BROADBAND PRINTED CIRCUIT 0°/180° COUPLERS AND HIGH POWER INPHASE POWER DIVIDERS

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Abstract
A broadbanding procedure is described, which is suited for increasing the useful bandwidth of rat-race couplers and Gysel-type power dividers considerably. The circuits are easily fabricated. Relative bandwidths in excess of 40% are reached.

1. Introduction

Magic-tees or 0°/180° couplers are often employed in microwave systems, including for example balanced mixers, modulators antenna-beam forming networks and power divider/combiners. Most printed-circuit realizations of magic tees are not strictly planar. Possible solutions use combinations of microstriplines, slotlines, striplines or coplanar lines on opposite sides of a dielectric substrate and require double sided processing of the circuit.

2. The problem

A uniplanar magic-tee, the "rat-race" coupler, is sketched in Fig. 1. This coupler consists of a ring structure, with four 50Ω lines connected via 70.7Ω λ/4-length lines for impedance matching. An additional λ/2-length line is included in one arm (70.7Ω too) in order to achieve phase reversal, thus limiting the bandwidth of the rat-race coupler typically to 20-30% with an isolation of 20dB between ports (1) and (4).

The rat-race coupler has been broadbanded by substituting the λ/2-phase-reversal line and the associated λ/4-transformer with a λ/4-section of coupled lines /1/. When two diagonal ports of the coupled lines are connected to ground, the section acts as both an impedance transformer and a 270° phaseshifter. However, the coupling of the lines has to be very strong, and is hard to realize with microstrips under normal conditions.

In /2/ it is suggested to divide the λ/2-phase-reversal line into two λ/4-sections, resulting in three λ/4-sections in series, and to equip the four ports of the coupler with additional λ/4-transformers. Such a coupler can be computer-optimized and shows a greatly increased useful bandwidth. However, some of the required characteristic impedances are extremely low, and the coupling characteristics shows a quite high power ripple.

If only the in-phase power division capability of the rat-race coupler is needed, it competes with the "Wilkinson"-power divider. This divider (Fig. 2) can be made extremely broadband. Similar to the rat-race coupler, it uses λ/4-coupling lines (70.7Ω). The out-of phase port (4) is non-accessible. It is balanced with respect to ground and terminated by a 100Ω resistor. This resistor has to be small compared to the wavelength (i.e. a lumped element). It is difficult to fabricate it at high frequencies and to heat-sink it due to its balanced nature.

A solution to these problems was found by Gysel /3/. A Gysel power divider is shown in Fig. 3. The balanced 100Ω resistor of the Wilkinson-divider is replaced by a network of transmission-lines and two 50Ω resistors connected to ground, which act as the out-of-phase load (4). The bandwidth of the Gysel-divider is narrower than that of the Wilkinson-structure, and is comparable to the rat-race coupler. In fact, when comparing the Gysel-divider and the rat-race coupler, both are very similar if the load resistor at port (4) in Fig. 1 is divided into two resistors twice as large and one part of it is shifted λ/2 in the direction of port (2) (i.e. at the other end of the phase-reversing λ/2-line section).

In summary, both, the rat-race coupler and the Gysel-power-divider are valuable and indispensible components for uniplanar microstrip-circuits but suffer from a too narrow operating bandwidth for many system applications. In the following, a technique for broadbanding these components will be presented.

3. Broadbanding technique

We start with the Gysel-power-divider of Fig. 3. This circuit is symmetrical with respect to port (1). We can analyze the circuit for even- and odd excitation form ports (2) and (3) /4/. For even excitation, the symmetry-plane is a magnetic wall, for odd excitation an electric wall. Therefore we can use the equivalent circuits of Fig. 4a and b.

First considering Fig. 4a (even-mode), we can see, that Z_1 acts as a λ/4-transformer for impedance matching. Z_2 acts essentially as a λ/4-stub, short circuited at its end by the transformed open-end impedance of the transmission line Z_3. Fig. 4b (odd mode) shows two short circuited λ/4-stubs Z_1 and Z_3 connected by a λ/4-line Z_2 and terminated with 50Ω at both ends. This is the structure of an ordi-

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nary second order bandpass. The essential coupling between both networks is via lines Z_1 and Z_2. With the conventional design of Fig. 3 both even- and odd-mode networks act as resonators, yielding an attenuation pole at the center frequency in the return-loss characteristics at port (2). However, by tuning the characteristic impedances Z_1, Z_2, Z_3, respectively, the odd-mode network of Fig. 4b can be altered to show two return-loss maxima at port (2) with somewhat reduced return-loss at the band-center, but with increased bandwidth. The return loss characteristics of the even-mode network Fig. 4a hardly improves because there remains a single pole at the band center due to lines Z_2 and Z_3 acting only as one stub.

