Efficient Mode-Matching Design of Substrate-Integrated Waveguide Filters

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Abstract—**For the purpose of providing faster CAD algorithms for substrate-integrated waveguide (SIW) filter design, an efficient mode-matching technique uses a model to convert circular via holes to square shapes. It is demonstrated that a conversion based on the side length of the equivalent square via being equal to the arithmetic mean of the side lengths of the inscribed and circumscribed squares of the circular via provides results acceptable even for advanced filter design procedures. Several filter examples using the SIW equivalents of metal-insert, inductive-iris and H-plane quasi-elliptic waveguide filters are designed using the mode-matching technique with square via holes. The results are then verified by commercially available field solvers modeling the respective filters with circular via holes. A final comparison with measurements verifies the design procedure in practical applications.**

Keywords—Microwave integrated circuits, substrate-integrated waveguides, filter design, bandpass filters, dualband filters, mode-matching methods.

I. INTRODUCTION

As substrate-integrated waveguide (SIW) components are gradually emerging from an experimental/research state to an established technology, e.g. [1], a significant number of typical all-metal waveguide structures are converted to SIW circuits. Especially filters and their performance as SIW components have attracted significant attention over the last few years, e.g. [2] – [10]. Although it is well established that a reduction of one order of magnitude in unloaded Q has to be accepted when compared to all-metal waveguide filters, the benefits of size reduction and planar fabrication techniques in SIW outweigh the increased losses in quite a number of applications.

However, the design of SIW components and especially filters is predominantly carried out by full-wave field solvers such as HFSS and CST Microwave Studio. While their accuracy is widely accepted, parametric studies and optimization are still cumbersome and time consuming. Only recently have other numerical methods emerged [11], [12] that take advantage of certain properties within the planar structure of SIW components and thus contribute to faster analysis and thus design times. One of those methods is the mode-matching technique (MMT) which uses square via holes and has been demonstrated to run many times faster than typical field solvers [13]. The method includes an arbitrary number of via holes in a slice of the SIW filter and considers waveguide as well as microstrip feeds in a straightforward manner. Moreover, dielectric and conductor losses can easily be incorporated. However, the restriction to square or rectangular via holes is expected to cause discrepancies when most of the SIW components are fabricated with standard circular via holes.

Therefore, this paper focuses on a conversion between circular and square vias so that the design of SIW filters and other SIW components can be performed in a reliable, accurate and timely fashion.

II. DESIGN PROCEDURE

In order to facilitate a simple yet efficient conversion between circular and square via-hole shapes for the design of SIW filters, four simple models have been investigated [14]:

1. The side length of the square via hole equals the diameter of the circular via hole.

2. The cross-section area of the square via hole equals that of the circular via hole.

3. The side length of a square via hole equals the *arithmetic* mean of the side lengths of the inscribed and circumscribed squares of the circular via.

4. The side length of a square via hole equals the *geometric* mean of the side lengths of the inscribed and circumscribed squares of the circular via.

Of those four methods, the third one turned out to give consistently the best results even for advanced filter configurations. Thus the square to circular via-hole conversion used in this paper is

$$a = \frac{d}{2}\left(1 + 1/\sqrt{2}\right) \tag{1}$$

where a is the width of the square via and d is the diameter of the circular via.

With this simple relationship, an SIW filter can now be designed with either circular or square via holes and can then be translated to the respective other via shape.

The fastest approach to an initial design, of course, is to apply filter design principles known from all-dielectric-filled H-plane waveguide technology. This can include direct-coupled as well as cross-coupled filter topologies as will be shown in the next section. For given SIW dimensions such as

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via diameter, spacing, substrate permittivity and height, an equivalent waveguide filter model is designed and optimized with the MMT, as available in in-house codes, or the commercial software package µWaveWizard. The dimensions of the square via holes, as derived from (1) for a given via diameter, can be incorporated from the onset in the all-dielectric waveguide design as, e.g., post thickness, aperture thickness, etc. Such an all-dielectric waveguide prototype is then translated to an SIW structure with square via holes. (The respective MMT algorithms with square via holes are outlined in [13] and thus will not be repeated here.) Fine optimization with square vias completes the design. In this step, the MMT procedure displays its full advantage as a single analysis over a given set of frequency points is at least, depending on code implementation, ten times faster than HFSS or CST. Thus a simple fine-tuning run with *n* optimization steps will be at least 10*n* times faster than a comparable optimization in HFSS or CST. Moreover, the MMT is well capable of considering arbitrarily placed via holes by inserting sections of vanishing length. Therefore, it does not depend on separate individual layers of slices of via holes as the reader might conclude from [13].

