pulses. The input pulse is modulated with a 3-MHz sinusoidal signal. The amplifier successfully retains the modulation envelope.

V. Conclusions

A variable-gain constant output power amplifier has been presented. The variable gain is obtained with a dual-gate FET amplifier and the constant output power is obtained through advanced AGC. The automatic gain adjustment prevents saturation of the amplifier and amplitude clipping. The amplifier has a wide dynamic range of the input signal of −45 dBm–0 dBm over a 3-GHz band. The amplifier described above has many applications as cited in Section I which makes it very versatile for multi-functional use. The amplifier has the capability of detecting two (or more) pulses at a fast rate and of preserving the amplitude modulation and has a wide bandwidth and dynamic range as well.

Acknowledgment

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Synthesis of Broad-Band 3-dB Hybrids Based on the 2-Way Power Divider

G. LENNART NYSTRÖM

***Abstract*—The synthesis of broad-band 2-way Wilkinson hybrids is well known. The even- and odd-mode analysis results in two equivalent circuits where the synthesis of the odd mode is done by computer optimization. This paper shows an exact synthesis of 2-way Wilkinson power dividers having one isolation resistor, but an arbitrary number of quarter-wave transformers. A large number of circuits have been synthesized with up to 6 quarter-wave transformers. The 2-way Wilkinson hybrid can be extended to a 4-port component. This 4-port component can operate as a 180° or 90° 3-dB hybrid depending on the input port. The hybrid has a high directivity independent of frequency when used as a 180° hybrid. Experimental results are given for a 2-way divider and a 3-dB hybrid built in microstrip with a center frequency of 5 GHz.**

I. Introduction and Theory

Broad-band 2-way Wilkinson power dividers (Fig. 1) are synthesized by using the even and odd modes [1]–[4]. The synthesis of the even mode is exact and well known. The synthesis of the odd mode has previously been carried out only by computer optimization. This paper shows how to make an exact synthesis of the odd mode when only one isolation resistor is employed (Fig. 2). The problem is that of an n-order matching with the character-

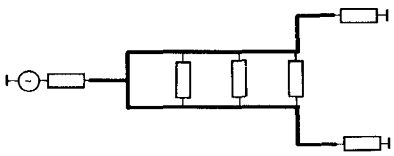

Fig. 1. The 2-way Wilkinson power divider.

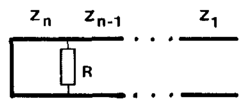

Fig. 2. The new odd-mode circuit.

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TABLE I
THE LIMITS OF THE VSWR WITH EQUAL-RIPPLE DESIGN FOR DIFFERENT NUMBER OF QUARTER-WAVE TRANSFORMERS TO SATISFY $Z_{0e} \geqslant Z_{0o}$

n	VSWR maximum
2	≤ 1.3
3	≤ 1.3
4	≤ 1.2
5	≤ 1.2
6	≤ 1.2

TABLE II
THE TABLE SHOWS SOME SYNTHESIZED POWER DIVIDERS WITH THE VSWR = 1.2, 1.1, 1.05 WITH 2 TO 6 QUARTER-WAVE SECTIONS; IT SHOWS THE NORMALIZED VALUES OF THE EVEN- AND ODD-MODE CHARACTERISTIC IMPEDANCES AND ISOLATION RESISTANCES; THEY ARE NUMBERED FROM THE OUTPUT TO THE INPUT PORT; THE BANDWIDTH $B=f_{max}/f_{min}$ IS ALSO SHOWN

VSWR = 1.2

n=2 B=2 6			n=3 B=3.97			n=4 B=5 44			n=5 B=6 94			n=6 B=8 45		
Z_{oe} Ω	Z_{oo} Ω	R Ω	Z_{oe} Ω	Z_{oo} Ω	R Ω	Z_{oe} Ω	Z_{oo} Ω	R Ω	Z_{oe} Ω	Z_{oo} Ω	R Ω	Z_{oe}	Z_{oo}	R
1.244	0 734	-	1 186	0 797	-	1 159	0 830	-	1.144	0.849	-	1 135	0 861	-
1 607	1.345	1 294	1.414	0 563	-	1.317	0 653	-	1.263	0.709	-	1 229	0.747	-
			1.686	1.360	1.000	1.518	0.471	-	1.414	0.556	-	1.348	0.618	-
						1 725	1.474	0.860	1.584	0.415	-	1 484	0 491	-
									1.748	1.606	0 777	1 627	0 378	-
												1 762	1 754	0 723

