

A Semi-Elliptical Wideband Directional Coupler

Yew-Chiong Lo^{1, *}, Boon-Kuan Chung², and Eng-Hock Lim²

Abstract—A new design of wideband directional couplers using a semi-elliptical edge-coupled structure is presented. This structure consists of two semi-elliptical patches on the top layer and an elliptical defected ground plane on the bottom layer to increase the coupling coefficient and operating bandwidth. Even and odd mode analysis is performed, and sets of design graphs are formulated to facilitate the design of the coupler on substrate with dielectric constants of 2.2 and 3.38. The operating frequency and coupling are controlled by the dimensions of the elliptical patch and the size of the air gap. Compared to the conventional parallel-microstrip coupler which requires extremely narrow air gap to achieve tighter coupling factor, the semi-elliptical coupler allows for wider air gap to be used, and it reduces fabrication difficulty. Both simulation and measurement results show that the proposed design exhibits wideband characteristic with a bandwidth ratio of more than 2.4 with a coupling deviation of ± 1 dB.

1. INTRODUCTION

Directional couplers are widely used in microwave circuits and subsystems. They are used to sample power for amplitude control and used in power splitting and combining. Directional couplers are commonly found in amplifiers, balanced mixers, microwave instruments, modulators and antenna beam-forming networks [1].

Edge-coupled directional couplers such as stripline couplers and microstrip couplers are backward-wave couplers. The coupling strength for these types of couplers is determined by the difference between the even and odd mode characteristic impedances. Since it is difficult to obtain large impedance difference, tight coupling is difficult to realize unless extremely small spacing between the coupled lines is used [1]. Multi-section coupled-line coupler is introduced [2] to realize tight coupling, but this technique increases the size and design complexity of the circuit.

When tight coupling is required, branch-line couplers, Lange couplers, and tandem couplers can also be used. Branch-line couplers suffer from limited bandwidth due to the quarter-wave requirement. Although the bandwidth can be increased by cascading multiple sections [3], the size of the coupler increases considerably. Lange coupler [4–7] and tandem coupler [8–10] require extra bonding wires, narrow strips and small spacing between the coupled lines, making them inconvenient to manufacture on a printed circuit board (PCB).

The problem of narrow spacing can be alleviated by using broadside coupled structure [11–13]. However, these circuits require multilayer substrates which are inconvenient to manufacture. Multilayer design is also sensitive to alignment error. Misalignment of the microstrip layers forming this type of coupler may lead to high insertion loss [12].

Defected ground structure has been used in various microwave circuits to increase the coupling coefficient and to reduce the size of microwave circuits [14–16]. In this paper, a semi-elliptical edge-coupled structure with a defected ground is proposed. As a result, larger spacing between the coupled

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lines can be used compared to the conventional microstrip coupler, making it practical to realize on a PCB. In order to facilitate the coupler design, analysis on even and odd mode characteristic impedances are performed and sets of design graphs are formulated. These design graphs can be used to determine the physical dimensions of the proposed coupler and will also be useful for the design of other microstrip devices such as a phase shifter [17], which requires tight coupling and wide bandwidth. The validity of the proposed design is verified experimentally.

2. DESIGN

The proposed directional coupler is a two-layer device. One layer consists of an edge-coupled semi-elliptical structure and the other layer consists of an elliptical defected ground plane, as shown in Figure 1. The use of elliptical structure provides an almost constant coupling coefficient over a wide bandwidth.

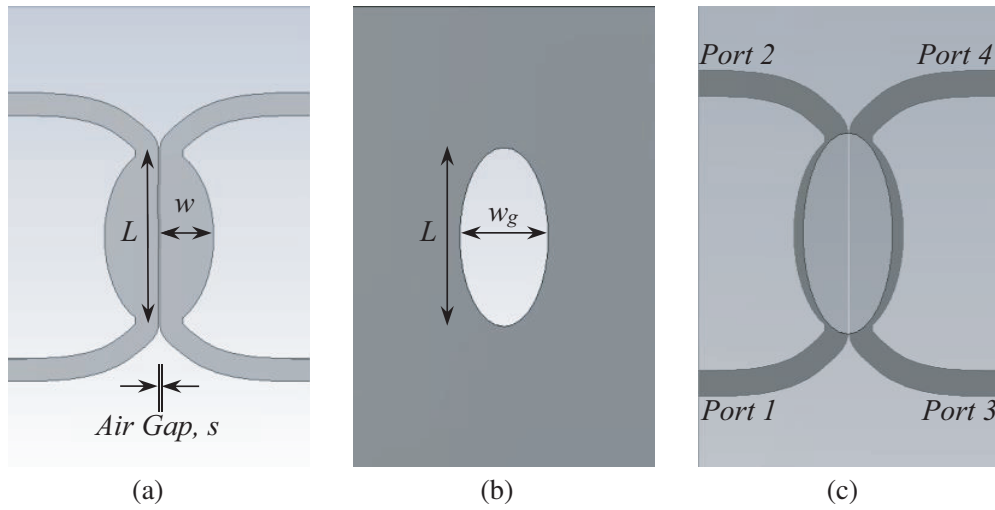


Figure 1. Configuration of the proposed directional coupler. (a) Top layer, (b) bottom layer, and (c) overlay of the two layers.

The directional coupler is a four-port device, having a symmetry with respect to the vertical plane. Curved microstrip lines are used to make connections to the subminiature A (SMA) connectors.

