Waveguide Branch Couplers for Tight Couplings

Tao Shen, *Student Member, IEEE,* and Kawthar A. Zaki, *Fellow, IEEE*

***Abstract*—Full-wave optimization design of waveguide branch couplers is presented. Waveguide T-junction equivalent circuit parameters are extracted from full-wave modeling results. They are used to explain why tight couplings are difficult to realize using waveguide branch couplers. Approaches used to obtain tight couplings are discussed and illustrated by two design examples of 3-dB couplers. Through random tolerance analysis, it is found that reasonable manufacturing tolerances have no significant effect on coupler performance.**

***Index Terms*—Waveguide couplers.**

I. Introduction

THE usual configuration for rectangular waveguide couplers consists of two main waveguides with some mechanism located in the common wall for coupling between them. According to the different coupling mechanisms used, several types of waveguide couplers are available: branch couplers, multiaperture couplers, cross couplers, etc. In his paper [1], Levy compared their different application ranges. Cross couplers are available for loose couplings only, and multiaperture couplers are too long for tight couplings. Levy also pointed out that waveguide branch couplers are especially useful for the 6- to 12-dB coupling range.

In this paper, full-wave optimization design of waveguide branch couplers is presented. Waveguide T-junction equivalent circuits are used to explain why tight couplings are difficult to realize using waveguide branch couplers. Approaches used to obtain tight couplings are discussed and illustrated by two design examples of 3-dB couplers. Random tolerance analysis of the couplers is also presented.

II. Modeling and Optimization

The coupler under investigation, as shown in Fig. 1(a), consists of two main waveguides coupled by means of a number of branch waveguides located in the common wall. Ports 1, 2, 3, and 4 are the input, through, coupled, and isolated ports, respectively.

For full-wave modeling, the coupler is decomposed into the cascade connection of waveguide bifurcation discontinuities, as shown in Fig. 1(b). The generalized scattering matrix $\mathbf{S}_B$ of the waveguide bifurcation discontinuity is obtained by mode matching method. The overall generalized scattering matrix $\mathbf{S}_C$ is obtained by cascading procedure. The dominant-mode scattering parameters S_{11} (return loss R), S_{21} (insertion loss T), S_{31} (coupling C), and S_{41} (isolation I) of the coupler are (1,1) entries of the corresponding generalized scattering submatrices $\mathbf{S}_{C11}$, $\mathbf{S}_{C21}$, $\mathbf{S}_{C31}$, and $\mathbf{S}_{C41}$, respectively.

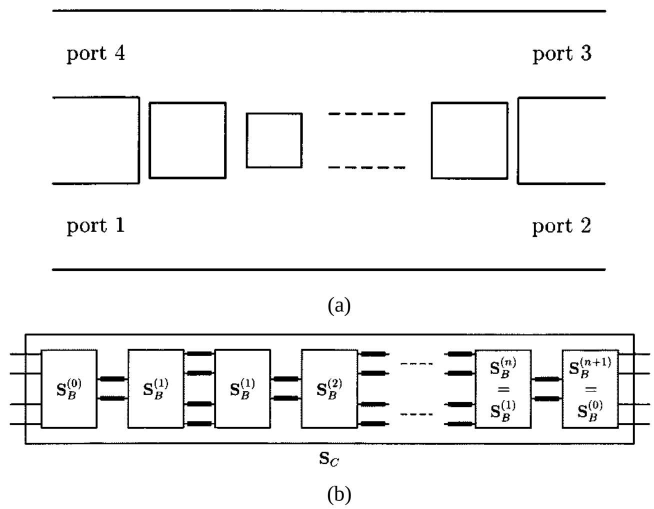

Fig. 1. Waveguide branch coupler. (a) Configuration. (b) Network representation.

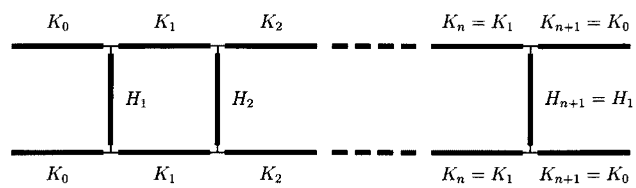

Fig. 2. Idealized branch-line coupler.

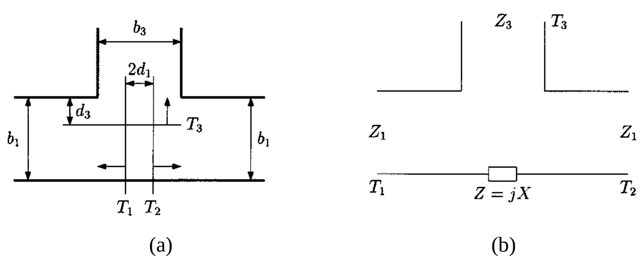

Fig. 3. Waveguide (E-plane) T-junction. (a) Configuration and reference plane positions. (b) Equivalent circuit at the reference plane positions.

