RIGOROUS DESIGN OF SIDEWALL APERTURE COUPLERS

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ABSTRACT

The rigorous field theory CAD of rectangular waveguide sidewall aperture couplers is introduced which are coupled by rectangular apertures of different size. Based on the rectangular waveguide T–junction and the double–step discontinuity key–building block modal S–matrices which are calculated by the mode–matching method, the design takes rigorously into account both the finite wall thickness and the higher order mode interaction between all discontinuities. Design examples for rectangular aperture 10dB–, 8.34dB–, and 3dB–couplers in the waveguide Ku–band (12 – 18 GHz) demonstrate the efficiency of the design method. The theory is verified by excellent agreement with measurements.

INTRODUCTION

Aperture coupling by holes in the sidewall of waveguides is a well–known technique to build a useful class of directional couplers for a great variety of applications [1] – [5]. Many refined equivalent–network synthesis methods are available for deriving the necessary coupling coefficients for desired directional coupler characteristics [2], [3], [5]. However, the design of the practical aperture geometries is still based on the approximate Bethe–Cohn theory [6], [7], [2], together with thickness correction factors [8], [3]. Although for small slots in the common waveguide wall improved calculations based on the variational [9] or reaction methods [10] are available, no rigorous analysis for large rectangular apertures in the sidewall of waveguides has been derived so far. The increasing need for high–quality low–cost products and the availability of high–precision fabrication techniques, therefore, have prompted the desire for accurate field theory methods which take adequately into account the effects of large apertures, finite wall thickness, and the higher–order mode interaction at all discontinuities.

This paper presents a rigorous computer–aided design method for aperture coupled rectangular waveguide sidewall couplers (Fig. 1). The design method proposed is based on the full wave mode–matching method for the T–junction key–building block element [11] (Fig. 2a) associated with the generalized S–matrix technique [11]–[13]. The combination with already known key–building block modal S–matrices, e.g. the double–step discontinuity (Fig. 2b) [12], achieves the rigorous description of the waveguide aperture coupling element as well as of the complete coupler structure.

Typical design examples for aperture coupled sidewall couplers for the waveguide Ku–band (R140 housing, 12–18 GHz) with weak (–10dB), moderate (–8.34dB), and tight (–3dB) coupling demonstrate the efficiency of the rigorous CAD method. For computer optimization, the evolution strategy method [11] is applied. The initial values are derived by utilizing the classical network theory synthesis methods [2], [3], [8]. The theory presented is verified by excellent agreement with measurements.

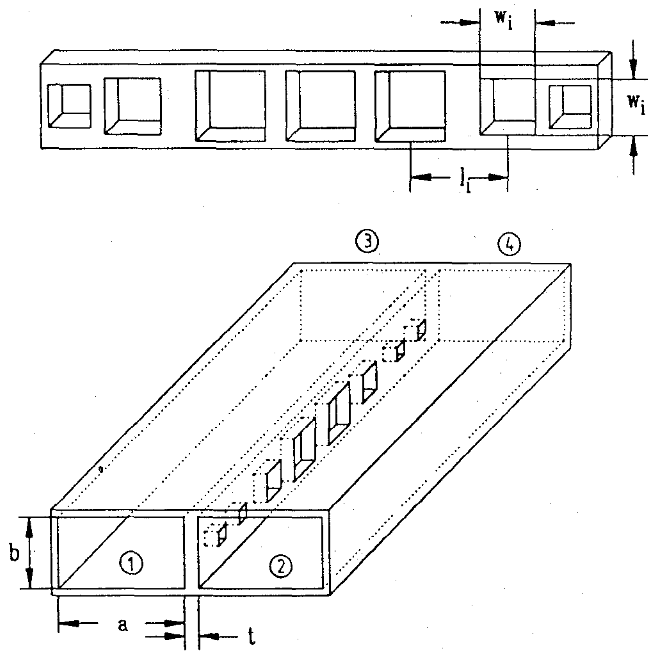

Fig. 1:
Sidewall aperture coupler.

THEORY

For the rigorous computer–aided design of the coupler structures to be investigated (Fig. 1), the full wave mode–matching method is applied for two key–building block elements associated with the generalized S–matrix technique for composite structures: the general T–junction [11], and the rectangular double–step [12] discontinuities. Note that for the corresponding inverse step discontinuity (which is required for calculating the apertures) merely the corresponding modal S–matrix needs to be transposed [11].

