SIMULATION OPTIMIZATION SYSTEMS
Research Laboratory

COMPUTER EXPERIMENTS WITH TOUCHSTONE

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Abstract

Three problems have been selected to test the performance of the popular microwave CAD program TOUCHSTONE. In addition to the standard random optimizer of the package, two different prototype versions of TOUCHSTONE with minimax and quasi-Newton least squares optimizers have been tested. The tests have been performed on a TI/PC system and all results, TOUCHSTONE circuit files and plots obtained using an HP7475A plotter are included.

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I. INTRODUCTION

In this report, a popular microwave CAD tool, namely TOUCHSTONE[1], has been used to solve three rather standard problems from the set of collected problems[2]. TOUCHSTONE enables microwave engineers to simulate a circuit design without physically constructing one. The main feature of TOUCHSTONE, namely its optimizer, seeks circuit parameters such that the reponses meet certain engineering specifications.

Three circuit problems were used to explore the performance of TOUCHSTONE's optimizer. These are questions 183, 188 and 189 of the collected set of problems[2]. These problems were tested with a powerful minimax optimizer and a quasi-Newton least squares optimizer in addition to the random optimizer.

Q.183 and Q.188 are 5-section and 7-section transmission line circuit problems, respectively. The 2-port network of the filter in Q.183 is terminated by constant normalized resistors while Q.188 deals with frequency-dependent terminations. In Q.183, the characteristic impedances of the transmission lines are fixed and their lengths are allowed to vary. In Q.188, the lengths of transmission lines are fixed and the characteristic impedances are optimized. Q.189 involves an active bandpass filter with two non-ideal operational amplifiers.

II. QUESTION 183

Question 183 involves 5 transmission lines in cascade, as illustrated in Fig. 1, and consists of a lowpass filter that has to have an insertion loss of no more than 0.01 dB over its passband (0-1 GHz). The insertion loss has to be maximized at 5 GHz. The characteristic impedances are fixed such that Z1=Z3=Z5=0.2 Ω and Z2=Z4=5 Ω. The section lengths are allowed to vary to meet the specifications. The structure is symmetrical, i.e., L1=L5 and L2=L4. In the passband, 21 uniformly distributed sample points are chosen and one point at 5 GHz is examined. The section lengths are given in electrical lengths in TOUCHSTONE. The frequency at which the electrical length has been defined is 1 GHz. This means that the electrical length of 90 degrees is quarter wavelength at 1 GHz.

A circuit file was created (Appendix A). The variables are all defined in the VAR block. The bounds were set under the guidelines of Charalambous' 1973 thesis[3]. A number of optimizations were tried. These included the random optimization, minimax optimization and quasi-Newton optimization.

The circuit parameters shown in the circuit file of Appendix A are the optimized values. The stopband specification was set at 56.69 dB after some trials with other values. Plots (Figs. A1-A6) of the responses after each optimization are also included in Appendix A.

The optimizations tested had the same starting points and the same specifications except minimax optimization which used a different set of starting values. Table I shows the results obtained by these optimizers and the parameter values are shown in Table II. Note that the random optimizer will not stop unless the specifications are met or the maximum number of iterations is exceeded. The other two

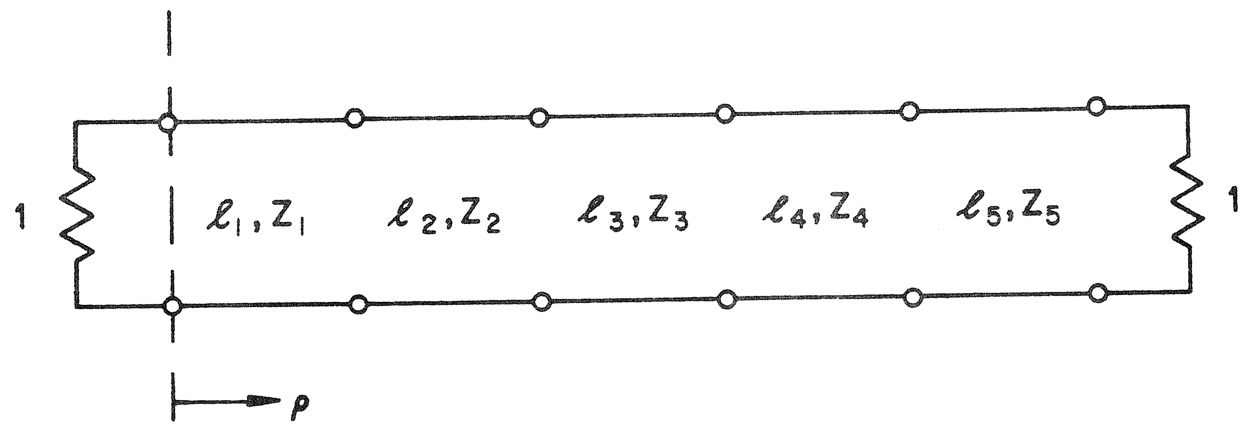

Fig.1 Five-section transmission line filter of Question 183.

TABLE I

RESULTS OF DIFFERENT OPTIMIZATIONS FOR Q.183

Optimization type	# of Iterations	Violating pts.	Initial error	Final error
Random optimization	480	0	33.97094	0.00000
Minimax optimization	3	3	5.82843	0.00033
Quasi-Newton method	14	3	33.97094	0.000005

Notes:
- -Violating points are points that violate the specification given in the circuit file of Appendix A.
- -No. of iterations is smaller than the actual no. of circuit simulations for minimax and quasi-Newton optimizers. On the other hand, for random optimizer, an iteration means one circuit simulation.
- -For minimax optimization, the starting values are L1=8.71266, L2=14.68840, L3=17.90357.
- -Error function indicated by the minimax optimizer is the maximum error.
- -Minimax and quasi-Newton optimizations were restarted after a solution was reached until no signifacant improvement was observed. The number of iterations reported is the sum of iterations for each optimizer.

TABLE II

PARAMETER VALUES AFTER THE OPTIMIZATION IN Q.183

Optimization type	L1	L2	L3
Random optimization	8.62671	14.64798	17.80745
Minimax optimization	8.68196	14.67314	17.87134
Quasi-Newton method	8.72598	14.84635	17.67046
Charalambous[3] solution	8.63370	14.65020	17.81820

Note: -All lengths are in electrical length.

optimizers have the ability to stop automatically whenever the solution is reached (possibly a local minimum). If the results are not satisfactory, different starting values may be tried.

III. QUESTION 188

Question 188 is similar in structure to question 183. It is a 7-section transmission line filter with frequency-dependent terminations. Here the lengths are fixed at 1.5 cm (this is converted to electrical length as 37.41188) and the characteristic impedances are the variables. Fig. 2 shows the circuit diagram. The specifications call for a maximum insertion loss of 0.4 dB in the range 2.16-3 GHz while the loss at 5 GHz is to be maximized.

In doing the problem using TOUCHSTONE, a 1-port S-parameter file had to be prepared to accomodate the frequency dependent terminations of the filter. The source and load terminations at frequency f are given by:

$$R_g=R_L=377/\sqrt{(1-(f_c/f)^2} \ (\Omega), \quad (1)$$

where f_c=2.077 GHz. This information was converted to reflection coefficient and put into a 1-port S-parameter file called FDT.S1P (supplemented in Appendix B). This file was treated as an external file and was used by the TERM block. There were no suggested starting points. Therefore, under the guidelines of Srinivasan's 1973 thesis[4], the bounds for variables as well as the starting values were selected. The circuit file and the results are shown in Appendix B. Minimax optimization, quasi-Newton optimization and random optimization were tried out. The initial values are given in the circuit file of Appendix B.

Tables III and IV contain the optimization results and the

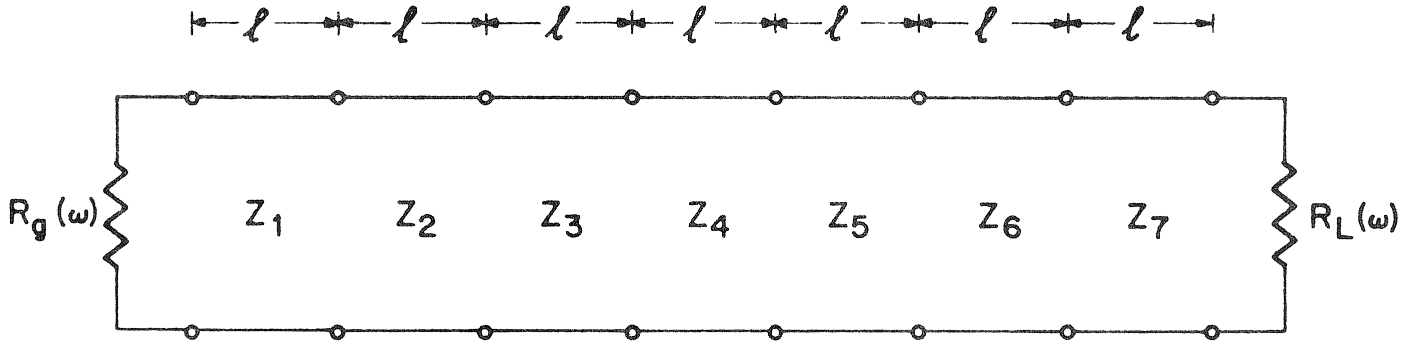

Fig.2 Seven-section transmission line filter of Question 188.

