Mode-Matching Design of Substrate-Integrated Waveguide Couplers

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***Abstract* — A mode-matching based full-wave analysis method is deployed to design H-plane substrate integrated waveguide (SIW) couplers. In order to apply simple and straightforward mode-matching techniques, commonly used circular vias are replaced by proper square ones. K-band and W-band SIW directional couplers are designed with square vias, and then analyzed and validated by commercially available full-wave field solvers using circular vias. Comparisons with measurements on a Ka-band SIW coupler with circular vias verify the analysis and design procedure.**

I. INTRODUCTION

Since the introduction of the Substrate-Integrated Waveguide (SIW) concept in 2001 [1], attention has been increased significantly towards using this new technology in designing millimeter-wave components and circuits. Inheriting low radiation loss, acceptable Q-factor and high power handling capability from traditional rectangular waveguide structures, SIW also utilizes low cost, low profile and easy integration capabilities of planar structures [2]. During the past few years, different types of microwave components have been designed based on this new technology, e.g. filters [3]-[5], couplers [6]-[9], mixers [10], [11], and power dividers [12], [13]. Although these SIW structures are mainly designed using commercially available full-wave field solvers such as CST Microwave Studio or Ansoft HFSS, some analytical approaches have been deployed recently to investigate SIW properties and introduce faster design procedures [14]-[17]. As there is a reduced set of modes in SIW structures (only TE_{m0} modes), modal analysis techniques would be an efficient choice.

One of these analytical methods, which is based on the Mode-Matching Technique (MMT), has been demonstrated to run many times faster than typical field solvers [18]. In this approach, square via SIW filters with waveguide and microstrip feed ports have been investigated. However, since most SIW components are designed and fabricated with circular via holes, there is a need to develop analytical approaches for circular vias. In this paper, the circular vias are converted to proper square ones, and the MMT is deployed to analyze and design SIW couplers.

II. DESIGN PROCEDURE

A. Equivalence Between Circular and Square Vias

In order to replace the circular vias with the proper square ones, four different approaches have been investigated in [19]. According to this paper, if the square vias are chosen properly, their electrical behaviour would be equivalent to circular vias within good accuracy over a broad range of frequencies. Three equivalencies between square and circular vias have been investigated here: first, square and circular vias have the same cross sections; second, the side length of the equivalent square via is equal to the *arithmetic* mean, and third, the *geometric* mean of the inscribed and circumscribed squares of the circular via. It has been found that the arithmetic mean of the inscribed and circumscribed squares of the circular via consistently provided the best match in our simulations. Thus every circular via in the SIW coupler designs presented in this paper is replaced by a square via whose side length l_{square} is related by

$$l_{square} = \frac{d_{circular}}{2}\left(1 + 1\big/\sqrt{2}\right) \tag{1}$$

to the diameter $d_{circular}$ of the circular via hole.

B. Coupler Design and Theory

As SIWs are planar realizations of traditional waveguide circuits [2], the fastest approach to an initial design of an SIW coupler is to apply coupler design principles known from all-dielectric-filled waveguide H-plane couplers, e.g. [20]. This initial design is then translated to SIW topology with square vias in order to apply the MMT. Fine optimization on this SIW structure completes the design.

The square vias in the optimized couplers are then replaced by circular vias according to (1) and analyzed with full-wave field simulators.

III. THEORY

The theory deployed in this paper is predominantly based on a method on two-ports [18]. Since the coupler is a four-port structure, the only difference for the analysis of couplers is the discontinuity between the feed ports and the SIW structure. In the following sub-sections, we present the modal scattering parameter calculations of discontinuities between the coupler feed ports (both waveguide and microstrip feeds) to an all-dielectric waveguide. For the treatment of sections of arbitrary numbers of via holes within a planar, all-dielectric waveguide, the reader is referred to [18].

