computer-aided interdigital bandpass filter design

For reproducible customized design in the 0.4-5 GHz frequency range

One of the more challenging difficulties facing the Amateur experimenter in UHF and microwave communications is to construct good bandpass filters at these high frequencies. Good filters are especially important in those bands where the Amateur frequency allocation is shared with or is near high power services, such as radar, which can cause ruinous interference. And although a number of articles have appeared in Amateur publications describing specific bandpass filter types and specific construction techniques, none has provided a simple means of designing filters for different requirements.

This article describes a flexible computer program that makes it possible for Amateurs to design and build their own bandpass filters, custom-tailored to their specific needs. The program performs the design tasks for interdigital filters, a common bandpass type. The article also shows, step by step, how to proceed from the computer printout to the building and testing of a working filter. In addition, two different examples are used to illustrate two different construction methods.

filter design

The design of narrowband bandpass filters — that is, of filters that have passbands of approximately 10 percent of the center frequency or less — is often based on the well-known work of Matthaei, Young, and Jones,[1] which provides a wealth of analytical and practical design methods for many types of RF and microwave filters. Among the most common types are filters that use comb or interdigitated coupled resonators. These two types are mechanically similar, but this article discusses only the interdigital form.

Interdigitated bandpass filters have been widely used in the microwave electronics industry for many years. These filters are commonly used because they provide reasonably good passband characteristics, moderate loss, and fairly high attenuation in the stopbands. Furthermore, they are simple to build and tune.

A typical interdigitated bandpass filter, such as shown in **fig. 1**, consists of a number of resonator elements or rods, each approximately a quarter wavelength long at the center frequency of the filter, which are electrically coupled together between two conducting ground planes. Each rod is shorted to ground at one end and open-circuited at the other end. The rods alternate, with one rod's shorted end opposing the next rod's open end. It is this alternating structure, which looks somewhat like interlaced fingers, that gives the interdigital filter its name. At the ends of the filter some form of impedance matching, either a transmission line transformer or a tap on the end rods, is used to couple energy into and out of the filter.

Interdigitated filters are most useful in the low microwave frequency range of about 0.5 to 5 GHz. In this region, lumped element filters are difficult to build, and waveguide filters are mechanically large. The inter-

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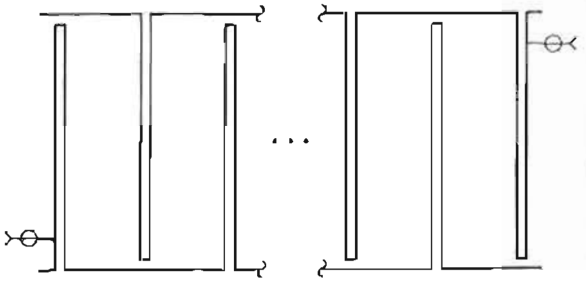

fig. 1. Typical interdigital bandpass filter structure. This filter consists of a number of rods, each open circuited at one end and grounded at the other, which are electrically coupled together between ground planes.

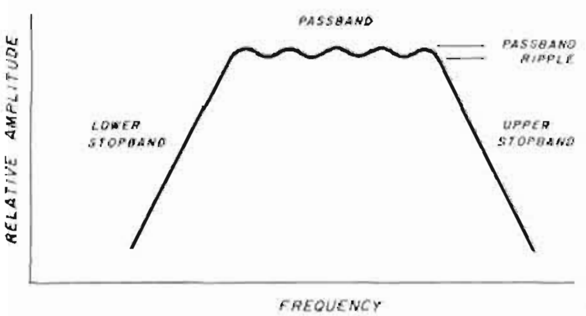

fig. 2. A generalized bandpass filter response. The ripple in the passband is exaggerated for clarity.

digital filter handily fills this gap between low frequency "coil and capacitor" filters, and microwave waveguide "plumbing." Thus, interdigital filters are of interest for frequencies up to at least several GHz, and down at least as low as the 420 MHz ham band

The traditional design of interdigitated filters described by Matthaei, Young, and Jones calls for both the spacing and sizes of the rectangular resonant elements to be variables. While there is no problem with this theoretically, in practice it is often simpler to use round rods of equal diameter in place of rectangular ones of various sizes. In the 1960's, Dishal[2] described a method of designing narrow bandwidth filters using equal diameter round rods. His method provides a simple and accurate design guide which results in bandpass filters of straightforward mechanical construction and good electrical performance.

