Design of Synthetic Quasi-TEM Transmission Line for CMOS Compact Integrated Circuit

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Abstract—This paper presents the design guidelines of the synthetic quasi-TEM transmission line (TL) based on standard 0.18- μm one-poly six-metal complementary metal-oxide-semiconductor (CMOS) technology. The synthetic quasi-TEM TL, also called the complementary-conducting-strip transmission line (CCS TL), is composed of five structural parameters to synthesize its guiding characteristics. Twenty-four designs of CCS TL are reported, with the following unique attributes. First, a characteristic impedance range of 8.62–104.0 Ω is yielded. Second, the maximum value of the slow-wave factor is 4.79, representing an increase of 139.5% over the theoretical limit of the quasi-TEM TL. Third, the ratio of the area of the CCS TL to its corresponding quality factor (Q factor) can help to estimate the cost of the loss for the circuit miniaturizations. Additionally, the important CMOS manufacturing of *metal density* is for the first time involved in the reported TL designs. By following the proposed design methodologies, a practical design example of a Ka -band CMOS rat-race hybrid is reported and experimentally examined in detail to reveal the feasibility of the proposed design guidelines to synthesize the CMOS CCS TL. The chip size without contact pads is 420.0 $\mu\text{m} \times 540.0 \mu\text{m}$. The measured loss and isolation of the hybrid at 36.3 GHz are 3.84 and 58.0 dB, respectively.

Index Terms—Complementary metal-oxide-semiconductor (CMOS), hybrid, quasi-TEM, thin-film microstrip (TFMS), transmission line (TL).

I. INTRODUCTION

COMPLIMENTARY metal-oxide-semiconductor (CMOS) technology promises a higher level of integration and lower cost than the III–V compounds, enabling the production of multifunction RF transceivers and RF system-on-chip (SOC) designs [1]–[5]. These multifunction circuits on silicon generally adopted lumped or lumped-distributed equivalence, which is faced with not only operation at ever-increasing frequencies, but also saving power consumption and chip area when the processes are scaled down. On the other hand, the transmission line (TL) frameworks, such as microstrip (MS) and coplanar waveguide (CPW), have gained popularity in CMOS RF circuit designs [6]–[12]. Moreover, such TLs can be made to establish a 3-D monolithic microwave integrated circuit (MMIC) in order to save chip area [13]–[19]. The concept of the synthetic quasi-TEM TL was recently reported and successfully employed to miniaturize RF integrated circuits [20]–[23]. Such

successes are mainly due to an efficient meandering of the TL to achieve the highest degree of integration.

Extensive studies indicate that the synthetic quasi-TEM TL, also called the complementary-conducting-strip transmission line (CCS TL), has better guiding properties than those of the conventional MS when the signal trace is meandered in a 2-D plane [21]. Following the same concept of miniaturization, this study focuses on the design of the CCS TL using standard 0.18- μm one-poly six-metal (1P6M) CMOS technology, which is available from most standard silicon foundry services in the world. Fig. 1 illustrates two approaches to designing a CMOS CCS TL. As shown in Fig. 1, the signal traces of the CCS TL are meandered by obeying two basic rules. First, the length of the signal trace is fixed. The length is defined as 270.0 μm in this study. Second, the CCS TL is meandered by at least four bends in the square area. By following the winding course defined above, the CCS TLs are designed for the characteristics impedance (Z_c) of 88.1, 50.7, and 22.7 Ω . The CCS TLs in the bottom row of Fig. 1 are designed by referring to the concept of thin-film microstrip (TFMS), which is regarded as a special limiting case. Although all the limiting cases are meandered with a line space of 2.0 μm , which is the minimum value defined in this study, the corresponding area increases when Z_c decreases. For example, the area of 22.7- Ω CCS TL in Fig. 1(f) is 10152.0 μm^2 , representing 10.25 occurrences of 88.1- Ω CCS TL in Fig. 1(d). However, the CCS TL is designed with stacked metal by manipulating the advantage of multilayer CMOS technology. Fig. 1(a) and (c) shows the 22.7- and 88.1- Ω CCS TLs, which can be designed with areas of 6750.0 and 1019.7 μm^2 , respectively. Conversely, the quality factor (Q factor) of the 88.1- Ω CCS TL in Fig. 1(a) at 10.0 GHz is 1.97, which is 6.8% lower than that in Fig. 1(d). The slow-wave factor (SWF) of the 22.7- Ω CCS TL in Fig. 1(b) at 10.0 GHz is 2.67, which is 33.5% higher than the theoretical limit of the quasi-TEM TL. Furthermore, by applying the stacked metal to the designs of 22.7- and 50.7- Ω CCS TLs in Fig. 1(a) and (b), two CCS TLs automatically meet the *metal density* requirement without inserting additional dummy metals. The *metal density*, which denotes the ratio of the total metal layout area to the TL area, is strongly required by the foundry to manage the variation of chemical-mechanical polishing (CMP) in the wafer manufacture, maintaining the wafer yield and design reliability [24]. The design approaches, which lead to different guiding characteristics of the CCS TL, are extensively investigated in Section III after the validity check of the full-wave EM simulation, which is presented in Section II for extracting the guiding characteristics of the CMOS CCS TL. Section IV reports a

