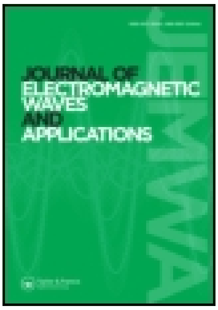

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Closed-form expressions for the propagation characteristics of coupled microstrip lines with a symmetrical aperture in the ground plane are derived. Expressions for the regular microstrip coupled lines have been modified using physical insights to incorporate the effect of the aperture. The accuracy of these expressions has been verified by full-wave simulations and compared with conformal mapping analysis. These expressions are accurate within 5% for a substrate whose thickness varies from 0.2 to 1.6 mm and permittivity in the range of 2–10. Designing a broadband filter based on planar multi-conductor coupled lines with aperture in the ground plane is demonstrated in this paper using the proposed expressions for its practical use.

1. Introduction

Planar coupled lines such as microstrip lines, striplines, and coplanar waveguides are used in filters, couplers, and their matching circuits.[1,2] Propagation characteristics of such coupled lines depend on their physical properties, and are mainly described by the even- and odd-mode characteristic impedances and the effective permittivities. Several methods are used for evaluating these parameters of coupled microstrip lines. Approaches based on various numerical methods may yield accurate results but these do not provide physical insight. Several analytical expressions for the design and analysis of coupled microstrip lines are also reported.[1–5] Synthesis formulas for microstrip transmission line with aperture in the ground plane are reported in [6] and a broadband filter has been designed using these formulas. Formulae for the characteristic impedance of microstrip line with aperture in the ground plane are presented using data extracted from full-wave simulations in [7]. In [8], characteristic impedance of defected ground microstrip line is obtained using the full-wave simulation data.

A modification to the coupled microstrip lines shown in Figure 1, which has a longitudinal aperture (slot) in the ground conductor, is found to be very useful in the design of broadband filters and couplers.[9–12] In [13], multiple coupled microstrip lines with short-circuited resonators on slotted ground plane are used to construct a broadband filter. Ground plane aperture is used in the design of parallel coupled-line bandpass filters for enhancing the coupling in [14]. Parallel coupled lines with aperture in the ground plane are used in [11] to design a tight coupler. It can be qualitatively stated that this slot reduces the capacitance per unit length and hence increases the even-mode impedance of the coupled microstrip line.

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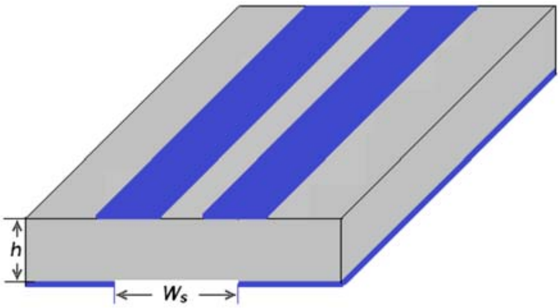

Figure 1. Microstrip coupled lines with a longitudinal aperture (slot) in the ground plane.

Conformal mapping analysis is used to design and analyze such a structure in [5]. Analytical formulae, ideally with closed-form expressions, would be helpful in understanding the behavior of components using such sections of coupled lines.

This paper presents closed-form expressions for the propagation parameters of a multi-conductor coupled microstrip structure with aperture in the ground plane (shown in Figure 1), using the expressions developed for regular coupled microstrip lines.[1] Section 2 analyzes two-line coupled microstrip structure with aperture in the ground plane. Results obtained through the derived expressions are compared against those from full-wave simulations and conformal mapping analysis in Section 3. Section 4 presents the analysis procedure for three-line coupled microstrips. Application of these expressions is discussed in Section 5 by way of designing a broadband filter. Section 6 concludes this present paper