For optimization design, according to design specifications, an error function to be minimized is constructed as

$$F(\mathbf{x}) = w_R \sum_i U[R_s, R(\mathbf{x}, f_i)] + w_T \sum_i U[|T(\mathbf{x}, f_i) - T_s|, T_t]$$

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The authors are with the Department of Electrical and Computer Engineering, University of Maryland, College Park, MD 20742 USA.
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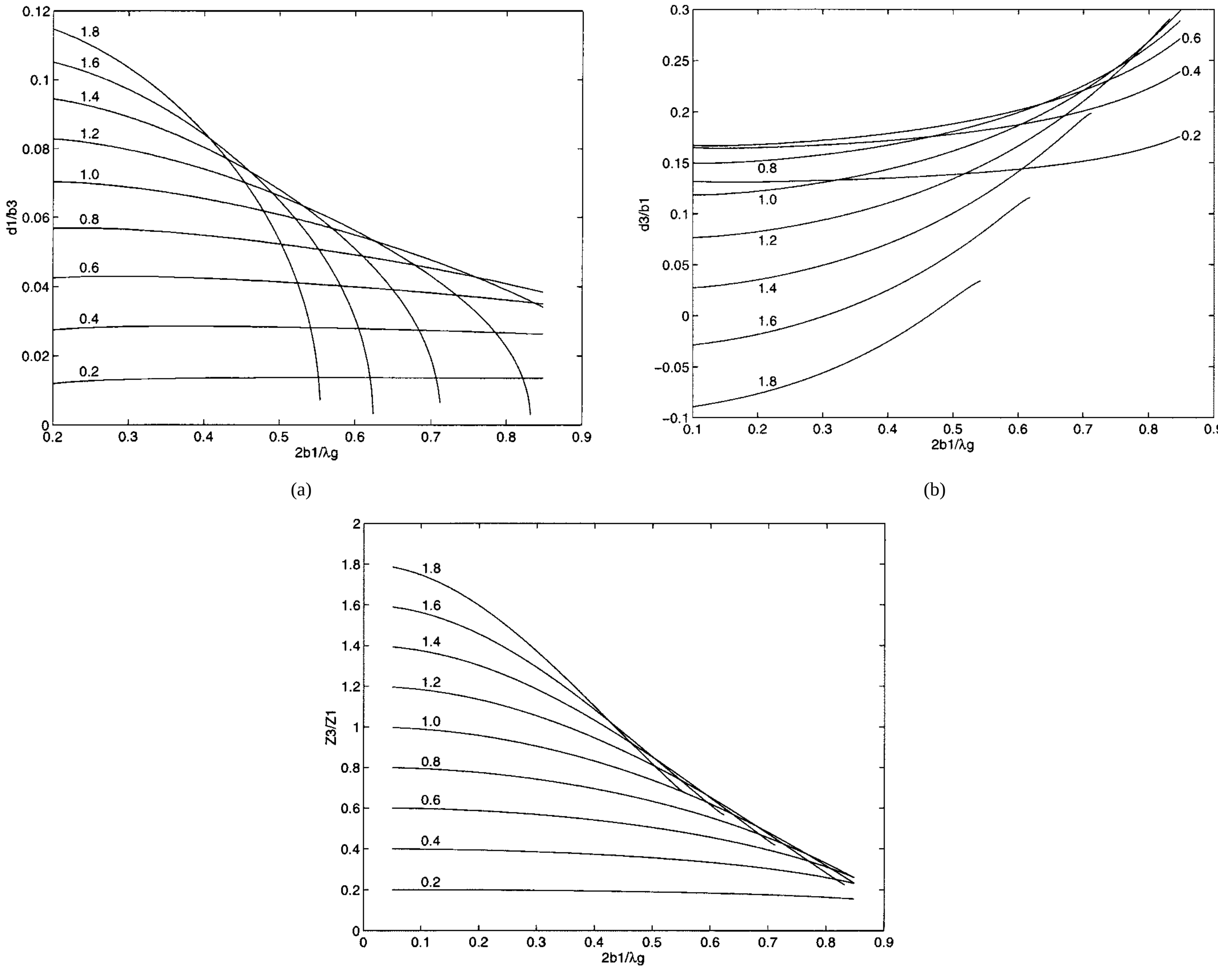