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Fig. 1. CMOS synthetic quasi-TEM TL. The length of all TLs is $270.0 \mu\text{m}$. (a) $Z_c = 88.1 \Omega$. (b) $Z_c = 50.7 \Omega$. (c) $Z_c = 22.7 \Omega$. (d) $Z_c = 88.1 \Omega$. (e) $Z_c = 50.7 \Omega$. (f) $Z_c = 22.7 \Omega$.

practical example of a *Ka*-band rat-race hybrid realized by the CCS TL, based on the design guidelines summarized at the end of Section III to reveal the superior performance in terms of low loss and compact area of the CMOS integration. Finally, Section V presents a brief summary.

II. CMOS MULTILAYER SYNTHETIC QUASI-TEM TL: CCS TL

The proposed CCS TL is constructed by the unit cell on the silicon substrate. As shown in Fig. 2(a), the unit cell, whose dimensions are much smaller than the guiding wavelength at the operating frequency, is the smallest element in the TL. The signal trace is composed of a central patch and four connecting arms, with the latter used to connect adjacent cells. Fig. 2(a) only displays two arms for simplicity. However, the central patch and mesh ground plane can be constructed by using solid vias to link metals in a multilayer structure. As shown in Fig. 2(b), the thickness of the mesh ground plane is increased by stacking M_1 to M_5 in order to decrease the series resistance of the TL, thus enhancing the Q factor of the CCS TL [21]. The unit cell in Fig. 2(a) shows a periodicity of P , and alternately combines two types of TLs shown in Fig. 2(b) and (c) to form a quasi-TEM TL. Fig. 2(b) displays a cross-sectional view of the $A-A'$ cut, and clearly shows the well-known MS structure, which is locally a capacitive region from the circuit point of view. In contrast, Fig. 2(c) displays an MS with a tuning septa [25], which can be regarded as an elevated CPW [26], and is a high-impedance inductive region alongside the $B-B'$ cut. Both microminaturized guiding frameworks support the quasi-TEM mode, alternating to guide the electromagnetic (EM) energy, thus allowing arbitrary syntheses of the quasi-TEM TL with required characteristic impedance [21]. The central patch with a dimension W and the mesh ground plane of an inner slot with a dimension

Fig. 2. CMOS CCS TL. (a) 3-D view. (b) Cross-sectional view of $A-A'$ cut in (a). (c) Cross-sectional view of $B-B'$ cut in (a).

W_h form the complementary conducting surfaces. The term S denotes the width of the connecting arm, thus forming the so-called CCS TL. If $S = W$ and $W_h = 0$, then the CCS TL is regarded as the conventional TFMS, forming a special limiting case in Fig. 2. Furthermore, the values of the structural parameters, namely, P , W_h , S , W , and the number of metal layer are restricted by the capability of the CMOS technology, which defines the minimum and maximum values of line space, linewidth, and number of metal layers. Hence, the proposed CCS TL design is scalable by following the continuing improvement of the semiconductor technology.

