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SOS-99-14-R

June 1999

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Abstract

An equivalent circuit for a waveguide H-plane filter is developed in this work. This equivalent circuit can be applied as a coarse model in the highly efficient Hybrid Aggressive Space Mapping (HASM) optimization algorithm, whenever a design of a rectangular waveguide structure containing H-plane septa is carried out. This coarse model is based on empirical formulas suggested by Marcuvitz, which give very good approximation of a variety of classical waveguide discontinuities. It is fast, simple and can be easily implemented in any commercial circuit simulator. The optimization of the coarse model is discussed and its optimal design is compared with the simulation results provided by HP HFSS.

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada under Grants OGP0007239, STP0201832, Com Dev, Nanowave Technologies, and through the Micronet Network of Centres of Excellence. N. Georgieva is supported by an NSERC Postdoctorate Fellowship and M.H. Bakr by an Ontario Graduate Scholarship.

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I. INTRODUCTION

Waveguide technology has long traditions in building a variety of passive devices, such as filters, impedance transformers, power dividers, couplers, etc. Many of these structures involve classical discontinuities, which have been well studied, such as H-plane and E-plane septa, waveguide junctions, T-junctions, bends, apertures, etc. An excellent source of models and empirical formulas regarding waveguide passive structures is [1].

A test example has been developed based on a waveguide filter, which was designed, manufactured and measured by Young and Schiffman [2]. The design was entirely done using empirical formulas. The measurements reported in [2] show that the measured VSWR is slightly larger than the predicted one, but, generally, the design is in very good agreement with the expectations of the designers. The nominal project was built after the values reported in [2] and in [3]. We verified this design with a HP HFSS [4] simulation. The HP HFSS simulation also shows that the nominal structure slightly violates the specifications.

We have built an equivalent circuit, which models the waveguide filter with acceptable accuracy and can be used as a coarse model in the Hybrid Aggressive Space Mapping (HASM) [5] algorithm.

II. STRUCTURE DESCRIPTION AND DESIGN SPECIFICATIONS

A waveguide with a cross-section of 1.372 inches by 0.622 inches is used for this design. The six resonators are separated by seven H-plane septa. This filter is designed to provide a very wide passband in the C-band frequency range. The design specifications are as follows:

$$|S_{11}| \leq 0.16, \text{ for } 5.4 \text{ GHz} \leq f \leq 9\text{GHz} \quad (1)$$

$$|S_{11}| \geq 0.32, \text{ for } f \leq 5.34\text{GHz} \quad (2)$$

$$|S_{11}| \geq 0.32, \text{ for } f \geq 9.46\text{GHz} \quad (3)$$

The nominal project of the HP HFSS model is shown in Fig. 1. Note that the symmetry of the dominant-mode field distribution is used and a perfect H boundary (magnetic wall) is applied. Thus, only half of the structure is discretized, which reduces the CPU-time required for a fine-model frequency sweep almost in half.

The structure is symmetrical with respect to the central septum (the center of its length). There are seven optimization variables: the four septa's widths and the three resonators' lengths. The geometrical dimensions correspond to the notations in Fig. 2. Nominal values of the optimization parameters are given in Table I together with the perturbed values used for the geometry capture of the fine model.

III. THE COARSE MODEL

This particular structure is relatively easy to model in terms of an equivalent circuit consisting of lumped inductances and dispersive transmission-line sections. The simulation of the coarse model is computationally much more efficient in comparison with a full-wave electromagnetic simulation, e.g., HP HFSS simulation. The equivalent circuit of the structure in Fig. 2 is shown in Fig. 3. The lumped inductances represent the H-plane septa, while the transmission-line sections represent the waveguide sections between any two septa. The characteristic impedance of these lines is taken equal to the wave impedance of the rectangular waveguide, which depends on the frequency. The equivalent circuit of Fig. 3 was implemented and optimized in OSA90/hope [6].

