Mode-Matching Analysis for Double-Layered Substrate Integrated and Rectangular Waveguide Filter Technology

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Abstract- **The adaption of Mode Matching Techniques (MMTs) for an E-plane double-layer discontinuity is presented. The bottom layer is realized in substrate integrated waveguide (SIW) and the top layer in conventional waveguide technology. The calculations are validated by comparison with data from commercial field solvers. The verification shows a good match and qualifies the MMT routine as a suitable method to prototype magnetically coupled, double layer, mixed technology filters.**

Index Terms **– Mode matching technique (MMT), substrate integrated waveguide (SIW), surface mounted waveguide (SMW), filter design.**

I. Introduction

Recent demands on modern wireless communication systems push for high performance and highly integrated RF/microwave circuitry. An emerging technology accommodating this need are substrate integrated waveguide (SIW) components [1]. With this development in microwave engineering, it became necessary to seek new or adapt known calculation methods from the area of conventional waveguides. A well-proven, reliable and efficient technique to evaluate electromagnetic fields in conventional waveguides is the mode-matching technique (MMT) [2]. Thus the MMT has been adapted to the design of SIW components, c.f. [3], [4], but mostly discontinuities in the H-plane have been modeled utilizing the MMT so far. Also multilayer, pure SIW circuits, such as couplers [5], [6] or power dividers [7] have been published.

The addition of conventional waveguide circuits, as surface mounted waveguide (SMW) technology, presents an expansion of SIW capabilities with a view to employ advantageous characteristics such as, for example, high quality factors and the low loss of conventional waveguides. It allows for a higher degree of integration, low cost, low foot-print and high volume fabrication. Mode matching techniques are well-suited calculation approaches to accommodate such a double-layered, mixed waveguide technology.

II. Theory

A. General

For the filter synthesis, we apply the well-known Chebyshev filter synthesis [8] to obtain impedance inverter values for given filter characteristics. The general procedure including the MMT is outlined in Fig. 1. The total scattering matrix of the respective discontinuity is used to calculate the characteristic impedance inverter values of the magnetic coupling aperture. By adjusting the dimensions of the coupling section, e.g. the E-, H-plane irises, one obtains a curve that maps the impedance value versus the aperture dimension. This curve is used to match the impedance values of the discontinuities to the ones obtained by the Chebyshev synthesis. To handle the different propagation media and waveguide technologies, the discontinuities involved are split up in sub-scattering matrices as shown in (1). These modal sub-matrices are obtained using the MMT.

[*E-Plane T-Junction (SIW)*] [*E- and H-Plane Iris*] …
[*E-Plane T-Junction (WG)*] = [*Total S-Matrix*]. (1)

The mode matching analysis is carried out as a full TE_{mn}, TM_{mn} mode analysis derived from an electromagnetic field with six components

$$\vec{\mathrm{E}} = \vec{E}_{TM} + \vec{E}_{TE} = \frac{1}{j\omega\varepsilon}\nabla \times \nabla(V_{ez}\vec{e}_z) + \nabla \times (V_{hz}\vec{e}_z) \tag{2}$$

$$\vec{\mathrm{H}} = \vec{H}_{TE} + \vec{H}_{TM} = \frac{1}{j\omega\mu}\nabla \times \nabla(V_{hz}\vec{e}_z) + \nabla \times (V_{ez}\vec{e}_z) \tag{3}$$

In order to entirely model the double-plane iris and the different dimensions of the SIW and conventional waveguide structures. The determination of the upper cut off frequencies for the coupling calculations in the different sub matrices is critical, since the propagation constants, admittances and impedances, as shown in (4) and (5), are dependent on the waveguide dimensions *a* and *b* and the different properties, e.g. permittivity, of the propagation medium.

$$\mathrm{Z}_{\mathrm{h,mn}} = \frac{\omega\mu}{\sqrt{k^2 - \left(\frac{\mathrm{m}\pi}{\mathrm{a}}\right)^2 - \left(\frac{\mathrm{n}\pi}{\mathrm{b}}\right)^2}} \tag{4}$$

$$\mathrm{Y}_{\mathrm{e,mn}} = \frac{\omega\varepsilon}{\sqrt{k^2 - \left(\frac{\mathrm{m}\pi}{\mathrm{a}}\right)^2 - \left(\frac{\mathrm{n}\pi}{\mathrm{b}}\right)^2}} \tag{5}$$

