Impedance-Transforming 3-dB 90° Hybrids

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Abstract —**Design techniques and performance results for impedance-transforming branch-line and coupled-line 3-dB 90° hybrids are discussed, and design equations for a single-section impedance-transforming branch-line coupler are presented. Test results for a 50- to 25-Ω branch-line hybrid show approximately 20-percent bandwidth at a 5.4-GHz center frequency with 3.15±0.25-dB amplitude balance. A broad-band hybrid with 50- to 20-Ω impedance transformation has also been realized by tandem connection of coupled-line sections. Measured results show an amplitude balance of 3.7±0.68 dB over the 3–5-GHz range for a section coupling of 11.44 dB. The amplitude balance is improved to ±0.2 dB for a design with section coupling of 12.1 dB. Test results for a 50-Ω tandem hybrid are also presented.**

I. INTRODUCTION

BRANCH-LINE [1] and coupled-line (Lange) [2] 3-dB hybrids have been used extensively in the design of balanced amplifiers and phase shifters. In the conventional approach, the hybrids are designed with 50-Ω input/output impedances. Hybrids that also transform 50-Ω input impedance to a lower value (20–25 Ω) significantly reduce the total number of elements required for FET matching. In-phase Wilkinson hybrids [3] and branch-line 90° hybrids [4] with impedance-transforming properties have been proposed in the literature; however, hardware realization of such hybrids has not been extensively investigated. This paper presents simple design equations and performance results for an impedance-transforming, single-section, branch-line, 3-dB, 90° hybrid.

Coupled-line hybrids have the potential of providing much larger bandwidth than that of branch-line hybrids. Nonsymmetrical directional couplers that use coupled lines of unequal characteristic impedances have been described previously [5], [6]. These broad-band couplers provide impedance transformation from incident and direct ports to coupled and isolation ports. This paper discusses coupled-line 90° hybrids that provide impedance transformation from incident and isolation ports to direct and coupled ports. These broad-band hybrids have been realized by the tandem connection of three coupled-line sections. For performance comparison and evaluation, test results for a 50-Ω tandem coupler are also presented.

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II. 50- TO 25-Ω BRANCH-LINE HYBRID

Design values of the branch- and main-line impedances for a single-section four-port structure (Fig. 1) can be readily obtained by using symmetrical four-port network analysis [1], [7], [8]. In the figure, Z_{01} and Z_{02} are the input and output impedances and Z_{c1}, Z_{c2}, and Z_T are the branch- and main-line impedances. In terms of the network S parameters, the ideal coupler must satisfy the following conditions at the center frequency:

$$S_{11} = S_{41} = 0 \tag{1a}$$

and

$$k = \left|\frac{S_{31}}{S_{21}}\right| < 1 \tag{1b}$$

where k is the coupling factor between ports 2 and 3.

The four-port S parameters of the network may be expressed in terms of even- and odd-mode reflection and transmission coefficients [7]. Using the ABCD matrices for symmetrical circuits [1] together with (1), it follows that the branch-line coupler impedances are related to the input/output impedances and coupling factor k by

$$Z_{c1} = \frac{Z_{01}}{k} \tag{2a}$$

$$Z_{c2} = \frac{Z_{c1}Z_{02}}{Z_{01}} \tag{2b}$$

$$Z_T = \sqrt{\frac{Z_{01}Z_{02}}{1+k^2}}. \tag{2c}$$

These equations were used to design a 3-dB, 90° hybrid with 50- to 25-Ω transformation and ±0.25-dB amplitude balance. Fig. 2 shows the circuit realization on a 15-mil-thick alumina substrate. Broad-band, three-stage, quarter-wavelength impedance transformers are designed to transform 25 Ω at the output ports to 50 Ω for measurements in a 50-Ω system. Fig. 3 depicts the measured and modeled transmission parameters at the two output ports.

