Coupling Between Neighboring CPW's in MMIC's

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***Abstract*—Coupling between neighboring coplanar waveguides (CPW's) is simulated and measured. Simulation is based on two-dimensional (2-D) electromagnetic analysis and a network description. The investigations show that, in general, coupling may be neglected (lower than −30 dB) if the distance between the CPW's is more than twice their ground-to-ground spacing. However, this does not hold in the conductor-backed case with a connection between CPW ground and backside metal. Then, one finds sharp resonance peaks in the coupling exceeding −10 dB.**

***Index Terms*—Coplanar waveguide, coupling, MMIC.**

I. Introduction

COPLANAR waveguides (CPW's) are increasingly used in monolithic microwave integrated circuits (MMIC's), since they offer low-dispersive microwave propagation properties and backside processing is not required. In order to keep MMIC chip area small, the distance between neighboring transmission lines should be as small as possible. Therefore, it is interesting to know the amount of parasitic coupling from one line to the other.

In the classical directional-coupler theory, the maximum possible coupling coefficient is simply

$$k_{\max} = \left| \frac{Z_e - Z_o}{Z_e + Z_o} \right| \tag{1}$$

where Z_e and Z_o denote even- and odd-mode characteristic impedances of the coupled section. Also, matched line terminations are assumed. This theory can be directly applied to neighboring symmetrical microstrip lines because only two fundamental quasi-TEM modes exist in the three-conductor configuration of two coupled microstrip lines. Z_e and Z_o may be determined by electromagnetic simulation of the cross section of only one microstrip line using a magnetic and electric wall, respectively, as boundary in the center between the lines.

This description was applied also to the CPW case in [1] and [2]. Strictly speaking, however, coupled CPW's consist of five conductors or even six if a backside metallization is present. Thus, the structure supports four or five fundamental quasi-TEM modes, respectively. Moreover, although the approach using an electric and magnetic wall between the lines may be applied as well, the even- and odd-mode characteristic impedances of the CPW become ambiguous because the voltages across the two slots of each CPW are no longer equal. Thus, for coupled CPW's, (1) cannot be used for determining the coupling without introducing several unknown error sources.

In this letter, a more general approach is presented. It accounts for the multimode effects described above. Moreover, restrictions in previous investigations [1], [2] such as matched terminations, zero-thickness perfect conductors, or infinitely wide ground conductors, which do not hold in MMIC applications, are overcome. Nevertheless, the approach does not require three-dimensional (3-D) analysis but is based on two-dimensional (2-D) electromagnetic simulations together with a network representation.

II. Method of Analysis

Fig. 1 illustrates the geometry under consideration and provides the definition of voltages and currents. The structure consists of two adjacent CPW's. It involves six conductors and, therefore, supports five fundamental quasi-TEM modes.

A 2-D mode-matching method [3] is used to calculate the electric and magnetic fields of the five modes in the cross section of the CPW configuration. The method includes metallic loss by a selfconsistent description. Because of symmetry, only one half of the structure needs to be analyzed, with a magnetic wall and an electric wall in the center corresponding to the even- and odd-mode case, respectively. For the even-mode case, one has a CPW mode, a slot-line mode, and the parallel-plate line (PPL) mode [4]. The odd-mode case contributes the remaining two modes—one of the CPW, the other of the slot-line type.

After calculating the mode fields, conductor voltages and currents of all five modes are determined according to

$$U_n = - \int_{\text{reference electrode}}^{\text{conductor } n} \vec{E} \cdot d\vec{s} \quad \text{and} \quad I_n = \oint_C \vec{H} \cdot d\vec{s} \tag{2}$$

with C denoting the boundary of conductor n, I_n the current on conductor n in propagation direction, and U_n the voltage on conductor n referring to the reference electrode. As explained above, only one half of the structure is treated, in our case the left-hand part. The conductor voltages and currents of the right-hand part may be derived easily from those of the left one by symmetry considerations.

