Wideband mm-Wave CMOS Slow Wave Coupler

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Wideband mm-Wave CMOS Slow-Wave Coupler

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***Abstract*—In this paper, we have presented a design of on-chip millimeter-wave 3-dB quadrature coupler that utilizes the coupled slow-wave coplanar waveguide (CS-CPW). The designed CMOS coupler covers the whole E- and W-band and occupies a silicon area of only 0.0115 mm^2 which is significantly smaller compared to the conventional microstrip-line-based Lange couplers. Measurement of the quadrature coupler shows a -3.5 dB through and a -4.4 dB coupling at 90 GHz. A less than ±1-dB amplitude and a ±4° phase errors from 55 to 110 GHz are recorded.**

***Index Terms*—Coupler, coupled line, CMOS, CS-CPW, E-band, Lange coupler, mm-wave, SiGe, slow-wave, quadrature, W-band, 3-dB.**

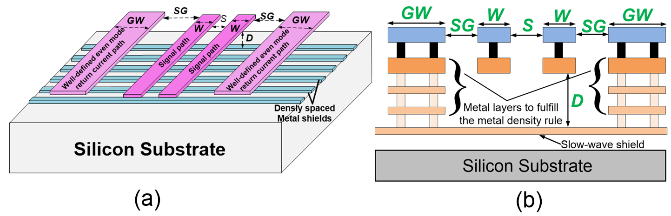

Fig. 1. Slow-wave coplanar waveguide (CS-CPW) (a) 3-D view, and (b) cross-sectional view. The signal lines are formed by connecting two metal layers on top of each other to reduce the resistive losses.

I. Introduction

A 3-DB coupler with a 90° phase difference between its outputs is a significant building block in a microwave or millimeter-wave (mm-wave) system. It can be used for the I/Q modulator-demodulators, phase shifters, triplers, and various mixer topologies. These couplers are often implemented by Lange couplers. The Lange coupler design technique involves quarter wavelength lines at the design frequency and is usually realized with microstrip lines. However, on a standard silicon technology, one major drawback of microstrip lines is the low effective dielectric constant (∼4), which is defined by the surrounding media (silicon dioxide). Therefore, the couplers become very large and occupy a noticeable silicon area.

Over the years, efforts have been made to miniaturize the size of silicon quadrature couplers. For example, in [1], a thin film microstrip line is used with an aggressive meandering to reduce the size of the coupler. In [2], a coupler based on the coupled slow-wave coplanar waveguide (CS-CPW) is presented, and the miniaturization is achieved by modifying the shielding ribbons. Nevertheless, none of the works addressed the modeling methodology (with a simulator) used for designing their proposed complex coupler structures, whereas customarily, an efficient and reliable modeling methodology is critical in the CMOS circuit designs. Therefore, in this work, we have shown how to model and design a novel compact 3-dB quadrature coupler using the balanced slow-wave coplanar waveguide. The CS-CPW is implemented to design the coupler because of its wideband and robust properties [3]. The proposed coupler structure is easy to model and scalable in length. Due to the presence of the slow-wave phenomenon in the structure, a carefully engineered design could reduce the size of the coupler significantly compared to conventional Lange couplers.

II. Design of a Coupler Using the CS-CPW

A CS-CPW is an efficient way of implementing a coupled line in silicon technology [3][4]. The CS-CPW consists of two signal lines, side-ground lines in both sides of the signal lines which serve as the well-defined ground return current paths for the even-mode signal propagation, and gridded metal shields under the signal and ground lines. A 3-D and cross-sectional view of a fundamental CS-CPW structure is illustrated in Fig. 1. Modeling of the CS-CPW structure by computer simulations is computationally heavy and time-consuming. Therefore, an efficient modeling methodology is proposed in [4] and successfully verified in [3]. The modeling approach divides the electromagnetic (EM) simulations of the CS-CPW structure into four parts, at first, it divides into odd- and even-mode analysis, and each mode is further decoupled into odd- and even-mode *R & L* and *C & G* analysis. The *R, L, C,* and *G* are the transmission line (Tline) parameters (Telegraphers equation) [5] which support the transverse electromagnetic (TEM) propagation. Four two-port *S*-parameter data sets are obtained from these four EM simulations, and using these data sets, the odd- and even-mode Tline parameters are calculated by the formulas stated in [6]. Once the Tline parameters for both the odd- and even-modes are obtained, the essential coupled transmission line (CP-Tline) parameters can be calculated from [5]. The necessary model parameters for a CP-Tline are odd- and even-mode characteristic impedances (Z_{0o}, Z_{0e}), effective dielectric constants (ε_{ro}, ε_{re}), attenuation constants (α_o, α_e), and a loss tangent (tanδ). Finally, a scalable (in length) electrical model of the CS-CPW is deduced with the CP-Tline model parameters for the simulation. Therefore, a fraction of the total coupler length, i.e., an $\lambda_g/8$ line is sufficient to model the coupler. Once the equivalent CP-Tline model is obtained, we can observe the final coupler

