A NOVEL MINIATURIZED WIDE-BAND WILKINSON POWER DIVIDER EMPLOYING TWO-DIMENSIONAL TRANSMISSION LINE

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Abstract – **The study proposes a novel miniaturized wide-band Wilkinson power divider, based on 0.18μm 1P6M CMOS foundry technology. The proposed two-dimensional transmission line, called a complementary-conducting-strip (CCS), replaces the conventional microstrip (MS) line structure. With this CCS structure, the occupying area of this novel divider is approximately 96 % smaller than that of the conventional MS Wilkinson power divider. The prototype, including the input/output (I/O) pads, occupies an area of only 673 μm by 645 μm. The new WPD has a coupling loss of -5.4 dB, an isolation of +15 dB and a return loss -12.5 dB from 8.7 GHz to 17.4 GHz..**

Keywords - **rfic, cmos, Wilkinson power divider, and two-dimensional transmission line**

I. INTRODUCTION

The Wilkinson power divider (WPD) is one of the most commonly used components in wireless communication, radar and many other microwave systems for power division and/or combination. It offers broad bandwidth and equal phase characteristics at each of its output ports, and good isolation between its output ports as well as reciprocal operation [1]. Since the physical dimension of the standard WPD is proportional to the guided wavelength of the central operating frequency. Consequently, when the power divider is incorporated into monolithic microwave integrated circuits (MMICs), its size becomes prohibitively large and derives MMIC chip larger size and higher cost. Therefore, techniques to shrinking Wilkinson power dividers (WPDs) are required for low cost and small size circuits. One of the first methods to reduce circuit size used capacitive loading to miniaturize WPDs [2-3]. In order to reduce the circuit size effectively, the concept of replacing the transmission line sections with lumped passive components has been adopted [4], but these designs are very dependent on the quality factor and self-resonant frequency of the inductors. Other approaches to reduce the size of WPDs include the use of three-dimensional (3-D) technologies [5-6], series stub loading [7-8], active inductors [9], and multiple coupled microstrip line structure (MCMLS) [10].

To deserve to be mentioned, the meandered thin-film microstrip (TFMS) structure plays a key role to miniaturize the WPD in MMICs [5-6]. However, the meandered TFMS has two drawbacks [11]. First of all, the line width W of the TFMS will become the single controlling parameter for varying the characteristic impedance Z_c , once the process parameters, such as the substrate thickness (h) and the dielectric material, are decided. This makes a strict limitation over the use of a high-impedance line since the MS will become unrealistically narrow. Furthermore, many of demands, such as unequal power output, broad bandwidth and multiple sections designs, for WPD, mandate the TLs of wide-range characteristic impedance. Consequently, the design of the TFMS passive and hybrid circuits will become a challenging issue. Secondly, the meandering of the MS dramatically alters the propagation characteristics of the bound EH_0 mode in phase constant β and characteristic impedance Z_c. Such drastic changes in β and Z_c are due to the result of coupling among the nearby TFMSs and the right-corner bends of the meandered lines. Thus, a larger ratio of the adjacent line spacing (l_g) to the substrate height (h), typically greater than two or larger, is applied to avoid serious degradation in guiding characteristics. This, however, adversely affects the efforts for making miniaturized microwave circuits.

In this paper, we will present a novel two-dimensional (2D) transmission line (TL) that possess the properties of wider choice of characteristic impedance and flatter less sensitive propagation characteristics in a very compact area [11], called complementary-conducting-strip (CCS) with excellent performances of low loss, high area reduction factor (ARF), and flexible design [11-12], to realize the novel miniaturized wide-band WPD based on Taiwan Semiconductor Manufacturing Company (TSMC) 0.18μm one poly – six metals (1P6M) CMOS foundry technology.

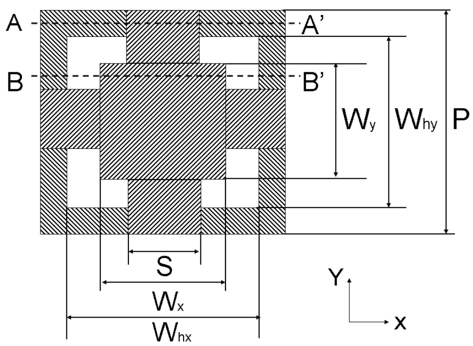
The rest of this paper is organized as follows. Section II describes the constitution of the CCS unit-cell and the CCS TL, the evaluation of ARF, and the topology of this novel CCS WPD. Section III briefly describes the design procedures of the CCS WPD; first, the dimensions of the CCS unit cell are properly chosen to provide the required electrical parameters of the CCS TL, such as a characteristic impedance of 70Ω and quarter guided wavelength, among others. Then, the CCS WPD, following the same design procedures, is elucidated; it is simulated and compared to the traditional MS WPD. Finally, the measurements and simulated results of the CCS WPD with I/O pads, are presented to verify the applicability of the miniature design of wide-band WPD using the 2D TLs. Section IV draws conclusions.