2. Formulations

Coupled microstrip lines with slot in ground plane are usually characterized using even- and odd-mode characteristic impedances and effective permittivities.[1–6] The aperture underneath a transmission line affects the field distribution between the line and the ground. As the effective transverse height "h_{eff}" (between the line and the ground conductor) increases due to the presence of the aperture, capacitance per unit length of the line reduces. Hence characteristic impedance of the line increases as aperture width "W_s" increases. For a coupled line shown in Figure 2(a), the even-mode capacitance per unit length of the coupled-line reduces, resulting in an increase in the even-mode impedance. Thus, employing an aperture in the ground plane results in tight coupling which may be difficult to realize using conventional edge coupling due to fabrication limitations. The equivalent standard microstrip coupled lines is shown in Figure 2(b).

Based on the effective height "h_{eff}" derived in [6] for microstrip lines, even- and odd-mode propagation parameters are estimated using the standard coupled microstrip line expressions [1] with "h" replaced by h_{eff}. Capacitance per unit length is calculated for the defected ground structure to evaluate h_{eff}. The capacitance is calculated by integrating the capacitance for an infinitesimal width dx separated by a height $h(x)$. Modified height "h_{eff}" can be given by [6]

$$h_{eff} = \begin{cases} \dfrac{W}{\left[2\sin h^{-1}\left(\dfrac{0.5W_s}{2h}\right) + \dfrac{(W-0.5W_s)}{h}\right]} & \text{for } 0 \le 0.5W_s \le W \\ \dfrac{W}{2\left[\sin h^{-1}\left(\dfrac{0.5W_s}{2h}\right) - \sin h^{-1}\left(\dfrac{0.5W_s - W}{2h}\right)\right]} & \text{for } 0.5W_s > W \end{cases} \quad (1)$$

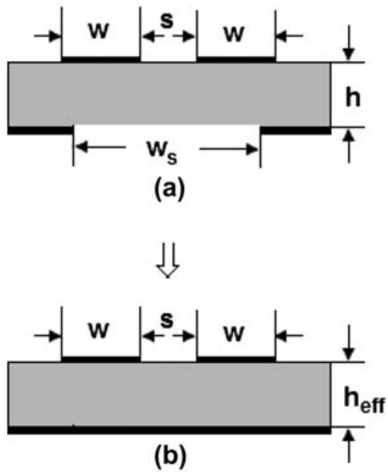

Figure 2. (a) Coupled microstrip lines with aperture in the ground plane. (b) Equivalent conventional coupled microstrip line.

It is understood from the above expressions that h_{eff} becomes h when there is no aperture in the ground plane and expressions converge to normal coupled microstrip line expressions.

2.1. Even-mode propagation

Even-mode capacitance "C_e" for the defected ground coupled lines is calculated using [1,6]:

$$C_e = C_p(W, h_{eff}, \varepsilon_r) + C_f(W, h_{eff}, \varepsilon_r) + C_f^d(W, h_{eff}, s, \varepsilon_r) \tag{2}$$

where C_p is the parallel plate capacitance, C_f is the fringing capacitance of single microstrip line, and C_f^d accounts for modification of fringing capacitance C_f of single line due to the presence of another line. Even-mode impedance "Z_{oe}" and even-mode effective permittivity "ε_{re}" are calculated using

$$Z_{oe} = \frac{1}{c\sqrt{C_e C_e^a}} \tag{3}$$

$$\varepsilon_{re} = \sqrt{\frac{C_e}{C_e^a}} \tag{4}$$

"C_e^a" is the even-mode capacitance when air is the medium.

