F. Arndt, J. Bornemann, D. Grauerholz & R. Vahldieck
Microwave Department, University of Bremen, Germany

Material and Circuit Evaluation for Millimetre-Wave Applications: A Microstrip 3 dB Hybrid Coupler with Low-Dielectric Substrate for Millimetre Waves*

Abstract 3 dB hybrid couplers have been designed using RT/duroid as substrate material. This low-ε-value dielectric-substrate technique is well suited for millimetre-wave applications. Design data are reported for frequencies of approximately 16 and 28.3 GHz. The measured directivities of the couplers are 50 dB and 18 dB, respectively.

Résumé On a mis au point des coupleurs hybrides à 3 dB avec substrat en RT/duroid. Ce type de substrat diélectrique à faible coefficient de permittivité convient bien aux circuits en ondes millimétriques. On présente les caractéristiques de conception pour des fréquences d'environ 16 et 28,3 GHz. Les mesures de la directivité des coupleurs donnent respectivement 50 et 18 dB.

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Introduction

Microstrip circuits are finding increasing application at centimetre and even millimetre wavelengths because of the compactness, low weight and reduced cost that their use brings[1–4]. Conventional microstrip techniques, however, utilising high-dielectric substrates[1] require critical precision in processing when used for millimetre-wave applications.

The purpose of this paper is to show that the choice of RT/duroid 5880 as a low-dielectric substrate allows 3 dB hybrid couplers to be designed for millimetre waves, thereby avoiding miniaturisation difficulties and so offering potential for low-cost production. In contrast to Rubin & Saul[4] who used a special reverse-phase twist technique for the lines, we have selected a directly producible $4\lambda/4$ hybrid coupler ('hybrid ring') technique and a $6\lambda/4$ hybrid coupler ('rat-race coupler') technique (Fig. 1), which guarantee production uniformity and reliability.

Design

Figure 1 shows a schematic of the two microstrip 3 dB hybrid couplers. The hybrid ring type (Fig. 1b) consists of four (at midband frequency) $\lambda/4$-long lines, where two opposite lines hold the lower characteristic impedance $Z_0/\sqrt{2}$ (Z_0 is the characteristic impedance of the feeding lines 1–4). The scattering matrix of this four-port is given by[5]:

$$(S)_h = \frac{1}{-\sqrt{2}} \begin{bmatrix} 0 & 0 & 1 & j \\ 0 & 0 & j & 1 \\ 1 & j & 0 & 0 \\ j & 1 & 0 & 0 \end{bmatrix} \qquad (1)$$

which means, for instance, that a signal fed into port 1 is ideally split into ports 3 and 4 and no signal is transported to port 2, etc., if all ports are matched.

The rat-race coupler (Fig. 1c) consists of three $\lambda/4$-long lines and a $3\lambda/4$-long line, all with a characteristic impedance of $Z_0\sqrt{2}$. The scattering matrix of that type of coupler is given by[5]:

$$(S)_r = \frac{-j}{\sqrt{2}} \begin{bmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{bmatrix} \qquad (2)$$

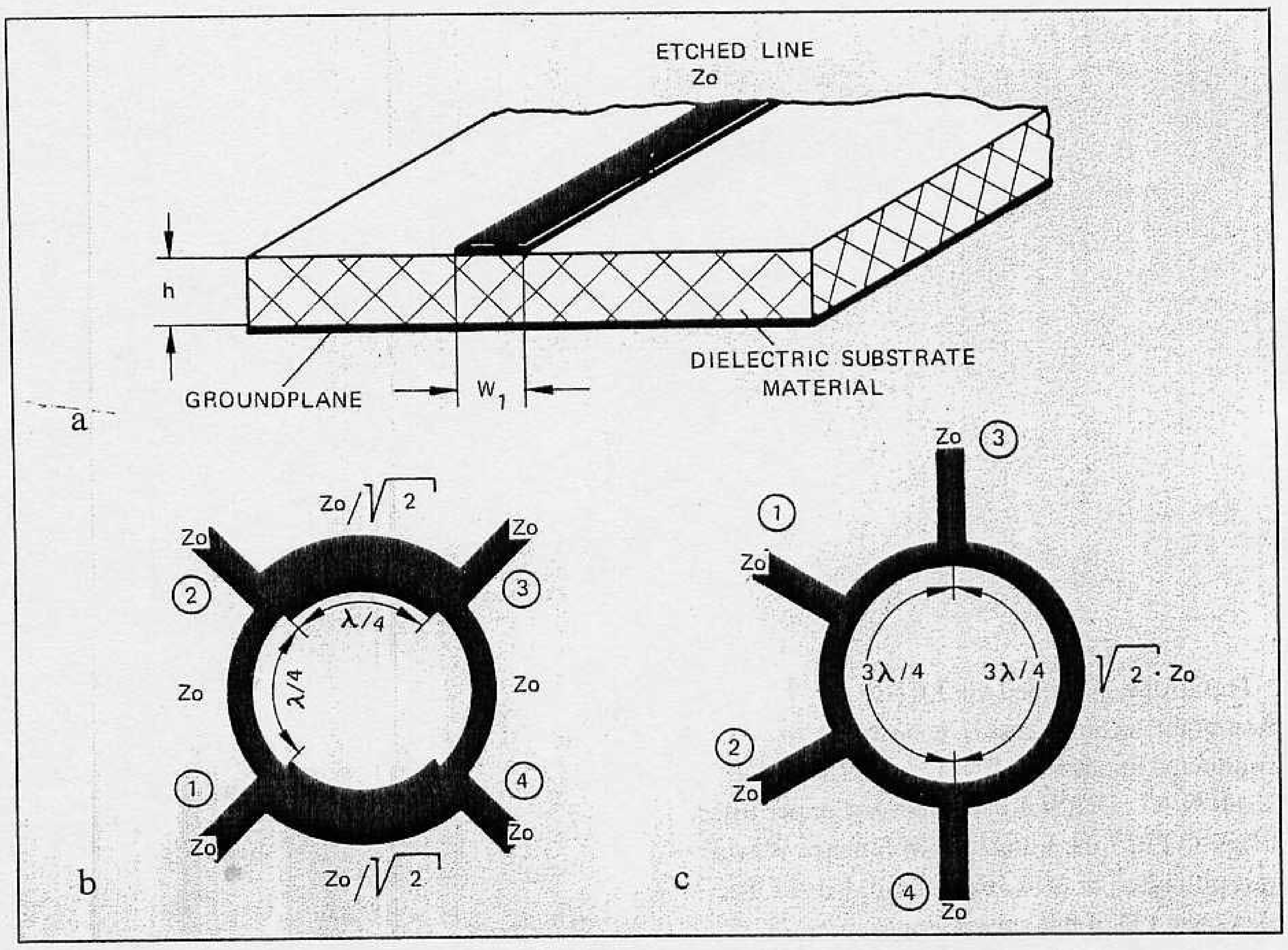
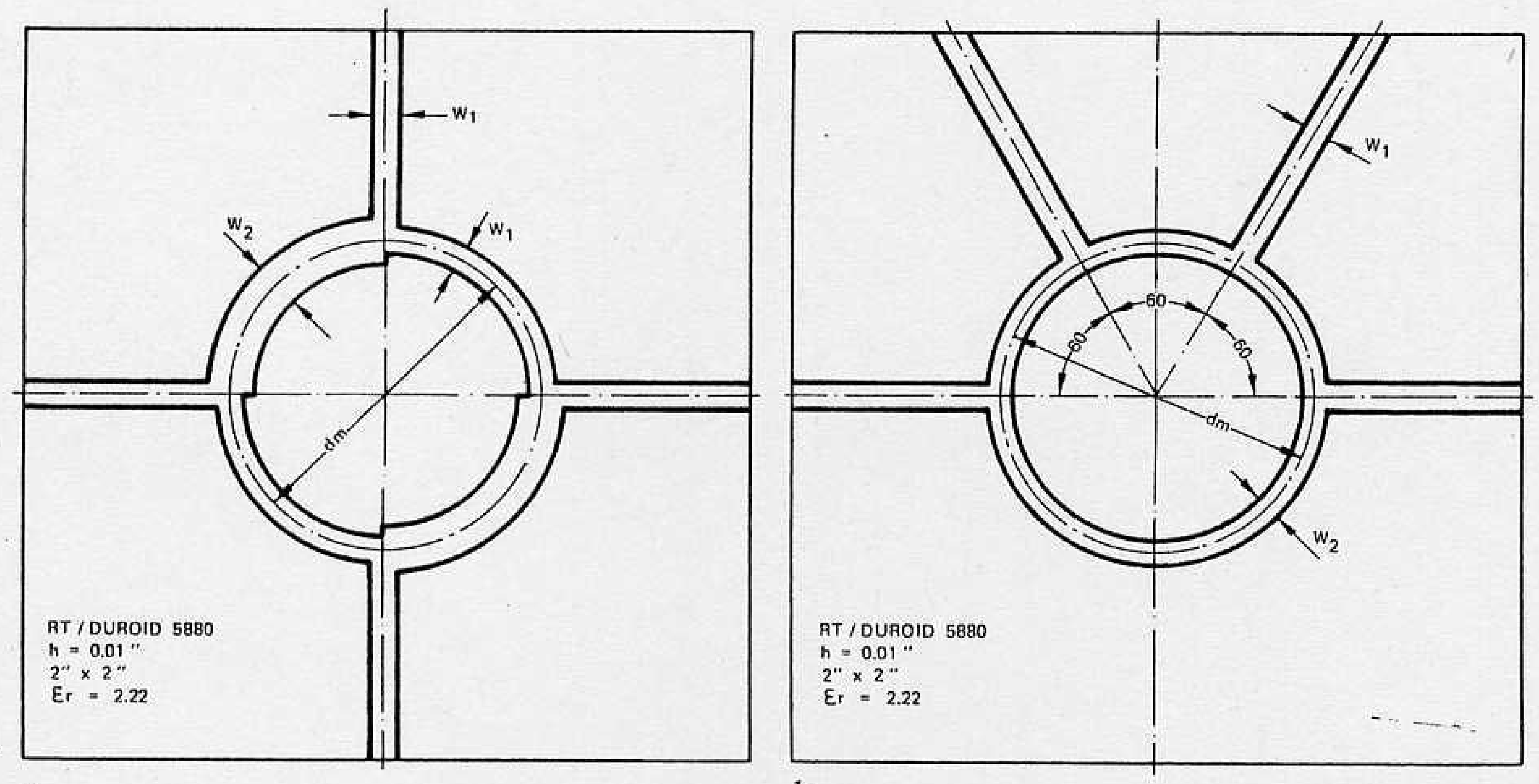


