

Efficient Design of Substrate Integrated Waveguide Power Dividers for Antenna Feed Systems

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Abstract—An efficient design technique for Substrate Integrated Waveguide (SIW) power dividers for applications in SIW antenna feed networks is presented. The analysis and optimization procedure employs mode-matching techniques using square via holes. A simple square-to-circular via hole conversion produces the final power dividers with only very little performance discrepancy between the components with square and circular via holes. Five power divider designs for K-band applications, ranging from two-way to four-way dividers, are presented and validated by commercial field solvers. Good agreement with measurements is demonstrated for a Ka-band two-way divider.

Index Terms—substrate integrated waveguide; feed networks; power dividers

I. INTRODUCTION

Substrate integrated waveguide (SIW) is a promising technology for planar antennas arrays in which antipodal linear tapered slot antennas (ALTSAs) are fed by a network of SIW power dividers [1] – [3]. These dividers have first been reported in [4], and Y- and T-junction SIW power dividers integrated with microstrip ports are proposed in [5] - [8].

The fastest approach for designing such structures is to apply design procedures known for all-dielectric-filled waveguide power dividers and then fine-optimize the divider in order to obtain a desired performance. In SIW technology, however, optimization is mostly carried out with commercially available field solvers such as CST Microwave Studio and ANSYS HFSS. This takes time and requires the designing engineer to be patient. In order to overcome this cumbersome process, analytical approaches based on modal techniques have been proposed recently, e.g., [9].

This paper focuses on the efficient design of SIW power dividers using a straight-forwardly implemented mode-matching technique (MMT) and a square-to-circular via hole conversion.

II. THEORY

In order to apply a simple MMT procedure, the SIW structure needs to be analysed in terms of discontinuities and straight waveguide sections. This is usually carried by analysing the structures in a sequence of slices, starting from the input and continuing until the output is reached.

Fig. 1 shows an example of a microstrip-to-SIW transition, a number of square via holes representing the SIW and an all-

dielectric output waveguide. Note that in practical applications, the microstrip taper is only used for access to measurement equipment. For SIW components to be integrated with other SIW structures, all-dielectric waveguide ports have been found to be more appropriate as they remove the taper behaviour from the SIW circuit response [10].

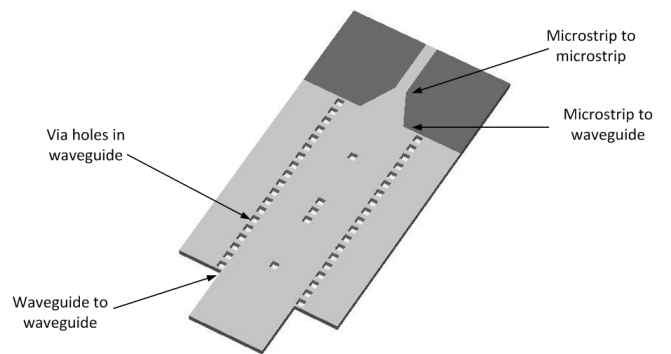


Figure 1. Individual discontinuities involved in the MMT analysis of SIW components.

For the MMT process, the individual discontinuities to analyse SIW circuits are: Microstrip to microstrip discontinuity, microstrip to all-dielectric waveguide discontinuity, a slice on N square via holes in an all-dielectric waveguide, and a waveguide to waveguide discontinuity. In all individual sections of Fig. 1, the electromagnetic field is derived from two electric and magnetic vector potentials as

$$\begin{aligned}\vec{E} &= \frac{1}{j\omega\epsilon} \nabla \times \nabla \times (A_{ez} \vec{e}_z) - \nabla \times (A_{hz} \vec{e}_z) \\ \vec{H} &= \frac{1}{j\omega\mu} \nabla \times \nabla \times (A_{hz} \vec{e}_z) + \nabla \times (A_{ez} \vec{e}_z)\end{aligned}\quad (1)$$

where only TE_{m0} modes (A_{hz}) are considered in SIW and all-dielectric waveguide sections. The microstrip line is modelled as an equivalent waveguide with magnetic sidewalls, e.g., [11]. Thus its mode spectrum is derived from vector potentials – the TEM mode from A_{ez} and the TE_{k0} modes from A_{hz} . For details on the complete formalism, the reader is referred to [9]. Note that losses are easily incorporated by considering the loss tangent of the dielectric and the conductivity of the metal for propagating modes in all individual waveguide sections.