There are various approaches to calculate the equivalent inductive susceptance corresponding to a H-plane septum (see Fig. 2). The simplest formula is provided by Smythe [7]. It is a quasi-static approximation:

$$\frac{B_i}{Y_0} \approx -\frac{l_g}{W_i}\left[1+\csc^2\left(\frac{p}{2}\frac{W_i}{a}\right)\right]\cot^2\left(\frac{p}{2}\frac{W_i}{a}\right),\ B_i=1/(jwL_i) \qquad (4)$$

Here l_g denotes the guide wavelength. For the dominant mode

$$l_g = \frac{1}{\sqrt{\left(\frac{f}{c}\right)^2 - \left(\frac{1}{4a}\right)^2}} \quad , \qquad (5)$$

where c denotes the speed of light in free space and f is the frequency**.** Y_0 denotes the wave admittance of the rectangular waveguide, $Y_0=1/Z_0$.

A more accurate model is provided in [1], Paragraph 5-2. The following approximate relations were implemented:

$$\frac{X_i}{Z_0} \approx \frac{2a}{l_g} \tan^2\left(\frac{p}{2}\frac{W_i}{a}\right)\left[1 + \frac{2}{3}\left(p\frac{W_i}{l}\right)^2\right], \text{ for } \quad \frac{W_i}{a} << 1 \qquad (6)$$

$$\frac{X_i}{Z_0} \approx \frac{2a}{l_g} \cot^2\left(\frac{p}{2}\frac{W_i^{'}}{a}\right)\left[1 + \frac{2}{3}\left(p\frac{W_i^{'}}{l}\right)^2\right], \text{ for } \quad \frac{W_i^{'}}{a} << 1, \text{ where} \qquad (7)$$

$$W_i^{'} = a - W_i$$

As explained in [1], the above approximations have their validity limits. These limits have to be taken into account when the range of perturbations of the septa widths is expected to be wide. Here, only one major limitation will be stated. The model is valid for a wavelength range specified by

$$(2/3)a < l < 2a \qquad (8)$$

Each waveguide resonator corresponds to a portion of an ideal transmission line characterized by its characteristic admittance Y_0 and by its electrical length q_i (i=1,2,3). The characteristic impedance, $Z_0=1/Y_0$, is equal to the waveguide impedance. The electrical length q_i is proportional to the physical length of the waveguide section l_i as

$$q_i = 360\frac{l_i}{l_g}, \text{ deg} \qquad (9)$$

Since l_g is frequency dependent, the electrical length q_i also depends on the frequency.

IV. OPTIMIZATION OF THE COARSE MODEL

The starting values for the optimization of the coarse model are taken equal to the values suggested in [2, 3]. These values are given in the first column of Table II. The $|S_{11}|$ response of the coarse model at the starting point is shown in Fig. 4.

The iteration report for the minimax optimization shows that the design is successfully optimized with an error of approximately –0.05 (see Fig. 5). The optimal parameter values are given in the second column of Table II. The $|S_{11}|$ response of the optimal coarse model design is shown in Fig. 6.

V. ADDITIONAL NOTES

Direct optimization using HP HFSS HP and Empipe3D was carried out starting from the nominal values given in Table I, which correspond to the design presented in [2]. It was observed that the fine model converges to another minimum when the optimal coarse model values of the optimization variables are used as a starting point. The obtained solution is worse in comparison with the one which starts with initial values set equal to the design presented in [1]. This means that the problem has multiple minima.

The optimal solution to the coarse model problem depends slightly on the number of frequency points used in the discrete sweep. Generally, the more the frequency points in the sweep, the more reliable the design should be.

REFERENCES

[1] N. Marcuvitz, *Waveguide Handbook*. New York, NY: McGraw-Hill, 1951.

[2] L. Young and B. M. Schiffman, “A useful high-pass filter design,” *Microwave Journal*, vol. 6, 1963, pp. 78-80.

[3] G. L. Matthaei, L. Young, E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*. New York, NY: McGraw-Hill, 1964, pp. 545-547.

[4] HP HFSS™ Version 5.2, HP EEsof Division, 1400 Fountaingrove Parkway, Santa Rosa, CA 95403-1799, 1998.

