Design of millimetre-wave diplexers with optimized H-plane transformer sections

Conception de diplexers à ondes millimétriques comprenant des sections de transformations dans le plan H

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A new millimetre-wave integrated diplexer arrangement is introduced utilizing metal insert channel filter technology and H-plane waveguide matching configurations. Due to a rigorous and efficient field theory method, special waveguide transformer sections are optimized which compensate for field distortions within the filter bandwidths. Since higher-order mode interactions are advantageously taken into account, the design is suitable for millimetre-wave applications requiring no additional fine-tuning elements. Computer-optimized design data are presented in the Ka- and W-band frequency range.

Un nouveau diplexer intégré à ondes millimétriques est présenté. Il utilise la technologie des filtres à insertion de métal et des configurations de correspondance des guides d'ondes dans le plan H. Par suite d'une rigoureuse et efficace méthode de la théorie des champs, des sections spéciales de transformations des guides d'ondes sont optimisées et ainsi compensent la distorsion des champs dans la bande passante des filtres. Puisque l'interaction des modes d'ordres supérieurs est avantageusement prise en compte, la conception est appropriée aux applications en ondes millimétriques ne nécessitant pas d'élément de syntonisation supplémentaire. Les données conçues et optimisées par ordinateur sont présentées dans les bandes de fréquences Ka et W.

Introduction

Recently, a number of waveguide integrated diplexers/multiplexers have been reported[1-4] which use rigorous field theory design methods and E-plane metal insert structures[5] as channel filters. The circuits are ideally suited for millimetre-wave applications where the following advantages may be stated: first, no mechanical fine-tuning is required since the computer-aided design covers the complete component; second, a high fabrication accuracy is achieved by utilizing metal etching techniques and computer-controlled milling facilities; third, high power application is possible because of the absence of lossy dielectrics.

Excluding other diplexer designs using different circuitries (e.g., suspended substrate[6], finline/suspended stripline[7], and circular waveguide dual-mode filters[8]), all-metal insert configurations can basically be divided into diplexers constructed by multihole couplers/slotted-fin filters[9]; E-plane types, where the two output ports are divided in the E-plane of the input signal[1,2,4,10,11]; and H-plane divided structures.[3,11,12]

This paper adds a new component to the H-plane family (see Figure 1). The main advantage in comparison with the H-plane types presented in References 3 and 11 is that the new design does not require additional compensation elements such as shorts and H-plane irises. A special computer-optimized transformer section profile[13] is used to compensate for all discontinuities involved and provides input return loss values of up to 25 dB within the bandwidths of the channel filters.

The computer-aided field theory design method takes into account high-order mode interactions, finite strip and finite separation wall thicknesses. In addition to the widths and lengths of the transformer section, the connecting lengths to the channel filters are advantageously used as optimization and compensation parameters.

Theory

A reduced-size modal scattering matrix method is used for the computer-aided design of the H-plane diplexer (Figure 1). Since the basic transitions involved (empty waveguide to waveguide bifurcation, waveguide to narrower/wider waveguide section; see Figure 2) have already been treated in References 5 and 14, only the principal steps of the TE_{mo}-mode analysis will be presented.

In each homogeneous subregion, the transverse field components to be matched are expressed as a sum of forward (+) and backward (−) travelling eigenmodes:

$$E_y^{\pm} = -\sum_{m=1}^{M} \sqrt{Z_{hm}} F_m(x) A_m^{\pm} \exp(\mp jk_{zm}z), \qquad (1)$$

$$H_x^{\pm} = \pm\sum_{m=1}^{M} \sqrt{Y_{hm}} F_m(x) A_m^{\pm} \exp(\mp jk_{zm}z), \qquad (2)$$