VSWR = 1.1

n=2 B=1 96			n=3 B=2.94			n=4 B=4 01			n=5 B=5.1			n=6 B=6.23		
Z_{oe} Ω	Z_{oo} Ω	R Ω	Z_{oe} Ω	Z_{oo} Ω	R Ω	Z_{oe} Ω	Z_{oo} Ω	R Ω	Z_{oe} Ω	Z_{oo} Ω	R Ω	Z_{oe}	Z_{oo}	R
1 218	0 748	-	1 147	0 825	-	1 116	0.865	-	1 099	0.887	-	1 089	0 900	-
1.642	1.197	1.231	1.414	0.555	-	1.296	0.661	-	1.23	0.729	-	1.190	0.774	-
			1 743	1 143	0 906	1 543	0.445	-	1 414	0 544	-	1 331	0.620	-
						1.792	1.171	0.746	1.626	0 378	-	1 502	0 466	-
									1 82	1 228	0 652	1 681	0 336	-
												1.837	1.304	0.593

VSWR = 1.05

n=2 B=1 61			n=3 B=2.34			n=4 B=3 15			n=5 B=4.01			n=6 B=4 92		
Z_{oe} Ω	Z_{oo} Ω	R Ω	Z_{oe} Ω	Z_{oo} Ω	R Ω	Z_{oe} Ω	Z_{oo} Ω	R Ω	Z_{oe} Ω	Z_{oo} Ω	R	Z_{oe}	Z_{oo}	R
1 204	0.756	-	1.125	0.844	-	1.09	0.888	-	1.072	0 912	-	1.061	0.927	-
1.661	1.133	1.200	1.414	0.551	-	1.28	0 667	-	1 207	0 745	-	1 163	0.799	-
			1 778	1 037	0 853	1 562	0 426	-	1.414	0 536	-	1.319	0 626	-
						1 835	1 007	0 674	1.657	0 356	-	1 517	0.452	-
									1.866	1.024	0 574	1 720	0.310	-
												1.885	1.098	0 521

istic impedances Z_1 through Z_n, and the isolation resistance R as independent variables.

The synthesis of the odd mode is done by starting with an equal-ripple function of the insertion loss function P_L [5]–[7]

$$P_L = 1 + \frac{\kappa P_n^2(x)}{1-x^2} \tag{1}$$

$$|\Gamma|^2 = \frac{\kappa P_n^2(x)}{1-x^2+\kappa P_n^2(x)} \tag{2}$$

where

$$2P_n(x) = \left(1+\sqrt{1-x_c^2}\right)T_n(x/x_c) - \left(1-\sqrt{1-x_c^2}\right)T_{n-2}(x/x_c) \tag{3}$$

and $x=\cos(\pi/2 \cdot f/f_0)$, $x_c=\cos(\pi/2 \cdot f_c/f_0)$. T_n is the nth order Chebyshev polynomial, κ is an arbitrary constant.

The synthesis of the even and odd modes are independent of each other, but the odd mode is chosen to have the same bandwidth and ripple level as the even mode. The characteristic impedances Z_n in Fig. 2 differs from the other impedances because its value increases beyond the even-mode impedance when the ripple level is too high. The maximum ripple level is shown in Table I below. Higher ripple levels can be used if a reduction in the optimum bandwidth is accepted. A number of synthesized power dividers are shown in Table II. A problem that arises is the tight coupling ($Z_{0e} \gg Z_{0o}$), but there exist several possible solutions, e.g., interdigital structures, or floating strip [8]–[15].

