# Substrate-Integrated Waveguide Filter Design Using Mode-Matching Techniques

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***Abstract*— Mode-matching techniques are employed for the analysis and design of substrate-integrated waveguide (SIW) filters. Recently developed fabrication techniques based on rectangular-shaped via holes facilitate a straight-forwardly implementable and powerful CAD code. Only two principle discontinuities, dielectric-to-dielectric waveguide and dielectric waveguide to multiple via-hole section, are involved. The basic theory, especially with respect to the treatment of sections with an arbitrary number of via holes, is presented. Design examples include a SIW metal-insert filter, a SIW inductive-iris filter and a SIW dual-mode filter with one transmission zero. Results are validated by comparison with the commercially available field solver CST Microwave Studio.**

***Index Terms* — Substrate-integrated waveguide technology, microwave filters, mode-matching techniques, computer-aided design.**

## I. Introduction

A reasonable compromise between microstrip and waveguide technologies, substrate-integrated waveguide (SIW) components have emerged as low-cost and planar alternatives [1], especially in the lower millimeter-wave frequency regime [2], [3]. Here they balance the losses of microstrip circuits with the bulkiness of waveguides.

The design of SIW components, as abundantly presented in the recent literature, is mostly carried out by employing commercially available field-solver packages, of which CST Microwave Studio and Ansoft's HFSS are the most prominent ones. Although these codes achieve excellent numerical accuracy, their numerical effort in circuit optimization is time-consuming, especially if component optimization/fine-tuning is required. In order to increase efficiency in the design process, other methods, which are more geared towards waveguide-based analysis and design, are in demand. Two such methods have surfaced: the Boundary Integral – Resonant Mode Expansion (BI-RME) technique, which is used for equivalent-circuit extraction in [4]; and the Mode-Matching Technique (MMT), which is primarily used to analyze dispersion effects in SIW circuits, e.g. [5].

Recently, new fabrication techniques have allowed the cross sections of via holes to become more arbitrary, e.g. [2], [6], and rectangular and square via cross sections have successfully been implemented and their performance experimentally verified [7]. Thus one of the restrictions in applying straight-forward MMT approaches, namely the circular shape of the via holes with respect to the Cartesian coordinate in traditional SIW circuits, has been removed, and the regular MMT in a rectangular coordinate system can be applied.

Therefore, this paper presents a MMT approach for the analysis and design of filters in SIW technology. Through the use of square via holes, an efficient MMT procedure following fundamental MMT principles in [8] is obtained. Moreover, the computational domain is reduced by using a low-reflective all-dielectric waveguide feed [9].

## II. Theory

As an example of a SIW filter with square via holes, Fig. 1 depicts the SIW equivalent of a two-resonator metal insert filter.

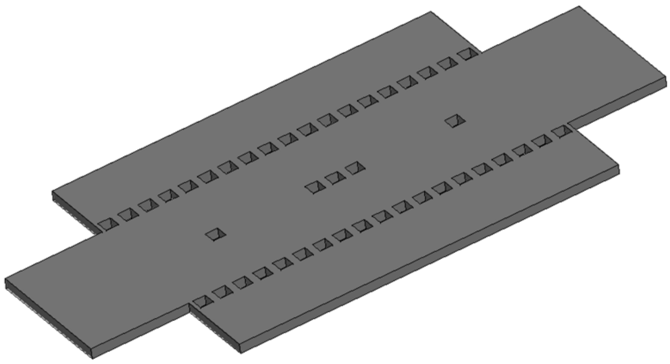


Fig. 1. Substrate-integrated waveguide filter with square via holes and all-dielectric interface ports..

In order to analyze the filter in Fig. 1 with an MMT algorithm, two basic discontinuities need to be solved: first, the transition between two all-dielectric waveguides of different width at the port interfaces and, secondly, an arbitrary number of rectangular via holes within an all-dielectric waveguide of width of the substrate.

The top view of the input port and its transition to a number N of via holes is shown in Fig. 2. The left discontinuity (superscripts F and D) represents the all-dielectric port transition to the dielectric substrate. Perfect electric (PEC) and perfect magnetic conductors (PMC) are used to define the boundary conditions. The right discontinuities (superscripts 0, 1 … N, and 0L) show a number of N-1 vias embedded in the dielectric substrate. Note that the vias can be of rectangular shape by varying widths $a_n$ and length L. (Note that in Fig. 2, the lengths of vias are exaggerated for showing wave amplitudes.)

