Capacitive Transmission Lines in Coplanar Waveguide for Millimeter-Wave Integrated Circuit Design

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***Abstract*—For use in millimeter-wave integrated circuits, theoretical and experimental design data for various useful capacitive transmission lines in coplanar waveguide on gallium arsenide are presented. Multifinger and metal–insulator–metal (MIM) lines enabling low characteristic impedance in the order of 10 Ω as well as broad-band capacitive coupled transmission lines are investigated. Simple design rules and accurate models validated with measurements up to 120 GHz demonstrate that such planar transmission lines can be used in monolithic microwave integrated circuits (MMIC's) to extend the impedance range and the design flexibility with respect to the conventional CPW.**

***Index Terms*—Coplanar waveguides, millimeter-wave, MMIC, planar transmission lines.**

I. Introduction

COPLANAR waveguide transmission lines (CPW's), as illustrated in Fig. 1(a), are nowadays extensively used for high-frequency monolithic integrated circuit (MMIC) applications. Compared to microstrips, CPW's offer the advantages of cost effective chip processing as they do not require any backside and via hole processes, and they have better isolation between adjacent lines and lower dispersion characteristics. In MMIC's, the common CPW covers an impedance range of about 30 to 80 Ω. In particular, the higher the ratio between center conductor width w and slot width s is, the lower is the impedance. However, low impedances are limited by the lateral process resolution that imposes a minimum slot width of only a few micrometers and this technological limit cannot be overcome simply by a larger ground-to-ground spacing d due to higher order modes problem. Moreover, in the case of narrow slots, these impedances become very sensitive to variations of slot widths and metallization thickness.

The low-impedance transmission lines are applicable in many applications, as for example in power amplifier designs where such low impedances facilitate the matching of large gate periphery devices and the current handling capability. Compared with capacitively loaded lines [1] in MMIC's, they furthermore give better broad-band characteristics.

In order to achieve lower impedance levels, the conventional CPW has to be modified: Thomson and Rogers [2] have first proposed the interdigital coplanar line (ICPW) shown in Fig. 1(b). Although, such a fabricated line on RT-Duroid substrate $(\varepsilon_r = 2.2)$ exhibits dimensions outside those commonly used in MMIC's, it has a characteristic impedance of about

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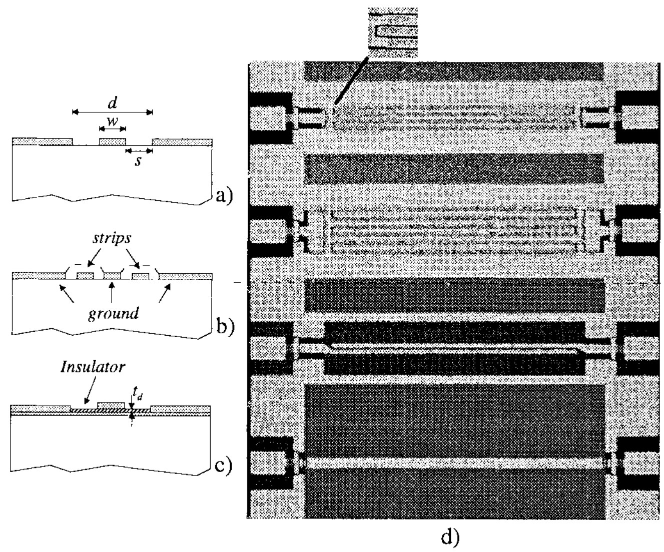

Fig. 1. Different configurations of coplanar waveguides: (a) conventional CPW line, (b) interdigital CPW line, (c) metal–insulator–metal line, and (d) example of transmission line test structures fabricated on GaAs.

30 Ω, demonstrated experimentally for very low-frequency operation. Our letter presents results extended to millimeter-wave frequencies as well as new design data for different capacitive transmission lines in CPW.

II. Capacitive Transmission Lines

As described in Fig. 1(b), the multifinger transmission or interdigital CPW line consists of at least two conductors (fingers) carrying the signal, each surrounded by ground strips. The ground connections are effected at both ends of the line with airbridges [3]. This transmission line can be considered merely as a *parallel* combination of single coplanar lines of width w and slot s, giving a unit impedance Z_u. The resulting impedance is estimated as a function of the finger number n to Z_u/n. This behavior is demonstrated in Fig. 2 by simulating various ICPW geometries by means of the commercial two and a half-dimenaional (2.5-D) electromagnetic simulator (EM) HP-Momentum$^{\text{TM}}$. Transmission lines having a slot s of 5 μm and a center conductor width w of 10 μm have been simulated. Clearly, for similar dimensions of CPW (minimum slot and line width), this concept allows to achieve relatively low impedances down to approximately 10 Ω with relative phase velocities close to that of a common CPW line.