II. TWO-DIMENSIONAL TRANSMISSION LINE: THE COMPLEMENTARY-CONDUCTING-STRIP (CCS) TL

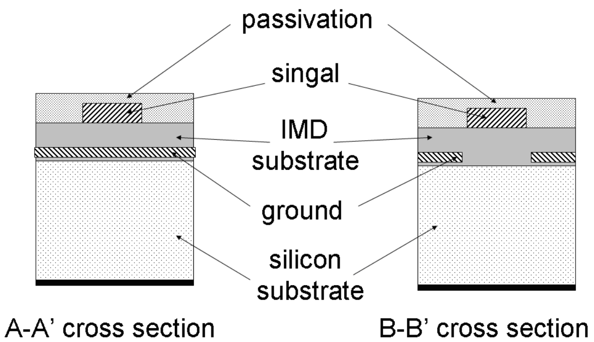
Recently, a novel synthetic 2-D TL—the so-called complementary-conducting-strip transmission line (CCS TL)—was reported to be an effective means of miniaturizing microwave circuits [11]. The CCS TL has the following characteristics. It firstly provides wide design choices for making characteristic impedance of the TL without changing the process parameters and material constants. Second, the meandered CCS TL exhibits less bending and adjacent coupling effects, as indicated by the slower change in characteristic impedance against the width variation in the TL than conventional meandered microstrip (MS) used in the same fashion [11, Fig. 5]. Therefore, a compact microwave circuit can be established using the meandered CCS TL, finally achieving miniaturization.

A. *The Constitution of CCS Unit-cell and CCS TL*

The CCS TL is made from a unit-cell, which has dimensions that are much smaller than the operating wavelength (λ_g). As shown in Fig. 1(a), a unit cell contains a mesh ground plane and a central patch with at least two series arms for cells in series and bent connection to the adjacent cells. The etched portion of the meshed ground plane complements to the central patch of the single layer, forming a CCS TL. The guiding structure integrates two transmission lines (TLs) in a single cell by drawing A-A' and B-B' cuts horizontally across the unit cell. The left column of Fig. 1(b) displays a cross-sectional view of the unit cell along the A-A' cut for monolithic microwave integrated circuit (MMIC) with lower Si substrate. The left-hand-side column clearly shows that the well-known MS structure is independent of the passivation in the MMIC process. The right-hand-side column in Fig. 1(b), however, presents an MS with the tuning septa or, equivalently, an elevated CPW across the B-B' cut of the unit cell. We can appropriately choose the dimensions of periodicity (P), and tune the widths of the central patch (W_x, W_y), connecting arms (S), and holes of grounding (W_{hx}, W_{hy}), to design the CCS TL that satisfy the required electrical performance, such as low loss, 70-Ω characteristic impedance etc., in order to design the miniaturized passive circuits using the CCS TLs.



(a) Two-dimensional (2-D) top view



(b) Cross-sectional view for the MMIC

Fig. 1. Geometries of the CCS unit cell. (a) 2-D top view. (b) Cross-sectional view.

B. *The Evaluation of ARF*

This paper will present a novel miniaturized WPD using CCS TLs as shown in Fig. 2 (inside pattern), which is the layout of the simulated X-band WPD designed by employing conventional MS and the CCS TL, respectively, to achieving nearly the same three-port network parameters. Both designs are analysed simultaneously on a TSMC 0.18μm 1P6M radio-frequency (RF) CMOS foundry technique and the relative process parameters. One immediately recognizes that the compacted WPD based on the CCS TLs occupies much less area than the familiar ring-shaped design using conventional microstrip, which wastes a substantial area by more than 96%. Section III will show the meandered CCS TL is match than conventional MS in guided-wave propagation characteristics for the microwave passive circuit designs. Here we report the basics necessary for accurate assessment of area size and made a comparison between the designs using the conventional MSs and CCS TLs before entering the serious design phase. Given the case study of the X-band WPD, total of wavelength of 2/4 λ_g is required for both designs using MSs and CCS TL's. In the typical ring-shaped configuration of a WPD based MS, the circumference of the ring is