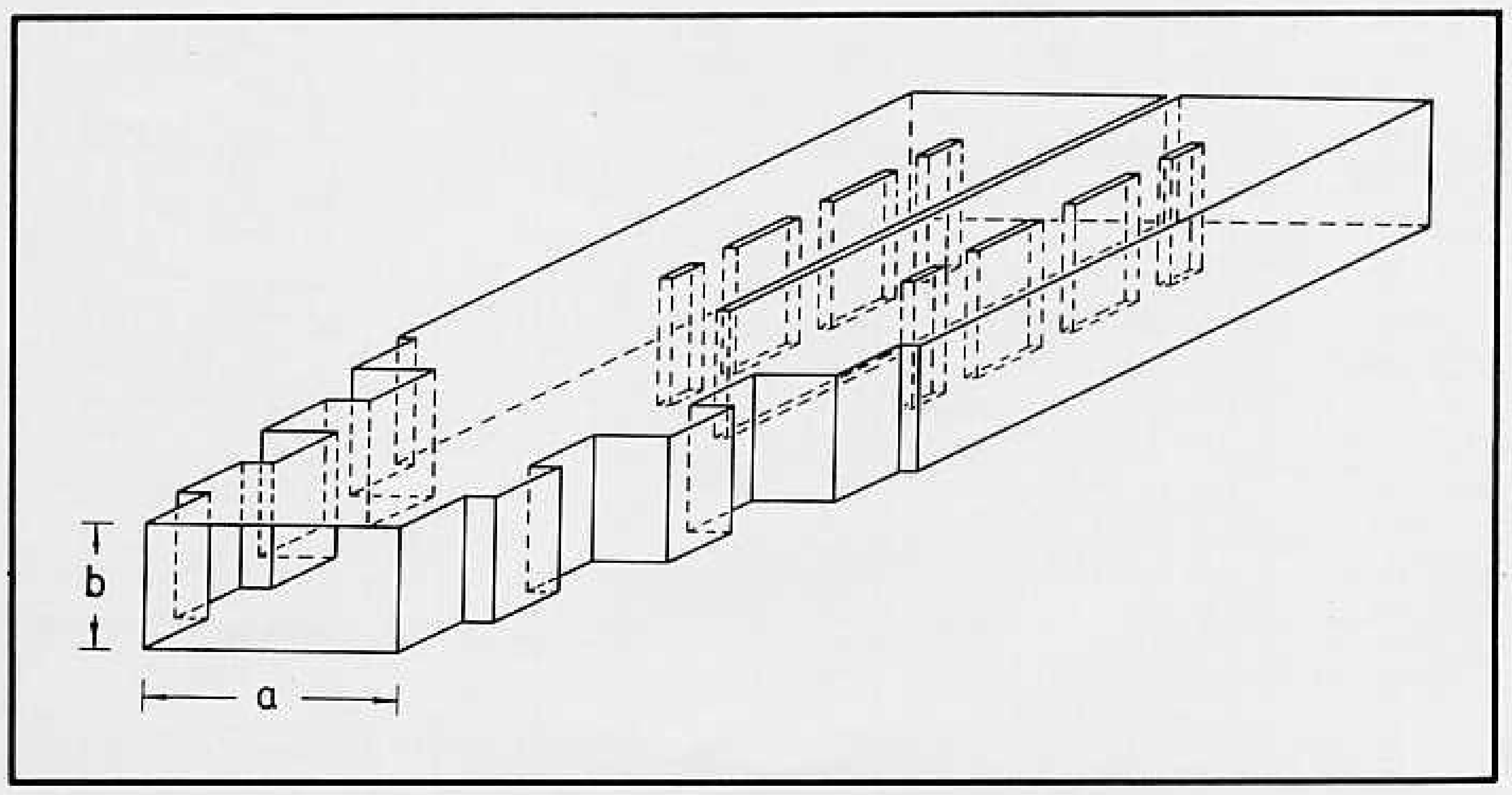

Figure 1: *H-plane integrated circuit diplexer.*

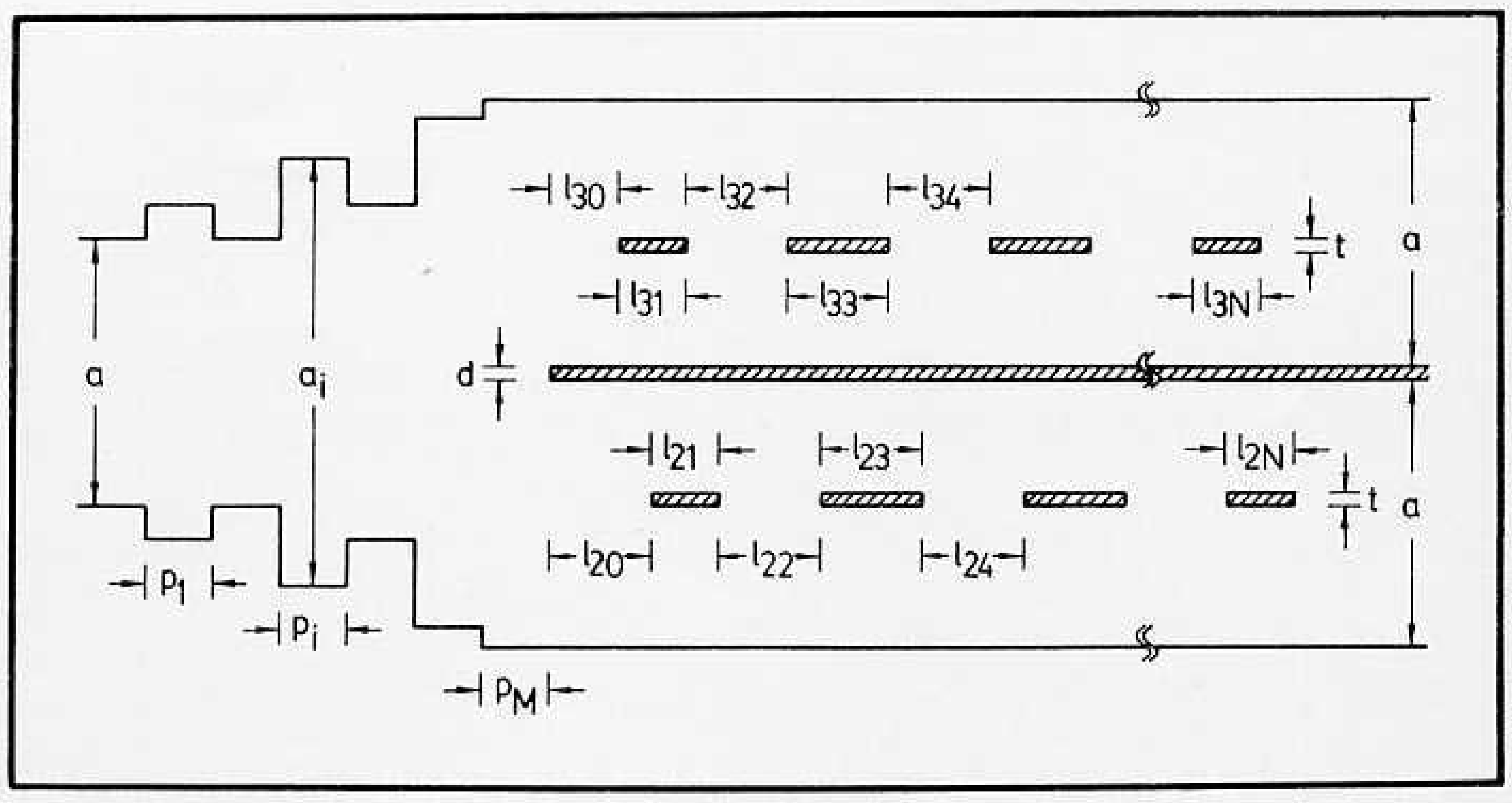

Figure 2: *Top view of the H-plane diplexer.*

$$F_m(x) = T_m \sin\left[\frac{m\pi}{w}(x - x_u)\right] \tag{3}$$

where k_{zm} is the propagation constant in the corresponding cross-section, and the wave impedance is given by

$$Z_{hm} = \frac{2\pi f \mu_0}{k_{zm}} = 1/Y_{hm}. \tag{4}$$

In Equation (3), w is the width of the cross-section, x_u is the distance from the $y - z$ plane to the lower subregion limit, and T_m normalizes the power

$$P_m^+ = \sqrt{Z_{hm}}\left(\sqrt{Y_{hm}}\right)^* \int_0^b \int_{x_u}^{x_u+w} [F_m(x)]^2 dxdy = \begin{cases} 1W \text{ (propagating mode)} \\ j1W \text{ (evanescent mode)} \end{cases} \tag{5}$$

for a given wave amplitude of $A_m^+ = 1\sqrt{W}$.

The modal scattering matrix of the step transition is then obtained by matching the transverse field components at the common interface of two subregions. By taking advantage of the fact that $F_m(x)$ constitutes a set of orthogonal functions, the amplitudes $A_m^{\pm}$ of the forward and backward travelling waves in the two adjacent regions can be related to each other to yield the modal scattering matrix of the transition. The homogeneous sections are described by diagonal matrices.[5] Cascading certain matrices[5] to form two-port groups (e.g., transformer section and channel filters), and combining these groups with the three-port matrix of the separation wall discontinuity[1], finally leads to the overall S-matrix of the H-plane diplexer.

