A Broad-Band Printed Circuit Hybrid Ring Power Divider

GERALD F. MIKUCKI AND ASHOK K. AGRAWAL, SENIOR MEMBER, IEEE

***Abstract*—A power divider in the form of a hybrid ring that provides substantially improved amplitude and phase characteristics over a broad frequency range compared to that of a conventional hybrid ring coupler is described. The improvement in bandwidth is obtained by the addition of a fifth port to the conventional four-port design [1]. The new design is applicable to both equal and unequal power divisions and uses the same design equations as the conventional hybrid ring design to obtain the desired degree of coupling. The new design provides substantially improved coupling and phase characteristics over a very broad frequency range; the usable bandwidth is limited primarily by the degradation in the other parameters such as input *VSWR* and isolation between coupled ports. The bandwidth is approximately twice that of a conventional hybrid ring coupler. A theoretical comparison of the performance characteristics of the improved and the conventional design was accomplished using a CAD program. Experimental verification of the improved design was carried out in a stripline configuration for both equal and unequal power divisions at *Ku*-band and a bandwidth of approximately 45 percent was achieved.**

I. Introduction

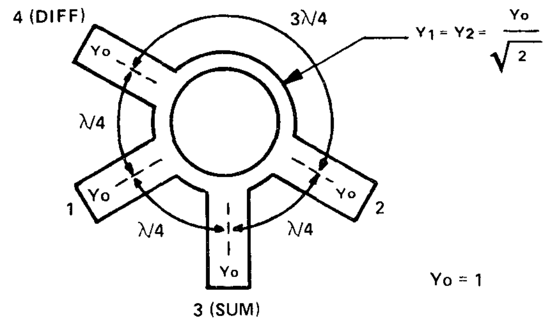
The CONVENTIONAL hybrid ring directional coupler is one of the fundamental choices for the basic power divider in printed circuit microwave antenna arrays. Several important characteristics that make it particularly appealing include: 1) the output arms are well isolated, a characteristic that is essential to minimize mutual coupling effects, and 2) an in-phase relationship can be obtained at the output ports, thereby eliminating the need for any phase-compensating element. The configuration of a conventional hybrid ring coupler, as shown in Fig. 1, allows for an equal or unequal power split, depending on the impedance chosen for the ring sections. The relative output voltages in output arms 1 and 2 are given by

$$b_1/b_2 = \pm Y_2/Y_1 \tag{1}$$

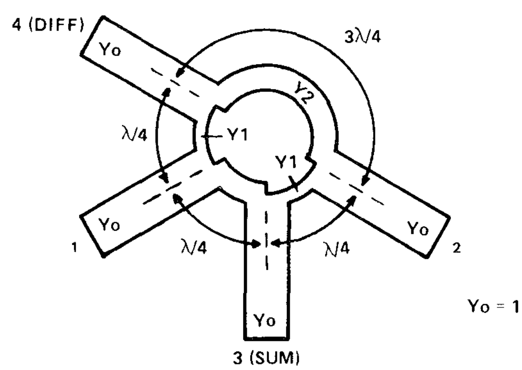
where the choice of + or − depends on whether the signal is fed in the sum (in phase) or difference (180° out of phase) port. In either case, the condition that the input arm be perfectly matched requires that Y_1 and Y_2 satisfy the condition

$$Y_1^2 + Y_2^2 = Y_0^2. \tag{2}$$

Variable parameters Y_1 and Y_2 represent the characteristic admittances of two lines of the ring normalized to the characteristic admittances of the four output arms. Since the hybrid ring is a resonant type structure, ideal performance is obtained only at the design frequency. An amplitude and phase deviation from the desired values between output ports occurs when a frequency other than the design value is chosen. This degradation with frequency from the desired amplitude and phase split values is often the most bandwidth limiting factor. The bandwidth of a conventional hybrid ring is only 20–25 percent, depending on the degree of performance required.



(a)



(b)

Fig. 1. Conventional hybrid ring coupler configuration. (a) Equal split hybrid ring. (b) Unequal split hybrid ring.