[5] M.H. Bakr, J.W. Bandler, N. Georgieva and K. Madsen, “A hybrid aggressive space mapping algorithm for EM optimization,” *IEEE MTT-S Int. Microwave Symp. Dig*. (Anaheim, CA), 1999.

[6] OSA90/hope™ Version 4.0, formerly Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7, 1997, now HP EEsof Division, Hewlett-Packard Company, 1400 Fountaingrove Parkway, Santa Rosa, CA 95403-1799.

[7] W. R. Smythe, *Static and Dynamic Electricity*, 2nd ed. New York, NY: McGraw-Hill, 1950.

TABLE I
NOMINAL AND PERTURBED VALUES
OF THE DESIGNABLE PARAMTERS
OF THE FINE MODEL

Parameter	Nominal Value	Perturbed Value
W_1	0.513	0.514
W_2	0.479	0.480
W_3	0.449	0.450
W_4	0.435	0.436
L_1	0.626	0.630
L_2	0.653	0.660
L_3	0.674	0.680
All values are in inches		

TABLE II
NOMINAL AND OPTIMIZED VALUES
OF THE DESIGNABLE PARAMETERS
OF THE COARSE MODEL

Parameter	Nominal Value	Optimized Value
W_1	0.513	0.556455
W_2	0.479	0.527037
W_3	0.449	0.510853
W_4	0.435	0.506619
L_1	0.626	0.648785
L_2	0.653	0.658020
L_3	0.674	0.674779
All values are in inches		

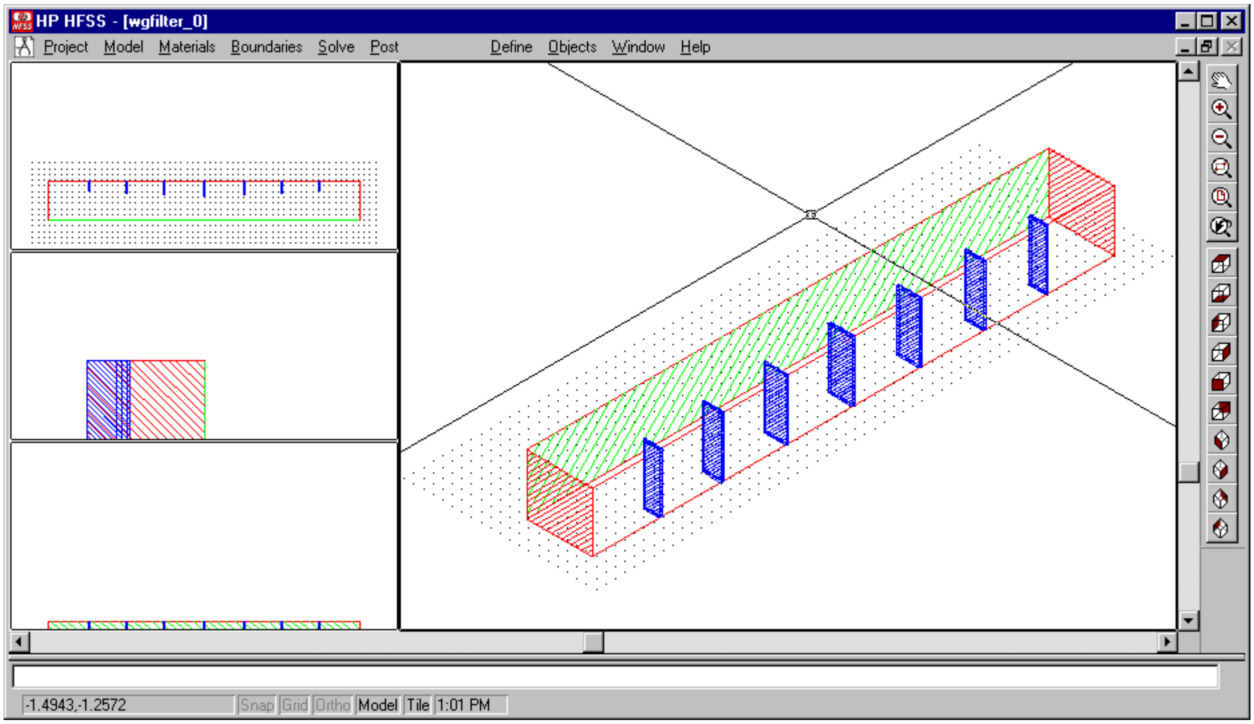

Fig. 1. The nominal geometry file of the fine model (HP HFSS simulation).