Figure 1. 3 dB hybrid coupler
(a) Microstrip line
(b) Hybrid ring
(c) Rat-race coupler



a b

Figure 2. Engineering drawings for the 3 dB hybrid couplers
(a) Hybrid ring
(b) Rat-race coupler

Figure 3. Waveguide-to-microstrip transition

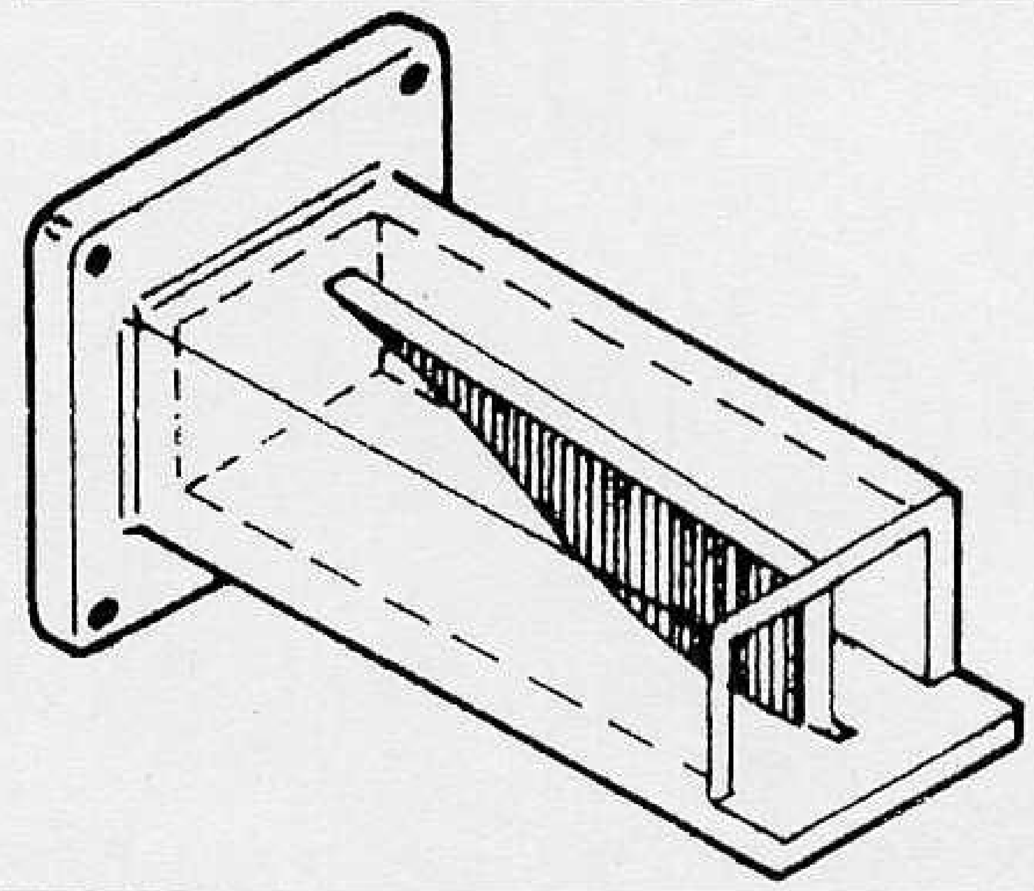


Table 1. Dimensions of the microstrip 50 Ω-line 3 dB hybrid couplers

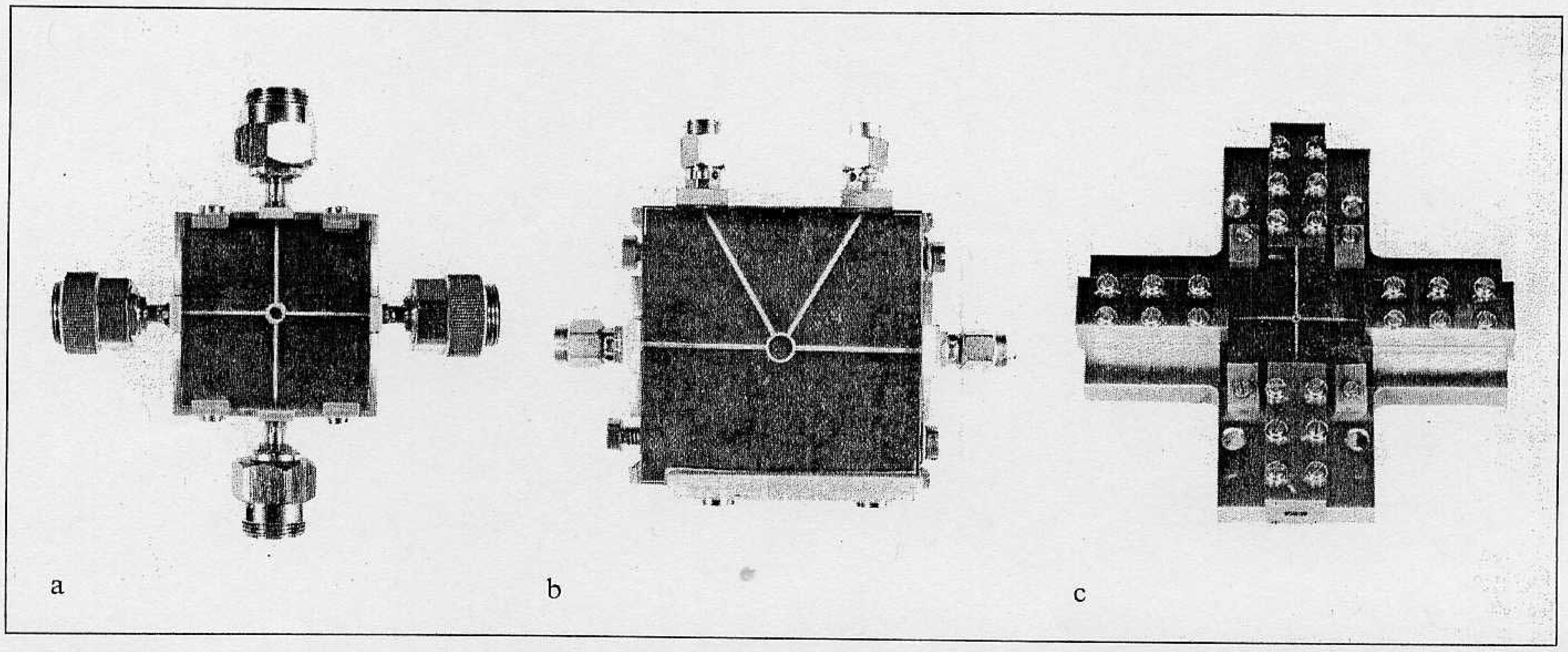
f(GHz)	Z_0(Ω)	d_m (mm)	W_1 (mm)	W_2 (mm)
Hybrid ring (Fig. 2a)				
16	50	4.595	0.789	1.281
28.3	50	2.298	0.789	1.281
Rat-race coupler (Fig. 2b)				
15.5	50	7.054	0.789	0.448

The dimensions of the microstrip lines calculated according to Reference 6 for the chosen midband frequencies of about 16 and 28.3 GHz are given in Table 1. The engineering drawings are shown in Figure 2.

