Design of a Novel Lumped Element Backward Directional Coupler Based on Parallel Coupled-Line Theory

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Abstract — **In this paper, a novel lumped equivalent circuit for a conventional parallel directional coupler is proposed. The equivalent circuit and design formula for the presented lumped element coupler is derived based on the even- and odd-mode properties of a parallel-coupled line. By using the derived design formula, we have designed the 3dB and 10dB lumped element directional couplers at the center frequency of 100Mhz. Furthermore, a chip type directional coupler has been designed to fabricate with multilayer configurations by employing the Low Temperature Cofired Ceramic (LTCC) process. Designed chip-type directional coupler has a 10dB-coupling value at the center frequency of 2GHz. Excellent agreements between simulations and measurements on the designed directional couplers show the validity of this paper.**

I. INTRODUCTION

Scaling down the overall module and packaging size is the demand for a various mobile handset to obtain electrically high reliable systems which meet the needs for wide band applications and of course which can provide multi-function. Thus, during the last years, size reduction of the passive components for a handset system came into discussion. This issue represents a developing design technology for passive components like filters, duplexers, and couplers in a multilayer ceramic configuration. In cellular wireless RF/microwave applications, quadrature 3-dB couplers are required to determine the phase error of a transmitter using the QPSK modulation scheme. [1] The basic requirements for such couplers include small size, low cost, tight amplitude balance, and 90-degree phase difference between the coupled and direct ports. [2] However, at the L-band, the conventional distributed couplers are big in size and also expensive. An equivalent lumped-element implementation is compact in size and has the potential to be cost effective. Several existing coupler configurations have been transformed into new configurations such as lumped-element couplers with a mutual inductance, the spiral directional coupler, and meander line couplers. [1]–[6] Further, some couplers are developing with Low Temperature Cofired Ceramics, which have advantages of low loss interconnections even in inner layers, low permittivity, the almost unlimited number of layers, the reproducible sheet thickness and various opportunities of material forming. It may provide the best-suited solution for mobile handset applications.

In this paper, we present a novel lumped-element backward directional coupler circuit to combine with the LTCC fabrication and a design method based on the even- and odd-mode properties of a parallel-coupled line. The proposed lumped-element coupler has only the self-inductors and capacitors, which can be accurately implemented by a multilayer configuration. In order to show the validity of this paper, we present comparison results between simulations and measurements on the designed 3dB and 10dB lumped element directional couplers. Furthermore, design and simulation result of a chip type directional coupler, which will be fabricated with LTCC process, is presented also.

II. DESIGN THEORY

Fig.1 shows the parallel-coupled directional coupler and a new lumped-element directional coupler, which has backward coupling performance.

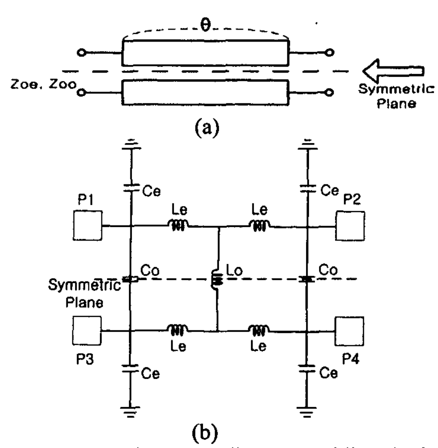

Fig. 1. (a) Conventional parallel coupled-line backward directional coupler. (b) Novel equivalent lumped element type backward directional coupler.

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The proposed lumped-element backward coupler circuit shown in Fig.1 (b) has only the self-inductance and -capacitance, which can be easily implemented with a lumped element. Basically the presented lumped-element coupler circuit is fully based on equality with a conventional parallel coupled line directional coupler in the even-and odd-mode operations. A symmetrical parallel coupled-line directional coupler has two symmetric planes that one is a longitudinal symmetric and the other is a transversal symmetric. By taking the longitudinal symmetry, the parallel coupled-line coupler can be divided into the even- and odd-mode transmission lines. The presented lumped-element coupler model in this paper is derived by investigating the even- and odd-mode transmission lines. L_e and C_e are determined by the even-mode parameters such as the even-mode impedance and electrical length of the transmission line. Fig.2 shows the even-mode transmission line representation of the parallel coupled-line coupler and its lumped equivalent circuit, which is a part of the proposed lumped-element directional coupler. The lumped equivalent circuit for the even-mode transmission line of the parallel coupled-line coupler becomes also the even-mode equivalent circuit of the proposed lumped-element directional coupler. [6]