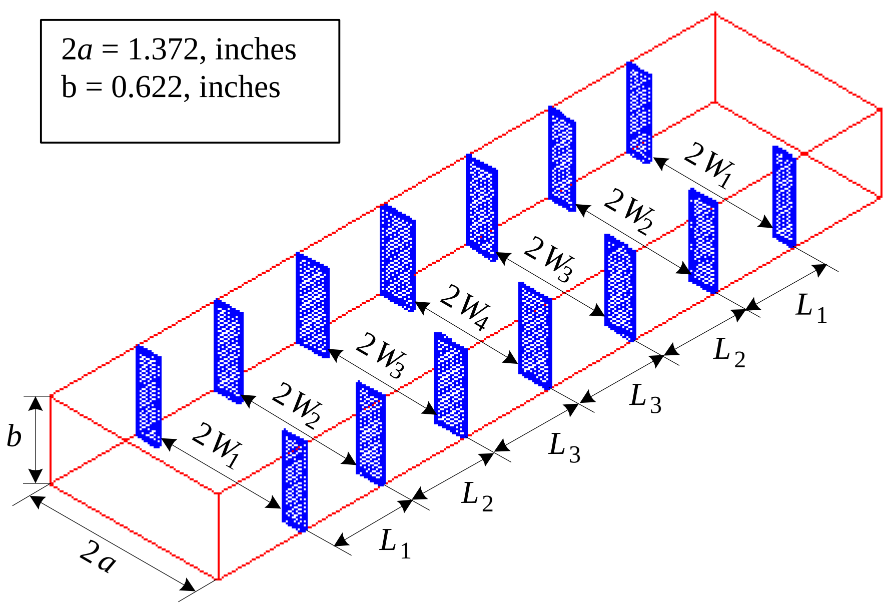

Fig. 2. General geometry of the H-plane six-section waveguide filter.

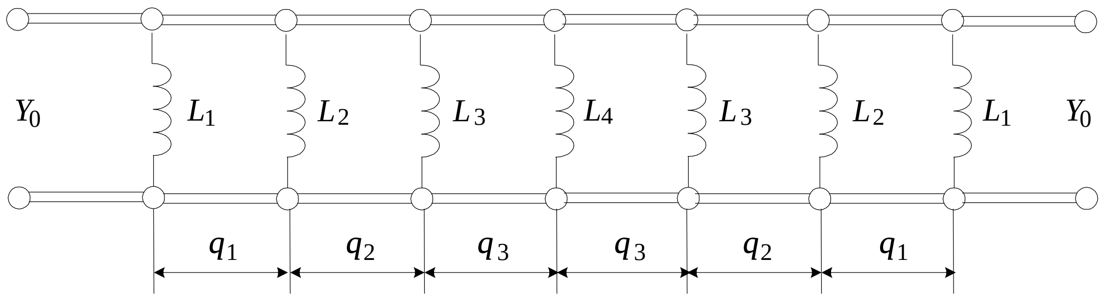

Fig. 3. Equivalent circuit of the six-resonator H-plane waveguide filter.