For the hybrid ring (Fig. 2a) a constant-mean-diameter technique has turned out to give the best results, the line steps being located equidistant from a common mean diameter d_m. The rat-race coupler (Fig. 2b) was foreseen for use with coaxial instrumentation only, because the lines lie too close together for simple waveguide instrumentation.

For the 28.3 GHz hybrid ring four Ka-band waveguide (7.112 mm × 3.566 mm) to microstrip transitions have been constructed (Fig. 3) with a linearly tapered metallic ridge. The three 3 dB hybrid couplers are shown in Figure 4.

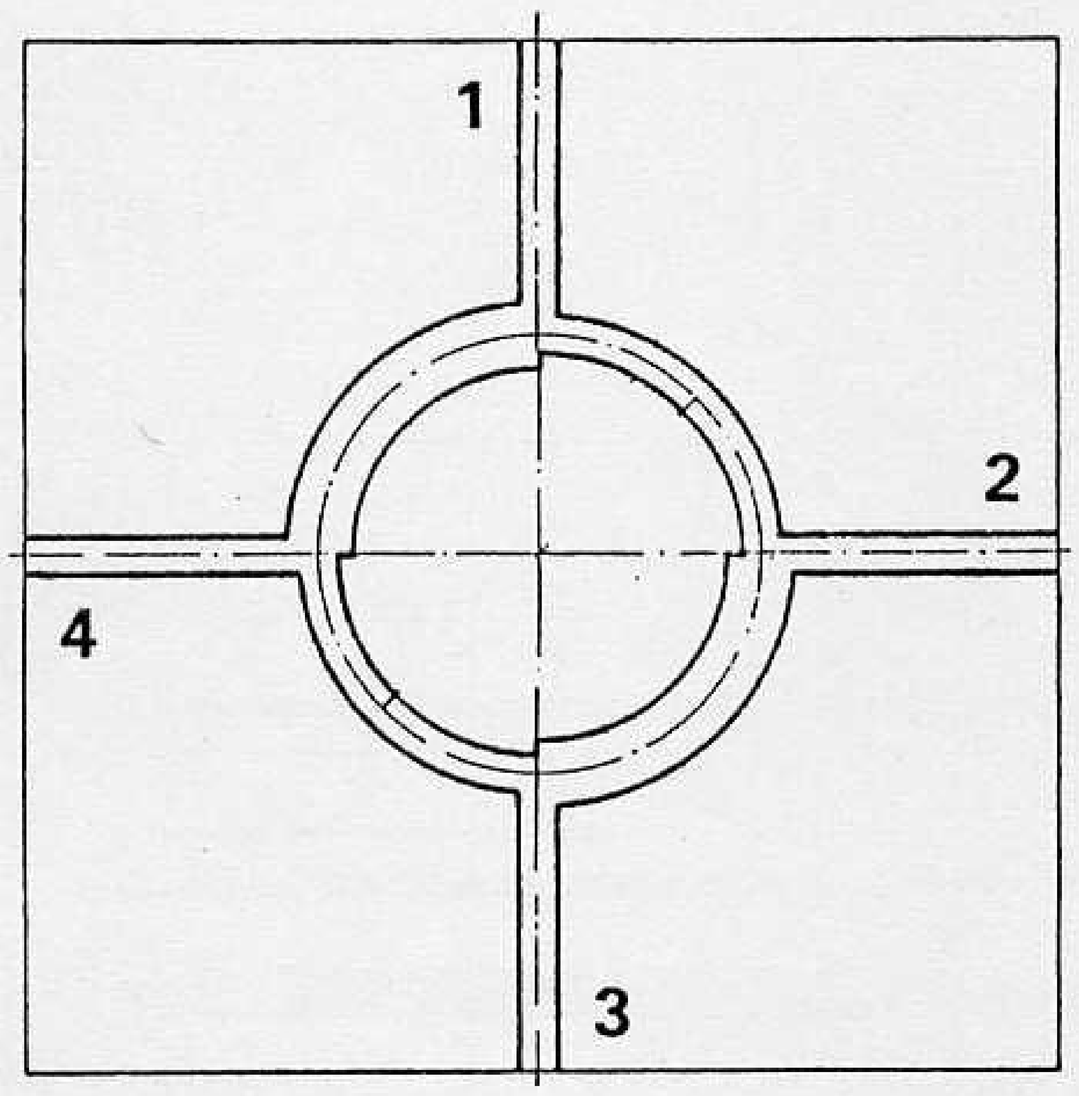
Figure 4. Photographs of the 3 dB hybrid couplers constructed
(a) Hybrid ring for 16 GHz
(b) Rat-race coupler for 15.5 GHz
(c) Hybrid ring for 28.3 GHz together with the four waveguide-to-microstrip transitions