A possibility for broadbanding the circuit consists of connecting a short circuited $\lambda/4$-stub or an open circuited $\lambda/2$-stub for the even mode network at port (1), marked with a cross in Fig. 4a. The stub will not influence the odd mode network because it has a virtual short circuit at that location. Analyzing the properly tuned even mode network of Fig. 4a together with the additional stub clearly shows a second maximum in the return loss characteristics of port (2) with increased bandwidth.

The broadbanding can be continued nearly independently for both even- and odd-mode networks, because port (1) is completely decoupled from the odd mode network. Further transmission-line elements at ports (4) influence the even mode network only slightly. Additional $\lambda/4$-series lines and short-circuited $\lambda/4$-stubs (or open-circuited $\lambda/2$-stubs) are connected in series to port (1) in order to obtain a given number of minima in the corresponding return-loss characteristics. Ports (4) are extended by additional $\lambda/4$-series lines connected by $\lambda/2$-branch lines. An example for such a circuit is given in Fig. 5. With more stubs and more branchlines a broader bandwidth is possible.

Considering the effect of the $\lambda/4$-coupled $\lambda/2$-branch lines in the odd mode network (Fig. 3, 4b and 5) it can be seen that a higher number of branches tends to force signals in the a and b-section to be out of phase over a broader and broader bandwidth. Even-mode signals cannot exist.

However, if this antimetry is maintained by the circuit, we can shift one of the odd mode loads, for example (4a) towards (4b). The shift along a $\lambda/2$-line does not alter the impedance, and (4b) can be paralleled with (4a), resulting in a single odd mode load (4). If a signal enters port (4) it will leave ports (2) and (3) with 180° phase difference over a broad bandwidth, and port (1) is decoupled.

We have now arrived at a broadbanded "rat-race" coupler, which (theoretically) could be extended with n short circuited $\lambda/4$-stubs (or open $\lambda/2$-stubs) at the even mode port and m $\lambda/2$-branches in front of the odd-mode port. An example is shown in Fig. 6.

4. Calculations

Computer optimization was used to calculate the performance of the couplers and to find the optimum characteristic impedances. The performance of power-dividers and 0°/189° couplers with up to four branches was calculated, completely confirming the viability of the method and the physical realizability of the results with microstrips. Results for a 0°/180° coupler with 3 branches are given in Fig. 7-8 as an example. As compared to the ordinary rat-race hybrid, the performance is drastically improved. Dependent on the performance criterion used, a relative bandwidth of approximately 40-45% is predicted. The simulated performance of a power-divider is shown in Fig. 9.

5. Experimental results

Various power dividers and 0°/180° hybrids were built and tested. Results are presented for a 0°/180° hybrid in Fig. 10. The circuits were fabricated at X-Band (8-12 GHz) on soft plastic substrate (RT duroid 5880, h = 0.254 mm, ε_r = 2.22). Fig. 10 shows a very flat equal power division, which is maintained over a bandwidth from 8-13 GHz. The even-mode input return loss is not yet sufficient. However, the measured imperfections can be attributed to the connectors, which were used. Also shown is the isolation between the even mode (1) and the odd mode (4) inputs, which is excellent over the whole bandwidth. Measurement-results for a broadband power divider are given in Fig. 11, fully demonstrating the viability of the broadbanding approach.

6. Conclusions

By applying the design approach outlined above, the useful bandwidth of 0°/180°-couplers and "Gysel"-power-dividers can be improved considerably (at least doubled). The resulting circuits have many advantages:

- isolation between even and odd mode inputs is excellent and all ports are matched
- very flat amplitude characteristics and low phase-deviation from the nominal value is obtained combined with low loss
- convenient and realizable characteristic impedances of the lines are involved,
- the design is based on a clear concept of bandwidth improvement, which can be logically continued.

