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## References

[1] C. Y. Ho, "VSWR, Power dissipation: Key to film resistors," *Microwaves*, vol. 20, pp. 69–78, Dec. 1981.
[2] G H B. Thompson, "An easy method of matching microstrip loads and attenuators," *IRE Trans. Microwave Theory Tech*, vol MTT-9, p. 263, May 1961.
[3] D. LaCombe, "A multioctave microstrip 50-Ω termination," *IEEE Trans Microwave Theory Tech.*, vol. MTT-20, pp. 290–291, Apr. 1972
[4] L J. P. Linnér, H. B. Lundén, and M. A. Larsson, "Design of MIC broadband loads and attenuators," in *Proc 14th Eur. Microwave Conf.*, 1984, pp. 503–509.
[5] R Levy and J. Helszajn, "Specific equations for one and two section quarterwave matching networks for stub-resistor loads," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 55–63, Jan. 1982.
[6] M. C. Horton and R. J. Wenzel, "General theory and design of optimal quarterwave TEM filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-13, pp. 316–325, May 1965.
[7] S. B. Cohn, "Parallel-coupled transmission-line resonator filters," *IRE Trans. Microwave Theory Tech.*, vol. MTT-6, pp. 223–231, Apr. 1958.
[8] H J Carlin and W Kohler, "Direct synthesis of band-pass transmission line structures," *IEEE Trans. Microwave Theory Tech*, vol. MTT-14, pp. 283–297, May 1965
[9] H. J. Riblet, "The application of a new class of equi-ripple functions to some familiar transmission-line problems," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-12, pp. 415–421, July 1964.
[10] K. Mayer, "Ein beitrag zur berechnung von kompensierten λ4-transformatoren," *Nachrichtentech. Z.*, vol. 23, pp. 345–346, Aug. 1970
[11] G. C. Temes and S. K Mitra, Eds., "*Modern Filter Theory and Design* New York: Wiley, 1973.
[12] R E. Williams, *Gallium Arsenide processing techniques*. Dedham, MA: Adtech House, 1984, pp. 346–351.

# A Wide-Band 12-GHz 12-Way Planar Power Divider/Combiner

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***Abstract*** **—A 12-way, low-loss, wide-band planar electrically symmetric hybrid power divider/combiner for the $X$-band is described. It is a two-stage fork, 12-way hybrid realized completely in microstrip. A circuit design is given to maximize the match and isolation at band center. Over a frequency band of 10–13 GHz, this divider/combiner has an insertion loss of less than 1 dB and an isolation between output ports of better than 17 dB.**

## I. Introduction

Symmetric $n$-way power dividers/combiners have the advantage of not having either amplitude or phase power-division imbalance at all frequencies. Thus, they are used in many broadband applications such as in the feed system of multi-element antennas and as combiners of solid-state amplifiers and oscillators.

Most of the dividers/combiners described in the literature [1]–[4] are either generalizations or variations of the Wilkinson [1] $n$-way divider/combiner. None of them can be realized with all interconnections in the circuit plane for $n > 2$ because they require either a resistive star network or a star of transmission lines using multilayer construction. Consequently, planar dividers/combiners might be realized using corporate structures of two-way Wilkinson split-tee [4] and hybrid circuits. The disadvantage of this approach is that the maximum value of $n$ is limited by the physical size and high loss of the corporate structure. The divider/combiner, which is realizable in a planar structure, was first reported by Galani and Temple [5] and it was a single-stage fork, four- or seven-way hybrid. Explicit formulas were developed by Saleh [6] for the scattering parameters of single- and two-stage fork, $n$-way hybrids. Saleh's [6] results show that the two-stage case gives considerably better match and isolation, and less dissipation requirements for the isolation resistors than the corresponding single-stage case, but these interesting results were not confirmed experimentally.

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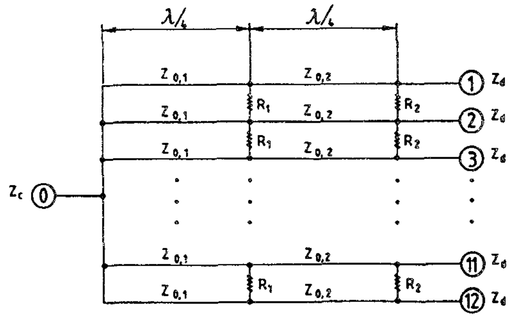


Fig. 1. A schematic representation of the two-stage fork, 12-way planar divider/combiner.

