Quadrature Directional Couplers Using Multisection Coupled Lines

Ki Mann Jee, Sung Wan Kim, and Dong Chul Park

***Abstract*—New structure and design methods of directional couplers that can achieve both loose coupling and tight coupling by use of multisection coupled lines are presented. Output voltage formulas at each port are derived from the coupled-line theory. Measured results agree very well with predicted ones. Since the proposed couplers are very small in size and have suitable shape for high-density integrated circuits, they have potential applications in portable terminals for mobile communication systems.**

***Index Terms*—Coupled lines, directional couplers, multilayer, multisection.**

I. Introduction

BRANCH-LINE 90° hybrids, rat-race 180° hybrids, and coupled-line directional couplers have been frequently used for power dividers/combiners. Research on size reduction of branch-line 90° hybrids and rat-race 180° hybrids have been reported by using combinations of short high-impedance transmission lines and shunt-lumped capacitors [1], by replacing each branch with impedance or admittance inverters, or by utilizing coplanar waveguide and slotline [2]. Miniaturization of parallel coupled-line directional couplers has also been reported by inserting a floating potential conductor over a dielectric overlay to reduce the odd-mode impedance or by using a ground conductor with a tuning septum to increase the transmission line impedance [3]. However, the size-reduced branch-line 90° hybrids and rat-race 180° hybrids are still too large to be used for high-density integrated circuits. In the case of [3], the coupler design needs a lot of numerical calculation to find the dimensions of the floating conductor and tuning septum. In this letter we propose a new structure whose design is simple and straightforward from loose coupling to tight coupling and whose size is small enough for high-density integrated circuits.

II. Design Methods and Results

Fig. 1 shows multisection coupled-line directional couplers which are made up of three layers. The shaded areas indicate the conductor patterns on the dielectric layers. In Fig. 1(a), each conductor pattern is composed of three sections which are input/output ports, coupled lines, and uncoupled lines. a and a', and b and b' are the coupled lines of which electrical lengths are θ's. The higher the operating frequency of a coupler is, the smaller number of coupling sections that is usually needed in order to reduce the discontinuity effect. On the contrary, as the operating frequency becomes lower, the structure using larger number of coupled lines as shown in Fig. 1(b) becomes more attractive.

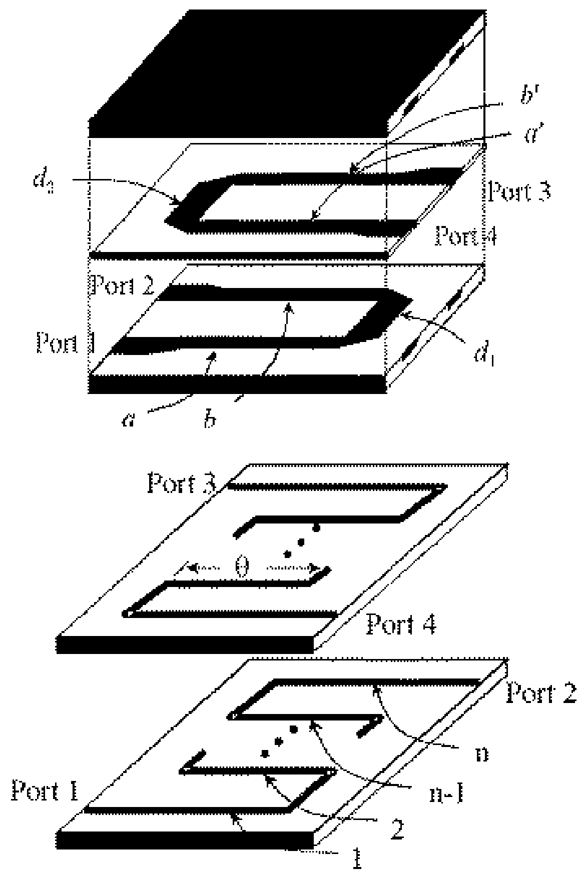

Fig. 1. (a) Two-section coupled-line directional coupler and (b) n-section coupled-line directional coupler with top layer removed.