Fig. 4. Waveguide (E-plane) T-junction equivalent circuit parameters versus normalized frequencies $2b_1/\lambda_g$. (a) Normalized reference place position d_1/b_3. (b) Normalized reference place position d_3/b_1. (c) Impedance ratio of branch to main guides Z_3/Z_1 at the reference plane positions d_1 and d_3. Parameters are height ratio of branch to main guides b_3/b_1.

$$+ w_C \sum_i U[|C(\mathbf{x}, f_i) - C_s|, C_t]$$
$$+ w_I \sum_i U[I_s, I(\mathbf{x}, f_i)]$$

where

$$U(x, y) = \begin{cases} x - y, & \text{if } x > y \\ 0, & \text{otherwise.} \end{cases}$$

$\mathbf{x}$ is the set of optimization variables, which includes all independent dimensions of the coupler structure; f_i is the sample frequency; R_s, T_s, C_s, and I_s are the design specifications of the return loss, insertion loss, coupling, and isolation, respectively; T_t and C_t are the design specifications of the insertion-loss and coupling variations, respectively; and w_R, w_T, w_C, and w_I are the weighting factors of the return-loss, insertion-loss, coupling, and isolation terms, respectively. The four weighting factors are used to balance the contributions of the four corresponding terms in the error function expression. From the unitary property of lossless networks, only three of the four scattering parameters S_{11} (R), S_{21} (T), S_{31} (C), and S_{41} (I) are independent, which means one of the four weighting factors may be set to be zero (in most cases, the insertion-loss term is not included.)

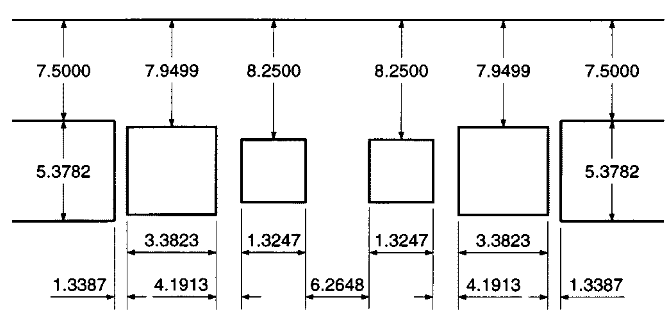

Fig. 5. Dimensions (given in inches) of the five-branch 3-dB coupler. The waveguide width is 15 in.

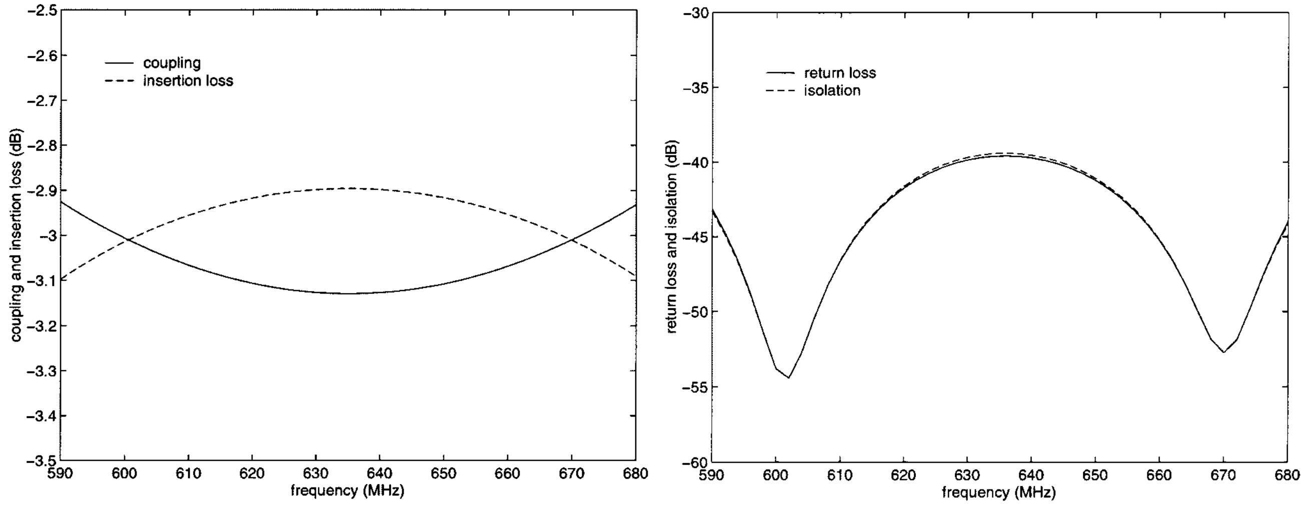

Fig. 6. Computed results of the five-branch 3-dB coupler. (a) Coupling and insertion loss. (b) Return loss and isolation.