Power dividers are multiport networks whose locations of input and output ports depend on the individual application. It is important to recognize that the MMT procedure related to the SIW part in Fig. 1 can handle an arbitrary number of via holes both in transverse and longitudinal direction. Therefore,

in order to incorporate the design of power dividers, a framework of multiple input and output ports is implemented in the MMT algorithm. Fig. 2a shows an example of a five-port network with three left and two right ports. The number of ports on each side is arbitrary as far as code implementation is concerned. However, if a scenario with no ports on one side is considered, such as the backward divider presented in Section IV, then a single port of extremely small width is implemented so that all possible modes in this port are below cutoff for the frequency range in question. The reader is referred to [12] for the MMT algorithm involving multipoint connections to SIW circuits.

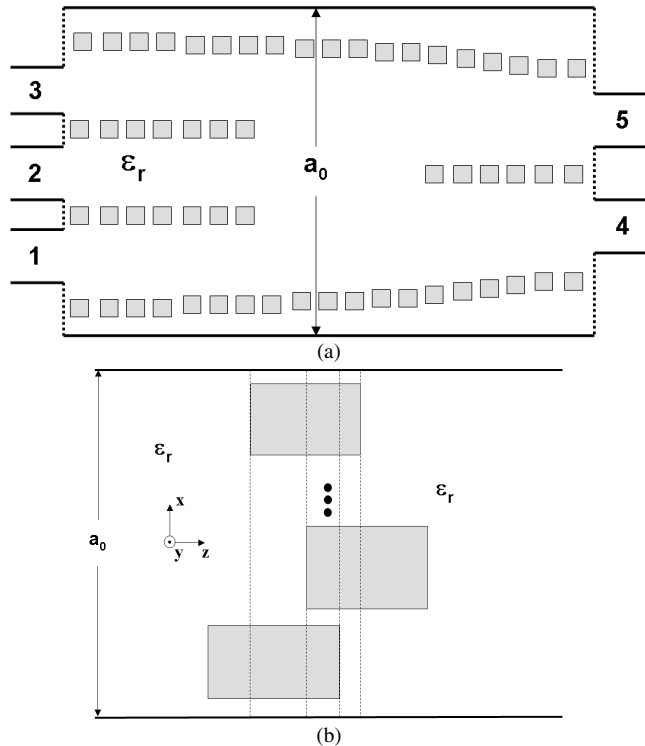


Figure 2. Multiport connections to SIW circuits (a), an example with three left and two right ports is shown. MMT segmentation (b) for the event of overlapping via holes.

So far, the MMT procedure allows for the analysis of a dielectric waveguide with an arbitrary number of square via holes and an arbitrary number of ports which can be either all-dielectric or microstrip ports [9, 12]. As MMT relies on the analysis of slices of homogeneous waveguide sections, an optimisation technique varying the positions of via holes might generate a scenario of so-called overlapping via holes where the vias are not confined within a single slice of an N -furcated waveguide. Such a scenario is shown in Fig. 2b along with the segmentation used in the MMT algorithm. The individual slices shown in Fig. 2b will be cascaded assuming a zero-length all-dielectric waveguide between them. In this way, the via holes in the SIW section of Fig. 2a can be placed at completely arbitrary locations within the encompassing waveguide of width a_0 , and the MMT analysis segments the individual slices according to the Fig. 2b.

III. DESIGN

With the MMT analysis framework in place, the design of a power divider proceeds as follows. First, the frequency range determines the width of the all-dielectric waveguide ports. The power divider in question is then designed and optimized in all-dielectric waveguide technology using MMT procedures and well-known waveguide design guidelines, e.g., [13]. In this step, the wall thickness between ports or between adjacent waveguides is already conforming to the via hole dimensions of the later-to-be-realized SIW component.

SIW or H-plane waveguide power dividers can be designed according to two basic principles. First, a waveguide N -furcation divides the input power into N output waveguides. However, the N -furcation usually represents a significant discontinuity which can be compensated only over a limited bandwidth. Therefore, power dividers based on waveguide bifurcation are not, under normal circumstances, capable of operating over an entire waveguide band. The second divider type employs waveguide coupler principles where an incoming waveguide couples to two or more adjacent guides. If the number of coupling sections is large enough, and this is certainly possible in SIW technology, then the bandwidth of such a power divider is much larger than that of an N -furcated divider and can cover an entire waveguide band.