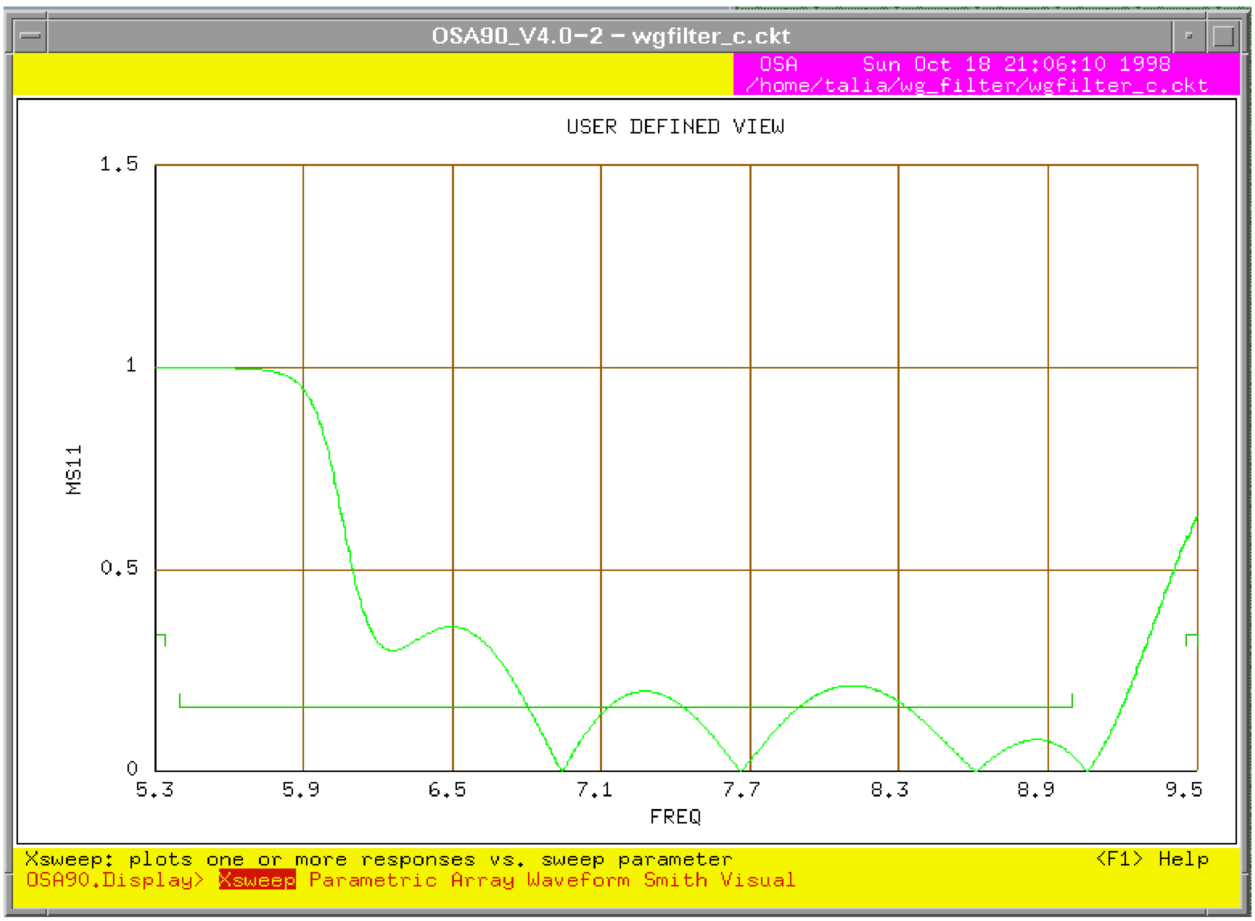

Fig. 4. The coarse model response before optimization.