The length and width of the top semi-elliptical patch are denoted as L and w , respectively. The defected ground plane has the same length, L as the top patch, and a width denoted by w_g . The axial ratio of the top elliptical patch is defined as $2w/L$ (denoted as “ratio”), whereas the axial ratio of the bottom defected ground is defined as w_g/L (also denoted as “gratio”).

Even and odd mode analysis has been performed to characterize the circuit. In this case, port 1 and port 3 are excited with even and odd mode signals. As shown in Figure 2, the electric field

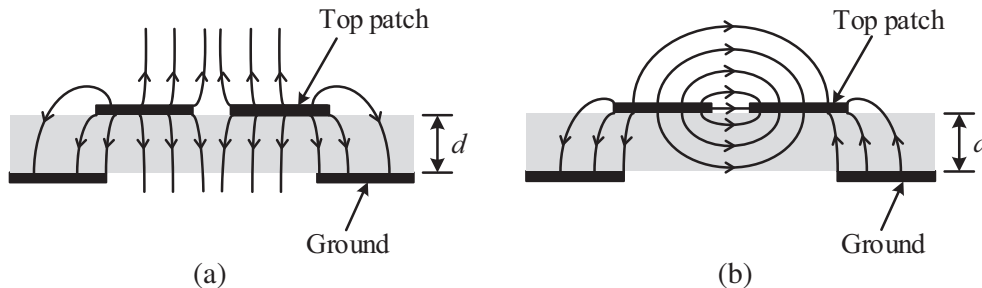


Figure 2. Electric field for (a) even mode excitation, (b) odd mode excitation.

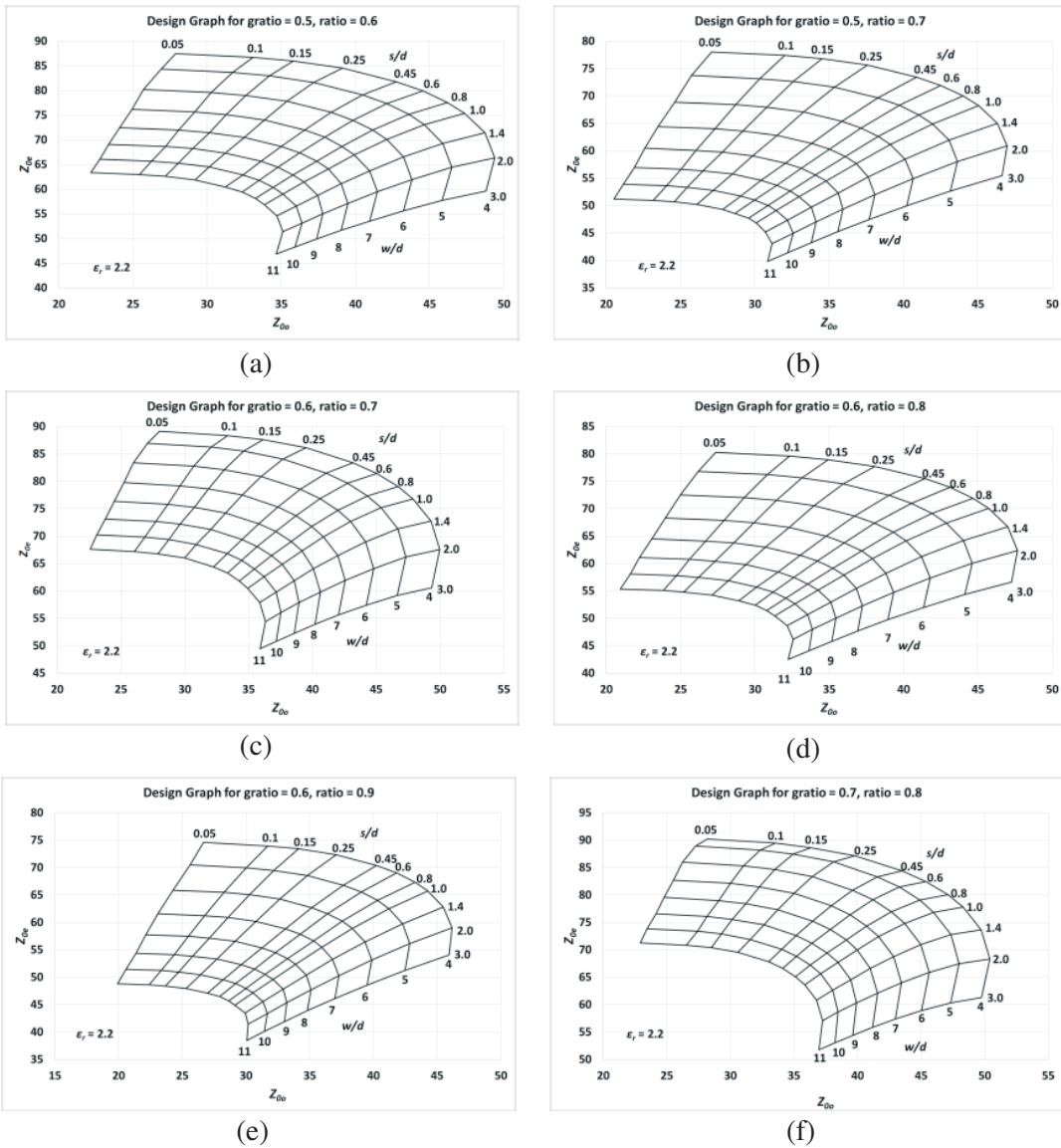
distributes itself in both the dielectric and in the air for even and odd mode excitations. For a certain desired coupling factor, the even (Z_{0e}) and odd (Z_{0o}) mode characteristic impedances can be calculated as follows:

$$Z_{0e} = Z_0 \sqrt{\frac{1 + 10^{-C/20}}{1 - 10^{-C/20}}} \tag{1}$$

$$Z_{0o} = Z_0 \sqrt{\frac{1 - 10^{-C/20}}{1 + 10^{-C/20}}} \tag{2}$$

where Z_0 is the characteristic impedance of the coupler, and C is the coupling factor.