In each region $\nu \in \{F, D, 0, n=1\ldots N, 0L\}$, the $TE_{m0}$-mode based vector potential is written as

$$A_{hz}^{\nu} = \sum_m \sqrt{Z_m^{\nu}} A_m^{\nu} \cos\left\{\frac{m\pi}{a_{\nu}}(x - x_{\nu})\right\} \cdot \left[F_m^{\nu} \exp\left(-jk_{zm}^{\nu} z\right) + B_m^{\nu} \exp\left(+jk_{zm}^{\nu} z\right)\right] \quad (1)$$

where F and B are forward and backward travelling wave amplitudes, respectively; $k_z$ are the propagation constants, A the normalization coefficients, Z the wave impedances and $x_{\nu}$ the lowest coordinate in the respective region.

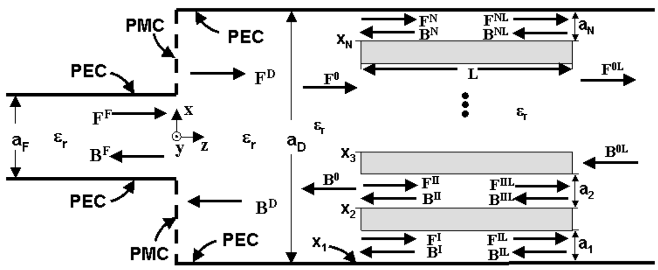



Fig. 2. Basic discontinuities and boundary conditions involved in the mode-matching process.

Following basic MMT procedures, the modal scattering matrix of the left discontinuity is obtained straight-forwardly, e.g. [8]. The discontinuity from the dielectric substrate to the N-furcated waveguide requires a reorganization of wave amplitudes. Recognizing that the number of modes in a subsections n is much smaller than that in the dielectric substrate, the matrix equation for the modal wave amplitudes, e.g. for N=4, can be written as

$$\begin{bmatrix} \left| F^0 + B^0 \right| \end{bmatrix} = \underbrace{\begin{bmatrix} \left|M^1\right| & \left|M^2\right| & \left|M^3\right| & \left|M^4\right| \end{bmatrix}}_{M} \begin{bmatrix} \left|F^1 + B^1\right| \\ \left|F^2 + B^2\right| \\ \left|F^3 + B^3\right| \\ \left|F^4 + B^4\right| \end{bmatrix} \quad (2)$$

where the size of wave amplitude vectors and coupling matrices M are indicated by the bars. Combining the right side vectors to a single vector, the modal scattering matrix is obtained as

$$\begin{aligned} S_{11} &= \left[MM^T + U\right]^{-1}\left[MM^T - U\right] \\ S_{12} &= 2\left[MM^T + U\right]^{-1} M = S_{21}^T \\ S_{21} &= M^T\left[U - S_{11}\right] = S_{12}^T \\ S_{22} &= U - M^T S_{12} \end{aligned} \quad (3)$$

with U being the unit matrix and T meaning transposed.

The scattering matrix of N-1 vias embedded in the dielectric substrate is obtained by cascading a diagonal matrix containing the mode propagation up to half the of the via length L. The diagonal matrix for a single subregion n is given by

$$D^n = \mathrm{Diag}\left\{\exp\left(-jk_{zm}^n \frac{L}{2}\right)\right\} \quad (4)$$

The resulting modal scattering matrix is cascaded by the same scattering matrix but with input and output ports interchanged. Following general procedures of cascading scattering matrices, e.g. [8], the overall modal scattering matrix of a SIW filter is obtained.

The design of a filter is carried out by using existing procedures for dielectric-filled metal waveguides. The translation of the dimensions into an SIW structure uses a code that iteratively determines the via positions and via spacings from the equivalent waveguide width [10] of the dielectric-filled metal waveguide model. Fine optimization of the SIW filter completes the design.

