Full Wave Hybrid Technique for CAD of Passive Waveguide Components with Complex Cross Section

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Abstract— A hybrid Galerkin Method/Mode Matching Technique/Generalized Scattering Matrix Method for CAD of waffle-iron filters, ridged and finned waveguide components is presented. The combined method is verified by available measurements as well as theoretical and experimental data of references. A number of low-pass waffle-iron filters have been designed for multi-band feeders of reflector antennas operating in S, C, X, Ku bands. New modifications of quasi-planar band-pass filters with improved performance have been designed for millimeter-wave communication applications.

1. INTRODUCTION

The passive components based on waveguides with complex cross section are widely used in many microwave and millimeter-wave applications. For example, waffle-iron filters are employed in both high-power and low-power applications as low-pass filters [1]. They were originally designed for high-power systems where it was desirable to suppress the harmonic frequencies generated by the transmitter. The general view of a typical waffle-iron filter section with rectangular teeth is schematically depicted in Fig. 1(a). In fact, this structure consists of cascaded multi-ridged waveguide subsections, which are coupled by rectangular waveguide subsections.

The main advantages of waffle-iron filters are both extended stop-band and pass-band and low insertion loss over a pass-band. Besides, waffle-iron filters attenuate all propagating waveguide modes whose frequency lies in the stop-band of filter. From this viewpoint the waffle-iron filters are very appropriate candidates for some satellite communication applications. For example, in reflector antennas of earth stations operating in S, C, X, Ku frequency bands multi-band feeders are used. Typically, diplexers included into multi-band waveguide feeder are implemented on the base of low-pass waffle-iron filters [2].

Ridged and all-metal finned waveguide structures find extensive applications in microwave and millimeter-wave filters, diplexers/multiplexers, transformers, polarizers etc. [3, 4]. In particular, evanescent-mode ridge waveguide filters (Fig. 1(b)) have well-known favorable electrical performances such as low insertion loss, wide stop-band and compact size. The finned version of the

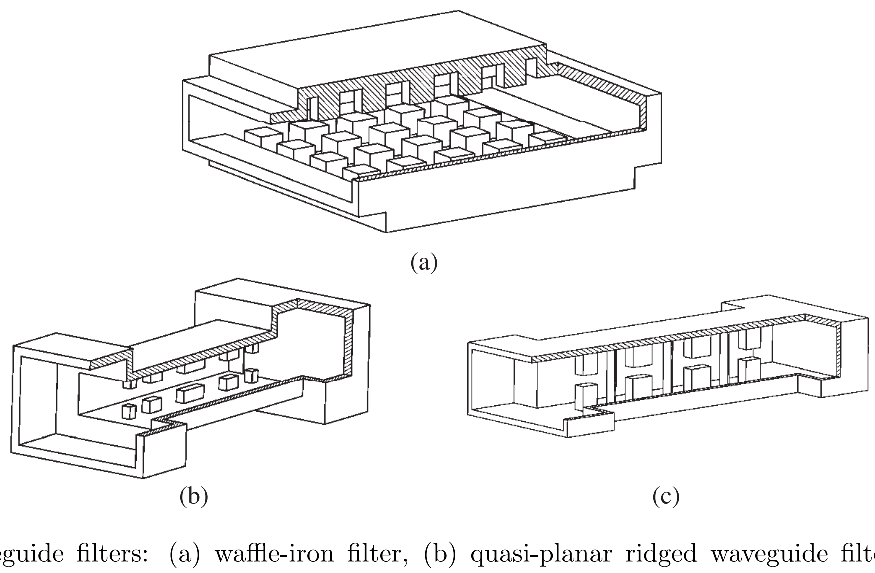

Figure 1: Waveguide filters: (a) waffle-iron filter, (b) quasi-planar ridged waveguide filter, (c) modified quasi-planar ridged waveguide filter with E-plane strips.

ridged waveguide components enables low-cost and easy-to-fabricate E-plane integrated circuits designs. On the other hand, there is a great potential of flexibility in ridge configuration according to different electrical and mechanical requirements.

Recently, electromagnetic CAD of waffle-iron filters, ridged and finned waveguide components is a point of a growing interest. Due to complexity of the problem the most advanced full wave CAD tools for waveguide components with complicated cross section are based on hybrid methods [5]. Undoubtedly, hybrid methods assure very high numerical efficiency, since they retain specific advantages of different EM methods and largely avoid their disadvantages. This paper presents a full wave approach to CAD of waffle-iron filters and ridge waveguide components including their analysis and numerical optimization.