Assuming that $Z_0 = 50 \Omega$ and the desired coupling factor C is $10 \text{ dB} \pm 1 \text{ dB}$, the values of Z_{0e} and Z_{0o} can be calculated using Eqs. (1) and (2) as 72.45Ω and 34.5Ω , respectively. Even and odd mode analysis is performed using CST Microwave Studio. Sets of design graphs are generated by varying the ratio s/d and w/d for various defected ground axial ratios (gratio) and top patch axial ratios (ratio) to facilitate the design of the directional coupler, as shown in Figure 3 and Figure 4 for dielectric constant, $\epsilon_r = 2.2$ and 3.38 , respectively.



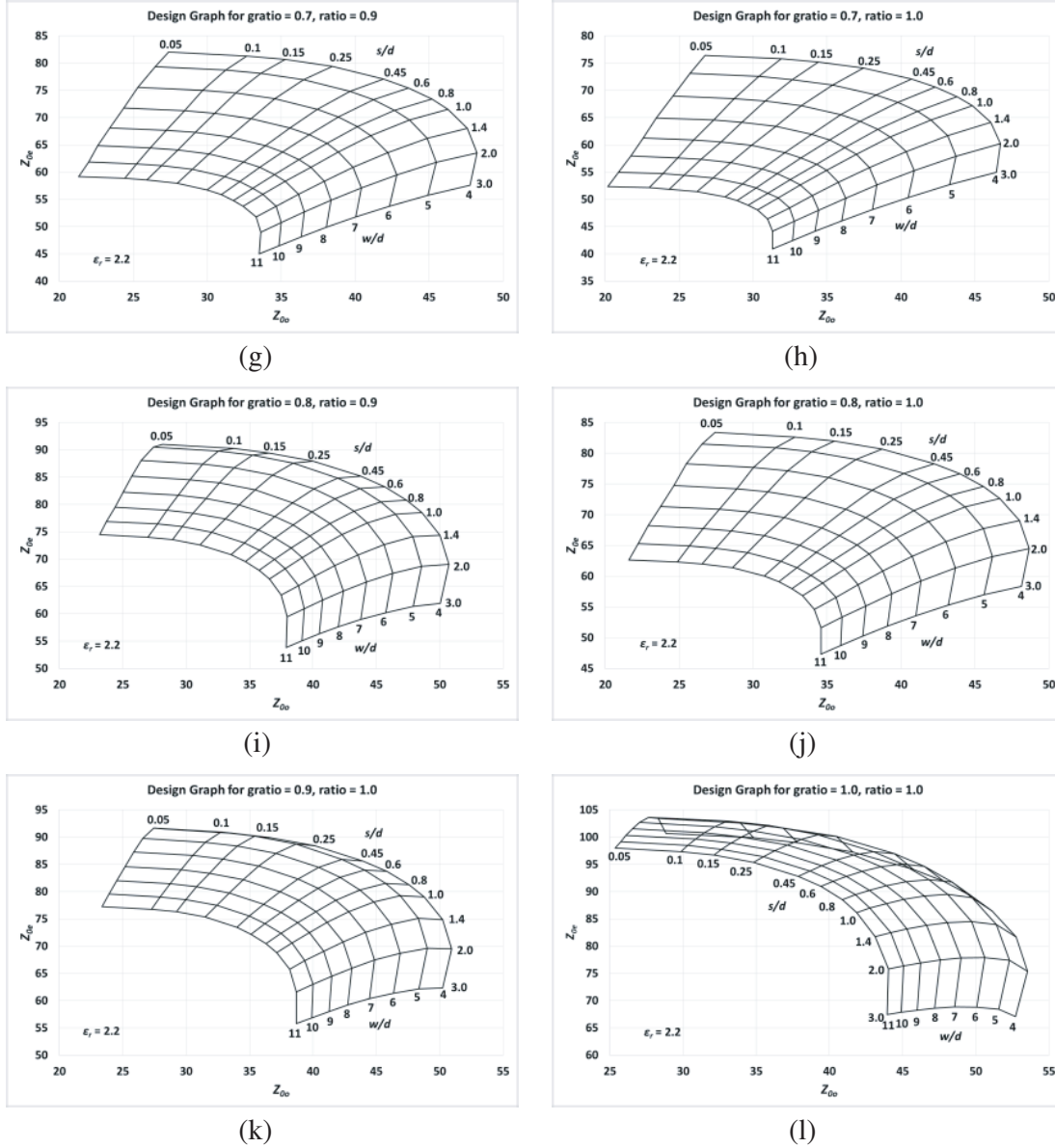


Figure 3. Design graphs for $\epsilon_r = 2.2$, (a) gratio = 0.5, ratio = 0.6, (b) gratio = 0.5, ratio = 0.7, (c) gratio = 0.6, ratio = 0.7, (d) gratio = 0.6, ratio = 0.8, (e) gratio = 0.6, ratio = 0.9, (f) gratio = 0.7, ratio = 0.8, (g) gratio = 0.7, ratio = 0.9, (h) gratio = 0.7, ratio = 1.0, (i) gratio = 0.8, ratio = 0.9, (j) gratio = 0.8, ratio = 1.0, (k) gratio = 0.9, ratio = 1.0, and (l) gratio = 1.0, ratio = 1.0.