TABLE III

OPTIMIZATION RESULTS FOR Q.188

Optimization type	# of Iterations	Violating pts.	Initial error	Final error
Random optimization	312	0	13980	0.00000
Minimax optimization	14	0	3739	-0.02193
Quasi-Newton method	34	3	13980	0.000009

TABLE IV

PARAMETERS VALUES FOR Q.188

Impedance	Random optimization	Minimax optimization	quasi-Newton optimization	Srinivasan's[4] solution
Z1	3068	3006	2966	3069.4
Z2	2836	2765	2782	2856.4
Z3	25060	23910	24620	25871.2
Z4	9998	9786	9979	10573.3
Z5	23970	24260	24150	25874.0
Z6	2731	2741	2790	2856.7
Z7	2935	2970	2998	3069.8

Note: -All the impedances are in ohms.

optimum circuit parameters after applying various optimizers on the problem. The specifications were set at 0.4 dB and 38.3 dB insertion loss for the passband and the stopband, respectively. Plots showing the responses after these optimizations (Figs. B1-B6) are also included in Appendix B.

IV. QUESTION 189

Question 189 is a tunable active bandpass filter centred at 100 Hz with a 20 Hz bandwidth. The equivalent circuit consists of 2 operational amplifiers, 2 identical capacitors and 3 resistors. Terminating the 2-port network is a source with 50 Ω internal impedance and an open circuit at the load. The OpAmps are identical, having a dc gain of 20000 and an internal resistance of 75 Ω. The 3 dB bandwidth for the OpAmps, which have a one pole roll-off model, is 6 Hz. In Fig. 3, R1 and R4 are two of the variables and C1=C2=C is the third variable.

Appendix C shows the circuit file, the specifications and the results produced by 3 optimizers. The starting values for the circuit elements are estimated using the solution provided in report SOS-78-10-R[5]. The circuit file in Appendix C contains both the upper and lower bounds as well as the starting values of the circuit parameters.

Tables V and VI show the results after the application of the three available optimizers. Plots (Figs. C1-C6) of the responses after optimization are also included in Appendix C. Frequency sample points are selected such that they not only represent the overall characteristics of the filter but also inhibit the optimizer from overflowing because of the surplus of the sample points.

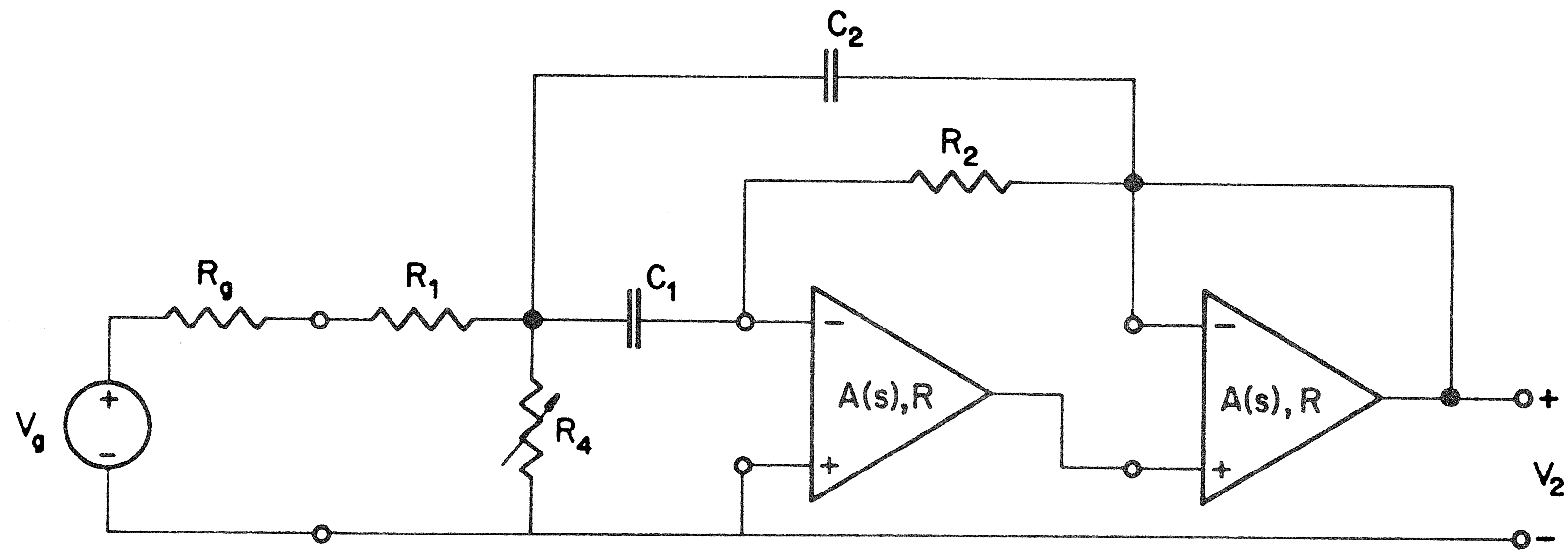

Fig.3 Active filter of Question 189.

TABLE V

RESULTS FROM VARIOUS OPTIMIZATIONS ON Q.189

Optimization type	# of Iterations	Violating pts.	Initial error	Final error
Random optimization	17	0	0.13273	0.00000
Minimax optimization	7	0	0.32538	-0.04045
Quasi-Newton method	5	1	0.13273	0.000003

TABLE VI

PARAMETER VALUES FOR Q.189

Optimization type	C	R1	R4
Random optimization	786.20970	12310	159.56460
Minimax optimization	754.78020	12490	170.99960
Quasi-Newton method	763.96670	13110	166.41180
SOS-78-10-R[5] solution	728.55600	12450	184.39980

Notes: -Capacitances and resistances are in nF and ohms, respectively.

V. CONCLUSIONS

In this report, TOUCHSTONE was examined and tested on three circuit examples, namely Q.183, Q.188 and Q.189 in the collected problems[2]. Random, minimax and quasi-Newton optimizers were examined and compared with each other. TOUCHSTONE's capability of handling various circuit configurations was exploited while circuits with transmission lines, frequency-dependent terminations and non-ideal OpAmps were put to test. Random optimizer's performance was proved to be acceptable when it was compared with more sophisticated optimizers. Minimax optimization was the fastest method used. It was also the most predictable and stable optimizer.

Our experience has proved TOUCHSTONE to be a handy and helpful **microwave** design software system, so justifying its reputation as a powerful CAD tool.

REFERENCES

[1] TOUCHSTONE, EEsof. Inc., Westlake Village, CA, 1985.

[2] J.W. Bandler, "Collected problems in computational methods, design, and optimization", Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, Report SOS-83-16-N, 1983.

[3] C. Charalambous, "Nonlinear least-pth approximation and nonlinear programming with applications in the design of networks and systems", Ph.D. thesis, Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, 1973.

[4] T. V. Srinivasan, "Minimax system modelling and design", Ph.D. thesis, Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, 1973.

[5] H.L. Abdel-Malek and J.W. Bandler, "Centering, tolerancing, tuning and minimax design employing biquadratic models", Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, Report SOS-78-10-R, 1978.

APPENDIX A

Appendix A includes the circuit file for Q.183 and the plots of the responses after each optimization.

```
! THIS IS A TOUCHSTONE PROGRAM DESIGNED TO SOLVE QUESTION 183
! OF THE COLLECTED PROBLEMS SET.

VAR
   ZF=.2                     ! CHARACTERISTIC IMPEDANCES OF L1,L3 AND L5
   ZH=5                      ! CHARACTERISTIC IMPEDANCES OF L2 AND L4
   FT=1
!
   L1#5  6.30000  9          ! INITIAL (STARTING) VALUES
   L2#5  13.50000 16
   L3#5  13.50000 18

!  L1#5 8.62671  9           ! VALUES OBTAINED BY RANDOM OPTIMIZATION
!  L2#5 14.64798 16
!  L3#5 17.80745 18

!  L1#5 8.68196  9           ! VALUES OBTAINED BY MINIMAX OPTIMIZATION
!  L2#5 14.67314 16          ! STARTING VALUE FROM OTHER MINIMAX VALUE
!  L3#8 17.87134 18          ! L1=8.71266, L2=14.68840, L3=17.90357

!  L1#5 8.72598  9           ! VALUES OBTAINED BY QUASI-NEWTON METHOD
!  L2#5 14.84635 16          ! 3 SAMPLE POINTS VIOLATING THE SPECS.
!  L3#5 17.67046 18

CKT
   TLIN 1 2 Z^ZF E^L1 F^FT
   TLIN 2 3 Z^ZH E^L2 F^FT
   TLIN 3 4 Z^ZF E^L3 F^FT
   TLIN 4 5 Z^ZH E^L2 F^FT
   TLIN 5 6 Z^ZF E^L1 F^FT
   DEF2P 1 6 TL
TERM
   TL 0.960784313 180 0.960784313 180 ! 1 OHM TERMINATIONS
FREQ
!  FREQUENCIES FOR OPTIMIZATION
!  SWEEP 1E-10 1  0.05       ! PASSBAND FREQUENCY (GRID 1)
!  STEP  5                   ! STOPBAND FREQUENCY
!  FREQUENCIES FOR DISPLAY
   SWEEP 1E-10 10 0.2        ! DISPLAY ONLY       (GRID 2)
OUT
   TL DB[S21] GR1
   TL DB[S21] GR2
GRID
   RANGE 1E-10  1  0.1
   GR1   -0.018 0  0.002
   RANGE 1E-10  10 1
   GR2   -70    0  5
```

```
OPT
   RANGE 0 1                ! THE PASSBAND SPECIFICATION
   TL DB[S21]>-0.01
   RANGE 5 5                ! THE SPEC. TO BE MET IN THE STOPBAND
   TL DB[S21]<-56.69
```