$$(2/4)\lambda_{g1} = 2\pi R_1 \; . \tag{1}$$

where R1 is the radius of the ring and λ_{g1} is the guided wavelength of the conventional 70-ohm MS line at the operating frequency f_o. Excluding the T-junctions required for the three-port interface and the 100−Ω resistor used for the isolation of port 2 and port 3, the estimated area of MS WPD (A_1) is

$$A_1 = \pi R_1^{\;2} = (1/16\pi)\lambda_{g1}^{\;2} \; . \tag{2}$$

The CCS transmission line realization of microwave passive circuits adopts entirely different philosophy by placing the meandered CCS TLs in a compacted, two-dimensional plane in array shape by simply connecting the connecting arms of the cells along the desired directions of propagation. Thus the total area (A_2) required to accomplishing the design example of the WPD is

$$A_2 = (2/4)\lambda_{g2} \cdot P \; . \tag{3}$$

To this end, an area reduction factor (ARF) of the particular case study can be expressed by

$$ARF = 1 - \frac{A_2}{A_1} = 1 - \frac{(8\pi)(P/\lambda_o)(SWF_{MS})^2}{SWF_{CCS\ TL}} \; . \tag{4}$$

where slow-wave factors (SWFs) of MS and CCS TL are respectively defined as $SWF_{MS} = \lambda_o/\lambda_{g1}$, $SWF_{CCS\ TL} = \lambda_o/\lambda_{g2}$, and λ_o is the guided wavelength in free-space at operating frequency f_o. Eq. (4) shows a linear dependence of ARF against the periodicity P of the CCS TLs. The smaller the value of P will result in larger area reduction factor, which is a figure of merit to demonstrate the important area of CCS TLs in the process of designing compacted microwave circuits. Quick estimation by assuming that SWF_{MS} = $SWF_{CCS\ TL}$ = 1.8, P = 15 μm, and f_0 = 10.5 GHz, the ARF will be 97.6 %, very close to detailed analyses and experimental layout results to be discussed later.

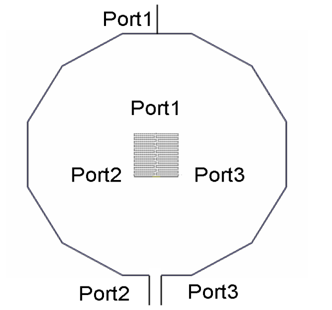


Fig. 2. Comparison of layout patterns of the 2-D guided structures of the CCS WPD prototype (inside pattern) and the traditional MS WPD (outside pattern).

III. DESIGN, SIMULATION AND VERIFICATION OF THE CCS WPD

Referring to Fig.2, the CCS MMIC is designed base on the TSMC 0.18μm 1P6M RF foundry technique and the relatively constructional and material parameters. On the bottom layer (as the mark "Ground" of Fig. 1) is the connected unit cell as shown by the crosshatched surface, which consists of the lower M2 layer of the 1P6M CMOS process. On the top surface of (as the mark "Signal" of Fig. 1) of the unit cell is patterned to make a 70-Ω CCS TL for the particular application. Throughout this paper, the full-wave finite element method (such as full wave EM simulator: **Ansoft** *HFSS*^{TM} etc.) is employed for obtaining the two-port scattering parameters of the CCS TL. Linking between the ABCD matrix and the scattering parameters (S-parameters), one can obtain complex propagation constant γ and characteristic impedance Z_c from the scattering parameters of CCS TL [11]. A 70-Ω CCS TL has been designed and applied to layout the novel miniaturized WPD, with the square unit cell of the periodicity P of 15 μm, the square central patch of the width W_x (= W_y) of 5 μm, the connecting arm width S of 2 μm, and the square hole grounding of the hole width W_{hx} (= W_{hy}) of 5 μm. The design procedure of the traditional MS case is the same as CCS case. Figure 3 presents simulated scattering parameters of the CCS and MS WPDs. It reveals that the return losses of |S11| and |S22| are smaller than -12.3 dB and -15.6 dB, respectively; the isolation (|S23|) exceeds 11.3 dB, and the coupling loss |S21| is constrained within the range -4.62 ± 0.30 dB in the frequency band from 6 GHz to 16 GHz, where |S11| = -18.5 dB, |S22| = -21.3 dB, |S23| = -28.2 dB and |S21| = - 4.5 dB at 11 GHz for the CCS WPD. For comparison, for the traditional MS WPD, the return losses of the |S11| and |S22| are less than -12.1 dB and -22.4 dB, respectively, the isolation (|S23|) exceeds 11.6 dB and the coupling loss |S21| is constrained within the range -4.4 ± 0.33 dB in the same frequency band, where |S11| = -19.9 dB, |S22| = -27.5 dB, |S23| = -26.6 dB and |S21| = - 4.2 dB at 11 GHz. The comparison indicates that the electrical performance of the CCS WPD is comparable with that of the traditional MS WPD, but the CCS WPD occupies a much smaller area than the MS WPD. Figure 4 presents a photograph of the CCS WPD.The chip size of the CCS WPD, including the input/output (I/O) pads, is 672.5μm by 645μm. The simulation and measurement results of the CCS WPD are shown in the Figure 5; it illustrates the wide-band responses and very closely performances in the frequency band of 8.7 GHz to 17.4 GHz for the above results. The measured return loss |S11| is better than -12.5 dB, |S22| at least -14.8 dB, and the coupling loss |S21| close to -5.43 dB in the interested band, 8.7 GHz - 17.4 GHz. Beside, the isolation between port 2 and port 3 is kept at least +15 dB across the band.