2. THEORY

A fast and accurate EM analysis of waffle-iron filters and ridge waveguide filters (Fig. 1) is based on Galerkin Method/Mode Matching Technique/Generalized Scattering Matrix Method. Galerkin technique with taking into account field asymptotic at the edges was reported in [6, 7]. It is assumed that a waveguide structure under consideration (Fig. 1) consists of an arbitrary number of multi-ridged waveguide sections and stepped transitions connecting the filter with input and output waveguides. The solution is subdivided into the following steps: (i) decomposition of filter into elementary basic blocks, (ii) solving eigenvalue problems for multi-ridged waveguide sections, (iii) solving key scattering problems for basic discontinuities, (iv) direct combination of all S-matrices and evaluation of total S-matrix of filter.

Three discontinuities are considered as basic blocks of the structure: junction between rectangular and multi-ridged waveguide of the same size, double-plane step junction between two rectangular waveguides and waveguide bifurcation. The scattering problems for basic discontinuities are solved in terms of H- and E-modes. Therefore, two independent eigenvalue problems for both H- and E-modes of multi-ridged waveguide have been considered. For each of these modes, cut-off frequencies and field distributions are found.

The eigenvalue problem formulation for generalized multi-ridged waveguide is shown in Fig. 2. These problems for both H- and E-modes are reduced to the system of integral equations of the first kind for unknown electric field components on the common interfaces of regular regions in Fig. 2(a), ($z = t_i$, $i = 1, 2, \ldots, M-1$). For the solution of the integral equation system the Galerkin method is utilized. A key point of this approach is a special choice of basis functions [6, 7]. The unknown tangential electric field components on the common interfaces are expanded into series of Gegenbauer or Chebyshev polynomials with weight factor taking into account field asymptotic at the edges. Such a choice of basic functions accelerates the convergence of the method. The algebraization of the problems in accordance with Galerkin technique yields the final uniform system of linear algebraic equations. The cutoff frequencies of H- and E-modes are calculated as the zeros of the determinant of the matrix operator. Typically, it is enough to take into account 2 or 3 basis functions for convergence of the numerical solution.

We used Mode Matching Technique for analysis of junction between rectangular and multi-ridged waveguide and both Mode Matching Technique and Galerkin method for analysis of step waveguide junction and waveguide bifurcation. Eigenfunctions of multi-ridged waveguide were written in accordance with transverse resonance method [3]. Since Mode Matching Technique is well established method for waveguide problems, let's focus attention on the implementation of Galerkin technique.

The electromagnetic fields in rectangular waveguides are written as modal expansions in terms of H- and E-modes. Using orthogonality of waveguide modes we represent unknown amplitudes of

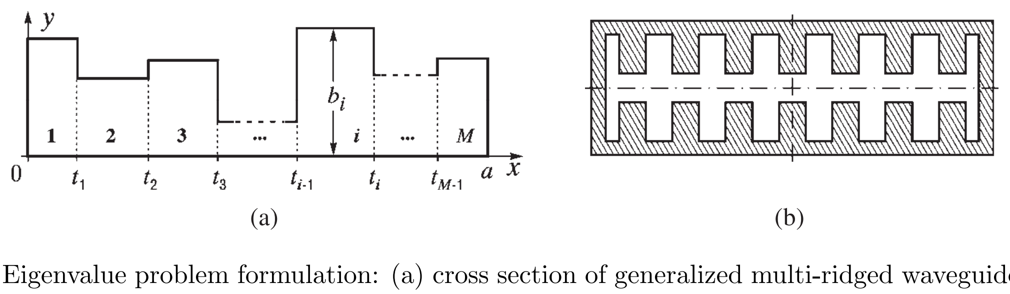

Figure 2: Eigenvalue problem formulation: (a) cross section of generalized multi-ridged waveguide; (b) cross section of waffle-iron filter.

scattered modes in terms of unknown tangential electric field on the aperture of the discontinuity. Enforcing the continuity of the tangential magnetic field on the aperture and substituting relations for amplitudes of scattered waves into corresponding equations yield integro-differential equations for tangential electric field on the aperture.