A. Discontinuity Between Two Waveguide Feed Ports and an All-Dielectric Waveguide

Fig. 1a shows the boundary conditions of the discontinuity of two waveguide feed ports to all-dielectric waveguide. For

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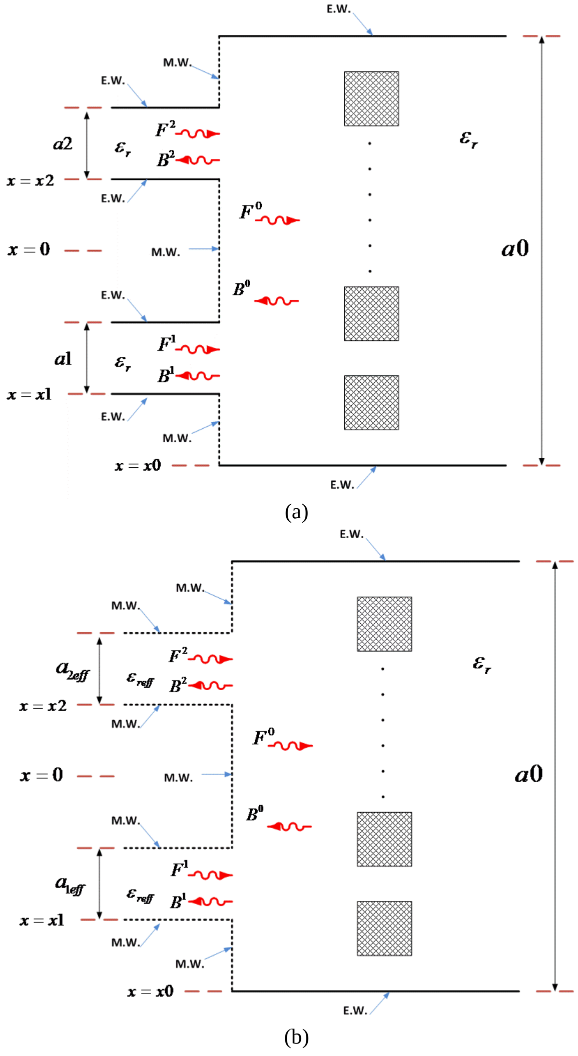
this case the coupling integrals are simply those of the TE_{m0} modes of the three different waveguides involved. Let T^0_{hm}, T^1_{hn}, and T^2_{hk} be the cross-sectional functions in waveguides 0,1,and 2 (Fig. 1a), then the two coupling integrals are

$$\left(J^1_{hh}\right)_{n,m} = \int_{A_1}\left(\nabla T^1_{hn}\right)\cdot\left(\nabla T^0_{hm}\right)da$$
$$\left(J^2_{hh}\right)_{k,m} = \int_{A_2}\left(\nabla T^2_{hk}\right)\cdot\left(\nabla T^0_{hm}\right)da \tag{2}$$

where A_1 and A_2 are the cross section areas of waveguides 1 and 2, respectively.



(a)

(b)

Fig. 1 Discontinuities between feed ports and all-dielectric waveguides; (a) waveguide feeds, (b) microstrip feeds.

B. *Discontinuity Between Two Microstrip Feed Ports and an All-Dielectric Waveguide*

In the case of microstrip feeds (Fig. 1b), the TEM mode and TE_{m0} modes in the microstrip feeds must be considered as they interact with the TE_{m0} modes of the all-dielectric waveguide. Thus cross-sectional functions of the electric (TEM) and magnetic (TE) vector potentials must be considered. Consequently, each coupling integral in (2) is replaced by two integrals such that

$$\left(J^i_{lh}\right)_{0,m} = \int_{A_i}\left(\nabla T^i_{e\ell}\right)\cdot\left(\nabla T^0_{hm}\times\vec{e}_z\right)da$$
$$\left(J^i_{hh}\right)_{n,m} = \int_{A_i}\left(\nabla T^i_{hn}\right)\cdot\left(\nabla T^0_{hm}\right)da \tag{3}$$

where i=1,2.