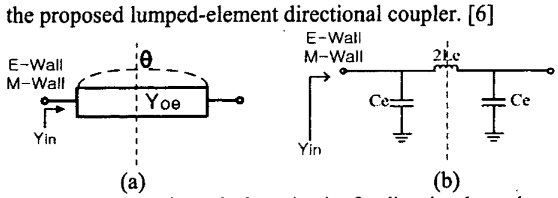


Fig. 2. Even-mode equivalent circuit of a directional coupler. (a) A parallel coupled-line directional coupler. (b) Lumped-element directional coupler.

C_e and L_e can be derived by simple manipulation for the input impedances of both circuits with opened and shorted terminations at each symmetrical plane, respectively. The resulting C_e and L_e are given by

$$C_e = \frac{Y_{oe}}{\omega}\tan\frac{\theta}{2} \tag{1}$$

$$L_e = \frac{1}{2}\frac{Z_{oe}}{\omega}\sin\theta \tag{2}$$

where Y_{oe} and Z_{oe} are the even-mode characteristic admittance and impedance of the transmission line, respectively.

For odd-mode equivalent circuit of the proposed lumped-element coupler, more parallel lumped-elements are included to explain the difference between the even- and odd-mode characteristic impedances of each transmission line. Fig.3 shows the odd-mode transmission line of the parallel coupled-line coupler and its lumped equivalent circuit, which is also equivalent circuit of the proposed lumped-element directional coupler. Parallel inductor $L_e/2$ shown in Fig.3 (b) increases the odd-mode input impedance of the equivalent circuit. Furthermore, the odd-mode parallel capacitor C_o guarantees the backward coupling behaviors of the proposed lumped-element coupler.

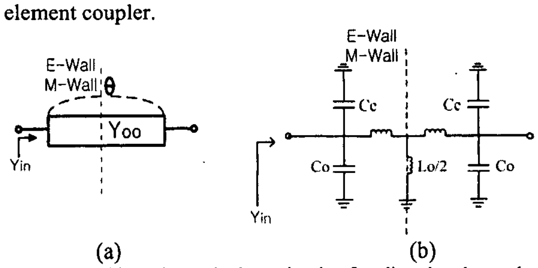


Fig. 3. Odd-mode equivalent circuit of a directional coupler. (a) A parallel coupled-line directional coupler. (b) Lumped-element directional coupler.

The odd-mode equivalent circuit parameters C_o and L_o can be derived by similar way to the even-mode equivalent circuit case. By placing the E-wall at the symmetric plane of both odd-mode circuits, both odd-mode equivalent circuits become simplified odd-mode excited circuits shown in Fig.4, respectively.

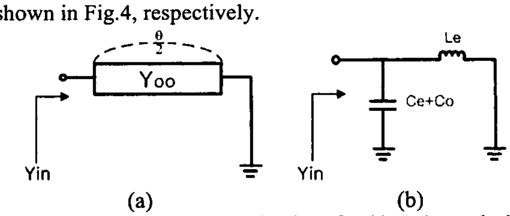


Fig. 4. Odd-mode excited circuits of odd-mode equivalent circuit of a directional coupler. (a) A parallel coupled-line directional coupler. (b) Lumped-element directional coupler.

The input admittances of the both odd-mode excited circuits are given by

$$Y_{in} = -jY_{oo}\cot\frac{\theta}{2} \tag{3}$$

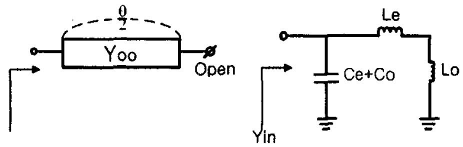
$$Y_{in} = j\omega(C_e + C_o) - \frac{1}{j\omega L_e} \tag{4}$$

where Y_{oo} means the odd-mode characteristic admittance of the transmission line. By employing the equality for the input admittances of the both odd-mode excited circuits, we can determine the odd-mode equivalent circuit parameter C_o as follow

$$C_o = -\frac{Y_{oo}}{\omega}\cot\frac{\theta}{2} + \frac{1}{\omega^2 L_e} - C_e \tag{5}$$

where C_e and L_e are given by (1) and (2), respectively.