The circuit model was analyzed using SUPERCOMPACT™, and the effects of discontinuities and T-junctions were included in the model [9], [10]. The bandwidth with 3.15±0.25-dB signal balance at the output ports is approximately 20 percent at a 5.4-GHz center frequency. Measured return losses and isolation are better than 15 and 17.5 dB, respectively, and the phase balance is 88.5°± 1.5° over the same frequency band. The useful bandwidth

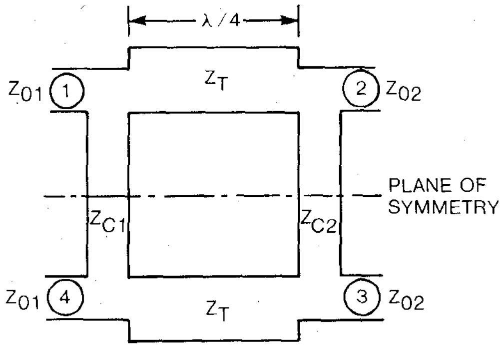


Fig. 1. Four-port representation of single-section branch-line coupler.

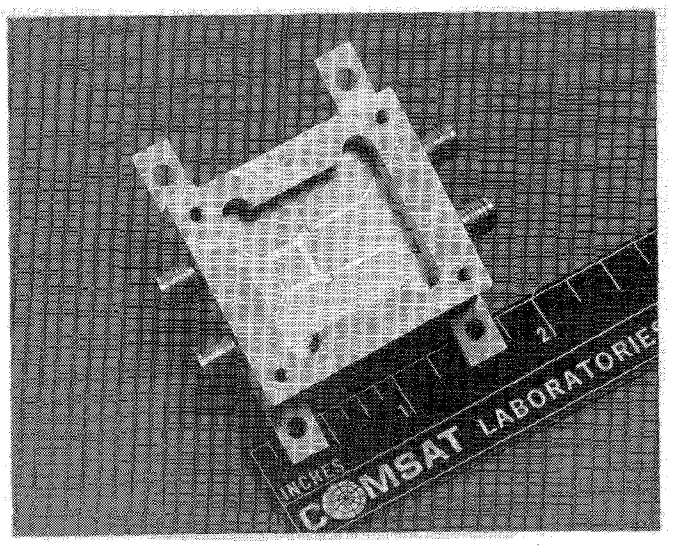


Fig. 2. 50- to 25-Ω impedance-transforming branch-line hybrid.

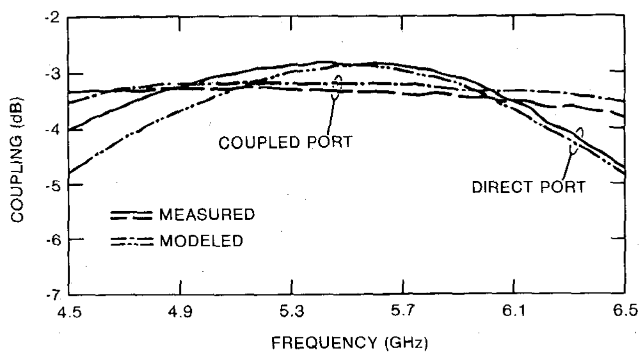


Fig. 3. Measured and modeled amplitude balance for 50- to 25-Ω branch-line hybrid.

of impedance-transforming branch-line couplers decreases as the impedance transformation ratio increases [4]; however, the insertion loss is lower than that of coupled-line hybrids. It should be possible to reduce the size of these hybrids by using folded branch- and coupled-line hybrid approaches [11].

III. Coupled-Line Tandem Hybrids

Hybrid 3-dB couplers have been constructed in the past by the tandem connection of two 8.34-dB couplers [12], which are much easier to realize because of relatively loose

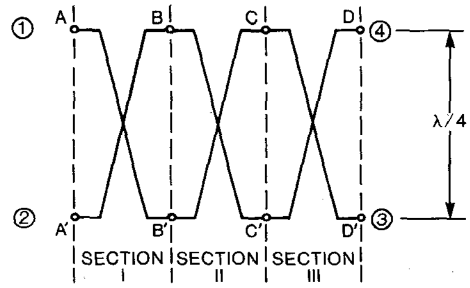


Fig. 4. Tandem interconnection of three couplers.