This paper describes the circuit design and the performance data of a 12-way planar hybrid power divider/combiner. This hybrid, which resembles the Wilkinson hybrid, is named the fork hybrid because of its geometry. It consists of two stages, each of 12-way, realized completely in a microstrip technology.

## II. Circuit Description

A schematic diagram of the planar divider/combiner is shown in Fig. 1, where $Z_c$ is the characteristic impedance of the input line. The divided ports are designated by the numbers 1 through 12 and are each terminated in $Z_d$. The characteristic impedance of each of the quarter-wave lines is $Z_0$ and the resistance of an isolation resistor is $R$. The subscripts 1 and 2 refer to the first and second stages, respectively. Optimum values of circuit elements are calculated on the bases of a perfectly matched port 0 at the center frequency, a maximally flat input–output frequency response [2], [3], and a maximum of both of the match and isolation of the divided ports [6] at band center. For $n = 12$, and for a simple match of the divided ports to 50-Ω coaxial lines, $Z_d$ is taken to be 50 Ω, and the following optimal results are obtained: $R_1 = 50$ Ω, $R_2 = 166$ Ω, $Z_{0,1} = 131.5$ Ω, $Z_{0,2} = 69$ Ω, and $Z_c = 15.1$ Ω. The port 0 can be matched to a 50-Ω microstrip line using two quarter-wave lines of impedances 20.5 and 36.9 Ω.

## III. Experimental Results

The 12-way divider/combiner is realized in microstrip, employing a 0.254-mm-thick Duroid substrate ($\epsilon_r = 2.22$). Chips resistors of 50 and 166 Ω are soldered according to the configuration of Fig. 1. A photograph of the realized circuit is shown in Fig. 2. The divider/combiner performance is measured in the frequency band 10–14 GHz using a semi-automatic network analyzer. The average power division coefficient of the 12 output ports is plotted versus frequency in Fig. 3. The power imbalance over the output ports is ±0.45 dB in the frequency band 10–13 GHz and ±0.8 dB in the frequency band 10–14 GHz. Isolation coefficients between output ports have also been measured. The

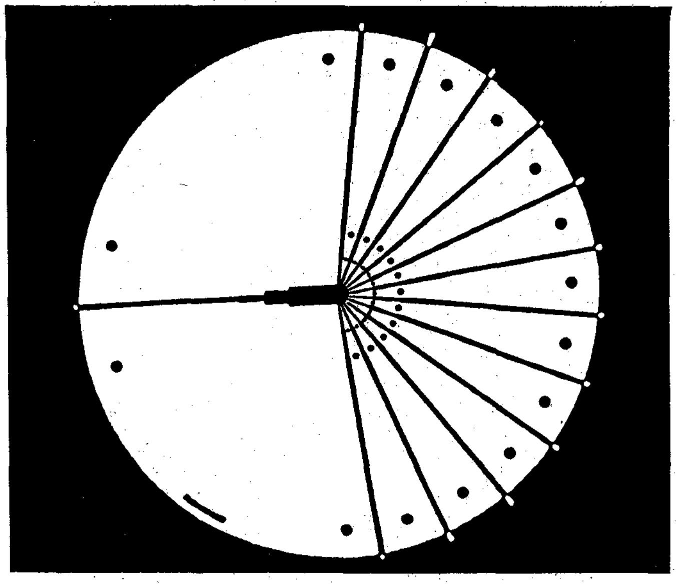

Fig. 2. Photograph of the realized 12-way $X$-band planar power divider/combiner.

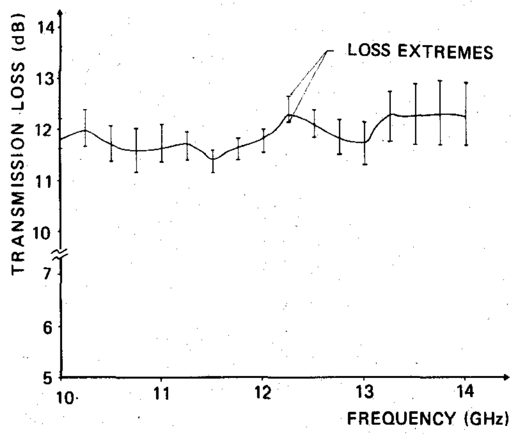


Fig. 3. Measured transmission loss from the input (common) port to one of the output (divided) ports of the 12-way planar power divider/combiner.

minimum registered isolation between output ports is 17 dB. This result agrees very well with the analytic prediction of a minimum isolation of 16 dB at the center frequency. Examples of the results of the measurements of the isolation coefficients of this power divider/combiner are presented in Fig. 4.