The coupling coefficient and characteristic impedance of the coupled lines in Fig. 1 are given by

$$C = \frac{Z_{oe} - Z_{oo}}{Z_{oe} + Z_{oo}} \tag{1}$$

$$Z_o = \sqrt{Z_{oe} Z_{oo}}. \tag{2}$$

Once the even/odd-mode characteristic impedances Z_{oe} and Z_{oo} are determined from (1) and (2), the width and gap of the broadside-coupled lines can be easily obtained. When the voltage V_1 is applied to port 1, all the port voltages can be derived from the coupled-line theory. If the electrical lengths ϕ_1

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and ϕ_2 of the uncoupled lines d_1 and d_2 satisfy $\phi_1 = \phi_2 = \phi$, the output voltages can be expressed as follows:

$$V_2 = V_1 \left[\frac{1 - C^2(1 + \sin^2 \theta)}{\left(\sqrt{1 - C^2} \cos \theta + j \sin \theta\right)^2} \right] e^{-j\phi} \tag{3a}$$

$$V_3 = V_1 \left[\frac{2jC\sqrt{1 - C^2} \sin \theta}{\left(\sqrt{1 - C^2} \cos \theta + j \sin \theta\right)^2} \right] e^{-j\phi} \tag{3b}$$

$$V_4 = 0. \tag{3c}$$

In the case of 3-dB coupling, that is $|V_2| = |V_3|$, the electrical length θ of the coupled line is

$$\theta = \sin^{-1} \left\{ (\sqrt{2} - 1) \frac{\sqrt{1 - C^2}}{C} \right\}. \tag{4}$$

The structure in Fig. 1(a), which has two coupled sections, is similar to that analyzed by Walker [4], but our structure uses broadside coupling instead of edge coupling to achieve tight coupling easily and has much shorter coupled line lengths than $\theta = \pi/2$ to minimize the size. For the conventional edge-coupled 3-dB coupler, which is but hardly realizable, $C = 0.707$ and $\theta = \pi/2 = 1.5708$. However, for the case of our proposed coupler having 3-dB coupling with $n = 2$ and $C = 0.707$, $\theta = 0.4271$ which is about one fourth of the conventional one.

Similarly, the generalized output voltage formulas for multi-section coupled-line coupler which is shown in Fig. 1(b) can be expressed as follows:

$$V_{2,n} = \left(\frac{V_{2,n-1}\sqrt{1 - C^2} + jV_{3,n-1}C \sin \theta}{\sqrt{1 - C^2} \cos \theta + j \sin \theta} \right) e^{-j\phi}, \quad (n \geq 3) \tag{5a}$$

$$V_{3,n} = \left(\frac{V_{3,n-1}\sqrt{1 - C^2} + jV_{2,n-1}C \sin \theta}{\sqrt{1 - C^2} \cos \theta + j \sin \theta} \right) e^{-j\phi}, \quad (n \geq 3). \tag{5b}$$

If the number of coupling sections n is increased from 2 to 3, 4, and 5, the electrical length θ of the coupled lines becomes 0.2713, 0.2003, and 0.1591, respectively, for 3-dB coupling and the same center frequency. The size of the fabricated coupler using Cu-clad Teflon sheets with relative permittivity of 2.2 is $44 \times 32 \times 2.556$ mm^3, where 2.556 mm is the total height of the coupler including the lid. Fig. 2 shows the frequency responses of the scattering parameters of the designed coupler with $n = 2$. The dashed lines indicate FEM simulated results, while the solid lines are measured ones. The coupling, return loss, and isolation of the designed coupler were measured to be -3.07, -31, and -33 dB, respectively, at the design center frequency of 1 GHz and $\phi = 0.621$. The -3 ± 0.5 dB bandwidth of the coupler is 170 MHz which corresponds to 17% fractional bandwidth. For some applications this bandwidth may not be