Applications are seen for example for high-power power combiners, electronic components such as mixers and push-pull-amplifiers and antenna beam forming networks, especially for low side-lobe antennas.

References

/1/ March, S.: A Wideband Stripline Hybrid Ring. IEEE Trans. Microwave Theory Tech., Vol. MTT-16, 1968, p. 361.

/2/ Kim, D.I., Naito, Y.: Broad-Band Design of Improved Hybrid Ring 3-dB Directional Couplers. IEEE Trans. Microwave Theory Tech., Vol. MTT-30, 1982, pp. 2040-2046.

/3/ Gysel, U.H.: A N-way Power Divider/Combiner Suitable for High Power Applications. MTT-S Symposium Digest 1975, pp. 116-118.

/4/ Reed, J., Wheeler, G.J.: A Method of Analysis of Symmetrical Four Port Networks. IRE Trans. Microwave Theory Tech., Vol. MTT-4, 1956, pp. 246-252.

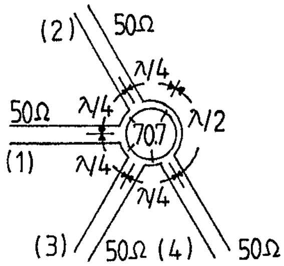


Fig. 1
"Rat-race" coupler

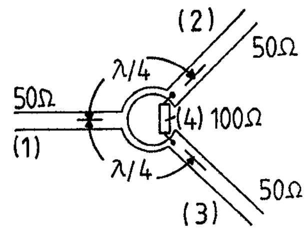


Fig. 2
"Wilkinson"-divider

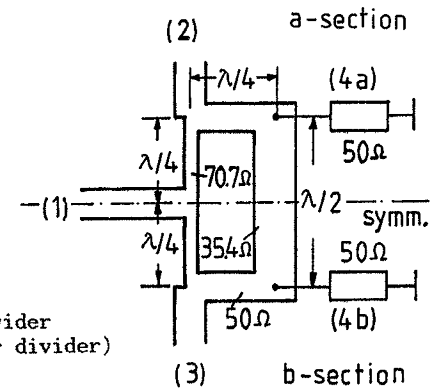


Fig. 3
"Gysel"-divider
(high-power divider)

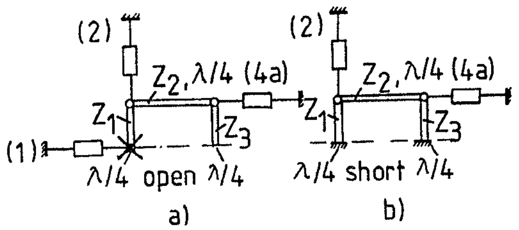
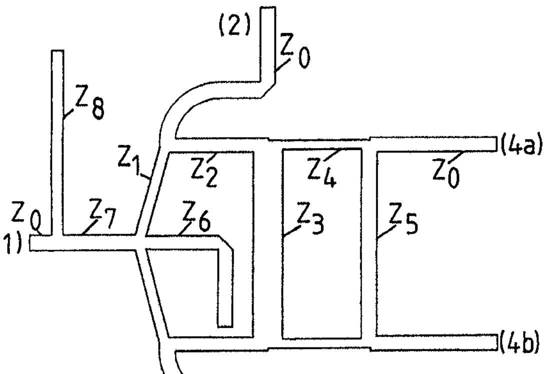


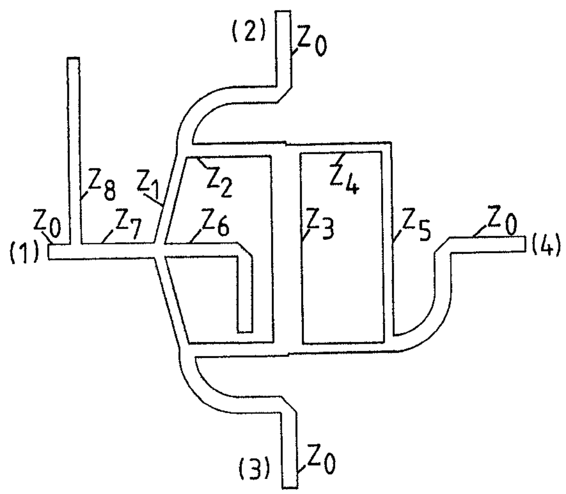
Fig. 4 Equivalent circuits for Gysel-divider
a) even excitation b) odd excitation