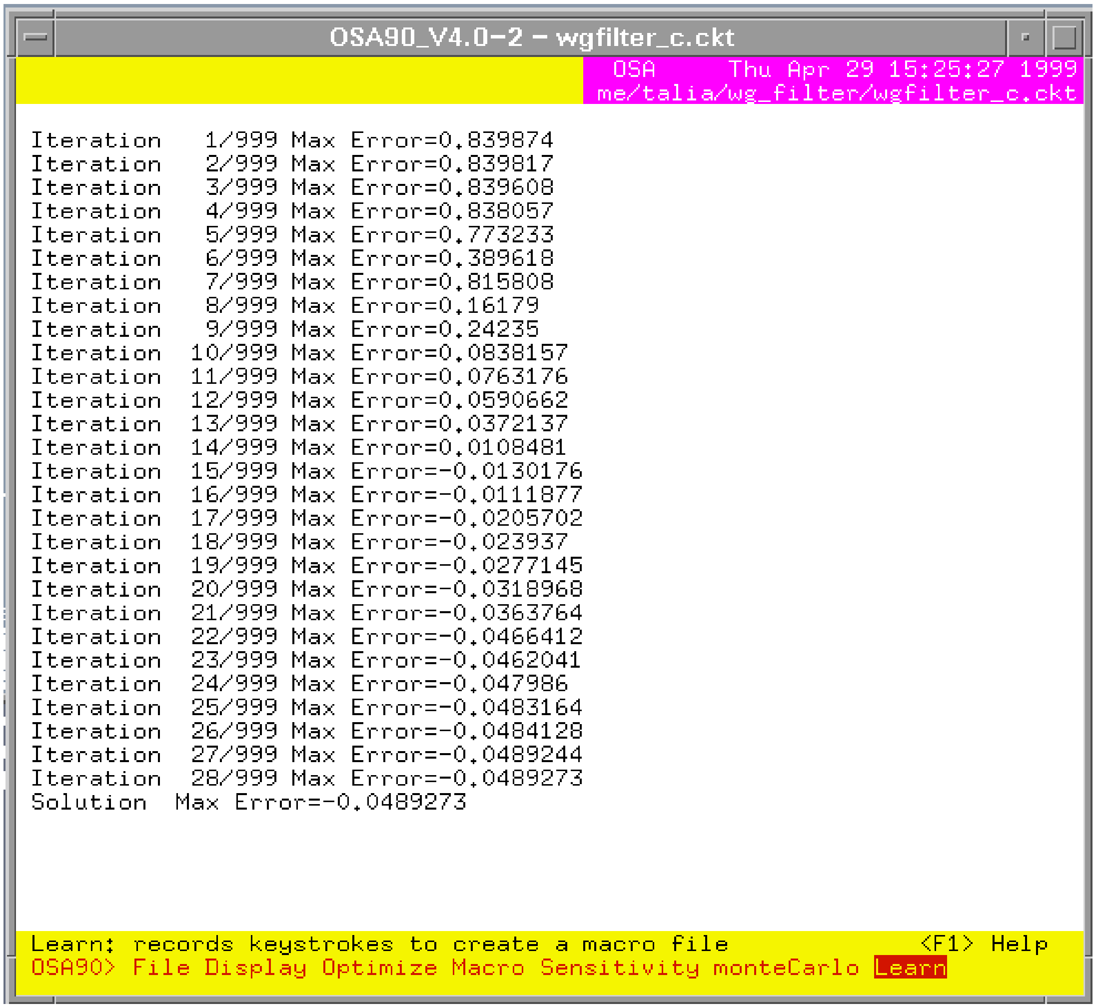

Fig. 5. The iteration report for the optimization of the coarse model of the H-plane waveguide filter.