It should be noted that the full set of TE_{mn} and TM_{mn} modes is required for each key–building block in order to model adequately the composed general structure. For the waveguide subregion under consideration, the fields [11] – [13]

$$\begin{aligned} \vec{E}^{\nu} &= \frac{1}{j\omega\epsilon} \nabla \times \nabla \times \vec{A}_e^{\nu} + \nabla \times \vec{A}_h^{\nu} \\ \vec{H}^{\nu} &= -\frac{1}{j\omega\mu} \nabla \times \nabla \times \vec{A}_h^{\nu} + \nabla \times \vec{A}_e^{\nu} \end{aligned} \tag{1}$$

are derived from the z components of the electric and magnetic vector potentials A_e, A_h, respectively,

$$\begin{aligned} A_{hz} &= \sum_{i=0}^{N_h} Q_{hi}\, T_{hi} [a_i e^{-\gamma_{hi} z} + b_i e^{+\gamma_{hi} z}] \\ A_{ez} &= \sum_{i=1}^{N_e} Q_{ei}\, T_{ei} [a_i e^{-\gamma_{hi} z} - b_i e^{+\gamma_{hi} z}] \end{aligned} \tag{2}$$

where a_i, b_i are the still unknown eigenmode amplitude coefficients of the forward (–) and backward (+) waves in z direction, $\gamma_{h,e}$ are the propagation factors of the N_h and N_e considered TE_{pq} and TM_{pq} modes, respectively, where i stands for p,q, Q is a normalization factor, so that the power carried by each mode is 1 W for propagation modes, j W for evanescent TE modes, –j W for evanescent TM modes [11] – [13], and T are the cross–section eigenfunctions for the rectangular waveguide [11], [12]. For a more detailed derivation of the mode–matching method for the key–building block elements, the reader is referred to the literature [11] – [13].

By matching the tangential field components interfaces at the individual step discontinuities, the wave amplitude coefficients of equation (2) can be related to each other after multiplication with the appropriate orthogonal functions. This yields the corresponding key building block two–port modal scattering matrices. The generalized S–matrix technique is then applied for the calculation of the overall coupler, where the four–port may be reduced conveniently to a two–port structure by placing an electric or magnetic wall, i.e. odd (o) or even (e) symmetry plane, respectively, along the longitudinal plane of geometrical symmetry.

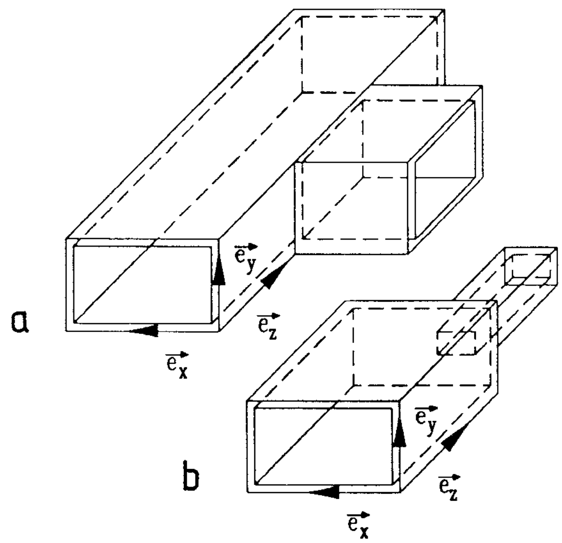

Fig. 2:
Key–building block discontinuities:
a) T–junction, b) double–plane step

The following relations are used to compute the scattering parameters S_{ij} of the coupler four–port

$$\begin{aligned} S_{11} &= \tfrac{1}{2}(S_{11}^e + S_{11}^o), \quad & S_{21} &= \tfrac{1}{2}(S_{11}^e - S_{11}^o), \\ S_{31} &= \tfrac{1}{2}(S_{31}^e + S_{31}^o), \quad & S_{41} &= \tfrac{1}{2}(S_{31}^e - S_{31}^o), \end{aligned} \tag{3}$$

where $S_{ij}^{e,o}$ are the scattering parameters of the related even or odd two–port structure.

A computer program was written using the preceding relations and utilizing the evolution strategy method [11] for optimizing the geometrical parameters. The initial values for the field–theory optimization are calculated by the classical network–theory synthesis method [3], [8]. For the field theory CAD of the aperture couplers, sufficient asymptotic behavior has been obtained by consideration of TE_{mn} – and TM_{mn} –modes up to m = 10, n = 6 in all waveguide sections. The computing time for optimizing a nine– aperture coupler is typically an overnight run on an IBM RISC 6000 type 320 low–cost workstation.