Based on these results, multifinger transmission lines with same dimensions were fabricated on GaAs [Fig. 1(d)]. The line

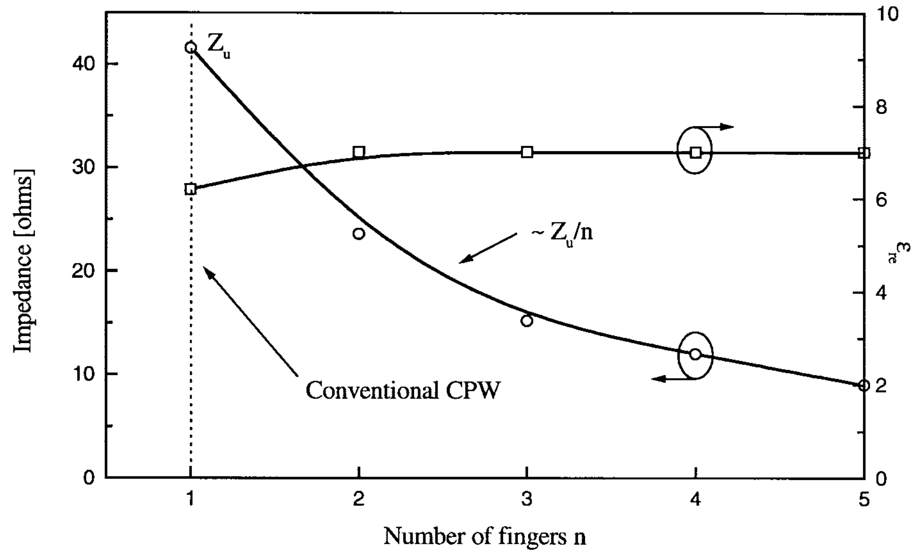

Fig. 2. Numerical simulations (HP-Momentum) of the multifinger transmission line with $w = 10$ μm and $s = 5$ μm.

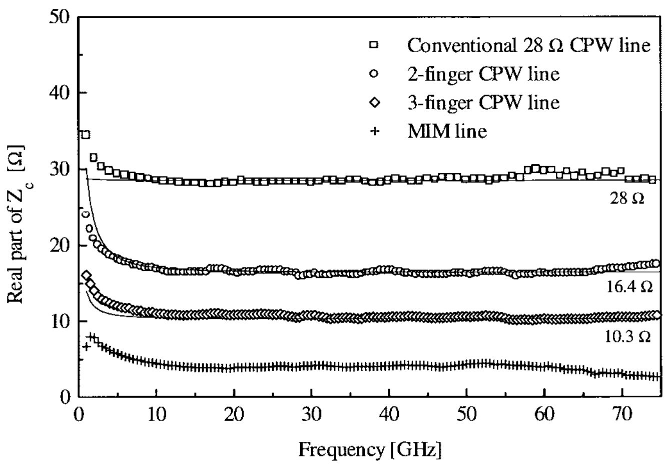

Fig. 3. Real part of the characteristic impedance of CPW of interdigital CPW and MIM lines over the frequency range 2–75 GHz. Measured (symbols) and modeled (solid curves).

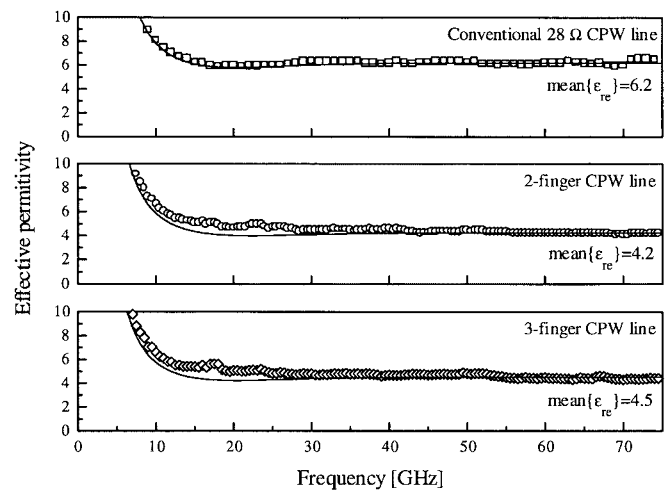

Fig. 4. Measured (symbols) and modeled (solid curves) effective relative dielectric constant of interdigital CPW lines, over the frequency range 2–75 GHz.