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TABLE I
MAPPING TABLE TO OBSERVE THE VARIATION OF L_{even}, L_{odd}, C_{even}, C_{odd}, Z_{0e}, AND Z_{0o} VS. GEOMETRICAL PARAMETER CHANGES

Geometrical parameter	Output					
	L_{even}	L_{odd}	C_{even}	C_{odd}	Z_{0e}	Z_{0o}
W ↑	↓	↓	↑	↑	↓	↓
S ↑	↓	↑	↑	↓	↓	↑
D ↑	↕	↕	↓	↓	↑	↑
SG ↑	↑	↕	↓	↕	↑	↕
GW ↑	↓	↕	↑	↕	↓	↕

performance, i.e., through, coupling, isolation, and directivity by simulating the CP-Tline at $\lambda_g/4$.

In this work, we have analyzed the characteristic of the CS-CPW structure by the EM simulations to develop a table which will show its behavior with respect to the geometric/design parameters. The derived table will help the designers to select suitable primary values of the CS-CPW design variables. For this study, we have varied the CS-CPW design variables *S, D, W, SG,* and *GW*, [see Fig. 1] and observed the changes in essential Tline parameters. While varying one design variable, the other variables are kept constant. A standard 65-nm CMOS technology is used for this analysis. The EM simulations are performed based on the modeling methodology described earlier with a 2.5D simulator. The outcomes of the experiments are shown in Table I. Table I shows line parameter variations over the changes in CS-CPW design variables with the indicators, increasing (↑), decreasing (↓), and no change (↕).

A coupler with a coupling factor of 3-dB requires a ratio of ∼1:6 for the odd- and even-mode characteristic impedances [5], which is the key design goal to be obtained. Also, the absolute value of the Z_{0o} and Z_{0e} are important for matching. As an example, for a 3-dB coupler, the Z_{0o} and Z_{0e} have to be 20.67 Ω and 120.9 Ω, respectively, for a 50 Ω system. Once the required odd- and even-mode impedances are known, the design starts with selecting the primary design variables of the CS-CPW for the EM simulations. Table I predicts the primary values of the CS-CPW design variables. However, in practice the required design goals with the fundamental CS-CPW structure shown in Fig. 1(b) are not possible to achieve using the given technology. This is mainly due to the tight technology-specific design rules present in a deep sub-micron CMOS technology. Higher Z_{0e} with adequate slow-wave effect is restricted by the SG, which cannot be increased arbitrarily (metal density issue). On the other hand, the required Z_{0o} is obtainable but this would affect the even-mode parameters because moving the slow-wave shielding position (D) closer to the signal lines would increase the ε_{ro} and ε_{re} but will decrease the Z_{0e} and Z_{0o}.

Therefore, we modify the CS-CPW structure to improve the odd-mode slow-wave effect locally without affecting the even-mode parameters as shown in Fig. 2(a). To obtain strong capacitive coupling in odd-mode propagation the top-most metal layer of the signal lines is modified to create L-shaped slabs. The value of L has adjusted as such that the new CS-CPW structure provides a higher ε_{ro} and at the same time the Z_{0o} value is closer to the desired. The changes in

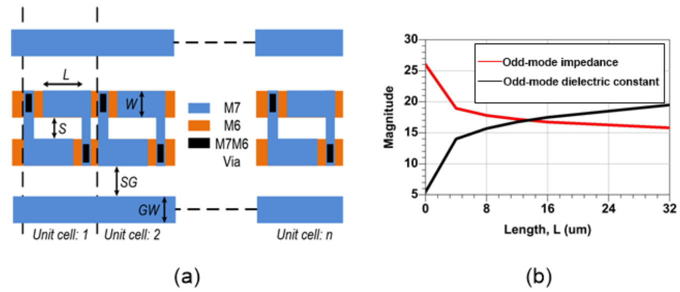

Fig. 2. (a) Top view of CS-CPW structure when the signal lines are modified to improve capacitive coupling in odd-mode signal propagation. Here, the slow-wave grids are not shown to avoid ambiguities in the figure. (b) The changes in Z_{0o} and ε_{ro} with respect to the L. The values at $L = 0$ correspond to the CS-CPW without the L-shaped structure.