## III. Results

The examples shown in this paper are designed on RT Duroid 5880 with a relative permittivity of $\varepsilon_r$=2.2 and a substrate height of h=508μm. The frequency range of interest is 18 GHz to 28 GHz, thus a cutoff frequency of approximately 15 GHz was chosen for the SIW input/output ports which, following guidelines in [10], leads to circular vias of diameters of 0.72 mm and longitudinal centre-to-centre spacing of 1.02 mm. The centre-to-centre width of the SIW is $a_{via}$=7.28 mm, and the equivalent waveguide width is $a_{equ}$=6.71 mm [10]. Square vias are derived from the circular ones by maintaining the cross-section area of the vias. Thus all via holes used in this work have a cross section of 0.64 mm x 0.64 mm. As far as mode numbers are concerned, all results have been obtained considering all modes up to 500 GHz for at discontinuities and up to 250 GHz for modal scattering matrix combinations. Note that all designs require only odd $TE_{m0}$ modes.

For the computer-aided design of SIW filters, it is important that discontinuities between the all-dielectric ports and the actual SIW substrate refrain from affecting the filter performance. Therefore, Fig. 3 demonstrates the back-to-back performance of ports connected to an SIW circuit of ten dual vias (inset of Fig. 3). The port width is $a_{equ}$=6.71 mm and the width between vias is $a_{via}$=7.28 mm measured centre to centre. As observed from Fig. 3, the port-discontinuity influence is below 50 dB as verified by CST. Note that this agreement is remarkable since the two curves that are compared at such a low level.

Fig. 4 shows the performance of the two-resonator metal insert filter in SIW technology as depicted in Fig. 1. The filter is initially designed using a standard dielectric-filled metal-insert filter synthesis routine [8] within a waveguide of width $a_{equ}$. Since the width of the vias have been used as insert thickness and as the minimum insert length in the waveguide design, porting the dimensions to SIW technology is straightforward. For the performance of the SIW filter in Fig. 4, excellent agreement is observed between the results of the MMT approach and those of CST, thus verifying the correctness of the MMT modelling process presented in this paper. It is also worth noting that the response of the pure metal-insert filter (not shown here), which is formed within an all-dielectric waveguide housing of width $a_{equ}$ and centre insert length of the combined three-via section in Fig. 1, falls within the plotting accuracy of the solid line in Fig. 4.

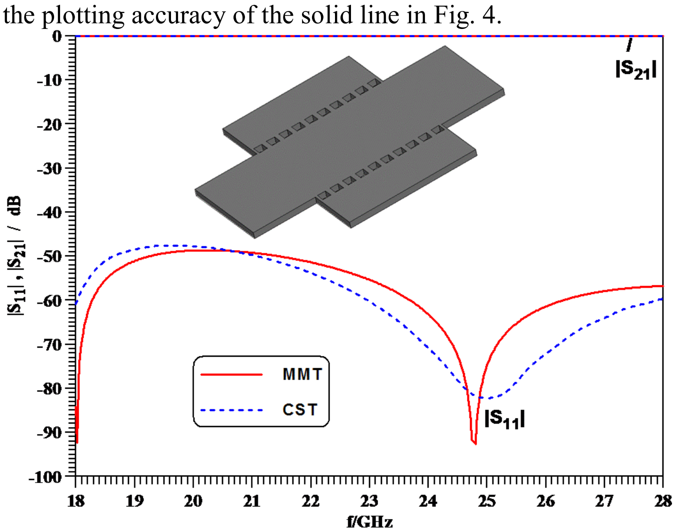



Fig. 3. Performance of back-to-back all-dielectric waveguide ports separated by 10 dual via holes; comparison between this method (solid lines) and CST (dotted lines).

