COMPUTER AIDED OPTIMIZATION OF MICROWAVE FILTER NETWORKS FOR SPACE APPLICATION

C.M. Kudsia
Com Dev Ltd.
155 Sheldon Drive
Cambridge, Ontario, Canada, N1R 7H6
and
M.N.S. Swamy
Concordia University
Montreal, Quebec, Canada

ABSTRACT

An efficient computer-aided optimization procedure is presented to synthesize the general class of microwave filters that can be realized in dual-mode canonical configuration. Tradeoffs for new response functions of such filters for typical satellite requirements are highlighted.

Introduction

This work was motivated by the continuing demands for improved microwave filtering by the communications satellite industry. Adaptation of optimization techniques to the needs of practising engineers is the main intent of this paper.

Prototype Filter for Computer-Aided Optimization

It is of paramount importance to define the filter parameters so that they reflect the practical requirements directly and at the same time be amenable to efficient optimization of the filter response. This is accomplished by characterising the amplitude response in dBs in terms of the attenuation zeros and poles - referred to as the critical frequencies.

$$T = -10 \log [|t(s)|^2_{s=j\omega}] = -10 \log \frac{1}{1+\varepsilon^2 |K(s)|^2_{s=j\omega}} \text{ dB}$$

$$R = -10 \log [|\rho(s)|^2_{s=j\omega}] = -10 \log \frac{1}{1+\varepsilon^{-2} |K(s)|^{-2}_{s=j\omega}} \text{ dB}$$

$$K(s) = \frac{(s^2+a_1^2)\ (s^2+a_2^2)\ \ldots(s^2+a_n^2)}{(s^2+b_1^2)\ (s^2+b_2^2)\ \ldots(s^2+b_m^2)}$$

where

$a_1, a_2, \ldots$: are the frequencies of attenuation zeros

$b_1, b_2, \ldots$: are the frequencies of attenuation poles

$t(s), \rho(s)$: are the transmission & reflection coefficients respectively

T, R : are the transmission & reflection loss in dB respectively.

The ripple factor ε governs the tradeoff between the maximum and minimum attenuation in pass and stop bands and therefore need not be considered as an independent parameter. The frequencies of attenuation maxima or minima are given by

$$\frac{\partial |t|}{\partial s} = 0$$

The objective function U is then represented by

$$U = \sum_{i \neq j} \text{ABS}[|R(i) - R(j)| - A_{ij}] + \sum_{j \neq \ell} \text{ABS}[|T(k) - T(\ell)| - B_{k\ell}]$$

where R(i), T(i) are return loss and transmission loss in dB at the ith attenuation maxima or minima.

A_{ij} and B_{ij} represent arbitrary constants. For equi-ripple passband, $A_{ij} = 0$ and for equi-ripple stopband, $B_{ij} = 0$. The summations extend over all attenuation maxima in the passband for the first term and over all attenuation minima in stopband for the second term.

Constraints on the independent variables, viz., the finite critical frequencies are given by

$$0 < a_1, a_2, \ldots < 1$$

$$b_1, b_2, \ldots > 1$$

The gradient of the objective function U therefore involves terms of the form $\frac{\partial R}{\partial a_i}$, or $\frac{\partial T}{\partial a_i}$.

These derivatives are derived analytically as

$$\frac{\partial T}{\partial a_i} = 40 \log e\ |\rho|^2 \frac{a_i}{(s^2+a_i^2)}$$

and

$$\frac{\partial R}{\partial a_i} = -40 \log e\ |t|^2 \frac{a_i}{(s^2+a_i^2)}$$

In a similar manner, gradients with respect to the attenuation poles b_i are determined.

The unconstrained objective function U_{art} is then constructed as [1, 2],

$$U_{art}(x, r_t) = U(x) + r_t \sum_{k=1}^{p} \frac{1}{\phi_k(x)} + r_t^{-1/2} \sum_{j=1}^{m} (\psi_j(x))^2$$

where ϕ and ψ are the inequality and equality constraints and r_t is a weighting factor. The gradients of the constraint functions are also derived analytically. For optimization of this function, we determined the algorithm of Fletcher [3] as the most efficient one. It shows improvement over the well known Fletcher & Powell method [4] of optimization for this class of problems.

New Response Functions for Filter Networks

As a test case, table 1 describes the computed critical frequencies for a six-pole elliptic filter using the optimization procedure outlined in this paper. This confirms the flexibility and efficiency of the software. For practical cases where an accuracy of 1% is adequate, computation time can be reduced to about one second.