In order to derive the odd-mode inductance L_o, we excite the even-mode source condition on the odd-mode equivalent circuit of a directional coupler. Fig. 5 shows the even-mode excited circuits of odd-mode equivalent circuit of a directional coupler. As we can see in Fig.5 (b), there is the odd-mode inductance.



(a) (b)

Fig. 5. Even-mode excited circuits of odd-mode equivalent circuit of a directional coupler. (a) A parallel coupled-line directional coupler. (b) Lumped-element directional coupler.

The input admittances of the both even-mode excited circuits are given by

$$Y_{in} = jY_{oo}\tan\frac{\theta}{2} \tag{6}$$

$$Y_{in} = j\omega(C_e + C_o) + \frac{1}{j\omega(L_e + L_o)} \tag{7}$$

And then the odd-mode inductance L_o could be derived exactly same way with C_o as follow

$$L_o = \frac{1}{\omega^2(C_e + C_o) - \omega Y_{oo}\tan\frac{\theta}{2}} - L_e \tag{8}$$

All the derived lumped-element coupler parameters L_e, C_e, L_o, and C_o are the self-inductances and capacitances. There is no mutual coupling lumped reactive element in the proposed lumped-element backward directional coupler.

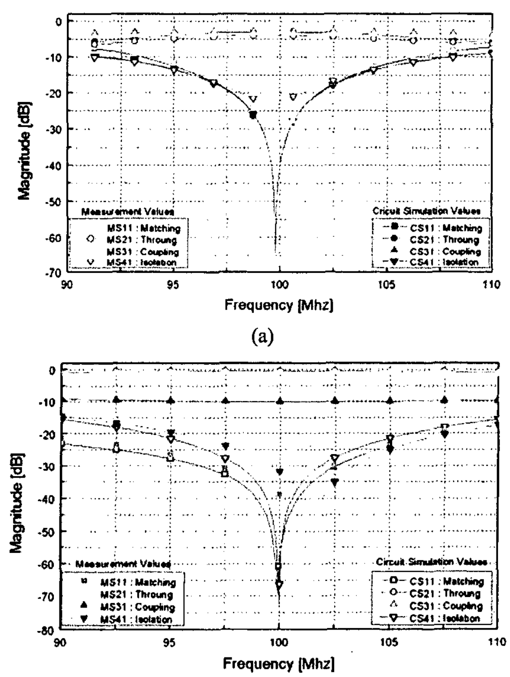
III. Simulations and Measurements

In order to show the validity of the proposed lumped coupler configuration and design theory, we have designed the lumped-element backward directional couplers by using the derived formula for the equivalent circuit parameters, which means the design formula of the proposed coupler. The design examples were chosen to be 3dB- and 10dB-couplers. For accurate fabrication, the center frequencies for both cases have been set identically to be 100MHz. Design results are shown in Table I.

TABLE I
Design Results of the Lumped Element Directional Couplers.

Element Values	3dB Case Z_{oe}=20.68Ω Z_{oo}=120.9Ω	10dB Case Z_{oe}=36.04Ω Z_{oo}=69.37Ω
C_e	76.98pF	44.16pF
L_e	16.45nH	28.68nH
C_o	31.91pF	10.61pF
L_o	3.39nH	31.01nH

The designed lumped-element couplers were fabricated on FR-4 organic substrate with lumped surface-mounted capacitors and inductors. Fig.6 shows the comparisons between the simulations and the measurements on the designed lumped-element directional couplers. It is seen that the fabricated lumped-element directional couplers have the excellent coupling and isolation characteristics with the good loss and matching performances. Furthermore, simulations and measurements show very good agreement in performance as seen in Fig.6.

