Modeling of Lumped-Element Coplanar-Stripline Low-Pass Filter

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***Abstract*— A novel coplanar-stripline low-pass filter using lumped-element spiral inductors and interdigital capacitors is proposed. To characterize this filter, a simple CAD equivalent-circuit model is established. The elements of this model, which consist of transmission lines, resistances, inductances, and capacitances, can all be handled by the closed-form formulas; hence this model is suitable for CAD application. In this study, results based on CAD model, full-wave simulation, and measurement are presented, and good agreement among these results validates the usefulness of the proposed CAD model. Being compact and uniplanar in structure, this coplanar-stripline low-pass filter is useful in the implementation of monolithic microwave integrated circuits (MMIC's).**

***Index Terms*—CAD model, coplanar-stripline filter.**

I. Introduction

The coplanar-stripline (CPS) structure has the merits of small dispersion, less sensitivity to substrate thickness, simple realization of short-circuited ends, easy integration of series and shunt active and passive components, and eliminating the need of via holes. It is also efficient in the use of wafer area and offers flexibility in the design of uniplanar circuits [1] such as mixers, antennas, and optoelectronic devices [2], [3]. But research work concerning CPS circuit components are relatively limited and only several CPS discontinuities, such as open, short, and slit structures, were examined [4], [5]. Recently, the CPS bandpass filter using series spur-slot elements was proposed [6]. This distributed filter structure does not require bond wires, but it occupies large chip size at lower microwave frequency due to the use of half-wavelength stubs.

This research proposes a novel CPS low-pass filter that composes of lumped-element rectangular spiral inductors and interdigital capacitors. This filter exhibits small physical size as compared to its distributed counterpart. Hence, it is suitable for monolithic microwave integrated circuits (MMIC's) with minimal size requirement. Furthermore, its lumped elements are symmetrically implemented in both signal and ground lines, thus balances in amplitude and phase are simultaneously achieved and the circuit layout may be denser. This balanced arrangement is difficult in the microstrip- and coplanar waveguide-based circuits.

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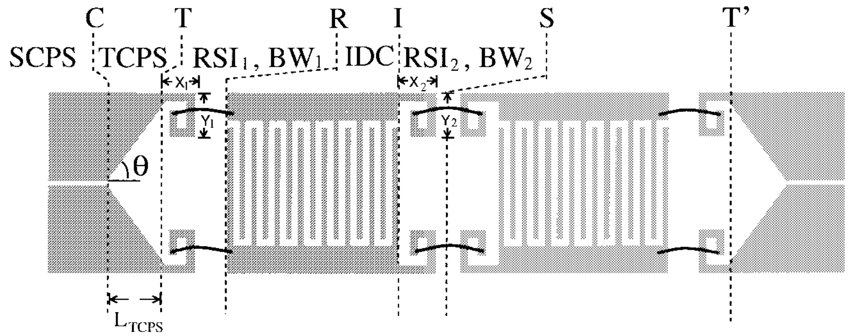
In this study, a simple CAD equivalent-circuit model is established to characterize the proposed CPS low-pass filter. This model consists of transmission lines, resistances, inductances, and capacitances to take care of the dominant and parasitic effects of tapered CPS, rectangular spiral inductors, interdigital capacitors, and bond wires. The usefulness of the proposed model is confirmed by comparison with the full-wave simulation and measurement. Since the full-wave simulation is time consuming and measurement is costly, this equivalent-circuit model, which has the merits of less numerical processing time and easy implementation into CAD software, is useful in characterizing the proposed filter configuration.

II. Filter Configuration and Equivalent-Circuit Model

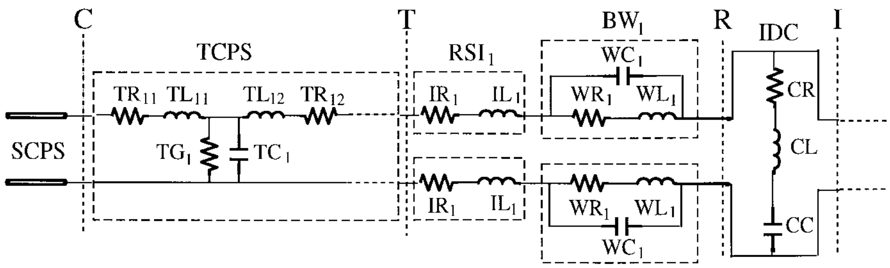
This study tries to propose a five-section Chebyshev CPS low-pass filter with 1-dB ripple and cutoff frequency at 5 GHz. This proposed CPS low-pass filter may be implemented by using the lumped-element rectangular spiral inductors, interdigital capacitors, and bond wires to realize the series inductors and shunt capacitors in the prototype circuit. The filter configuration is shown in Fig. 1(a), which will be modeled by an equivalent circuit discussed later.