Fig. 3(a) shows a chip photograph of a practical design example of the proposed CCS TL in Fig. 2(a). The signal trace is realized by M_6 , and the mesh ground plane is made of metal layers from M_1 to M_5 . As shown in Fig. 3(a), the prototype is designed with the following structural parameters: $W = 5.0 \mu\text{m}$, $S = 4.0 \mu\text{m}$, $P = 30.0 \mu\text{m}$, and $W_h = 28.0 \mu\text{m}$. The relative dielectric constants of the inter-media-dielectric (IMD) and silicon substrate are 4.0 and 11.9, respectively. The thickness and conductivity of the silicon substrate are $482.6 \mu\text{m}$

Fig. 3. Validity checks of the simulated results of CCS TL against measurement. (a) Chip photograph of the prototype fabricated by 0.18- μm 1P6M CMOS technology. (b) Complex characteristic impedance of prototype. (c) Complex propagation constant of prototype. Structural and material parameters are $W = 5.0 \mu\text{m}$, $S = 4.0 \mu\text{m}$, $P = 30.0 \mu\text{m}$, and $W_h = 28.0 \mu\text{m}$. The relative dielectric constants of the IMD and silicon substrate are 4.0 and 11.9, respectively. The thickness and conductivity of the silicon substrate are 482.6 μm and 11.0 S/m, respectively. The thickness and resistivity of M_6 layer are 2.0 μm and 37 m Ω/sq , respectively. The thickness and resistivity of the layers M_1 – M_5 are 0.55 μm and 79 m Ω/sq , respectively.

and 11.0 S/m, respectively. The thickness and resistivity of M_6 layer are 2.0 μm and 37 m Ω/sq , respectively. The thickness and resistivity of the layers M_1 – M_5 are 0.55 μm and 79 m Ω/sq , respectively. The characteristics of the CCS TL are gained from the on-wafer measurements. The two-port S -parameters of the CCS TL are measured after the short-open-load-thru (SOLT)

calibration procedures have been carried out to eliminate the parasitics of the signal-ground (SG) pads. After the two-port S -parameters are obtained, the complex propagation constant ($\gamma = \alpha + j\beta$, where α is the attenuation constant and β is the phase constant) and characteristic impedance (Z_c) are extracted by the well-documented procedures in [21]. Parallel to the on-wafer measurements, the CCS TL shown in Fig. 3(a) is also theoretically examined by Ansoft's commercial software package High Frequency Structure Simulator (HFSS) with the structural and material parameters mentioned above. The simulated results are also compared to those of the extracted results based on the measurements to verify the validity of full-wave EM simulations.

Fig. 3(b) and (c) shows the comparisons. The maximum deviation of 5.7% in the real part of characteristics impedance (Z_c) is achieved in the range from 5.0 to 30.0 GHz. Two imaginary parts of Z_c are nearly identical. Furthermore, the measured normalized phase constants, denoted by β/k_0 , indicate a maximum difference of 8.0%, as opposed to the HFSS simulations, and two normalized attenuation constants are nearly identical. The normalized phase constant is 2.37 at 10.0 GHz, which is higher than the theoretical limit $\sqrt{\epsilon_r}$ of the quasi-TEM TL. The value ϵ_r is the relative dielectric constant of the IMD. Two sets of curves in Fig. 3(b) and (c) shows excellent agreement in the range from 5.0 to 30.0 GHz, confirming the validity of the on-chip CCS TL characteristics using full-wave EM simulations. Section III presents the analysis of the CMOS CCS TL shown in Fig. 2(a) with various structural parameters via Ansoft's commercial software HFSS. The design guidelines for CCS TL to synthesize the specific guiding properties are also summarized based on the extensive EM simulations.