For the algebraization of the integro-differential equations we used Gegenbauer or Chebyshev polynomials as basis functions. The weight factors of polynomials take into account field asymptotic at the edges in an explicit form. It leads to an extremely fast convergence of solution. In most cases, it is necessary to account only for 3 or 4 basis functions for each coordinate. As a result, the problems are reduced to the final systems of linear algebraic equation of minimal order. After solving these final systems the generalized scattering matrices of the corresponding discontinuities are calculated. The modal S-matrix of the filter is computed on the base of efficient combination procedure using only one matrix inversion.

3. RESULTS

For verification of the presented theory the obtained results have been compared with experimental and theoretical data of some references for waffle-iron filters [1] and quasi-planar ridged waveguide filters [3]. In all cases a good agreement is observed.

A number of waffle-iron filters for multi-band feeders of reflector antennas operating in S, C, X, Ku bands have been designed. The typical design specifications for low-pass waffle-iron filters are formulated as follows. The filter should have a pass-band and one or two separate stop-bands. One of the main requirements is a low insertion loss within the pass-band. So VSWR of the filter has to be minimized (VSWR < 1.05). Attenuation within stop-band should be usually greater than 30 dB.

In accordance with the analysis results, the initial dimensions of the filter are chosen to meet approximately pass-band and stop-band design specifications. The initial structures are taken consisting of identical equidistant multi-ridged subsections. The optimization is based on direct search method. The vector of arguments of the goal function includes longitudinal and transversal dimensions of the filter.

The design example of waffle-iron filter is plotted in Fig. 3. The blank rectangle corresponds to specified pass-band of the filter and the shaded rectangles show the stop-bands with required insertion loss. Calculated return loss within pass-band is about 40 dB and VSWR < 1.02. The total stop-band width by 30 dB value of attenuation is about 9.5 ... 15.5 GHz. The filter in Fig. 3 was implemented as the cascade of four 5-ridge sections and its total length is about 35 mm.

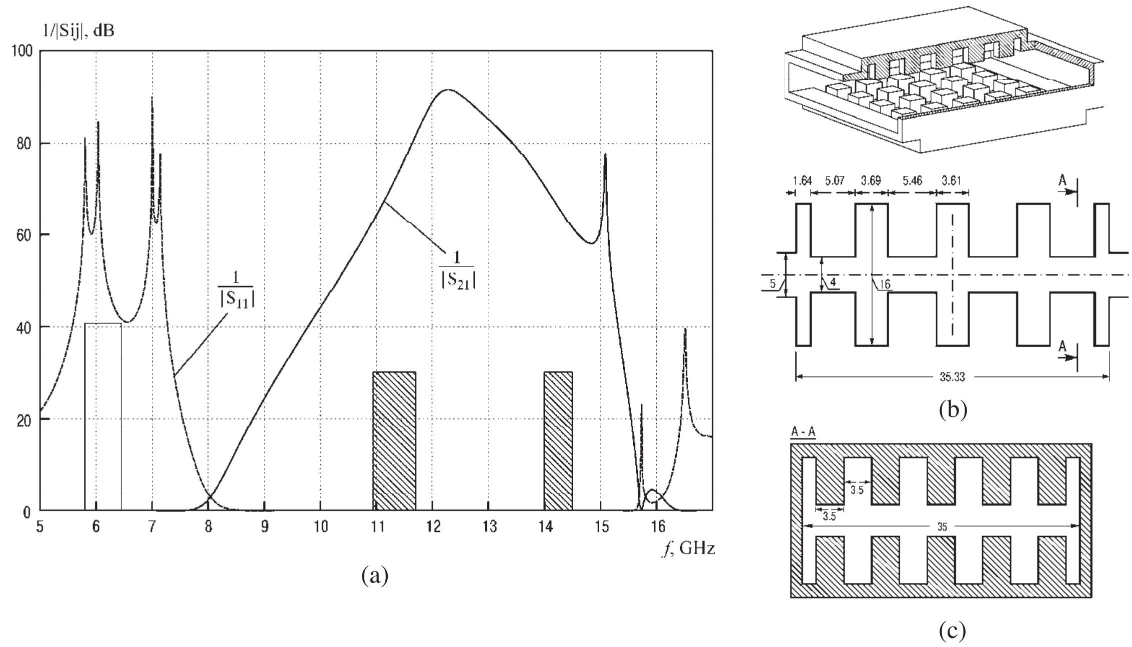

Figure 3: Frequency response (a) and configuration of longitudinal (b) and transversal (c) cross section of waffle-iron filter with 4 multi-ridged subsections (input waveguide 35×5 mm).