In the past, several design techniques have been used to increase the bandwidth of the hybrid ring coupler. One technique is to substitute a quarter-wave coupled line section for the three-quarter-wave section of the conventional 1.5 wavelength ring [2]. Although the bandwidth of this device is increased to approximately an octave, it has not found wide acceptance because of its extreme diffi-

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The authors are with the RCA electronic Systems Department of the General Electric Company, Borton Landing Road, Moorestown, NJ 08057.
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culty of construction. This circuit requires short circuits at the ends of the coupled line sections, limiting its use to lower frequencies, where short circuits may be conveniently constructed.

Another approach for increasing the bandwidth of a hybrid ring is the design proposed by Kim and Naito [3]. The equal split power divider, described in [3], has approximately 1.8 times the bandwidth of a conventional hybrid ring. This design approach incorporates four different ring impedances and requires quarter-wave matching circuits at all four ports. For a 50 Ω characteristic impedance of the output arms, the equal power divider described in [3] requires impedances lower than 7 Ω. This would require very wide lines, limiting its use to lower frequencies. In addition, the large number of different impedances will increase the number of iterations required to achieve optimum performance. Furthermore, the increase in bandwidth is partially achieved by setting the maximum deviation in coupling at the design frequency and optimizing the coupling at two frequencies located an equal amount from the design frequency, which may not be desirable for certain applications. Although it is claimed in [3] that the design is applicable for a hybrid ring coupler with any degree of coupling, this is not demonstrated; nor is it clear on applying the technique for unequal power division, since the design requires optimizing six impedances using CAD.

The broad-band power divider described in this paper extends the usable bandwidth of the conventional hybrid ring coupler to approximately 50 percent. The increased bandwidth of the new design is achieved by adding a fifth port to the conventional four-port design. The design is relatively simple in that it uses the same impedances of the ring as the conventional hybrid ring design.

The broad-band design method proposed in this paper was analyzed and optimized using MIDAS, a microwave circuit analysis program [4]. The theoretical performance of the new power divider is compared with the conventional hybrid ring design for both equal and unequal power divisions. In the equal power split configuration, the new design provides theoretically flat coupling and phase characteristics over a broad frequency range. An experimental verification of both equal and unequal power division was obtained in a stripline configuration at *Ku*-band.

II. Broad-Band Design Approach

The theoretical amplitude and phase of the output voltage at the two output ports of a conventional equal-split hybrid ring coupler, when the input signal is fed into port 3 (sum mode), is shown in Fig. 2. It is observed that the amplitude and phase of the voltage at port 2, located on the opposite side of the difference port, are much more frequency sensitive than at port 1, located on the same side as the difference port. Alternatively, the difference port could be moved one half wavelength clockwise from its present location. In this case, the response at ports 1 and 2 will be interchanged. By intuition, one would expect that if a hybrid ring were constructed with two difference ports,