III. DESIGN OF MEANDERED CMOS CCS TLS

A. Simulation Setups for Theoretical CCS TL Designs

The design of the CCS TL by using standard 0.18- μm 1P6M CMOS technology is focused upon here. The material parameters, including the substrate thicknesses and relative dielectric constant, for the HFSS simulations, are set up by following the definitions reported in Section II. Furthermore, M_6 of all TLLs in this study are designed with the maximum and minimum linewidths of 30.0 and 2.0 μm , respectively. The minimum line space of M_6 is 2.0 μm . Both the minimum linewidth and line space for layers M_1 – M_5 are 0.5 μm . It is to be noted that the design rules for all these metal layers mentioned above conform to the standard foundry rules defined by most manufacturers. Conversely, before performing the HFSS simulations, the CCS TL is meandered by following two basic rules reported in Section I. The physical length of the TL is 270.0 μm , and the TL is meandered by at least four bends in each square area. The guiding properties of the CMOS CCS TL at 10.0 GHz, namely, characteristic impedance (Z_c), SWF, and Q factor are extracted by the same procedures reported in Section II. The SWF is defined as the normalized phase constant (β/k_0) of the CCS TL, and the Q factor is the ratio of the phase constant to twice of the attenuation constant. Table I summarizes the extracted results of varying the corresponding structural parameters P , W_h , S , W , and the metal layers for discussions in the following sections.

TABLE I
REFERENCE DESIGNS OF 10.0-GHz CCS TLs USING STANDARD 0.18- μm 1P6M CMOS TECHNOLOGY

Type	$\text{Re}(Z_c)$ (Ω)	P (μm)	W_h (μm)	S (μm)	W (μm)	Signal Trace						Mesh Ground					Q	SWF
						M_1	M_2	M_3	M_4	M_5	M_6	M_1	M_2	M_3	M_4	M_5		
CCS TL ($W_h \neq 0$)	104.0	30.0	29.5	2.0	2.0												3.15	2.03
	98.1	20.0	19.5	2.0	2.0												3.11	1.82
	95.6	15.0	14.5	2.0	2.0												3.05	1.70
	92.6	10.0	9.5	2.0	2.0												2.74	1.48
	91.9	20.0	14.5	2.0	2.0												3.50	1.82
	88.1	4.0	3.5	2.0	2.0												1.93	0.97
	71.8 ²	30.0 ²	28.0 ²	4.0 ²	4.0 ²												4.81 ²	2.01 ²
	69.2	5.0	4.0	2.0	2.5												2.27	1.24
	65.8	30.0	28.0	4.0	4.0												5.19	2.35
	64.7 ¹	30.0 ¹	28.0 ¹	4.0 ¹	5.0 ¹												5.04 ¹	2.37 ¹
	50.7	10.0	7.0	3.5	3.5												3.17	1.97
	36.0	15.0	10.0	6.0	9.0												3.62	2.15
	34.1	15.0	10.5	6.0	6.0												3.38	2.37
	35.1	30.0	20.0	10.0	10.0												4.97	2.51
	34.3	30.0	25.0	10.0	12.0												4.77	2.64
	30.7	30.0	26.0	10.0	14.0												4.63	2.76
	22.7	30.0	22.0	14.0	16.0												4.03	2.67
	12.4	10.0	5.0	4.0	4.0												2.01	4.79
	8.62	30.0	17.0	14.0	16.0												1.97	4.18
CCS TL ($W_h=0, S=W$) or TFMS	88.1		0	2.0	2.0												2.07	0.96
	69.2		0	4.0	4.0												2.93	1.09
	50.7		0	8.0	8.0												3.58	1.21
	35.8		0	16.0	16.0												4.21	1.49
	22.7		0	30.0	30.0												4.42	1.62

¹ design parameters and extracted results in Fig. 3.

² design parameters applied in Fig. 7(a).

The metal layer, which is applied to the CCS TL design, is highlighted in Table I, which also shows the corresponding **metal density**, defined as the ratio of the total metal layout area to the TL area. The metal layers with the metal density below and above 30.0% are shown in gray and black, respectively. This work on CMOS TL design is the first to take the process issue of the **metal density** into consideration. Such a process issue, which is specifically defined by the manufacturer, dominated the yield of the CMOS circuit.

B. Special Limiting Designs of CCS TL

The CCS TL is identical to the conventional TFMS when $W_h = 0$ and $S = W$. Conversely, as indicated in [27, Fig. 5], the Q factor of the TFMS significantly decreases if the effective thickness between the signal trace and ground plane decreases. Hence, the CCS TL in this category applied M_1 to the ground plane and M_6 to the signal trace to achieve low loss. However, the drawback of the low-loss design is that the metal densities of the rest of the metal layers, from M_2 to M_5 , are zero. Additional chip area is stipulated to accommodate the dummy metal inserts. Additionally, due to the limiting designs of the CCS TL reported in Table I, the line space of M_6 is set to 2.0 μm to minimize the area of the layout. Based on the closed-form expressions of the limiting designs of the CCS TL, Z_c and complex propagation constant γ ($\gamma = \alpha + j\beta$) are determined by the linewidth once