2.2. Odd-mode propagation

Odd-mode capacitance "C_o" can be evaluated using,[1,6]

$$C_o = C_p(W, h_{eff}, \varepsilon_r) + C_f(W, h_{eff}, \varepsilon_r) + C_{gd}(W, h_{eff}, s, \varepsilon_r) + C_{ga}(W, h_{eff}, s, \varepsilon_r) \tag{5}$$

where C_{gd} and C_{ga} represent the fringing capacitances for the air and the dielectric regions across the coupling gap "s", respectively. Odd-mode electrical parameters (Z_{oo} and ε_{ro}) are given by

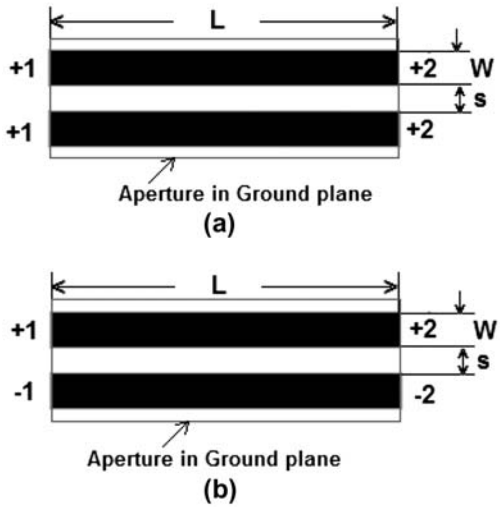

Figure 3. EM simulation setup to extract even-and odd-mode impedances. (a) Even-mode excitation. (b) Odd-mode excitation.

$$Z_{oo} = \frac{1}{c\sqrt{C_o C_o^a}} \tag{6}$$

$$\varepsilon_{ro} = \sqrt{\frac{C_o}{C_o^a}} \tag{7}$$

where Z_{oo} is odd-mode characteristic impedance and ε_{ro} is odd-mode effective permittivity. "$C_o{}^a$" is the odd-mode capacitance, when air is the medium. In expressions (2) and (5), h_{eff} which accounts for the perturbation (slot) in the ground plane can be evaluated using Equation (1).[6]

3. Comparison with other approaches

The derived expressions will be useful for the initial synthesis of microstrip line components such as broadband filters, couplers, matching circuit, etc. Different sets of even- and odd-impedances for various values of h, ϵ_r, W, and W_s are extracted using EM simulator "IE3D" from mentor graphics [15] and conformal mapping [5] for the purpose of comparison. Even- and odd-mode characteristic impedances of the coupled line sections (over the slotted ground plane) are extracted, using even-mode (positive ports) and odd-mode (positive and negative ports) features (as shown in Figure 3) of IE3D. In [5], conformal mapping technique is followed to derive even-and odd-mode capacitances of coupled lines with aperture in the ground plane. This involves complex elliptic integrals which are in terms of physical parameters of the coupled line sections. Figures 4 and 5 compare these results. Results derived from the proposed expressions match well with other approaches and are accurate with the tolerance of $\pm 6\,\Omega$. The error is minimal (1–2%) for $(2W_s + s) \leqslant W$. The error increases (3–6%) when $(2W_s + s)$ is greater than W.