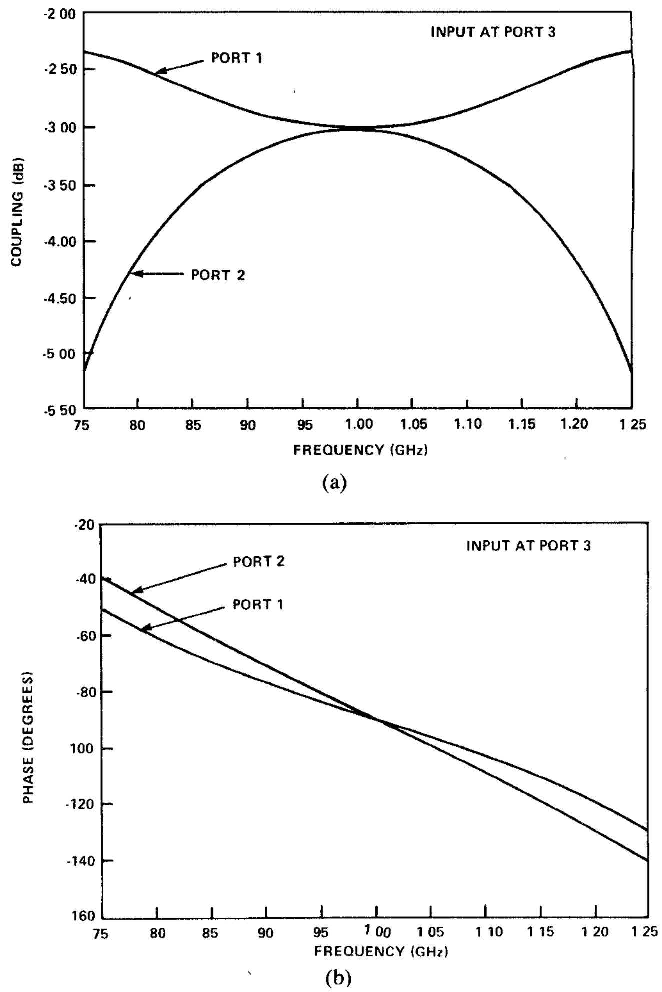

Fig. 2. Theoretical response of a conventional equal split hybrid ring coupler. (a) Amplitude. (b) Phase.

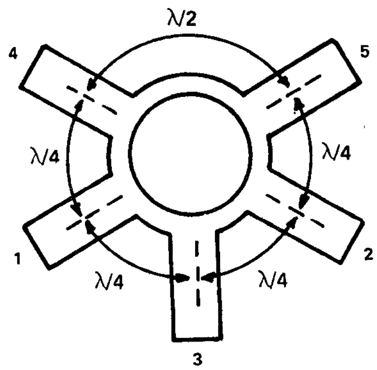

Fig. 3. A five-port hybrid ring equal power divider.

as shown in Fig. 3, the amplitude and phase response at ports 1 and 2 would be identical. A CAD analysis of such a coupler with an additional port confirmed this. The theoretical amplitude and phase responses of each output port of the new equal-split design with the added port are shown in Fig. 4. As is observed, the addition of the fifth port has made the theoretical amplitude and phase response at port 2 identical to that at port 1 at all frequencies. A very important feature of identical amplitude and phase response at ports 1 and 2 is that the difference in

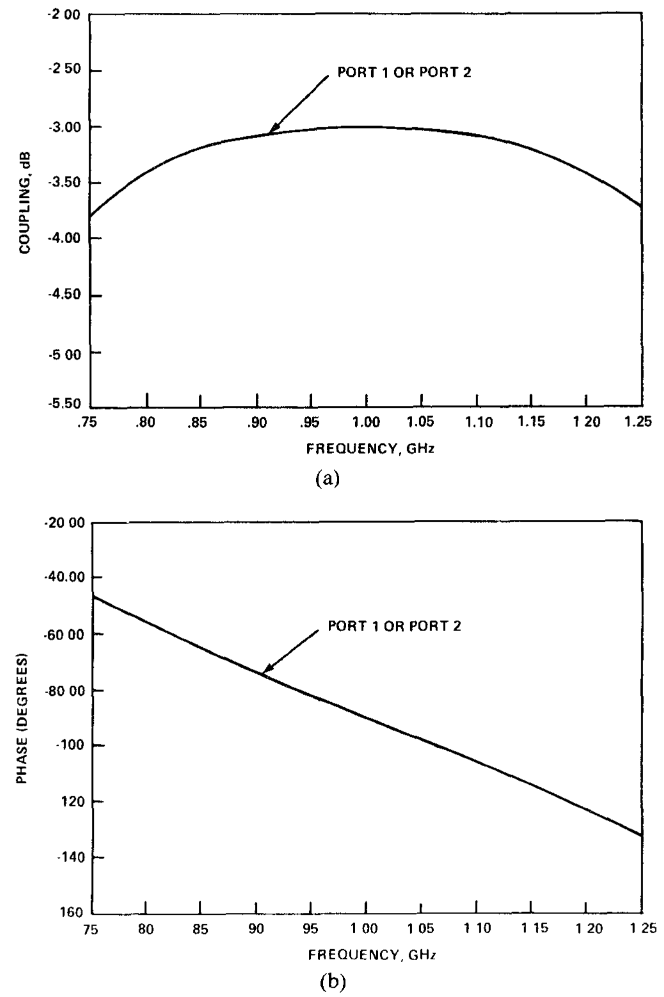

Fig. 4. Theoretical response of a broad-band equal power divider. (a) Amplitude. (b) Phase.