From these coupling matrices, the modal scattering matrices are determined as in [18], and the total coupling matrix M, including the respective wave impedances, is

$$\boldsymbol{M} = \begin{bmatrix} Diag\left\{\sqrt{Y^1}\right\}\left(\boldsymbol{J}^1\right)Diag\left\{\sqrt{Z^0}\right\} \\ Diag\left\{\sqrt{Y^2}\right\}\left(\boldsymbol{J}^2\right)Diag\left\{\sqrt{Z^0}\right\} \end{bmatrix} \tag{4}$$

from which the modal scattering matrix is computed as

$$\begin{aligned} \boldsymbol{S}_{11} &= \left[\boldsymbol{MM}^T + \boldsymbol{U}\right]^{-1}\left[\boldsymbol{MM}^T - \boldsymbol{U}\right] \\ \boldsymbol{S}_{12} &= 2\left[\boldsymbol{MM}^T + \boldsymbol{U}\right]^{-1}\boldsymbol{M} = \boldsymbol{S}^T_{21} \\ \boldsymbol{S}_{21} &= \boldsymbol{M}^T\left[\boldsymbol{U} - S_{11}\right] = \boldsymbol{S}^T_{12} \\ \boldsymbol{S}_{22} &= \boldsymbol{U} - \boldsymbol{M}^T\boldsymbol{S}_{12} \end{aligned} \tag{5}$$

where $\boldsymbol{U}$ is the unit matrix.

After calculation of the total modal S matrix of the coupler, the desired parameters S_{11}, S_{21}, S_{31} and S_{41} of the four-port structure are extracted from the computed overall modal two-port scattering matrix (5).

IV. RESULTS

The inset of Fig. 2 shows a 3dB K-band H-plane SIW directional coupler with waveguide ports which is designed with the µWaveWizard with circular via holes and analyzed with the MMT (square vias) and simulated with CST Microwave Studio (circular vias). The substrate is chosen as RT/duroid 6002 with ε_r=2.94, substrate height b=0.508mm and metallization thickness t=17µm. The diameters of the circular vias are chosen as d=0.71mm so that

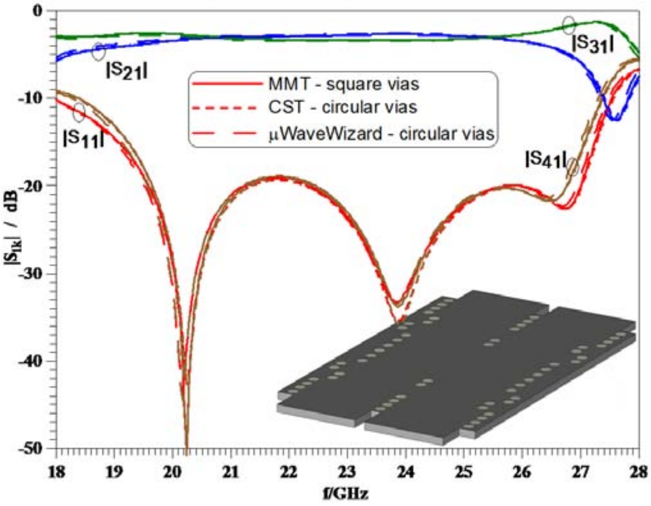


Fig. 2 Comparison between results obtained with MMT (square via holes – solid lines), CST (circular via holes – dotted lines) and the µWaveWizard (circular via holes – dashed lines) for a 3dB K-band SIW coupler.

the side lengths of the equivalent square vias are l_{square}=0.606mm according to (1). The results of the MMT approach with square vias and CST and µWaveWizard simulations, both with circular vias, are compared in Fig. 2. Excellent agreement is obtained. Note that for structures involving separate individual layers of slices of via holes, the µWaveWizard permits a fast direct design and fine optimization of SIW components with circular vias.

Fig. 3 shows the layout (Fig. 3a) and performance (Fig. 3b) of a multi-aperture 6dB H-plane coupler in SIW technology on RT/duroid 6002. Due to the SIW width and the relatively large coupling sections, higher-order mode effects come into play beyond 27 GHz. Excellent agreements are again observed between results obtained with the MMT with square via holes and CST with circular via holes.