the material parameters and the thickness between the signal trace and ground plane are fixed [28]. Therefore, as indicated in Table I, characteristic impedance (Z_c) increased from 22.7 to 88.1 Ω when the linewidth of M_6 decreased from 30.0 to 2.0 μm . It is to be noted that 30.0 and 2.0 μm are the maximum and minimum linewidths defined in Section III-A, which limit the Z_c syntheses of the CCS TL. Moreover, at 10.0 GHz, the Q factor of the 88.1- Ω CCS TL is 2.07, which is over 100% lower than that of the 22.7- Ω CCS TL. The SWF of five special-limiting designs is below 2, which is the theoretical limit of the quasi-TEM TL on the substrate with a relative dielectric constant of 4.

C. CCS TL With $W_h \neq 0$

The CCS TLs with $W_h \neq 0$ in Table I show the following design characteristics. The characteristic impedance (Z_c) can be elevated above 88.1 Ω simply by decreasing the ratio of P to W_h . As shown in Fig. 2(c), P and W_h determine the effective area of the high-impedance region in CCS TL. Therefore, Z_c can be raised by adjusting P and W_h without varying S and W , which determine the effective linewidth of the CCS TL. Conversely, to synthesize Z_c below 22.7 Ω , the metal layer of central patch is vertically extended from M_6 to M_1 . Such an extension enlarges the overlapping area between the signal trace and ground plane, resulting in an increase of capacitance

Fig. 4. AMD against the SWF for CCS TLs at 10.0 GHz.

per unit length of the CCS TL. By applying the design guidelines to Z_c syntheses, the value of Z_c ranges from 8.62 up to 104.0 Ω , showing a Z_c ratio of 12.06 (104.0 Ω /8.62 Ω). This ratio is significantly wider than that of the TFMS designs reported in Section III-B.

Moreover, the SWF of the CCS TL can be raised by the following two design guidelines. The first guideline is to reduce the ratio of P to W_h . This approach is applied to designing the CCS TL with Z_c from 88.1 to 104.0 Ω . As indicated in Table I, the SWF increased from 0.97 to 2.03 when P/W_h is reduced from 1.14 to 1.02. The second approach is to adopt stacked metal to realize the central patch or mesh ground of the CCS TL. In Table I, all the designs of the CCS TL with Z_c below 50.0 Ω , designed by following the second approach mentioned above, have SWF values exceeding the theoretical limit of the quasi-TEM TL. Meanwhile, these CCS TLs meet the 30.0% **metal density** requirement for all metal layers and need no additional chip area for filling dummy metal, attaining true miniaturization. To the best of the authors' knowledge, the proposed design is the first to comply with CMOS **metal density** rules for designing the CMOS TL. To discuss these two design approaches in details, Fig. 4 plots the SWF at 10.0 GHz against average metal density for all the CCS TL designs in Table I. The average metal density (AMD), as follows in (1), indicates the average value of the metal densities for all six metal layers:

$$\text{AMD} = \frac{\sum_{i=1}^6 \left(\frac{\text{Total metal area at } M_i \text{ layer}}{\text{Area of transmission line}} \right) \times 100\%}{6}. \quad (1)$$

As shown in Fig. 4, the CCS TLs, which are marked by symbols in hollow squares ($\square$), represent the special limiting designs presented in Section III-B. Additionally, the filled circles ($\bullet$) indicate that the metal densities of all six metal layers in the CCS TL design are higher than or equal to 30.0%. The half-filled circles ($\bullet$) mean at least one metal layer with metal density less than 30.0%. The quantity adjacent to the symbols represents the Z_c values of the CCS TL design listed in Table I.