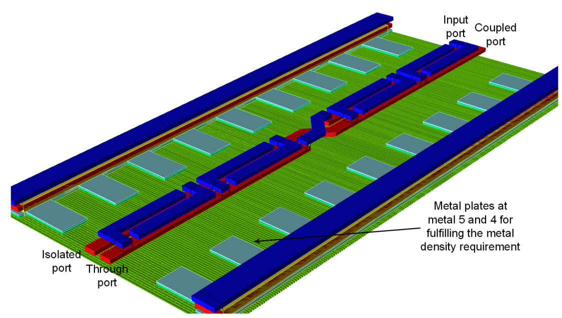

Fig. 3. 3D illustration of the CS-CPW structure used for obtaining the scalable coupler model. The structure is 110 μm long and includes four unit cells.

Z_{0o} and ε_{ro} with respect to the L is plotted in Fig. 2(b). Again, it is important to note that this modification of the CS-CPW structure has a negligible effect on the even-mode line parameters. So, the required ratio between the odd- and even-mode impedances is achieved. Furthermore, the structure is modified in such a way that it remains scalable in length. Therefore, we have considered a unit cell approach so that the complete coupler structure can be made by repeating the number of required unit cells. The gap between the unit cells is set by the technology-specific design rules of minimum metal gaps. Table II shows that the effect of repeating the unit cells on the line parameters are negligible, hence, the proposed structure is scalable in length.

Four unit cells with the design parameters, *W*=2.5μm, *S*=1.5μm, *D*=1.54μm, *SG*=19.75μm, *GW*=5μm, and *L*=16μm are considered to design the scalable coupler model. For the purpose of illustration, a 3-D view of the simulation structure

TABLE II
VALUE OF LINE PARAMETERS FOR DIFFERENT NUMBER OF UNIT CELLS

Odd-mode line parameters							
No. of unit cell	Corresponding Length (μm)	R_{odd} (Ω/mm)	L_{odd} (pH/mm)	C_{odd} (fF/mm)	α_o (dB/mm)	Z_{0o} (Ω)	ϵ_{ro}
4	110	17.71	232.87	835	4.59	16.75	17.47
6	156	17.87	231.23	877	4.80	16.27	18.25
8	202	17.80	230.5	894	4.90	16.12	18.50
Even-mode line parameters							
No. of unit cell	Corresponding Length (μm)	R_{even} (Ω/mm)	L_{even} (pH/mm)	C_{even} (fF/mm)	α_e (dB/mm)	Z_{0e} (Ω)	ϵ_{re}
4	110	30.97	1300	129.6	1.29	100.15	15.14
6	156	30.95	1297	129.1	1.31	100	15.15
8	202	31.55	1298	130.1	1.36	99.77	15.20

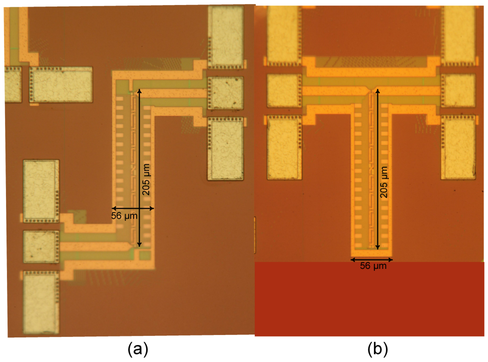

Fig. 4. Micrograph of the CS-CPW based coupler test structures for (a) through and (b) coupling measurements. The core dimension of the coupler is 56 μm $\times$ 205 μm, and consists of the proposed eight unit cells.

