Mode-Matching CAD of Rectangular or Circular Multiaperture Narrow-Wall Couplers

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***Abstract*— A rigorous and efficient mode-matching computer-aided design (CAD) method for rectangular waveguide H-plane couplers is presented. The couplers employ multiple large rectangular or circular apertures of different sizes and nonuniform distance. The decomposition of the coupler structure into adequate mode-matching key-building blocks, i.e., the T-junction, double-plane step discontinuity, and rectangular-to-circular waveguide transition, together with the homogeneous intermediate waveguide sections of finite lengths yield the desired high flexibility. Both the finite wall thickness and the higher order mode interaction between all discontinuities are accurately taken into account by the combination of the individual building blocks of the generalized scattering matrix technique. Design examples for rectangular and circular aperture provide coupling values of −10.7, −10, −8.1, −5.3, −4.7, −3, −2.6, and −2.3 dB in Ku-band (12–18 GHz), thus demonstrating the flexibility and the efficiency of the method. The theory is verified by excellent agreement with measurements.**

I. Introduction

NARROW-WALL couplers have found numerous applications for many purposes, such as power dividers in antenna feed elements and in waveguide networks, [1]–[10]. This is mainly due to their good high-power performance as compared with their more common broad-wall counterpart. Possible realizations of the coupling mechanism include narrow slots [4], [5], [7], [10], [15], [16], rectangular apertures with heights identical to the waveguide height [1], [6], [8], and rectangular [9] or circular apertures [3] of different sizes. The aperture size and nonuniform distance between the aperatures provide an additional freedom for choosing the optimization parameters. This is, therefore, appropriate for designs requiring higher flexibility. An accurate computer-aided design (CAD) method for such couplers is very desirable, directly involving the effects of large apertures, finite thickness, and higher order mode couplings.

For a rather long time, equivalent-network synthesis methods were available to derive the necessary coupling coefficients for desired directional coupler characteristics [2], [3], [7], [8], which utilize the quarter-wave transformer prototype formulation [11]. The design of practical aperture geometries, however, is still commonly based on the approximate Bethe–Cohn theory [11]–[13], together with thickness correction factors [14]. For slots in the common narrow-wall of rectangular waveguides, variational or moment-method expressions have been derived [4], [7], [15], [16], which utilize the assumption for narrow slots of a uniform field distribution in the height direction of the slot. The completeness of these approaches is still the topic of recent discussion [17].