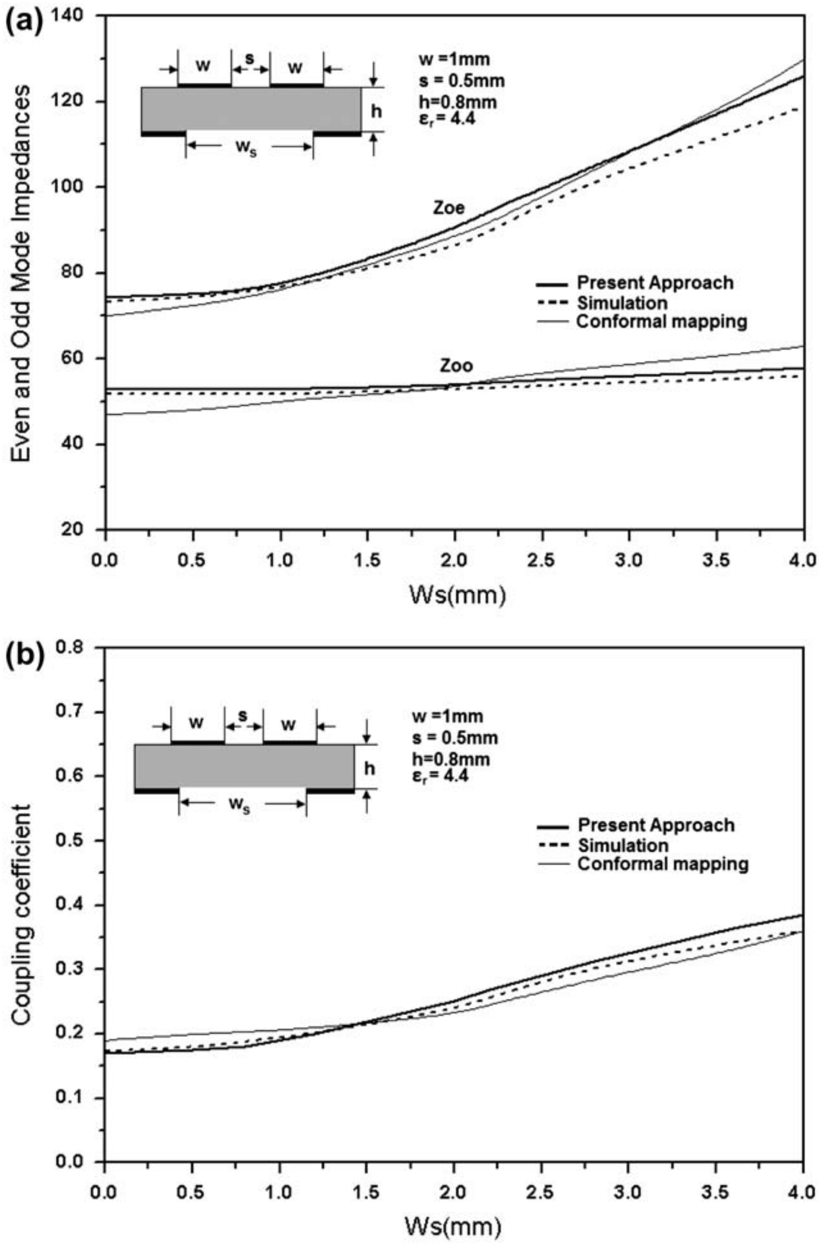

Figure 4. (a) Validity of even-and odd-mode impedances for $\varepsilon_r = 4.4$. (b) Validity of coupling coefficient for $\varepsilon_r = 4.4$.

As seen from Figures 4 and 5, even-mode characteristic impedance increases monotonically as the slot width increases. Odd-mode characteristic impedance also increases as slot width increases and the rate of increase is small. This behavior increases the coupling between the lines. From the study, it is understood that odd-mode impedance is nearly constant for thicker substrate (greater than 1.6 mm) and slot has negligible effect on the odd-mode impedance for narrow strip widths on thick substrates. However, impedances are

