QUASI-LUMPED-ELEMENT 3- AND 4-PORT NETWORKS FOR MIC AND MMIC APPLICATIONS*

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ABSTRACT

Design and analysis techniques are presented for quasi-lumped-element Wilkinson divider/combiner networks (3-port) and branch-line couplers (4-port) for MIC/MMIC applications. The circuit area is reduced to less than 20 percent of conventional transmission line realizations at 4 GHz. Test results are presented for a CPW 10-dB coupler (2 x 2 mm) and an MIC 3-dB Wilkinson divider/combiner circuit (1.75 x 2.75 mm). Good agreement is obtained between measured and modeled results.

INTRODUCTION

The use of distributed transmission lines for the design of Wilkinson-type power divider/combiner networks and branch-line couplers [1] limits the minimum achievable size of the networks. In MIC circuits for on-board satellite applications where the size and weight of the circuits are major design criteria, and for MMICs in which a higher circuit count per wafer results in lower circuit costs, the quasi-lumped-element circuit approach may be used to realize very small circuits [1]-[3].

This paper presents synthesis and design techniques for the realization of quasi-lumped-element, 3-dB, Wilkinson divider/combiner and branch-line coupler networks.

ANALYSIS

Distributed and lumped circuit representations of a single-section, branch-line coupler are shown in Figure 1. In terms of the network S-parameters, the coupling factor, k, may be defined as

$$k = |S_{31}/S_{21}| < 1.0 \qquad (1)$$

The 4-port S-parameters of the network may be expressed in terms of even- and odd-mode reflection and transmission coefficients of the ABCD matrices for symmetrical circuits [4],[5]. Using symmetrical 4-port network analysis [4] and equation (1), it follows that branch-line coupler impedances (Z_{c1}, Z_{c2}, and Z_T) are related to input/output impedances (Z_{01} and Z_{02}) and coupling factor k by

$$Z_{c1} = Z_{01}/k \qquad (2a)$$

$$Z_{c2} = Z_{c1}Z_{02}/Z_{01} \qquad (2b)$$

$$Z_T = \sqrt{Z_{01}Z_{02}/(1 + k^2)} \qquad (2c)$$

These characteristic impedances may be transformed into high- or low-pass lumped equivalent π- or T-networks. The selection of high- or low-pass configuration is based on component realizability and circuit layout considerations. The high-pass equivalent π-network between each port of the branch line coupler (Figure 1b) may be represented by two L-sections, each with 45° phase shift. Based on the image parameters of typical L-sections [5], the equivalent branch capacitances and junction inductances at center frequency f_0 are given by

$$C_{ij} = 1/Z_{0i}2\pi f_0 \qquad (3)$$

where

$$Z_{0i} = Z_T \text{ for } C_{ij} = C_{12} \text{ and } C_{34}$$
$$= Z_{c1} \text{ for } C_{ij} = C_{14}$$
$$= Z_{c2} \text{ for } C_{ij} = C_{23}$$

and

$$L_{Tj} = \frac{Z_T Z_{cj}}{2\pi f_0(Z_T + Z_{cj})}, \quad j = 1 \text{ and } 2 \qquad (4)$$

For a 10-dB coupler design with input/output impedances of 50 Ω and a center frequency of 4 GHz, equations (2) through (4) result in inductances of $L_{T1} = L_{T2} = 1.45$ nH, and capacitances of $C_{12} = C_{34} = 0.84$ pF and $C_{14} = C_{23} = 0.25$ pF.

Figure 2 is an equivalent representation for 3-port analysis of a Wilkinson divider/combiner. For the low-pass equivalent T-network (with 90°

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phase shift) which consists of two L-sections, the equivalent inductances and capacitances may be obtained from

$$L = \frac{\sqrt{2} \cdot Z_0}{2\pi f_0} \quad \text{and} \quad C_T = \frac{1}{\sqrt{2}Z_0 \cdot 2\pi f_0} \qquad (5)$$

For a 4-GHz Wilkinson divider design, these equations result in inductance of L = 2.8 nH and capacitance of C_T = 0.56 pF.

