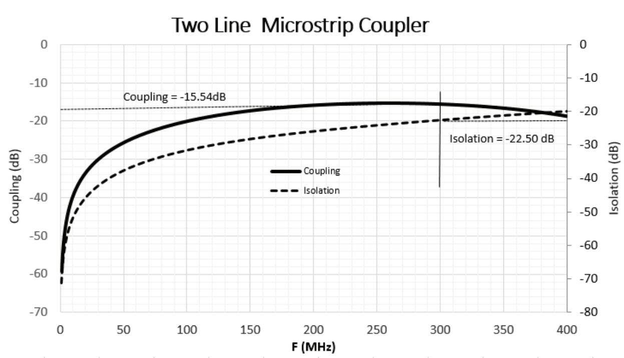


Figure 16. Simulation results of two-line microstrip coupler at 300 MHz for Coupling Level = −15.54 dB and Isolation Level = −22.50 dB.

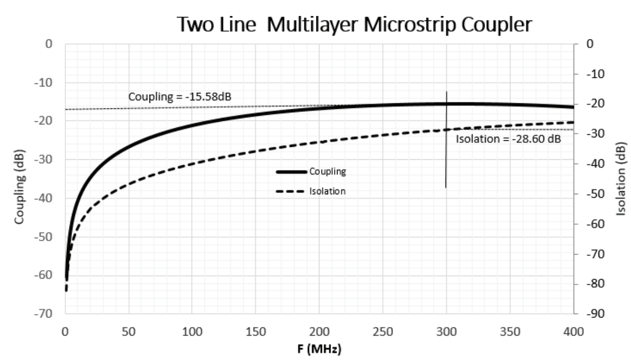


Figure 17. Simulation results of two-line multilayer microstrip coupler at 300 MHz for Coupling Level = −15.58 dB and Isolation Level = −28.60 dB.

The design method in Section 2.3 is now applied to obtain the three-line multilayer coupler as illustrated in Fig. 7. The coupler is simulated using the physical dimensions obtained. The coupling and isolation levels are obtained to be −15.79 dB and −28.76 dB as shown in Fig. 18, respectively. All directional coupler configurations were built and measured. The prototypes that were built are shown in Fig. 19.

The prototypes have been measured and results are tabulated in Table 6. It has been shown that the analytical, simulation, and measurement results are all in agreement.

Furthermore, the implementation of multilayer coupler design demonstrated between 4 dB to 6 dB improvement in directivity based on simulation and measurement results.

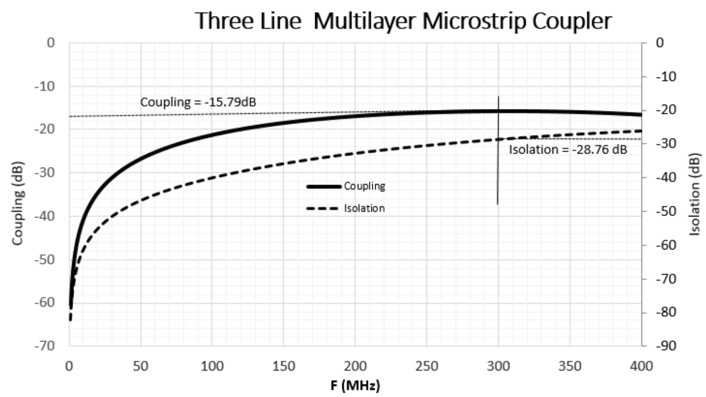
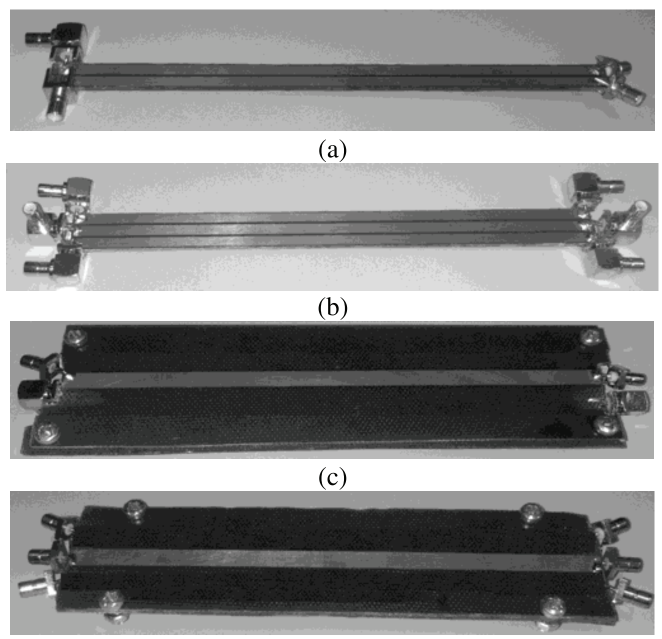


Figure 18. Simulation results of two-line multilayer microstrip coupler at 300 MHz for Coupling Level = −15.79 dB and Isolation Level = −28.76 dB.



(a) (b) (c) (d)

Figure 19. The prototype of microstrip couplers using FR 4 material for −15 dB coupling. (a) Two-line coupler design. (b) Three-line coupler design. (c) Two-line multilayer coupler design. (d) Three-line multilayer coupler design.

Table 6. Measurement Results for two-line and three-line multilayer couplers.

Coupler Type	**Frequency (MHz)**	**Coupling (dB)**	**Isolation (dB)**
Two Line	300	−13.91	−22.45
Two Line Multilayer	300	−13.72	−26.29
Three Line	300	−13.85	−21.94
Three Line Multilayer	300	−13.97	−25.85

4. CONCLUSION

In this paper, design, simulation, implementation methods and measurement results for two-line and three-line multiline and multilayer microstrip directional couplers with closed form relations are presented. The detailed step-by-step design process is given, and several different configurations of two- and three-line couplers are created using conventional and multilayer structures. The formulations obtained are used to develop Matlab GUI programs. The Matlab GUI programs used to calculate the physical dimensions of the structures for different coupler configurations. The physical dimensions are then used to simulate the configurations. The presented method is the only available method that would reflect the practice which requires only the knowledge of port impedances, coupling level and operational frequency as outlined in [6, 7] to design multilayer and three-line directional couplers. Several prototypes have been built and tested after verification of the results between analytical and simulation values. Based on the analytical, simulation and measurement results, the design method proved to be an accurate method within acceptable error to implement any type of two- and three-line multilayer structures. It has also been shown that the implementation of multilayer structure improves the directivity level around 4 dB to 6 dB based on the simulation and measurement results. This is due to improved equalization of the odd and even mode velocity due to implementation of multilayer configuration. The proposed method can also be extended to include inhomogeneous structures where each layer can be a different material. This can be done following the parametric analysis with curve fitting method outlined in Section 2.2 and 2.3. The practical method and results presented in this paper can be used for several RF and microwave applications including RFID systems and energy harvesting applications.

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