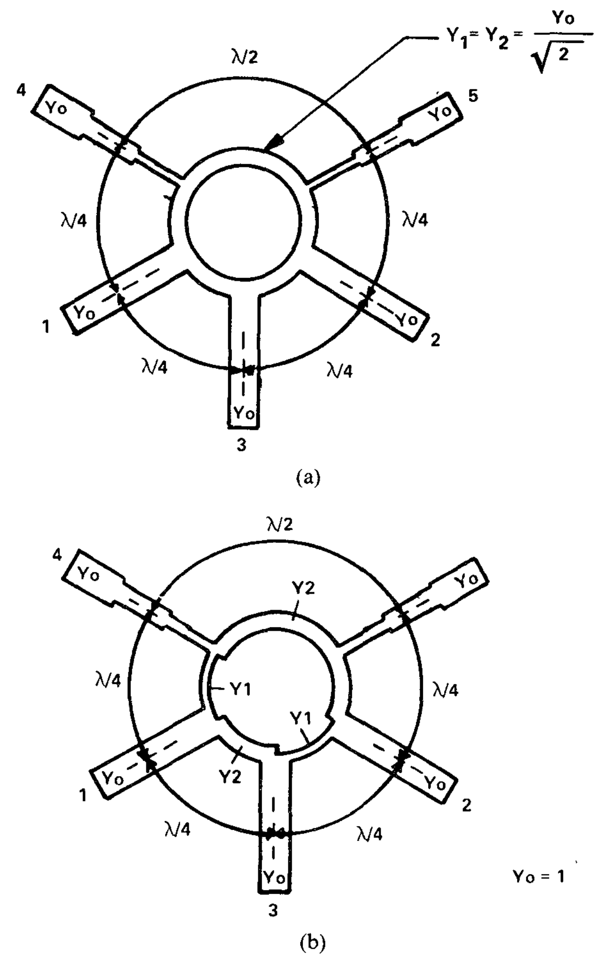

Fig. 5. Broad-band power divider configuration. (a) Equal power divider. (b) Unequal power divider.

amplitude and phase between ports 1 and 2 is zero over all frequencies, theoretically, over an infinite frequency range, although the coupling to ports 1 and 2 varies with frequency. The operational bandwidth of this coupler is then limited by the other two parameters, namely, input match at the ports and isolation between ports. An identical response at the output ports 1 and 2 makes this coupler a perfect choice for applications where such a characteristic is required, e.g., beam-forming networks for phased array antennas.

The broad-band design approach for the equal power divider can be extended to unequal power division. Although perfect coupling and phase split are not obtained for unequal power dividers over an infinite bandwidth, substantial improvement over the conventional design is achieved over a broad bandwidth. The results for an unequal power divider are presented in Section III.

The configuration of the new design incorporating the fifth port is shown in Fig. 5. The added port is located an equal distance (one half wavelength) from the sum and difference ports. It is well isolated from the sum port but not the difference port. Therefore, the new design is useful in the sum mode of operation only, and both the difference port and the added port must be terminated in a proper impedance.

The theoretical frequency response of the new power divider was analyzed using MIDAS. It was found that compensating circuits are necessary at both the difference port and the added port in order to achieve a proper match at the input and output ports and a sufficient isolation between the output ports. The desired performance characteristics are dependent on achieving the proper junction impedance with the ring impedance at both the difference port and the fifth port. The proper junction impedances were optimized for output port *VSWR* and isolation with the aid of MIDAS. A 100 Ω impedance provided the optimum performance. A quarter-wave transformer can be used to achieve the proper match at the difference port to a standard 50 Ω termination. No further modifications are necessary to achieve the broad-band performance.