In addition to using uniform round rods in place of rectangular elements of various sizes, Dishal questioned the common practice of using additional elements, one at each end of the filter structure, whose only purpose was to match the filter to the desired input and output connections when a simple tap on the first and last element would serve as well. Taking it

defining terms

A *bandpass filter* is a device that permits the passage of signals within a certain range of frequencies only, but blocks out signals from above or below that range. The range of frequencies where signals can pass through the filter with low loss is called the *passband*. The frequencies outside the passband are variously referred to as the *rejection bands*, *stop bands* or *"skirts"* of the filter. (**Figure 2** shows a general filter response.)

An ideal bandpass filter would have zero loss in the passband and infinite rejection of undesired signals in the stopbands. In real life, however, the situation is not as clear-cut: the passband of a real filter has a certain finite loss, even though it may be quite low. Likewise, a real filter's stopbands do not absolutely reject signals, but merely reduce their amplitudes. The attenuation depends mainly upon the separation, in frequency, of the undesired signal from the passband.

The loss in the passband may be nearly constant, or flat, as in a Butterworth design, or it may vary with regular undulations or "ripple" in the attenuation curve. In a Chebyshev type filter, this passband ripple is related to an increase in stopband rejection. For our purposes, it is enough to consider a Butterworth filter as a variation of the Chebyshev design, but with zero passband ripple. It is important to realize that we can obtain better stopband rejection if we're willing to trade off passband flatness and accept higher ripple and VSWR.

Since the transition from passband to stopband in a real (rather than ideal) filter is not abrupt, we must define its location. For a Chebyshev filter, the "edges" of the passband are defined as those points where the attenuation exceeds the maximum ripple amplitude. Thus the passband of a Chebyshev filter is often known as the *ripple bandwidth*. The bandwidth of a Butterworth design, which has no ripple, is traditionally defined at the 3 dB points. This measure is called the *3 dB bandwidth*.

There are many good texts and articles dealing with filter topics, and the interested reader should refer to them if a better background is desired. A few of these sources are listed in the references. However, the terms and concepts introduced above are sufficient for a basic understanding of the design and construction of the bandpass filters we describe.