parameters were extracted from S-parameter measurements up to 120 GHz with the method described in [4]. As shown in Fig. 3, compared to the lowest impedance line in conventional CPW technology (i.e. ~30 Ω with $w = 37$ μm and $d = 50$ μm and 2.7-μm metallization thickness), the ICPW exhibit lower impedances over a broad frequency range (17 and 10 Ω for two and three fingers, respectively), with similar relative effective permittivity ε_{re} and attenuation as the normal CPW line (Fig. 4 and 5). Practically, lower impedances and ε_{re} are achieved than those predicted by 2.5-D electromagnetic simulations. This is explained by the influence of metallization thickness, which is not accounted for in HP-Momentum, and which causes an additional line capacitance (i.e., reduced Z_c) and lower energy propagation velocity in the substrate (i.e., reduced $\varepsilon_{\rm re}$).

From Figs. 3 and 4, the ICPW lines exhibit very low dispersion for impedance and effective relative permittivity. Thus, they can be easily modeled using a simple quasi-static model: as the imaginary part of the impedance remains negligible at millimeter-wave frequencies (in the order of 10^{-1} Ω at 100 GHz), the impedance can be assumed to be real, namely $\mathrm{Re}\{Z_c\}$ (Fig. 3), with constant $\varepsilon_{\rm re}$ (Fig. 4) and a frequency-dependant attenuation α well approximated by $\alpha = a_0 \cdot (\mathrm{f/GHz})^n$ [5] (Fig. 5). The parameters $Z_c, \varepsilon_{\rm re}$ and α are determined by fitting the S-parameters of the equivalent circuit model, to those obtained from measurements. The simulated and measured S-parameters for a two-finger 550-μm-long line on GaAs are illustrated in Fig. 6 (dimensions are $w = 10$ μm, $s = 5$ μm); as shown, the model provides an excellent agreement between simulation and measurements up to 120 GHz.

In a MMIC process, very low impedances lines can also be realized by exploiting silicon nitride as insulator which is used for metal–insulator–metal (MIM) capacitors [Fig. 1(c)]. Although in this case the imaginary part of Z_c is in the same order as the real part (approx. 3 Ω), simple parallel plate approximation gives an estimation of the impedance value,

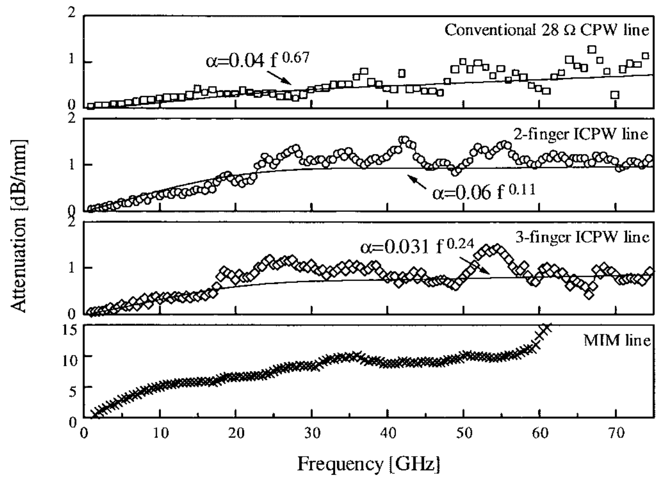

Fig. 5. Measured (symbols) and modeled (solid curves) attenuation of CPW, ICPW and MIM lines, over the frequency range 2–75 GHz.