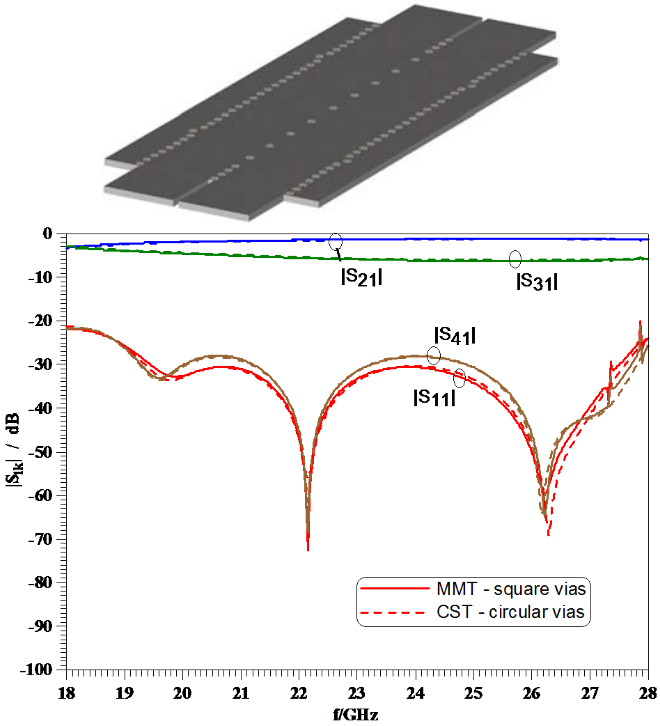


Fig. 3 Layout and performance comparison between results obtained with MMT (square via holes – solid lines) and CST (circular via holes – dashed lines) for a 6dB K-band multi-aperture SIW coupler.

For a 3dB multi-aperture W-band SIW coupler, the wide bandwidth specification and fabrication restrictions on minimum via dimensions and distances do not allow a straight-forward synthesis using standard coupler theory. Thus such a coupler is realized as a tandem connection of two 8.34dB couplers. The substrate is RT/duroid 6002 with a substrate height of b=0.254mm. The diameters of the circular vias are chosen as $d_{circular}$ =0.2929mm so that the side lengths of the equivalent square vias are l_{square} =0.25mm.

Fig. 4 shows the layout and performance of the 8.34dB coupler with 12 apertures and Fig. 5 those of the tandem connection with 24 apertures. Excellent agreement is observed between the MMT results with square via holes and those from CST using circular via holes.

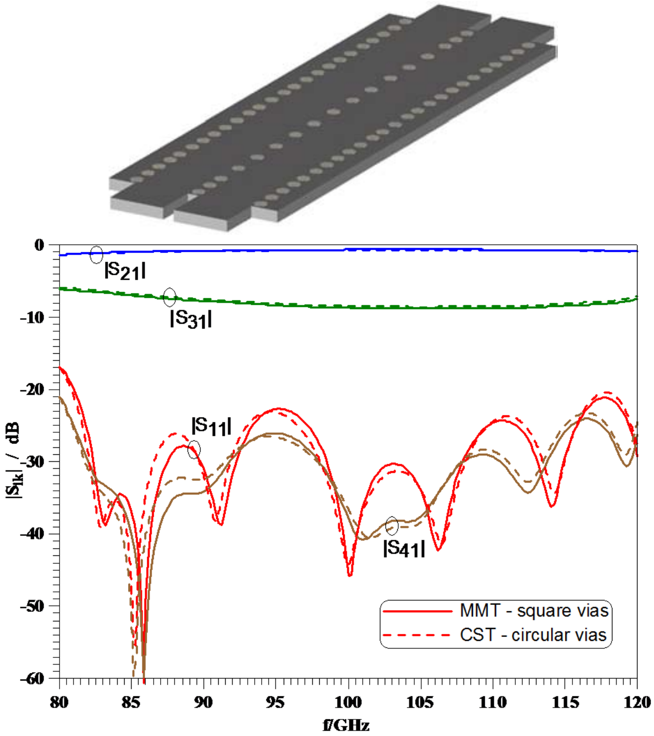


Fig. 4 Layout and performance comparison between results obtained with MMT (square via holes – solid lines) and CST (circular via holes – dashed lines) for a 8.34dB W-band 12-aperture SIW coupler.