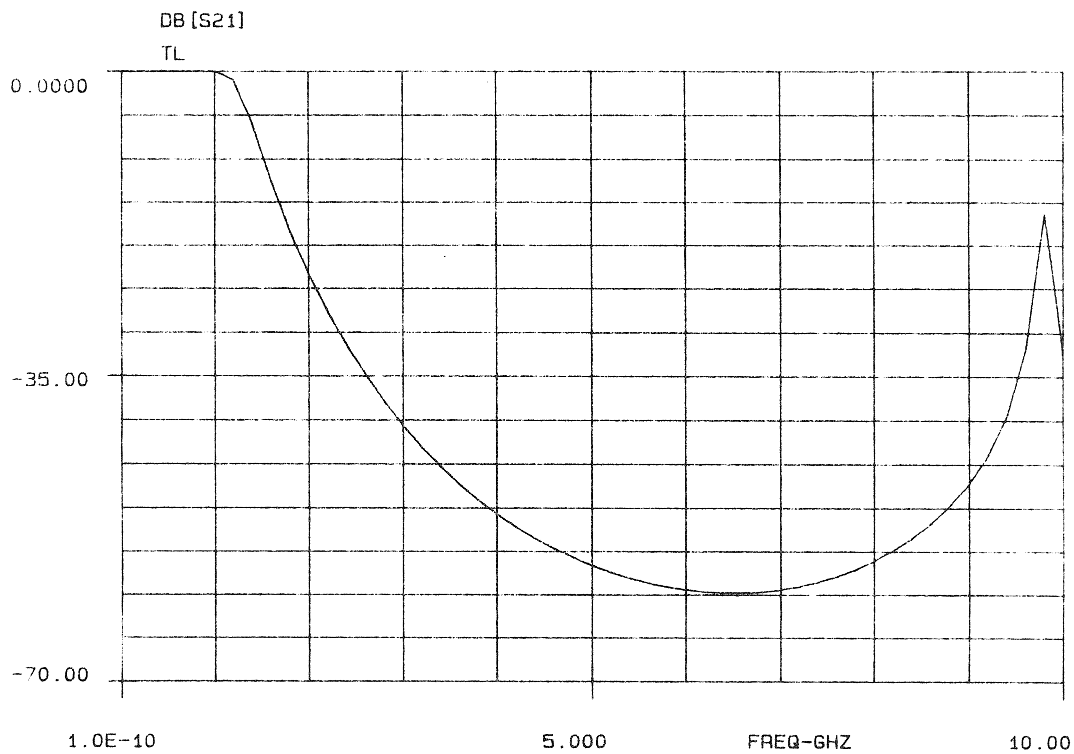

Fig.A1 Insertion loss of the filter in Q.183 after random optimization.

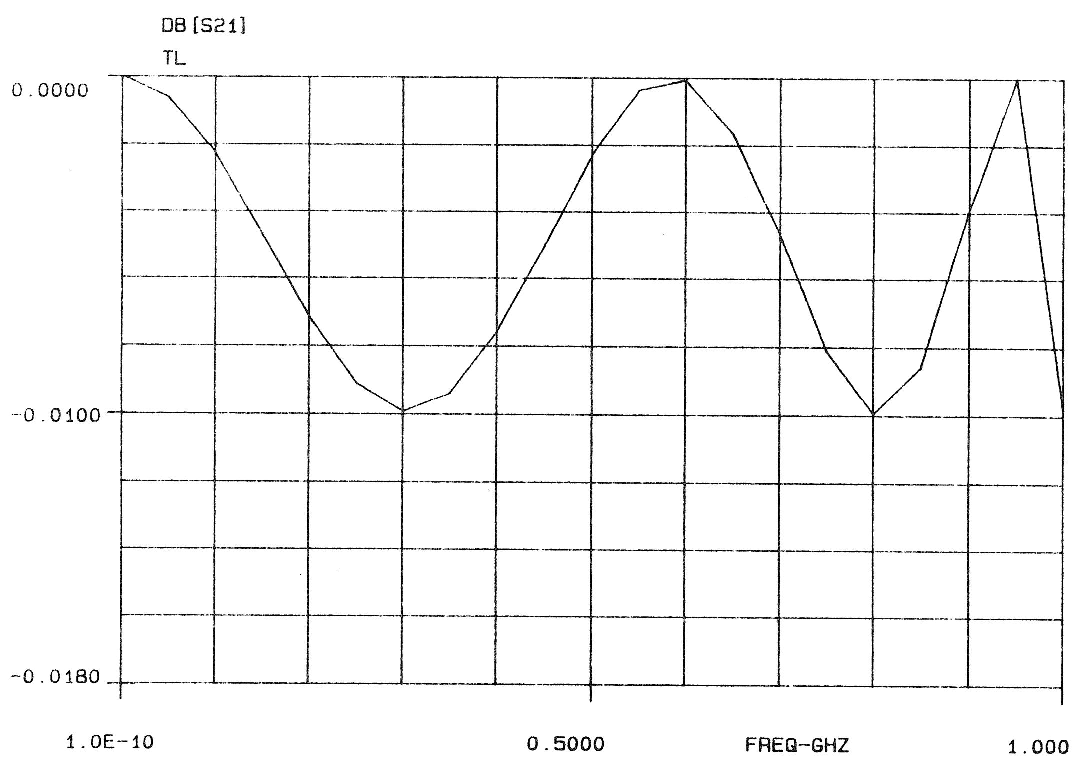

Fig.A2 Passband insertion loss of the filter in Q.183 after random optimization.

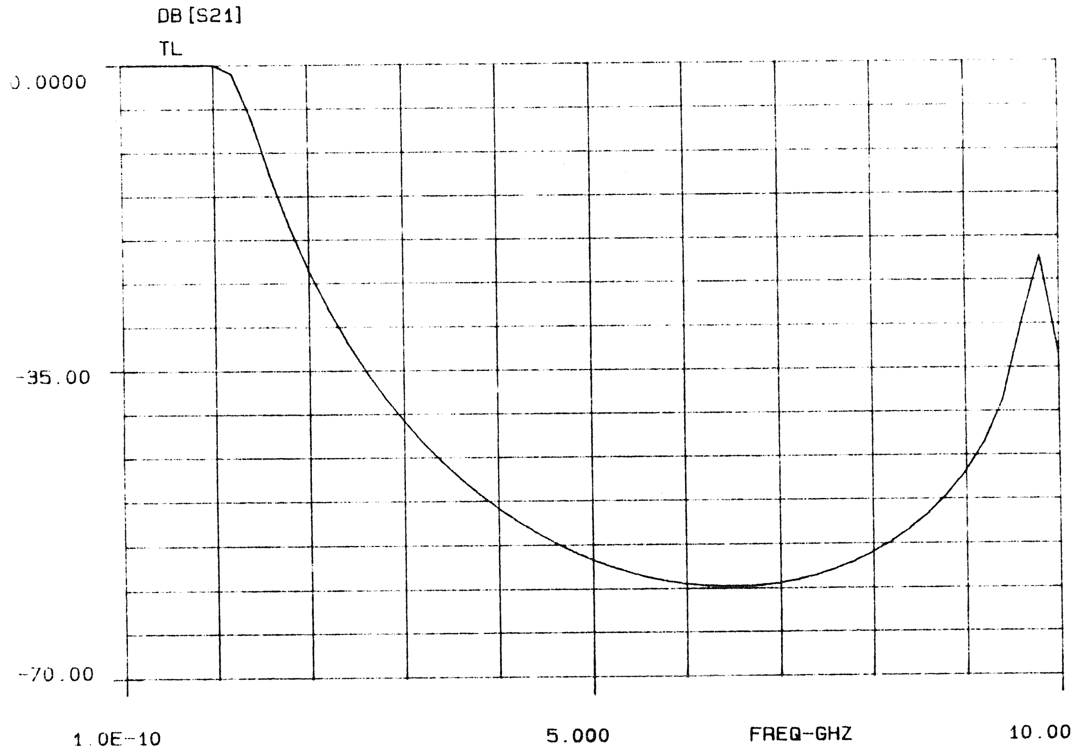

Fig.A3 Insertion loss of the filter in Q.183 after minimax optimization.

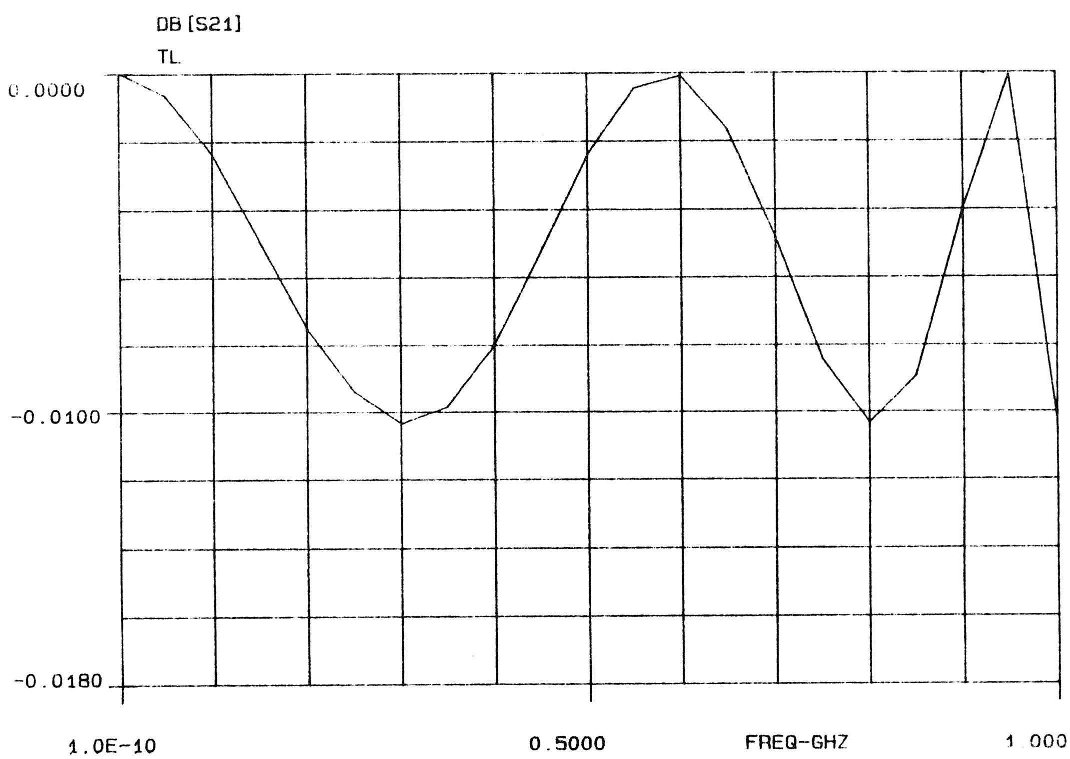

Fig.A4 Passband insertion loss of the filter in Q.183 after minimax optimization.