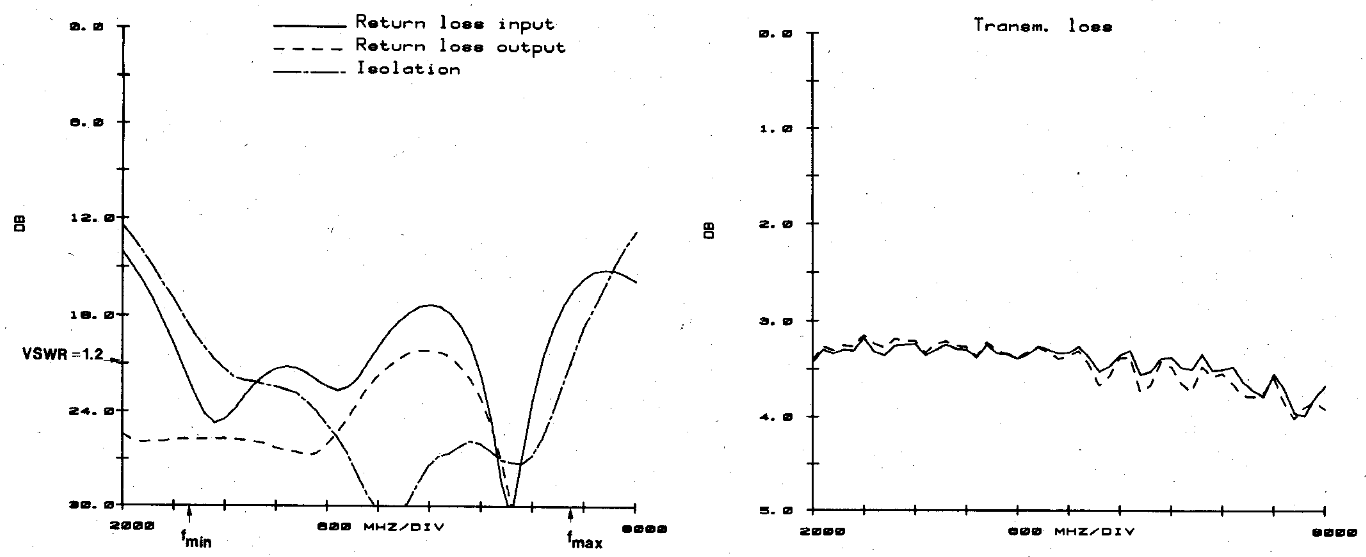
II. EXPERIMENTAL POWER DIVIDER

A second-order power divider has been built with a ripple-level VSWR = 1.2 center frequency 5 GHz and band limits 2.78 and 7.22 GHz. It was built in microstrip with the dielectric Rexolite 200 ($\epsilon_r = 2.65$, thickness = 0.79 mm). The values of the characteristic impedances were taken from Table II. A standard 50-Ω chip resistor was used as isolating resistance instead of the optimum value 64.7. The theoretical bandwidth (2.63:1) of the return loss at the input port is indicated on the measured curves in Fig. 3. The theoretical bandwidth of the isolation curve is reduced, because of the 50-Ω resistor, from 2.63:1 to 2.07:1. A photo of the power divider is shown in Fig. 4.

III. THE 180°/90° dB HYBRID

The new synthesis of the broad-band 2-way power divider makes it possible to convert the power divider into a 3-dB hybrid with 4 output ports (Fig. 5). The hybrid can be used as a 180° or 90° 3-dB hybrid depending on the input port. If port 1 is used as the input port the powers to ports 2 and 3 are 3 dB down with equal phases, and port 4 is isolated independent of frequency. If port 4 is used as the input port the phase shift between ports 2 and 3 will be 180°. Thus the hybrid can be used as a 180° 3-dB hybrid. If the power enters at port 2 the powers to ports 1 and 4 will be 3 dB down with 90° phase shift between the output signals, if the power enters at port 3 the phase shift will be −90°. Thus the hybrid can be used as a 90° 3-dB hybrid.

It is not possible to put in the fourth port between the transmission lines because that will interfere with the even mode. The slots between the transmission lines can be moved to the groundplane (Fig. 6) [10], [11]. Little is known about the even- and odd-mode characteristics of the structure with the slot in the groundplane. However, when the ratio w/h is big enough the interference between the fring-



(a) (b)

Fig. 3. Measured results of the 2-section power divider built in microstrip. The theoretical bandlimits and ripple levels are indicated. (a) Return losses and isolation. (b) Transmission loss from input to output port.