coupling. For an impedance-transforming coupler design, three couplers may be connected in tandem to obtain a 3-dB coupler, as shown in Fig. 4. For computation of the coupling ratios for each section, it may be assumed that the signal level at A is 1 and at A′ is 0, and that the coupling coefficient of each section is k. The remaining signal levels are

$$\mathrm{B}=k \qquad \mathrm{B}'=j\left(\sqrt{1-k^2}\right) \tag{3}$$

$$\mathrm{C}=k^2-(1-k^2) \qquad \mathrm{C}'=j2k\sqrt{1-k^2} \tag{4}$$

$$\mathrm{D}=k(4k^2-3) \qquad \mathrm{D}'=j(4k^2-1)\sqrt{1-k^2}. \tag{5}$$

For 3-dB power division, signals at D and D′ must be equal. Therefore,

$$k(4k^2-3)=(4k^2-1)\sqrt{1-k^2}. \tag{6}$$

Defining $l=k^2$ yields

$$32l^3-48l^2+18l-1=0. \tag{7}$$

Equation (7) is a cubic and can be solved analytically for

$$l=k^2=0.5, \quad 0.5\pm\tfrac{1}{4}\sqrt{3}. \tag{8}$$

The first solution ($k^2=0.5$) corresponds to a 3-dB coupler section and is not useful due to practical considerations. The remaining two solutions ($k^2=0.067$ and $k^2=0.933$) are complementary and result in identical coupler sections when the direct and coupled ports are interchanged.

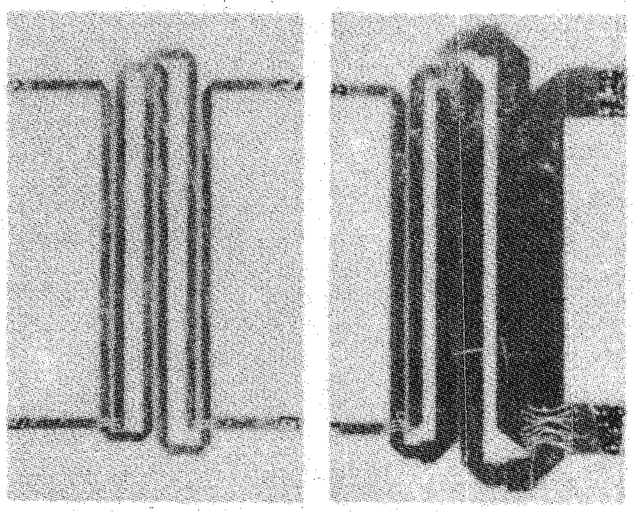
A value of $k=0.2588$ (-11.74 dB) results in a 3-dB power split at the band center (with narrow bandwidth). For increased bandwidth, a coupling ratio of -11.44 dB ($k=0.2679$) may be used, which corresponds to a balance of ± 0.25 dB. For the 50-Ω hybrid, all three sections have 50-Ω characteristic impedances. For the 50- to 20-Ω hybrid design, each coupled section also performs an impedance transformation. The impedances of the three sections were selected to be 41.55, 31.62, and 24.06 Ω, respectively [7]. The length of these couplers is essentially quarter wavelength, plus additional interconnect lines. The width is determined by the spacings between different coupling sections and by the width of the coupled lines.

IV. Realization of a 50- to 20-Ω Hybrid and a 50-Ω Tandem Hybrid

A 50- to 20-Ω impedance-transforming hybrid was designed for a 4-GHz center frequency. For performance comparison, a three-section 50-Ω tandem coupler without

TABLE I
DESIGN PARAMETERS FOR 50-Ω AND 50- TO 20-Ω THREE-SECTION TANDEM HYBRIDS

Coupler	Sections	Characteristic Impedance, Z_o (Ω)	Even-Mode Impedance, Z_{oe} (Ω)	Odd-Mode Impedance, Z_{oo} (Ω)	Line Width, W (mil)	Line Spacings, S (mil)
50-Ω	I, II, and III	50.00	66.02	37.87	8.71	4.07
50- to 20-Ω	I	41.55	54.68	31.68	12.44	3.38
	II	31.62	41.62	24.03	19.39	2.24
	III	24.06	31.67	18.28	28.48	1.25



(a) (b)

Fig. 5. 50-Ω and 50- to 20-Ω 3-dB hybrids (substrate: 10-mil-thick alumina). (a) 50-Ω tandem hybrid. (b) 50- to 20-Ω tandem hybrid.