Table 2 describes the computed critical frequencies of an unconventional eighth order filter characterised by a pair of attenuation poles, double zero at origin, equi-ripple passband and variable stopband attenuation minima. Such a lowpass prototype network can then be used to realize the practical filters - be they low pass, high pass, band pass or band stop using frequency transformation. At microwave frequencies, such a generalized function can be realized most conveniently in a dual-mode configuration.

Filter Tradeoffs for Space Application

A dual-mode structure is the optimum configuration for microwave filters for space application. Besides advantages of weight and volume, it permits realization of completely generalized characteristics. As as example of this and based on the optimization package described here, Figures 1 and 2 highlight the amplitude and group delay tradeoffs for an 8-pole dual-mode 0.5% bandwidth filter at 12 GHz with a single pair of transmission zeros and varying number of equi-ripple peaks in the passband. Similar tradeoffs can be determined for an eight-pole filter with two or three pairs of transfer function zeros. Dual-mode waveguide structure permits physical realization of these response functions [5]. As expected, the attenuation rise is sharpest when the number of peaks in pass band is maximum. As the number of peaks is decreased, the attenuation is reduced and so is the relative time delay in the pass band. The computed value of amplitude and delay have a close correlation with practical filter networks.

Conclusions

An efficient procedure is described to determine the critical frequencies of the completely general class of prototype filters using computer-aided optimization. Equi-ripple class of filters is a special case of this program package. The objective function is defined in terms of the practical parameters of transmission loss in dB; gradients including those of constraints are derived analytically. New algorithm of Fletcher is incorporated in the program for optimization. Classic filters like Chebyshev or elliptic fall out as special cases in about 1 to 5 seconds of CPU time. Practical narrowband filters in a dual-mode structure can then be realized using frequency transformation and general coupled cavity synthesis procedure of Atia et al [5]. Using this program package, tradeoffs for an eight-pole bandpass filter with a single pair of transmission zeros and varying number of equi-ripple peaks in passband are highlighted.

This optimization program package thus offers the following distinct advantages.

- The technique is completely general and is capable of generating new types of filter functions determined solely by the overall system requirements.
- The objective function and constraints are defined in terms of the practical parameters of transmission or reflection loss in dB.
- Use of analytic gradients and the new algorithm of Fletcher permits very efficient determination of critical frequencies of prototype networks.
- Practical filter networks are easily derived using frequency transformations and realized in a dual-mode configuration using general coupled-cavity synthesis techniques.

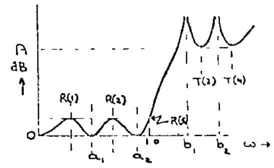
References

1. J.W. Bandler, "Optimization Methods for Computer-Aided Design", IEEE Trans. on MTT, August 1969.
2. A.V. Fiacco and G.P. McCormick, "Non Linear Programming", John Wiley and Sons, 1968.
3. R. Fletcher, "A New Approach to Variable Metric Algorithms", The Computer Journal, August 1970.
4. R. Fletcher and M.J.D. Powell, "A Rapidly Convergent Descent Method for Minimization", Computer Journal, Vol. 6, June 1963.
5. A.E. Atia, A.E. Williams and R.W. Newcomb, "Narrow-Band Multiple-Coupled Cavity Synthesis", IEEE Trans. on Circuits and Systems, Vol. Cas-21, No. 5, September 1974.

TABLE 1 - COMPUTED CRITICAL FREQUENCIES FOR A SIX-POLE ELLIPTIC FILTER USING OPTIMIZATION TECHNIQUES

$$K(s) = \frac{s^2(s^2-a_1^2)(s^2-a_2^2)}{(s^2+b_1^2)(s^2+b_2^2)}$$

$b_1 = 1.2995$



Starting Values: $a_1 = .4, a_2 = .8, b_2 = 2.0$
Objective Function: $|R(1)-R(2)| + |R(2)-R(5)| + |T(3)-T(4)|$
Constraints: $0 < a_1, a_2 < 1$
$1 < b_2 < 15$

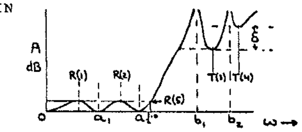
OPTIMIZATION METHODS	COMPUTED CRITICAL FREQUENCIES a_1	a_2	b_2	CPU TIME SECONDS
SIMPLEX	.4631	.6342	1.7775	143*
NEW FLETCHER ALGORITHM	.7583	.9768	1.6740	4.75
ANALYTIC VALUES	.7583	.9768	1.6741	-

* Optimum value could not be found after 200 seconds of CPU time.