table 1. Interactive program calculates expected electrical performance and computes mechanical dimensions of filter.

```
10 REM **********************************************
20 REM   DESIGNS INTERDIGITAL BPFs
30 REM **********************************************
40  DEF FNRJ(TA,B,C,D)=(B*C-TA*D)/(C*C+D*D)
50 REM using equal diameter rods
60 REM g values based on ripple bw . q/coup on 3-bd
70 DIM G(200) , C(200) , RK(200) , AK(200) , FR(40) , ALOSS(40)
80  DIM A(200), B(200)
90 PI=3.14159265#
100 INPUT"# OF ELEMENT $ P-P RIPPLE IN PASSBAND (DB)";N,RIP
110 REM
120 INPUT"INPUT FILTER CENTER FREQ.(GHZ),BW(MHZ)&LOAD IMPEDENCE
     ZO";FZGC,BWMC,R
130 REM
140 PRINT"INPUT GROUND PLANE SPACING , ROD DIAMETER"
150 INPUT"& DISTANCE TO CENTER OF FIRST AND LAST ROD";H,D,E
160 REM
170 REM
180 INPUT"NO. OF FREQ. REJECTION PTS AND STEP SIZE (MHZ)";NFR,STP
190 FOR IP=-NFR/2 TO NFR/2
200      CONTER=CONTER+1
210      FR(CONTER)=FZGC+(STP*.001*IP)
220 NEXT IP
230 IDAT=1
240 GOTO 250
250 F1=FZGC-.0005*BWMC
260 F2=FZGC+.0005*BWMC
270 IF RIP>0 THEN GOTO 330
280 BW3GC=F2-F1
290 BWRGC=0
300 BW3=1
310 GOSUB 1960
320 GOTO 390
330 B=1/SQR(10^(.1*RIP)-1)
340 CA=LOG(B+SQR(B*B-1))/(N)
350 BW3=(EXP(CA)+EXP(-CA))/2
360 GOSUB 1740
370 BWRGC=F2-F1
380 BW3GC=BWRGC*BW3
390 REM
400 W=2*(F2-F1)/(F2+F1)
410 QF=FZGC/BW3GC
420 NFM=N-1
430 QWVL=11.8028/(4*FZGC)
440 FOR K=1 TO NFM
450      AK(K)=1/(BW3*SQR(G(K)*G(K+1)))
460      RK(K)=AK(K)/QF
470 NEXT K
480 AKO=G(1)*BW3
490 AK(N)=AKO
500 AK(N+1)=0
510 QS=G(1)*BW3*QF
520 CANH=(EXP(2*PI*E/H)-1)/(EXP(2*PI*E/H)+1)
530 ZM=59.9585*LOG(4*H/(PI*D))
540 ZE=59.9585*LOG(CANH*H*4/(PI*D))
550 RKM=RK(1)*SQR(ZM/ZE)
560 Z=PI*D/(2*H)
570 COTH=(EXP(Z)+1)/(EXP(Z)-1)
580 Y=PI*RKM/4
590 T=COTH^Y
600 C(1)=(H/PI)*LOG((T+1)/(T-1))
610 MFL=N-2
620 REM IF N-3<0 THEN AG=1 ELSE IF N-3=0 THEN AG=2 ELSE AG=3
630 ON (2+SGN(N)*1) GOTO 690 , 690 , 640
640 FOR K=2 TO MFL
650      Y=PI*RK(K)/4
660      T=COTH^Y
670      C(K)=(H/PI)*LOG((T+1)/(T-1))
680 NEXT K
690 C(N-1)=C(1)
700 X=SQR(PI*R/(4*ZE*QS))
710 AQ=2*QWVL*ATN(X/SQR(1-X*X))/PI
720 QU=2200*H*SQR(FZGC)
730 SUMG=0
740 FOR J1=1 TO N
750      SUMG=SUMG+G(J1)
760 NEXT J1
770 BLOSS=4.34*FZGC*SUMG/(QU*(F2-F1))
780 DELAY=SUMG/(2*PI*(F2-F1))
790 IF RIP > 0 THEN GOTO 820
800 PRINT"DESIGN DATA FOR ";N;" POLE INTERDIGITAL FILTER.
     BUTTERWORTH RESPONSE"
810 GOTO 830
820 PRINT "DESIGN DATA FOR";N;"POLE INTERDIGITAL FILTER .BAND
     PASS RIPPLE";RIP;"DB"
830 PRINT"CENTER FREQ. ";FZGC ;"GHZ"
840 PRINT"CUTOFF FREQ. ";F1;" (GHZ) AND ";F2;"  GHZ"
850 PRINT"RIPPLE BW.  ";BWRGC;"GHZ"
860 PRINT"3 DB BW.    ";BW3GC;"GHZ"
870 PRINT"FRACTIONAL BW.";W
880 PRINT"FILTER Q  ";QF
890 PRINT"EST QU    ";QU
900 PRINT"LOSS BASED ON THIS QU  ";BLOSS;"  DB"
910 PRINT"DELAY AT BAND CENTER ";DELAY;"NANOSECONDS"
920 FOR JK=1 TO NFR
930    IF JK=1 THEN PRINT "FREQUENCY REJECTION INFORMATION "
940    NFN=ABS(2*(FR(JK)-FZGC)/(W*FZGC))