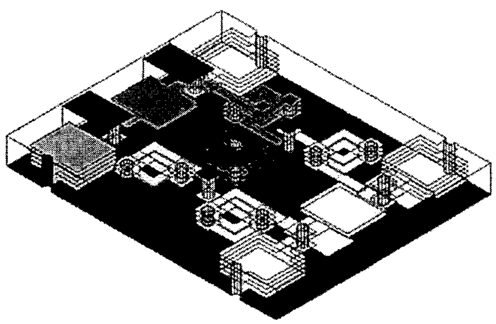


(a)

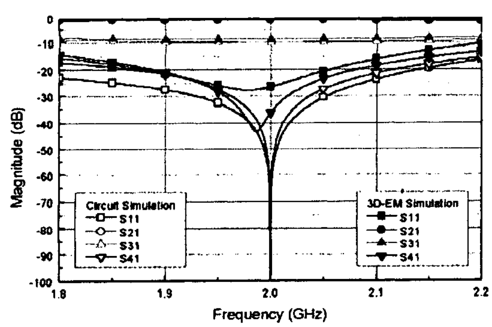
(b)

Fig. 6. Comparisons of the simulations and measurements on the designed lumped-element directional couplers. (a) 3dB-coupling value case. (b) 10dB-coupling value case.

The other design result of this paper is the chip-type lumped-element directional coupler. The motivation for the proposed lumped-element directional coupler is to develop the chip-type lumped coupler for mobile handset applications. Therefore, we have designed the chip-type lumped coupler with a multilayer configuration. Fig.7 (a) shows the layout of the designed chip-type coupler, which has 10dB-coupling value at the center frequency of 2GHz. The material for the designs was a Dupont 943, which has the most good loss characteristic. DP943 green tape is one of most popular material for LTCC. Dielectric constant of substrate was chosen to be 7.8 that is the dielectric constant of DP943. Overall size of the designed chip-type directional coupler included numbers of the embedded lumped-elements is 3mm×2.4mm×0.5mm. EM-simulation results are shown in Fig.7 (b). Simulations were carried out by three–dimensional (3-D) HFSS. Simulations on the designed chip-type coupler show very good performances. The embedded lumped elements can be easily constructed by applying the LTCC process.



(a)



(b)

Fig. 7. Designed chip-type lumped-element directional coupler with a multilayer configuration. (a) Layout of the designed chip-type directional coupler with 10dB-coupling value. (b) EM simulation results.

IV. Conclusion

In this paper, a novel lumped-element backward directional coupler circuit and its design method have been proposed. The design formula for the proposed lumped-element coupler has been derived based on the even- and odd-mode properties of a parallel-coupled line. Since there are only the self-inductances and capacitances in the presented coupler of this paper, the proposed lumped-element coupler is much easier to implement than the case that has the mutual coupling elements. Several simulations and experiments have demonstrated that the presented lumped-element coupler configuration and design formula is extremely effective in designing lumped-element directional couplers. In addition, a chip-type coupler example has been designed for LTCC applications. At this time, we are trying to fabricate the designed chip-type directional coupler by employing LTCC process. The proposed lumped-element backward coupler should be able to find applications in future RFICs and MMICs.

Acknowledgement

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References

[1] Arai, S. et. Al. "A 900Mhz 90 degree hybrid for QPSK modulator," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp.857-860, 1991.

[2] Hagerheiden, J., M. Ciminera, and G. Jue, " Improved planar spiral transformer theory applied to a miniature lumped element quadrature hybrid," *IEEE Trans. Microwave Theory Tech.*, vol.MTT-45, pp.543-545, Apr. 1997.

[3] Y-C. Chiang and C-Y Chen, "Design of lumped-element quadrature coupler," *Electron Lett.*, vol.34, pp.465-466, Mar. 1998.

[4] Y-C. Chiang and C-Y Chen, "Design of a wide-band lumped-element 3-dB quadrature coupler," *IEEE Trans. Microwave Theory Tech.*, vol.MTT-49, pp.476-479, Mar. 2001.

[5] Shibata, K., et. al., "Microstrip spiral directional coupler," *IEEE Trans. Microwave Theory Tech.*, vol.MTT-29, July, pp.680-689, 1981.

[6] Rajesh Mongia, Inder bahi, and Prakash Bhartia "*RF and Microwave Coupled Line Circuits*," Artech House pp.181_193.1999.