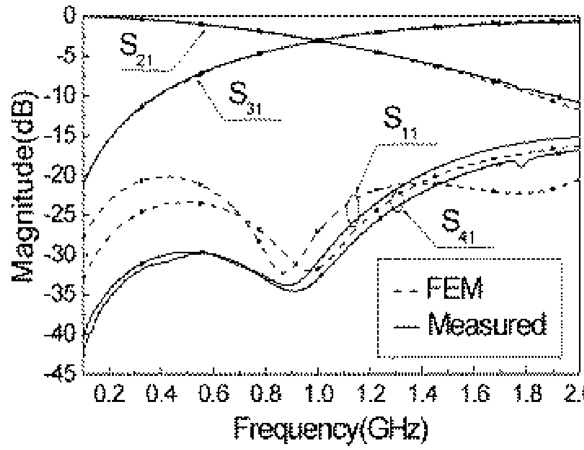

Fig. 2. Frequency responses of the designed coupler.

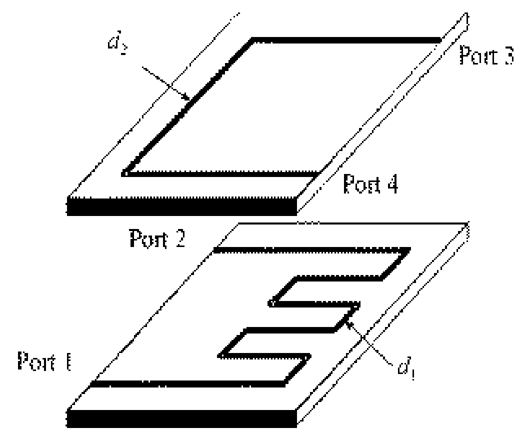

Fig. 3. Directional coupler using different-length uncoupled lines with top layer removed.

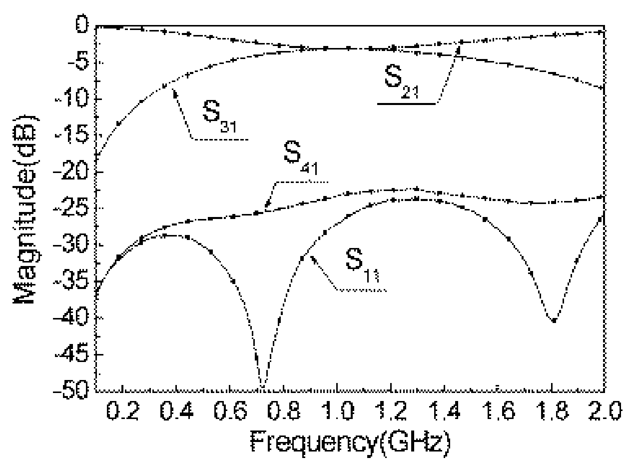

Fig. 4. Measured frequency responses.

wide enough. Wider bandwidth can be obtained in our proposed coupler by using lower value of C or by choosing d_1 and d_2 unequally. Fig. 3 shows the structure of the directional coupler which has different lengths of d_1 and d_2. The difference between electrical lengths of uncoupled line d_1 and d_2, $\phi_{12}(=\phi_1-\phi_2)$, is derived as follows:

$$\phi_{12}=\cos^{-1}\left(-\frac{1}{4C^2(1-C^2)}\{\csc^2\theta(-1+C^2(2-C^2) + 2C^2(1-C^2)\sin^2\theta - C^4\sin^4\theta)\}\right). \quad (6)$$

If we choose the value of C, the electrical length ϕ_{12} and θ can be found from (6) by use of computer optimization. When $C=0.707$, the calculated results for ϕ_{12} and θ are 1.224 and 0.612, respectively. The total size of the manufactured coupler, the length of d_1 and d_2, and lateral separation of the lines are $44\times32\times2.556$ mm^3, 66, 26, and 3.7 mm, respectively. The measured frequency characteristics are shown in Fig. 4. The bandwidth of 51.8% was achieved within -3 ± 0.5 dB coupling range. Isolation and insertion loss are better than -22 and -23 dB, respectively.

III. Conclusion

New structure and design methods of the multisection coupled-line directional couplers that can be miniaturized and can achieve both loose coupling and tight coupling have been proposed. We derived the generalized formulas for the output voltages and verified the performance of the proposed coupler. If the proposed coupler is made using high-permittivity material, it can be potentially used for mobile terminal components and applied to many MMIC applications.

References

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