Progress In Electromagnetics Research B, Vol. 1, 291–305, 2008

ANALYSIS AND DESIGN OF AN ULTRA WIDEBAND DIRECTIONAL COUPLER

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Abstract—In this paper, a novel wideband directional coupler using coplanar waveguide multilayer slot-coupled technique is presented and implemented. The coupler uses two coplanar waveguide lines etched on two layers and coupled through an hexagonal slot etched on the common ground plane located between these layers. Firstly, conformal mapping techniques were used to obtain analytic closed-form expressions for the even- and odd-mode characteristic impedances. Secondly, using this approach, a new design of the directional coupler was performed. Both simulation and experimental results show a good performance in terms of bandwidth.

1. INTRODUCTION

High performance and low-cost directional couplers are highly desirable for developing new microwave components for modern wireless communication systems. Directional couplers are fundamental and indispensable components used in microwave integrated circuits applications. Indeed, these components are often used in microwave systems to combine or divide RF signals, and they are commonly applied in many applications, such as antenna feeds, balanced mixers, modulators and so on.

Tight-coupling directional couplers are often required in the design of various multiport circuits or beamforming networks of antenna arrays. In the practical issue, these couplers should be compact in order to be easily integrated with other components in the same circuit. For instance, the microstrip branch line couplers or hybrid ring couplers have extensively been employed in printed microstrip array feeding networks [1]. However, these couplers have inherently narrow bandwidths.

To overcome this situation, CPW technology has been proposed to implement various couplers. Indeed, CPW technology offers several attractive features: absence of costly and inductive via holes, ease of making shunt and series connections, ease of controlling the characteristics of CPW lines by changing the slot and strip widths, and possible implementability at millimeter-waves applications. Furthermore, directional couplers with CPW structures can also provide a higher directivity [1]. Using this technology, different configurations of CPW directional couplers have been proposed [2–5]. Moreover, to improve directional coupler performances, the conductor-backed coplanar waveguide technology was also proposed to reduce the coupler size and to avoid air bridges used to connect ground planes of the conventional CPW technology [6]. In this area, few works on CB-CPW couplers have been reported in literature [6–9]. A 3-dB CB-CPW coupled-line directional coupler has been used in tunable analog phase shifting [6]. A finite-extent backed conductor on the other side of the substrate is added to the conventional edge-coupled CPW structure has been suggested in [7] to enhance the coupling. Recently, broadside CB-CPW directional coupler has been proposed in [8]. However, this coupler has not been optimized to have the maximum of bandwidth to covers ultra-wideband applications.

In this paper, a new wideband multilayer directional coupler using hexagonal slot-coupled is proposed. In addition, using this coupling through hexagonal slot geometry located in a common ground plane, the coupler can offer more parameter design flexibility than the proposed one in [8]. First, a conformal mapping technique was developed and used to obtain fast and accurate design in the microwave frequency range. Second, a two-layer hexagonal slot coupled coupler was designed and implemented. The use of multilayer technology in this design is considered as an alternative method to conventional single-layer circuits to develop more compact couplers with tight coupling and small size. These couplers can find important applications to design beamforming networks and multiport amplifiers, where the CPW crossovers can be avoided.

To validate the proposed approach, a prototype circuits were analyzed, designed and fabricated. Simulations and measurements were performed, and the obtained results show a good performance in terms of bandwidth. The remainder of this paper is organized as follows. In Section 2, a quasi-static analysis for the proposed coupler is presented. The design and the performance of this coupler are described in Section 3. Finally, concluding remarks are given in Section 4.

2. QUASI-STATIC COUPLER ANALYSIS

Figure 1 shows the layout of the proposed slot-coupled directional coupler. It allows coupling two CPW lines placed in two stacked substrate layers through a rectangular slot etched on the common ground plane located between these layers. This component is symmetrical and has the following property: if Port 1 is fed, then the signal travels to Port 2 (direct), and consequently, Port 3 is coupled while Port 4 is isolated. The input power is split equally (3 dB off) between the two output ports, and the two signals present 90° out of