The fields of all modes have a spatial dependence in propagation direction z of $\exp(\pm k_z \cdot z)$ with the propagation constant $k_z = \beta - j \cdot \alpha$. The sign "+" corresponds to a wave in negative z-direction, the sign "−" to a wave in positive z-direction. The amplitudes A_+ and A_- are unknowns and are determined by the terminations of the lines at $z = 0$ and $z = l$ (l denotes the line length). Superposing the contributions of

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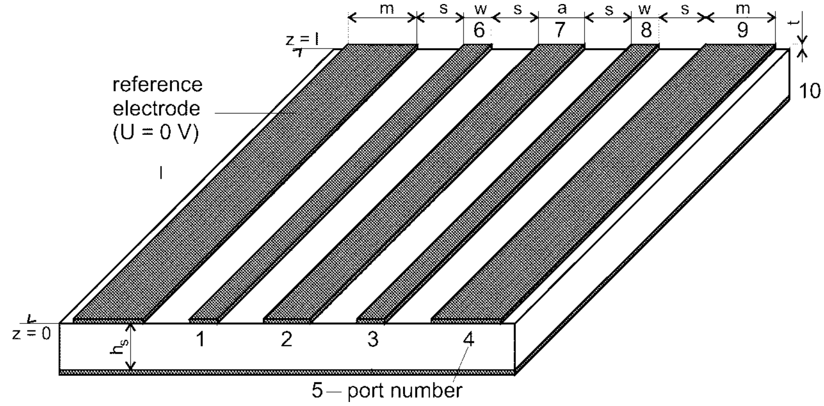

Fig. 1. The coupled CPW-structure under investigation.

all modes m on all conductors n yields the following system of equations:

$$U_n(z_0) = \sum_{m=1}^{5} U_n^{(m)} \cdot [A_+^{(m)} \cdot e^{-j \cdot k_z^{(m)} \cdot z_0} + A_-^{(m)} \cdot e^{+j \cdot k_z^{(m)} \cdot z_0}] \quad (3)$$

$$I_n(z_0) = \sum_{m=1}^{5} f(z_0) \cdot I_n^{(m)} \cdot [A_+^{(m)} \cdot e^{-j \cdot k_z^{(m)} \cdot z_0} + A_-^{(m)} \cdot e^{+j \cdot k_z^{(m)} \cdot z_0}] \quad (4)$$

with $z_0 = 0$, 1 and $f(z_0)$ being the sign function, which takes into account symmetric notation of the currents at the 10-port in Fig. 1:

$$f(z_0) = \begin{cases} 1, & \text{for } z_0 = 0 \\ -1, & \text{for } z_0 = 1. \end{cases} \quad (5)$$

Written in matrix form, the terminal behavior of the coupling structure is

$$\begin{bmatrix} U(z_0 = 0) \\ U(z_0 = 1) \end{bmatrix} = \begin{bmatrix} \overline{U} & \overline{U} \\ \overline{U} \cdot e^{-j \cdot k_z \cdot l} & \overline{U} \cdot e^{+j \cdot k_z \cdot l} \end{bmatrix} \cdot \begin{bmatrix} A_+ \\ A_- \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} I(z_0 = 0) \\ I(z_0 = 1) \end{bmatrix} = \begin{bmatrix} \overline{I} & -\overline{I} \\ -\overline{I} \cdot e^{-j \cdot k_z \cdot l} & +\overline{I} \cdot e^{+j \cdot k_z \cdot l} \end{bmatrix} \cdot \begin{bmatrix} A_+ \\ A_- \end{bmatrix}. \quad (7)$$

