Fast Waveguide Filter Synthesis, using the Mode Matching Method for Analysis and Practical Swarm Optimization

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Abstract

In this paper, we give two examples of rectangular waveguide bandpass filter synthesis. Starting from the filter specifications (order of the filter, position of zeros, band-edge frequencies, and passband return loss) our aim was to realize one program that makes all steps of the filter synthesis (calculate the coupling matrix, create the equivalent circuit, convert the equivalent circuit to waveguide structure, analyze this structure, and then optimize its dimensions), and doing this as fast as possible (less than two minutes). For the coupling matrix we used the Atia and Williams's method, for the analysis we used the mode matching method, which is the most adequate for this kind of structures, and for the optimization we used the Practical Swarm Optimization PSO. The complete combination has been successfully applied for several waveguide filters synthesis.

1. Introduction

In the early 1970s, Atia and Williams introduced the concept of the coupling matrix as applied to dual-mode symmetric waveguide filters. The circuit model they investigated was a bandpass prototype comprised of a cascade of lumped-element series resonators intercoupled by transformers, and each loop is theoretically coupled to every other loop through cross-mutual couplings between the mainline transformers, this circuit model is called Transversal topology [1]. The inconvenience of this topology is to be unsuitable for practical realization especially in waveguide filters; this led many researchers to investigate in other topologies more suitable for realization, most of them are calculated from the transversal topology, for instance: Folded, Cascaded Quadruplets, Parallel-connected networks, Box sections, and Cul-de-sac [2], [3]. After choosing the adequate topology we can deduce equivalent circuit "the prototype" which consists of joining inverters and resonator. The next step and probably the most important one is to convert this equivalent circuit to micro-wave structure; rectangular waveguide filters in this work, then we have to create equivalent structure for both inverters and resonators [4]. The final step consists to optimize this structure to fit the filter specification and for this step we chose Practical Swarm Optimization (PSO) [5], which is fast and easy to program optimization method. To reduce the calculation time we try deferent fitness functions.

2. Methods and Techniques Background

2.1. Coupling matrix synthesis

For the great majority of the filter circuits, we shall initially consider two-port networks; a "source port" and a "load port" then the scattering matrix is represented by a 2 x 2 matrix. The S parameters are important because they are capable of providing a great insight into the transmission and reflection coefficient (S21 and S11 respectively) of RF energy in microwave circuits.

In this work, for generating the coupling matrix we followed step by step the technique proposed by J. Cameron, M. Kudsia, and R. Mansour in [2].starting by generating polynomials of the transfer and reflection functions S21(s) and S11(s) respectively, where E(s) and F(s) are Nth degree, P(s) is a polynomial of degree n ,the number of finite-position transmission zeros, and ε and ε_R are real constants normalizing P(s) and F(s).

$$S_{21}(s) = \frac{P(s)/\varepsilon}{E(s)} \qquad (1)$$

$$S_{11}(s) = \frac{F(s)/\varepsilon_R}{E(s)} \qquad (2)$$

After calculating the S parameters we can convert this scattering matrix to admittance matrix Y, and then calculate the reciprocal N+2 transversal coupling matrix M using the residues method [2].

2.2. The mode-matching technique

The mode-matching technique is a powerful method for analyzing waveguides with varying cross-section; it is based on the matching of the total mode fields at each junction between uniform sections. The amplitudes of the separate modes at the output of a junction can be deduced in terms of the amplitudes of the mode spectrum at the input to the junction [6]

If $a^{(h)(or(e))}$ and $b^{(h)(or(e))}$ are the modal weighting coefficients vectors in guide 1 and 2 respectively, we can write:

$$\begin{bmatrix} b^{(h)} \\ b^{(e)} \end{bmatrix} = \begin{bmatrix} [H] & [K] \\ [Q] & [E] \end{bmatrix} \begin{bmatrix} a^{(h)} \\ a^{(e)} \end{bmatrix} \quad (3)$$

Where the elements of the submatrices $[H]$, $[K]$, $[Q]$ and $[E]$ are respectively the TE-TE, TE-TM, TM-TE and TM-TM E-field mode-coupling coefficients at the junction.