RESULTS

Fig. 3 shows the calculated and measured scattering parameters of an optimized –10dB–coupler with eight rectangular apertures designed for the waveguide Ku–band (12–18 GHz), R140 waveguide housing: 15.799mm x 7.899mm). Very good agreement between the field theory results and the measured S–parameters S_{41}, S_{31} may be stated (the same is true for the return loss and isolation values – not shown in the Figs. – which are better than 40dB). Moreover, in principle, the results predicted by the network–theory [3] (dashed lines in Fig. 3) are in tolerable agreement with those of the field–theory method (solid lines).

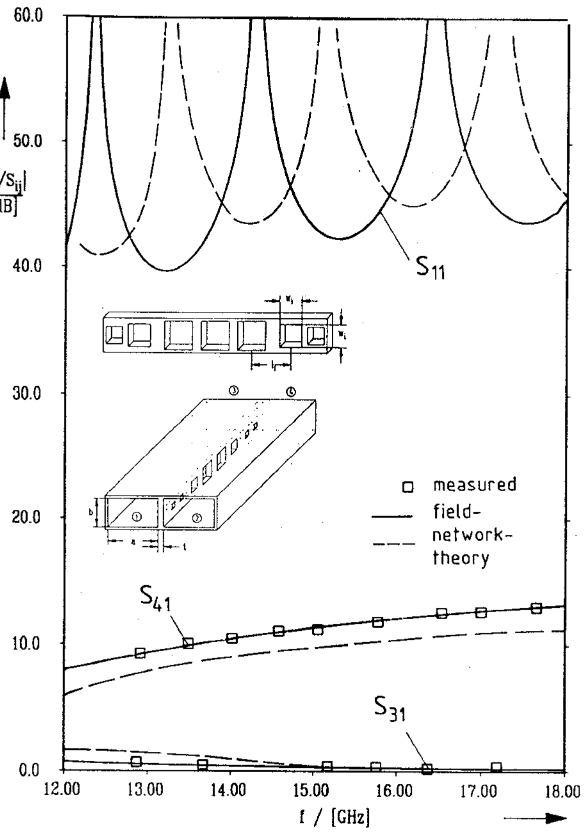

Fig. 3:
Calculated and measured scattering parameters of an optimized –10dB–coupler with eight quadratic apertures designed for the waveguide Ku–band (12–18 GHz, R140 waveguide housing: 15.799mm x 7.899mm).

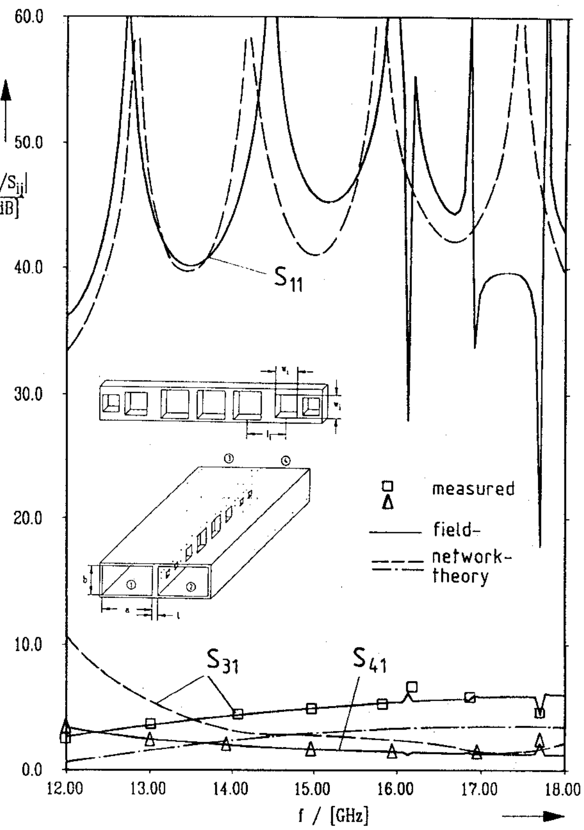

Fig. 4:
Ku–band –3dB–coupler with nine rectangular apertures designed by using the network–theory approach (dashed, dash–dotted lines). Field theory analysis (solid lines)

For the –3dB–design, however, significant discrepancies between the network–theory predictions and the field–theory analysis may be observed. This is demonstrated in Fig. 4 for the example of a Ku–band –3dB–coupler with nine rectangular apertures which was designed by using the network–theory approach (dashed and dash–dotted lines). The subsequent analysis of this coupler geometry with the rigorous field–theory method yields results (solid lines) which are is in close agreement with the measurements.

