CAD of Waveguide Structures with Production Based Radii at Arbitrary Double (E-H) Plane Steps And Junction Ports

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Abstract — **The introducation of an enhanced Boundary Contour Mode Matching (BCMM) approach is shown to provide accurate and efficient analysis of waveguide structures with curved shapes at double (E-H) plane discontinuities of junctions and steps. Such geometries take account of the capabilities of state-of-the-art CNC milling production techniques, commonly used for integrated waveguide subsystems. The method is based on direct expansion of the electro-magnetic fields of the double-plane discontinuities into the modes of the connecting rectangular waveguides and additionally in case of junctions into cylindrical cavity modes. Validation of the approach has been proven by several component designs, that exhibit almost coincidence of computed and measured responses. The results of a special 4-pole filter design at 10 GHz using bypass couplings for a tailored asymmetric response and a 3 dB E-plane short-slot coupler, operating at 32 GHz, are presented as quite different examples.**

I. Introduction

The steadily increasing need of microwave and millimeter wave transmission equipment for the fast growing communications networks imposes short term development of proper component designs satisfying the dedicated electrical function while maintaining low cost and large scale production. Owing to its low loss properties, waveguide technology is still a prior candidate for component designs that are designated between the transceiver amplifiers and antenna like e.g. filters or couplers. However, proper interfacing, and integration within the overall equipment [1] as well as the consideration of inherent restrictions and properties of suitable state-of-the-art manufacturing methods is often necessary to successfully compete with other solutions. Since the 90^{th}, computer numerical controlled (CNC) milling technology become more and more attractive for the fabrication of integrated waveguide circuits and components from aluminium. An essential prerequisite for the economical utilisation of this technology is the consideration of reasonable milling radii within the microwave structures. Consequently, one significant development task is the adaptation of the required component designs to the inherent production demands, this is, double-plane discontinuities at waveguide steps and junctions will no longer have rectangular shapes (c.f., Fig.1). Suitable CAD methods are required for such real structure designs to essentially reduce experimental expense and development time. Commercially available tools based on the Finite Element (FE) or Finite Difference Time Domain (FDTD) method (like HFSS or CST Microwave Studio) allow analysis of waveguide structures with special curved shapes at double plane steps and junction ports that inherently occur by the use of CNC milling techniques (c.f., Fig.1); but necessary optimizations of the structure lack of high computation expense. Recently, the combination of the two-dimensional FE method with the mode-matching method was introduced for the analysis of one plane steps [2]. Despite this method may be extended for the analysis of double plane waveguide steps it will only provide poor flexibility for structural changes necessary in case of optimisation and, moreover, cannot be applied to general waveguide junctions. The Boundary Contour Mode-Matching (BCMM) can be used efficiently for computation of structures with curved shapes. However, up to now, this method has been restricted to either one-plane discontinuities [3], i.e., one dimension, width or height of the smaller and larger waveguides, are identical, or two-plane discontinuities [4], where the smaller waveguides have to lie entirely on a planar surface, which essentially restricts the design capabilities.

This paper presents the extension of the BCMM method accounting for special radii shapes at double (E-H)-plane steps and junction ports. These geometries inherently oc-

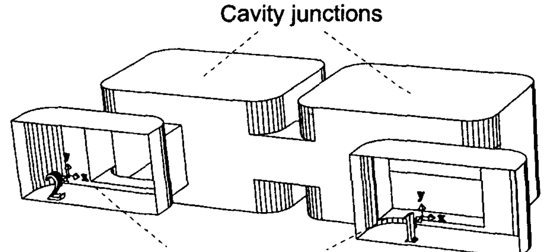

Fig. 1. Waveguide steps and junctions with radii occurring by application of CNC milling techniques