Once the waveguide power divider's performance is found to conform to specifications, the individual waveguide sections are translated to SIW circuits with square via holes by considering the equivalent width of the SIW, e.g., [14].

The so-obtained SIW power divider is analysed and fine-optimized [15] with the MMT algorithm. In this step, the MMT procedure displays its full advantage. Since a single analysis over a given set of frequency points is at least, depending on code implementation, ten times faster than HFSS or CST, a fine-tuning run with n optimization steps will at least be $10n$ times faster than a comparable optimization in HFSS or CST.

With the positions and locations of all via holes known, the final step consists in translating the square via holes into circular ones which are more amenable to standard printed-circuit fabrication techniques. The conversion adopted in this work is based on an investigation presented in [16]. Among equivalences presented in that paper, approximating a circular via with a square via with side length equal to the arithmetic mean of the side lengths of inscribed and circumscribed squares of the circular via has shown the best match in our simulation results [12, 17]. Thus every square via in the SIW power divider optimized with the MMT algorithm is replaced by a via whose diameter $d_{circular}$ is related to the side length l_{square} of the square via by

$$d_{circular} = 2l_{square} / (1 + 1/\sqrt{2}) \quad (2)$$

The power dividers presented in the next section will demonstrate the validity of the conversion in (2).

IV. RESULTS

Five K-band power dividers with waveguide ports have been designed and analyzed using the MMT procedure with

square via holes. The final configurations are then recomputed with CST Microwave Studio employing circular via holes. The substrate is chosen as RT/duroid 6002 with $\epsilon_r=2.94$, substrate height $b=0.508$ mm and metallization thickness $t=17$ μm . The diameters of the circular vias are chosen as $d_{\text{circular}}=0.644$ mm so that the side lengths of the equivalent square vias are $l_{\text{square}}=0.55$ mm according to (2). The ports are set for a cutoff frequency of 15 GHz with a normal operating band between 18 GHz and 28 GHz.

Fig. 3 shows a 3dB H-plane SIW bifurcation power divider with all-dielectric waveguide ports. First of all, excellent agreement is observed between results obtained with the MMT using square via holes and CST with circular via holes. Secondly, this being a divider based on SIW bifurcation, the 15 dB return loss bandwidth covers a frequency range between 17 GHz and 24.6 GHz. Thus the fractional bandwidth is 36.5 percent.

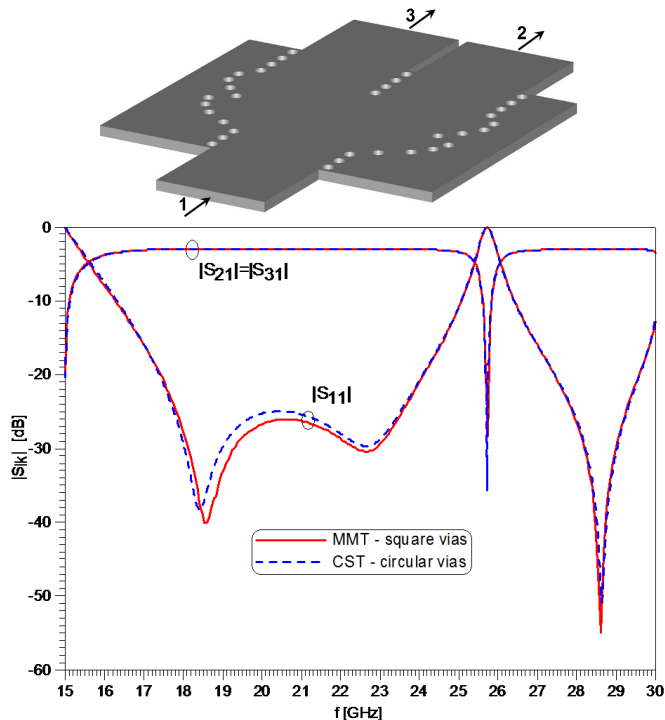


Figure 3. Layout and performance comparison between results obtained with MMT (square via holes – solid lines) and CST (circular via holes – dashed lines) for a 3 dB K-band SIW bifurcation power divider.

Fig. 4 depicts the layout and performance of an asymmetric K-band SIW power divider which is designed for 10dB power division using H-plane coupler principles. Due to ten coupling sections, the return loss of this divider is below 30 dB over the entire 18 – 28 GHz range (43.5 percent). As is typical for H-plane waveguide couplers, e.g. [13], the signal to the coupled port varies between -6.6 dB at 18 GHz and -11.2 dB at 28 GHz. Excellent agreement is again observed between the MMT results with square via holes and the ones from CST with circular vias.