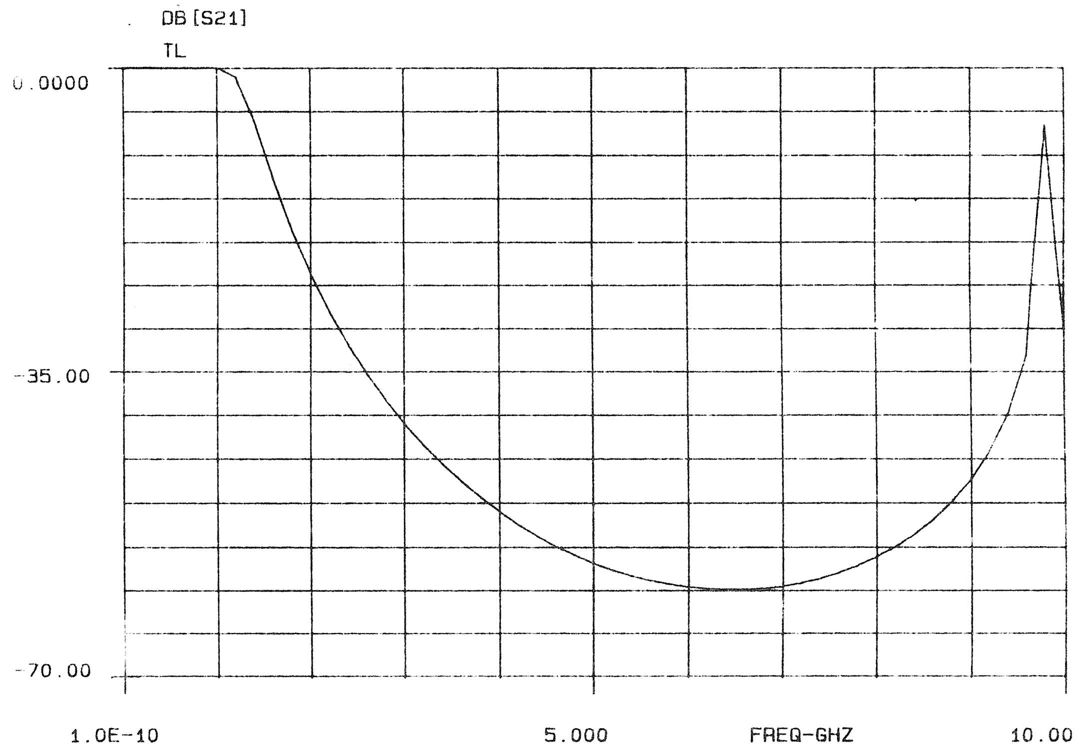

Fig.A5 Insertion loss of the filter in Q.183 after quasi-Newton least squares optimization.

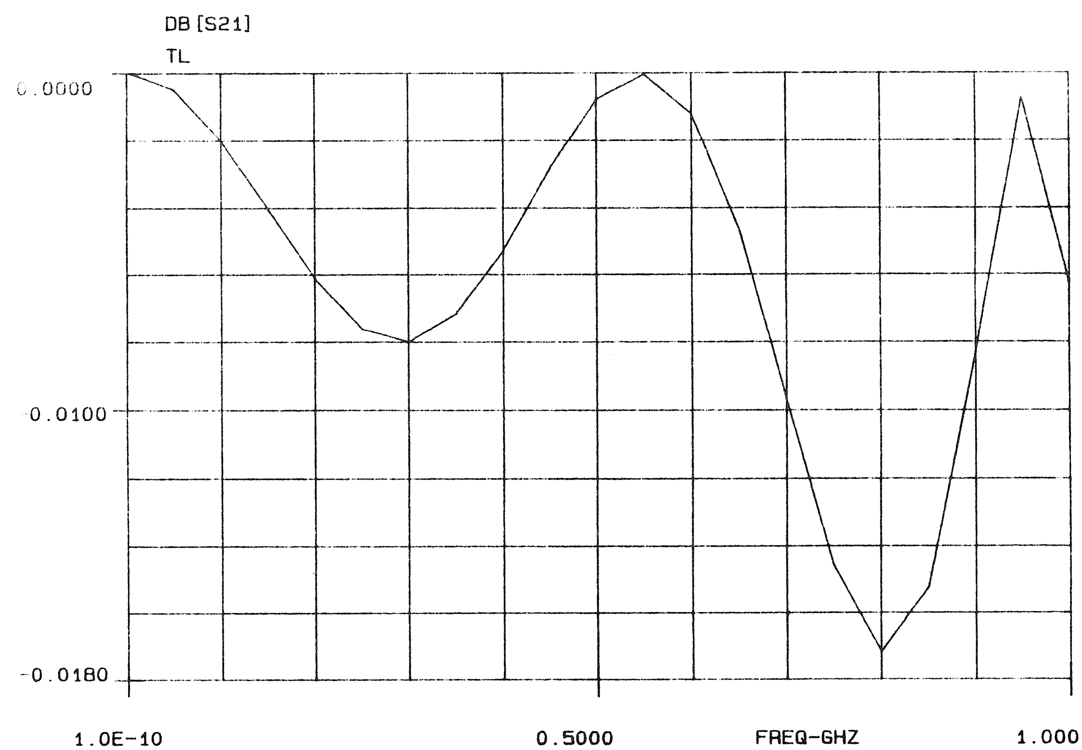

Fig.A6 Passband insertion loss of the filter in Q.183 after quasi-Newton least squares optimization.

APPENDIX B

Appendix B includes the circuit file for Q.188 and the plots of the responses after each optimization. The 1-port S-parameter file FDT.S1P is also included.

```
! THIS IS A TOUCHSTONE PROGRAM DESIGNED TO SOLVE QUESTION 188
! OF THE COLLECTED PROBLEMS SET.

VAR
   FT=2.077
   EL=37.41188
CKT
   TLIN 1 2 Z#2400 2.800E+03 3200 E^EL F^FT    ! STARTING POINT
   TLIN 2 3 Z#2200 2.600E+03 3000 E^EL F^FT
   TLIN 3 4 Z#20000 2.300E+04 26000 E^EL F^FT
   TLIN 4 5 Z#9000 1.200E+04 15000 E^EL F^FT
   TLIN 5 6 Z#20000 2.300E+04 26000 E^EL F^FT
   TLIN 6 7 Z#2500 3.000E+03 3500 E^EL F^FT
   TLIN 7 8 Z#2400 2.800E+03 3200 E^EL F^FT

!  TLIN 1 2 Z#2400 3.068E+03 3200 E^EL F^FT    ! RANDOM OPTIMIZATION
!  TLIN 2 3 Z#2200 2.836E+03 3000 E^EL F^FT
!  TLIN 3 4 Z#20000 2.506E+04 26000 E^EL F^FT
!  TLIN 4 5 Z#9000 9.998E+03 15000 E^EL F^FT
!  TLIN 5 6 Z#20000 2.397E+04 26000 E^EL F^FT
!  TLIN 6 7 Z#2500 2.731E+03 3500 E^EL F^FT
!  TLIN 7 8 Z#2400 2.935E+03 3200 E^EL F^FT

!  TLIN 1 2 Z#2400 3.006E+03 3200 E^EL F^FT    ! MINIMAX OPTIMIZATION
!  TLIN 2 3 Z#2200 2.765E+03 3000 E^EL F^FT
!  TLIN 3 4 Z#20000 2.391E+04 26000 E^EL F^FT
!  TLIN 4 5 Z#9000 9.786E+03 15000 E^EL F^FT
!  TLIN 5 6 Z#20000 2.426E+04 26000 E^EL F^FT
!  TLIN 6 7 Z#2500 2.741E+03 3500 E^EL F^FT
!  TLIN 7 8 Z#2400 2.970E+03 3200 E^EL F^FT

!  TLIN 1 2 Z#2400 2.966E+03 3200 E^EL F^FT    ! QUASI-NEWTON OPTIMIZER
!  TLIN 2 3 Z#2200 2.782E+03 3000 E^EL F^FT
!  TLIN 3 4 Z#20000 2.462E+04 26000 E^EL F^FT
!  TLIN 4 5 Z#9000 9.979E+03 15000 E^EL F^FT
!  TLIN 5 6 Z#20000 2.415E+04 26000 E^EL F^FT
!  TLIN 6 7 Z#2500 2.790E+03 3500 E^EL F^FT
!  TLIN 7 8 Z#2400 2.998E+03 3200 E^EL F^FT

   DEF2P 1 8 7STL    ! DEFINE 2-PORT NETWORK
   S1PA 1 0 FDT      ! TERMINATIONS ARE READ FROM AN EXTERNAL FILE
   DEF1P 1 ZS
   S1PB 8 0 FDT
   DEF1P 8 ZL
```

```
TERM
   7STL ZS ZL  ! FREQUENCY DEPENDENT TERMINATION
FREQ
!  FREQUENCIES FOR OPTIMIZATION
   SWEEP 2.16 3 0.04 ! (GRID 1 DISPLAY)
   STEP 5
!  FREQUENCIES FOR DISPLAY
!  SWEEP 2.1 5 0.05  ! FOR DISPLAY ONLY (GRID 2)
OUT
   7STL DB[S21] GR1
   7STL DB[S21] GR2
GRID
   RANGE 2.12 3 0.08
   GR1 -0.45 0 0.05
   RANGE  2 5 0.5
   GR2 -50 0 10
OPT
   RANGE 2.16 3      !SPECIFICATION FOR PASSBAND
   7STL DB[S21]>-0.4
   RANGE 5 5         !SPECIFICATION FOR STOPBAND
   7STL DB[S21]<-38.3 1000
```