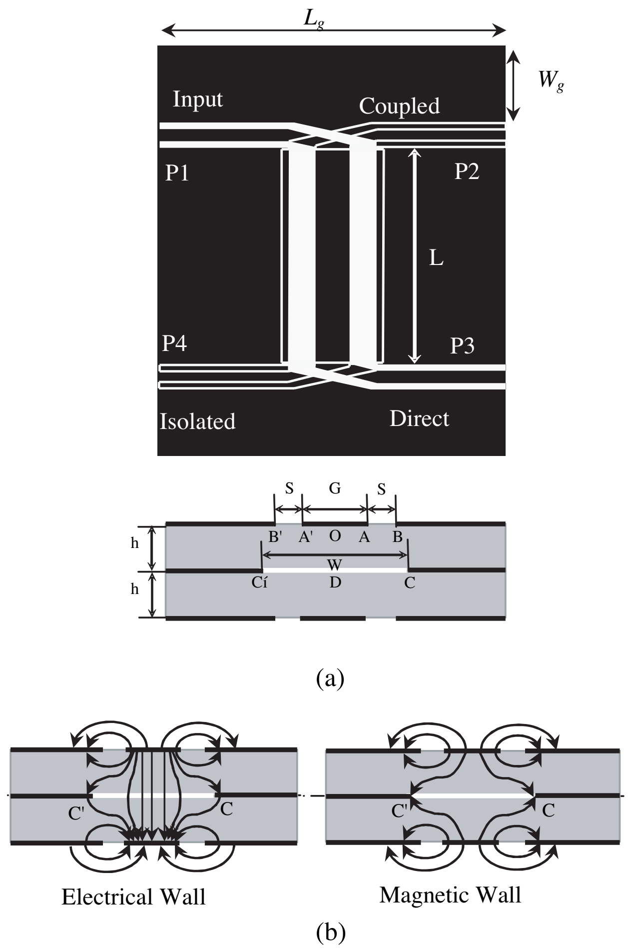


Figure 1. Broadside directional slot-coupled coupler: (a) layout, (b) odd and even-mode electric field distribution.

phase.

The cross section of the symmetrical CPW slot-coupled broadside directional coupler is shown in Fig. 1. This configuration is assumed to have infinitely wide ground planes. All conductors are assumed perfectly conducting and with zero thickness. This structure supports