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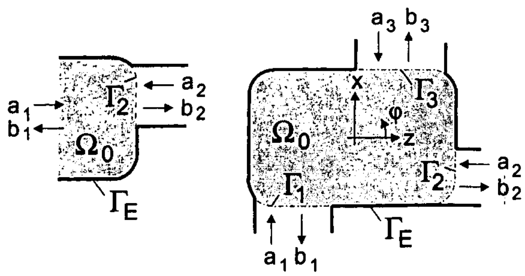

Fig. 2. Regions with different types of electro-magnetic field expansions – left: two plane step; right: resonator junction.

cur by common component realizations with state-of-the-art CNC milling techniques. The theory for these particular structures involves cylindrical wave and rectangular waveguide mode expansions with direct mode-matching at non-planar surfaces on all common interfaces. Verification of the approach has been obtained by several component designs exhibiting accurate agreement of computed and experimental results. Two of which, namely, a four-pole cavity filter design with bypass couplings at 10 GHz and a 3 dB E-plane short slot coupler, operating at 32 GHz are introduced as quite different examples.

II. Theory

The double-plane geometries under consideration can be distinguished for the BCMM method in single waveguide steps and junctions. For step structures, the BCMM uses a direct expansions of the electro-magnetic fields of both regions (c.f., Fig.2) into the well-known rectangular waveguide modes. In case of junctions, the modes of the connecting waveguide ports are expanded into rectangular waveguide modes, and a cylindrical wave expansion is used for the electro-magnetic fields inside the cavity regions, similar as in [4]. Prerequisite for the approach of both structures is the satisfaction of the boundary and continuity conditions of the transverse electric and magnetic field components on the surfaces Γ_i shown in Fig.2

$$\boldsymbol{E}_{0\,tang} = \begin{cases} \boldsymbol{E}_{i\,tang} & \text{on} \quad \Gamma_i,\ i = 1 \dots p \\ 0 & \text{on} \quad \Gamma_E \end{cases} \tag{1}$$

$$\boldsymbol{H}_{i\,tang} = \boldsymbol{H}_{0\,tang} \quad \text{on} \quad \Gamma_i,\ i = 1 \dots p. \tag{2}$$

These conditions are fulfilled by mutual matching the tangential electric and magnetic field components of the modes of the respective larger grey region, indicated in Fig.2, to the modes of the smaller step and port regions, respectively. For the calculation of the modal scattering matrix of the respective structure, a Galerkin procedure for the field components of the scattered waves at the surfaces is applied. Both, -the use of either the scalar or the vector product - are possible. The numerical results are exiguously different with the same truncated set of modes. The integration itself is done analytically, in axial direction of the structure and for the planar parts of the double-plane steps in transverse direction. Numerical integration using Gauss-Legendre or Gauss-Chebyshev methods is applied to the curved non-planar parts of the structures. It should be noted, that due to the decoupling of axial dependencies within the larger grey regions (c.f., Fig.2), the resulting self-coupling matrix for the electric field is sparse. Consequently, it can be inverted with minimal computational effort.

Inserting the coefficients of the electric field of the grey region into the set of equations resulting from matching the magnetic field, leads to a final, dense system of equations comprising the considered modes in the smaller, connecting waveguides only. This system is solved for a given number of right hand sides (accessible modes) by lower and upper triangular matrix (LU)- decomposition, leading to the modal scattering matrix of the structure. Multiple steps and junctions are easily handled by the general scattering matrix (GSM) combination.

The truncation of the set of considered modes is given by a common maximum cut-off frequency $f_{c\,max}$ for the connecting waveguides or the equivalent for the cylindrical waves in the cavity region. Numerical limitations result from the dynamic range of $\exp(2\gamma\Delta z)$ in the connecting waveguides, where γ is the attenuation constant and Δz is the maximum variation of the coordinate in propagation direction. In addition, the achievable resolution has to be considered for $(r_{max}/r_{min})^n$ in the cavity region, where r_{max} and r_{min} are the maximum and minimum surface distances, respectively, and n is the maximum circumferential order of the cylinder functions, respectively. With increasing value of $f_{c\,max}$ and, thus, the number of modes, the system matrices become more and more singular, so the system of equation becomes unsolvable in standard double-precision arithmetics beyond a certain limit. However, it should be noted, that a reasonable number of modes, far below these limits, is commonly sufficient in view of component designs for state-of-the-art CNC milling fabrication. The proper definition of the required modes also improves the computational expense of the method.