Finally, the square–via design is translated to one with circular vias, and the performance is verified with an independent numerical technique provided by commercially available software packages.

III. RESULTS

Fig. 1 shows a two-resonator post filter in SIW technology which has been designed by the procedure outlined above. Note that all-dielectric waveguide I/O ports are used here as they eliminate additional influences, e.g., of microstrip feeds which are commonly used for measurement purposes. It is seen in Fig. 1 that both the CST and µWaveWizard simulations of the filter with circular vias are in excellent agreement with the MMT design using square vias according to (1).

Fig. 2 shows a comparison between circular and square vias for a three-resonator dual-post filter in which the dual-post arrangements resemble inductive-iris sections as the main coupling between resonators is obtained through the centered apertures. This design was originally proposed in [7] and obtained using repeated parametric analyses in Ansoft HFSS. We recomputed the design in CST and additionally, converted the circular vias to square ones for comparison with the MMT routine. Excellent agreement between square (MMT) and circular (CST) vias is observed in Fig. 2.

A quasi-elliptic filter design example is shown in Fig. 3. The filter was designed with square via holes in MMT and then translated to circular vias using (1). It is easily verified that the four-resonator routing scheme can support a single transmission zero, e.g. [15], which, when the filter is symmetric with respect to its center, will be positioned in the center of the passband. Thus a dual-band filter performance with two poles in each band is obtained as shown in Fig. 3, and excellent agreement is observed between the MMT results with square vias and those from CST with circular vias.

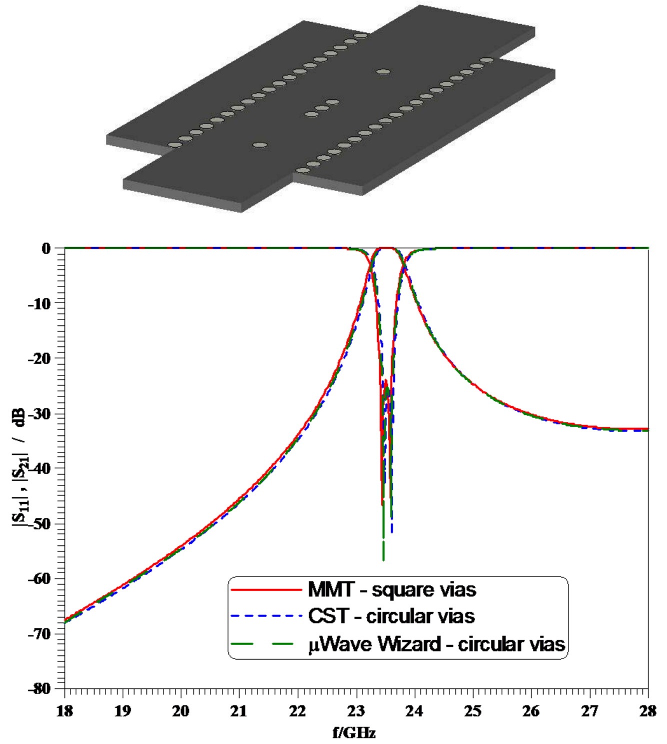

Figure 1. Performance comparison between square via holes (MMT) and circular vias (CST and µWaveWizard) at the example of a two-resonator post filter in SIW technology.