For theoretical modeling, the filter structure [Fig. 1(a)] is decomposed into five parts, i.e., the symmetric coplanar stripline (SCPS), the tapered coplanar stripline (TCPS), the rectangular spiral inductor (RSI), the bond wire (BW), and the interdigital capacitor (IDC). To derive the equivalent circuit, the RSI is modeled by a lumped inductance together with a series parasitic resistance. By dividing the RSI into several straight line segments, the lumped inductance may be calculated from the sum of the segmental self inductances and mutual inductances [7, eq. (14)], while the parasitic resistance is the sum of the segmental resistances [7, eq. (1)].

The IDC is modeled by a lumped capacitance in series with the parasitic resistance and inductance. Based on the partial capacitance method, the lumped capacitance may be computed from the capacitances of all two-finger sections, that of a three-finger section, and those due to all finger ends [8, eq. (44)]. The parasitic resistance and inductance are the parallel combination of the corresponding ones for all fingers [7, eqs. (1) and (4)]. The BW for connecting the inner inductor node to the circuit is represented by a lumped inductance [10, eq. (A1)] and a series resistance [9, eq. (17)] together with a parallel capacitance [10, eq. (A2)] to include the effect between bond wire and inductor segment.



(a)



(b)

Fig. 1. Coplanar-stripline low-pass filter. (a) Physical configuration. (b) Equivalent-circuit model.

The proposed filter is constructed in the CPS environment with the input and output ports connected to 50.7-Ω SCPS's. The impedance levels would be largely different if the lumped-element RSI_1 is directly connected to the SCPS. Hence, the TCPS with inclined angle θ and length L_{TCPS} should be included to provide good impedance matching. As suggested by [11], the TCPS is modeled by the cascaded sections of lumped-element series inductances and resistances as well as shunt capacitances and conductances.

Fig. 1(b) shows part of the equivalent circuit for the filter elements between the planes C and I [Fig. 1(a)] which consist of TCPS, RSI_1, BW_1, and IDC. The cascade of the ones similar to Fig. 1(b) yields the complete equivalent circuit of the low-pass filter in Fig. 1(a). Due to less dispersive characteristics of CPS, it is advantageous to apply the quasi-TEM approximation to discuss the CPS propagation characteristics, at least up to millimeter-wave frequency range [6]. Hence, the characteristic impedance, effective dielectric constant, and attenuation constant of SCPS may be obtained by the formulas based on the conformal mapping technique [12, eqs. (7.75), (7.72), and (7.112)]. Notably, the elements of equivalent circuit in Fig. 1(b) are all calculated by the closed-form approximation formulas hence the model can easily be implemented into CAD packages.

III. Simulated and Experimental Results

Filter performance is degraded by the discontinuity mismatch in filter components. To reduce this mismatch effect, the inclined angle θ and length L_{TCPS} of TCPS structure are varied to optimize the filter response. Fig. 2 shows the simulated input impedances of the filters with 53° and 30° tapers as well as the one without TCPS, based on the equivalent-circuit model in Fig. 1(b). In comparison with the filter structure with 30° taper and the one without TCPS, the filter with 53° taper has input resistance and reactance which are much close to 50 and 0 Ω, respectively, in the passband (0 to 5 GHz) and exhibit opposite characteristics in the stopband (5 to 10 GHz). For better performance, the 53° taper is chosen in the filter configuration.

TABLE I
Dimensions (All in Micrometers) of CPS Low-Pass Filter in Fig. 1(a)

	gap width	strip width	strip length	
RSI_1	76.2	76.2	$X_1 = 253$	$Y_1 = 381$
RSI_2	76.2	76.2	$X_2 = 330.2$	$Y_2 = 381$
IDC	50.8	50.8	1016	
SCPS	length = 508, strip width = 762, slot width = 30.48			
TCPS	length = 508, strip width = 762, slot width = 30.48 -- 1402			
BW_1	length = 711.2, diameter = 17.7			
BW_2	length = 889, diameter = 17.7			

Let us implement the CPS low-pass filter [Fig. 1(a)] with dimensions summaried in Table I. All the circuits in this paper are fabricated on a 635-μm-thick alumina substrate ($\epsilon_r = 9.8$ and $\tan\delta = 0.0001$) and have strips of metallization thickness $t = 3$ μm and conductivity $\sigma = 4.1 \times 10^7$ S/m. For measurements, the HP 8510B network analyzer is used together with a set of CPS TRL on-wafer standards [4]. Fig. 3 shows the return and insertion losses of this filter from the