Inline structures can be computed in principle with ei-

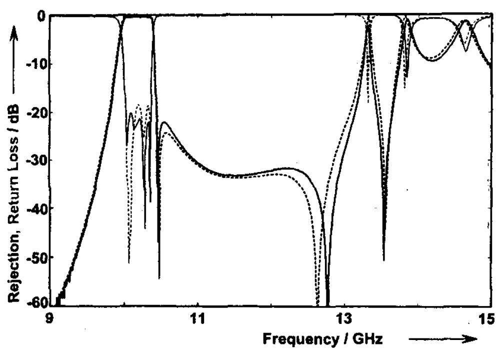

Fig. 3. 10.2 GHz 4-pole filter with bypass coupling irises - rejection and return loss characteristics: computed (dashed lines) and measured (solid lines)

ther the direct rectangular waveguide mode expansion for the step geometry or the cylindrical mode expansion for the cavity structure. Considering the same set of modes, the cylindrical wave expansion needs a higher computational effort, but shows a faster convergence than the rectangular waveguide expansion, especially in the case of large radii. For small radii or almost planar interconnecting surfaces, the direct rectangular waveguide mode expansion is preferable.

III. Verification

The BCMM method has been used for several component designs. Two of which are introduced in the following to demonstrate the validation of the approach.

A. Cavity Filter Structure with Bypass Couplings

First, a filter at 10.2 GHz has been designed with a 4-pole asymmetric characteristic providing transmission zeros at dedicated frequencies above the filter pass band for improved rejection requirements. Prerequisite for the realization of such particular responses is the proper implementation of bypass couplings [5]. Consequently, a special E-plane folded arrangement of three TE_{101} and one TM_{110} single mode cavities has been introduced, that allows an inductive iris bypass coupling of two top wall adjacent cavities[1]. To accommodate the realization in two symmetrical halves with CNC milling production techniques, the radii within the cavities, in particular at the iris locations, have been considered by CAD. The analysis of the optimized structure yields the expected asymmetric filter response with transmission zeros above the passband at 10.5 and 12.7 GHz, respectively. These results agree closely to the measured ones of the reference hardware filter vs. the broad frequency band from 9 to 15 GHz as Fig. 3 shows. Please note, since the final filter design is fully integrated in a transceiver equipment housing without any external accessible interfaces a reference hardware of the structure, shown in Fig.4, has been manufactured with the respective WR75 waveguide ports for verification purposes.

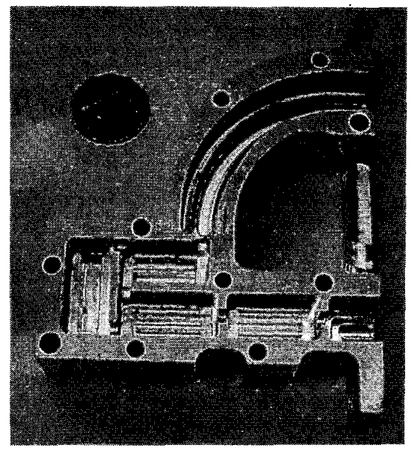

Fig. 4. Photograph of one half of the 4-pole filter reference hardware

B. E-Plane Short-Slot Coupler

E-plane short-slot couplers that are based on a waveguide region with higher order mode propagation were recently introduced in [6][2]. These couplers are favorably suited for large scale production by CNC milling techniques. To account for the respective radii shapes, the BCMM CAD tool has been applied to the design of a 3 dB broadband hybrid type for the operating frequency band 31.8 to 33.4 GHz. The computed responses of the optimized structure are depicted in Figs. 5, 6 vs. an extended frequency band 30 to 35 GHz. For the realization, reasonable waveguide bends have been considered at the four ports to allow suitable interfacing with standard WR28 waveguide flanges. A photograph of the realized hardware, comprising two symmetrical halves, is shown in Fig.7. Measured return loss and isolation results are in close agreement down to less than -30 dB (c.f.,Fig.5). The differences at the lower levels can