Results

Figure 5 shows the measured scattering coefficients S_{41}, S_{31}, and S_{21} for the 16 GHz hybrid ring design (Fig. 4a). The coupling between ports 1-3 and 1-4 at midband is almost exactly -3 dB. The directivity of the coupler $D = S_{21} - S_{31}$ is better than -50 dB. Because of the $\lambda/4$-long lines required, this directivity is only realised for a narrow frequency band.

The rat-race coupler (Fig. 4b) exhibits a broader band operation (Fig. 6), because the phase difference between the $\lambda/4$ and $3\lambda/4$-long lines is not so frequency sensitive. If a 15 dB directivity limit is chosen, for instance, as a criterion for bandwidth definition, the rat-race coupler operates well from about 12.4 to about 18 GHz (i.e. over the whole Ku band).



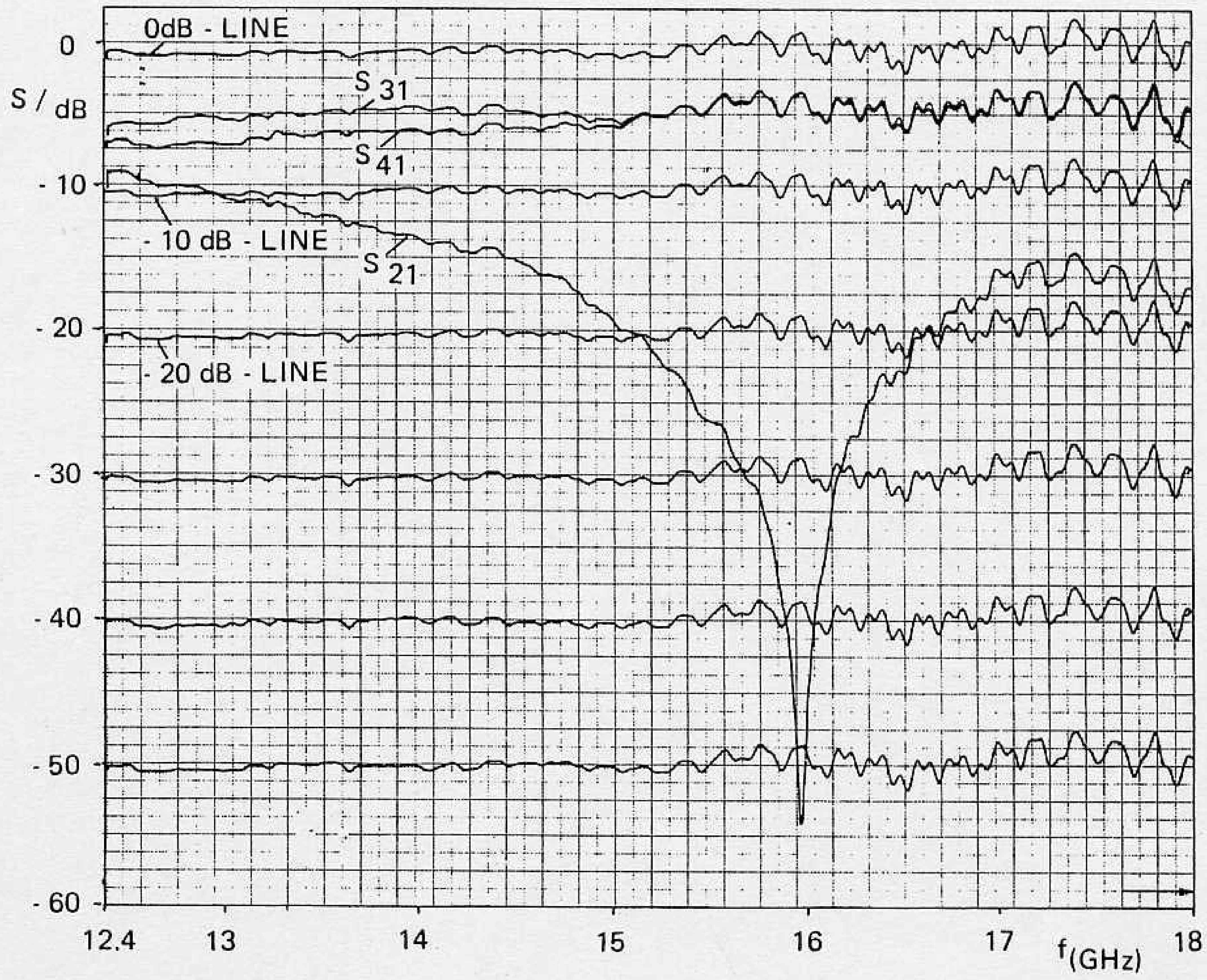
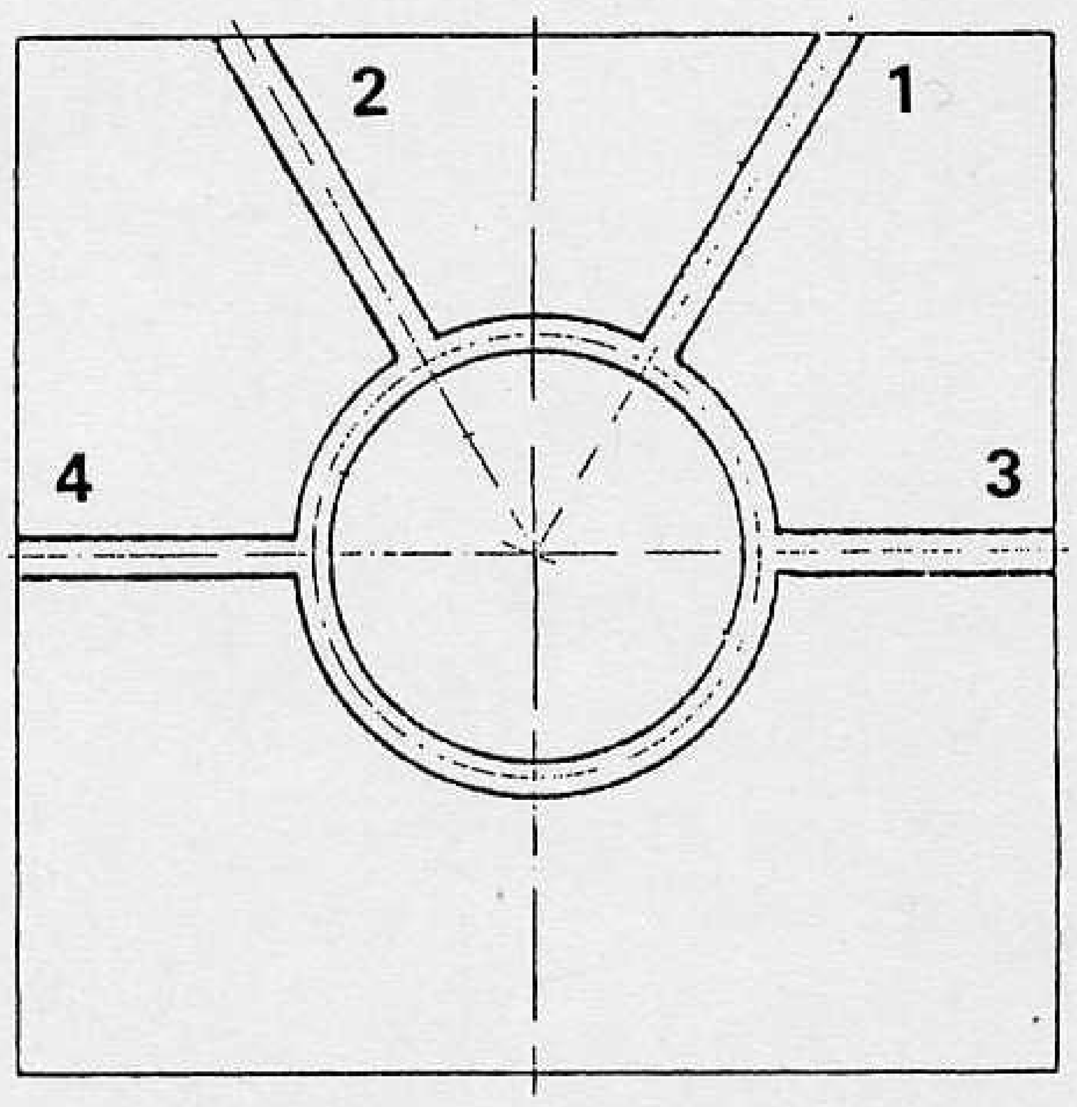