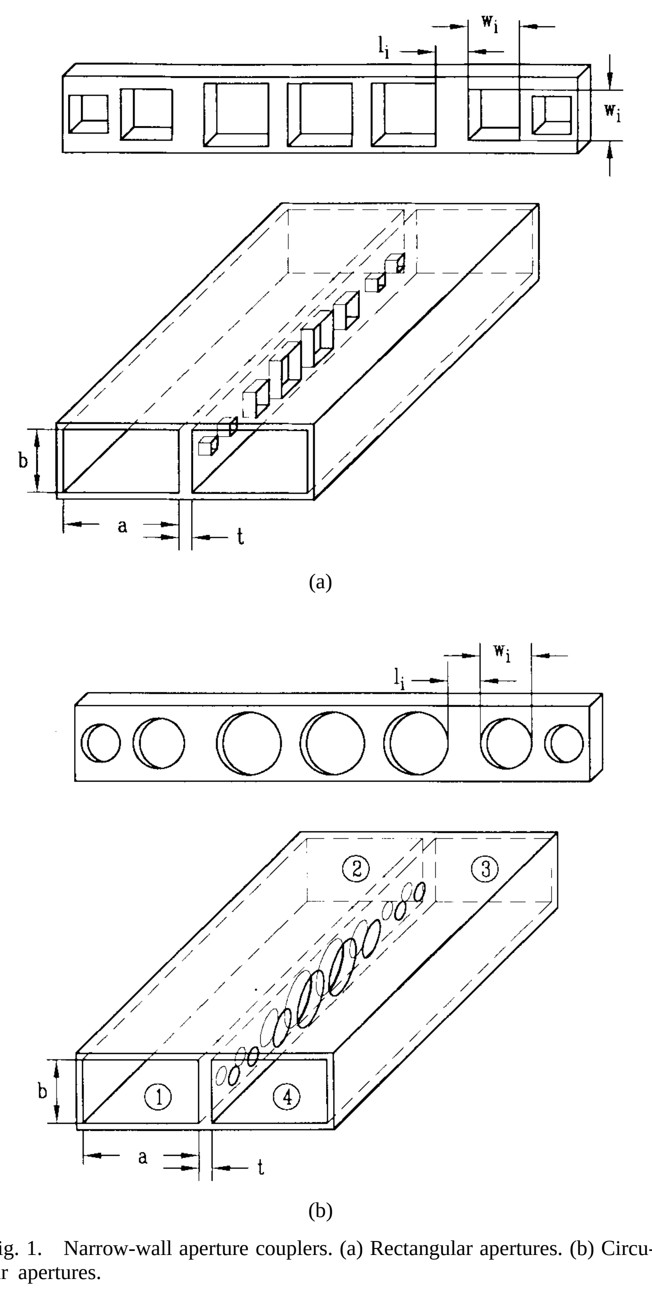

Fig. 1. Narrow-wall aperture couplers. (a) Rectangular apertures. (b) Circular apertures.

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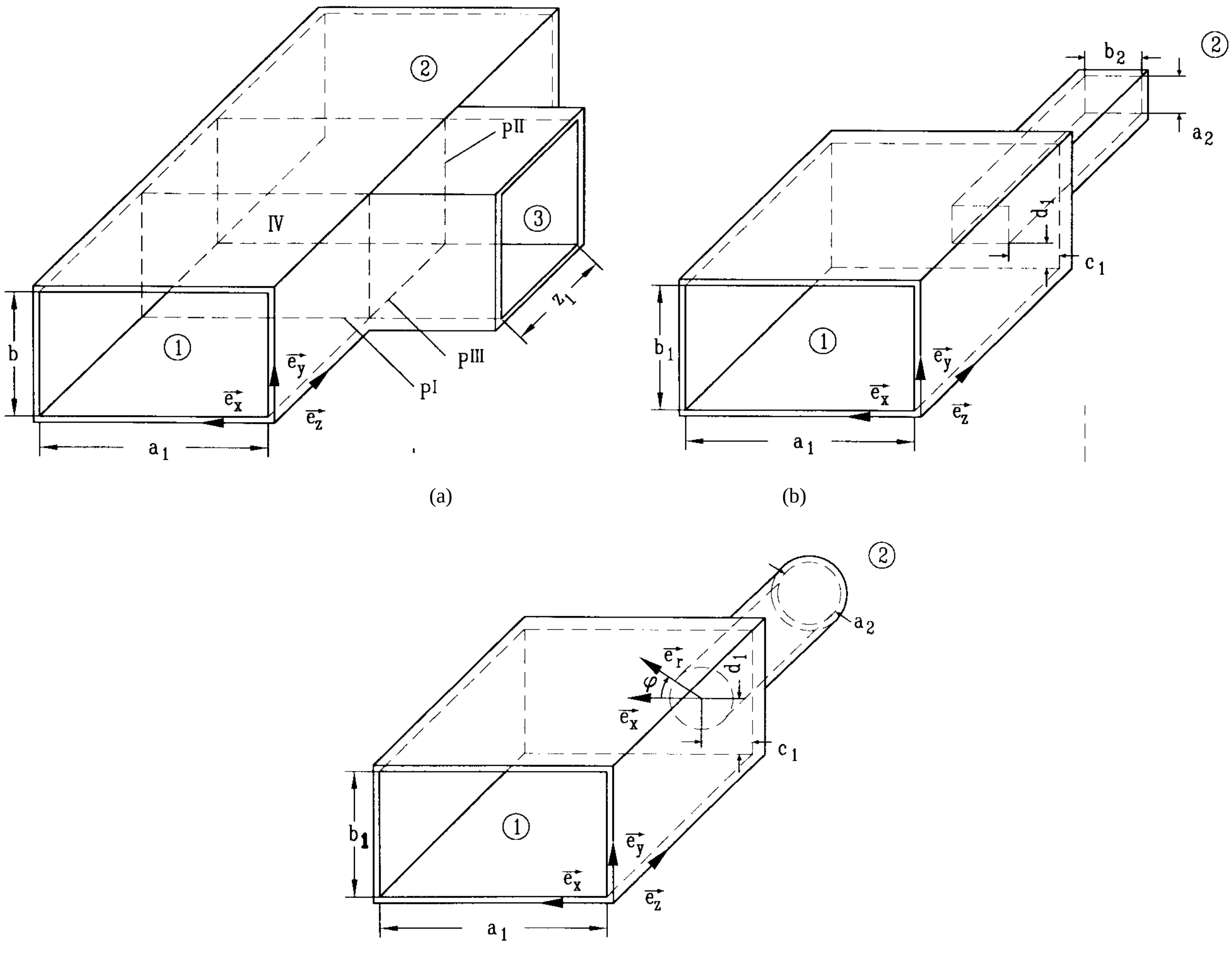


Fig. 2. Required mode-matching key building blocks. (a) T-junction. (b) Double-plane step. (c) Rectangular-to-circular waveguide transition.