[1]Design according patent DE19818947C1

[2]Design according patent US 6,127,902

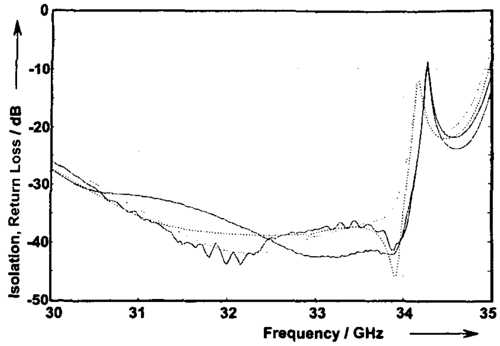

Fig. 5. 32 GHz 3dB-coupler - return loss and isolation characteristics: computed (dashed lines) and measured (solid lines)

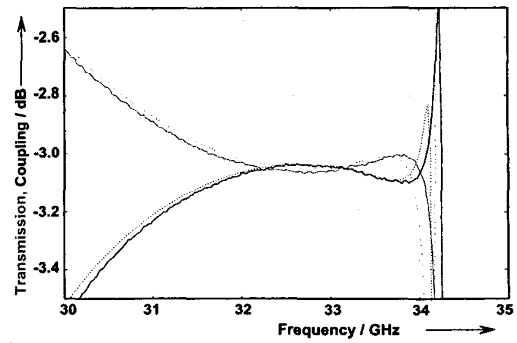

Fig. 6. 32 GHz 3db-coupler - transmission and coupling characteristics: computed (dashed lines) and measured (solid lines)

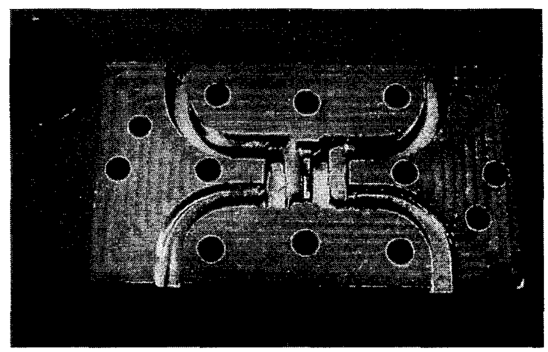

Fig. 7. Photograph of one half of the 32 GHz 3 dB-coupler

be attributed to manufacturing tolerances and the limited accuracy of the test equipment. The experimentally obtained transmission and coupling responses also show very good agreement to the computed ones.

IV. Conclusion

The introduced CAD, using an extended BCMM approach provides accurate consideration of radii shapes at double plane (E-H) waveguide steps and junction ports, which are the basic building blocks of nearly all kinds of passive components. Such special shaped geometries are attributed to state-of-the-art CNC milling technology, that is well suited for rapid and low cost production of waveguide integrated circuits and components. The BCMM is based on direct mode expansion for the step geometry and cylindrical cavity mode expansion for the junction structure with up to 4 arbitrarily located ports. Validation is provided, first, by a special 4-pole filter design at 10GHz with bypass couplings to generate transmission zeros above the passband for improved rejection demands, and second, by a short-slot E-plane coupler at 32 GHz with an overmoded coupling region.

The application of the introduced CAD method will essentially support the design of integrated waveguide circuitries due to significant reduced experimental effort and short term development.

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