(1): input
(2), (3): in phase outputs
(4a),(4b): external odd-mode loads

3,5,6,8: λ/2-length
all other: λ/4-length
6,8: can be made shorted λ/4-length

Fig. 5 Broadbanded high-power divider



(1): even-mode port
(4): odd-mode port
(2),(3): outputs

3,5,6,8: λ/2-length
all others: λ/4-length
6,8: can be made shorted λ/4-length

Fig. 6 Broadbanded 0°/180°-coupler

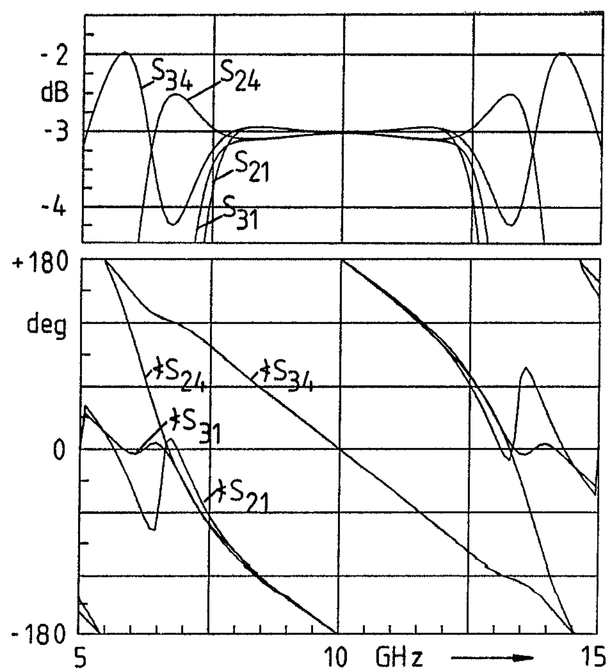


Fig. 7 Amplitude and phase characteristics for a 0°/180°-coupler according to Fig. 6

Z_1 = 69.64Ω Z_2 = 55.78Ω Z_3 = 41.70Ω
Z_4 = 77.81Ω Z_5 = 69.97Ω Z_6 = 86.03Ω
Z_7 = 49.95Ω Z_8 = 91.96Ω
(Simulated results)