III. Theoretical Results and Analysis

The theoretical frequency response of the new hybrid ring circuit in both equal and unequal power division was calculated using MIDAS. A 3 dB power division between output ports was chosen for the unequal power divider model. The input *VSWR*, output port isolation, coupling,

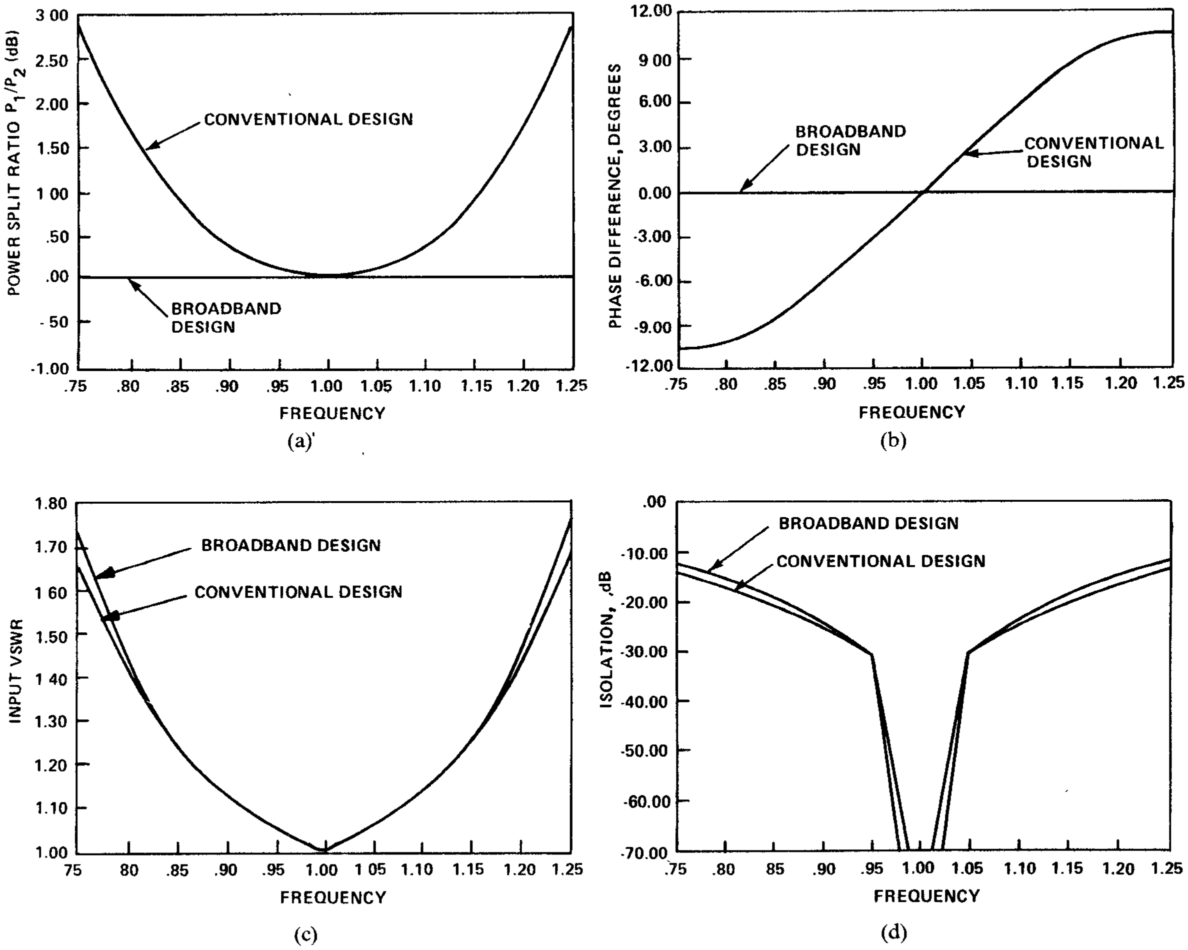

Fig. 6. Theoretical comparison of a broad-band equal power divider and a conventional hybrid ring coupler. (a) Power split ratio P_1/P_2. (b) Phase difference between output ports. (c) Input *VSWR*. (d) Isolation between output ports.

and phase split of both the improved coupler design and the conventional hybrid ring coupler are plotted versus normalized frequency for both equal and 3 dB power divisions in Figs. 6 and 7, respectively. As is observed, excellent performance is achieved with the new hybrid ring compared to that of the conventional design for both power dividers. For the equal power divider design, a theoretically perfect amplitude and phase split between output ports is obtained. Although a substantial improvement in coupling and phase split is achieved in the new design, particularly in the equal power version, slightly less isolation is achieved across the bandwidth. However, sufficient isolation exists for most applications. A negligible difference in input *VSWR* is observed.