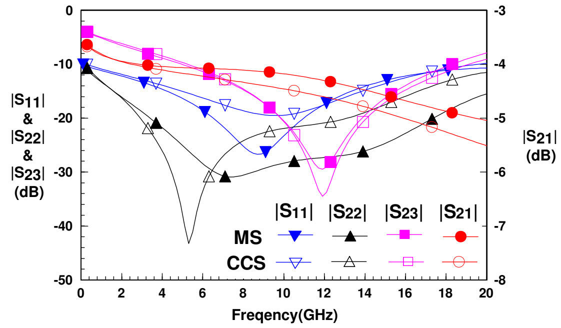


Figure 3 Simulated scattering parameters of the CCS and MS WPDs.

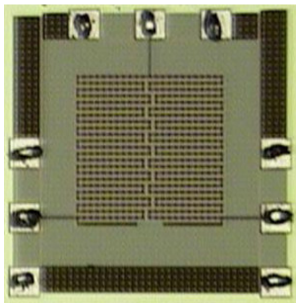
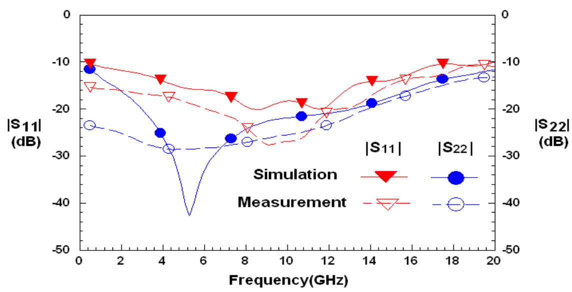
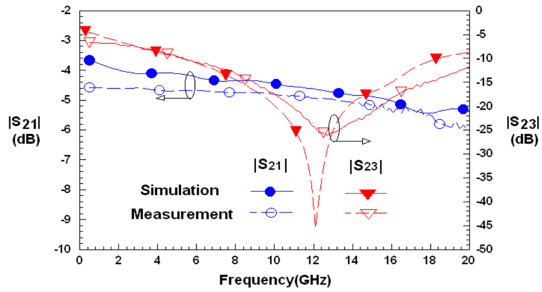


Figure 4 the photograph of the CCS WPD with I/O Pads.



(a) Return loss



(b) Coupling loss and Isolation

Figure 5 the simulated and measured (a) return loss (|S11|, |S22|), (b) coupling loss (|S21|) and isolation (|S23|) of the CCS WPD as Fig. 4.

V. CONCLUSION

This paper presents a miniaturized wide-band WPD using the novel 2-D TLs that based on 0.18 μm 1P6M CMOS foundry technology. The occupied area of the CCS WPD is only 345 μm × 360 μm. The study results illustrate that the occupying area of the CCS WPD is only 4 % of that of the conventional MS WPD, while they possess very closely performances. The new WPD has a return loss -12.5 dB, and an isolation of +15 dB and a coupling loss of -5.4 dB between 8.7 GHz and 17.4 GHz.

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