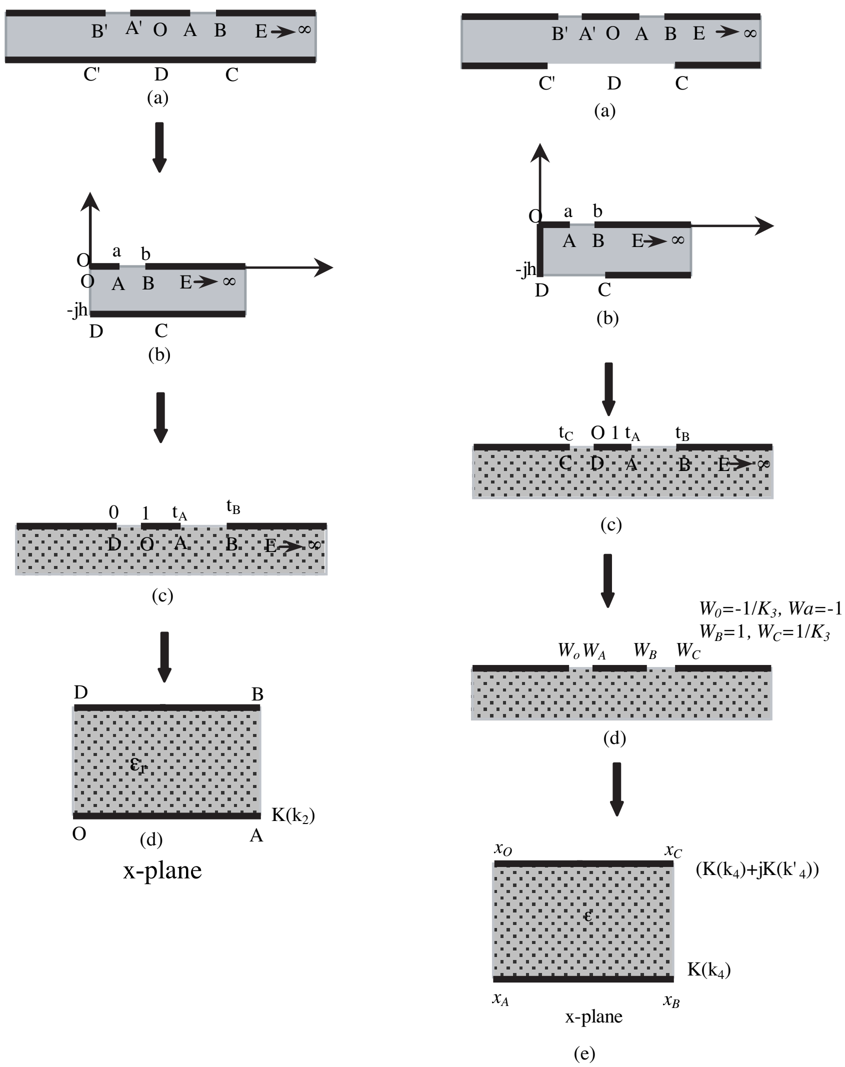


Figure 2. Conformal mapping transformation of the odd- and even-mode (dielectric region).

both fundamental modes, namely odd and even. The even and odd-mode coupler impedances, Z_{e0} and Z_{o0}, are calculated using conformal mapping techniques to determine the coupling capacitance per unit length. These modes are illustrated in Fig. 1(b). They can be isolated by assuming an electrical wall for the odd mode and a magnetic wall for the even one. The even mode propagates when equal currents, in amplitude and phase, flow on the two coupled lines, whereas the odd mode is obtained when the currents have equal amplitudes, but opposite phases [10]. For each mode, the overall capacitance per unit length, CT, can be considered as the sum of the coupling capacitance for the air and the dielectric region. To obtain these capacitances for the even mode, C_{e1} and C_{e2}, the sequence of conformal transformations shown in Fig. 3 is used, where the line CC' is considered as a magnetic wall. The goal in the two cases is to map the original boundary value problem in the z plane into a rectangular final x plane. Hence the total even-mode capacitance per unit length can be put in the form:

$$C_{eT} = C_{e1} + C_{e2} \tag{1}$$

The even-mode permittivity $\varepsilon_{e,\mathit{eff}}$ is defined as

$$\varepsilon_{e,\mathit{eff}} = \frac{C_{eT}(\varepsilon_r)}{C_{eT}(\varepsilon_r = 1)} \tag{2}$$

In the same manner, the odd-mode coupling characteristics, where the line CC' is considered as an electrical wall. So the capacitance C_{o1} and C_{o2} are obtained in a similar way to that utilized for obtaining C_{e1} as detailed in [9]. So we can write their values as follows:

$$C_{oT} = C_{o1} + C_{o2} \tag{3}$$

The odd-mode permittivity $\varepsilon_{o,\mathit{eff}}$ is defined as [12]:

$$\varepsilon_{o,\mathit{eff}} = \frac{C_{oT}(\varepsilon_r)}{C_{oT}(\varepsilon_r = 1)} \tag{4}$$

The coupling coefficient K found in [11] is defined as

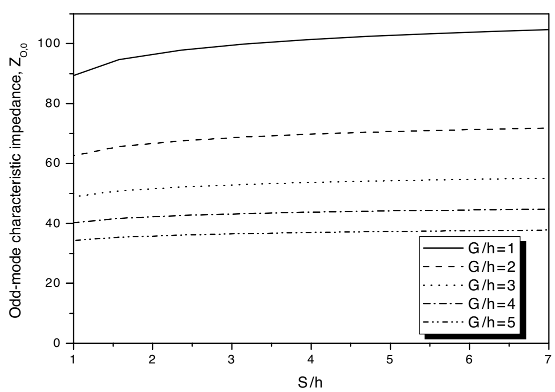
$$K = \frac{Z_{0,e} - Z_{0,o}}{Z_{0,e} + Z_{0,o}} \tag{5}$$

The coupling length L, is defined as [15]:

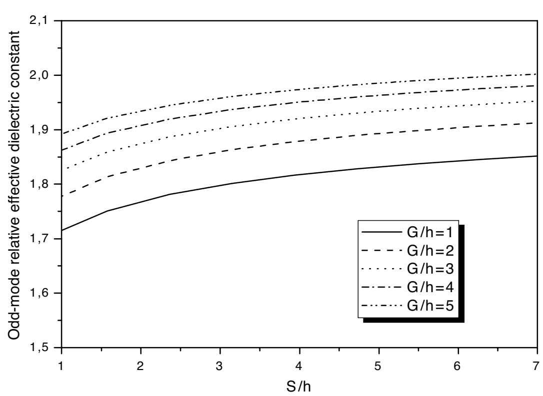
$$L = \frac{\lambda_{ge} + \lambda_{go}}{8} \tag{6}$$

3. RESULTS AND DISCUSSION

Numerical results of the odd-mode characteristic impedances and the effective permittivity of the CPW multilayer slot coupled-coupler are plotted in Fig. 3, versus the normalized gap width S/h and normalized strip width G/h. From these curves, it is seen that, for a fixed substrate thickness ($h = 0.254\,\text{mm}$), as the gap width (S) increases, the odd-mode characteristic impedance and the effective permittivity are increased. When the strip conductor width (G) increases, the characteristic impedance $Z_{0,o}$ decreases and the effective permittivity increases as shown in Fig. 3(a) and Fig. 3(b), respectively. In fact, the odd-mode parameters change slowly as the gap width is increased up to a certain limit.

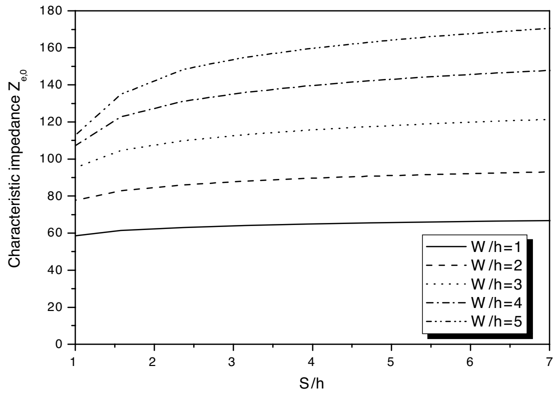


(a)

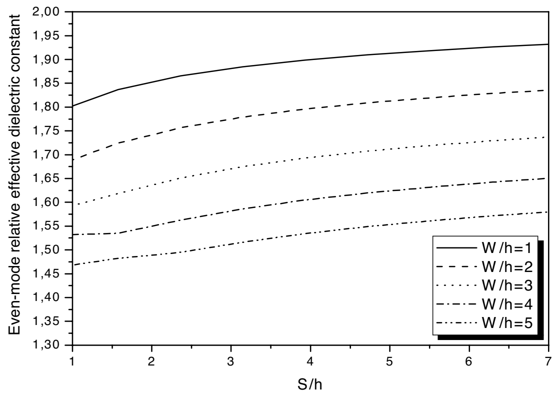


(b)

Figure 3. (a) Odd-mode characteristic impedance, (b) effective permittivity.



(a)



(b)

Figure 4. (a) Even-mode characteristic impedance, (b) effective permittivity as a function of S and W/h.

The even-mode characteristic impedance and the effective permittivity as a function of the normalized gap width S/h, normalized slot-coupled width W/h and W/G are shown in Fig. 4 and Fig. 5, respectively. As can be seen for a fixed strip conductor and thickness (G, h), $Z_{e,0}$ increases and the effective permittivity decreases when the slot-coupled width (W) increases. In addition, it is shown that the slot-coupled width Waffects the characteristic impedance $Z_{0,e}$ considerably (Fig. 5). However, the parameter W does not affect the odd-mode characteristic impedance, which is forced to be short circuited via the electrical wall.

The computed coupling coefficient K is illustrated in Fig. 6(a) in terms of both normalized slot-coupled width $W$and normalized slot