The modified evanescent-mode ridge waveguide filter (Fig. 1(c)) proposed in [4] has enlarged height of the below-cut-off waveguide section. Moreover, additional inductive strips have been introduced between the ridged sections. This filter modification has more compact total size, wide spurious-free response and reduced ohmic loss. Fig. 4 shows frequency response of Ka-band four-resonator filter operating within pass-band 29–29.5 GHz. Return loss of the filter is better than 20 dB, upper stop-band limit is 48 GHz by $1/|S_{21}| = 50$ dB and the total length is approximately 22 mm.

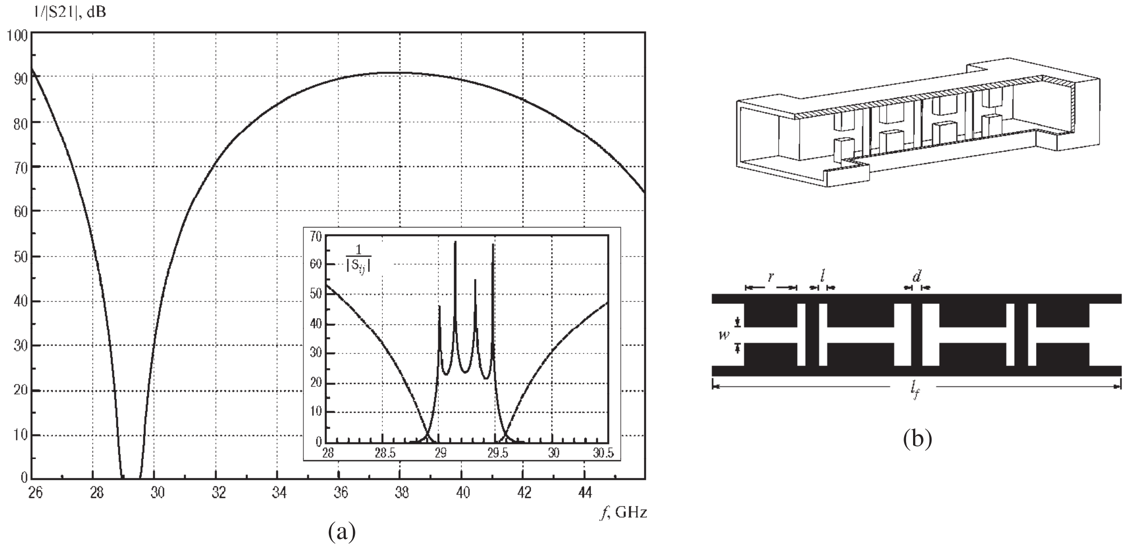

Figure 4: Frequency response (a) and configuration of Ka-band quasi-planar four-resonator waveguide filter (b). Dimensions in mm: input waveguide 7.2 × 3.4, evanescent waveguide 4.0 × 3.4, insert thickness 0.2, $r_i = 2.881$, 3.639; $d_i = 0.716$, 0.571; $l_i = 1.776$, 0.462, 0.968; $w = 0.88$; $l_f = 22.379$.

4. CONCLUSION

A hybrid full wave method for analysis and design of a wide class of ridged and finned waveguide components and waffle-iron filters is presented. The solution is based on Galerkin Method/Mode Matching Technique/Generalized Scattering Matrix Method. By implementation of Galerkin method for solving eigenvalue problems and key scattering problems the weighted Gegenbauer and Chebyshev polynomials were used as basis functions taking into account the field asymptotic at the edges. It leads to dramatically fast convergence and high accuracy of the solution. The obtained results are in good correspondece with available experimental and theoretical data of references.

A number of waffle-iron filters for multi-band feeders of reflector antennas operating in S, C, X, Ku bands has been designed. The potential of the new quasi-planar waveguide filter configuration has been studied. This filter configuration has improved pass-band selectivity and extended stop-band in comparison with the conventional ridge waveguide filters. Some modified quasi-planar pass-band filters with improved performance have been designed for Ka-band.

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