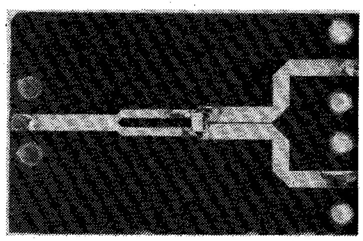


Fig. 4. Photo of the measured power divider.

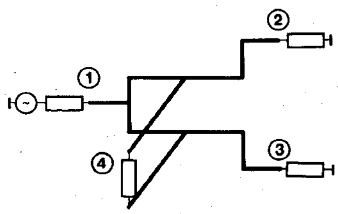


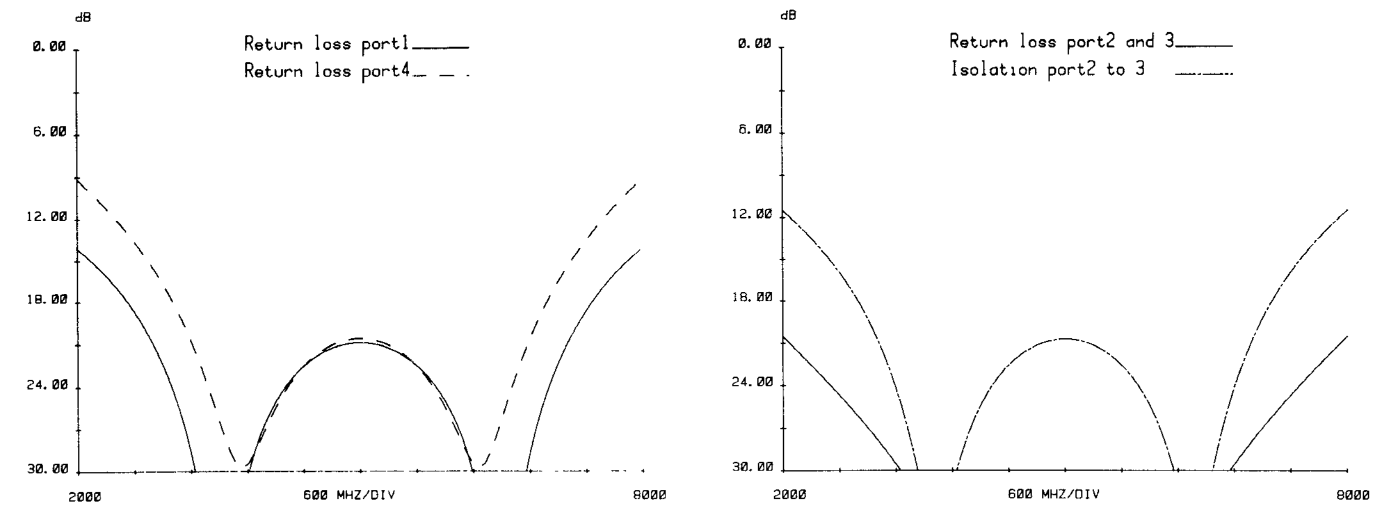
Fig. 5. The 2-way power divider as a 4-port 3-dB hybrid.

Fig. 6. The slot can be moved to the groundplane.

ing capacitances in the slot and at the other edges are small. A first order approximation was made that the same dimensions could be used in the two cases (Fig. 6).