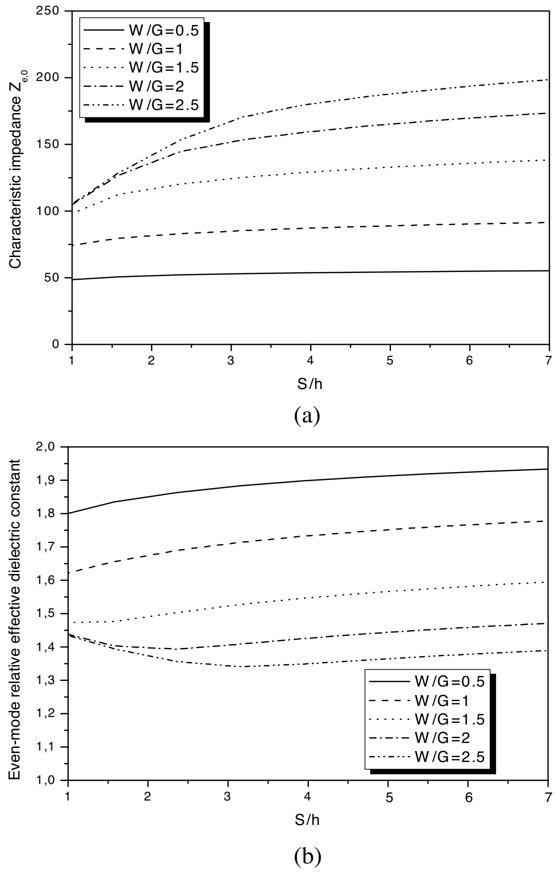
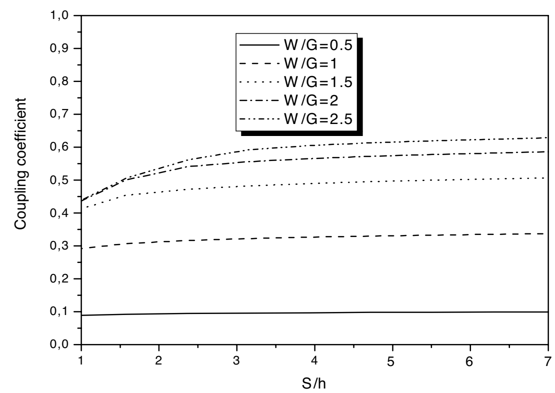


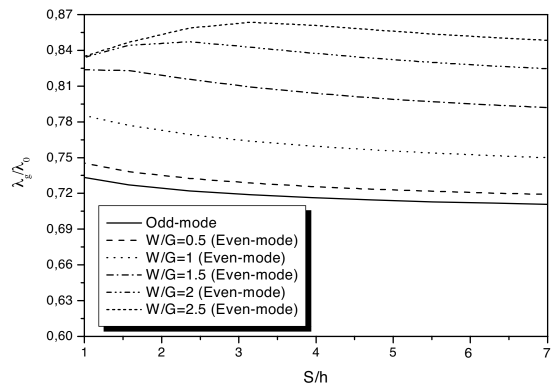
Figure 5. (a) Even-mode characteristic impedance, (b) and effective permittivity as a function of S and W/G.

width S. For a fixed strip conductor (G), the coupling increases as $S$and W increase. Moreover, it can be noted that the parameter W affects the coupling coefficient of the coupler considerably. The normalized wavelengths for the even- and odd-mode are shown in Fig. 6(b). These results are useful to determine the coupling length of the coupler.

The main drawback of the CB-CPW technology is the parallel-plate modes, which are considered as unwanted bulk modes [20]. This parasitic leakage effects observed in the conventional CB-CPW geometry, which are a trouble some issue in microwave circuits, are quite negligible for the proposed geometry up to 18,33 GHz, owing to



(a)



(b)

Figure 6. (a) Coupling coefficient, (b) normalized wavelength of even and odd modes.

smaller lateral dimensions of the CBCPW as well as a lower dielectric constant of the thin substrate ($\varepsilon_r = 2.2$). This indicates that the minimum parasitic resonant frequency from the parasitic parallel-plate modes of the CB-CPW, which can be predicted based on a simple rectangular patch theorem [20], by directly calculating the resonance frequency derived from the following equation, shifts to a higher frequency regime:

$$f_{mn} = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{W_g}\right)^2 + \left(\frac{n}{L_g}\right)^2} \tag{7}$$

where c is the velocity of light, ε_r is the relative permittivity, and

W_g (= 7 mm) and L_g (= 30 mm) are the width and the length of the ground in the proposed coupler as shown in Fig. 1. Using the above equation, the calculated lowest order mode resonance frequency f_{11} of 18.33 GHz is obtained. In this case, it can be noted that the leaky wave phenomenon does not affect the performance of the proposed coupler, which allows avoiding the use of via in the circuit.