In some applications, input and output ports of a power divider have to be accessible at the same interface. Such a so-called backward-coupled divider in SIW technology is presented in Fig. 5. However, since the backward coupling is

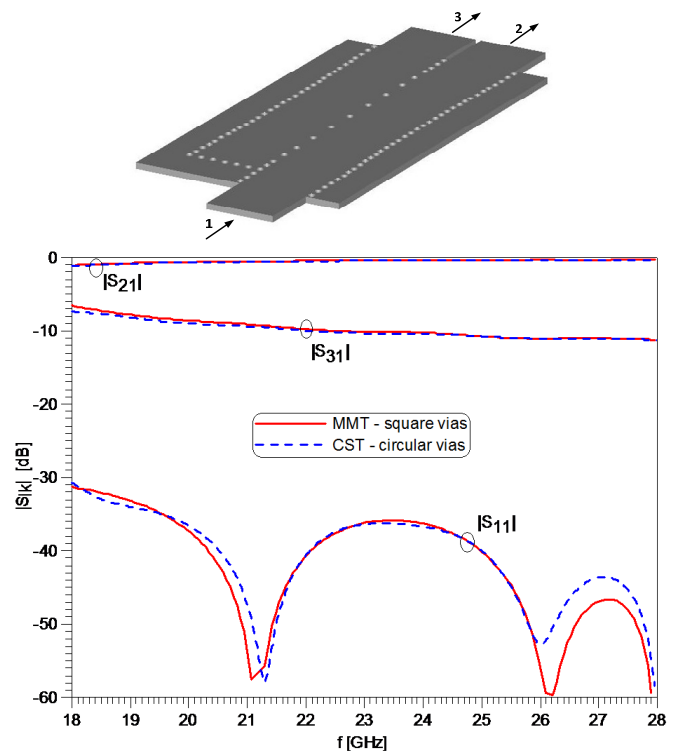


Figure 4. Layout and performance comparison between results obtained with MMT (square via holes – solid lines) and CST (circular via holes – dashed lines) for a 10 dB K-band SIW power divider based on 10 coupling sections.

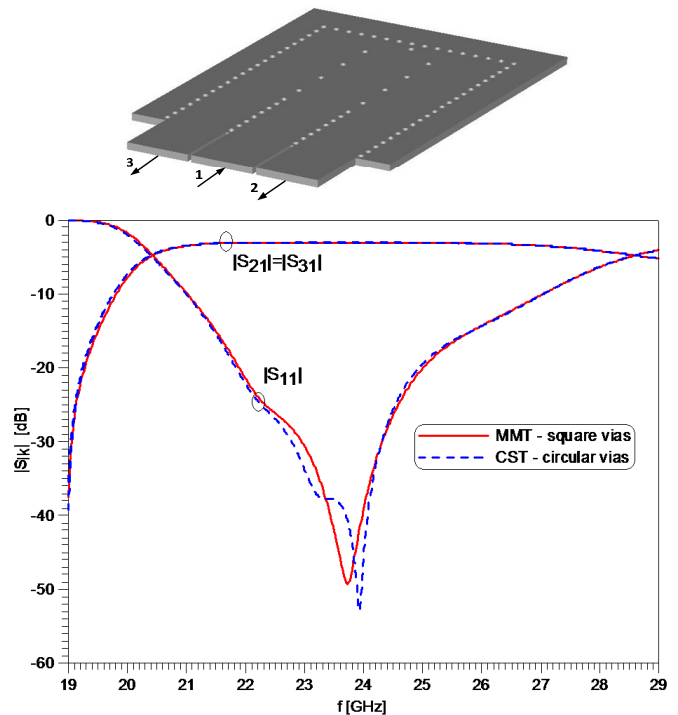


Figure 5. Layout and performance comparison between results obtained with MMT (square via holes – solid lines) and CST (circular via holes – dashed lines) for a 3dB K-band backward-coupled SIW power divider.

achieved by placing a short at the far end of the divider, it is more susceptible to frequency changes. Thus the 15 dB return loss bandwidth is only 18.2 percent (21.5 – 25.8 GHz). Note

again the excellent agreement between results with the MMT and CST. As in previous comparisons, differences are observed only below the -20 dB value.