In this paper, large rectangular or circular apertures in the narrow-wall of rectangular waveguides (Fig. 1) are rigorously investigated by the mode-matching method. This method proves to be very efficient and accurate as has been recently shown by the example of couplers with rectangular apertures [9]. The further advantage of the method is its flexibility as the theory is based on already available mode-matching key-building blocks, [18]–[20] by which coupling apertures of different size can be simulated very conveniently. Their combination with the generalized S-matrix technique achieves the fast and rigorous overall coupler description, which immediately takes into account the effects of large apertures, finite wall thickness, and the higher order mode interaction at all discontinuities. Based on starting values obtained by the standard quarter-wave transformer prototype synthesis approach [3], [8], [11], the direct CAD of related narrow-wall couplers (Fig. 1) is possible by applying, for instance, the evolution strategy optimization technique [6].

II. Theory

The proposed full-wave design theory is based on the known rigorous mode-matching method for the three central waveguide elements of the coupler structure which are already available as key-building blocks, the T-junction [Fig. 2(a)] [18], the double-plane step [Fig. 2(b)] [20], and the junction rectangular-to-circular waveguide [Fig. 2(c)] [19]. The desired coupler structure is then built up by these key building blocks utilizing empty rectangular or circular waveguide sections of finite lengths to include finite thickness effects of the apertures or the finite distance between the discontinuities along the coupler structure (Fig. 1).

The full set of TE_{mn} and TM_{mn} modes is required for each key building block in order to adequately model the composed general structure. For the waveguide subregion under consideration, the fields [18]–[20]

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

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

$$
\begin{aligned}
\vec{A}_{hz} &= \sum_{i=0}^{N_h} Q_{hi} T_{hi} \left(a_{hi} e^{-\gamma_{hi} z} + b_{hi} e^{+\gamma_{hi} z} \right) \\
\vec{A}_{ez} &= \sum_{i=1}^{N_e} Q_{ei} T_{ei} \left(a_{ei} e^{-\gamma_{ei} z} - b_{ei} e^{+\gamma_{ei} z} \right)
\end{aligned} \tag{2}
$$

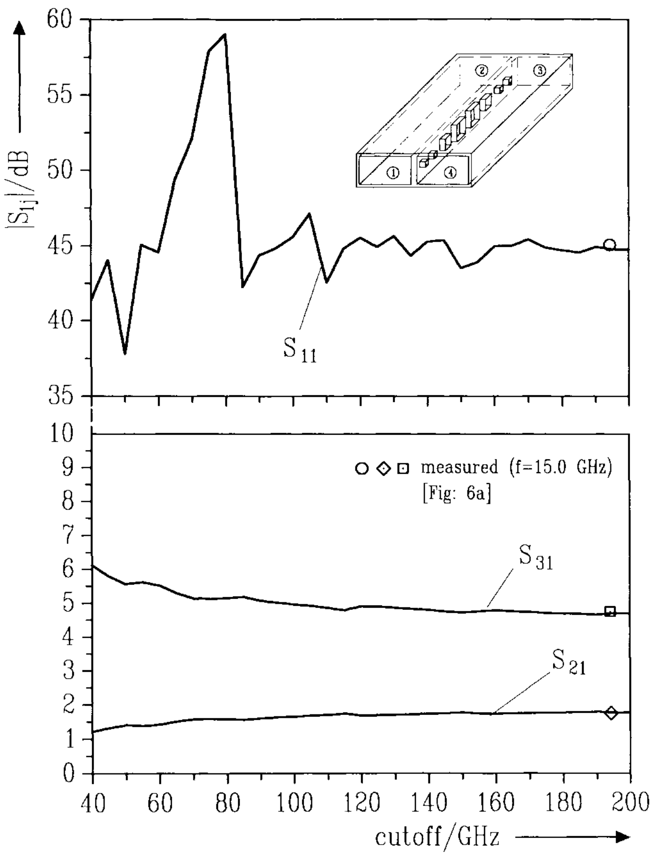


Fig. 3. Convergence behavior. Coupler with nine square apertures, cf. Fig. 6(a); design parameters cf. Table I. Scattering parameters as a function of the cutoff frequency of the considered TE_{mn} and TM_{mn} modes.

where a_i, b_i are the still unknown eigenmode amplitude coefficients of the forward (−) and backward (+) waves, $\gamma_{h,e}$ 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. $Q_{h,e}$ is the normalization factor and $T_{h,e}$ are the cross-section eigenfunctions for the rectangular or circular waveguide, respectively. For the more detailed treatment of the mode-matching method for the key building block elements, the reader is referred to the corresponding literature [18]–[20], where the required coupling integrals and modal S-matrix elements are explicitly derived.