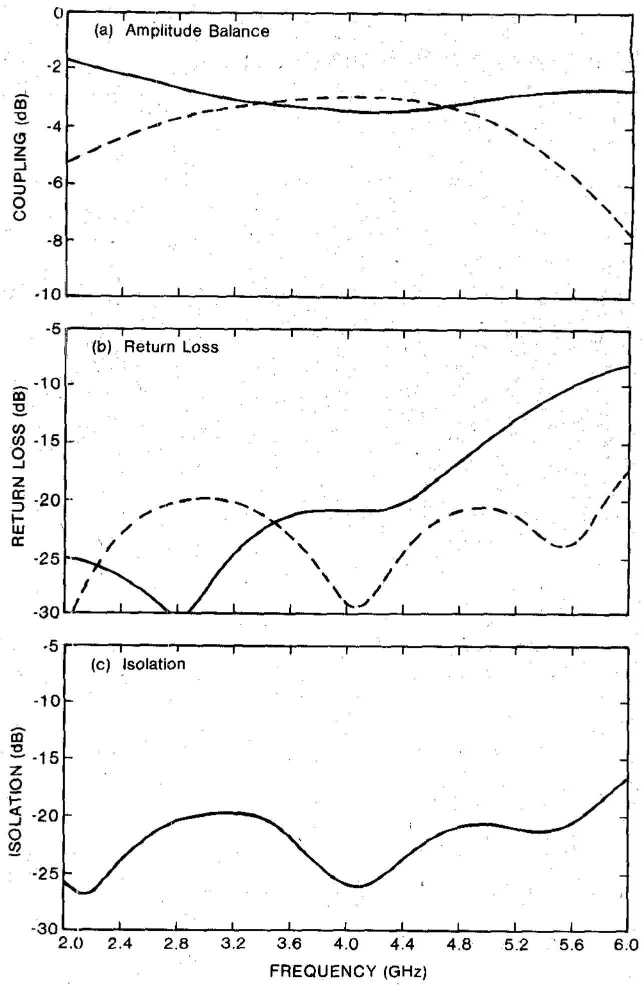


Fig. 6. Modeled performance of 50- to 20-Ω impedance-transforming hybrid (design section coupling: 11.44 dB).

impedance transformation was also designed. Table I lists the even- and odd-mode impedances and corresponding line widths and spacings for the three sections. Fig. 5 shows photographs of 50-Ω and 50- to 20-Ω tandem hybrids fabricated on 10-mil-thick alumina substrate. The minimum spacing between coupled lines is 1.25 mil. A gold plating thickness of 2 μm was used. The overall dimensions of the 50-Ω and 50- to 20-Ω hybrids were 0.34×0.096 in and 0.39×0.16 in, respectively. The impedance-transforming coupler is larger than the 50-Ω hybrid because of wider interconnect lines and the width of the low-impedance lines.

To minimize mutual coupling effects, the spacing between the coupler sections was enlarged (20 to 25 mil) relative to gaps in the coupled lines. The effect of mutual coupling between different sections was not included in the initial analysis. To maintain 90° phase difference at the output ports, the interconnect lines were maintained to be symmetrical and of the same physical length. The crossovers were achieved with minimum-length bond wires across a gap of 2 mil between the microstrip lines of each crossover. These bond wires introduce some asymmetry in the coupling structure. To minimize their effect, a large number of bond wires (minimum of four) are required. The effect of bond wires, 90° bends, and steps associated with interconnect lines were modeled on SUPERCOMPACT. The modeled amplitude balance, return losses, and isolation results for the 50- to 20-Ω 3-dB hybrid are shown in Fig. 6.

Fig. 7 is a photograph of the test fixture with an impedance-transforming hybrid. The hybrids were fabricated on 0.75×0.25-in substrate with access lines. For testing the 50- to 20-Ω hybrids, a broad-band, three-section, quarter-wavelength transformer (0.75×0.871 in) was designed. This transformer was replaced with same-length 50-Ω lines for testing the 50-Ω hybrid.

Figs. 8 and 9 show test results for the 50-Ω tandem hybrid and the 50- to 20-Ω impedance-transforming hybrid, respectively. For the impedance-transforming hybrid, the amplitude balance is 3.7 ± 0.68 dB and the return loss and isolation are approximately 15 dB over the 3–5-GHz frequency band. In comparison, the amplitude balance for the 50-Ω tandem hybrid is 3.5 ± 0.5 dB and the return loss and isolation are better than 19 dB and 17.5 dB, respectively, over the same frequency band. These return loss measurements are made at fixture ports and include the effect of the 50-Ω access line, impedance transformers, and connectors.