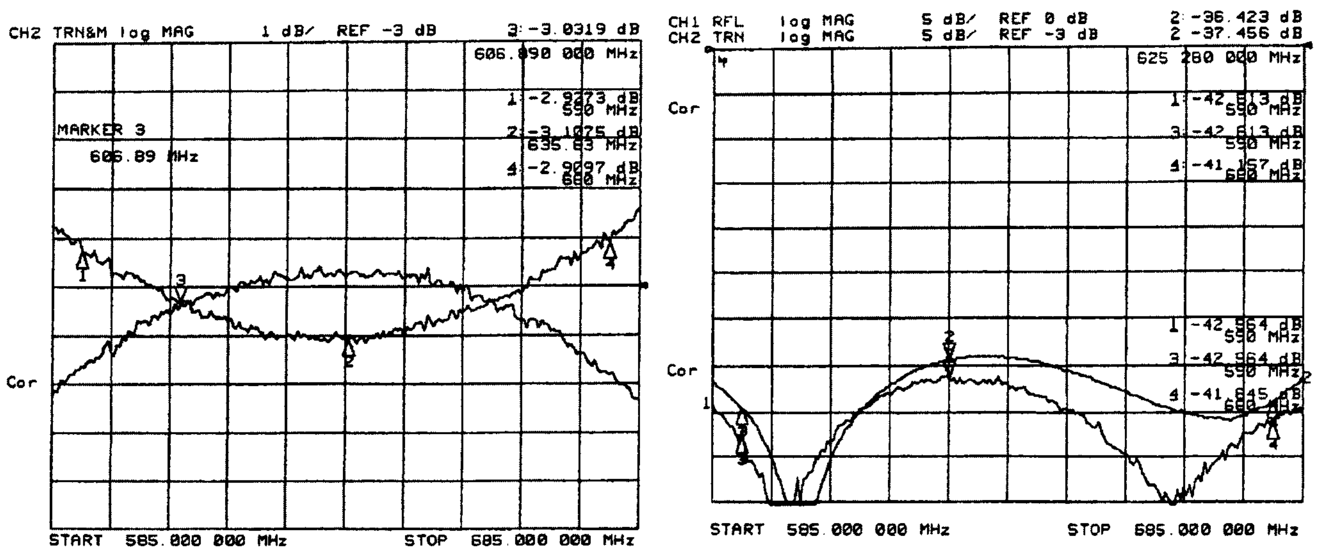

Fig. 7. Measured results of the five-branch 3-dB coupler. (a) Coupling and insertion loss. (b) Return loss and isolation.

In optimization, the initial values of optimization variables are extremely important. Thus, it is necessary to synthesize the initial values of the coupler structure before optimization design.

III. Synthesis

A. Review of Synthesis of Branch-Line Couplers

Fig. 2 shows an idealized branch-line coupler. The lengths of the branch lines and their spacings (lengths of the main lines between two neighboring branch lines) are all quarter-guide wavelength at the center frequency. K_i and H_i represent the normalized main- and branch-line immittances, respectively. The terminology immittance here denotes the impedance for series-branch couplers (e.g., the waveguide E-plane branch couplers discussed in this paper) or the admittance for shunt-branch couplers (e.g., the waveguide H-plane branch couplers in [2].)

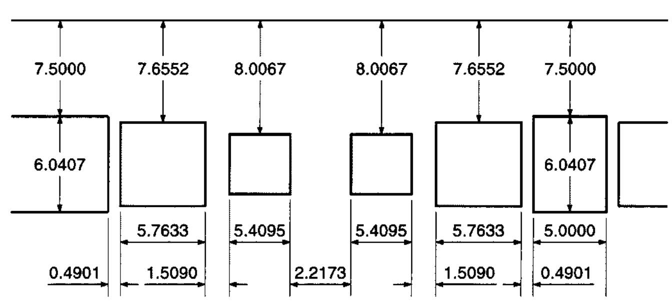

Fig. 8. Dimensions (given in inches) of half the ten-branch 3-dB coupler. The waveguide width is 15 in. Only half-dimensions are shown here since the ten-branch 3-dB coupler is composed of two identical five-branch 8.33-dB couplers.