The generalized modal scattering-matrix technique [6], [9], [18]–[21] is applied for the rigorous calculation of the overall coupler. It should be emphasized that the advanced S-matrix combination technique described in [21] has been applied (as in [18], [20]), which requires only the inversion of a submatrix with a quarter of the size of the original matrix of the coupling integrals. For the symmetric structures treated in this paper, the four-port may conveniently be reduced to a two-port structure by placing an electric or magnetic wall along the plane of symmetry and then using the well-known Reed and Wheeler S-parameter relations for symmetric four-ports [6].

A computer program has been written by using the described mode-matching technique and utilizing the evolution-strategy method [6] for optimizing the geometrical parameters. The initial values for the field theory optimization are calculated by the classical network-theory synthesis method [3], [8], [11].

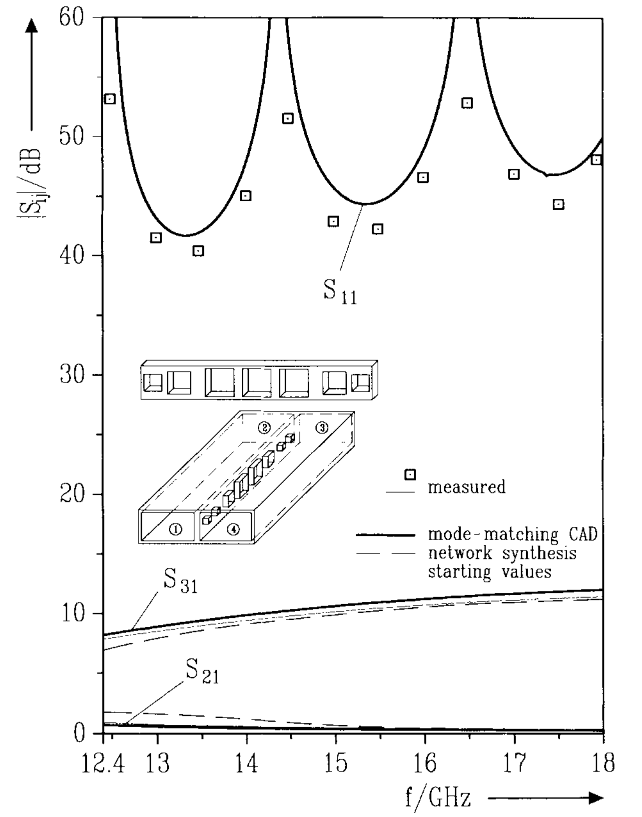
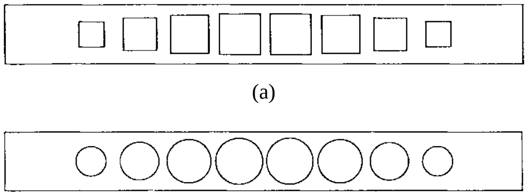


Fig. 4. −10.7-dB coupler with eight square apertures. Apertures shown in Fig. 5(a). Design parameters cf. Table I.

TABLE I
DESIGN DATA IN MILLIMETERS FOR THE OPTIMIZED SIDEWALL APERTURE COUPLERS

Fig.	n-holes	w_1 / l_1	w_2 / l_2	w_3 / l_3	w_4 / l_4	w_5 / l_5
		3.6506	4.6654	5.3890	5.7474	
4	n=8	2.3906	1.6737	1.2683	1.143	
		4.1770	5.5126	6.4615	6.9956	7.1657
6a	n=9	1.8343	1.01115	0.60345	0.46385	
		5.591	7.092	6.830	7.296	7.523
6b	n=9	1.650	1.954	2.343	1.753	
		4.3051	5.4271	6.2039	6.5829	
8	n=8	1.6825	0.8854	0.4431	0.3075	
		4.8921	6.3350	7.3317	7.3545	7.3545
9a	n=9	1.06555	0.16647	-0.0111	0.1900	
		7.16775	7.8900	7.88928	7.8900	7.8900
9b	n=9	0.50000	1.00328	1.4348	1.38805	
		2.05078	6.20100	6.28371	5.30736	
10a	n=8	2.97759	1.15011	4.38326	2.93696	
10b tandem of 10a; intermediate length: l_{in} = 0.5						
a = 15.799 b = 7.899 t= 0.205						