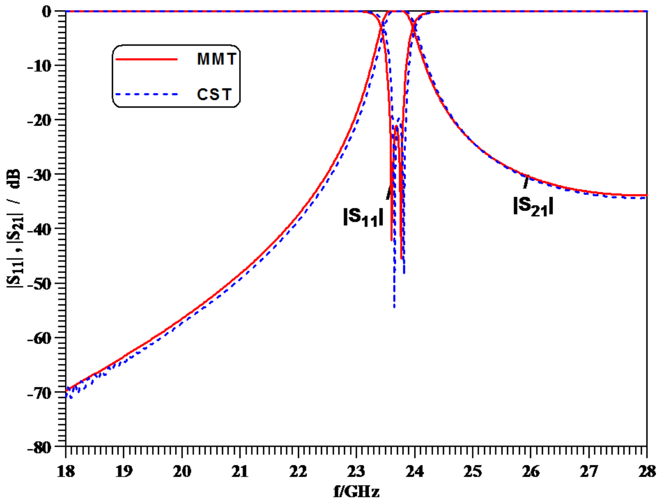
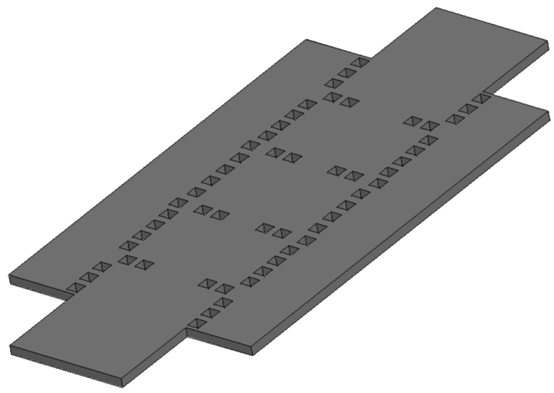



Fig. 4. Performance of the two-resonator SIW filter (solid lines) shown in Fig. 1 and performance comparison with results obtained with CST (dotted lines).

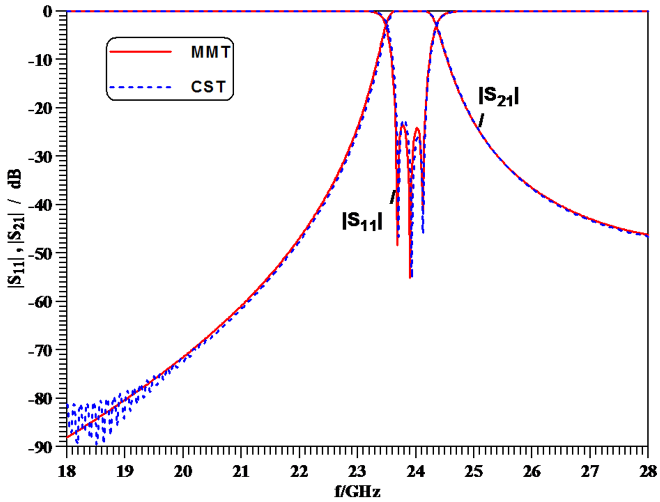
Fig. 5a shows the SIW equivalent of a three-resonator inductive-iris filter. The filter was designed for a midband frequency of 23.9 GHz and a 20 dB return-loss bandwidth of 520 MHz. Fig. 5b shows its performance and a comparison between results obtained with the MMT (solid lines) and those of CST (dotted lines). Excellent agreement is observed. Note that for the CST simulations, the accuracy is set to the minimum limit of -80 dB, which explains the oscillatory behaviour of the $|S_{21}|$ response between 18 GHz and 20 GHz.

As an example of a more sophisticated filter design, Fig. 6a shows the SIW version of a dual-mode in-line microwave filter which, in all-metal rectangular waveguide technology, is presented in [11]. The design features a dual-mode resonator employing $TE_{102}$ and $TE_{301}$ modes and a single-mode resonator operating in the $TE_{101}$ mode only.

Midband frequency and bandwidth specifications are 23 GHz and 560 MHz, respectively. Due to the square-via dimensions, which influence the minimum thickness of the coupling apertures, and the proximity of the transmission zero at 22.56 GHz to the passband, the achievable return loss is only 17 dB. Fig. 6b shows the direct comparison between the MMT and CST. Excellent agreement is observed in general and specifically for the location of transmission and reflection zeroes. The minimum passband return loss as computed by CST is 13.8 dB.