DATA FILE FDT.S1P

```
! THIS IS A DATA FILE THAT CONTAINS THE TERMINATION REFLECTION
! COEFFICIENT FOR THE 7-SECTION TRANSMISSION LINE CIRCUIT. THE
! ZSOURCE AND ZLOAD ARE CALCULATED BY USING THE FORMULA :
!                  ZS=ZL=377/SQRT(1-(FC/F)**2),
! WHERE FC=2.077 GHz AND F IS THE SWEEPING FREQUENCY. THE REFLECTION
! COEFFICIENT IS THEN CALCULATED AS :
!               RC=(ZS-50)/(ZS+50)=(ZL-50)/(ZL+50)
! AND IS PRESENTED IN POLAR FORM.
!
!               FREQ        MANGITUDE        ANGLE

                2.10       0.961601323        0
                2.16       0.929734718        0
                2.20       0.916213869        0
                2.24       0.905366690        0
                2.28       0.896262888        0
                2.32       0.888411685        0
                2.36       0.881515283        0
                2.40       0.875376299        0
                2.44       0.869855664        0
                2.48       0.864850909        0
                2.52       0.860283899        0
                2.56       0.856093425        0
                2.60       0.852230480        0
                2.64       0.848655111        0
                2.68       0.845334255        0
                2.72       0.842240198        0
                2.76       0.839349450        0
                2.80       0.836641912        0
                2.84       0.834100241        0
                2.88       0.831709359        0
                2.92       0.829456075        0
                2.96       0.827328777        0
                3.00       0.825317187        0
                5.00       0.784691661        0
```

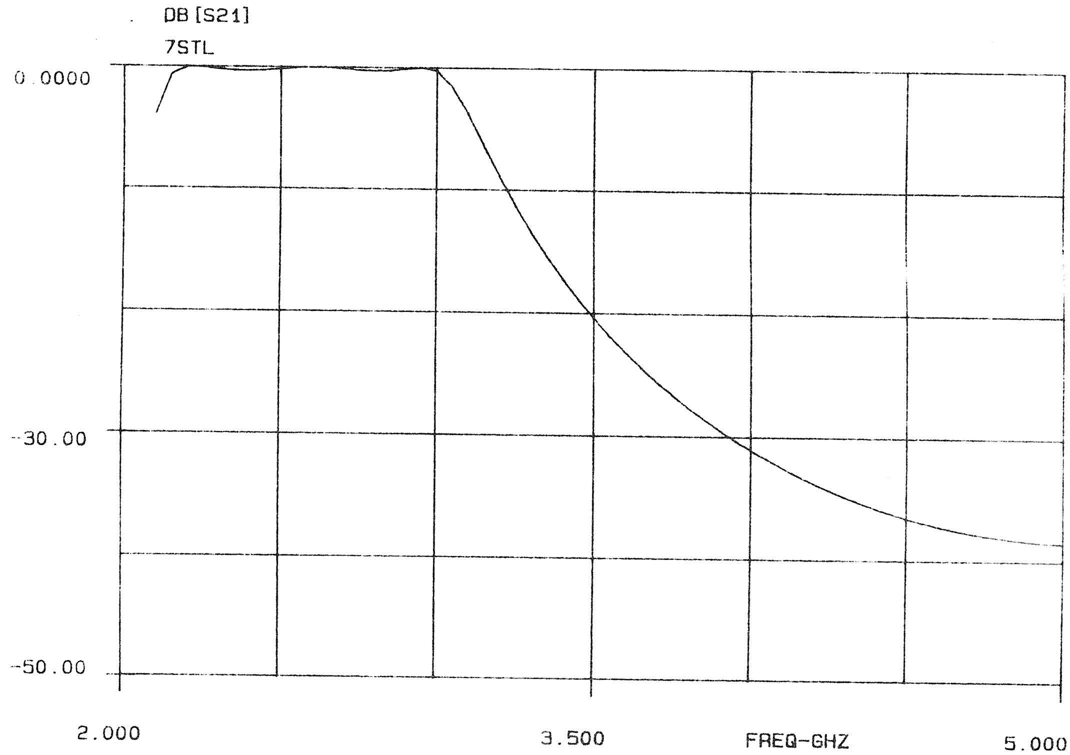

Fig.B1 Insertion loss of the filter in Q.188 after random optimization.

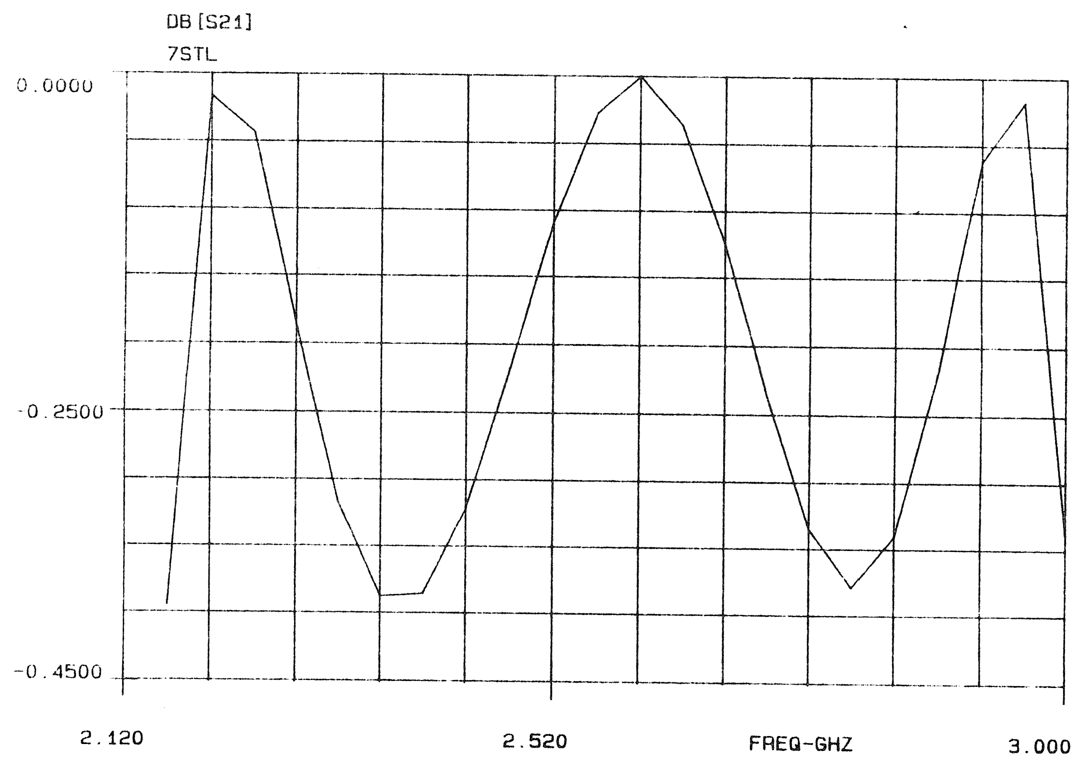

Fig.B2 Passband insertion loss of the filter in Q.188 after random optimization.

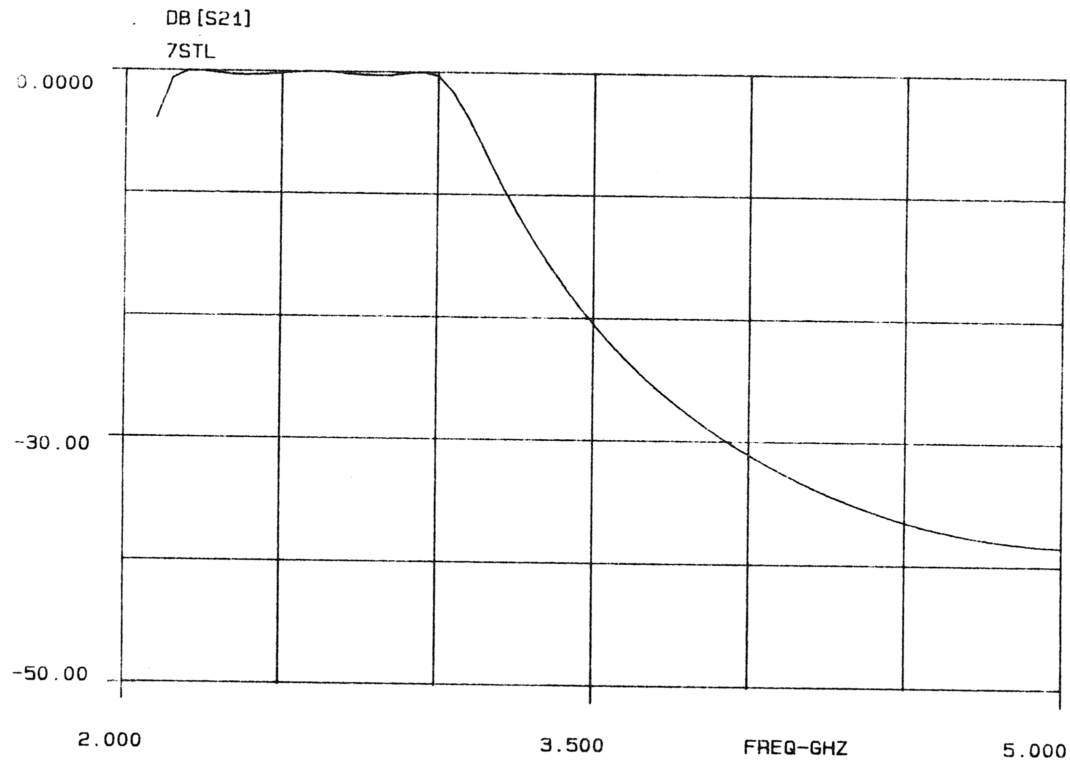

Fig.B3 Insertion loss of the filter in Q.188 after minimax optimization.