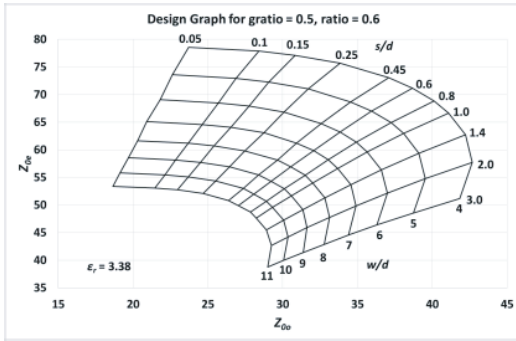
From Figure 3 and Figure 4, one can see that Z_{0o} increases with s , as the larger separation between the top patches reduces its capacitance. However, the rate of increment reduces as the top patches are separated further apart. The larger separation distance reduces the capacitance between the top patches, but increases the capacitance between the top patches and the ground conductor. On the other hand, Z_{0e} decreases with s because of the larger overlapping area between the top patch and the ground plane, which in effect increases the capacitance. Increase in w causes the capacitance per unit length to increase. This results in the decrease of both even and odd mode impedances.

From the design graphs, it can be shown that there are many possible combinations of s/d and w/d to achieve the same coupling factor. Different parameter combinations, together with the thickness of the substrate, result in different physical dimensions of the coupler. The effective wavelength at center

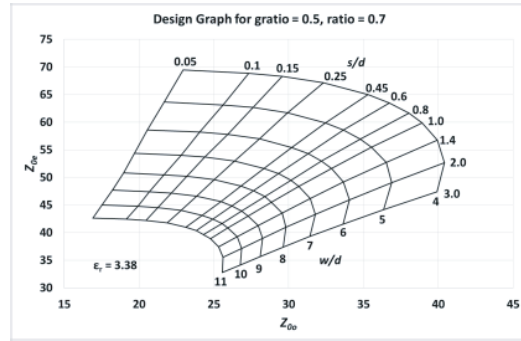
frequency, $\lambda_{0(eff)}$ can be estimated using the following equation:

$$\lambda_{0(eff)} = \frac{\lambda_0}{\sqrt{\epsilon_{eff}}} \tag{3}$$

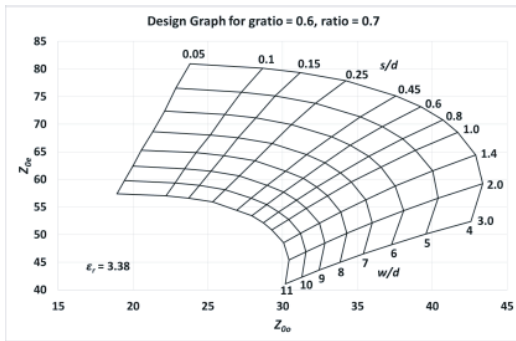
where $\epsilon_{eff} \approx \frac{1+\epsilon_r}{2}$.



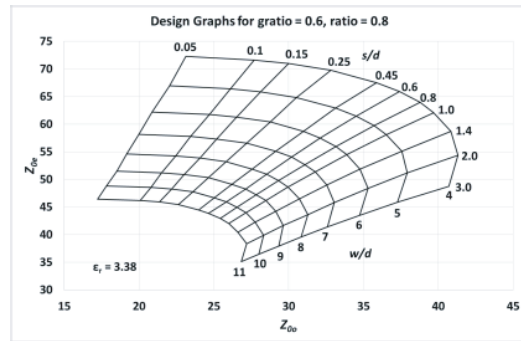
(a)



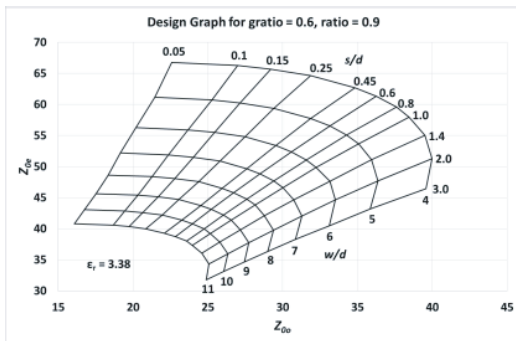
(b)