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 120 GHz in all waveguide sections (see Fig. 3), as has been checked by measurements. All results in this paper have been finally verified by including the modes up to 200 GHz. The computing time for post-optimizing a nine-aperture coupler is typically an overnight run on a IBM RISC 6000 workstation. For the optimization,



(a)

(b)

Fig. 5. Layout of the coupling structure for the −10.7-dB (Fig. 4) and −10-dB (Fig. 8) couplers. Apertures are fabricated by etching techniques. Metal sheet: 99% pure copper, thickness $t = 0.205$ mm. (a) Square apertures for the coupler in Fig. 4. (b) Circular apertures for the coupler in Fig. 8. Dimensions cf. Table I.

either the evolution strategy method [6] or, if already good starting values are available [8], a gradient method [22] have been applied.

III. Results

Fig. 4 shows the calculated and measured scattering parameters (solid lines) of an optimized −10.7-dB coupler (at 15 GHz) with eight square apertures designed for the waveguide Ku-band (12–18 GHz, WR-42 waveguide housing: 15.799 mm × 7.899 mm). Good agreement between theory and measurements may be noted. The aperture dimensions are listed in Table I.[1] The apertures have been etched in a metal sheet with thickness $t = 0.205$ mm, which is placed between the narrow-walls of the corresponding waveguides. The layout of the coupling structure is shown in Fig. 5(a). For completeness, the scattering parameters of the coupler for the geometrical starting values obtained by the standard network theory synthesis method [8] are presented in Fig. 4 as dashed lines.

An example for tight coupling is presented in Fig. 6, showing a Ku-band coupler with nine square apertures. The network theory synthesis predictions [8] based on the approximate Bethe's expressions are shown as dashed lines [Fig. 6(a)]. The mode-matching analysis of this coupler (solid lines) reveals that the −3-dB coupling predicted by the network synthesis method is not obtained (−4.7 dB at 15 GHz). As in Fig. 4, good agreement with measurements is demonstrated in Fig. 6(a). An additional direct mode-matching optimization of the geometrical parameters of the apertures with the goal of −2.6 dB yields an improved coupler behavior, cf. Fig. 6(b). Excellent agreement with the measurements may also be noted. Fig. 7 illustrates the corresponding coupler aperture structure by the layouts for the metal sheet with the square apertures. The dimensions are given in Table I.

Circular apertures yield the advantage that more convenient drilling techniques may be applied for fabrication. Fig. 8 shows the calculated and measured scattering parameters (solid lines) of an optimized −10-dB coupler with eight circular apertures designed for the waveguide Ku-band. Again, excellent agreement between theory and measurements may be noted. The coupling apertures are shown in Fig. 5(b), with the dimensions listed in Table I. The scattering parameters of the coupler for the geometrical starting values obtained by the

[1]The couplers are symmetric in longitudinal direction.