Since we are using inductive obstacles, the study is reduced to calculate only one integral.

$$H_{mn} = \int_S \vec{e}^{\,h}_{1m} \cdot \vec{e}^{\,h}_{2n} dS \quad (4)$$

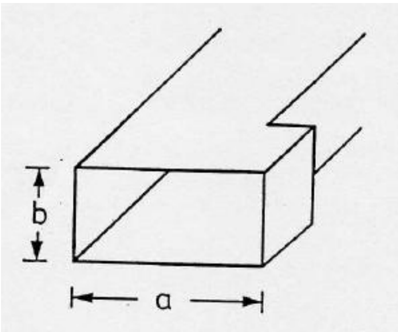


Figure 1: Waveguide inductive discontinuity.

2.3. Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a relatively new technique, for optimization of continuous non-linear functions. It was first presented in 1995. Jim Kennedy discovered the method through simulation of a simplified social model [5], the graceful but unpredictable choreography of a bird swarm. PSO is a very simple concept, and paradigms are implemented in a few lines of computer code. It requires only primitive mathematical operators, so is computationally inexpensive in terms of both memory requirements and speed. PSO has been recognized as an evolutionary computation technique

PSO is basically developed through simulation of bird flocking in two dimension space. The position of each agent is represented by XY axis position and also the velocity is expressed by vx (the velocity of X axis) and vy (the velocity of Y axis).

Each individual i in the swarm contains parameters for position x_i and velocity y_i, the position of each particle represents a potential solution to the optimization problem.

The swarm behavior in conventional particle swarm optimization is influenced by the number of particles, neighbourhood size, inertia weight, maximum velocity, and acceleration calculation to modify the velocity.

2.3.1. PSO Notation

For each particle *i*:

- x_i is a vector denoting its position and y_i denotes its objective function value
- y_i is the vector denoting its velocity.
- p_i is the best position that it has found so far and $Pbest_i$ denotes its objective function score.
- g_i is the best position that has been found so far in its neighborhood and $Gbest_i$ denotes the objective function value of g_i.

Velocity update:

- $\vec{U}(0,\varphi_i)$ is a random vector uniformly distributed in $[0,\varphi_i]$ generated at each generation for each particle.
- φ_1 and φ_2 are the acceleration coefficients determining the scale of the forces in the direction of p_i and g_i.
- $\otimes$ denotes the element-wise multiplication operator.

2.3.2. PSO Algorithm

- Randomly initialize particle positions and velocities
- While not terminate:
- For each particle i:
  - Evaluate fitness y_i at current position x_i
  - If y_i is better than $Pbest_i$ then update $Pbest_i$ and p_i
  - If y_i is better than $Gbest_i$ then update $Gbest_i$ and g_i
- For each particle
  - Update velocity y_i and position x_i using:

$$\vec{v}_{i+1} \leftarrow \vec{v}_i + \vec{U}(0,\varphi_1) \otimes (\vec{p}_i - \vec{x}_i) + \vec{U}(0,\varphi_2) \otimes (\vec{g}_i - \vec{x}_i) \quad (5)$$

$$\vec{x}_{i+1} \leftarrow \vec{x}_i + \vec{v}_i \quad (6)$$

2.4. Fitness function

The fitness function is the most important part of any optimization method; it should correspond to an evaluation of how good the candidate solution is, then the optimal solution is the one which minimizes the fitness function. To find the best fitness function (faster and best probability of convergence) we tried three functions (Least Pth

Approximation, Direct Minimax Formulation and Discrete Target Approximation)[7],[8]

2.4.1. *Least Pth Approximation*

A frequently employed class of fitness functions may be written in the generalized form

$$U = \sum_{i=0}^{n} \left| F(\phi_i) - S_i \right|^P \qquad (7)$$

Where the subscript i refer to quantities evaluated at the sample point ϕ_i, F is the filter response, and S is the desired response. Thus, the objective is essentially to minimize the sum of the magnitudes raised to some power p (p may be any positive integer) [7].