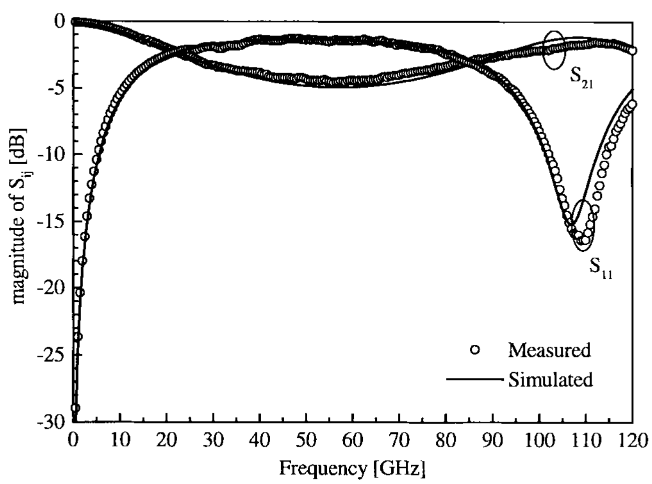

Fig. 6. Simulated and measured magnitude of S_{11} and S_{21} of 16 Ω ICPW line with $w = 10$ μm, $s = 10$ μm, over the frequency range 2–120 GHz.

namely $Z_c = 1/c_0\varepsilon_{re}\sqrt{\varepsilon_{\text{rep}}} \cdot t_d/w$. As shown in Fig. 3, with a center conductor width of $w = 17$ μm on silicon nitride, an impedance of 4 Ω is achieved. However, such a transmission line should be modeled rather as a miniature microstrip line than as a lumped capacitor; design data available in the literature are applicable [6]. The microstrip model with $w = 17$ μm, $h = 200$ nm, $\varepsilon_{rd} = 5$ has been used as an accurate description. If high attenuation (Fig. 5) prevents the use of long line lengths in matching networks, the knowledge of these transmission line parameters remains useful especially for dc path modeling in CPW designs as well as for capacitively loaded transmission lines [2].

Although coupled transmission lines have been studied theoretically by Fouad-Hanna [7], they still are not as popular in CPW design as for microstrip technology. However, $\lambda/4$ coupled transmission lines depicted in Fig. 3 are of great interest for dc-blocking as well as for broad-band interstage-matching networks in MMIC amplifiers. EM analysis shows that a large ground-to-ground spacing with narrow coupled center conductors is required to achieve efficient coupling and broadband input and output matching. Optimizing the structure

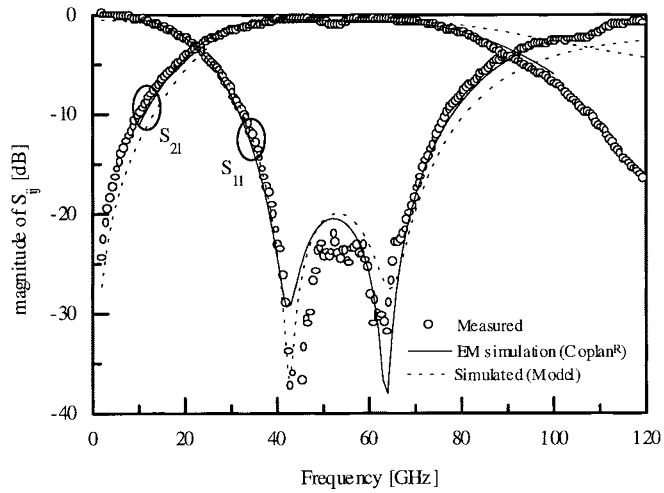

Fig. 7. Simulated and measured magnitude of S_{11} and S_{21} of $\lambda_0/4 = 550$ μm coupled transmission line with $w = 7$ μm, $s = 6$ μm and $d = 120$ μm, over the frequency range 2–120 GHz.

in this way resulted in dimensions of $w = 7$ μm, $s = 6$ μm and $d = 120$ μm on GaAs. This synthesized line is verified using the commercial electromagnetic simulator Coplan®. As shown on Fig. 7, the reflection and the transmission coefficients are lower than −20 dB and −1 dB, respectively, in the 40–70-GHz range. For design flexibility, a simple quasi-static model with odd- and even-mode parameters $Z_o = 34.4$ Ω, $Z_e = 148.1$ Ω, $\varepsilon_{re,o} = 4.3, \varepsilon_{re,e} = 8.7$ is extracted. From S-parameters plotted in Fig. 7, this model is able to describe accurately the structure up to W-band frequencies.

III. Summary

Multifinger, MIM, and coupled CPW transmission lines on gallium arsenide enabling low impedances down to 10 and 4 Ω, respectively, and broad-band coupling have been investigated. From numerical analysis and experiment, simple design rules and accurate models validated with measurements up to 120 GHz have been extracted. The broad-band characteristics of such transmission lines make them very well suited for use in millimeter-wave coplanar waveguide integrated circuits.

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