Since substantial improvement in coupling and phase characteristics versus frequency is obtained with the new coupler, and new design can be used to extend the operational bandwidth of the hybrid ring coupler in applications where an in-phase relationship between output ports is desired. Although, the new design extends the usable bandwidth of a conventional hybrid ring, this new design would provide improved amplitude and phase characteristics over a relatively narrow bandwidth for low-sidelobe antenna beam-forming networks, where small amplitude and phase errors between output ports are required. In addition, the theoretical isolation from the couplers is greater than 20 dB over a reasonable bandwidth, which is essential to minimize mutual coupling effects.

IV. Experimental Results

To confirm the performance of the broad-band power divider design, both an equal power divider and a 3 dB (between output ports) power divider were designed and tested in a stripline configuration. The design frequency for both couplers was 18 GHz and the circuits were etched on a 50 mil PTFE substrate with a relative dielectric constant of 2.2. The ring impedance values used (calculated from (1) and (2)) were 70.70 Ω for the equal power divider and 86.54 and 61.26 Ω for the 3 dB power divider. The measured coupling, phase difference between output ports, input *VSWR*, and output port isolation are plotted in Figs. 8 and 9 for the equal and 3.0 dB power dividers, respectively. As is observed, a reasonably close agreement to the theoretical results is obtained over a 45 percent bandwidth. The input *VSWR* is somewhat higher than expected and is due to the ring impedances being different from the design values, caused by the manufacturing tolerances. This is also shown in the unequal power design in which the measured coupling is approximately 3.2 dB instead of the design value of 3 dB. Additional iterations

