# Mode Matching Design of Substrate Integrated Waveguide Diplexers

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*Abstract* — **A K-band diplexer based on Substrate Integrated Waveguide (SIW) technology is presented. The diplexer has input and output ports on opposite sides and bandwidths of 2.75 percent and 2.11 percent at 18.15 GHz and 19 GHz, respectively. The diplexer is designed using an efficient Mode-Matching Technique (MMT), verified by CST and prototyped. Measured results are in good agreement with theory and simulation results and show good isolation between the channels. Attenuation towards higher frequencies is better than 40 dB up to 25 GHz. The measured insertion losses are 3.05 dB in the lower band and 2.3 dB in the upper band.**

*Index Terms* — **Multiplexing, microwave filters, waveguide junctions, numerical simulation, microwave integrated circuits, microwave measurements.**

## I. INTRODUCTION

Over the past ten years, Substrate Integrated Waveguide (SIW) technology has shown great promise to replace conventional waveguide structures by planar circuitry. The technology inherits merits from conventional waveguide technology, such as low loss and good Q-factor, as well as from planar circuits which are known for their low cost, low profile and ease of integration. Consequently, numerous microwave and millimeter-wave components have been designed in SIW technology in the past decade. Especially the numbers of filter structures that have been converted from all-metallic waveguide to SIW circuits are enormous. It is thus surprising that only a few SIW diplexer designs have been reported.

Diplexers are essential structures in front-end systems in order to separate transmit and receive bands. A 10 GHz SIW diplexer using asymmetric dual-mode iris filters in a branching-ports configuration is proposed in [1]. A similar configuration with single-mode iris filters operates at 6 GHz [2]. The one presented in [3] has input and output ports on opposite sides of the substrate and uses iris filters, including a tri-section, at 12 GHz. A T-junction diplexer with iris filters is presented for 61 GHz in [4]; however, the performance is not verified by measurements. The T-junction SIW diplexer in [5] uses complementary split-ring resonators at 6 GHz. A 2 GHz SIW triplexer is reported in [6], but the insertion loss in one of the channels is in the order of 7 dB. Finally, a diplexer operating at 26 GHz [7] uses dual-mode SIW filters with circular and elliptic cavities.

In this paper, a K-band SIW diplexer is introduced that has been designed using an efficient Mode-Matching Technique (MMT) proposed for SIW structures [8, 9]. The SIW diplexer is similar in configuration to [3], [6] but operates at a significantly higher frequency. The structure is fabricated, and experimental results are in good agreement with simulations.

## II. THEORY AND DESIGN PROCEDURE

As the first step in the diplexer design, direct coupled all-dielectric waveguide iris filters are synthesized [10] using the MMT. During this step and the following fine optimization of the waveguide (not SIW) diplexer, the lengths of the resonators are fixed so that their equivalent lengths [2] fall within the given via-diameter-to-spacing ratio of the later to be implemented SIW structure. This limits the number of optimization parameters for the SIW diplexer as only cavity widths and aperture widths need to be optimized.

The second step consists in translating the entire all-dielectric waveguide diplexer into SIW technology. The procedure presented in [8] demonstrates the analysis of SIW slices by the MMT including connections to tapered microstrip lines. This technique uses square via holes. The extension to circular vias, which are required for fabrication, and the extension to multiple ports are detailed in [9]. A fine optimization with the MMT, which is at least an order of magnitude faster than field solvers such as HFSS or CST, varies the transverse position of all via holes until a given return loss and attenuation has been reached. Note that this might not necessarily lead to a performance where all possible reflection zeros are shown. Also, the maximum number of resonators was kept to five in order to keep the prototype short enough to fit into a universal test fixture for prototype measurement purposes.

In order to measure the diplexer prototype, SIW ports are being fitted with SIW-to-microstrip tapers. The initial parameters of the taper are chosen according to [11] and are then optimized to reach the best performance. As the two output ports of the diplexer are located close to each other, two separate structures were built. In each of the two structures, one of the output ports is curved in order to provide access with measurement equipment to the respective other port. The parameters of the bent microstrip ports, $R_c=2W_m$, $\alpha=\pi/2$, are based on the data presented in [12], where $R_c$ is the radius of the bend, $W_m$ the microstrip width, and $\alpha$ the curve angle. The structures are presented in the next section.