Figure 5. Measured scattering coefficients S_{41}, S_{31} (coupling), and S_{21} (isolation) for the hybrid ring (Fig. 4a) as a function of frequency



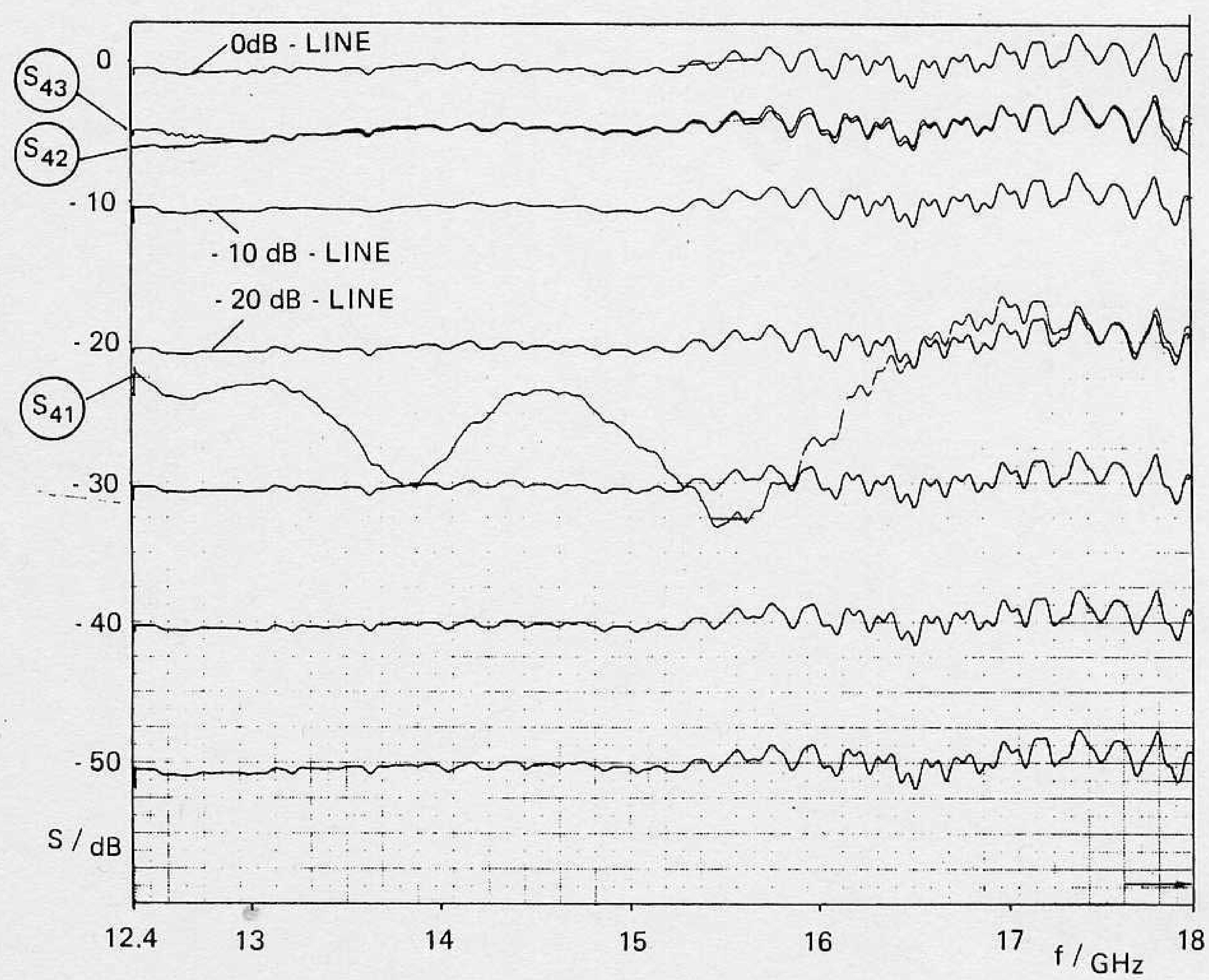
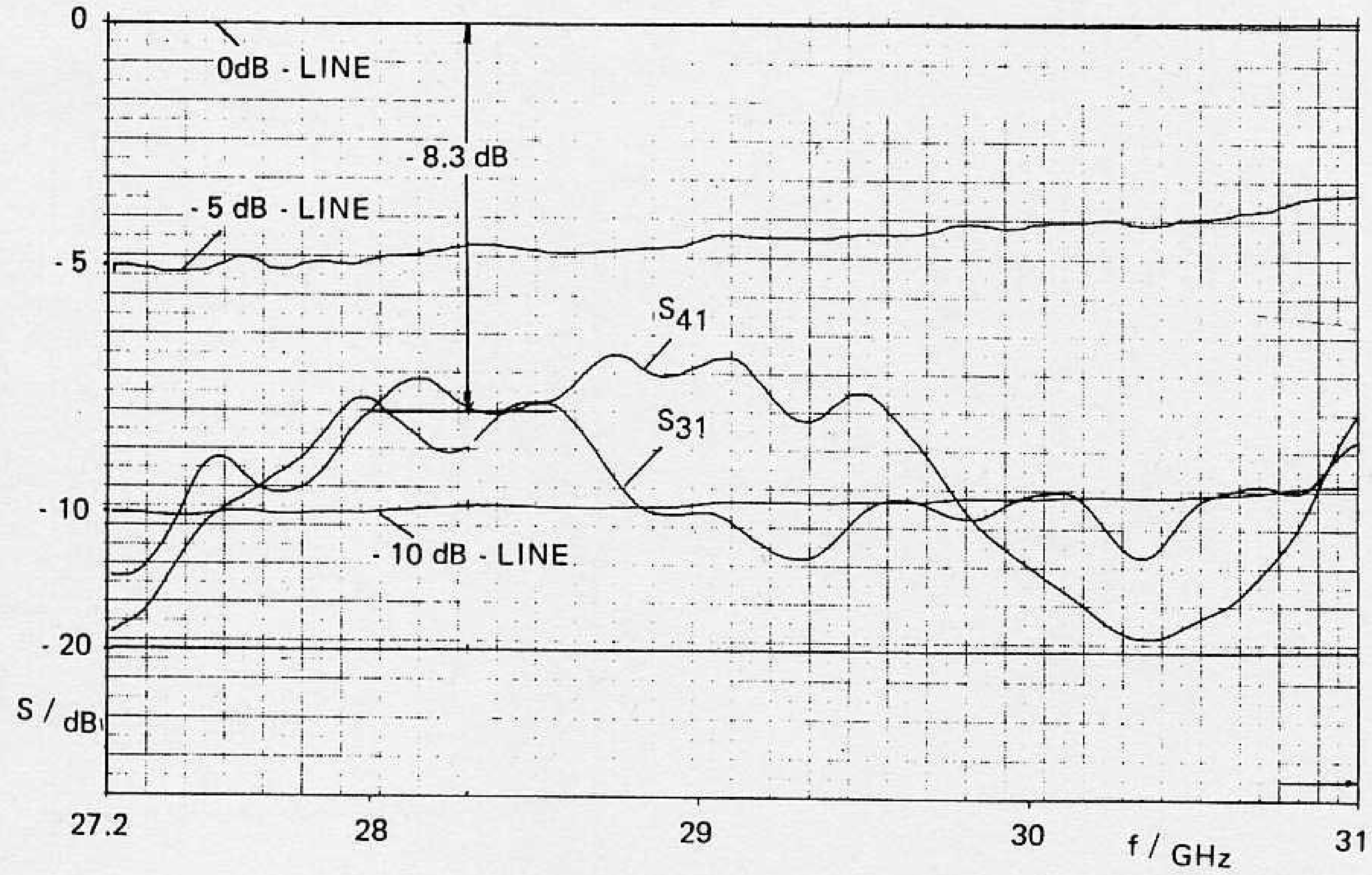
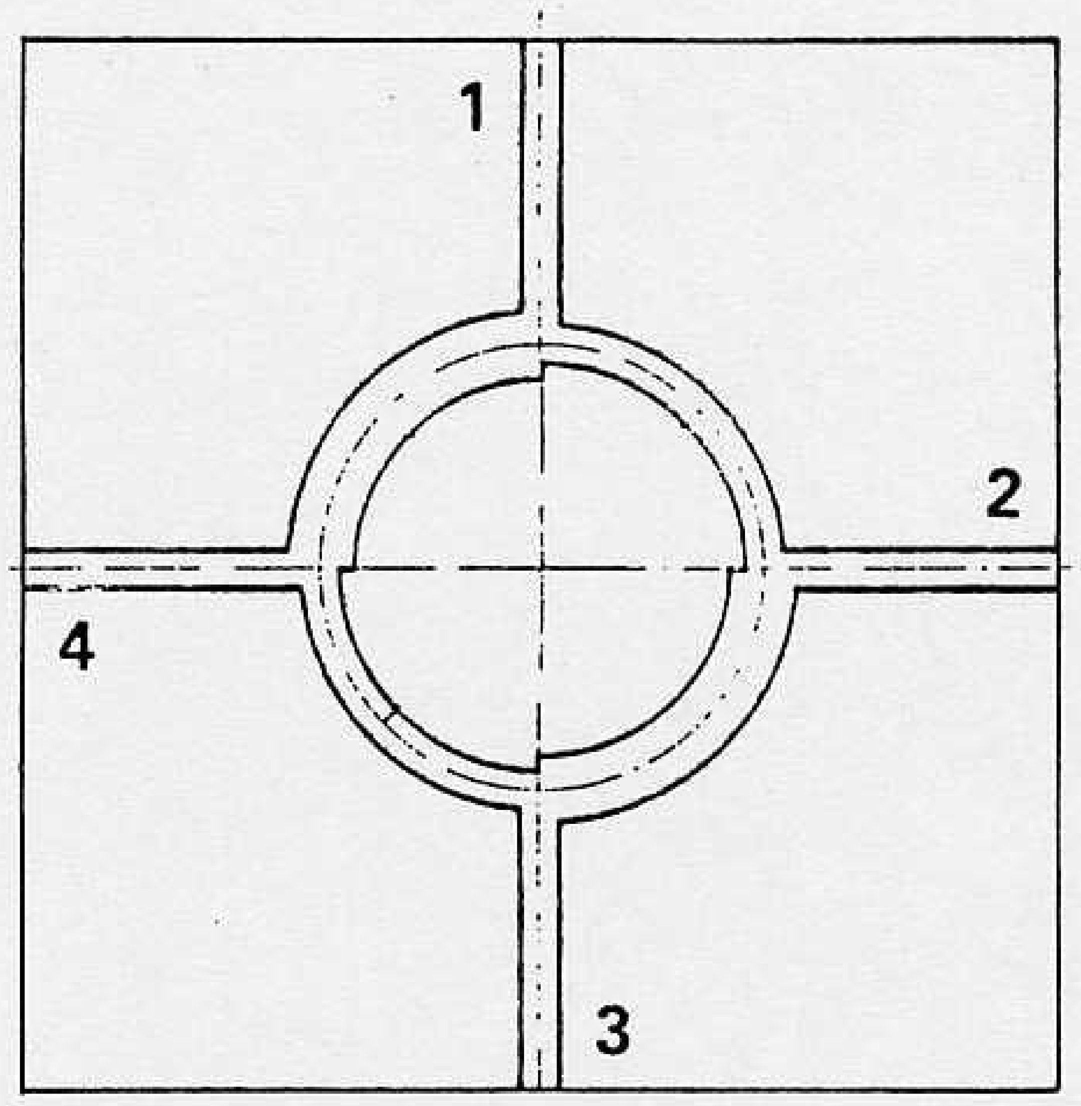


Figure 6. Measured scattering coefficients S_{34}, S_{24} (coupling) and S_{14} (isolation) for the rat-race coupler (Fig. 4b) as a function of frequency

Figure 7 shows the measured results for the 28.3 GHz hybrid ring (Fig. 4c), together with the four waveguide-to-microstrip transitions. Since the two actual transitions between two ports show a mean insertion loss of about 4.8 dB (Fig. 7c), this value has to be taken into account for the measured coupling (Fig. 7a) and isolation curve (Fig. 7b). The coupling at midband is about 3.5 dB, while the directivity is about 18 dB.