$\overline{U}$ and $\overline{I}$ are 5 × 5 matrices of the voltages and currents of the five modes on the five conductors. The system of (6) and (7) can be written as

$$[U] = [M_U] \cdot [A]$$
$$[I] = [M_I] \cdot [A]. \quad (8)$$

One has for the admittance matrix of the 10-port in Fig. 1

$$[Y] = [M_I] \cdot [M_U]^{-1}. \quad (9)$$

From the admittance matrix Y, all other network description forms can be derived. CPW coupling is determined as S-matrix transmission coefficient between ports 1 and 8, whereas the ports of the ground conductors (ports 2, 4, 7, and 9—see Fig. 1) are short-circuited to the reference electrode and the ports of the backside metallization (ports 5 and 10) are open-circuited. Ports 3 and 6 are open or short circuits to get the maximum possible CPW coupling for worst case estimations in MMIC applications.

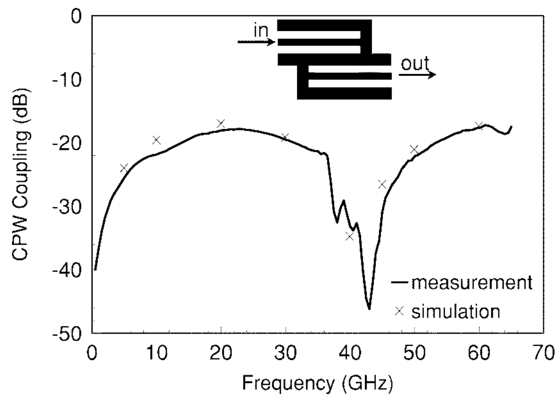

Fig. 2. Measured and simulated coupling: magnitude of transmission coefficient S_{81} against frequency (for dimensions see Fig. 1 with $w = 16$ μm, $s = 12$ μm, $m = a = 20$ μm, $t = 2.6$ μm, gold metallization with a conductivity of $3 \cdot 10^7$ S/m, $l = 1.6$ mm); ports 3 and 6 are terminated by short circuits (see inset).

III. Results

The simulations were validated by test structures fabricated at the RWTH Aachen, Germany, on high-resistivity silicon substrates ($\varepsilon_r = 11.67$, $h_s = 380$ μm). The coupling area is 1.6 mm long. The ground conductors of the CPW's are connected at all CPW terminations. There are two kinds of coupling structures either with short- or open-circuit CPW terminations. Network S-parameter measurements of the coupling from 0.5 to 65 GHz were performed. Maximum coupling is listed in Table I for several CPW distances and ground conductor widths. In Fig. 2, as an example, the curve for a test structure with CPW short-circuit terminations is shown. Additionally, the coupling calculated as described in Section II is included.

The simulation data in Table I was obtained by varying the line length at a frequency of 50 GHz. This requires less computer effort than frequency variation, because line variation is a simple network calculation, whereas a separate electromagnetic simulation run is necessary for each of the five propagation modes at each frequency point. Since the

TABLE I
MAXIMUM COUPLING IN DECIBELS BETWEEN TWO CPW'S AS A FUNCTION OF SEPARATION FOR SHORT- AND OPEN-CIRCUIT TERMINATIONS, RESPECTIVELY (FOR STRUCTURE, SEE FIG. 1; d DENOTES CPW GROUND-TO-GROUND SPACING $w + 2s$). TOP AND BOTTOM GROUND CONDUCTORS ARE NOT CONNECTED

distance	CPW short		CPW open	
a/d	simulation	measurement	simulation	measurement
1. CPW with w = 16 μm, s=12 μm, m = 160 μm				
0.5	-19.0	-20.6	-20.2	-21.0
1	-24.4	-26.0	-25.5	-26.9
2	-29.4	-32.8	-31.0	-34.0
2. CPW with w = 16 μm, s=12 μm, m = a				
0.5	-16.7	-17.9	-16.0	-19.0
1	-22.5	-23.7	-22.4	-25.5
2	-29.9	-31.4	-29.9	-32.8

propagation quantities of the CPW, especially characteristic impedance and propagation constant, show only low dispersion, the results remain valid in the range from about 15 to 100 GHz. If the coupling section is longer than half the wavelength λ, parasitic modes (e.g., the slot line mode) may interfere with the CPW mode at multiples of $\lambda/2$. To avoid such effects in MMIC's, one includes air bridges connecting the ground conductors at all discontinuities and with a spacing of less than $\lambda/2$. Therefore, we checked the influence of such air-bridge connections on the results of Table I and Fig. 2 and found that the maximum coupling data is not affected.