In the computer analysis, only the discontinuities are calculated with $M = 35$ modes. For all S-matrix combining procedures, however, only the lowest seven types are taken into account, reducing the size of the matrices to be handled from 35×35 to 7×7. This measure speeds up the algorithm considerably and allows the software to be operational on enhanced personal computers. The deviations are within the plotting accuracy compared with an analysis on the basis of a fixed 35-mode matrix size.

The design is carried out by pre-optimizing the channel filters separately using the method described in Reference 5. For a given separation wall thickness d (Figure 2), the parameters to be optimized are the widths a_i and lengths p_i of the transformer section[13], and the connecting lengths l_{20}, l_{30} from the separation wall discontinuity to the channel filters.

Results

Figure 3 demonstrates the capability of the transformer section to compensate for high field distortion caused by the separation wall discontinuity. The dashed lines show the response of a commonly used quarter-wavelength transformer, which accounts for the change in waveguide width but neglects the discontinuity at distance p_M (Figure 2), hence ignoring the presence of the channel separation wall by assuming only one output port of width $2a + d$ (see Figure 2).

Table 1
Design data of optimized diplexers
(see Figure 2, dimensions in mm)

	Ka-band	W-band
Input-output port dimensions a, b	7.112 3.556	2.540 1.270
Separation wall thickness d	0.5	0.5
Metal insert thickness t	0.19	0.05
Transformer Sections		
a_1, p_1	13.237, 0.850	4.962, 0.267
a_2, p_2	13.908, 1.856	5.373, 0.531
a_3, p_3	9.184, 2.212	2.713, 0.906
a_4, p_4	8.284, 2.681	3.174, 0.927
a_5, p_5	11.820, 2.008	4.379, 0.742
a_6, p_6	8.198, 1.500	2.760, 0.459
a_7, p_7	12.590, 3.526	4.800, 1.392
a_8, p_8	14.724, 0.609	5.580, 0.223
Channel Filters		
l_{20}	8.918	2.869
$l_{21} = l_{211}$	1.097	0.405
$l_{22} = l_{210}$	4.625	1.519
$l_{23} = l_{29}$	4.405	1.507
$l_{24} = l_{28}$	4.643	1.525
$l_{25} = l_{27}$	5.342	1.814
l_{26}	4.644	1.525
l_{30}	3.537	0.846
$l_{31} = l_{311}$	1.391	0.522
$l_{32} = l_{310}$	3.975	1.364
$l_{33} = l_{39}$	5.067	1.738
$l_{34} = l_{38}$	3.977	1.364
$l_{35} = l_{37}$	6.067	2.016
l_{36}	3.977	1.364

In the case of two output channels as required for the diplexer, however, the maximum electric field concentration is short-circuited by the face of the separation wall. As a result, the high field distortions at this point allow for only a moderate return loss of 14 dB. Commonly used quarter-wave transformers, therefore, are not suitable for this diplexer application due to the lack of compensation capability. The solid lines in Figure 3, however, indicate the possibility of a narrow-band compensation by choosing a somewhat different profile for the transformer section. The peak return loss is better than 45 dB; the 30-dB bandwidth is 5.6 per cent.

Based on these investigations, a Ka-band diplexer with midband channel frequencies at 32 and 34 GHz has been optimized (Figure 4 and Table 1). The four-resonator metal insert filters provide a cross-attenuation of more than 75 dB at 33.15 GHz, which compares very well with results reported in References 2 and 3. Moreover, it is demonstrated that the channel filter characteristics