As shown in Fig. 4, the CCS TLs, which are designed by decreasing the ratio of P/W_h , show that the SWF increases from 0.97 to 2.03, while the AMD falls from 12.2% to 1.7%. The designs based on the first approach do not easily meet the required 30.0% metal density. Conversely, in the designs following the

Fig. 5. Normalized area (A_N) against real part of the characteristic impedance (Z_c) for 270.0- μ m-long CCS TLs at 10.0 GHz. The symbols in Fig. 5 are identical to those shown in Fig. 4.

second approach, the corresponding SWF increases from 1.97 to 4.79, and meanwhile the AMD also increases from 36.3% to 82.5%. This trend indicates that the second approach can realize a CCS TL with high SWF, and that the CCS TL design can easily meet the metal density requirement, enabling successful circuit miniaturization. The design approaches for the CCS TL, which can synthesize a TL with various structure parameters, reveal the fundamental modifications to the design of the CMOS TL. Furthermore, a glance back at Fig. 1 reveals that the CCS TLs can be realized in different areas for the same Z_c , thus attaining different Q factors. Hence, Section III-D is devoted to the discussion of the CCS TL designs with different area.

D. Area-Influence Loss (AL) of CCS TL

Fig. 5 plots the normalized area (A_N) versus the characteristic impedance (Z_c) for the CCS TL designs listed in Table I. The term A_N , defined by (2) as follows, represents the ratio of the total occupying area of the meandered CCS TL with a fixed length of 270.0 μ m to the square of guided wavelength in free space at 10.0 GHz:

$$A_N = \frac{\text{Area}}{(\lambda_0)^2} = \frac{A \cdot (f_0)^2}{c^2} \quad (2)$$

where c denotes the velocity of light in free space and f_0 is the operating frequency. As shown in Fig. 5, the quantity adjacent to the symbols is the Q factor of the CCS TL listed in Table I. The symbols in Fig. 5 are identical to those shown in Fig. 4. As reported in Section III-B, the designs for the special limiting case of the CCS TL, which are meandered by following two basic rules defined in Section I, set the minimum line space at 2.0 μ m to achieve the smallest compact layout area. As reported in Section III-B, these special limiting cases of the CCS TL are designed according to the closed form in [28]. Therefore, as shown in Fig. 5, the limiting designs of the CCS TL denoted by the symbols in hollow squares ($\square$), which can form a virtually continuing curve, show the increase of A_N inversely proportional to the increase of Z_c . Such limiting designs are well controlled by only linewidth (S), and can be scaled down with the continuing improvement of semiconductor technology.

Conversely, the design approaches presented in Section III-C, which can synthesize a wider range of Z_c than that of the design approaches in Section III-B and provide multiple designs for one specific Z_c , lead to different A_N distributions. As shown in Fig. 5, to synthesize Z_c between 88.1–104.0 Ω , the CCS TL requires a higher A_N value than the one predicted by the limiting case designs. This trend shows a reduction of the ratio of P/W_h in the CCS TL. Additionally, Fig. 5 shows two group designs with different A_N for realizing a 35- Ω CCS TL. The first design is the CCS TL with $P = 30.0$ μm , which achieve the A_N approaching that of the limiting case. The second design has $P = 15.0$ μm , and results in A_N below the predicted value of the limiting case. The Q factor of the CCS TL with $P = 30.0$ μm is approximately 4.87, which is 39.14% higher than that of the CCS TL with $P = 15.0$ μm . The Q factor of the CCS TL is relatively proportional to the period of the unit cell. This observation reflects the fundamental physical phenomenon of the CCS TL design, which is studied in Fig. 6.

The derivations in [29, Ch. 7.4] for a rectangular cavity in dominate-mode operation indicate that the conductor loss of the cavity is inversely proportional to its volume [29, Ch. 7.4, pp. 503, eq. (7.48)]. If the width, length, and height of the rectangular waveguide cavity are all identical, then the cavity is regarded as a cubic resonator, and the conductor loss in the resonator is related only to the quantity of the length since all the CCS TLs presented in Table I are designed on the silicon substrate with a fixed thickness, and meandered in a nearly square area, as shown in Fig. 1. Following the concept of the conductor loss in the cubic resonator, this study indicates that the loss of the meandered CCS TL with fixed length is exactly the same as the AL with the ratio of the square root of the normalized area (A_N) to the Q factor. Additionally, shown in (3) as follows, the AL also can be represented by a function of f_0 , A , c and the Q factor after some algebraic manipulation:

$$AL = \frac{\sqrt{A_N}}{Q} = \frac{\sqrt{A/\lambda_0^2}}{Q} = \frac{\sqrt{A}}{Q\lambda_0} = \frac{f_0\sqrt{A}}{cQ} \quad (3)$$

where A , which denotes the total occupying area of the meandered CCS TL with a fixed length, is identical to that in (2), f_0 represents the operating frequency of the TL, and c is the speed of light in free space. As defined in Section I, the length of all the CCS TLs in Table I is set to 270.0 μm . Therefore, Fig. 6 plots the AL versus characteristic impedance (Z_c) for the CCS TLs in Table I at 5.0, 10.0, 20.0, and 30.0 GHz. The values of the parameters at 10.0 GHz are listed in Table I, and the values for 5.0, 20.0, and 30.0 GHz are obtained by following the same analytical procedures reported in Section II, except for the operating frequency. The definitions of the symbols, which represent various CCS TL designs in Fig. 6, are identical to those in Fig. 4.

Due to the skin effect, the Q factor of the CCS TL is proportional to the square root of the frequency. Thus, the AL of the 50.7- Ω CCS TL at 30.0 GHz is 0.89×10^{-3} , which is $\sqrt{6}$, $\sqrt{3}$, and $\sqrt{1.5}$ times those at 5.0, 10.0, and 20.0 GHz, respectively. Such physical trends also can be observed at different CCS TL designs with characteristic impedance (Z_c) from 22.7 to 88.1 Ω .

Fig. 6. Characteristic impedance (Z_c) against the AL for CCS TLs with a length of 270.0 μm . The symbols in Fig. 6 are identical to those shown in Fig. 4.

TABLE II
DESIGN GUIDELINES OF CMOS CCS TL

	$P/W_h \uparrow$	$S \uparrow$	$W_h/W \uparrow$	# Metal Layer $\uparrow$
Z_c	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
Q	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
SWF	$\downarrow$	$\uparrow$	$\downarrow$	$\uparrow$
AMD	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$

Furthermore, a close observation of the multiple CCS TL designs with a specific Z_c from 22.7 to 88.1 Ω indicates that the corresponding AL value are nearly identical to each other at the same operating frequency, showing a constant ratio between the square root of the normalized area (A_N) to the Q factor in different designs. This result confirms the observation of the two design approaches for the 35- Ω CCS TL in Fig. 5. The CCS TL can be designed with a relatively high value of A_N to raise the corresponding Q factor. Consequently, as shown in Fig. 5, the 22.7- Ω CCS TL can be designed with $A_N = 7.5 \times 10^{-6}$ for a Q factor of 4.03, or designed with $A_N = 11.28 \times 10^{-6}$ for a Q factor of 4.42. Similarly, the 69.2- Ω CCS TL can be designed with $A_N = 1.35 \times 10^{-6}$ for a Q factor of 2.27, or designed with $A_N = 2.04 \times 10^{-6}$ for a Q factor of 2.93.

As reported here, the proposed CCS TL provides a high flexibility for synthesizing the desired guiding characteristics. By summarizing the design guidelines reported here, Table II shows the universal trends of synthesizing the desired guiding characteristics by adjusting the structural parameters of the CCS TL. Section IV applies the proposed CCS TL to designing a practical example of the Ka -band rat-race hybrid by following the design guidelines reported here, demonstrating the capability of the CCS TL.

IV. DESIGN EXAMPLE: Ka -BAND RAT-RACE HYBRID

Fig. 7(a) shows a 34.3-GHz CMOS rat-race hybrid design incorporating the proposed CCS TLs designed according to the guidelines reported in Section III. The operations of the rat-race

Fig. 7. *Ka*-band CMOS rat-race hybrid. (a) Chip photograph of the prototype. (b) Simulated and measured results of the prototype.

and its equivalent TL network are well documented [29]. As shown in Fig. 7(a), the electrical length between Port 2 and Port 4 is three times as great as the quarter-wavelength and the remaining adjacent ports has the length of one quarter-wavelength. The reference impedance of all four ports is 50.0Ω , and the characteristic impedance of the TLs in the entire rat-race is designed as 70.7Ω to establish the equal power split and power combination. The CCS TL with $Z_c = 71.8 \Omega$ is applied to the rat-race realization winding course shown in Fig. 1, and the design is fabricated by standard $0.18\text{-}\mu\text{m}$ 1P6M CMOS technology. The chip area of the prototype shown in Fig. 7(a) is $420.0 \mu\text{m} \times 540.0 \mu\text{m}$ without the contact pads.