The coupled guide principle is now applied to a 3-way (4.77 dB) SIW power divider as shown in Fig. 6. The return loss is better than 15 dB over the entire 18 – 28 GHz range (43.5 percent), but the coupling varies slightly between the through port (port 3) and the coupled ports (ports 2 and 4) – as expected from typical H-plane waveguide couplers.

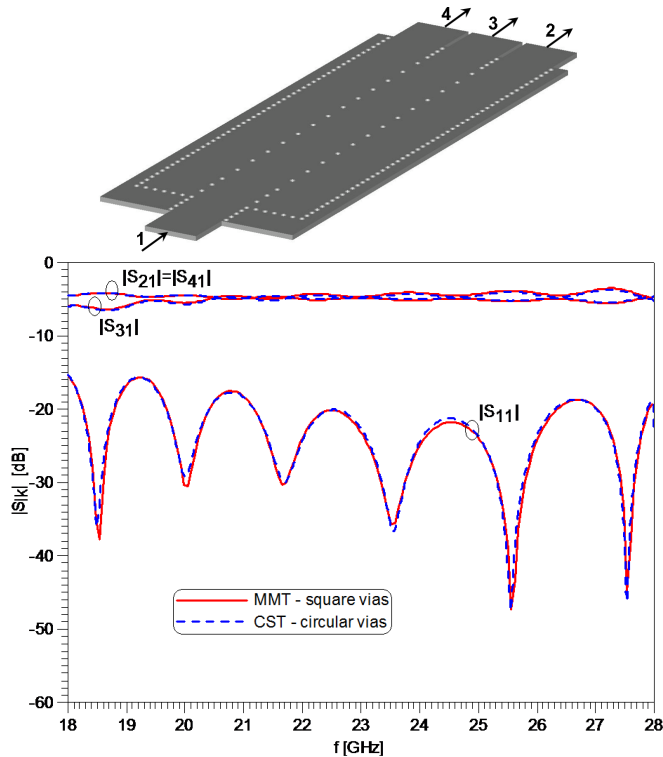


Figure 6. Layout and performance comparison between results obtained with MMT (square via holes – solid lines) and CST (circular via holes – dashed lines) for a 3-way (4.77 dB) K-band SIW power divider based on 17 coupling sections.

Of course, the individual dividers presented above can now be combined to create an entire antenna array feed network in SIW technology. However, as more of them are combined, especially those based on the bifurcation principle, the bandwidth will be reduced due to the limited bandwidths of the individual dividers. This is demonstrated in Fig. 7 for a 4-way (6 dB) divider based on three individual 2-way bifurcation dividers. The return loss is 15 dB between 19.8 GHz and 24.6 GHz (21.6 percent) which is a 14.9 percent bandwidth reduction compared to the individual SIW 2-way divider presented in Fig. 3. Again note the excellent agreement between the MMT and CST for this power divider with a rather complex arrangement and locations of via holes.

Finally, Fig. 8a compares the MMT results with measurements of a Ka-band 3dB H-plane SIW power divider with microstrip ports as presented in [5]. This divider was built on RT/Duroid 5880 substrate with $\epsilon_r=2.2$, substrate height $b=0.254$ mm and metallization thickness $t=17$ μm . The agreement between measurements and both MMT and CST is acceptable but not as good as compared to previous results.

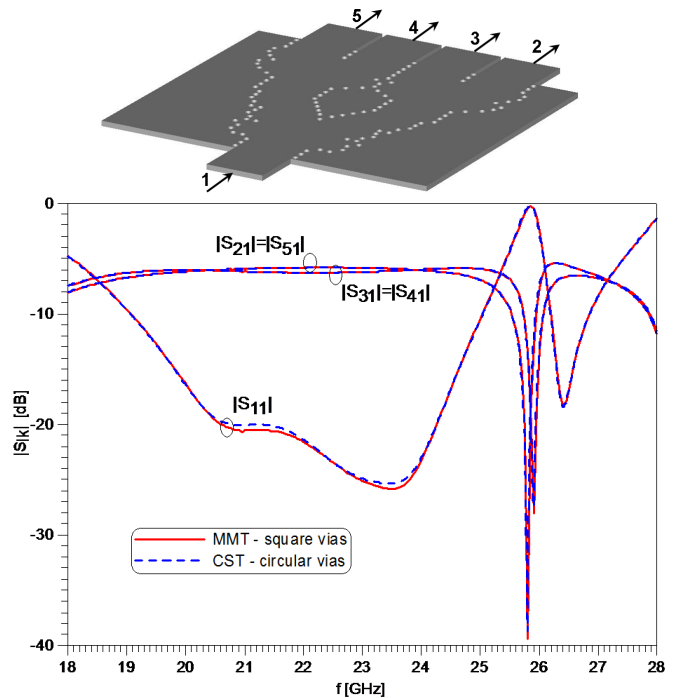


Figure 7. Layout and performance comparison between results obtained with MMT (square via holes – solid lines) and CST (circular via holes – dashed lines) for a 6-way (6 dB) K-band SIW bifurcation power divider.