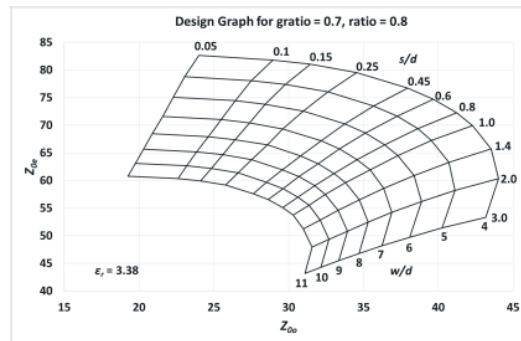
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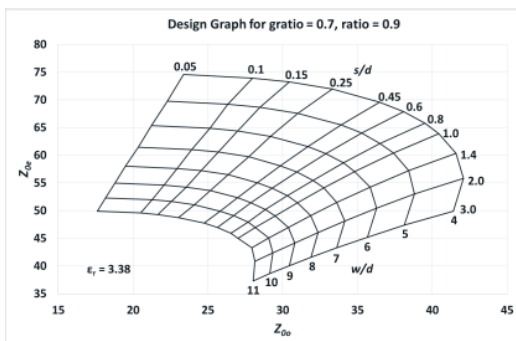
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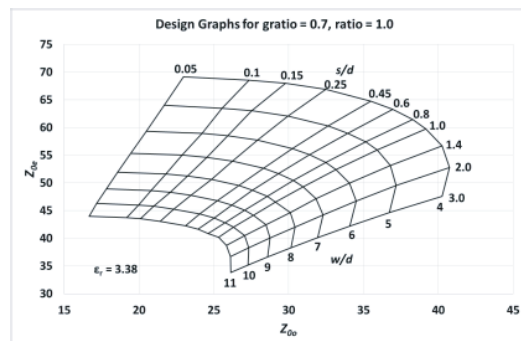
(e)



(f)



(g)



(h)

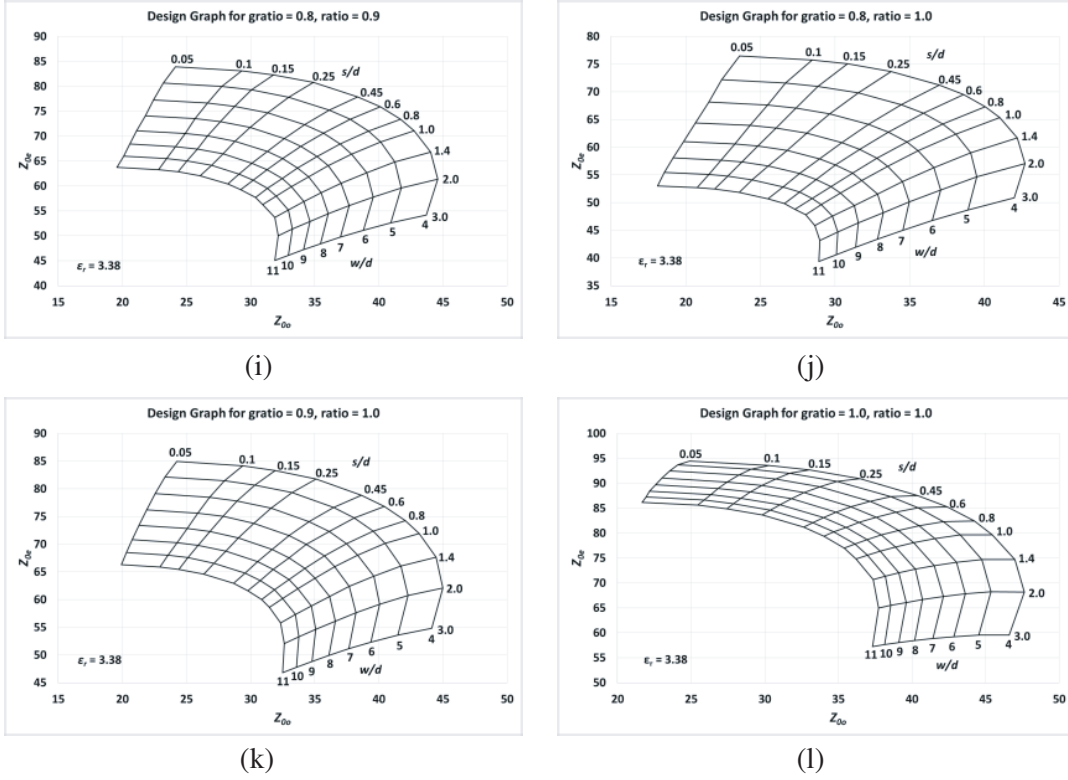


Figure 4. Design graphs for $\epsilon_r = 3.38$, (a) gratio = 0.5, ratio = 0.6, (b) gratio = 0.5, ratio = 0.7, (c) gratio = 0.6, ratio = 0.7, (d) gratio = 0.6, ratio = 0.8, (e) gratio = 0.6, ratio = 0.9, (f) gratio = 0.7, ratio = 0.8, (g) gratio = 0.7, ratio = 0.9, (h) gratio = 0.7, ratio = 1.0, (i) gratio = 0.8, ratio = 0.9, (j) gratio = 0.8, ratio = 1.0, (k) gratio = 0.9, ratio = 1.0, and (l) gratio = 1.0, ratio = 1.0.

This approximation is made based on the assumption that the electric field is distributed equally in the dielectric and in the air for this coupler structure, as illustrated in Figure 2.

Using the approximate equation of an ellipse, the physical dimension of the structure can be related to the effective wavelength, $\lambda_{0(eff)}$ (and hence the center frequency) using the following approximation:

$$\lambda_{0(eff)} \approx \pi(L + w) \left(1 + \frac{3k}{10 + \sqrt{4 - 3k}} \right) \quad (4)$$

where $k = \frac{(L-w)^2}{(L+w)^2}$, L is the coupler length, and w is the coupler width.