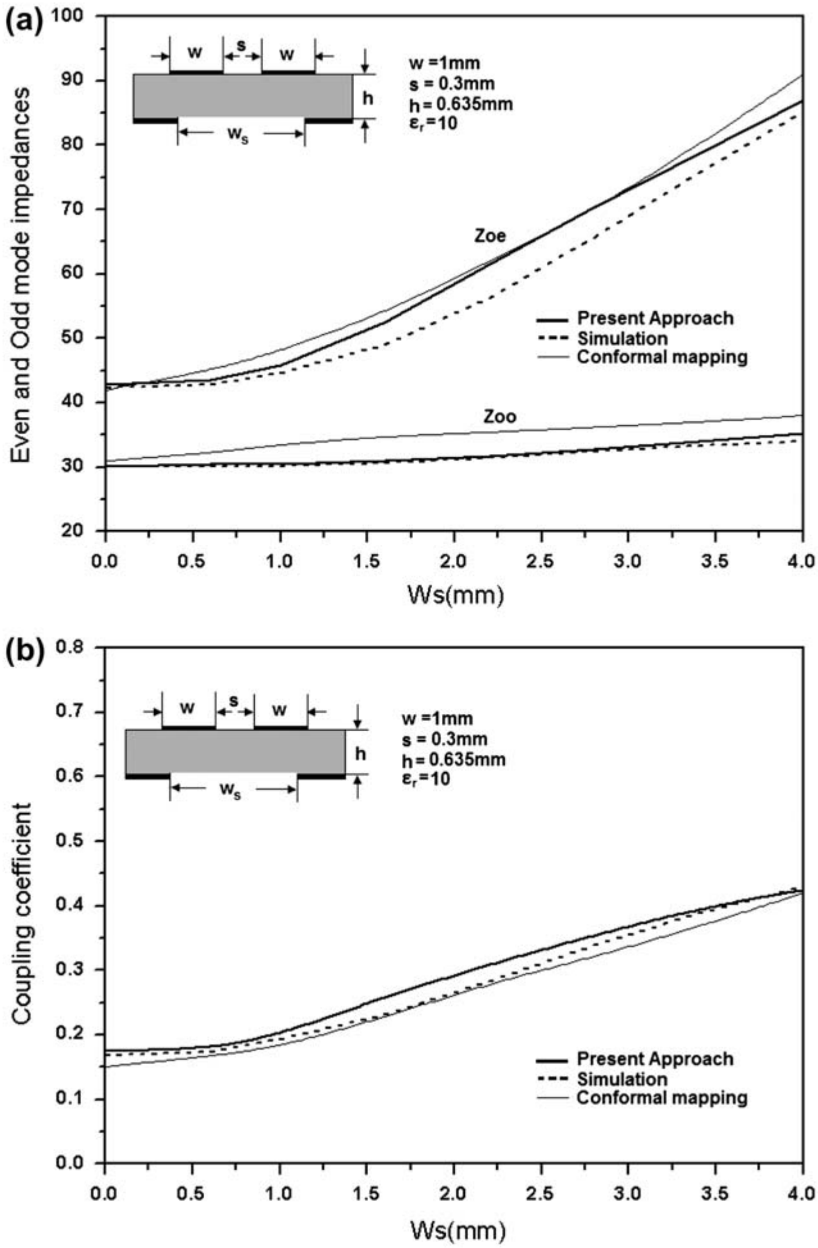

Figure 5. (a) Validity of even-and odd-mode impedances for $\varepsilon_r = 10$. (b) Validity of coupling coefficient for $\varepsilon_r = 10$.

affected by slot significantly for wide strips. The even-and odd-mode impedances of the coupled line (using Equations (3) and (6)) reduce to the even- and odd-mode characteristic impedances of conventional microstrip coupled line, when slot (aperture) width reduces to zero. These expressions estimate even- and odd-mode characteristic impedances "Z_{oe} and Z_{oo}", respectively over a widely used range of geometrical parameters $0.2\,\text{mm} < h < 1.6\,\text{mm}$, $2 < \epsilon_r < 10$, $0 < W_s/W < 3$ and $0.5\,\text{mm} < W < 4\,\text{mm}$.

4. Extension for multi-conductor lines

The broadband filter layout with multi-conductor coupled lines and its equivalent circuit are shown in Figure 6. The filter is a multi-conductor coupled line device with aperture in the ground plane.[16] This multi-conductor coupled line configuration shown in Figure 6 offers larger coupling than the two-line coupled structure.[17] The three-line-coupled structure, shown in Figure 6(b), is symmetrical and hence perfect magnetic conductor (PMC) can be used at the center of the structure, as shown in Figure 6(c), for the analysis. Now the resultant structure is an asymmetrical coupled line section which can be analyzed using the analysis of asymmetrical coupled lines explained in the literature.[18] The effect of slot in the ground plane is taken into the account by using effective height "h_{eff}" in the place of "h."

5. Application to filter design

A broadband filter with aperture in the ground plane is designed with the following specifications to demonstrate the use of derived expressions.