Results for both cases reveal overcoupling. The effective section coupling for the impedance-transforming hybrid for measured amplitude balance is 10.6 dB. Mutual cou-

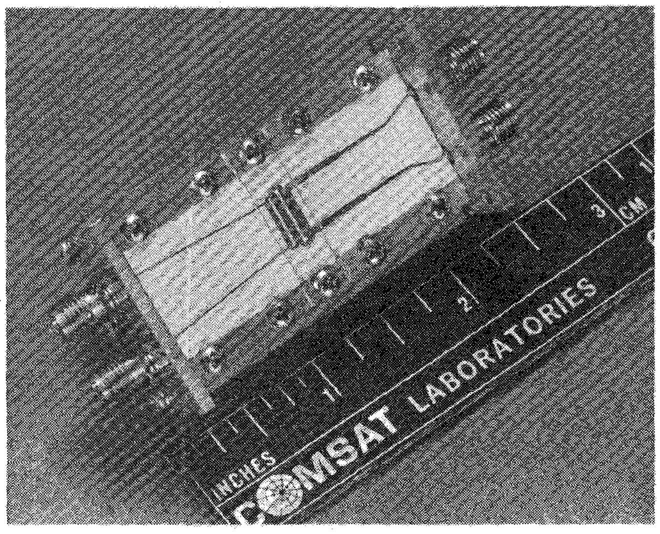


Fig. 7. Test fixture with 50- to 20-Ω hybrid.

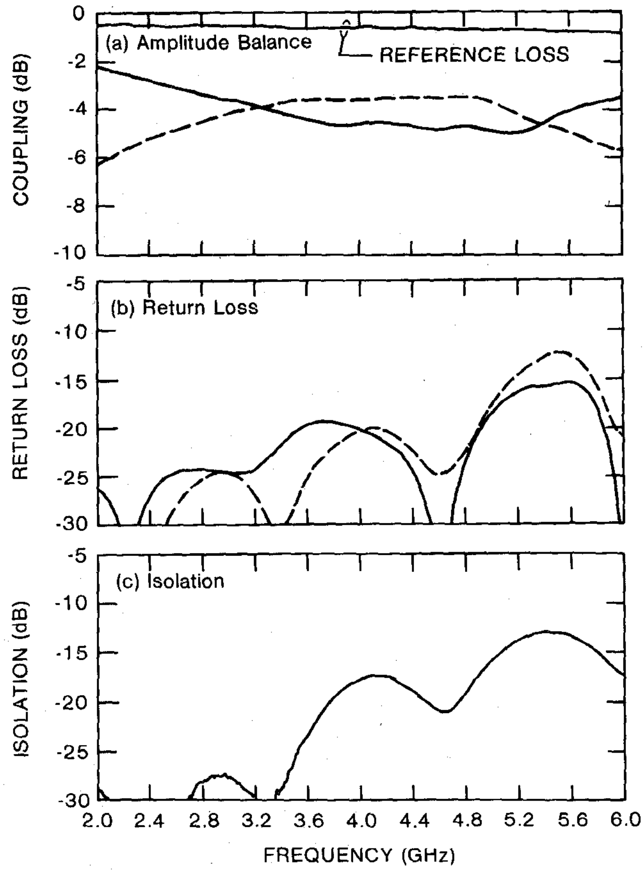


Fig. 8. Measured performance of 50-Ω tandem hybrid (design section coupling: 11.44 dB).