Idealized branch-line couplers are synthesized by Young [3], [4] and by Levy and Lind [5], where normalized immittance tables are given. From these tables, it can be seen that the main

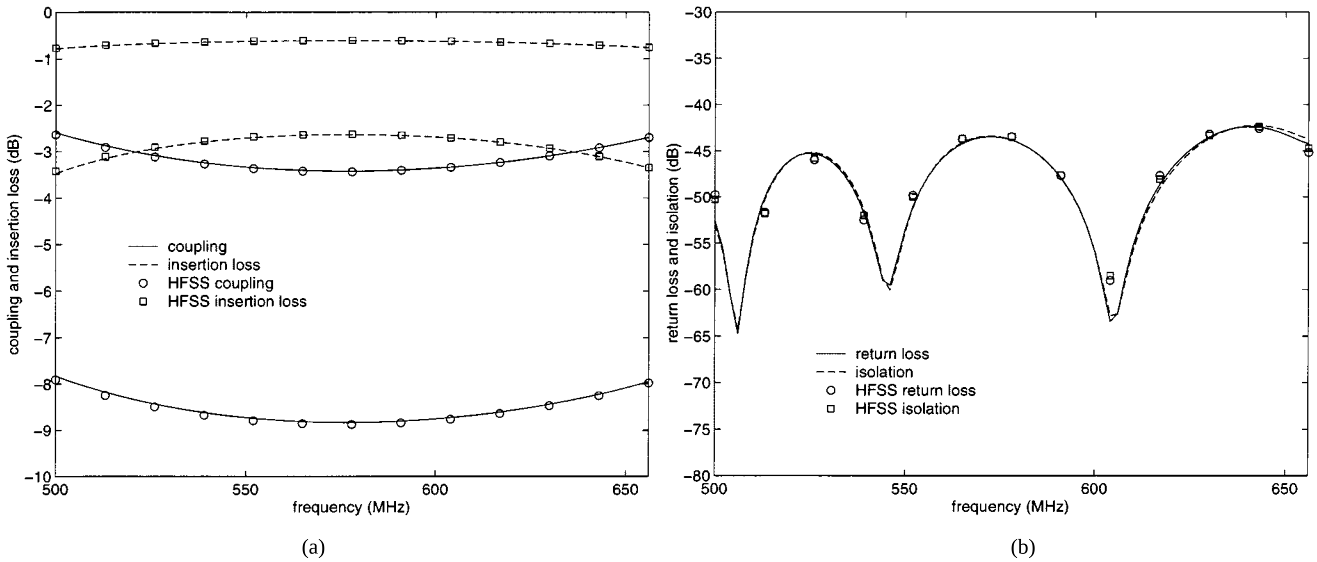

Fig. 9. Computed results of the ten-branch 3-dB coupler. (a) Coupling and insertion loss. Results of the five-branch 8.33-dB coupler are also plotted. (b) Return loss and isolation.

and branch immittances increase progressively from the ends to the center of the couplers.

B. Waveguide T-Junctions

The synthesized immittances given in [3] or [4] and [5] are for the idealized branch-line couplers (no T-junction discontinuities are taken into account.) In the case of waveguide branch couplers, compensation for the T-junction discontinuities should be carried out, and the waveguide T-junction equivalent circuit shown in Fig. 3 is used. The conventional way of compensation of T-junction discontinuities is to use the curves given by Marcuvitz [6], which is inconvenient (iterative calculation should be carried out [4].) In this paper, the waveguide T-junctions are modeled by mode matching method. The modeling approach is similar to that given in [7] for ridge waveguide T-junctions. The T-junction equivalent circuit parameters are extracted from the scattering parameters of the T-junctions by the approach described in [6].

Fig. 4(a)–(c) shows the normalized reference plane positions d_1/b_3 and d_3/b_1, and the impedance ratio of branch to main guides Z_3/Z_1, respectively, as a function of normalized frequencies $2b_1/\lambda_g$. In the synthesis of waveguide branch couplers, the series reactance X in the T-junction equivalent circuit is ignored with only slight effect on the (synthesized) coupler performance [4]. Therefore, the curves of the series reactance X versus normalized frequencies $2b_1/\lambda_g$ are not shown here. The curves in the explicit form of Fig. 4 are not presented in [6]; however, they can give a clear explanation on why tight couplings are difficult to realize using waveguide branch couplers, as discussed below.

C. Discussion

Detailed inspection of the immittance tables given in [3] or [4] and [5] shows that low branch immittances are required for loose couplings and high immittances for tight couplings. For example, the highest branch immittance for a five-branch 6-dB coupler is about 0.4, depending on specifications and which table (Levy's or Young's) is used, while for a five-branch 3-dB coupler, the highest branch immittance is about 0.9.