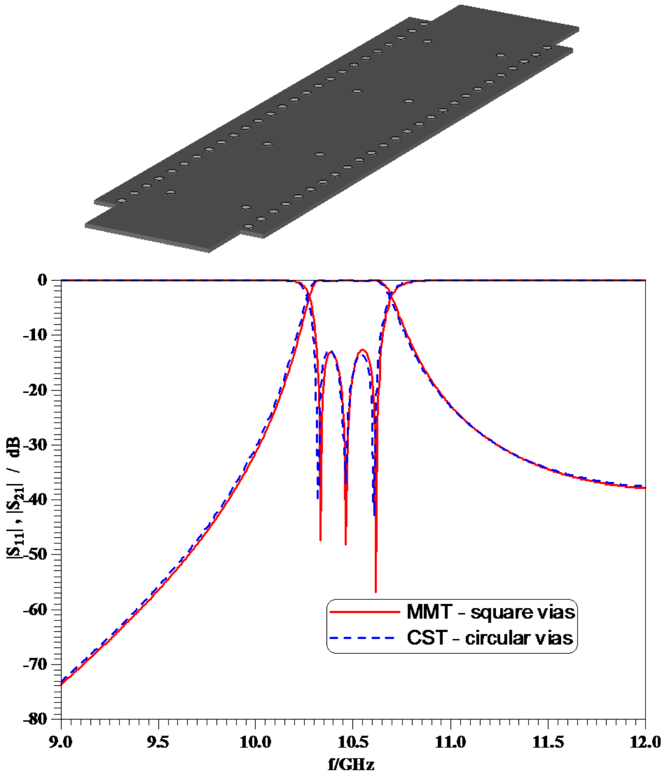

Figure 2. Performance comparison of square via-hole geometries (MMT) with circular vias (CST) at the example of a three-resonator post filter in SIW technology [7].

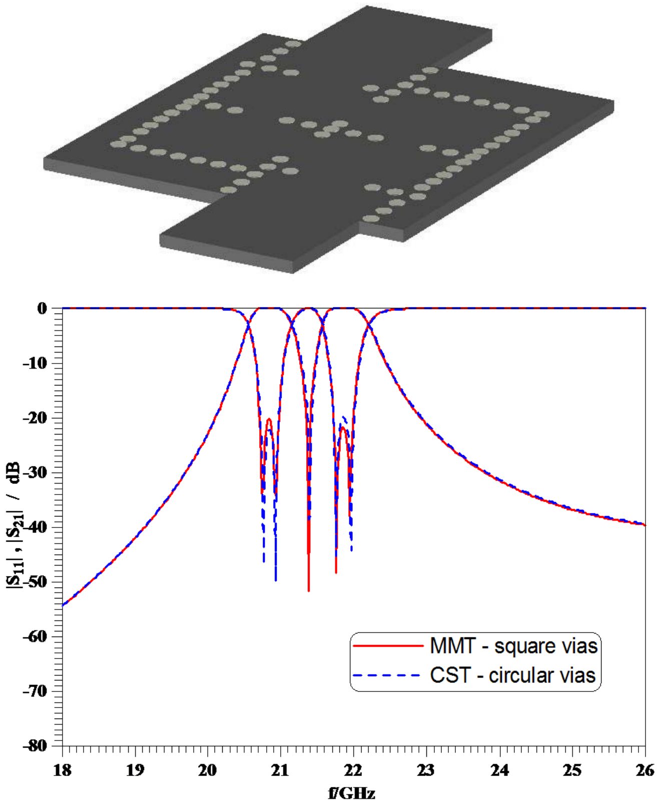

Figure 3. Performance comparison between square (MMT) and circular vias (CST) at the example of a four-resonator (dual-band) SIW filter with a transmission zero at midband frequency.

For measurement purposes or connection to other circuitry, SIW components are often equipped with microstrip transitions. Therefore, a dual-mode filter with microstrip ports is shown in Fig. 4-top. (For the original all-metal waveguide filter design, the reader is referred to [16].) In the MMT computation, the microstrip tapers have been approximated by a three-step staircase function. The procedure of obtaining the individual discontinuities including the quasi-TEM mode of the microstrip ports is outlined in [13]. The MMT performance shown in Fig. 4-bottom is that of the filter with square via holes in [13]. However, dielectric and metallic losses are added by considering the respective losses of all propagating modes in waveguide and microstrip sections. The comparison with results obtained with circular via holes in CST is very good. The slight discrepancies in the return loss are due to the modeling of the microstrip tapers (stair-cased in MMT versus continuous in CST).

In order to provide a comparison with experimental data, Fig. 5 shows the responses of the MMT with square vias and prototype measurements with circular vias presented in [17] at the example of a three-resonator filter with off-center posts. In the MMT computation, the microstrip tapers at each end have been approximated by a three-step staircase function [13]. Moreover, the first set of vias at the input and output, which have been moved partly outside the bottom and top metallization in the prototype (Fig. 6 in [17]) are modeled slightly differently as shown at the top of Fig. 5.