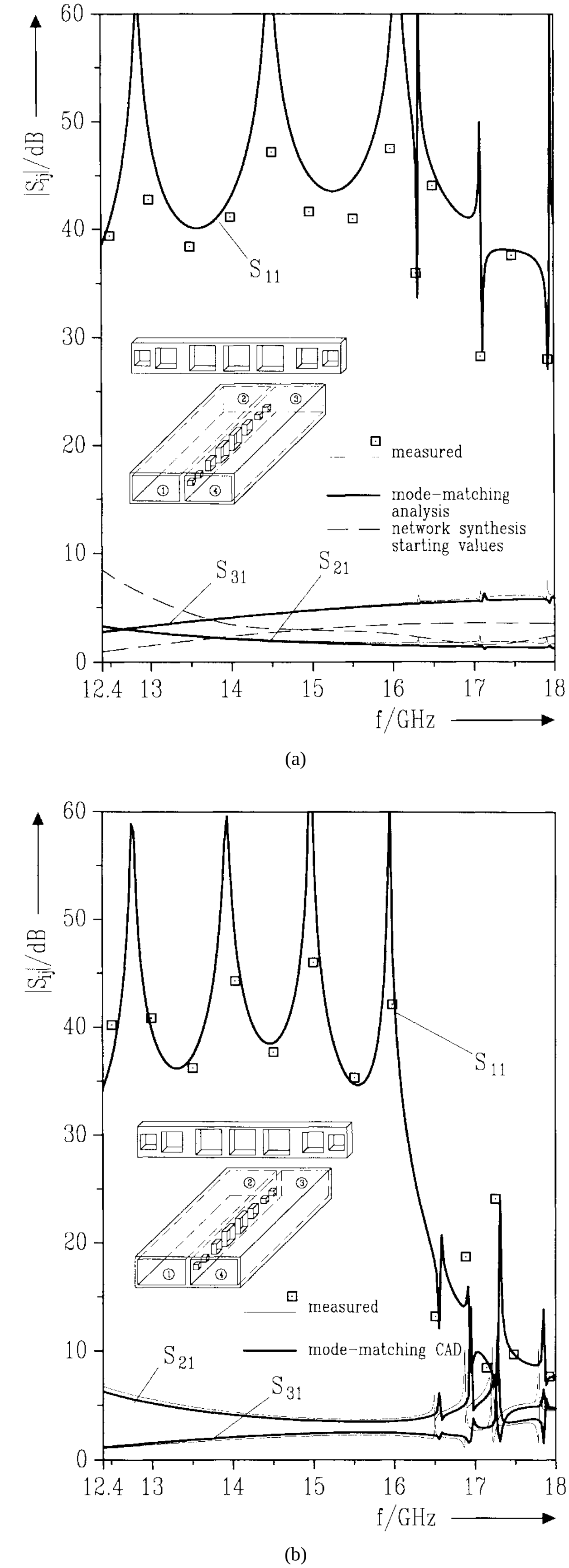


Fig. 6. Coupler with nine square apertures. Apertures shown in Fig. 7. Design parameters cf. Table I. (a) Results of the network synthesis [8] and mode-matching analysis (−4.7-dB coupler). (b) Result of the subsequent direct mode-matching optimization (goal: −2.6-dB coupler).

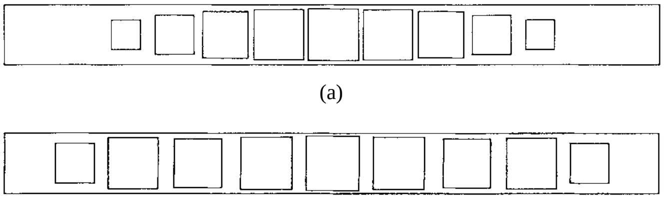


Fig. 7. Layout of the coupling structure for the couplers in Figs. 6. Apertures are fabricated by etching techniques. Metal sheet: 99% pure copper, thickness $t = 0.205$ mm. (a) Square apertures for the coupler in Fig. 6(a). (b) Square apertures for the coupler in Fig. 6(b). Dimensions cf. Table I.

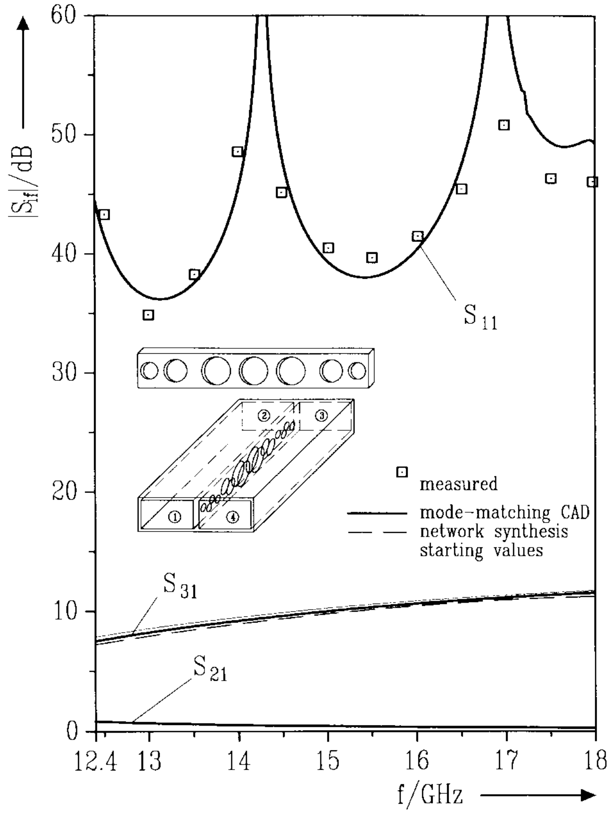


Fig. 8. −10-dB coupler with eight circular apertures. Apertures shown in Fig. 5(b). Design parameters cf. Table I.

network theory synthesis method [8] are presented in Fig. 8 as dashed lines.