2.4.2. *Direct Minimax Formulation*

The objective of this function is to minimize the maximum amount by which the network response fails to meet the specifications, or to maximize the minimum amount by which the network response exceeds the specifications [7].

$$U = \max\left[(F(\phi_U) - S_U) - (F(\phi_L) - S_L) \right] \qquad (8)$$

$F(\phi)$ is the response function

S_U is a desired upper response specification

S_L is a desired lower response specification

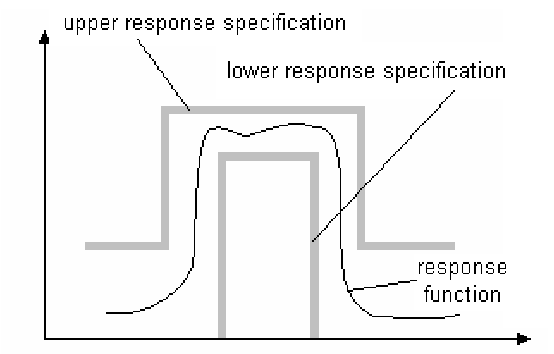


Figure 2: filter specification

2.4.3. *Discrete Target Approximation*

Is a simple evaluation of the specifications fulfillment consist of assigning to each one of the N frequency points a value of 0 if the response function does not satisfy the corresponding specification and on the contrary a value of 1 if it satisfies the specification. The final fitness is the sum of the $\{0,1\}$ values for all the response points, divided by the number of points [8].

3. Numerical results

In order to calculate initial dimensions of the filters we used the image method for computing the iris opening [4] and waveguide resonant cavity for RC resonator equivalent circuit [9]. In the second example which is a dual-mode filter we used two modes that resonate at the same frequency TE_{102} and TE_{201}, in the same cavity [10]. The iris thickness is 2mm for the two examples.

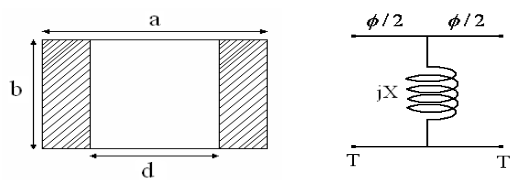


Figure 3: Cross sectional view and inductive iris equivalent circuit

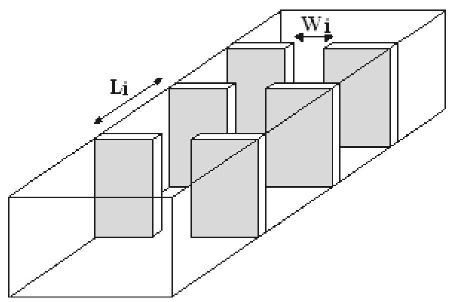


Figure 4: waveguide filter and geometrical unknown factors.

The obtained coupling matrix for the first example (second order filter with no transmission zero) is

$$M = \begin{bmatrix} 0 & 1.2250 & 0 & 0 \\ 1.2250 & 0 & 1.6580 & 0 \\ 0 & 1.6580 & 0 & 1.2250 \\ 0 & 0 & 1.2250 & 0 \end{bmatrix}$$

The housing waveguide is the WR 112 (28.5x12.62 mm) and the filter dimensions are: $L_1 = L_2 = 19.507mm$ $W_1 = W_3 = 14.886mm$ and $W_2 = 11.173mm$.

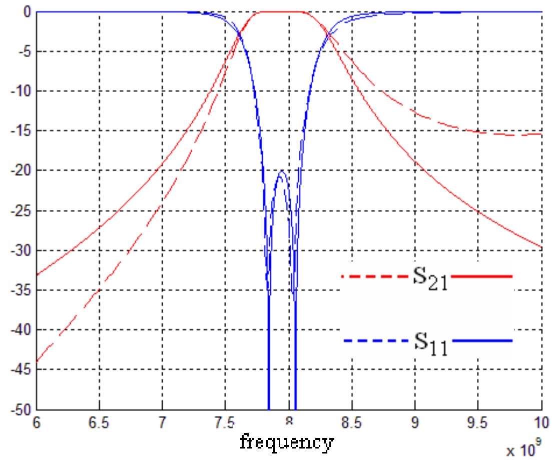


Figure 5: Superposition of waveguide filter (broken line) and equivalent circuit response

To validate our results we insert the obtained dimensions in a commercial software simulator HFSS then we superposed the two responses.