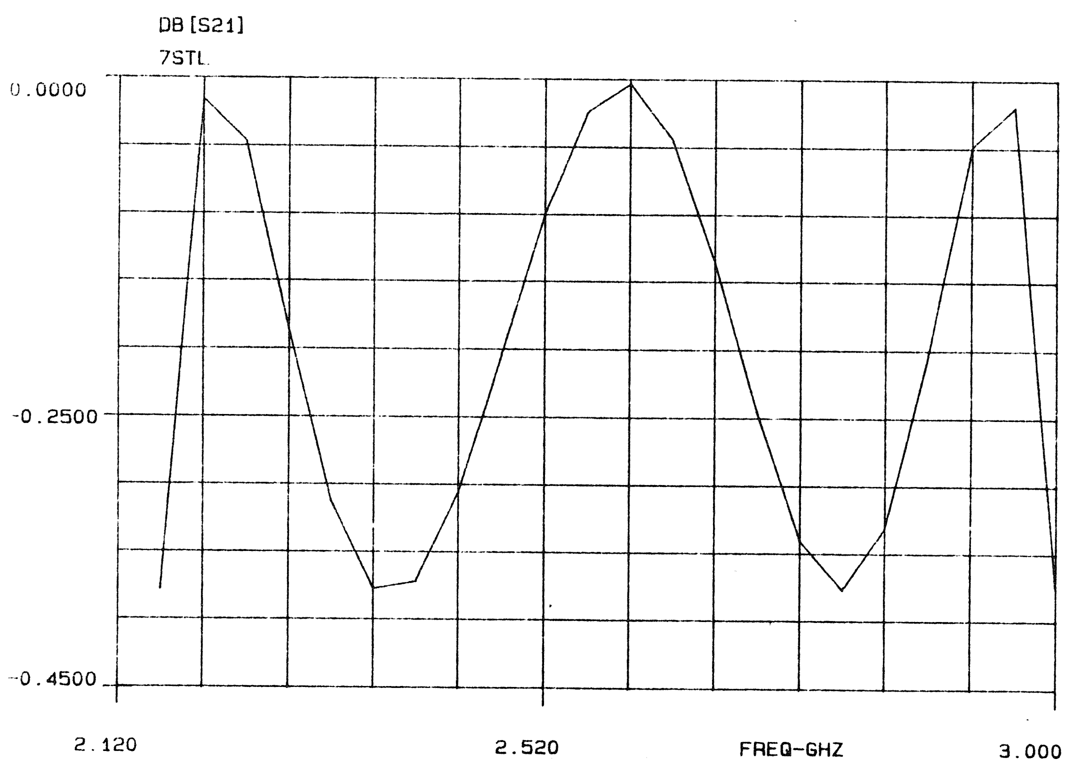

Fig.B4 Passband insertion loss of the filter in Q.188 after minimax optimization.

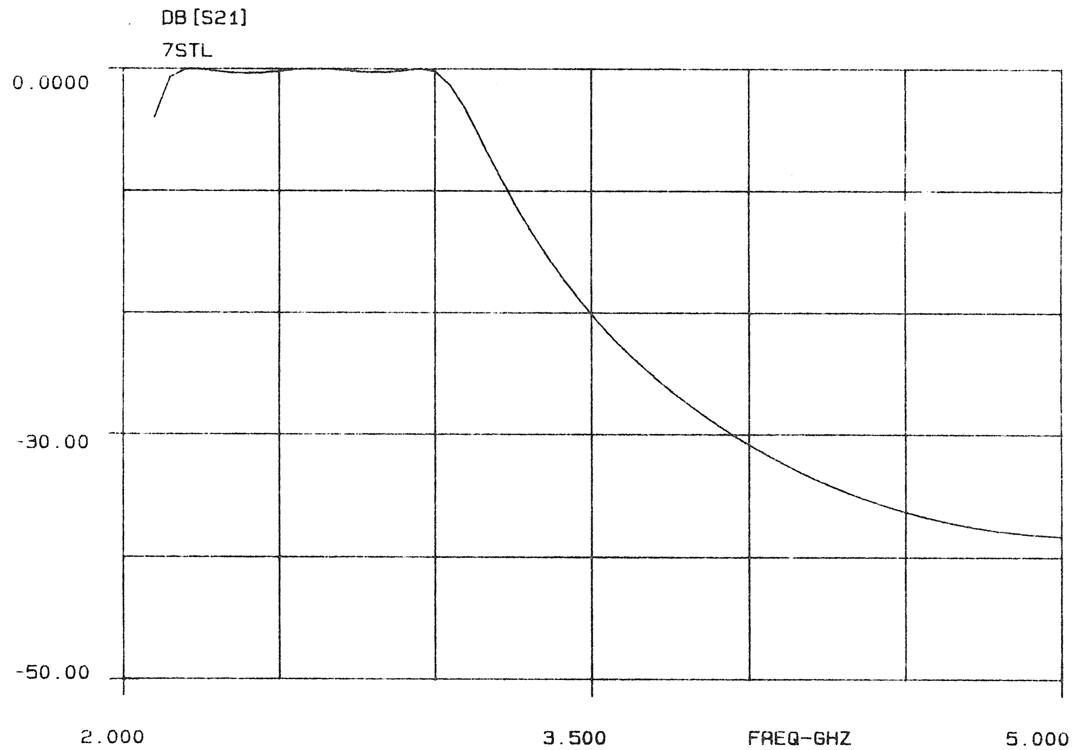

Fig.B5 Insertion loss of the filter in Q.188 after quasi-Newton least squares optimization.

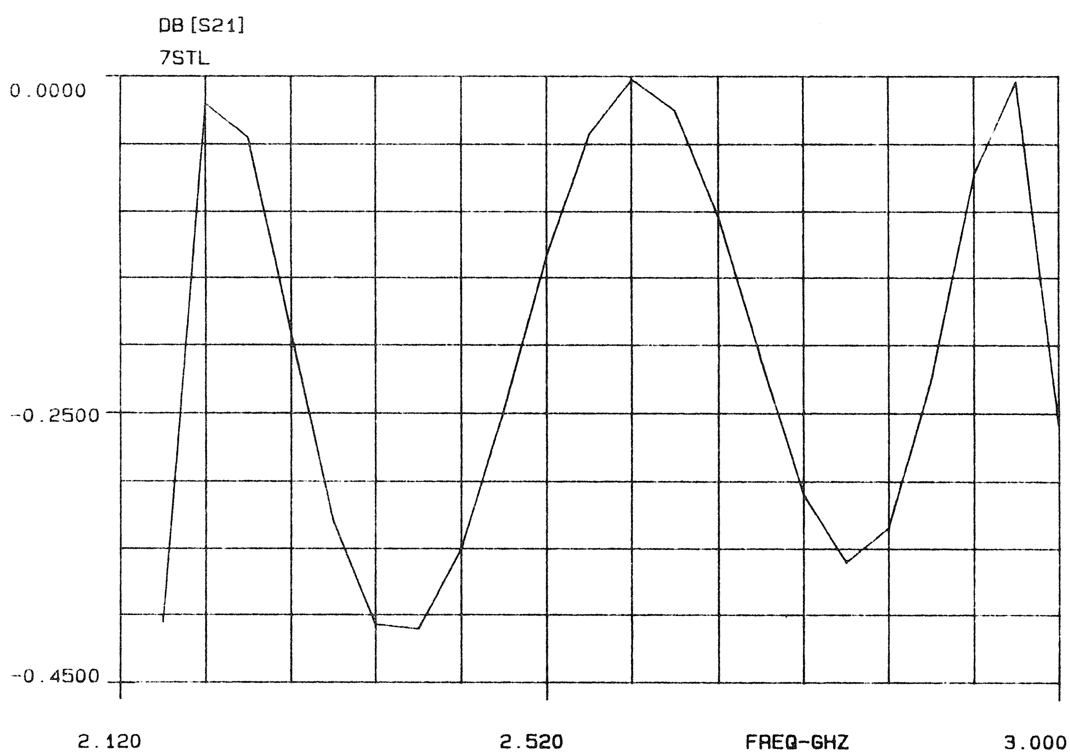

Fig.B6 Passband insertion loss of the filter in Q.188 after quasi-Newton least squares optimization.