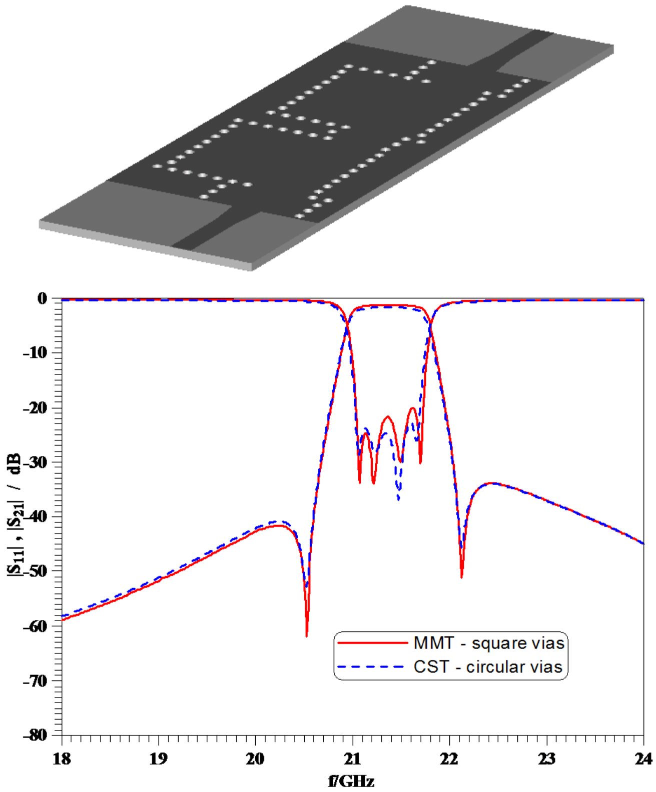

Figure 4. Comparison between square (MMT) and circular vias (CST) at the example of a four-pole SIW dual-mode filter.

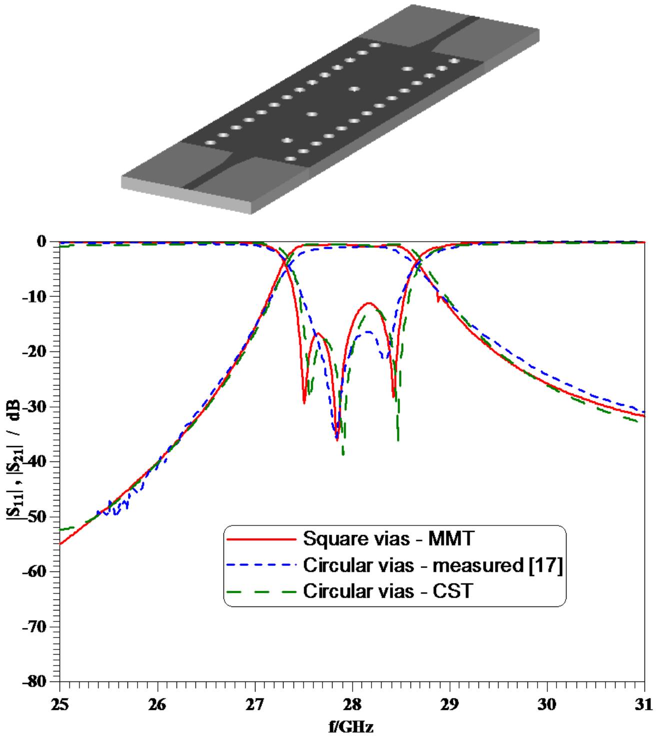

Figure 5. Comparison between square (MMT) and circular vias (measured [17] and CST) at the example of a three-resonator SIW filter with off-center posts.

The overall agreement between the simulations and measurements is very good for the filter at 28 GHz and thus demonstrates the applicability of the faster SIW filter design procedure using the MMT. The slight differences between the CST and MMT results are attributed to the fact that the microstrip transformers are modeled by a staircase approximation of three steps in the MMT whereas it is a continuous transformer in CST.

IV. CONCLUSIONS

Using equivalence between square and circular via holes speeds up substrate-integrated waveguide (SIW) filter design as it allows the use of a fast mode-matching technique in the initial design and final optimization stages. The actual component can be built using standard circular via holes with hardly any change in the filter response. Five filter examples including direct-coupled and quasi-elliptic configurations demonstrate that a via-shape conversion, which obtains the width of a square via hole from the arithmetic mean of the side lengths of the inscribed and circumscribed squares of the circular via, provides results acceptable for advanced filter design procedures. Excellent agreement is obtained with results of commercially available field solvers. The agreement with measurements on a three-resonator off-center post filter is very good and validates the basic design procedure presented in this paper.

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