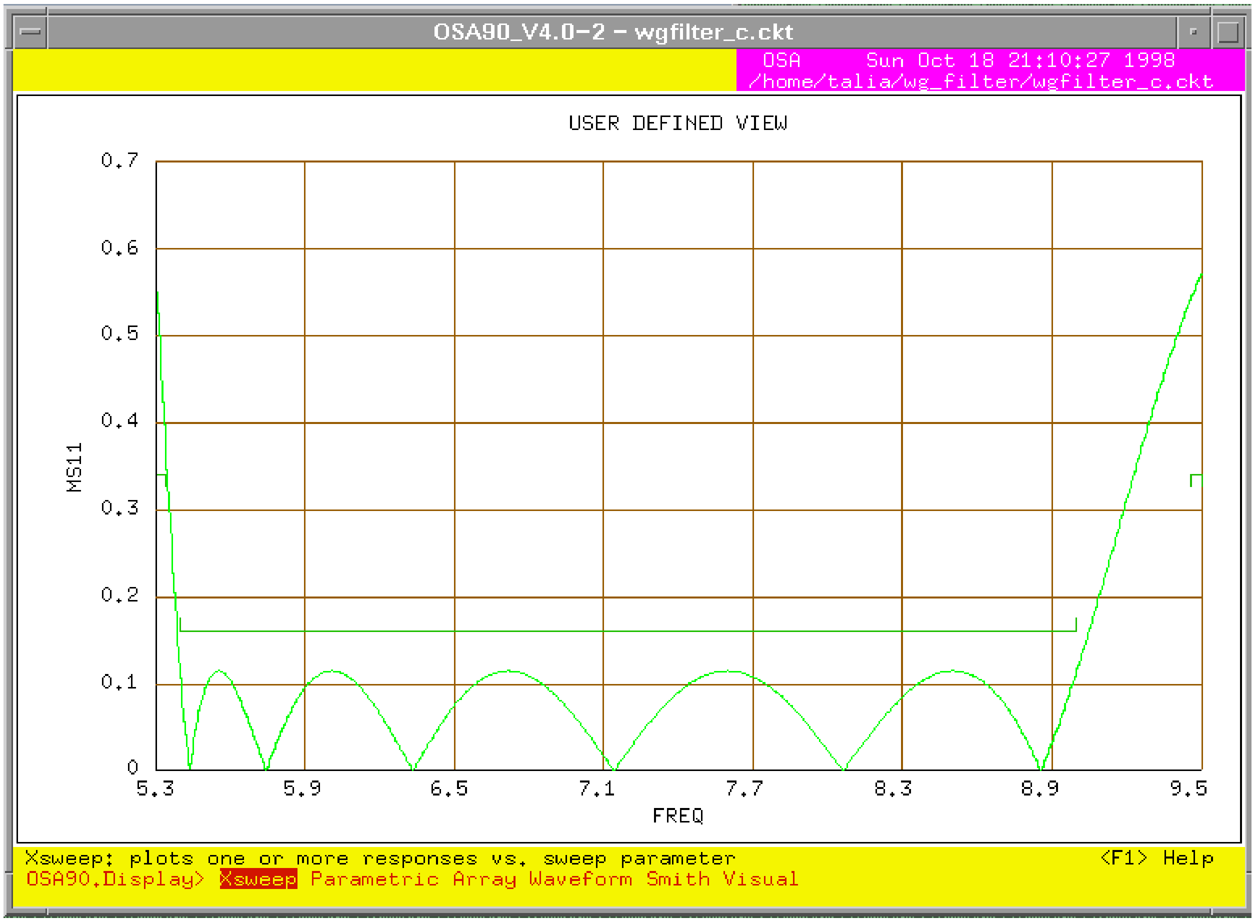

Fig. 6. The optimal coarse model response.