For the optimum –3dB–coupler design, an additional field–theory optimization of the geometrical parameters is required. About 1500 supplement iterations of the geometrical parameters achieves the desired –3dB–coupler behavior (cf. Fig. 5). As very often a tandem connection of two –8.34dB–sections is used for a –3dB–design in order to relieve the tolerance requirements for the otherwise very sensitive coupling structure, in Fig. 6 a direct field–theory optimized –8.34dB–coupler with eight rectangular apertures is presented. The coupler achieves a bandwidth of about 26% for about 35dB isolation.

CONCLUSION

A rigorous field theory CAD of rectangular waveguide sidewall aperture couplers is introduced which takes rigorously into account both the finite wall thickness of the coupling holes and the higher mode interaction between all discontinuities. The adequate combination of the rectangular waveguide T–junction and the double–step discontinuity key–building block modal S–matrices yields directly the overall scattering matrix. For computer optimization, the evolution strategy method is applied. As the initial values are derived by utilizing the classical network theory synthesis methods, relatively fast and very reliable designs are achieved. The theory presented is verified by excellent agreement with measurements.

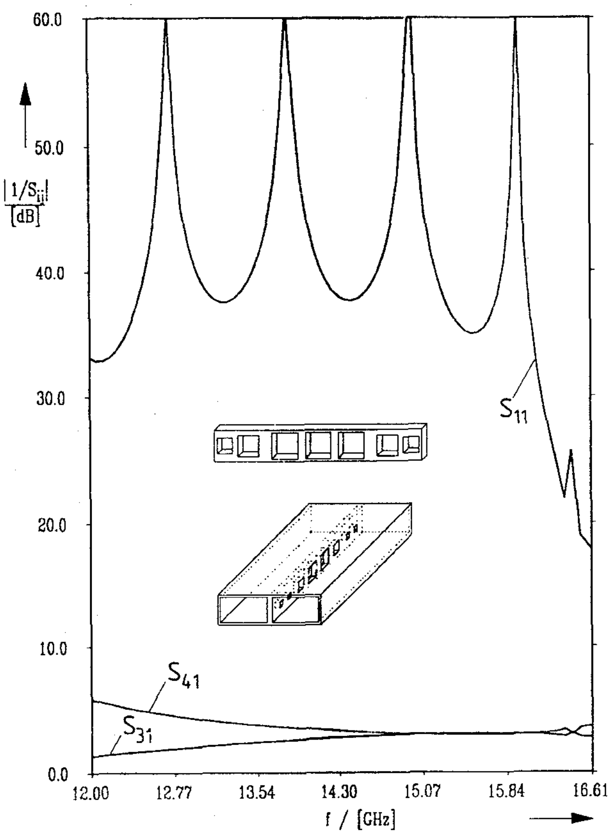

Fig. 5:
Ku–band –3dB–coupler (Fig. 4) with additional field–theory optimization of the geometrical parameters

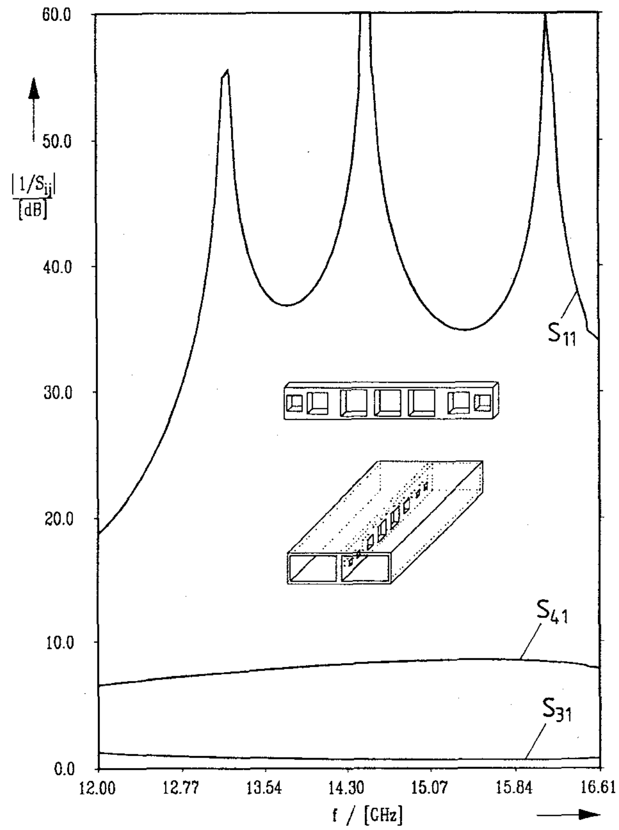

Fig. 6:
Directly field–theory optimized –8.34dB–coupler with eight rectangular apertures suitable for a tandem connection in order to yield a –3dB–overall–coupler behavior.

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