## III. RESULTS

For the design of the K-band diplexer, RT/duroid 6002 with $\varepsilon_r$=2.94 is chosen as substrate. Its height is 0.508 mm, and the

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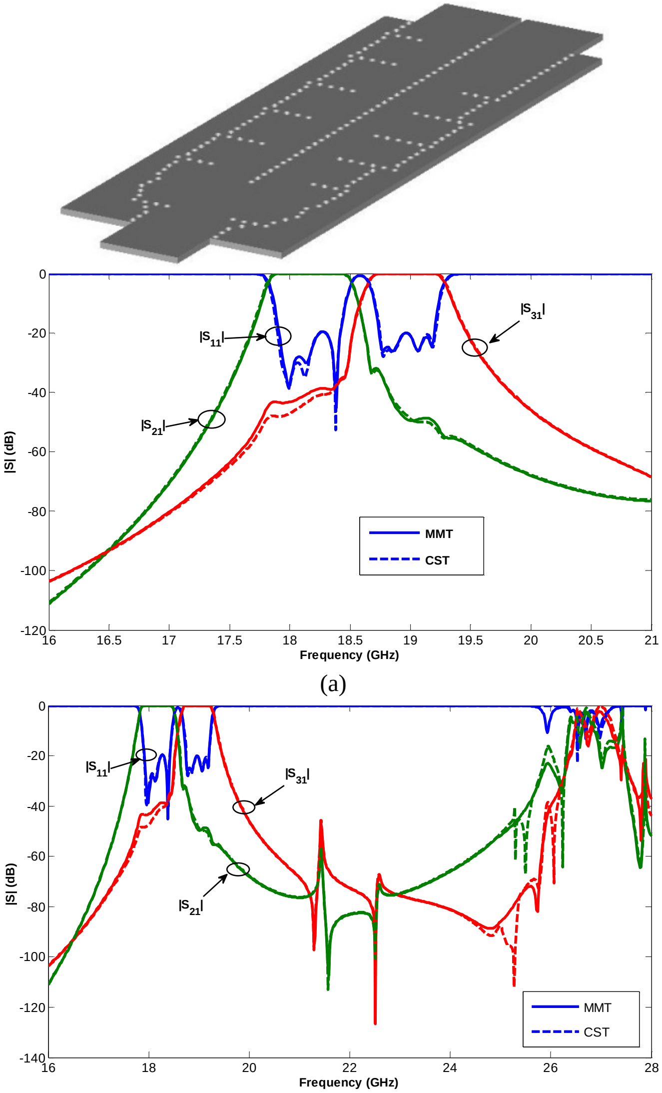
metallization thickness is 17µm. The loss factors are $\tan\delta=0.0012$ for the dielectric and $\sigma=5.8\text{x}10^7$ S/m for the copper layers and vias. The longitudinal center-to-center spacing of via holes is set to $p$=1 mm.

Fig. 1a depicts the layout, with five and four resonators in the lower and upper frequency channels, and performance of the diplexer with waveguide ports. This is an inline diplexer similar to [3], [6], where input and output ports are located on opposite sides of the substrate. For the design with the MMT, the square vias were chosen to have side lengths of 0.55 mm so that the equivalent circular via diameters are $d$=0.644 mm [9]. This diplexer is designed for bandwidths of 17.9 GHz to 18.4 GHz and 18.8 GHz to 19.2 GHz, respectively, which resemble those of 19 GHz satellite specifications. The comparison between the MMT design using square vias and the CST results with circular vias is excellent. Note that the performances shown in Fig. 1 are calculated without the consideration of losses in order to demonstrate the concept. Losses can easily be implemented as shown in [9]. In order to demonstrate attenuation properties towards higher frequencies, Fig. 1b shows the performance over an extended frequency range up to 28 GHz. It is observed that the attenuation is better than 40 dB up to 25 GHz where the harmonic filter responses start to appear.



(a)

(b)

Fig. 1 (a) Layout of the diplexer and comparison between the MMT data with square vias and CST data with circular vias for the K-band SIW diplexer with waveguide ports; (b) extended frequency range.

In Fig. 2, the same structure is shown with SIW-to-microstrip transitions at all ports. The width of the microstrip ports is $W_m$=1.523 mm, and the widths and lengths of the tapers after optimization are 2.321 mm and 2.729 mm, respectively. In the MMT analysis, the taper is approximated by small microstrip step discontinuities. That is the reason for the fact that the agreement between the MMT and CST is not as good as in Fig. 1 where waveguide ports are used.