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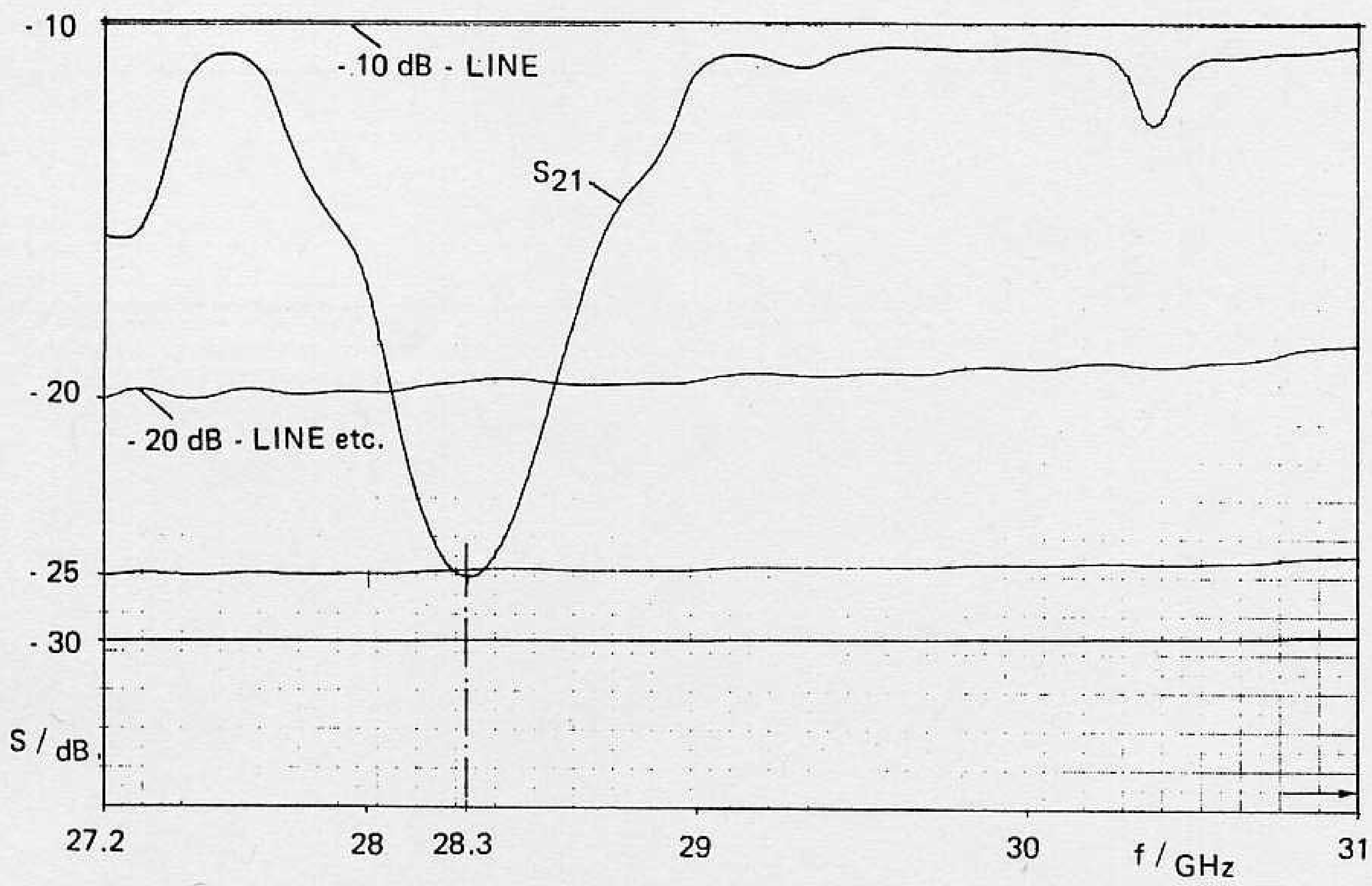