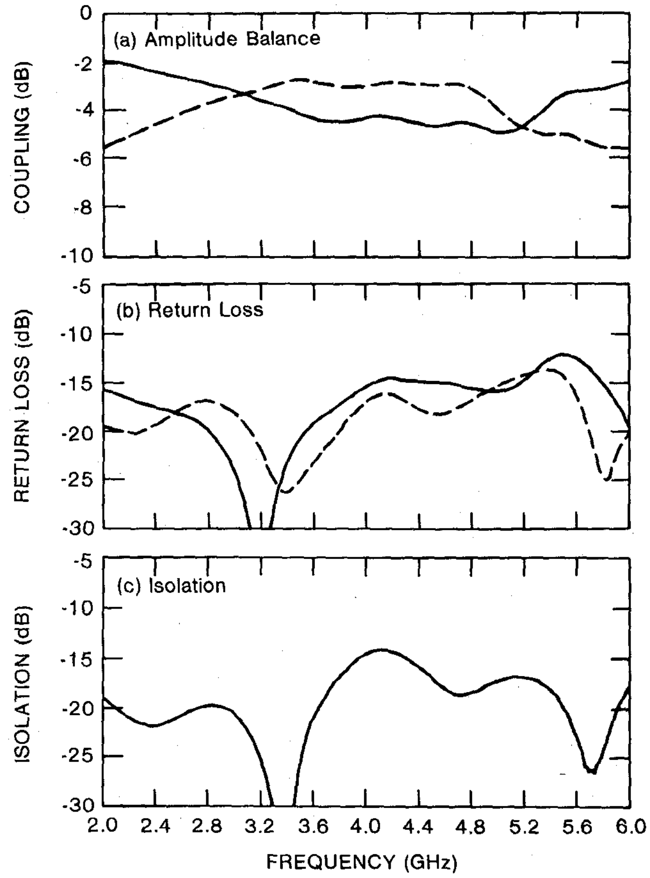


Fig. 9. Measured performance of 50- to 20-Ω impedance-transforming hybrid (design section coupling: 11.44 dB).

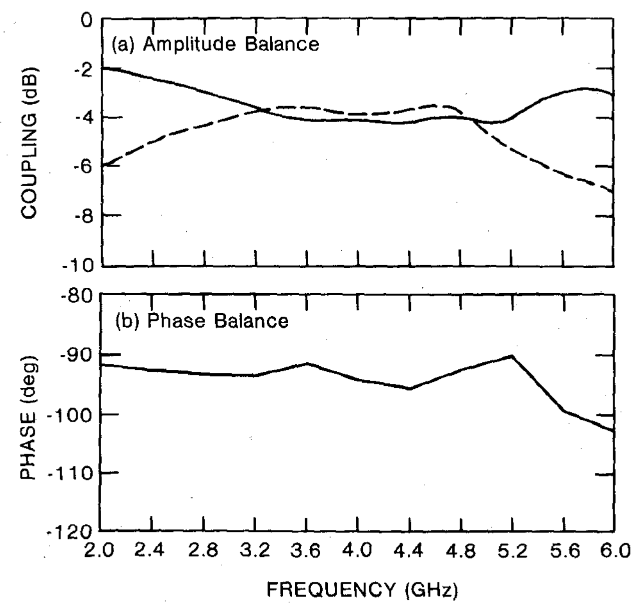


Fig. 10. Measured performance of 50- to 20-Ω impedance-transforming hybrid (design section coupling: 12.1 dB).

pling effects between different sections should be included in a more rigorous analysis of tandem couplers. The balance in these couplers can be improved by compensating for these effects. For example, a hybrid with a balance of ±0.2 dB over 3–5 GHz was realized (Fig. 10) by redesigning the hybrid with section coupling to 12.1 dB. The phase balance was 93° ±3° over the same frequency band.

Impedance-transforming hybrids can be used to reduce the size of MIC and MMIC balanced amplifiers and phase shifters. For a 4-GHz, 1-W balanced amplifier example [13], analysis has shown that the size of matching networks could be reduced by more than 40 percent compared to the

50-Ω Lange hybrid design. This reduction in size is possible despite the fact that the impedance-transforming hybrid is larger than a conventional 50-Ω hybrid.

V. Conclusions

Simple expressions for the design of impedance-transforming branch-line and coupled-line 3-dB 90° hybrids have been presented. Performance of a single-section branch-line hybrid with a 2-to-1 impedance transformation ratio has shown approximately 20-percent bandwidth with ±0.25-dB amplitude balance. A broad-band, 50- to 20-Ω impedance transforming hybrid realized by tandem connection of coupled-line sections has been demonstrated to have more than 50-percent bandwidth and ±0.2-dB amplitude balance. This bandwidth performance is comparable to that of conventional Lange [2] couplers.

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