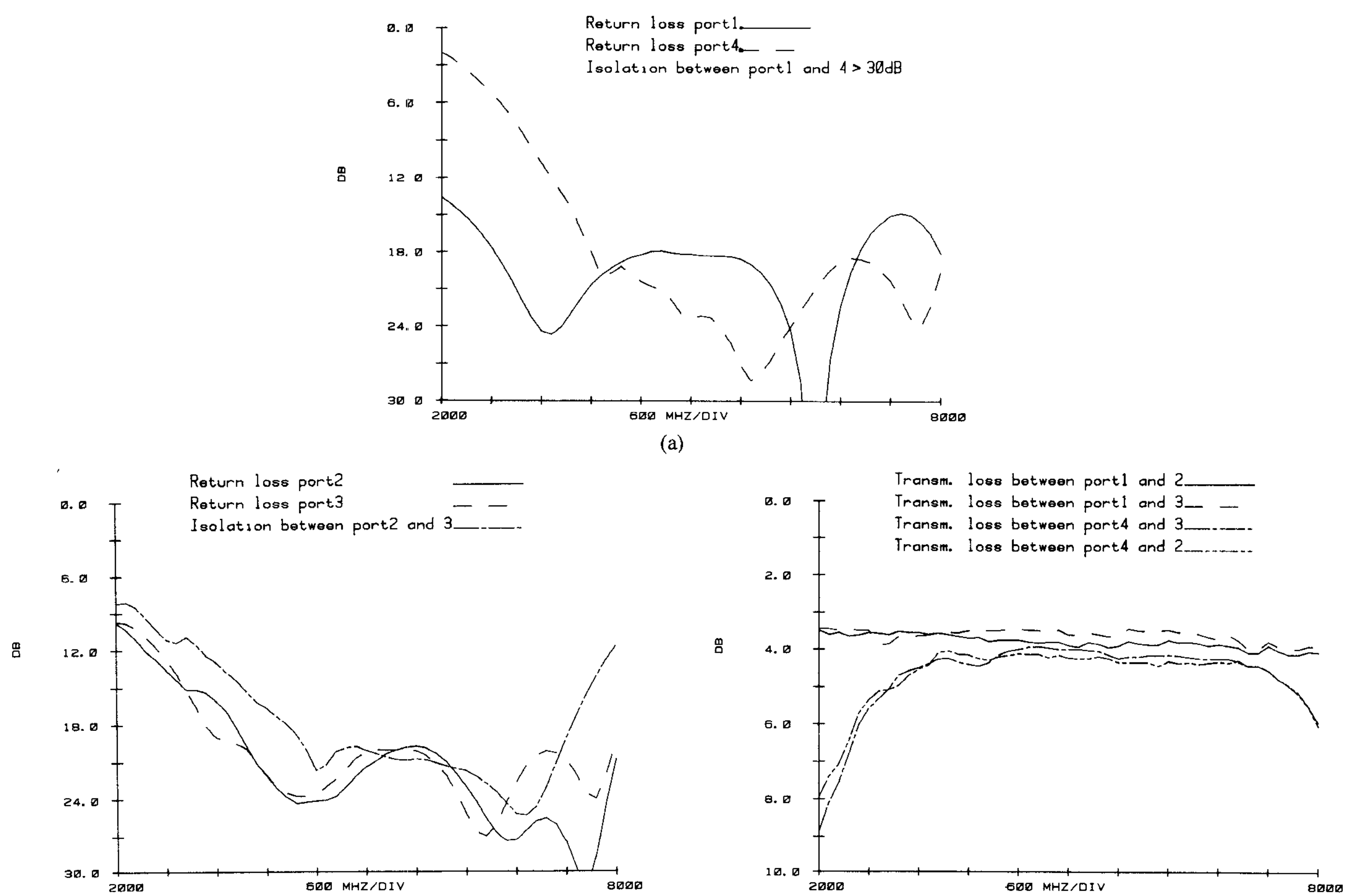
IV. Experimental 180°/90° 3 dB-Hybrid

A 3-dB hybrid has been built with the same dimensions and dielectric material as the second-order power divider described above. The coupling of the odd mode to port 4 is done by a slotline–microstrip coupling so that one side of the slotline is solder to the groundplane of port 4. The other side of the slotline is connected to the strip through a solder thin wire. A short stub is used to compensate for the inductance in the thin wire. The measurement together with an analysis showed that the odd-mode characteristic impedance of the tight coupling section was too low. The measured ripple level of the odd mode at port 4 was measured to be about 10 dB (theoretically 20.8 dB) with the first-order approximation. The analysis pointed out



(a) (b)

Fig. 7. Theoretical curves for the 3-dB hybrid. (a) Ports 1 and 4. (b) Ports and 3.