3. RESULTS AND DISCUSSION

Using the design graphs in Figure 3 and Figure 4, the parameters for coupling factor, $C = 10 \text{ dB} \pm 1 \text{ dB}$ are determined and shown in Table 1.

Table 1. Design parameters of directional couplers.

ϵ_r	s/d	w/d	d (mm)	L (mm)	w (mm)	s (mm)	w_g (mm)
2.2	0.325	7.240	1.575	38.010	11.403	0.512	19.005
2.2	0.325	7.240	0.787	18.993	5.698	0.256	9.496
3.38	0.353	4.400	1.524	22.352	6.706	0.538	11.176
3.38	0.353	4.400	0.813	11.924	3.577	0.287	5.962

Using Eq. (4), the estimated center frequencies for $\epsilon_r = 2.2$ and substrate thickness of 1.575 mm and 0.787 mm are found to be 1.423 GHz and 2.847 GHz, respectively. For $\epsilon_r = 3.38$ and substrate thickness of 1.524 mm and 0.813 mm, the estimated center frequencies are 2.029 GHz and 3.804 GHz, respectively.

The reflection coefficient, insertion loss, coupling, and isolation of the proposed couplers are first verified using CST Microwave Studio. The designs are fabricated on Rogers RT/duroid 5880 and RO4003C with different substrate thicknesses and tested using a vector network analyser. The photographs of the fabricated couplers are shown in Figure 5.

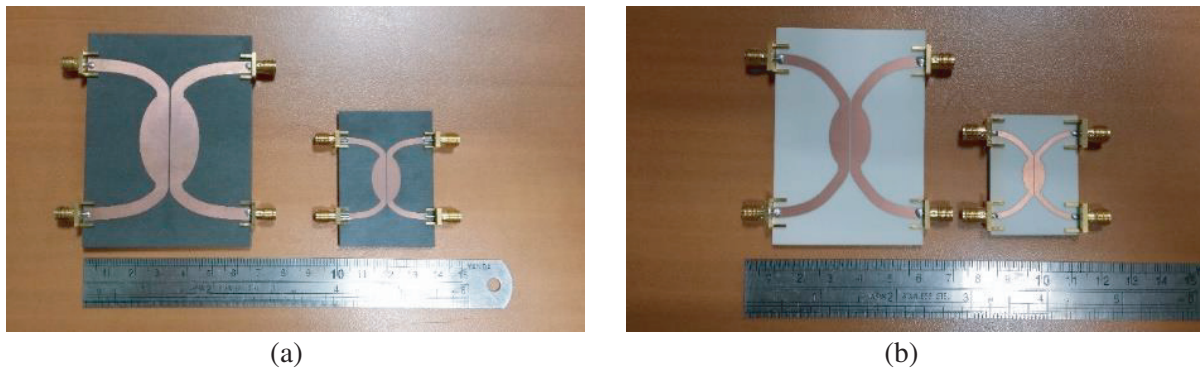


Figure 5. Fabricated couplers, (a) RT/duroid 5880, (b) RO4003C.

The simulation and measurement results are shown in Figure 6 to Figure 9.

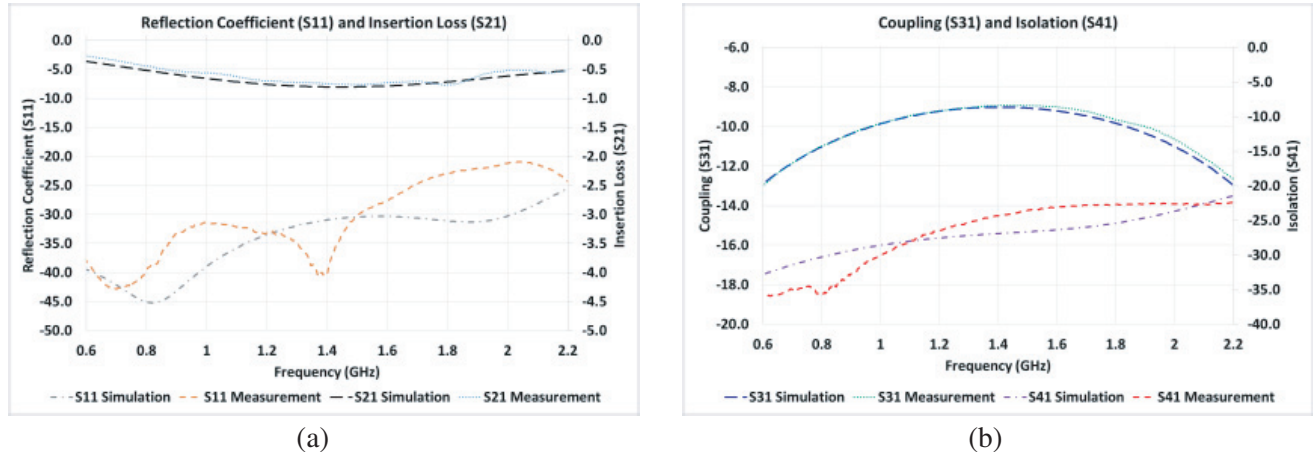


Figure 6. Simulation and measurement results for RT/duroid 5880, $d = 1.575$ mm, (a) reflection coefficient and insertion loss, and (b) coupling and isolation.

The center frequencies and the couplers' bandwidths are summarized in Table 2 and Table 3.