As can be seen in Table I, short- and open-circuit terminations of the CPW's result in similar values for maximum coupling. The differences between measurements and simulation are attributed to inaccuracies in both approaches, which easily may occur at coupling levels below -20 dB as found here. Summarizing the results, a simple rule of thumb can be deduced: Choosing the distance a between the CPW's larger than two times the CPW ground-to-ground spacing, a coupling of less than -30 dB is achieved.

In the case of matched CPW terminations, we obtain simulation results similar to the analytic approach of Ghione and Naldi [1]. We did not choose the matched condition, however, because for open or short circuit terminations coupling is about 6 dB larger, which appears to be more realistic for worst case estimations in MMIC applications.

It is interesting to note that a completely different coupling behavior of the CPW's can be observed, if the backside metal is connected to the CPW ground conductors somewhere. In order to model this situation using the structure in Fig. 1, we short-circuit the reference electrode to the backside conductor at ports 5 and 10. In practice, this connection may be caused by via holes or a package wall. Fig. 3 demonstrates the resulting changes. If there exists a connection between top and backside, sharp resonance peaks occur in the coupling curve. Up to -3-dB microwave power may be scattered from one CPW to the

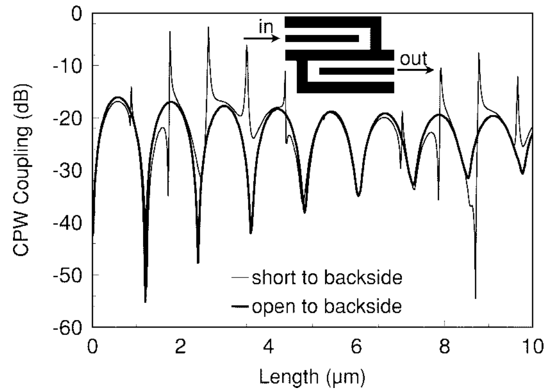

Fig. 3. Simulated CPW coupling of conductor-backed CPW's with open-circuit termination as a function of coupler length l (for dimensions see Fig. 2). Comparison of structures with and without connection between CPW ground conductors and backside metallization at $z = 0$ and $z = l$.

other at certain frequencies and coupling lengths, which is observed also for larger distances between the CPW's. This phenomenon does not take place only for the ideal short between top and backside ground metallization. In order to study this we replaced the connection by an impedance with reflection coefficient r and varied the value of r. One finds that the peaks vanish for the open-circuit ($r = +1$), but already for small deviations from this condition, e.g., when changing r from $+1$ to $\exp(\pm j5^{\circ})$, sharp resonance peaks occur. This behavior changes only if resistive terminations are used. On the other hand, the peaks are reduced below -10 dB if the CPW's are terminated with short circuits at ports 3 and 6. Results in [4] confirm the findings described above.

IV. CONCLUSIONS

Simple design rules can be derived describing the coupling of neighboring CPW's. Given the distance a of the lines worst case coupling k varies as follows (ground-to-ground spacing $d = w + 2$s, see Fig. 1):

- $a/d = 0.5$ $k < -16$ dB
- $a/d = 1$ $k < -22$ dB
- $a/d = 2$ $k < -30$ dB.

That means a distance of twice the CPW ground-to-ground spacing ensures enough isolation for most applications. When connecting top and backside ground conductors in conductor-backed CPW structures, however, these values may deteriorate drastically. In this case, sharp resonance peaks in the coupling up to -3 dB occur.

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