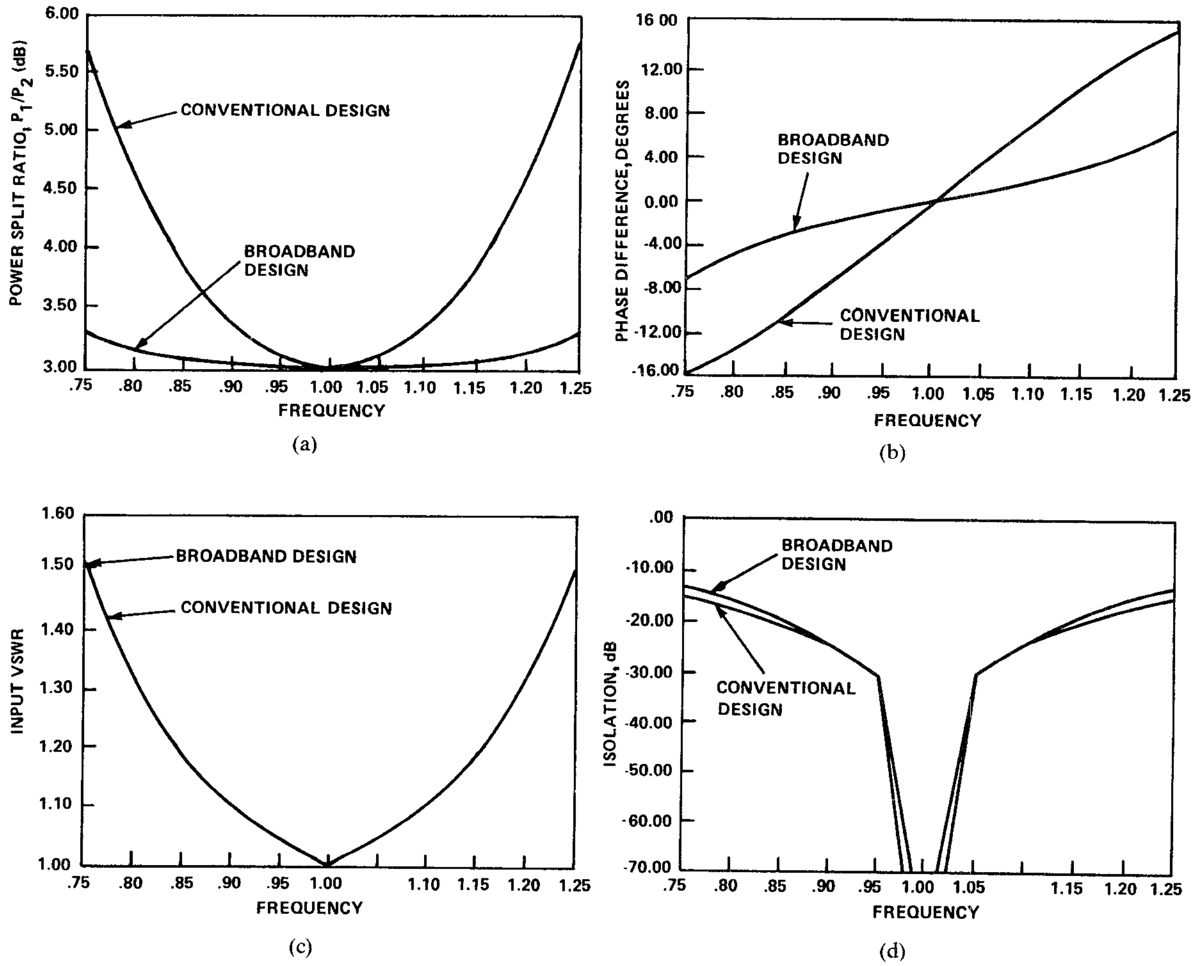

Fig. 7. Theoretical comparison of a broad-band 3 dB power divider and a conventional hybrid ring coupler. (a) Power split ratio P_1/P_2. (b) Phase difference between output ports. (c) Input *VSWR*. (d) Isolation between output ports.

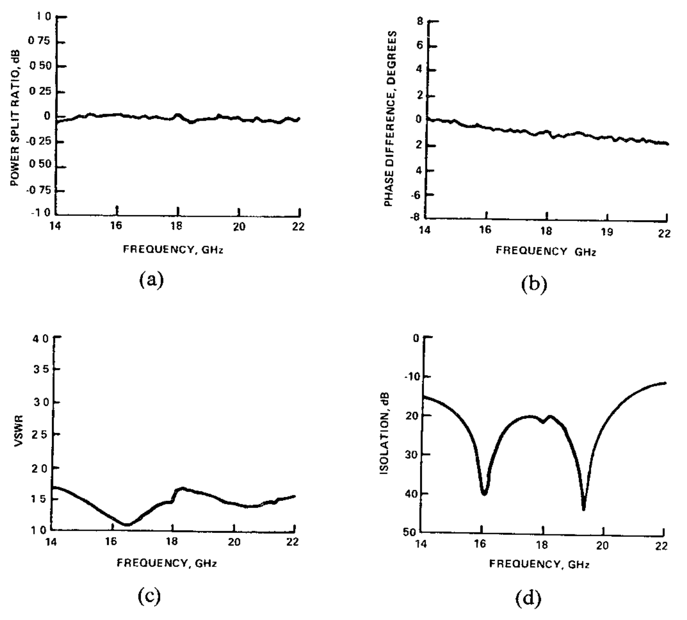

Fig. 8. Measured performance of a broad-band equal power divider. (a) Power split ratio P_1/P_2. (b) Phase difference between output ports. (c) Input *VSWR*. (d) Isolation between output ports.