The measured insertion loss is generally higher than the simulated results, especially at higher frequencies due to the slight mismatch between the SMA connectors and the microstrip line. Apart from that, the simulation and measurement results for all four couplers agree very well.

Both the simulated and measured center frequencies agree very well with the estimated center frequencies that are generated using Eq. (4). The simulation and measurement results show that the proposed coupler design exhibits wideband characteristics.

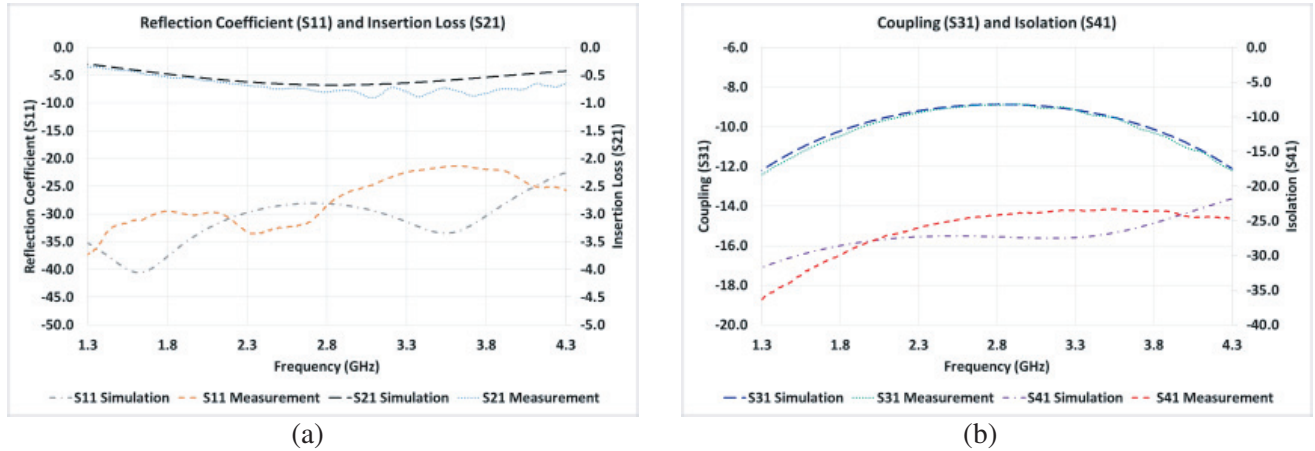
Figure 6 and Figure 7 show the simulation and measurement results for the coupler fabricated on RT/duroid 5880 with a coupling of $10 \text{ dB} \pm 1 \text{ dB}$. The operating frequency range is 0.8–2 GHz and 1.6 GHz–4 GHz for substrate thicknesses of 1.575 mm and 0.787 mm, respectively. Both couplers have a

Table 2. Simulated and measured center frequencies and bandwidths for RT/duroid 5880.

	Simulation Results		Measurement Results	
Substrate thickness (mm)	1.575	0.787	1.575	0.787
Center frequency, f_c (GHz)	1.401	2.811	1.420	2.808
Bandwidth (GHz)	1.194	2.490	1.246	2.364
Bandwidth ratio	2.485	2.590	2.564	2.453
Fractional Bandwidth (%)	85.22	88.58	87.77	84.16

Table 3. Simulated and measured center frequencies and bandwidths for RO4003C.

	Simulation Results		Measurement Results	
Substrate thickness (mm)	1.524	0.813	1.524	0.813
Center frequency, f_c (GHz)	1.917	3.753	1.922	3.727
Bandwidth (GHz)	1.674	3.306	1.699	3.279
Bandwidth ratio	2.550	2.574	2.583	2.576
Fractional Bandwidth (%)	87.32	88.09	88.37	88.15

**Figure 7.** Simulation and measurement results for RT/duroid 5880, $d = 0.787$ mm, (a) reflection coefficient and insertion loss, and (b) coupling and isolation.

reflection coefficient of better than 20 dB, isolation of better than 22 dB, and insertion loss of less than 1 dB.

For the coupler fabricated on RT/duroid 4003C with the same coupling factor, the results in Figure 8 and Figure 9 show that the operating frequency ranges are 1.1–2.7 GHz and 2.1 GHz–5.4 GHz for substrate thicknesses of 1.524 mm and 0.813 mm, respectively. Both couplers have a reflection coefficient of better than 18 dB, isolation of better than 22 dB, and insertion loss of less than 1 dB.

The required air gaps for the proposed 10 dB coupler are 0.512 mm and 0.256 mm for the RT/duroid 5880 substrate with thicknesses of 1.575 mm and 0.787 mm, respectively. For the RO4003C substrate with thicknesses of 1.524 mm and 0.813 mm, the required air gaps are 0.538 mm and 0.287 mm, respectively. In the case of the parallel microstrip coupler, the required air gaps for the 10 dB coupler are 0.142 mm and 0.0787 mm for the RT/duroid 5880 substrate with thicknesses of 1.575 mm and 0.787 mm, respectively. For the RO4003C substrate with thicknesses of 1.524 mm and 0.813 mm, the required air gaps for 10 dB coupling coefficient become 0.18 mm and 0.106 mm, respectively, in the case of parallel microstrip coupler. The required spacing and tolerance can be difficult for practical implementation, especially when tight coupling is required for substrate with low dielectric constant.