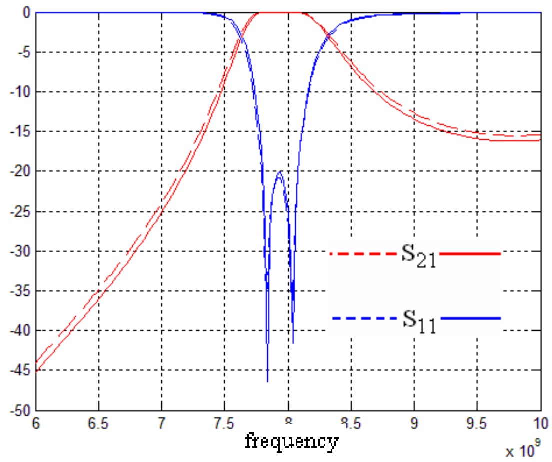


Figure 6: Superposition of our results (broken line) and HFSS response.

For the second example (second order filter with one transmission zero) the obtained coupling matrix is

$$M = \begin{bmatrix} 0 & -1.3990 & 0 & 0 \\ -1.3390 & 0.8960 & 0.9280 & 0.9950 \\ 0 & 0.9280 & -1.1640 & 0.8960 \\ 0 & 0.9950 & 0.8960 & 0 \end{bmatrix}$$

The housing waveguide is the WR 112 (28.5x12.62 mm) and the filter dimensions are: L(cavity length) =35.729mm, A(cavity width)=62.190mm and W(iris opening)=15.860mm

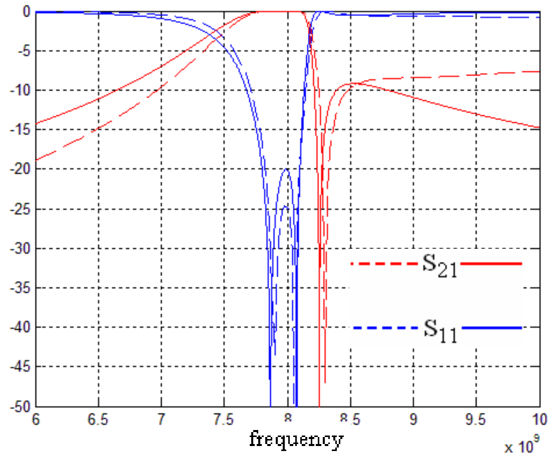


Figure 7: Superposition of waveguide filter (broken line) and equivalent circuit response

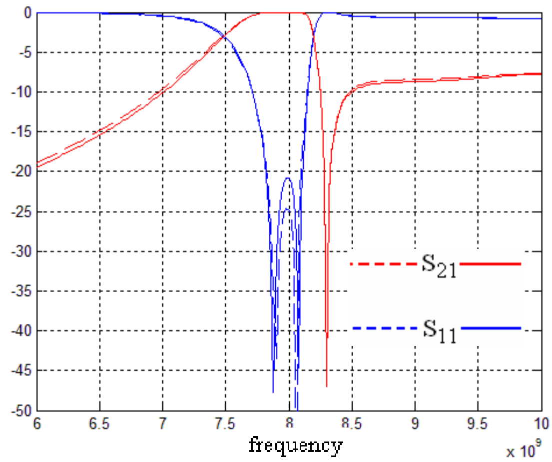
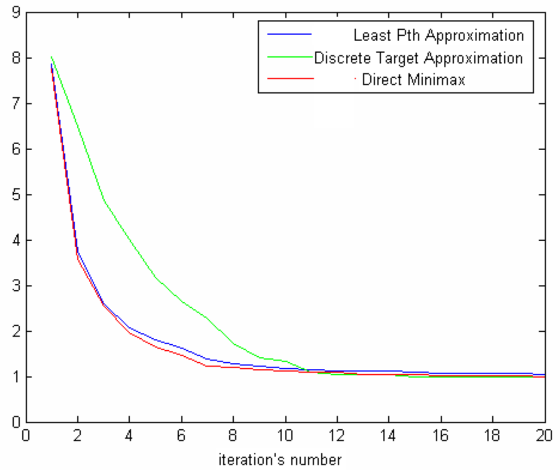


Figure 8: Superposition of our results (broken line) and HFSS response.

We plotted the following curves in order to compare the convergence of the three tested fitness functions according to the iteration's number.



We noted that all of the curves converge approximately at the same iteration (the 12th iteration) but through repeated simulations we noticed that the Discrete Target Approximation has the best success probability 95%.

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