FABRICATION AND PERFORMANCE RESULTS

A 10-dB, single-section, branch-line coupler with input/output impedances of 50 Ω was implemented in CPW configuration on 50-mil (1.27-mm)-thick alumina substrate (Figure 3). The 50-Ω input/output transmission lines were made 2 mil (50 μm) wide by adjusting the width-to-gap ratios to minimize discontinuity effects at the junctions. Since the modeling of CPW inductors has not been thoroughly explored and is not well understood, inductor elements were realized with 2.7-mm-long shorted transmission lines of 62-Ω impedance that meandered over a 0.75- x 0.75-mm area. The circuit contained 1-mil-wide air bridges across CPW ground planes and overlay capacitors realized with 0.65-μm-thick Si_3N_4. The overall dimensions of the coupler circuit were less than 2 x 2 mm.

Modeling of the coupler on Super-Compact indicates that realized element values are within 10 percent of design values. The measured and modeled performance of the coupler over a 3.5- to 5-GHz frequency range is shown in Figure 4. The measured transmission loss at the direct port is approximately 0.4 dB higher than that modeled, and at the coupled port is within 0.6 dB of the modeled response. The coupling ratio at 4 GHz is 9.5 dB. Measured return loss and isolation are 16.5 and 23.5 dB, respectively. The return loss and isolation measurements show large variation with respect to modeled performance. This may be because parasitic capacitances to ground were not included in the present model.

A 3-dB Wilkinson divider/combiner MIC circuit was designed and realized on 12.5-mil (0.318-mm)-thick GaAs substrate with overall dimensions of less than 1.75 x 2.75 mm (Figure 5). The lumped-element inductors were designed to be less than 0.35 mm square, consisting of coupled-line segments 11.5 μm wide with interline spacing of 9 μm. The 1-3/4 turn inductors have been analyzed by using a coupled-line distributed model [6]. The parasitic capacitances associated with the multi-turn inductor [2] were obtained by computer-aided optimization, and values of external capacitances were adjusted to absorb these parasitics. The effect of bond-wires is included in the series inductor models. An equivalent lumped-element circuit model for the divider/combiner network was derived and used to model the circuit response on Super Compact. Figure 6 shows a measured and modeled power division loss of 3.3 dB, with measured insertion loss imbalance between output ports of less than 0.1 dB. The measured phase imbalance between output ports was less than 1° over the 3- to 4.5-GHz frequency range. The area of the circuit is less than 20 percent of the corresponding distributed element design and may be reduced still further by a completely monolithic implementation.

CONCLUSIONS

A 4-GHz, 3-dB Wilkinson divider/combiner and a 4-GHz, 10-dB branch-line coupler were realized in lumped-element form on GaAs and alumina substrates, respectively. Good agreement was obtained between modeled and measured results for both circuits. These circuits are highly miniaturized designs, suitable for MMIC applications where reliability, number of circuits per wafer, and cost are important considerations.

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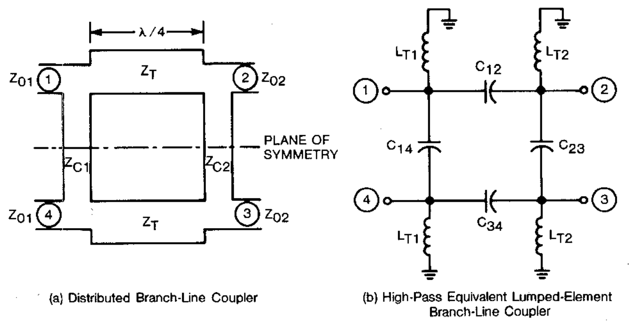

Figure 1. Lumped-Element Equivalent of the Distributed Branch-Line Coupler Circuit

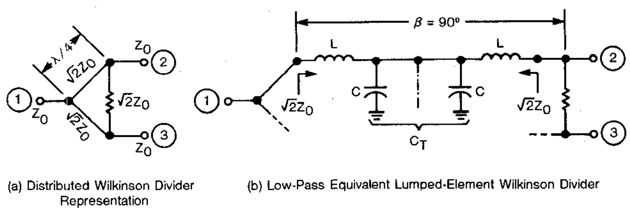

Figure 2. Lumped-Element Equivalent of the Distributed Power-Divider Circuit

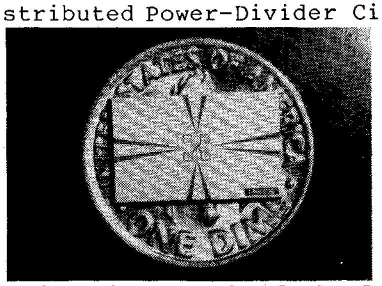

Figure 3. Photograph of the Lumped-Element Coupler (2 x 2 mm)