The corresponding example for tight coupling with nine circular apertures is presented in Fig. 9. The network theory synthesis predictions [8] based on the approximate Bethe's expressions are shown as dashed lines [Fig. 9(a)]. The mode-matching analysis of this coupler (solid lines) with tight coupling shows again [Fig. 9(a)] that the predicted −3-dB coupling is not obtained (−5.3 dB at 15 GHz). An additional direct mode-matching optimization of the geometrical parameters of the apertures with the goal of a −2.3-dB coupler yields an improved coupler behavior, cf. Fig. 9(b). The design, however, is more narrow banded than with square apertures. This is because for circular apertures, the parameters w_i (diameter) and l_i (distance) (cf. Table I) are more geometrically limited by the requirement of nonoverlapping apertures.

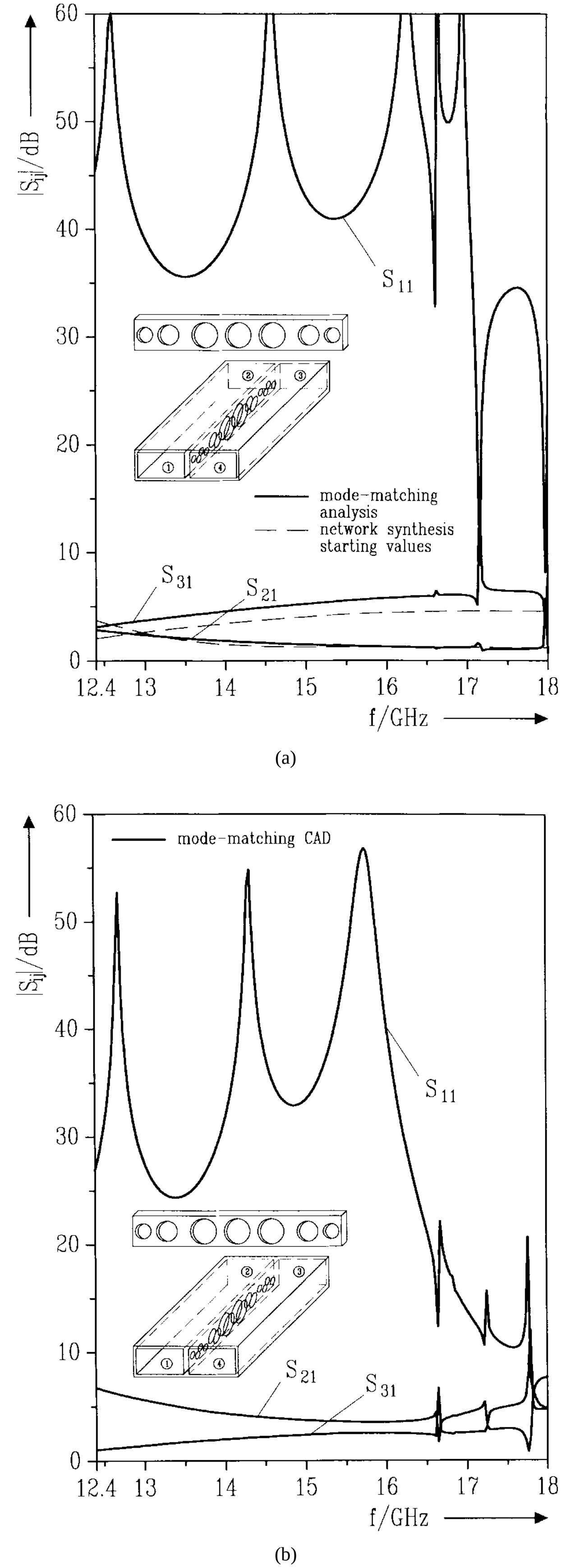
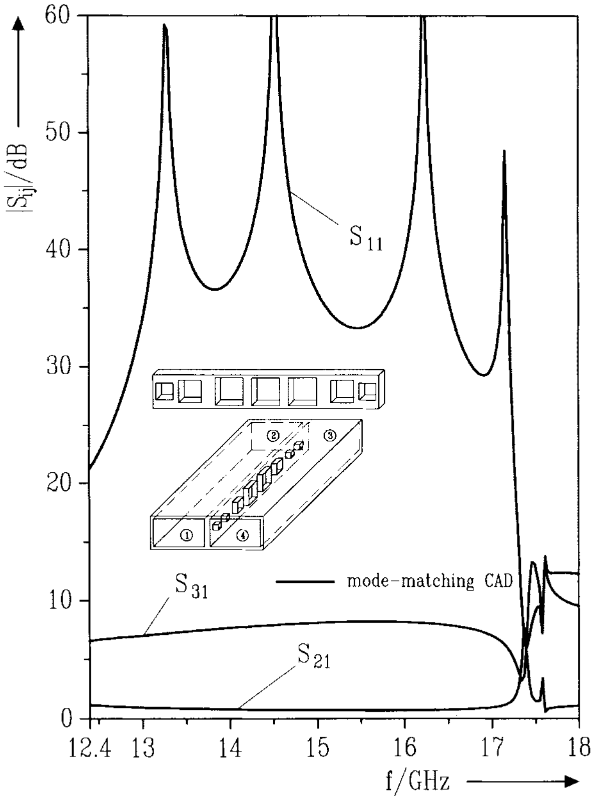
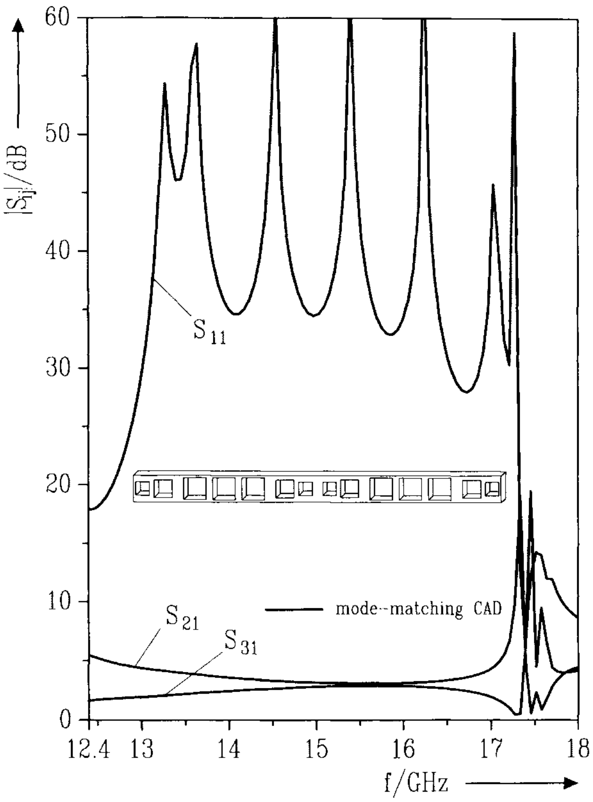