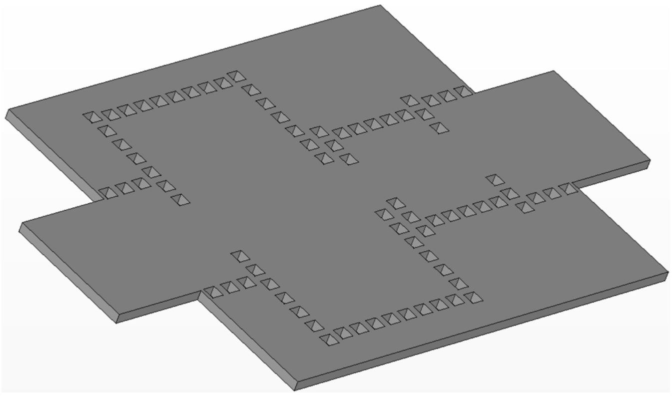
(a)



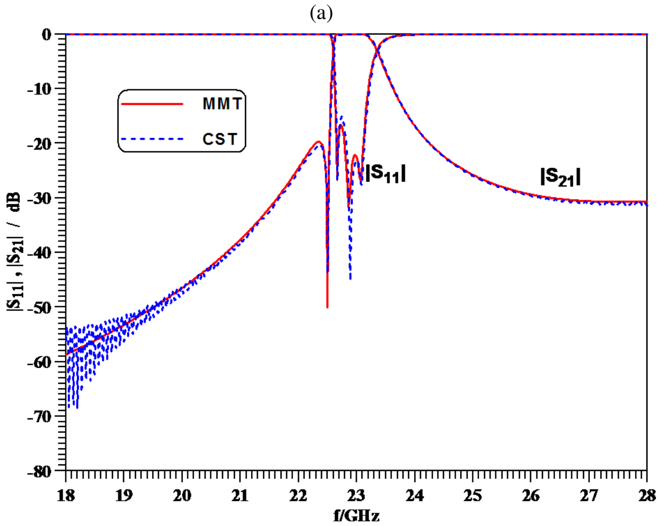

(b)

Fig. 5. A three-resonator inductive-iris filter in SIW technology (a) and performance comparison (b) between this method (solid lines) and CST (dotted lines).

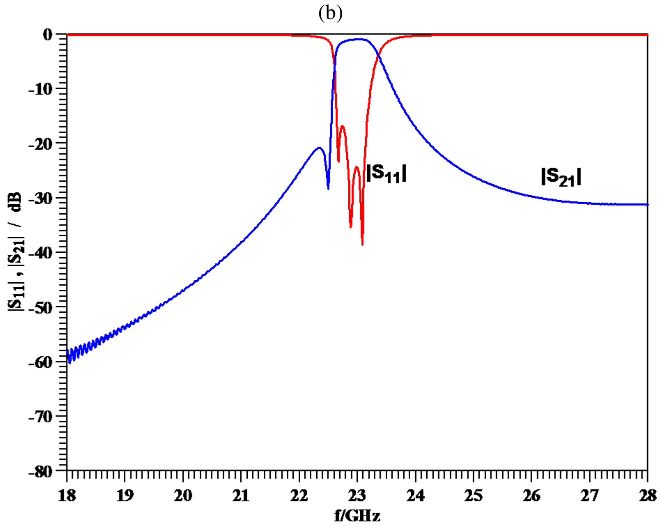
In order to estimate the unloaded Q of the resonators, the filter in Fig. 6a has been analysed in CST including all dielectric and metallic losses. The respective performance is shown in Fig. 6c. The midband frequency insertion loss is 1.03 dB. Assuming that the return loss behaviour is nearly equi-ripple for the same bandwidth and employing commonly used approximations known from [12], the unloaded Q of the resonators in this filter is around 550. This compares well with the general notion that at or close to the millimetre-wave frequency range, SIW technology is a fair compromise between microstrip circuitry and all-metallic waveguides.



(a)




(b)




(c)

Fig. 6. A three-pole H-plane filter in SIW technology using a dual-mode and a single-mode cavity (a), performance comparison (b) between this method (solid lines) and CST (dotted lines), and CST analysis including all losses (c).

## IV. Conclusions

It is demonstrated that mode-matching techniques are a viable option for the analysis and design of substrate-integrated waveguide (SIW) filters with rectangular cross sections of via holes. Since only two principle discontinuities, are involved, an easy-to-implement and powerful CAD tool is obtained. The basic theory is presented. The possibility of specifying an arbitrary number of via holes in transverse direction gives rise to the possible design of a multitude of other SIW components. Several design examples are presented which include the SIW equivalents of a metal-insert filter, an inductive-iris filter and a dual-mode filter with one transmission zero. Results are shown to be in excellent agreement with those obtained with the commercially available field solver CST Microwave Studio, thus verifying the analysis and design approach presented in this paper.

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