APPENDIX

The Coarse Model of the Waveguide Filter: OSA90 Netlist File

```
!  Thu Oct 15 12:37:52 1998. Minimax Optimizer. 18 Iterations. 00:00:00 CPU.
Expression
      MS11_SPEC = 0.16;

      INMM = 25.4;
      V = 2.99792458E+11;
      MU0 = 4*PI*1E-10;
      EPS0 = 1/(36*PI)*1E-12;
      GAMMA = SQRT(MU0/EPS0);

      A = 1.372*INMM; B = 0.622*INMM;
! Septa half-widths in inches
      CC1: ?0.557111?;
      CC2: ?0.523275?;
      CC3: ?0.510365?;
      CC4: ?0.508484?;

      C1 = 2*CC1*INMM; C2 = 2*CC2*INMM;
      C3 = 2*CC3*INMM; C4 = 2*CC4*INMM;

      LL1: ?0.633067?;
      LL2: ?0.65315?;
      LL3: ?0.675303?;

      L1 = LL1*INMM; L2 = LL2*INMM;
      L3 = LL3*INMM;
      LIO = 0.7*INMM;
! wave impedance Z0 and wavelength LAMBDA
      Fc=(1E-9*V)/(2*A); ! GHz
      Z0=GAMMA/SQRT(1-(Fc/FREQ)^2);
      Y0=1/Z0;
      LAMBDA=1/SQRT((FREQ*1E+9/V)^2-(1/(2*A))^2);
! Susceptances (quasistatic, after Smythe)
      C1A=C1/A;C2A=C2/A;C3A=C3/A;C4A=C4/A;

      B1=-Y0*(LAMBDA/A)*(1+(1/sin(PI*C1A/2))^2)/((tan(PI*C1A/2))^2);
      B2=-Y0*(LAMBDA/A)*(1+(1/sin(PI*C2A/2))^2)/((tan(PI*C2A/2))^2);
      B3=-Y0*(LAMBDA/A)*(1+(1/sin(PI*C3A/2))^2)/((tan(PI*C3A/2))^2);
      B4=-Y0*(LAMBDA/A)*(1+(1/sin(PI*C4A/2))^2)/((tan(PI*C4A/2))^2);
! inductances (nano-henry)
      LI1=-1/(2.*PI*FREQ*B1);
      LI2=-1/(2.*PI*FREQ*B2);
      LI3=-1/(2.*PI*FREQ*B3);
      LI4=-1/(2.*PI*FREQ*B4);
! electrical lengths of resonators/input lines (degrees)
      THETA1=360.*L1/LAMBDA;
      THETA2=360.*L2/LAMBDA;
      THETA3=360.*L3/LAMBDA;
      THETAIO=360.*LIO/LAMBDA;
end
Model
      TEM 1 2 0 0 Z=Z0 E=THETAIO F=FREQ;
```

```
      IND 2 0 L=LI1;
      TEM 2 3 0 0 Z=Z0 E=THETA1 F=FREQ;
      IND 3 0 L=LI2;
      TEM 3 4 0 0 Z=Z0 E=THETA2 F=FREQ;
      IND 4 0 L=LI3;
      TEM 4 5 0 0 Z=Z0 E=THETA3 F=FREQ;
      IND 5 0 L=LI4;
      TEM 5 6 0 0 Z=Z0 E=THETA3 F=FREQ;
      IND 6 0 L=LI3;
      TEM 6 7 0 0 Z=Z0 E=THETA2 F=FREQ;
      IND 7 0 L=LI2;
      TEM 7 8 0 0 Z=Z0 E=THETA1 F=FREQ;
      IND 8 0 L=LI1;
      TEM 8 9 0 0 Z=Z0 E=THETAIO F=FREQ;

      PORT 1 0  R=Z0;
      PORT 9 0  R=Z0;
CIRCUIT;
      MS_dB[2,2] = if (MS > 0) (20 * log10(MS)) else (NAN);
      MS11_dB = MS_dB[1,1];
      MS21_dB = MS_dB[2,1];
end
Sweep
      AC: FREQ: from 5.3GHz to 5.34GHz step=0.04GHz
                from 5.4GHz to 9GHz step=0.36GHz
                from 9.46GHz to 9.5GHz step=0.04GHz
      MS MS_dB PS MS11_dB MS21_dB
      {XSWEEP X=FREQ Y=MS11
            SPEC=(from 5.4 to 9, < 0.16) &
                 (from 5.3 to 5.34 , > 0.34) &
                     (from 9.46 to 9.5 , > 0.34)};
end
Spec
      AC: FREQ: from 5.4GHz to 9GHz step=0.36GHz
      MS11 < 0.16;
      AC: FREQ: from 5.3GHz to 5.34GHz step=0.04GHz
      MS11 > 0.34;
      AC: FREQ: from 9.46GHz to 9.5GHz step=0.04GHz
      MS11 > 0.34;
end
Report
      Xos=[$CC1$
           $CC2$
           $CC3$
           $CC4$
           $LL1$
           $LL2$
           $LL3$];
end
```