Fig. 9. Coupler with nine circular apertures. Design parameters cf. Table I. (a) Results of the network synthesis [8] and mode-matching analysis (−5.3-dB coupler). (b) Result of the subsequent direct mode-matching optimization (goal: −2.3-dB coupler).



(a)



(b)

Fig. 10. Coupler realized by two tandem-connected coupler sections with eight square apertures. (a) Direct mode-matching CAD results of the −8.34-dB coupler. (b) Scattering parameters of the tandem connection of the corresponding coupler sections (−3–dB coupler). Design parameters cf. Table I.

A more convenient realization of couplers with tight coupling is the known tandem connection of two coupling sections of reduced coupling. For square apertures, this is demonstrated in Fig. 10(a) and 10(b). Fig. 10(a) shows the corresponding results of a directly optimized −8.34-dB coupler (actual value for the optimization −8.1 dB) with eight square apertures. The scattering parameters of the related −3-dB coupler realized by the tandem connection of the two coupling sections according to Fig. 10(a) are presented in Fig. 10(b): −2.9 dB at 15 GHz is obtained. The design parameters for all presented couplers are listed in Table I.

IV. Conclusion

A rigorous mode-matching CAD method is described for the efficient design of circular and rectangular aperture narrow-wall couplers. Only three mode-matching key-building blocks are required for the flexible and accurate simulation of the coupling structures. Their combination with the generalized S-matrix technique achieves the reliable and fast coupler design, which immediately takes into account the effects of large apertures, finite wall thickness, and the higher order mode interaction at all discontinuities. The flexibility of the described CAD method is demonstrated by coupler design examples covering the coupling range between −10.7 and −2.3 dB. The accuracy is verified by excellent agreement with measurements.

Acknowledgment

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