The on-chip performances of the prototype are characterized by conducting the same experimental procedures reported in [23] and are compared to the theoretical data, which is computed by the full-wave HFSS simulations with the circuit layout in Fig. 7(a). Fig. 7(b) shows the composite plots, revealing good agreements between the measurements and HFSS simulations. The transmission coefficients, which are shown in Fig. 7(b) in

TABLE III
Ka-BAND CMOS RAT-RACE DESIGNS

	Loss (dB)	f_0 (GHz)	ARF (%)	P (μm)	Q	Metal Layer
[23]	5.4	30.0	97.6	20.0	6.3	M_1, M_6
This work	3.8	34.3	96.9	30.0	9.4	M_1, M_2, M_6

detail, are less than 4.0 dB from 34.0 to 38.0 GHz, indicating the intrinsic loss of less than 1.0 dB. Additionally, the two transmission coefficients in Fig. 7(b) are -3.94 and -3.75 dB at 34.3 GHz, showing an amplitude in balance of 0.19 dB. Such results show a nearly equal power distribution at two output ports of the prototype. The measured input return loss from 32.8 to 38.1 GHz, illustrated by the curve with hollow squares, is higher than 20.0 dB. The measured isolation from 31.5 to 40.0 GHz, illustrated by the curve with hollow triangles, is higher than 20.0 dB and has a maximum value of 58.0 dB at 36.3 GHz. From 31.0 to 37.0 GHz, the phase difference between two output ports is approximately $180^\circ \pm 5^\circ$. By referring to the calculation of the area reduction factor (ARF) reported in [21, eq. (4)], the prototype in Fig. 7(a), which consisted of 14×18 unit cells with $P = 30.0 \mu\text{m}$, achieved an ARF of 96.9% at 34.3 GHz.

A similar design of the *Ka*-band rat-race, realized by incorporating CCS TLs on the standard $0.18\text{-}\mu\text{m}$ 1P6M CMOS technology, was also recently reported in [23]. Table III summarizes these two rat-race hybrid designs for the following discussions. The ARF values shown in Table III are calculated by following the definition of Chen and Tzuang [21]. Two rat-race hybrids are designed at different operating frequencies, and implemented by different CCS TLs. The rat-race design in [23] based on a smaller period of unit cells reveals higher ARF values than those obtained by the design reported herein. This observation confirms the prediction reported in [21, Sec. II-B]. The smaller value of the periodicity (P) resulted in a higher ARF. Furthermore, the ARF is 97.1%, which is only 0.5% lower than that of [23], when the operating frequency of the rat-race design in Fig. 7(a) are scaled down from 34.3 to 30.0 GHz. Moreover, the scaling design, which is theoretically analyzed by performing the full-wave HFSS simulations mentioned above, achieved a transmission loss at 30.0 GHz of 4.2 dB, which is 22.2% lower than that of the design in [23]. Two different approaches are applied to designing CCS TLs, producing two rat-race hybrids with different performances in terms of loss, area, and ARF. The comparisons summarized above lead to the following observations. Increasing P of the CCS TL enhances the Q factor of the CCS TL. As shown in Fig. 1, since P is the main factor managing the occupying area of the CCS TL, increasing P simultaneously causes A_N to increase and ARF to decrease. These observations validate the design guidelines in Table II and the predictions of [21]. Moreover, the rat-race hybrid designs presented here demonstrate that CCS TL can systematically miniaturize the TL-based circuit with predictable electrical performances. The loss of the CCS TL-based circuit is confined to the desired area, and the CCS TL circuit designed by different approaches produced different ARF values for circuit miniaturization.

V. CONCLUSION

The CMOS CCS TL has been reported in detail. By following the universal design guidelines, the CCS TL can be designed with a wide range of characteristic impedance, high SWF, and the satisfaction of the *metal density* requirement. Additionally, when the physical length is fixed, the ratio of the CCS TL area to its corresponding Q factor approaches a constant and can be applied to estimating the cost of loss for the CMOS circuit miniaturization.

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