This is due to the following reasons. First, reflection and transmission measurements in [5] were carried out in a two-port set-up where the third microstrip port was covered with absorbing material. This can introduce some reflection which will propagate back to the input (port one) and the other output port (port 2). Secondly, the differences between MMT and CST are due to the staircase approximation of the microstrip tapers in the MMT algorithm [9]. This is demonstrated in Fig. 8b where the same divider is analysed with waveguide ports. It is observed that the agreement between MMT and CST is significantly improved compared to Fig. 8a. The remaining small differences between MMT and CST in Fig. 8b are due to the different modelling of the vias at the input and output ports. They cover the top metallisation (inset in Fig. 8a) only partly and extend into the substrate. In MMT, they were modelled as half vias.

V. CONCLUSIONS

Substrate-integrated waveguide power dividers with both waveguide and microstrip ports are effectively modelled and designed by a simple and straightforward mode-matching approach which uses square via holes for an efficient code implementation. A simple conversion from square to circular vias allows for a direct implementation of the SIW dividers by standard printed-circuit board fabrication processes. Design examples of five different K-band SIW dividers based on both bifurcation and coupler principles demonstrate the validity of the design approach. Excellent agreement between the MMT results with square via holes and those of CST with circular vias is obtained. Comparisons with measurements are deemed acceptable in practical applications but show some discrepancies based on the measurement technique and the modelling of the microstrip-to-SIW transformers.

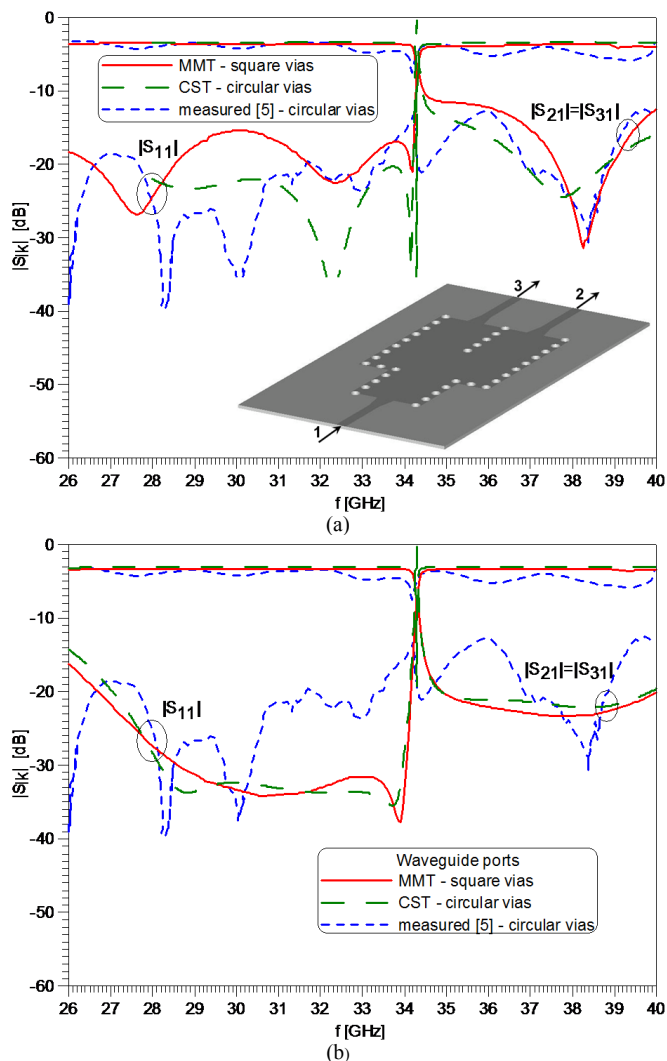


Figure 8. Layout and performance comparison between results obtained with MMT, CST and measurements according to [5] for a 3 dB SIW bifurcation divider; (a) microstrip ports in MMT and CST, (b) waveguide ports in MMT and CST.

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