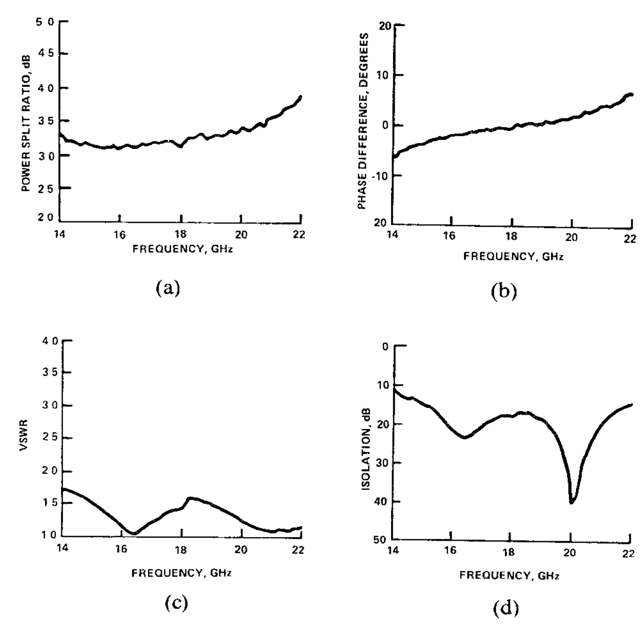

Fig. 9. Measured performance of a broad-band 3 dB power divider. (a) Power split ratio P_1/P_2. (b) Phase difference between output ports. (c) Input *VSWR* (d) Isolation between output ports.

on the design would improve the match and improve the measured performance even further. It should be noted that the experimental verification was carried out at *Ku*-band. The coupler performance will be closer to theoretical results at the lower frequencies (e.g., *S*- or *C*-bands) since the tolerance errors in construction of these circuits are smaller at lower frequencies.

V. Conclusions

The design of a broad-band ring power divider that provides substantial improvement in coupling and phase characteristics over a wide frequency range compared to that of a conventional hybrid ring has been presented.

The new power divider design can be easily constructed using realizable impedances and is applicable to both equal and unequal power divisions. Experimental verification of the broad-band power divider was achieved in a stripline configuration at *Ku*-band for an equal power divider and a 3 dB power divider. Close agreement was observed between theoretical and experimental results for both of the power dividers. The usable bandwidth of the broadband power divider is approximately 45 percent.

This broad-band power divider is particularly suited for a narrow-band low-sidelobe antenna array beam-forming network, for it provides substantially improved amplitude and phase characteristics, a requirement for low-sidelobe array antennas, and good isolation between output ports.

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Gerald F. Mikucki was born in Point Pleasant, NJ, in February, 1961. In 1983, he received the BSEE degree from Pennsylvania State University, University, Park.

From 1983 to 1985, he was with the Combat Surveillance and Target Acquisition Laboratory, Fort Monmouth, NJ, where he was involved in the development of electronic scan techniques for millimeter wave antennas. Since 1985 he has been with the RCA Electronic Systems Department of the General Electric Company in Moorestown, NJ, where he is actively involved in the design and development of microwave circuits and antennas.

Ashok K. Agrawal (S'76–M'79–SM'82) received the M.S. and Ph.D. degrees in electrical engineering from the University of New Mexico, Albuquerque, in 1976 and 1979, respectively.

From 1973 to 1974 he was a Research Fellow at the Indian Institute of Technology, Kharagpur, India. From 1976 to 1982, he worked as a research scientist at the Mission Research Corporation in Albuquerque, and form 1982 to 1983 as a Senior Research Engineer at the Dikewood Corporation in Albuquerque. During 1982–1983 he also was an adjunct faculty member at the University of New Mexico, where he taught a graduate course on antennas. In 1983 he joined the RCA Electronic Systems Department of the General Electric Company in Moorestown, NJ, as a principal member of the engineering staff. Since then, he has been involved in research and development work on phased array and microwave antennas. His current research includes broadband and active phased-array antennas.

Dr. Agrawal has published and presented over 25 papers on printed-circuit antennas, microwave circuits, multiconductor transmission lines, electromagnetic coupling, lightning, and EMP. He was Vice Chairman of the APS/MTTS/EMC Albuquerque Chapter during 1982–1983 and Chairman of the APS/MTTS Philadelphia Chapter during 1986–1987. Dr. Agrawal is a member of Tau Beta Pi.