4. COUPLER DESIGN AND PERFORMANCES

The design procedure for the proposed coupler is given as follow:

1) Calculate the even-odd mode characteristic impedances for the desired coupling C.
2) Determine the coupling strip width G and the slot width S corresponding to the characteristic impedance.
3) Evaluate the coupling slot width$W$ corresponding to the even-mode characteristic impedance.
4) Compute the coupling length L, as defined in (13).

Using the obtained results from the coupler analysis, two coupler prototypes were designed. The first prototype uses a rectangular slot between to layers of the coupler, where the top and bottom 50 Ω transmission lines were designed using a Duroid substrate (RT/ Duroid 5880) having a dielectric constant of $\varepsilon_r = 2.2$ and a thickness of $h = 0.254$ mm. The initial dimensions of the rectangular shaped slot coupled are obtained for $Z_{0,o} = 25\,\Omega$ and $Z_{0,e} = 96\,\Omega$ at 5 GHz. These initial parameters were simulated with *IE3D* [16], and the optimized values are estimated and implemented. The optimum rectangular slot has $G = 2$ mm, $S = 1.5$ mm, $W = 5$ mm and $L = 11.9$ mm. The length L of the coupler was designed to be a quarter wavelength at 5 GHz. The simulated and measured data of this prototype have been reported in [8], where a bandwidth of 4 GHz has been achieved.

In order to increase further the bandwidth of the proposed coupler, a second configuration using hexagonal-slot was also-proposed and designed. Fig. 7 shows the layout of the proposed CPW hexagonal-slot coupled directional coupler. With IE3D software, an optimization was carried out to determine the optimal values of the coupler dimensions. As a result, the optimal values of this coupler: $G = 2.8$ mm, $S = 1.2$ mm, $W = 6.5$ mm and $L = 12.1$ mm. To validate this design, a second prototype was fabricated and measured using an HP8772 network analyzer. The simulated and measured of the return loss and the insertion loss are shown in Fig. 8. From these results, it can be concluded that this second prototype offers a bandwidth of 6 GHz, which is a significant improvement compared to the first structure with a rectangular slot (4 GHz) reported in [8]. The average value of the coupling for the direct port and the coupled port is 3.5 dB, and the return loss and isolation are better than 20 dB within the operating band. It can be seen that the performances of the coupler were improved by adjusting the slot geometry. In addition, this second design chosen slot coupled geometry (hexagonal) offers a good transition and enough coupling between the CPW feed line and the slot coupled region line. The simulated and measured phase shifts between the two ports are plotted in Fig. 8(c). The phase difference between the direct and coupled ports is approximatively 90° across the operating band, which supports the proposed approach. Data comparisons of the simulated and experimental results show a good agreement.

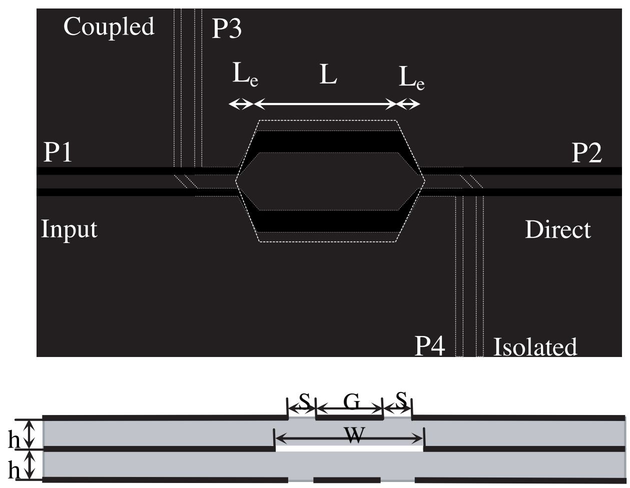


Figure 7. Layout of the proposed CPW hexagonal slot coupled directional coupler.

It is obvious that, the parameter L_e of the transition region, affects the behavior of the coupler. This parameter is used to investigate its characteristic in terms of bandwidth. Fig. 9 shows the simulation results, related to the variation of the direct and coupled port (S_{12}, S_{13}) versus L_e. According to these results, it can be concluded that the parameter L_e has a significant effect on the bandwidth of the directional coupler. As L_e varies from 0.5 mm to 2 mm, the bandwidth increases from 4.5 GHz to 6 GHz.