(a)

(b) (c)

Fig. 8. Measured curves for the 3-dB hybrid. (a) Ports 1 and 4. (b) Ports 2 and 3. (c) Transmission loss.

that the odd-mode impedance was about 29 Ω instead of 36.7 Ω. Calculations show that this corresponds to an increase in the equivalent slot impedance of about 70 percent. Some different circuits were measured where only the slotwidth (originally $s = 0.2$ mm) was increased. A value of $s_1 = 0.4$ mm was found to be good, with negligible change of return loss at the input port (even mode). The theoretical matching and isolation curves are shown in Fig.

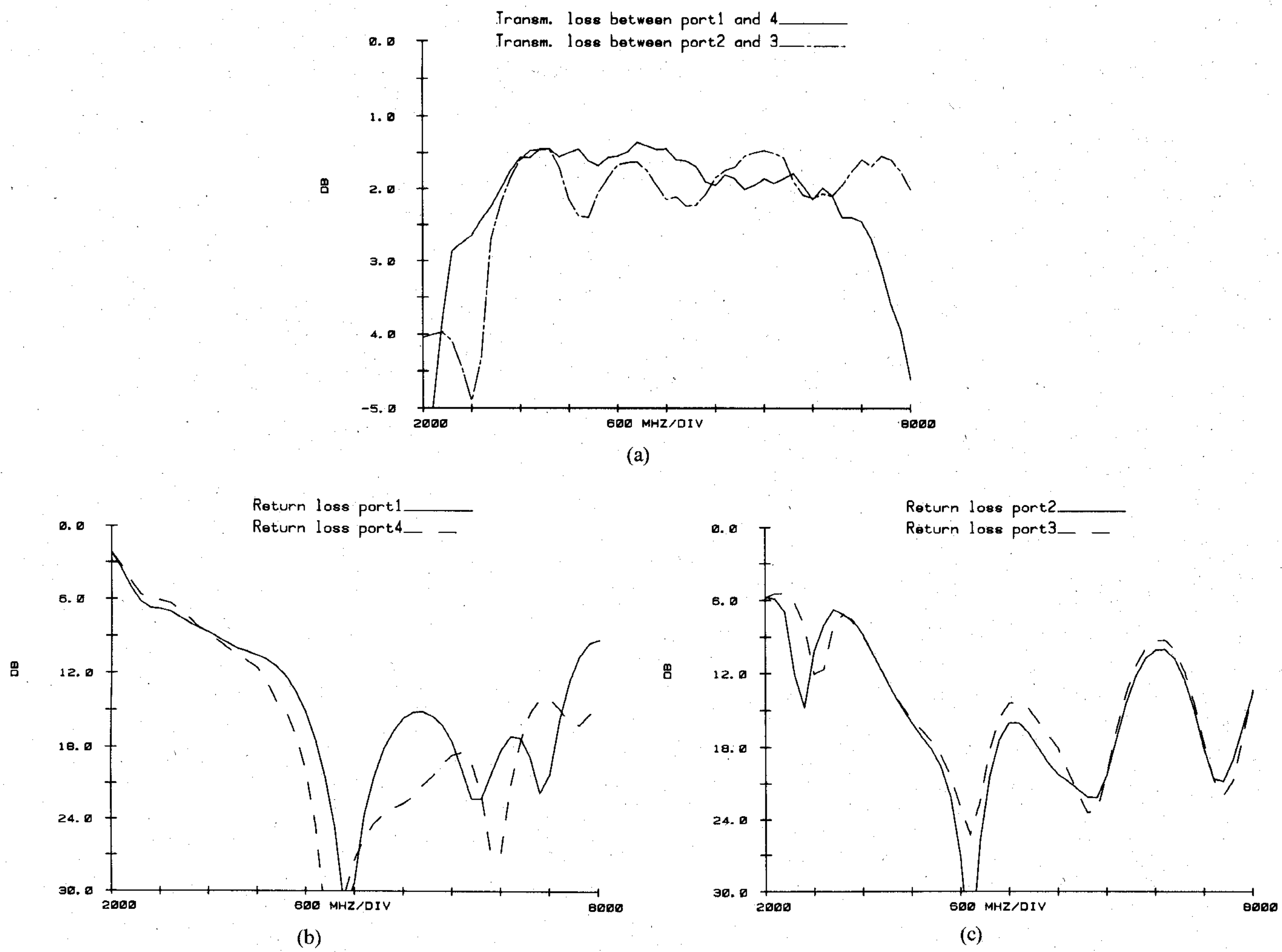


Fig. 9. Measured curves for the 3-dB hybrid working as a 2-port circuit. (a) Solid line: port 2 short-circuited and port 3 open-circuited 180° 3-dB hybrid. Dotted line: ports 1 and 4 short-circuited, 90° 3-dB hybrid. (b) 180° 3-dB hybrid. (c) 90° 3-dB hybrid.

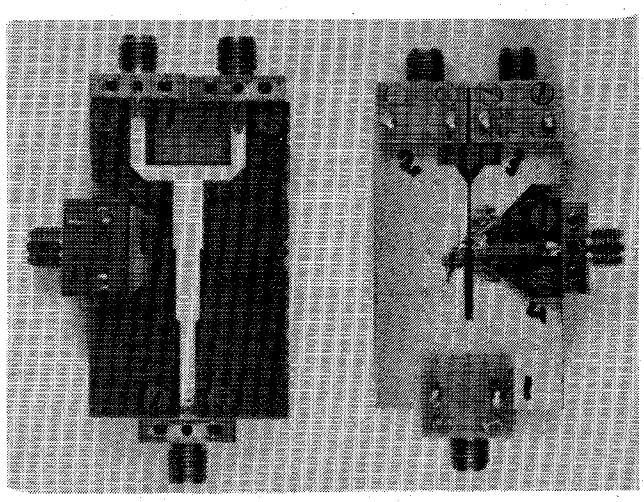


Fig. 10. Photo of the measured 3-dB hybrid.

7. The measured curves are shown in Fig. 8. Fig. 9 shows the hybrid as a 2-port circuit, where the output ports are terminated in either an open or a short-circuit. When measuring ports 1 and 4, port 2 is a short-circuit and port 3 is an open-circuit (180° 3-dB hybrid). When measuring ports 2 and 3, ports 1 and 4 are both short-circuit (90° 3-dB hybrid). A photograph of the measured 3-dB hybrid is shown in Fig. 10.

V. Conclusions

An exact synthesis of the 2-way Wilkinson broad-band power divider with only one isolating resistor has been developed. A large number of dividers have been synthesized and the result is shown in Table II. A second-order power divider has been built in microstrip with good correspondence between measured and theoretical curves. A new hybrid has been developed which can be used as either a 180° or 90° 3-dB hybrid. The directivity is high and independent of frequency when the