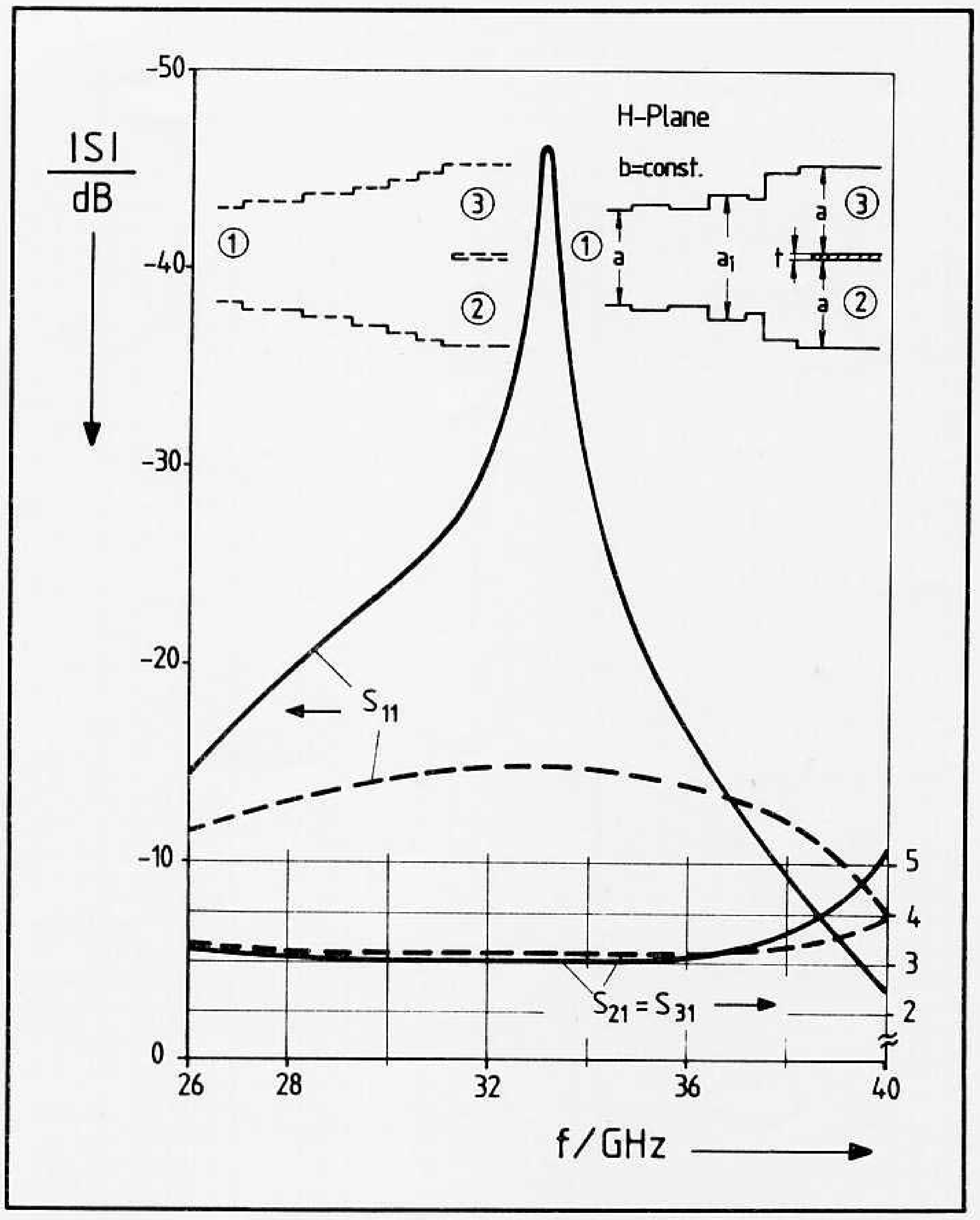

Figure 3: *Frequency response of a Ka-band H-plane power divider.*

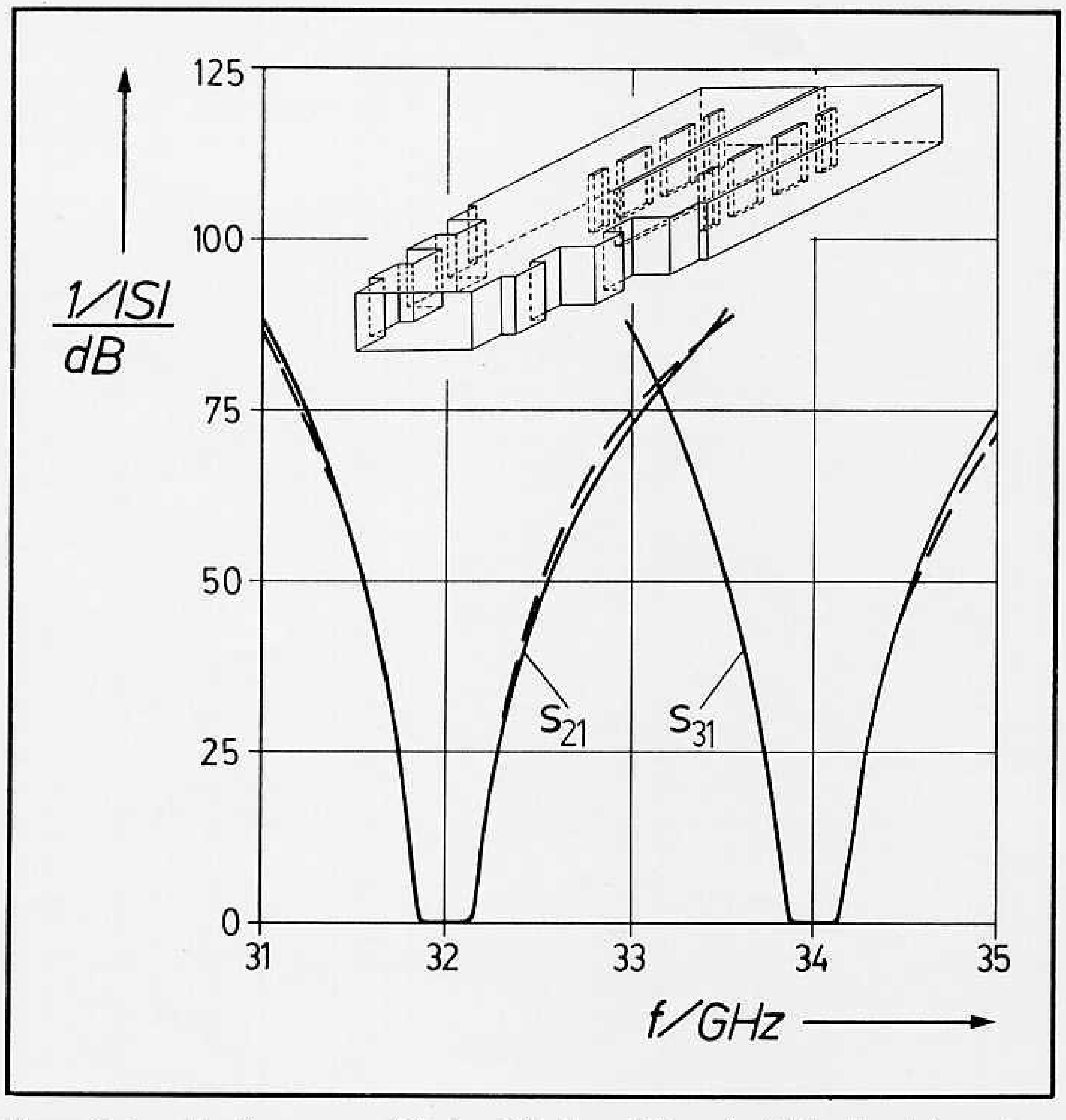

Figure 4: *Insertion loss curves of Ka-band H-plane diplexer (solid lines) and channel filters (dashed lines); for design data, see Table 1.*