Frequency band: 3–8 GHz
Substrate permittivity "ϵ_r": 10
Substrate thickness: 0.635 mm

Different sections of the filter under analysis are shown in Figure 7. The filter analysis starts with the calculation of even- and odd-modes of the coupled lines. As the filter structure is symmetrical about AA', the filter can be analyzed by considering half of the structure with PMC as in Figure 6(c). Each coupled line section is characterized by using transmission matrix $[ABCD]_C$.[16] The coupling coefficient is determined by filter specifications, which in turn determine the spacing between the coupled lines. For the above specifications, the required coupling coefficient between resonators is 0.51. The filter prototype values are given in Table 1.

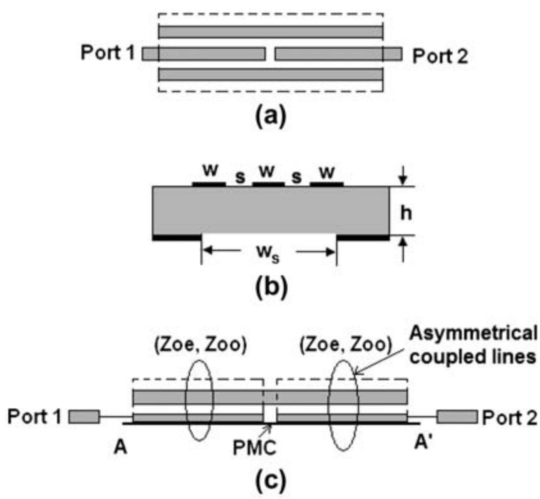

Figure 6. (a) Layout of broadband filter. (b) Cross-section. (c) Equivalent circuit of filter.

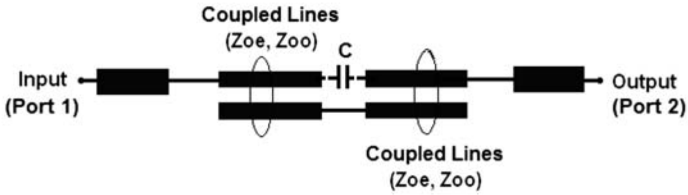

Figure 7. Different sections of filter.

Table 1. Filter prototype values.

Elements	Inverters	Coupling coefficients
$g_0 = g_2 = 1.0$	$J_0 = 0.845$	$K_{01} = 0.51$
$g_1 = 2.0$	$J_1 = 0.845$	$K_{12} = 0.51$

Table 2. Electrical and physical parameters of the filter.

Parameters	Values
Even-mode impedance "Z_{oe}"	125 Ω
Odd-mode impedance "Z_{oo}"	29 Ω
Width "w"	250 μm
Aperture width "W_s"	2200 μm
Spacing between the resonators "s"	250 μm
Gap "g"	800 μm

Table 2 gives the electrical and the corresponding physical parameters for the desired specifications. These physical parameters are extracted by following the method described in Section 4 using the equations in Sections 2.1 and 2.2.

The modified height "h_{eff}" for the above-mentioned physical dimensions using (1) is 0.84 mm and this value is used in the analysis of asymmetrical coupled lines [18] to extract the even- and odd-mode propagation characteristics. The values of even- and odd-mode impedances (Z_{oe} and Z_{oo}) are 125 and 29 Ω, respectively for the required coupling. Resonator length "L_c" is quarter wavelength at the center frequency of the filter (5.5 GHz), which is 5300 μm. Circuit model simulation is carried out by cascading *ABCD* matrices of broadband filter sections. Effect of gap in the center line is not considered in the analysis as it has negligible value of series capacitance "*C*." Reflection and transmission parameters are extracted from the overall transmission matrix ($[ABCD]_T$) calculated using MATLAB.