APPENDIX C

Appendix C contains the circuit file for Q.189 and the plots of the responses after each optimization.

```
! PROBLEM 189 IN THE COLLECTED PROBLEMS SET. THIS PROBLEM INVOLOVES A
! BANDPASS ACTIVE FILTER WITH 2 OPAMPS, 4 RESISTORS AND 2 CAPACITORS.
!
! THE FILTER HAS TO SATISFY THE FOLLOWING SPECIFICAITONS:
!           F <= 0.707107      for         f < 90 Hz
!           F <= 1.1           for    90 < f < 110 Hz
!           F <= 0.707107      for         f > 110 Hz
!           F >= 0.707107      for    92 < f < 108 Hz
!           F >= 1.0           for         f = 100 Hz
!   WHERE F IS THE MAGNITUDE OF THE VOLTAGE GAIN FROM SOURCE TO LOAD.
!         f IS THE SWEEP FREQUENCY.

DIM
    FREQ  HZ
    RES   OH
    CAP   NF
VAR
    CV#720    760.00000 800          ! INITIAL VALUES
    R1#1.0E4  1.600E+04 3.0E4
    R4#100    150.00000 200

!   CV#720    786.20970 800          ! RANDOM OPTIMIZATION
!   R1#1.0E4  1.231E+04 3.0E4
!   R4#100    159.56460 200

!   CV#720    754.78020 800          ! MINIMAX OPTIMIZATION
!   R1#1.0E4  1.249E+04 3.0E4
!   R4#100    170.99960 200

!   CV#720    763.96670 800          ! QUASI-NEWTON OPTIMIZATION
!   R1#1.0E4  1.311E+04 3.0E4
!   R4#100    166.41180 200

CKT
    RES     1 2         R^R1          ! R1
    RES     2 0         R^R4          ! R4
    CAP     2 3         C^CV          ! C1
    CAP     2 4         C^CV          ! C2
    RES     3 4         R=2.65E4      ! R2
    RES     4 6         R=0           ! WIRE CONNECTING NODES 4 AND 6
    OPAMP   3 0 5 0 0   M=2E5 A=0 R1=0 R2=0 R3=75 R4=0 F=6 T=0
    OPAMP   4 5 6 0 0   M=2E5 A=0 R1=0 R2=0 R3=75 R4=0 F=6 T=0
    DEF2P   1 6         ACTFIL
TERM
    ACTFIL 0 0 1 0  ! Rg=50 OHM AND THE LOAD IS AN OPEN CIRCUIT
```

```
FREQ
!   FREQUENCIES FOR OPTIMIZATION
    SWEEP  10     90     20     ! (GRID 1)
    SWEEP  92     108    4      ! LOWER AND UPPER 3 dB FREQUENCIES
    SWEEP  110    1110   200
!   FREQUENCIES FOR DISPLAY
!   SWEEP  90     110    2      ! (GRID 2 AND 3 DISPLAY)
!   STEP   1 10 30 70 130       ! (GRID 3 DISPLAY ONLY)
!   SWEEP  150    300    25     ! (GRID 3 DISPLAY ONLY)
OUT
    ACTFIL MAG[VG] GR1
    ACTFIL MAG[VG] GR2
    ACTFIL MAG[VG] GR3
GRID
    RANGE  1E-10 1200   200
    GR1    0      1.2    0.1
    RANGE  90     110    5
    GR2    0.6    1.2    0.1
    RANGE  1E-10 300    100
    GR3    0      1.2    0.1
OPT
    RANGE  10     90
    ACTFIL MAG[VG] < 0.707107
    RANGE  90     110
    ACTFIL MAG[VG] < 1.1
    RANGE  92     108
    ACTFIL MAG[VG] > 0.707107
    RANGE  110    1110
    ACTFIL MAG[VG] < 0.707107
    RANGE  100    100
    ACTFIL MAG[VG] > 1.0
```

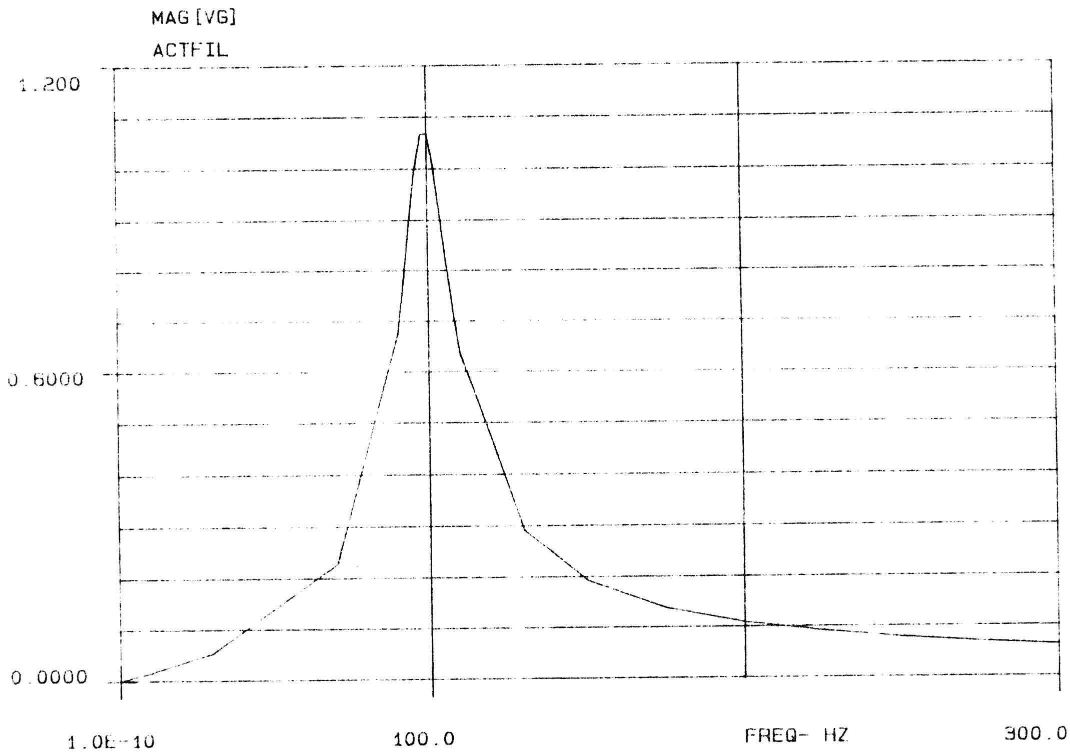

Fig.C1 Voltage gain of the filter in Q.189 after random optimization.

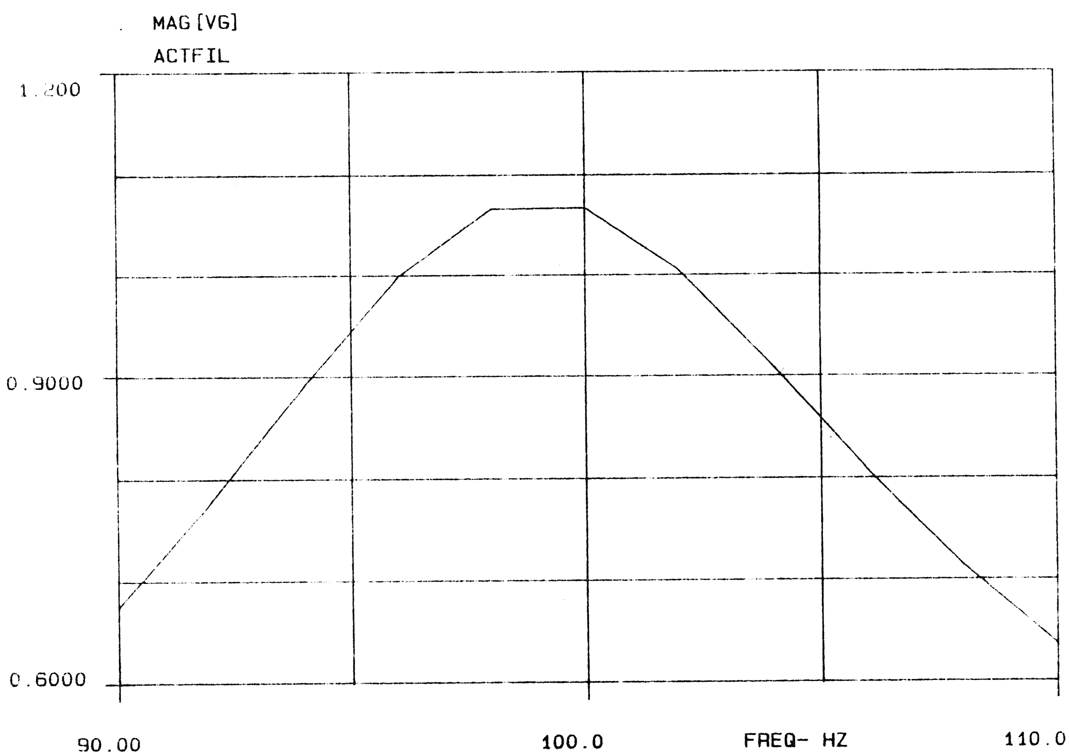

Fig.C2 Passband voltage gain of the filter in Q.189 after random optimization.