Moreover, the number of cutoff frequencies of the modes used to cascade the sub matrices has to be chosen carefully to

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enclose the necessary number of modes that couple signal energy and avoid miss-mapping of the single modes in the scattering matrices between the different propagation areas *R1* and *R2* as see (6).

$$\begin{bmatrix} \mathrm{TE_{R1}} \to \mathrm{TE_{R2}} & \mathrm{TE_{R1}} \to \mathrm{TM_{R2}} \\ \mathrm{TM_{R1}} \to \mathrm{TE_{R2}} & \mathrm{TM_{R1}} \to \mathrm{TM_{R2}} \end{bmatrix} \tag{6}$$

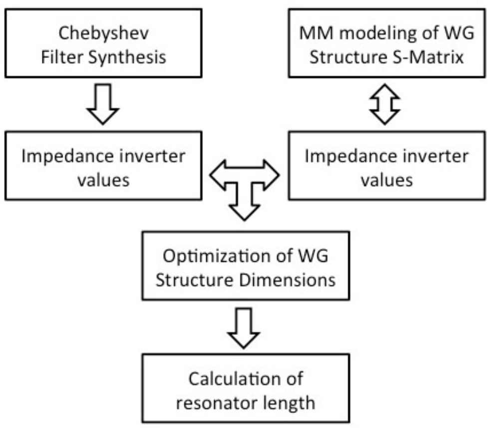

Fig. 1. Mode matching routine to obtain filter dimensions for one discontinuity.

B. E-Plane T-Junction SIW

The T-Junction is split in four areas (Fig. 2), and the vector potentials ((6), (7)) for each region (*R*) are determined as

$$V_{hx}^{R} = \sum_{m=0}^{M} \sum_{n=0}^{N} \sqrt{Z_{h,mn}^{R}}\, K_{h,mn}^{R}(x,y) \left(I_{h,mn}^{R} e^{-jk_{z,h,mn}^{R} z} - O_{h,mn}^{R} e^{jk_{z,h,mn}^{R} z}\right) \tag{6}$$

$$V_{ex}^{R} = \sum_{m=1}^{M} \sum_{n=1}^{N} \sqrt{Y_{e,mn}^{R}}\, K_{e,mn}^{R}(x,y) \left(I_{e,mn}^{R} e^{-jk_{z,e,mn}^{R} z} - O_{e,mn}^{R} e^{jk_{z,e,mn}^{R} z}\right) \tag{7}$$

K^R are constants for the cross sections of the different area intersections. The coordinates (*x,y,z*) have to be selected according to the geometry and orientation towards the overall coordinate grid of the region (*R*). $I_{h,e}^{R}$ is the wave traveling in propagation direction through the region boundary. $O_{h,e}^{R}$ is the wave traveling in the opposite direction.

Using the vector potentials, it is possible to develop the coupling integrals for the different boundaries of the junction [9]. The obtained modal matrix of size [*3nx3n*], where *n* represents the number of modes, is reduced to a [*2nx2n*] matrix by adding a shortened waveguide stub of length $\lambda/2$ of the transition's center frequency to area A3 (Fig. 2). Area A1 represents the input and A2 the output of the SIW sub matrix. The SIW is modeled as an equivalent-width, dielectric-filled waveguide, based on formulas presented in [10]. The iris is placed in the center of the T-junction output. Therefore, possible inaccuracies at the SIW sidewalls, not modeled due to the simplification of using the equivalent waveguide width, are not affecting the result.

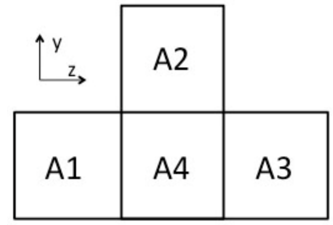

Fig. 2. E-plane T-junction SIW, vector potential areas.