On the other hand, it can be seen from Fig. 4(c) that at the low-frequency band, the impedance ratio of branch to main guides (Z_3/Z_1) is approximately equal to the height ratio of branch to main guides (b_3/b_1), as expected. At the high-frequency band, however, the impedance ratio falls down rapidly. At the edge of the high-frequency band, the impedance ratio is no more than 0.4. The low impedance ratio is nearly frequency independent, while the high impedance ratio is highly frequency dependent. The less the impedance ratio is, the less it is frequency dependent.

Therefore, the loose couplings (less than 6 dB) are easier to realize using waveguide branch couplers, and they are wide band. For the tight couplings, either the required branch impedances could not be realized by the waveguide T-junctions or the branch impedances could be realized but are too frequency dependent, which results in a narrow band performance. For the former case, two couplers of loose couplings can be cascaded into a coupler of tight couplings [3]. For the latter case, using full-wave optimization design outlined in the last section, the tight couplings can be obtained over a wide band. A critical case that is often encountered in practice is that for a specified coupling, the required branch impedances could be realized by the waveguide T-junctions at the low-frequency band but not at the high-frequency band. For this case, if a coupler at the high-frequency band is desired, two methods could be used. One method is to design a coupler of a little looser (than the specified) coupling first and then use full-wave optimization design to increase the coupling to the specified value. The other method is to design a coupler of the specified coupling at the low-frequency band first and then use full-wave optimization design to move the coupler to the specified high-frequency band.

It should be noted that in the above discussion, only the branch impedances of waveguide T-junctions are considered for clarity of discussion. The practical design involves the