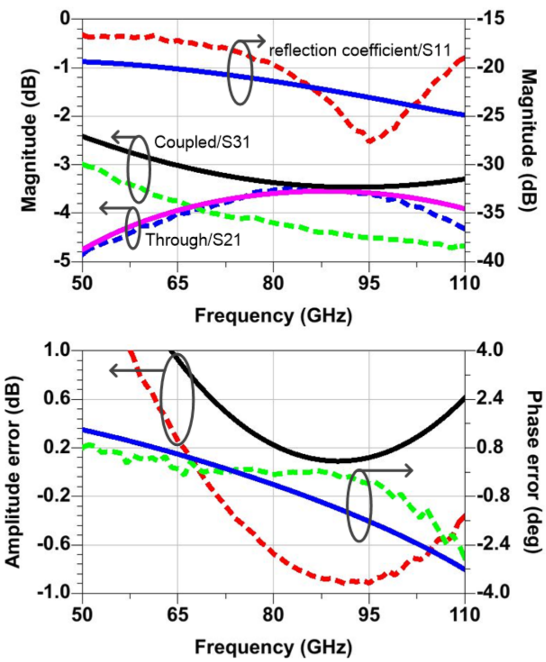

Fig. 5. Measured (dotted) and simulated (solid) S-parameters, amplitude, and phase errors for the designed 3-dB quadrature coupler.

is shown in Fig. 3. The model parameters obtained from these design parameters are shown in Table II. Although, the desired absolute value of Z_{0o} and Z_{0e} for the 50Ω system could not be obtained, the required impedance ratio ($\sim$1:6) and a more than 20 dB return loss are achieved by the proposed structure. The obtained coupler model suggests a length of 205μm long proposed CS-CPW structure is required for the desired 3-dB coupler at 90 GHz.

III. Measurement Results

The 3-dB quadrature coupler is fabricated in a 65-nm bulk CMOS technology. The core dimension of the coupler is 56 μm $\times$ 205 μm. The coupler consists of the eight proposed unit cells to cover the entire length. On-wafer S-parameter measurements are carried out for the coupler characterization. The coupled line coupler is a four-port device, and due to the unavailability of the four-port VNA, we have fabricated two identical coupler structures but with different port configurations for through and coupling measurements. The contribution of the pads and the extra Tlines are de-embedded from the measurement results. The micrographs of the coupler test structures are shown in Fig. 4. The measured and simulated results for the coupler are shown in Fig. 5. A good correlation is observed between the simulated and the measured coupler performance. An insertion loss of -0.5 dB at the through-port and -1.4 dB at the coupled-port at 90 GHz are recorded. A less than $\pm$2.5° phase variation, $\pm$1-dB amplitude error, and a better than 18 dB return loss is measured over a wide bandwidth from 55 GHz to 110 GHz.

TABLE III
State-of- the-Art Performance of mm-wave 3-dB Quadrature Couplers on Silicon Technology

Ref.	**This work**	[1]	[7]	[8]	[2]
Technology	**65-nm CMOS**	130-nm BiCMOS	130-nm BiCMOS	90-nm CMOS	130-nm BiCMOS
Topology	**CS-CPW**	Meander	QLQC	EC-CPW	CS-CPW
Frequency	**90 G**	60 G	62 G	62 G	60 G
Through	**3.5 dB**	4 dB	-	4.8 dB	3.3 dB+
Coupling	**4.4 dB**	5 dB	4.1 dB	5.5 dB	3.5 dB+
Return loss	**>18 dB**	15 dB	12.7 dB	22 dB	29+ dB
1-dB BW	**55 G**	-	4 G	6.5 G	-
$\pm 3^0$ BW	**>60 G**	19 G*	10.5 G	9 G	-
Size**	**0.001λ^2**	0.001λ^2	0.0015λ^2	0.004λ^2	0.003λ^2

*$\pm 2^0$ BW; +simulation data; **free space wavelength

IV. Conclusion

A 3-dB quadrature coupler covering the whole E- and W-band has been successfully demonstrated in a 65-nm CMOS technology. The state-of-the-art results published for the 3-dB quadrature couplers realized on monolithic silicon technologies are shown in Table III. The presented results show an excellent wideband coupler performance along with a very compact size. Moreover, the good agreement between the simulation and the measurement results indicates the validity of the CS-CPW modeling technique. The proposed scalable CS-CPW based coupler is easy to model and well suited for the design of the compact mm-wave silicon radio front-ends.

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