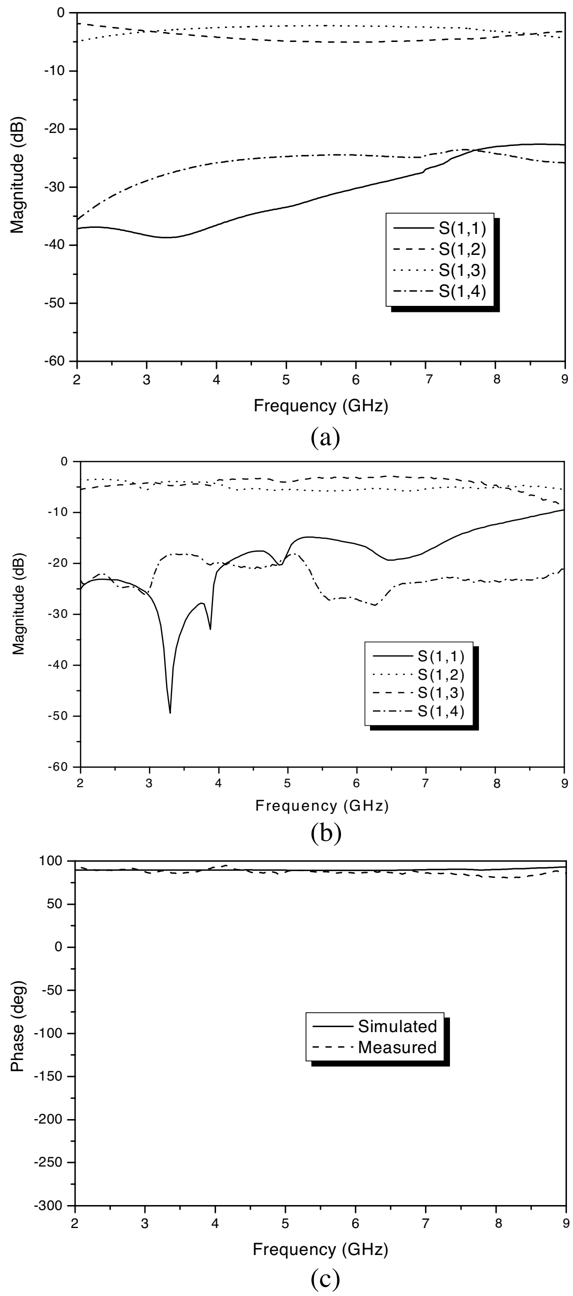


Figure 8. Scattering parameters of the proposed coupler (a) simulated, (b) measured, (c) phase difference.

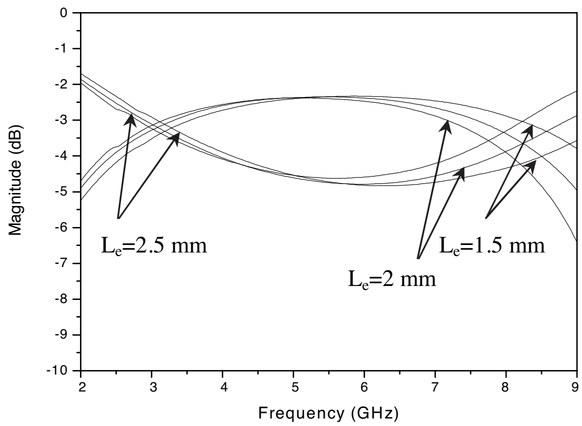


Figure 9. Simulated of the scattering parameters of the coupler versus L_e.

5. CONCLUSION

In this paper, a multilayer directional coupler using broadside CPW slot-coupled has been designed and analyzed. Simple analytic closed form expressions for the CPW slot-coupled coupler have been obtained using conformal mapping techniques. To validate this approach, experimental prototypes have been designed, fabricated and tested. Furthermore, it has been shown that by choosing the optimum dimensions of the coupling region, a bandwidth of 6 GHz has been achieved. The comparison between simulated and measured results shows a good agreement, with these features, the proposed coupler can find applications for ultra-wideband systems.

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