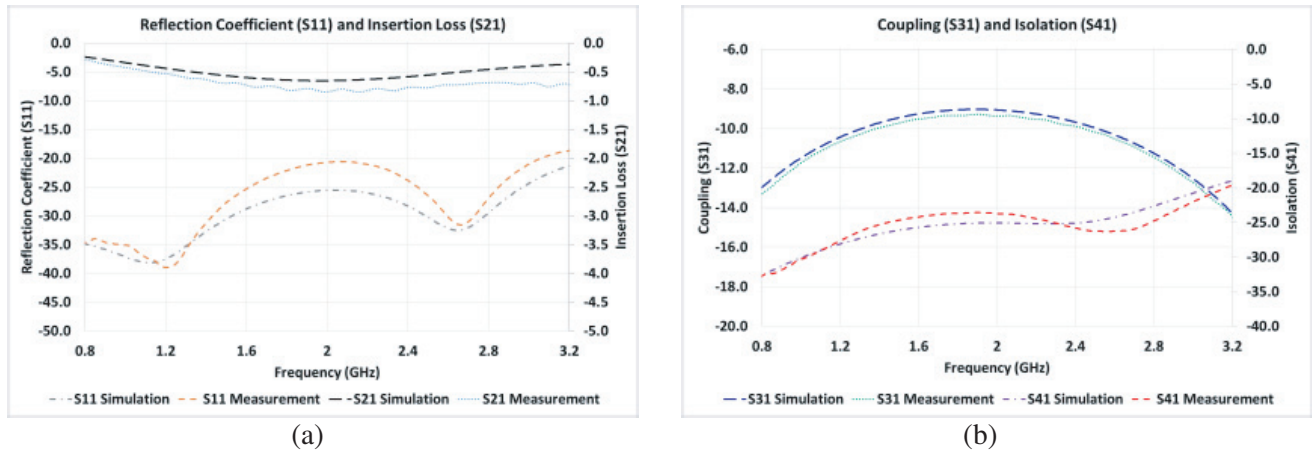


Figure 8. Simulation and measurement results for RO4003C, $d = 1.524$ mm, (a) reflection coefficient and insertion loss, and (b) coupling and isolation.

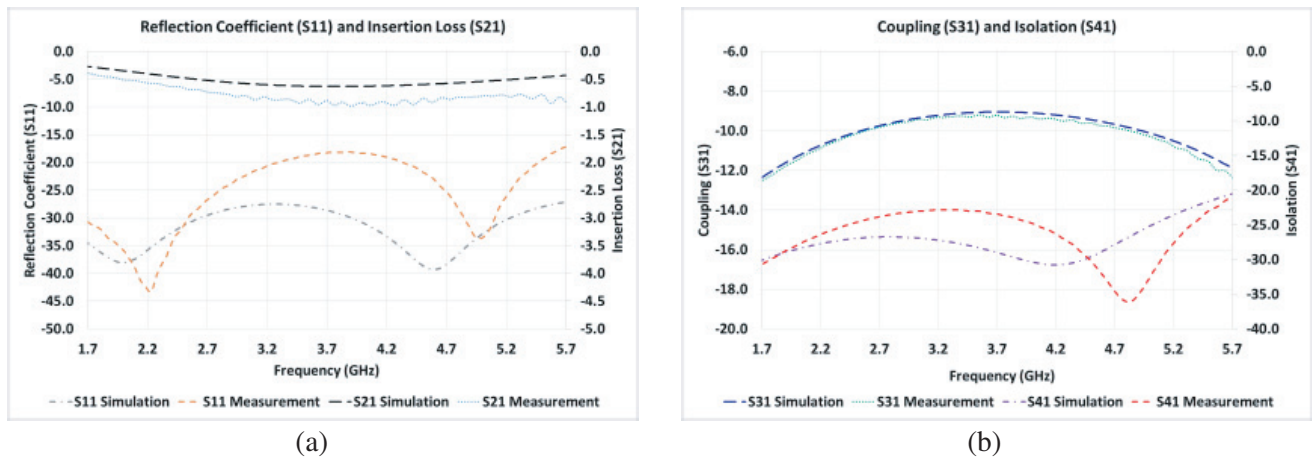


Figure 9. Simulation and measurement results for RO4003C, $d = 0.813$ mm, (a) reflection coefficient and insertion loss, and (b) coupling and isolation.

The bandwidth ratio for $10\text{ dB} \pm 1.5\text{ dB}$ coupling coefficient of the three-layer broadside coupler in [12] is approximately 3.4. Applying the same criteria, the bandwidth ratio for the proposed coupler will be approximately 3.2. This shows that the proposed coupler has a bandwidth comparable to [12] despite being a two-layer device. At the same time, the proposed coupler offers similar performance in terms of insertion loss, reflection coefficient and isolation.

4. CONCLUSION

A new wideband directional coupler that is designed using a semi-elliptical edge-coupled structure is presented. This structure consists of two semi-elliptical patches on the top layer and an elliptical defected ground plane on the bottom layer. Sets of design graphs are formulated to facilitate the design of the coupler. The operating frequency and coupling can be controlled by changing the dimensions of the elliptical patch and the width of the air gap. The structure is compact, simple, easy to fabricate and low cost. Both the simulation and measurement results show that the proposed design exhibits wideband characteristic with a bandwidth ratio of more than 2.4 for coupling deviation of $\pm 1\text{ dB}$. Both of the reflection coefficient and the isolation are better than 20 dB, while the insertion loss is less than 1 dB.

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