C. E- and H-Plane Iris

The double step iris (Fig. 3) is the actual discontinuity in the propagation medium. The vector potential in A1 is characterized by the substrate's electrical properties, the vector potential in A2 and A3 by air. They are determined using (6) and (7). The coordinates *y* and *z* are interchanged; also the cross sections K^R are adapted to reflect the different geometry. After calculating the coupling integrals and matching the modes, the two occurring discontinuities are cascaded together with a short plain waveguide representing the iris thickness, leading to a [*2nx2n*] matrix.

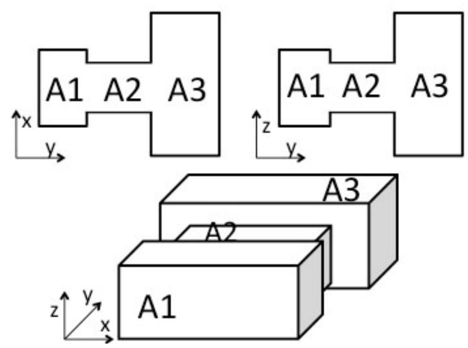

Fig. 3. Double E- and H- plane step, vector potential areas.

D. E-Plane T-Junction WG

The waveguide T-junction is calculated similar to the SIW T-junction with an adjusted coordinate system and differently defined input and output ports. To reduce the obtained [*3nx3n*] to a [*2n*x*2n*] matrix, A3 is short-circuited directly at the boundary to A4, leading to an E-plane corner.

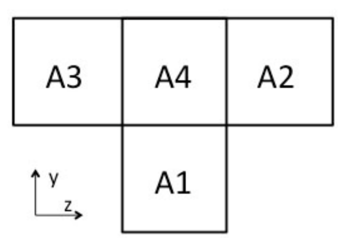

Fig. 4. E-plane T-junction WG, vector potential areas.

III. RESULTS

The results presented in Fig. 5 are for a one-resonator filter. The first iris is realized as described above, e.g., as an aperture in between the SIW and the SMW. The second iris is an H-plane discontinuity in conventional waveguide technology within the SMW. The graph shows good agreement between the mode matching calculations and the reference calculations obtained by the commercial field solvers CST and HFSS. Only a slight deviation of less than 10 MHz for the reflection zero is observed. To exactly match the result of the field solvers to that of the MMT, an optimization run with CST was conducted. This optimization led to a deviation of less than one percent in the iris width.

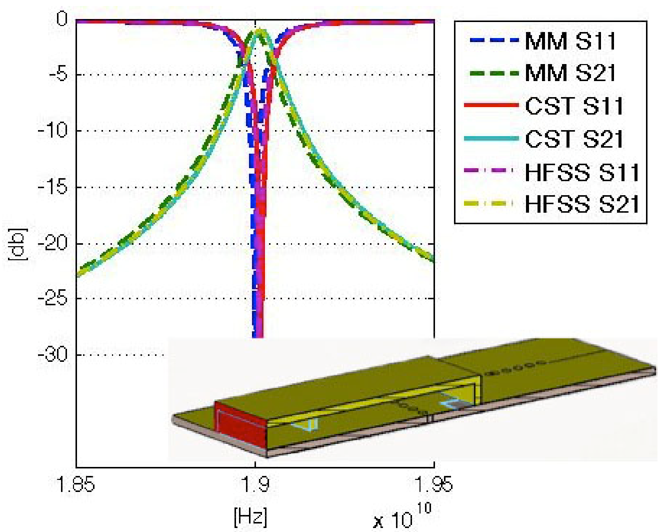

Fig. 5. Results for a single resonator SIW-SMW filter obtained with the MMT, CST, and HFSS.

IV. CONCLUSION

A mode matching routine to analyze and design the magnetic coupling between double-layer SIW and conventional waveguide is presented for filter applications. The routine first obtains the scattering matrix, then calculates impedance inverter values and matches them to impedance inverter values from a Chebyshev filter synthesis. This routine is an efficient method for the prototyping of such discontinuities. A comparison to results from numerical field solvers (CST and HFSS) validates the accuracy of the calculations. The advantage of this technique compared to commercial field solvers lies in the fact that the MMT is about one order of magnitude faster which presents an important factor for the timely design of double-layered SIW/SMW filters.

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