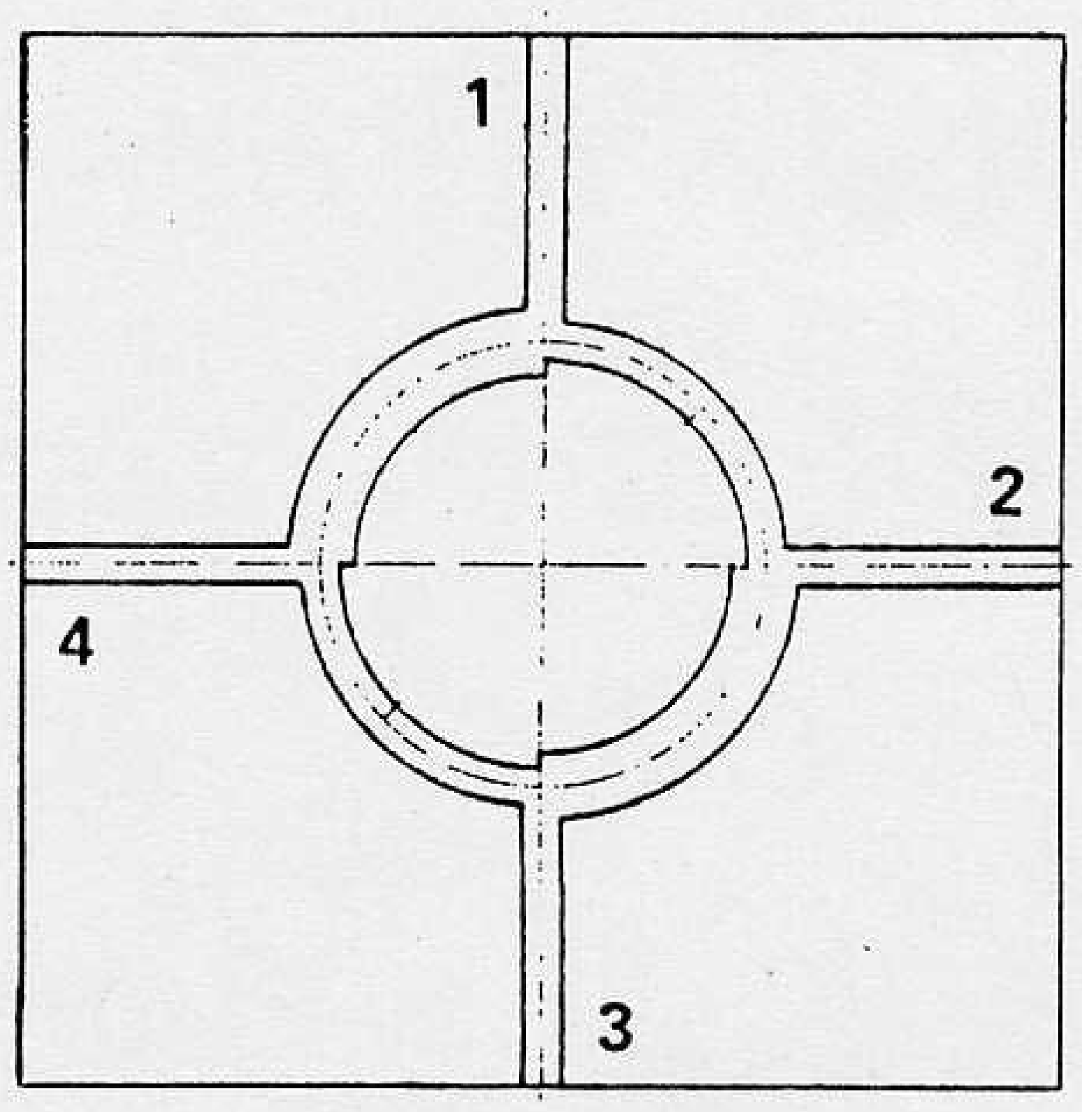

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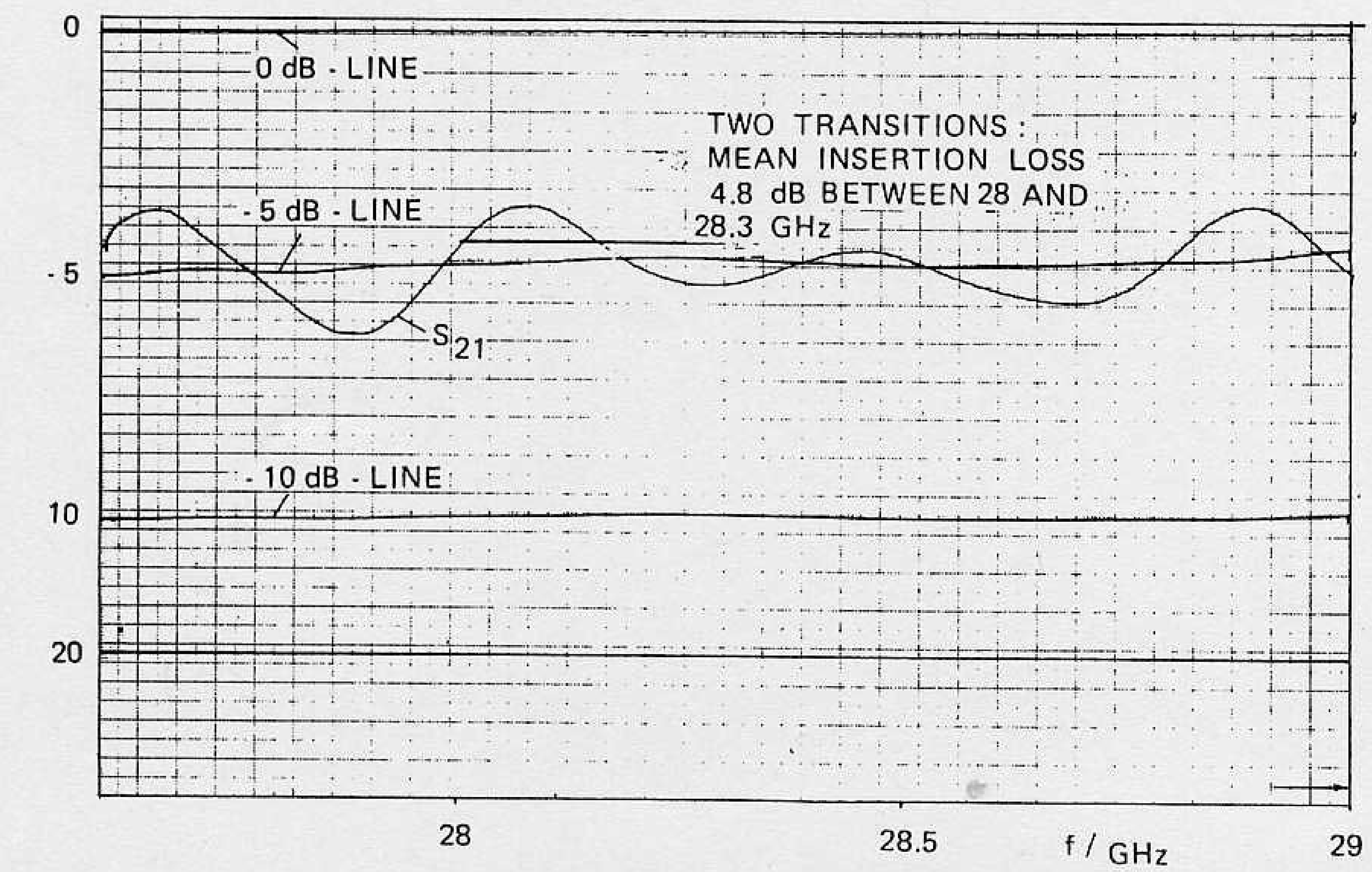

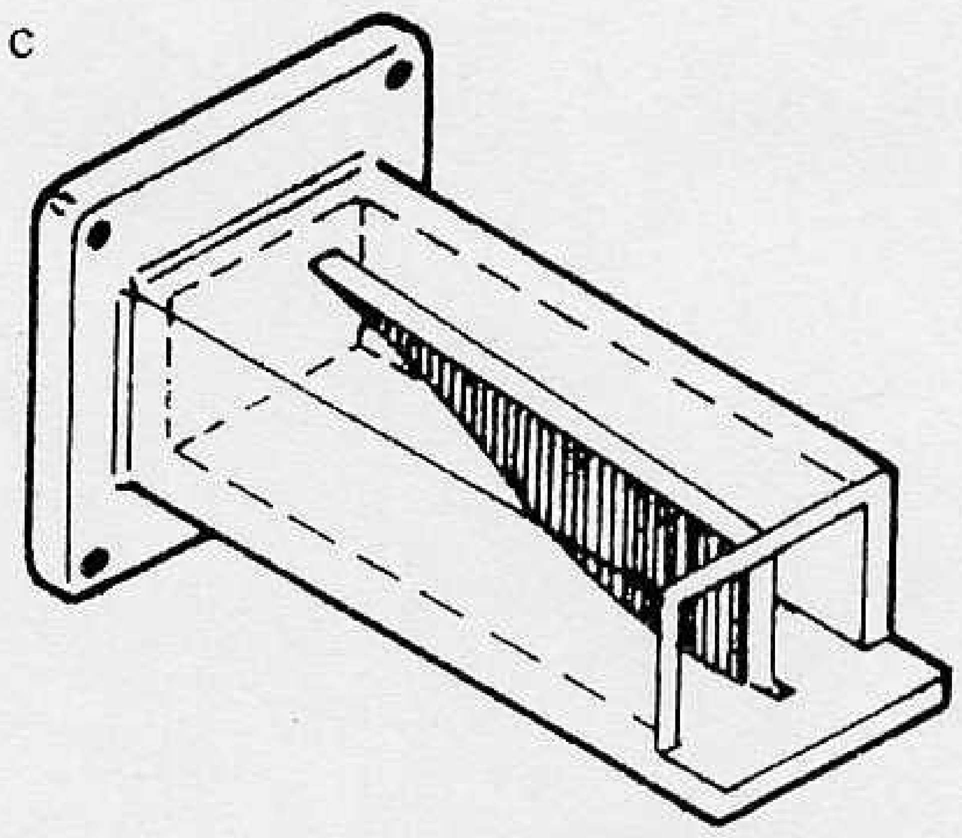

Figure 7. Measured scattering coefficients for the hybrid ring (Fig. 4c), including the transitions
(a) S_{41}, S_{31} (coupling)
(b) S_{21} (isolation)
(c) Insertion loss for the overall waveguide – microstrip line – waveguide transition (two single transitions)

Conclusions

The low-ε-value substrate design for 3 dB hybrid couplers leads to circuits well suited for millimetre-wave application. Instead of a complicated reverse-phase twist technique already known in the literature, the conventional low-frequency hybrid ring and rat-race coupler technique has been chosen, with associated benefits of good production uniformity and reliability.

References

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