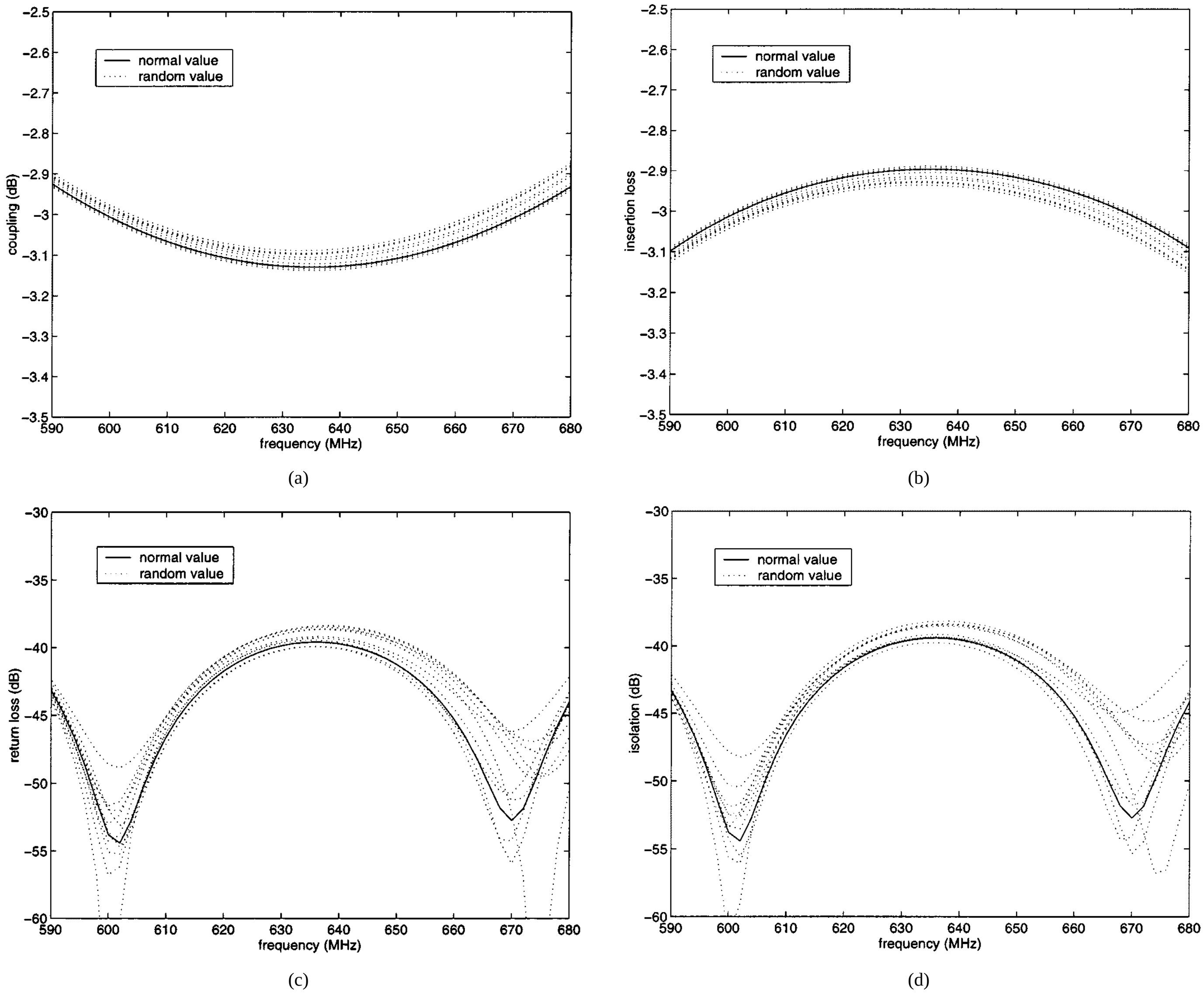

Fig. 10. Random tolerance analysis of the five-branch 3-dB coupler. In computation, a margin tolerance of ±5 mil is assumed. (a) Coupling. (b) Insertion loss. (c) Return loss. (d) Isolation.

consideration of the main-guide impedances and the reference plane positions, which makes the tight couplings more difficult to realize.

IV. Results

Two 3-dB waveguide branch couplers are designed. Both are constructed in a WR1500 waveguide having cross dimensions of 15 × 7.5 in.

Fig. 5 shows the dimensions of a five-branch 3-dB coupler. It is obtained by using full-wave optimization directly. The total length of the coupler is about 27 in. Fig. 6 shows the computed results of the coupler. Over the 23% guide-wavelength (or 14% frequency) bandwidth, the coupling variation is within ±0.1 dB, and the return loss and isolation are greater than 40 dB. The performance is comparable with that for the loose couplings predicted by Levy [1]. Fig. 7 shows the measured results. The measured results are in good agreement with the computed results.

Fig. 8 shows the dimensions of a ten-branch 3-dB coupler. It is obtained by cascading two identical five-branch 8.33-dB couplers together. The total length of the coupler is about 63 in. Fig. 9 shows the computed results of the coupler. The HFSS results are also shown in Fig. 9 to verify the design. The computed results are in good agreement with the HFSS results. Over the 52% guide-wavelength (or 27% frequency) bandwidth, the coupling variation is within ±0.4 dB, and the return loss and isolation are greater than 42 dB.

Figs. 10 and 11 show the random tolerance analysis of the five- and ten-branch 3-dB couplers, respectively. In computation, a margin tolerance of ±5 mil is used. For the five-branch coupler, it is seen from Fig. 10 that manufacturing tolerances tend to increase the coupling and decrease the insertion loss by about 0.05 dB, and they have more effect on the return loss and isolation at the high-frequency band. The measured results shown in Fig. 7 are consistent with the observation. Comparison of Fig. 11 with Fig. 10 shows that the effect of manufacturing tolerances on the ten-branch coupler is much less than