$$[ABCD]_T = [ABCD]_C[ABCD]_C \tag{8}$$

Full-wave simulation has also been performed using the method of moments-based simulator "IE3D" from mentor graphics.[15] Circuit model simulation results are compared against full- wave simulation results in Figure 8. The close agreement between both the results confirms the validity of the proposed analysis. From the results, it can be noticed that the bandwidth of the proposed filter (with aperture on ground plane) is 5 GHz (90.1% bandwidth), while the bandwidth of the filter without aperture in the ground plane is 2.25 GHz (41%

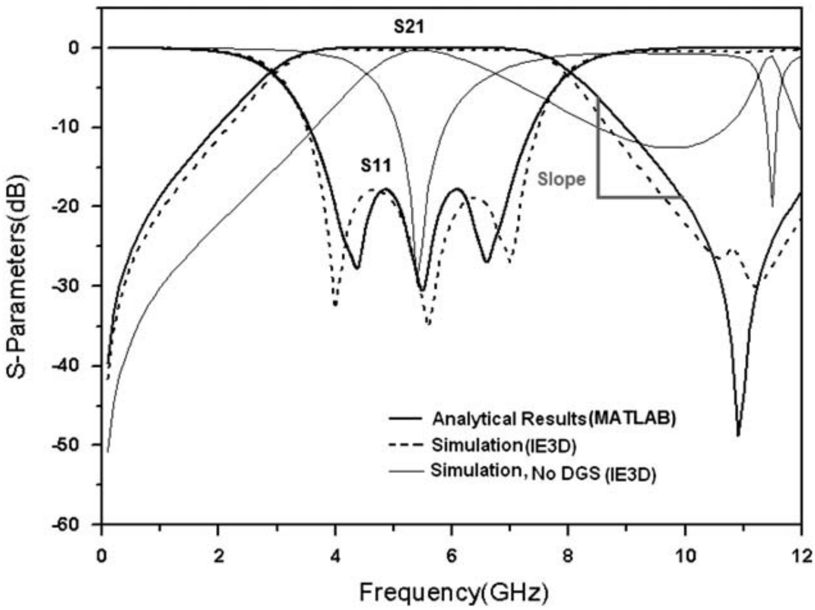

Figure 8. Analytical results of filter.

Figure 9. Assembled broadband filter.

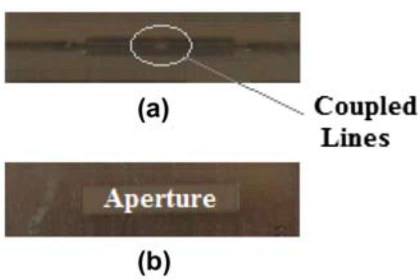

Figure 10. Top and bottom layers of broadband filter.

bandwidth). Due to multi-conductor coupled lines and slotted ground plane, the proposed filter has good shape factor (30/3 dB) of 1.36:1.

The filter has been fabricated and assembled as shown in Figure 9. Top and bottom layers of the realized filter are shown in Figure 10. Response of filter is measured using a vector network analyzer. A comparison is made between measured and simulation results in