TABLE 2 - COMPUTED CRITICAL FREQUENCIES FOR A NEW TYPE OF 8-POLE FILTER WITH TWO ATTENUATION POLES AND A DOUBLE ATTENUATION ZERO AT ORIGIN

$$K(s) = \frac{s^4(s^2+a_1^2)(s^2+a_2^2)}{(s^2+b_1^2)(s^2+b_2^2)}$$

$b_1 = 1.25$

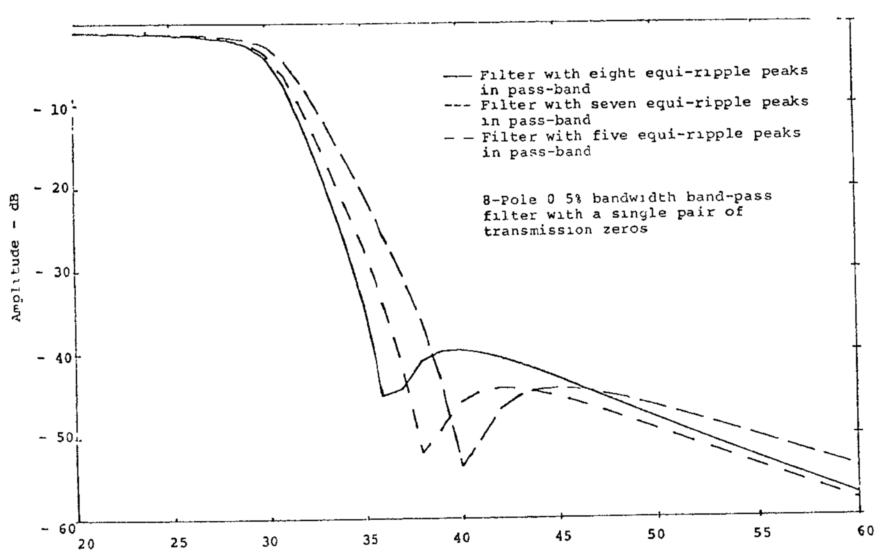


Objective Function: $|R(1)-R(2)|$ $|R(2)-R(5)|$ $|R(5)-R(1)|$ $|\pm T(3) \mp T(4) - \delta|$

δ: represents the difference in dB between the two attenuation minima in stopband

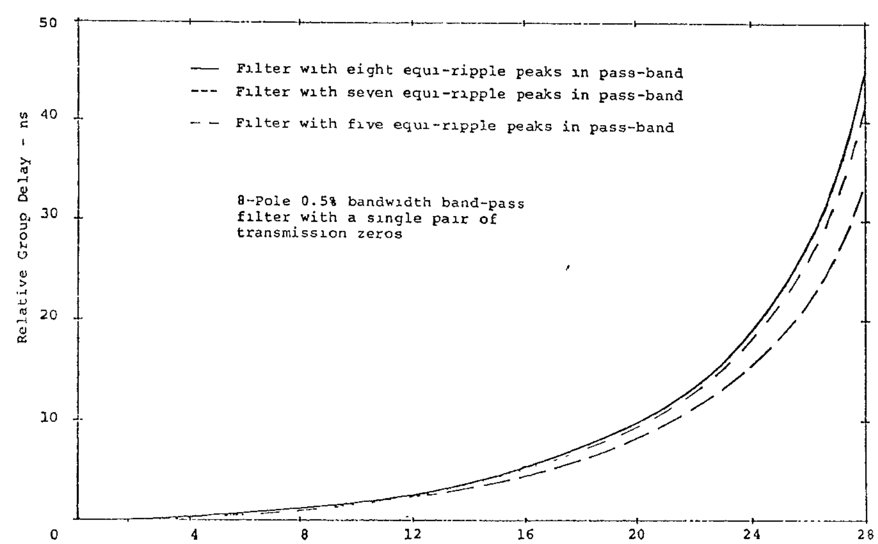
δ dB	COMPUTED a_1	CRITICAL a_2	FREQUENCIES b_2	CHARACTERISTIC * FACTOR 'F' dB	CPU TIME SECONDS
0	.8388	.9845	1.4671	67.4	4.66
10	.8340	.9839	1.6211	63.1	6.37
-10	.8636	.9878	1.1541	63.25	4.46

* 'F' is the characteristic factor in dB. It is defined by R(5)+T(3)-T(5)-R(3).



Frequency Deviation From Band-Center-MHz

FIG. 1 - COMPARISON OF AMPLITUDE RESPONSE



Frequency Deviation From Band-Center-MHz

FIG. 2 - COMPARISON OF GROUP DELAY RESPONSE