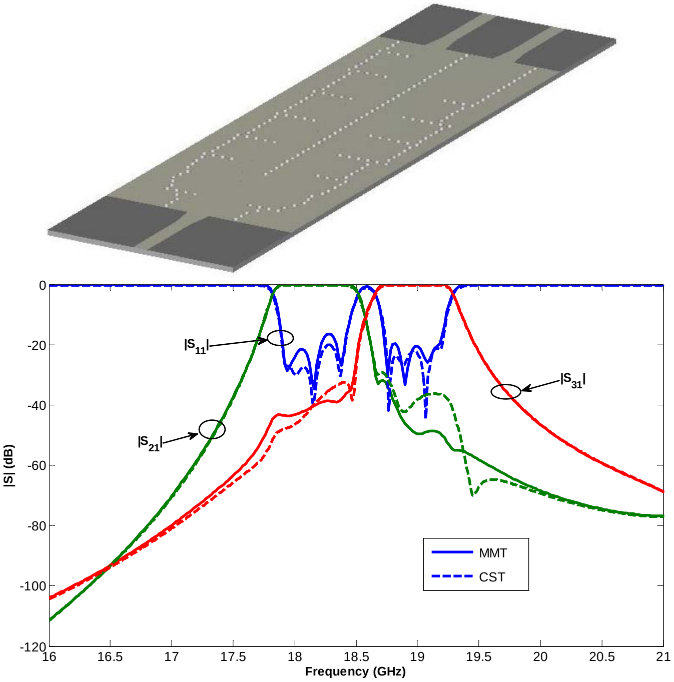


Fig. 2 Comparison between the MMT data with square vias and CST data with circular vias for the K-band SIW diplexer with microstrip ports.

Photographs of the fabricated diplexer prototypes are shown in Fig. 3. Although the taper can be included in the MMT analysis, the microstrip-to-SIW transitions have been deembedded in the measurements. As pointed out earlier, the two circuits are necessary to gain access to the respective ports by a universal test fixture. During transmission measurements, the curved ports were terminated by absorbing material.

Fig. 4 shows a comparison between measurements and the MMT and CST predictions. Measured inband insertion losses are 3.05 dB and 2.3 dB compared with 2.0 dB and 1.8 dB, respectively, in the MMT analysis. The minimum measured return loss in the two bands is 18 dB and 15 dB, respectively, compared to about 20 dB in the simulation. This difference is explained by the absorbing material used for the curved ports in the measurements (Fig. 3). This material, when placed on top of the curved microstrip ports, does not represent a matched load. Moreover, these ports could not be deembedded from the measurements so that the SIW-to microstrip taper contributes to the reflection of such ports. Also a slight shift of the measurements towards higher frequencies is observed. This is due to the fact that the via holes of designed diameter *d*=0.644 mm have been manufactured with an actual drill size of 0.65 mm.

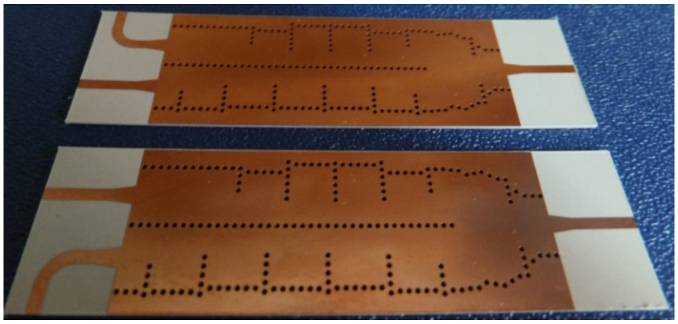


Fig. 3 Photograph of the two fabricated diplexer prototypes with microstrip ports.

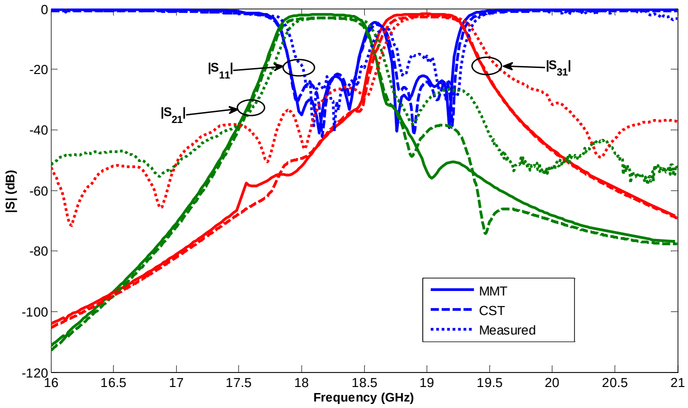


Fig. 4 Comparison between measurements and simulation (MMT and CST) for the diplexer prototypes shown in Fig. 3.

The general transmission curves are also reproduced but differences in the slopes of the respective passbands are observed. We can only attribute these discrepancies to the measurement procedure. The actual positions and sizes of via holes have not been measured. However, the measurements confirm in principle the simulations and the design procedure.

## IV. CONCLUSION

SIW diplexers are efficiently designed using MMT procedures. This is demonstrated for the example of a K-band diplexer in inline configuration with center frequencies of 18.15 GHz and 19 GHz. The experimental results verify the design process in principle. Measured inband insertion losses are 3.05 dB and 2.3 dB, and attenuation towards higher frequencies is better than 40 dB up to 25 GHz.

## ACKNOWLEDGEMENT

The authors wish to acknowledge funding for this work by the Natural Science and Engineering Research Council of Canada.

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