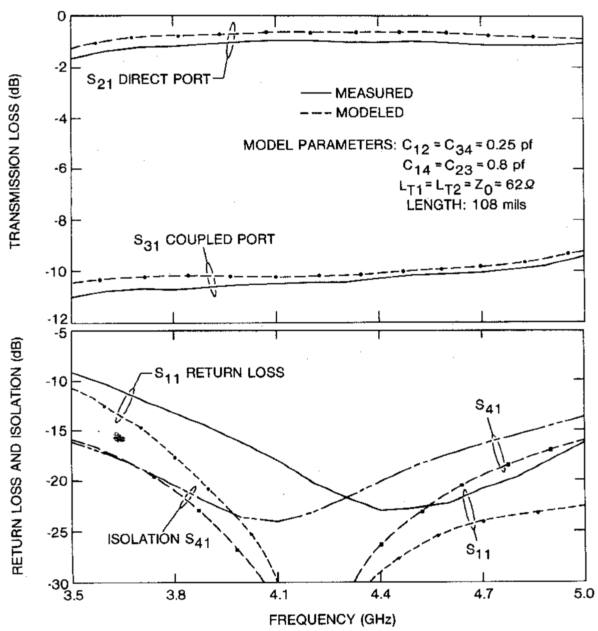

Figure 4. Measured and Modeled Response of Lumped-Element 10-dB Coupler

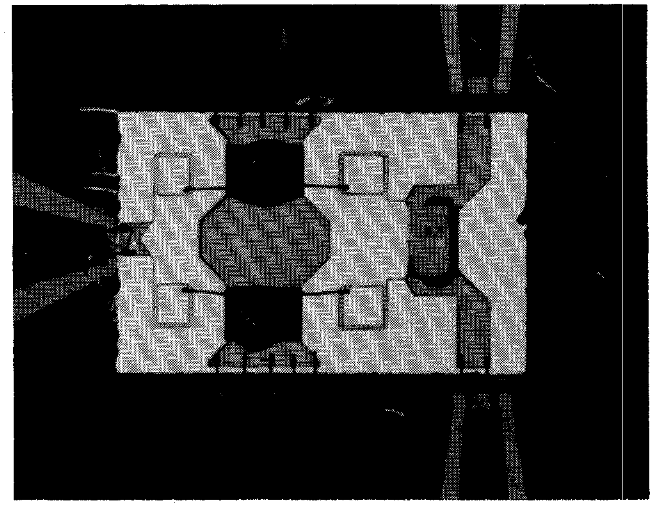

Figure 5. Photograph of the Wilkinson Divider Circuit (1.75 x 2.75 mm)

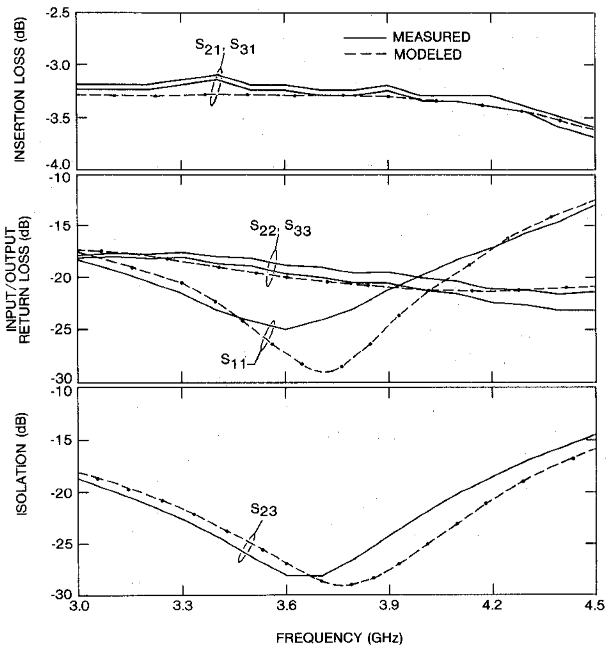

Figure 6. Measured and Modeled Response of Lumped-Element 3-dB Wilkinson Divider