hybrid works as a 180° hybrid. This has been confirmed by the measurements. A second-order 180°/90° 3-dB hybrid has been built in microstrip with fairly good correspondence between theoretical and measured curves. The difference is mainly due to the different phase-velocities of the even and odd modes.

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Computer-Oriented Synthesis of Optimum Circuit Pattern of 3-dB Hybrid Ring by the Planar Circuit Approach

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***Abstract*—A fully computer-oriented synthesis of the optimum circuit pattern of a 3-dB hybrid ring based upon the planar circuit concept is described. In the synthesis process, the contour-integral method and Powell's method are used for the circuit analysis and the optimization, respectively. The synthesized optimum patterns are given in normalized curves and parameters which can directly be used in practical circuit design. The validity of the theory is confirmed by experiment.**

It is shown both theoretically and experimentally that the planar circuit approach can, not only prevent the deterioration of the hybrid characteristics due to the widening of the circuit, but bring forth hybrid characteristics somewhat better than the distributed constant model. It is also shown that the obtained optimized characteristics can further be improved by addition of simple external circuits.

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I. Introduction

A TWO-BRANCH 3-dB hybrid (Fig. 1(a)) consists of four stripline sections (arms) having length l equal to $\lambda_0/4$ and characteristic impedance equal to Z_0 and $Z_0/\sqrt{2}$, where λ_0 and Z_0 denote the center wavelength (reduced by dielectric material) and the impedance of the external striplines, respectively [1]. When the frequency becomes higher, however, the line widths W and W' become com-