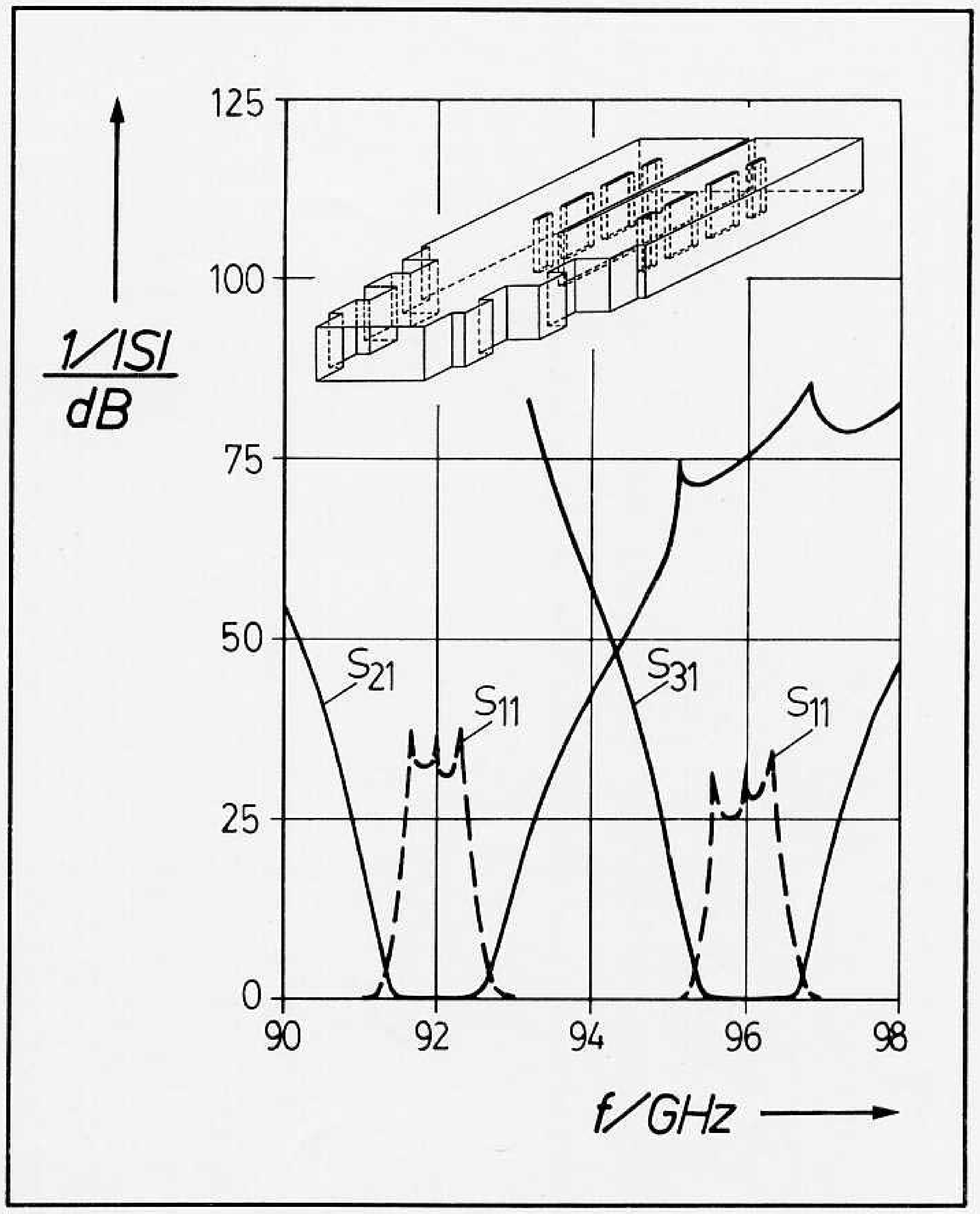

Figure 5: *Insertion loss and return loss of W-band H-plane diplexer; for design data, see Table 1.*