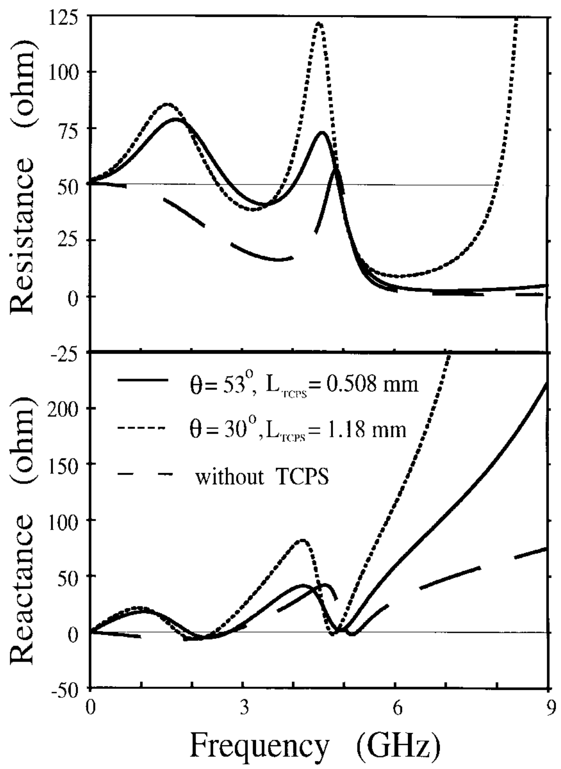


Fig. 2. Input impedances of CPS low-pass filters with and without tapered coplanar stripline.

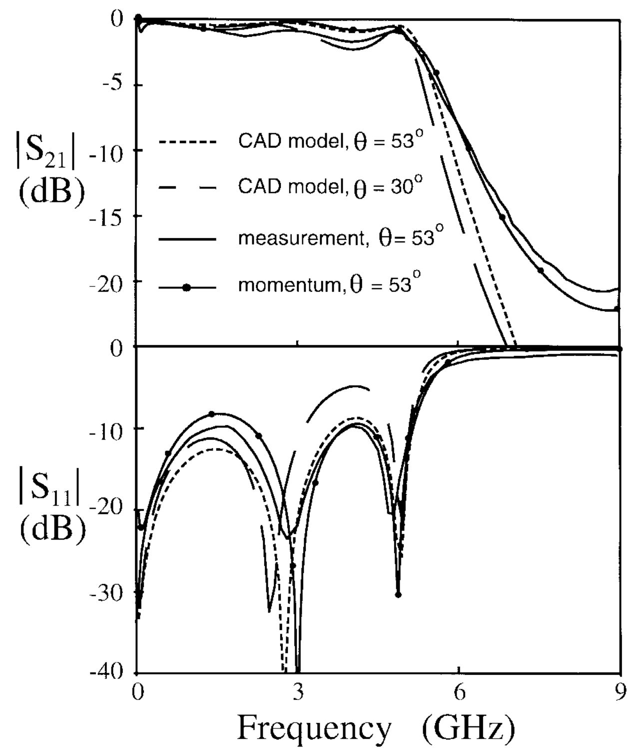


Fig. 3. Simulated and measured return and insertion losses of CPS low-pass filter.

CAD equivalent-circuit model [Fig. 1(b)], *HP momentum* full-wave simulator, and measurement. Good agreement among our CAD simulated results, full-wave simulated ones, and measured ones confirms the validity of the proposed CAD model. As compared with the 53° taper, the 30° one which possesses lower $|S_{21}|$ and higher $|S_{11}|$ is less suitable as shown in Fig. 3. Note that the effect of inclined angle and length of TCPS structure is important in determining the filter response. By using the efficient CAD model in the design process, the optimum inclined angle and length of TCPS for better filter response can easily be achieved in seconds compared to hours in full-wave simulation.

IV. Conclusion

In this study, a novel CPS low-pass filter consisting of lumped-element spiral inductors and interdigital capacitors has been fabricated and tested. A simple CAD equivalent-circuit model has been established to analyze this CPS filter. Results from CAD model, full-wave simulation, and measurement have been compared and discussed, and good agreement among these results supports the usefulness of the CAD model. The developed CAD model can easily be modified to characterize the other lumped-element CPS filters with Chebyshev, Butterworth, and elliptic responses.

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