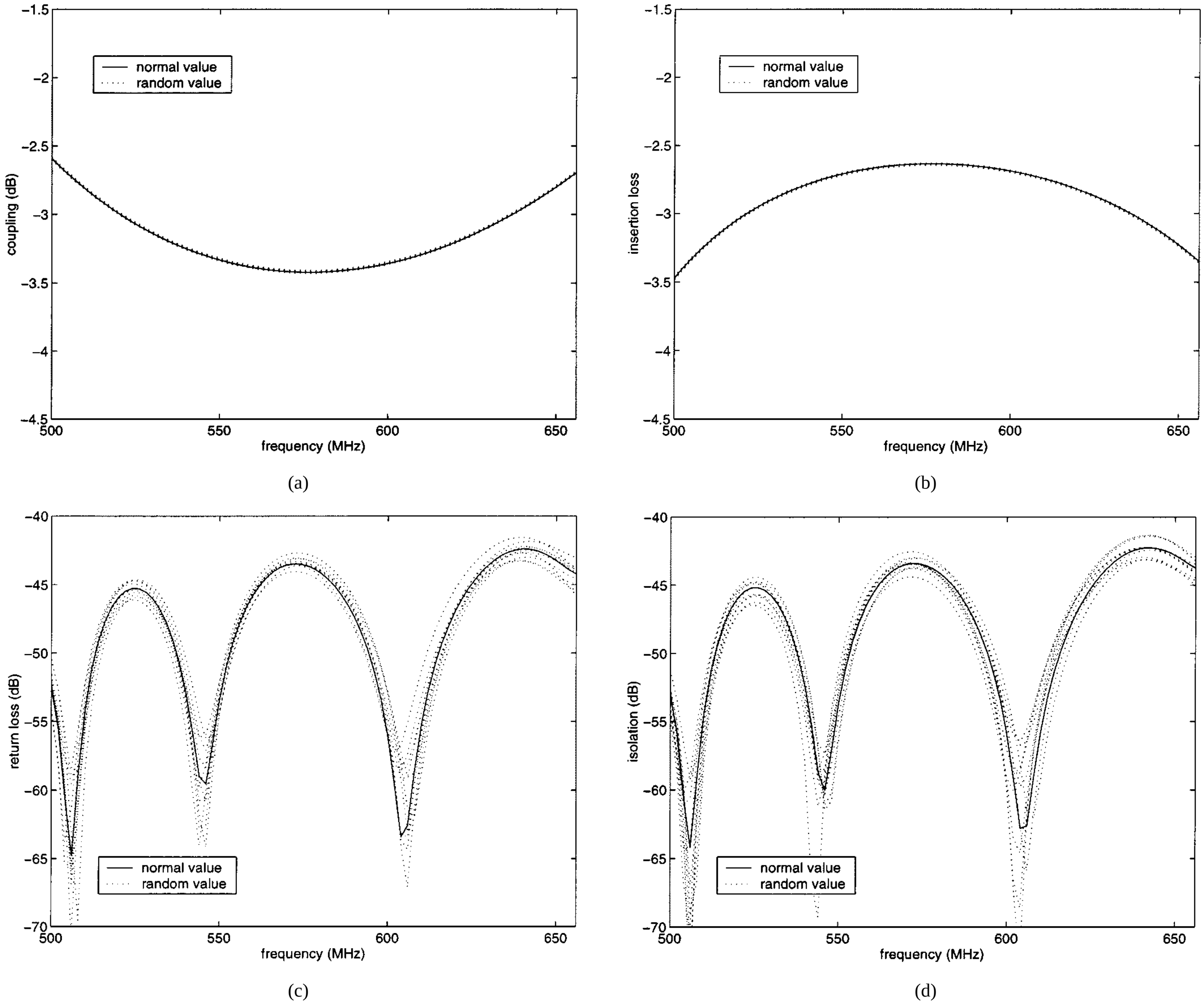

Fig. 11. Random tolerance analysis of the ten-branch 3-dB coupler. In computation, a margin tolerance of ± 5 mil is assumed. (a) Coupling. (b) Insertion loss. (c) Return loss. (d) Isolation.

their effect on the five-branch coupler. A reasonable explanation is that with the number of branches increasing, there are more tolerance variables and therefore their effects on the coupler performance tend to cancel each other more easily. Generally speaking, reasonable manufacturing tolerances have no significant effect on coupler performance.

V. Summary

In this paper, full-wave optimization design of waveguide branch couplers is presented. Waveguide T-junction equivalent circuit parameters are extracted from full-wave modeling results. They are used to explain why tight couplings are difficult to realize using waveguide branch couplers. Approaches used to obtain tight couplings are discussed and illustrated by two design examples of 3-dB couplers. Through random tolerance analysis, it is found that reasonable manufacturing tolerances have no significant effect on coupler performance.

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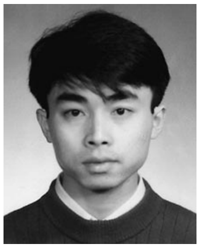

Tao Shen (S'95) was born in Suzhou, China, in 1969. He is currently pursuing the Ph.D. degree in electrical and computer engineering at the University of Maryland at College Park.

Kawthar A. Zaki (SM'85–F'91) received the B.S. degree (with honors) from Ain Shams University, Cairo, Egypt in 1962 and the M.S. and Ph.D. degrees from the University of California, Berkeley, in 1966 and 1969, respectively, all in electrical engineering.

From 1962 to 1964, she was a Lecturer in the Department of Electrical Engineering, Ain Shams University. From 1965 to 1969, she was a Research Assistant in the Electronics Research Laboratory, University of California, Berkeley. She joined the Electrical Engineering Department, University of Maryland, College Park, in 1970, where she is presently a Professor of electrical engineering. Her research interests are in the areas of electromagnetics, microwave circuits, simulation, optimization, and computer-aided design of advanced microwave and millimeter-wave systems and devices. She has more than 200 publications and five patents on filters and dielectric resonators.

Prof. Zaki has received several academic honors and awards for teaching, research, and inventions.