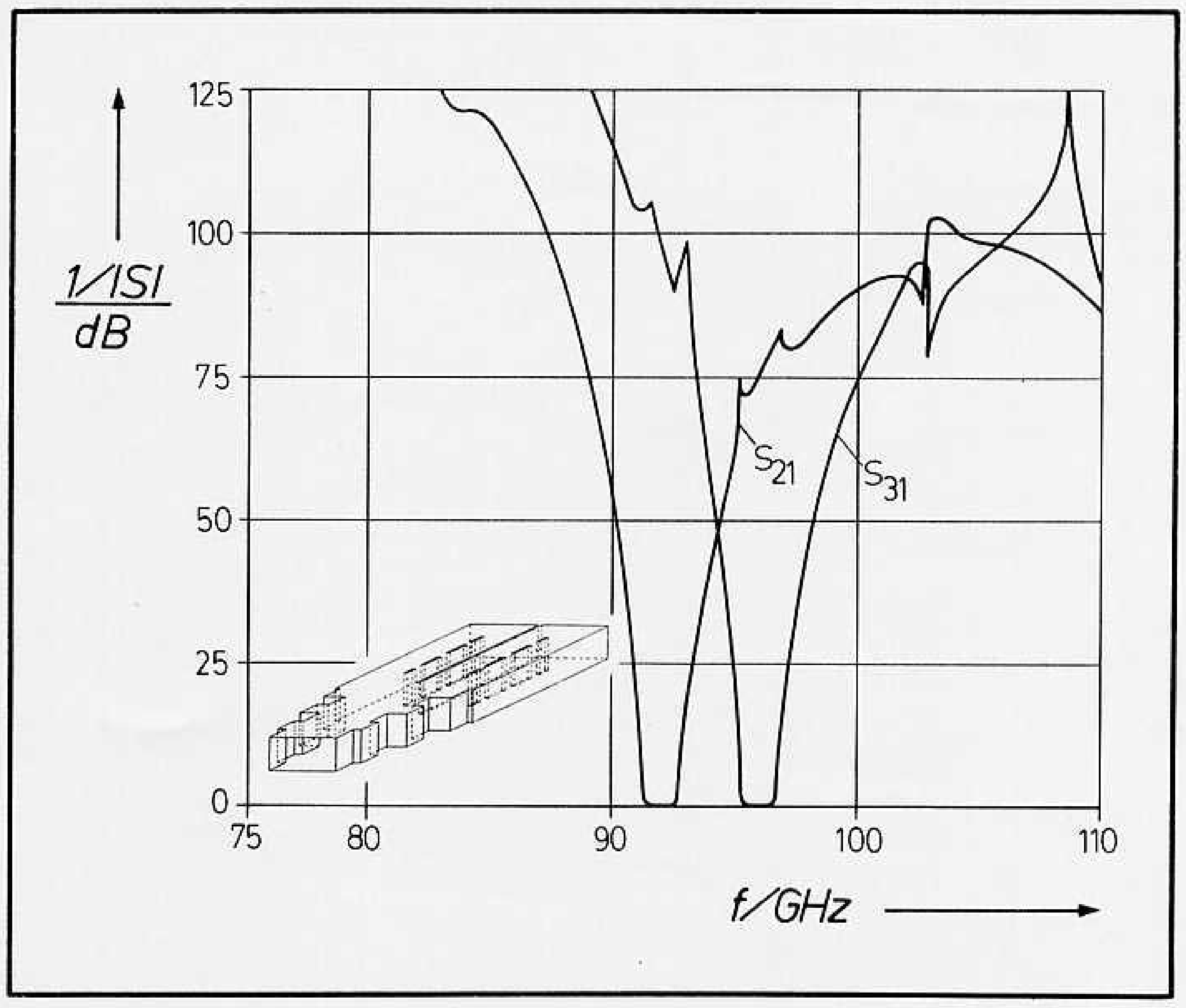

Figure 6: *W-band diplexer (extended frequency range).*

(dashed lines) remain almost unchanged when incorporated into the diplexer arrangement (solid lines).

The efficiency of the design method is demonstrated in Figures 5 and 6 at a W-band diplexer example (see Table 1). Emphasis was placed on keeping the passband return loss above the 25-dB value (Figure 5). Figure 6 presents the response in the full W-band frequency range. Typical stopband interactions occur within the passbands of the adjacent channels[1] and towards higher frequencies. This is due to the increasing number of propagating higher-order modes within the transformer section. However, since higher-order mode excitations and interactions are considered in the optimization process, their influence on the diplexer design and performance can be kept well above a specified attenuation level of, for example, 60 dB.

A tolerance analysis of E-plane metal insert filters has been presented in Reference 15. It concludes that the resonator dimensions are the most critical parts of the filter realization. Here, the sensitivity of the diplexer arrangement is tested by varying the waveguide section widths, hence changing the electrical lengths of all sections involved. The overall diplexer performance of the Ka-band design (Figure 4) is not affected by $\pm 12.7\mu$m (0.5 mil) variations, except for slight midband frequency shifts of up to ∓ 35 MHz. Keeping the channel filters at their optimized dimensions and merely varying the transformer sections by $\pm 12.7\mu$m results in only slight changes in the input return loss at values above 20 dB. This leaves the channel filters as the most sensitive components of the design. For the W-band structure of Figures 5 and 6, the margin should be set to $\pm 4.5\mu$m to obtain comparable results. Using modern precision NC machines, however, tolerances of $\pm 1\mu$m are achievable, as reported in Reference 16 at the example of a 94-GHz bandpass filter design.

Conclusions

A new millimetre-wave integrated H-plane diplexer has been presented. Due to a rigorous field theory method, the complete structure is optimized in one design procedure, taking into account higher-order mode interactions and allowing a special transformer section to compensate for field distortions. The component is suitable for applications in the millimetre-wave range, since it can be fabricated by metal etching and computer-controlled milling facilities. Moreover, fine tuning elements are not required.

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