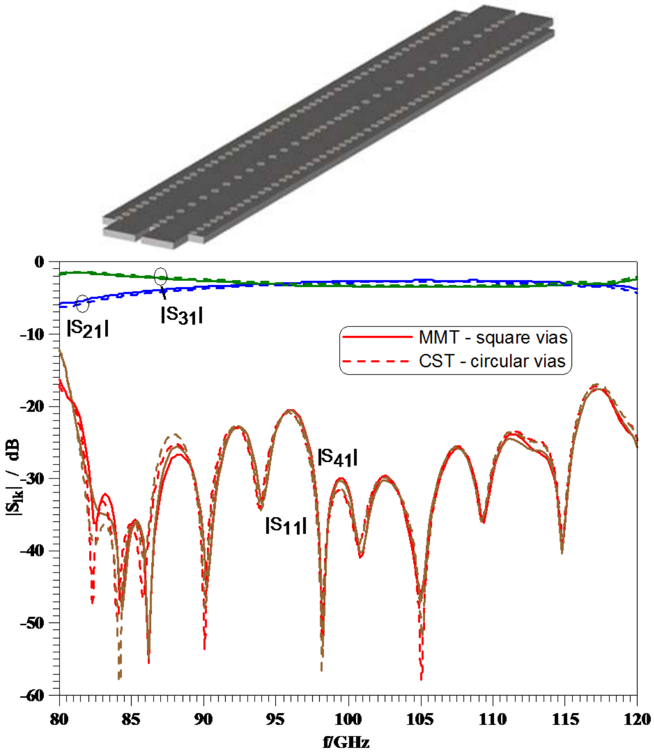


Fig. 5 Layout and performance comparison between results obtained with MMT (square via holes – solid lines) and CST (circular via holes – dashed lines) for a 3dB W-band 24-aperture SIW coupler.

Finally, Fig. 6 compares the MMT results with measurements of a Ka-band 3dB H-plane SIW coupler with microstrip ports as presented in [6]. While the agreement is not as good as compared to previous results, the agreement between measurements with circular via holes and MMT computations with square via holes is deemed acceptable in many technical applications and thus verifies the MMT analysis procedure using square via holes. Note that a comparison with a different measured SIW coupler in [10] (not shown here) shows similar agreement.

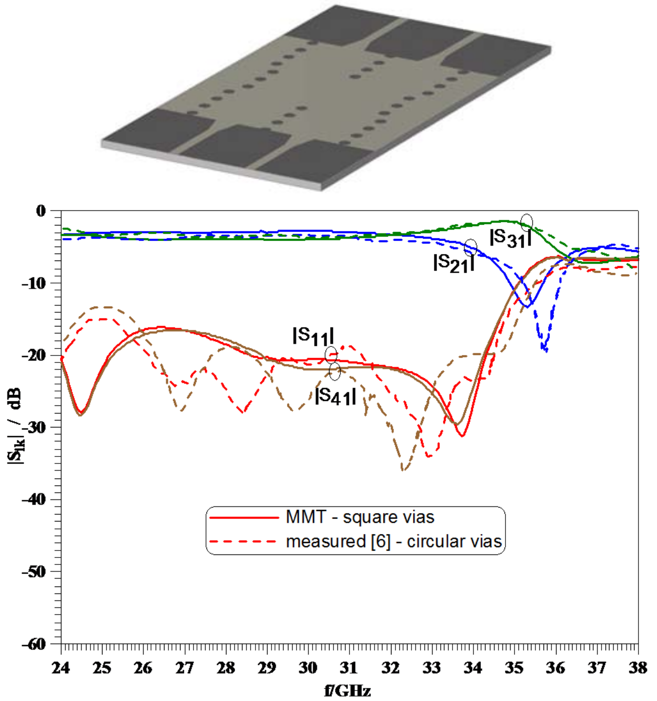


Fig. 6 Layout and performance comparison between results obtained with MMT (square via holes – solid lines) and measurements (circular via holes – dashed lines) for a 3dB Ka-band SIW coupler according to [6].

V. CONCLUSIONS

K-band and W-band substrate-integrated waveguide couplers with circular vias and both waveguide and microstrip ports are effectively modelled by a simple and straightforward mode-matching approach. The circular vias are replaced with square ones which allows for a fast and accurate design of SIW H-plane couplers. The results from the theory are validated by data obtained from full-wave simulations of the same structures with circular vias. It is demonstrated that the proposed analytical approach accurately models the SIW couplers, and results are in excellent agreement with those obtained by full-wave field solvers. Moreover, the results from the proposed technique are verified by measured data of a 3dB Ka-band SIW coupler.

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