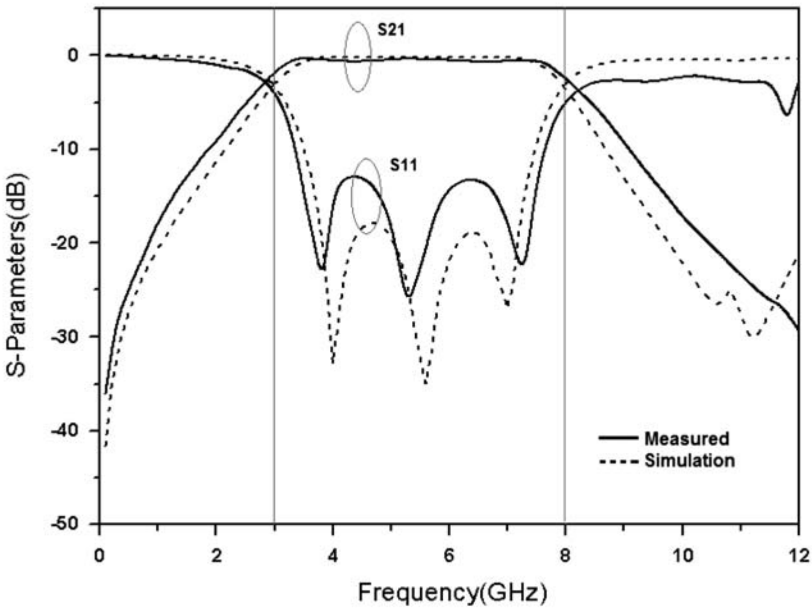

Figure 11. Measured S-parameters of broadband filter.

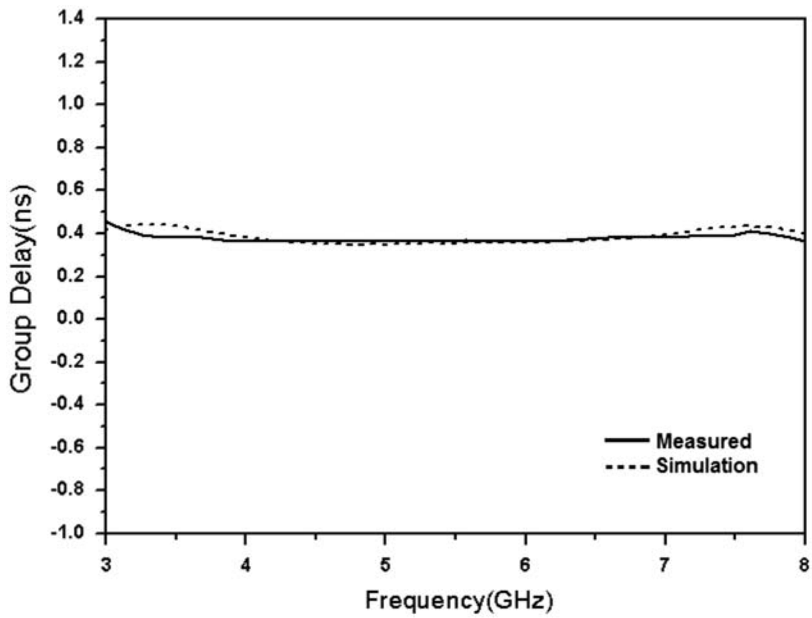

Figure 12. Measured group delay.

Figure 11. While the simulated results show a pass band from 3 to 8 GHz, the measured pass band is from 2.9 to 8.08 GHz with a maximum insertion loss of 0.9 dB and a minimum return loss of 13.5 dB. Figure 12 shows the measured and simulated group delay. Group delay

variation is within ±0.03 ns. The size of the realized broadband filter is $21 \times 12 \times 0.635\,\text{mm}^3$. The measured results confirm the analysis and application of multi-conductor coupled lines proposed in this paper.

6. Conclusions

This paper presented an analysis method for parallel coupled microstrip lines with a symmetrical aperture in the ground plane. Effect of aperture in the ground plane was considered by increasing the substrate effective height of the microstrip structure in the analysis. The coupled line parameters such as even- and odd-mode characteristics, obtained using the proposed approach, were compared against the results obtained from conformal mapping and full-wave simulations. The results are in good agreement. This analysis has been extended to multi-conductor coupled transmission lines for use in the design of broadband microwave passive circuits. Potential of the expressions of the coupled line analysis in the design of microstrip components was demonstrated by designing a broadband microstrip filter with a defected ground. The three-conductor coupled lines with slotted ground plane achieve wide pass band response with practically realizable spacing between the coupled lines, which otherwise with a two-conductor coupled lines may be practically impossible due to etching limitations on narrow spacing between the lines. Experimental results of the designed broadband filter have been presented in this paper for the validation of the slotted ground coupled line analysis.

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