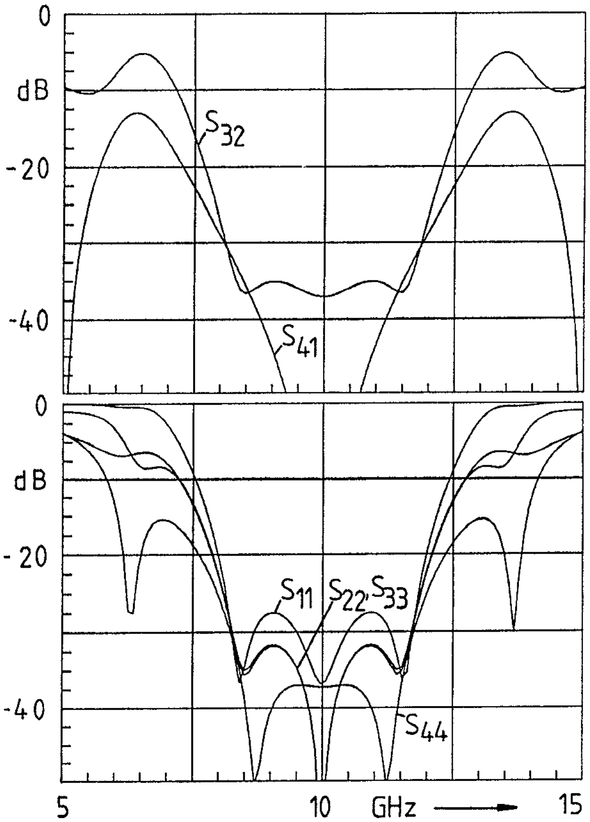


Fig. 8 Isolation and return-loss characteristics for the coupler of Fig. 7

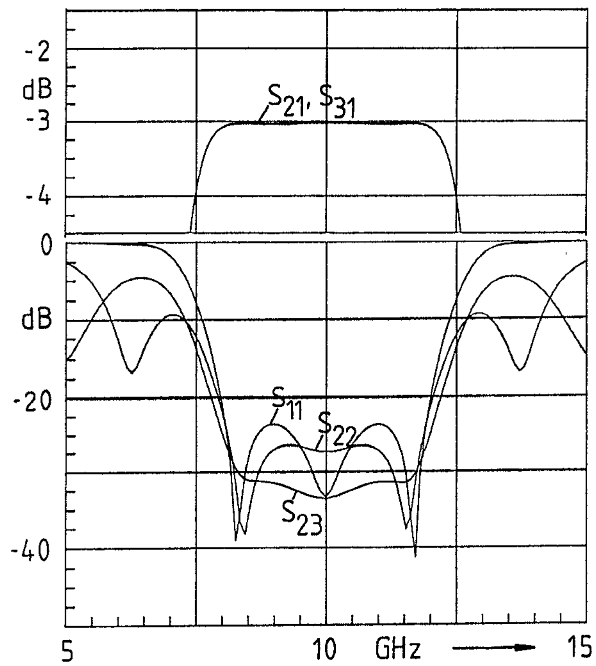


Fig. 9 Amplitude characteristics of a broadbanded high-power divider (Ref. Fig. 5)

Z_1 = 71.98Ω Z_2 = 56.87Ω Z_3 = 46.19Ω
Z_4 = 53.34Ω Z_5 = 33.49Ω Z_6 = 85.39Ω
Z_7 = 49.81Ω Z_8 = 66.52Ω
(Simulated results)

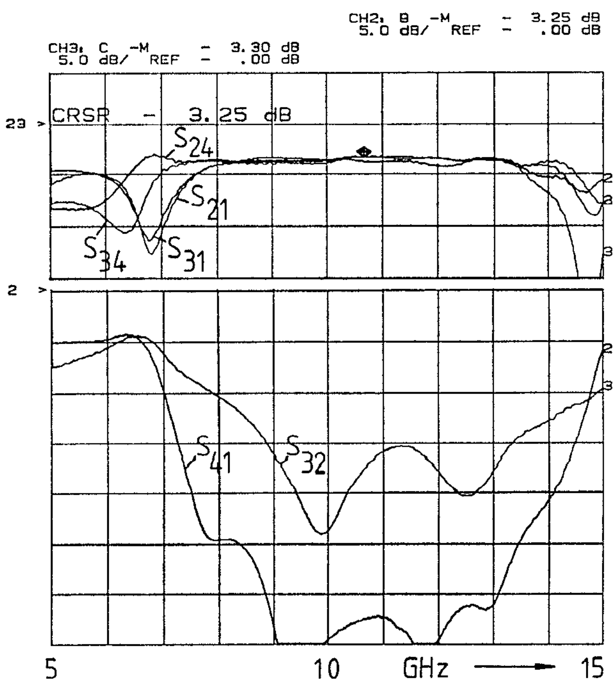


Fig. 10 Measured amplitude characteristics of the 0°/180°-coupler

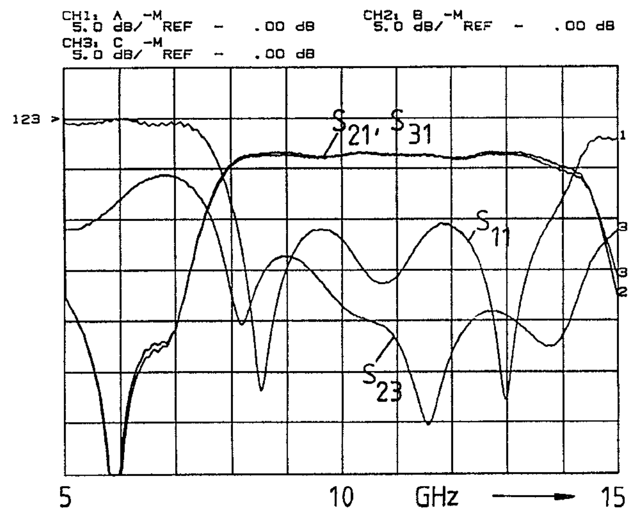


Fig. 11 Measurement results for the broadband high-power divider