Fig. 5 shows the return loss of an input port and a typical output port of this network. These last results are not in good accordance with the analytical prediction of a minimum return loss of 16 dB. This is probably either a result of the coupling between the fork transmission lines [7] or a result of the effect of the microstrip–coaxial-line transition, which was not taken into consideration in the theoretical calculations. The use of external ferrite components will be necessary to obtain a sufficiently good input and output match.

## IV. Conclusion

A 12-way planar electrically symmetric two-stage fork hybrid power divider/combiner for a 12-GHz center frequency is realized. It shows low insertion loss and excellent isolation properties over wide bandwidth. This makes it suitable for applications such as the power combining of solid-state amplifier modules and also for phased array antennas.

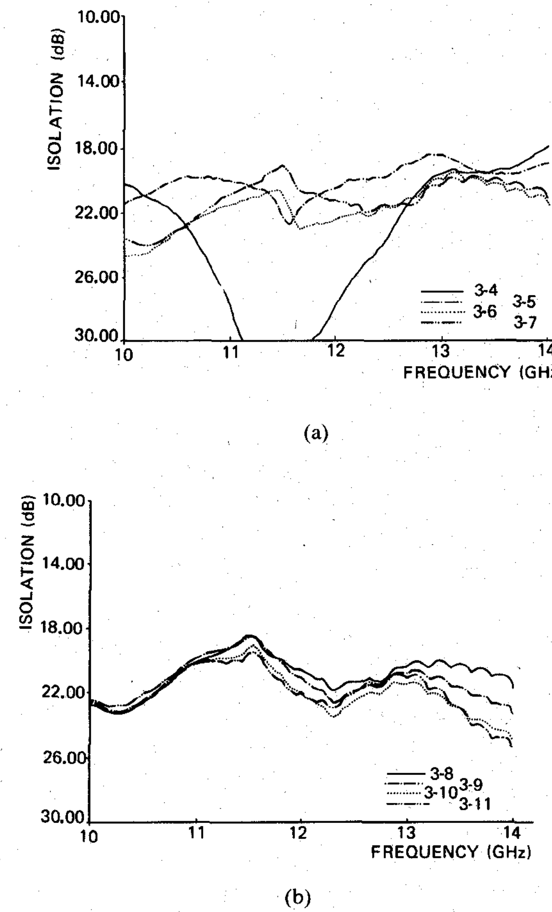


Fig. 4. Isolation between output ports on the 12-way planar power divider/combiner. (a) Ports 3–4, 3–5, 3–6, and 3–7. (b) Ports 3–8, 3–9, 3–10, and 3–11.

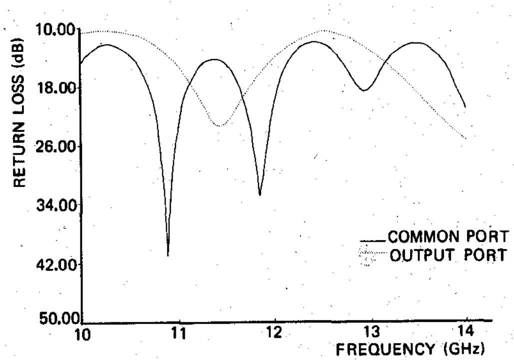


Fig. 5. Return loss of both input (common) port and a typical output (divided) port on the 12-way power divider/combiner.

## References


[1] E. J. Wilkinson, "An $N$-way hybrid power divider," *IRE Trans. Microwave Theory Tech.*, vol. MTT-8, pp. 116–118, 1960.

[2] S. B. Cohn, "A class of broadband three-port TEM-mode hybrids," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 110–116, 1968.

[3] H. Y. Yee, F. C. Chang, and N. F. Audeh, "$N$-way TEM-mode broadband power dividers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 682–688, 1970.

[4] L. I. Parad and R. L. Moynihan, "Split-tee power divider," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-13, pp. 91–95, 1965.

[5] Z. Galani and S. J. Temple, "A broadband planar $N$-way combiner/divider," *IEEE MTT-S, Int. Microwave Symp. Dig.*, 1977, pp. 499–502.

[6] A. A. M. Saleh, "Planar electrically symmetric $n$-way hybrid power dividers/combiners," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 555–563, 1980.

[7] ——, "Computation of the frequency response of a class of symmetric $n$-way power dividers," *Bell Syst. Tech. J.*, vol. 59, pp. 1493–1512, 1980.