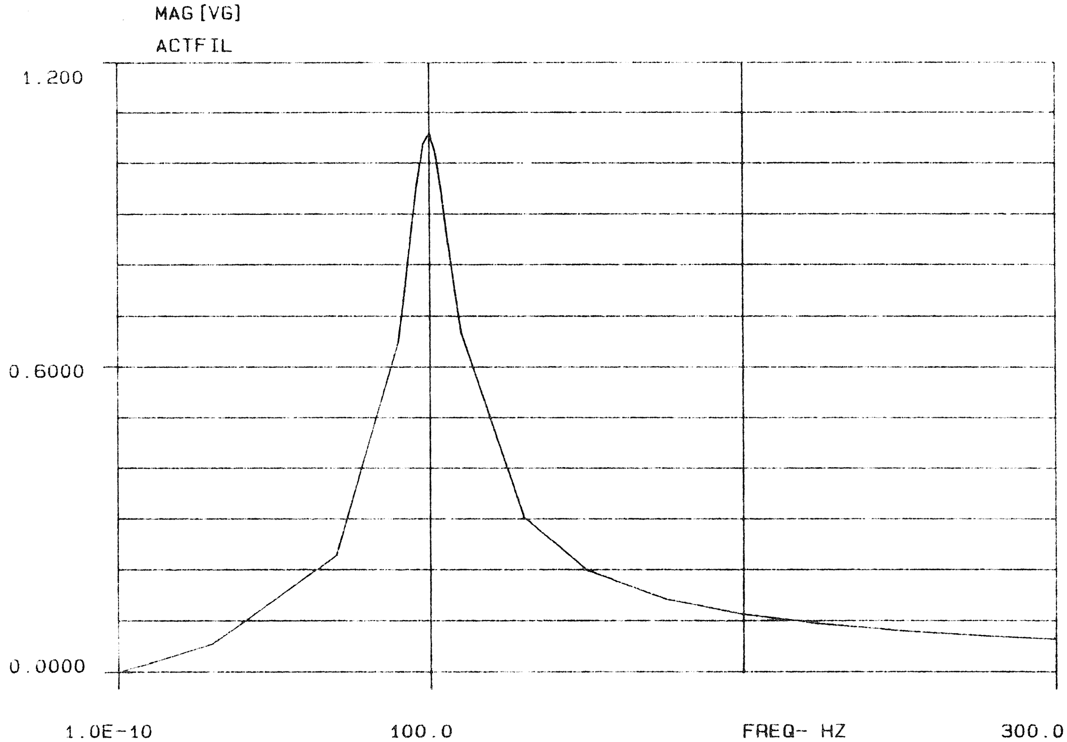

Fig.C3 Voltage gain of the filter in Q.189 after minimax optimization.

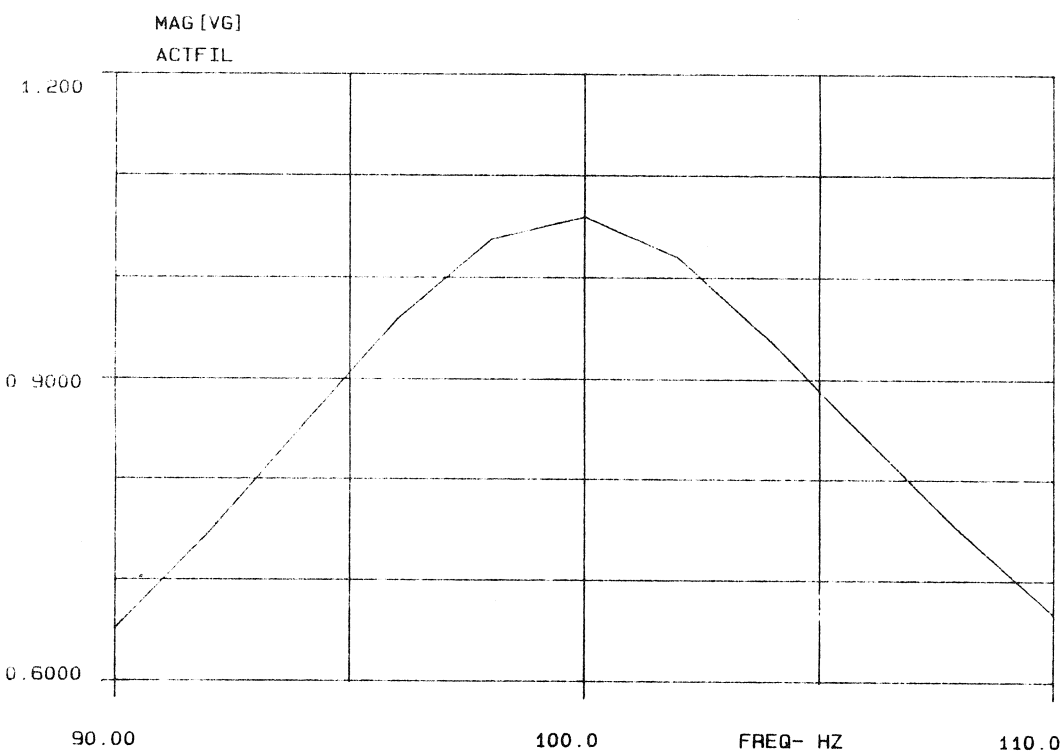

Fig.C4 Passband voltage gain of the filter in Q.189 after minimax optimization.

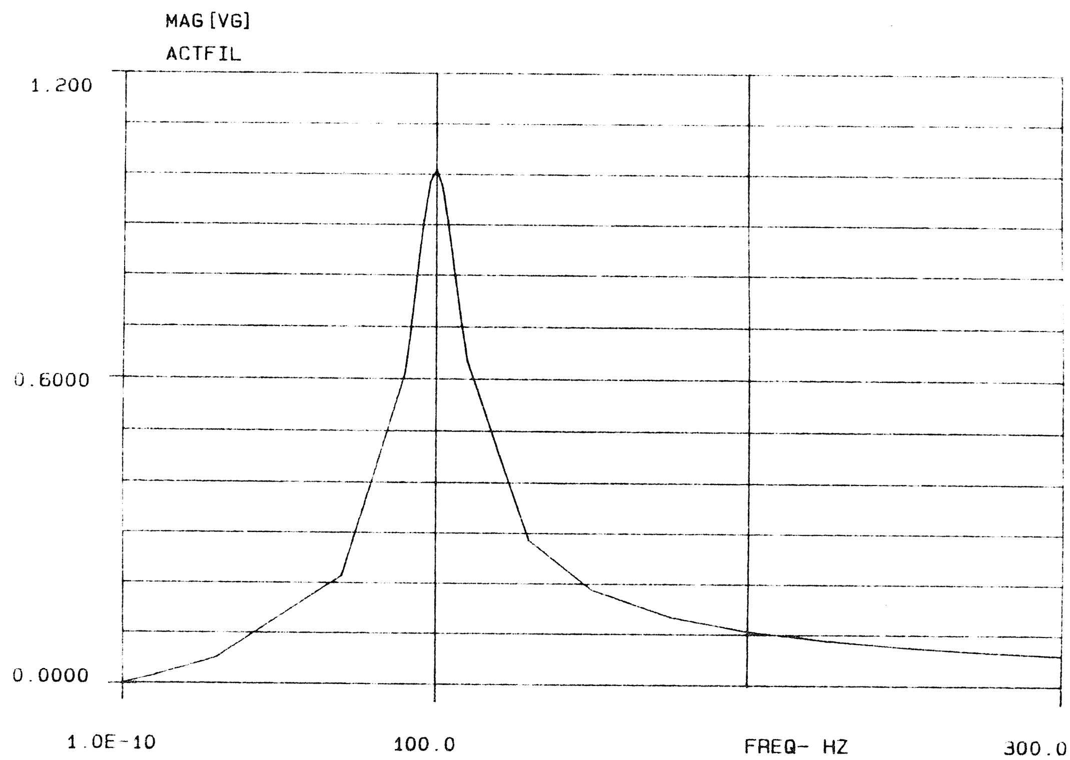

Fig.C5 Voltage gain of the filter in Q.189 after quasi-Newton least squares optimization.

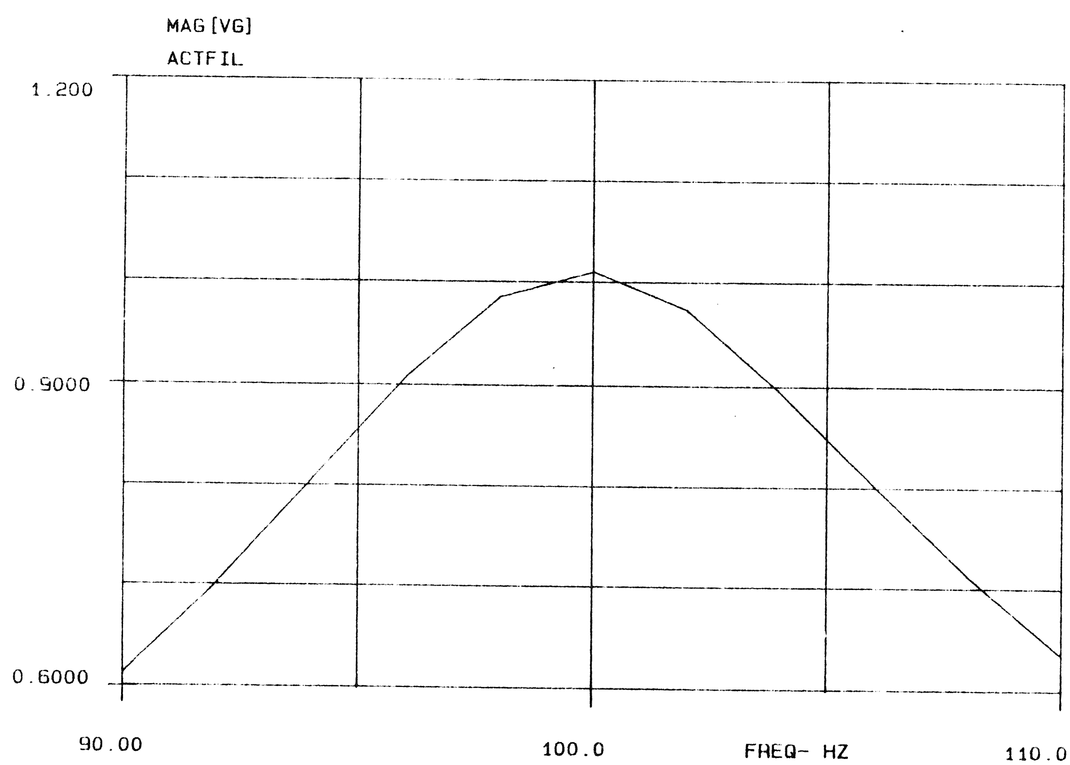

Fig.C6 Passband voltage gain of the filter in Q.189 after quasi-Newton least squares optimization.