950    IF RIP >0 THEN GOTO 980
960    ALOSS(JK)=10*LOG(1+NFN^(2*N))/LOG(10)
970    GOTO 1040
980    IF NFN<1 THEN NFN=1
990    ANG=N*LOG(NFN+SQR(NFN*NFN-1))
1000    YAK=.5*(EXP(ANG)+EXP(-ANG))
1010    ALOSS(JK)=10*LOG(1+(10^(.1*RIP)-1)*YAK*YAK)/LOG(10)
1020    IF ALOSS(JK)>65 THEN ALOSS = 65 ELSE ALOSS = ALOSS(JK)
1030    FR=INT(FR(JK)*10000)/10000 : ALOS=INT(ALOSS(JK))
1040    PRINT TAB(INT(ALOSS))"*";TAB(66)FR;TAB(73)ALOS
1050 NEXT JK
1060 WO=2*PI*FZGC*1E+09
1070 F=D/H
1080  CF=(-.0000422+.0857397*F+.0067853*F*F-9.092165E-
     02*F^3+.169088*F^4)*PI*H*2.54
1090 REM
1100 WW=WO*1E-12
1110 B2=PI*AQ/(2*QWVL)
1120 GG=1/R
1130 BB=-COS(B2)/(ZE*SIN(B2))
1140 EL1=.8*QWVL
1150 ANG=EL1*PI/(2*QWVL)
1160 B1=ANG-B2
1170 YL=-COS(ANG)/(ZM*SIN(ANG))
1180 CP=WW*(CF+.17655*D*D/(QWVL-EL1))
1190 Y1=CP+YL
1200 EL2=.87*QWVL
1210 ANG=EL2*PI/(2*QWVL)
1220 B4=ANG-B2
1230 YL=-COS(ANG)/(ZM*SIN(ANG))
1240 CD=WW*(CF+.17655*D*D/(QWVL-EL2))
1250 Y2=CD+YL
1260 EL3=.95*QWVL
1270 ANG=EL3*PI/(2*QWVL)
1280 B5=ANG-B2
1290 YL=-COS(ANG)/(ZM*SIN(ANG))
1300 CQ=WW*(CF+.17655*D*D/(QWVL-EL3))
1310 Y3=CQ+YL
1320  ELEM=Y3*Y2*EL1/((Y1-Y2)*(Y1-Y3))+Y1*Y3*EL2/((Y2-Y1)*(Y2-
       Y3))+Y1*Y2*EL3/((Y3-Y1)*(Y3-Y2))
1330 TANN=SIN(B1)/COS(B1)
1340 YL=FNRJ(GG,BB+TANN/ZE,1-ZE*BB*TANN,ZE*GG*TANN)
1350 Y1=CP+YL
1360 TANN=SIN(B4)/COS(B4)
1370 YL=FNRJ(GG,BB+TANN/ZE,1-ZE*BB*TANN,ZE*GG*TANN)
1380 Y2=CD+YL
1390 TANN=SIN(B5)/COS(B5)
1400 YL=FNRJ(GG,BB+TANN/ZE,1-ZE*BB*TANN,ZE*GG*TANN)
1410 Y3=CQ+YL
1420  ELEQ=Y3*Y2*EL1/((Y1-Y2)*(Y1-Y3))+Y1*Y3*EL2/((Y2-Y1)*(Y2-
       Y3))+Y1*Y2*EL3/((Y3-Y1)*(Y3-Y2))
1430 REM
1440 PRINT"QUARTER WAVELENGTH =";QWVL ;"INCHES"
1450 PRINT"THE LENGTH OF INTERIOR ELEMENTS =";ELEM;" INCHES"
1460 PRINT"LENGTH OF END ELEMENTS =";ELEQ;" INCHES"
1470 PRINT"GROUND-PLANE SPACE =";H," INCHES "
1480 PRINT"ROD DIAMETER  =";D;" INCHES"
1490 PRINT"END PLATES";E;" INCHES FROM C/L OF END ROD "
1500 PRINT"TAP EXTERNAL LINES UP ";AQ;" INCHES FROM SHORTED END "
1510 PRINT"LINE IMPEDANCES: END ROD";ZE;" ,OTHER ";ZM;" , EXT.
     LINES ";R;"OHM"
1520 PRINT"DIMENSIONS"
1530 PRINT"EL. NO.     END TO C     C TO C    G(K)       Q/COUP"
1540 DOM=E
1550 GOO=1
1560 PRINT "0";TAB(41)GOO;TAB(55)AKO
1570 PRINT "1";TAB(16)E;TAB(41)G(1);TAB(55)AK(1)
1580 FOR K=1 TO NFM
1590    L=K+1
1600    PRINT TAB(28)C(K)
1610    DOM=DOM+C(K)
1620    PRINT L;TAB(16)DOM;TAB(41)G(L);TAB(55)AK(L)
1630 NEXT K
1640 LQ=N+1
1650 PRINT LQ;TAB(41)G(LQ)
1660 DOM=DOM+E
1670 PRINT TAB(16)DOM
1680 IF IDAT =1 THEN GOTO 2070
1690 REM
1700 REM
1710 REM DEFINE FUNCTION
1720 DEF FNRJ(TA,B,C,D)=(B*C-TA*D)/(C*C+D*D)
1730 END
1740 REM SUB CHEB
1750 REM
1760 C=2*RIP/17.37
1770 BETA=LOG((EXP(C)+1)/(EXP(C)-1))
1780 GAMMA=.5*(EXP(BETA/(2*N))-EXP(-BETA/(2*N)))
1790 FOR K=1 TO N
1800    A(K)=SIN(.5*(2*K-1)*PI/N)
1810    B(K)=GAMMA^2+SIN(K*PI/N)^2
1820 NEXT K
1830 G(1)=2*A(1)/GAMMA
1840 FOR K=2 TO N
1850    G(K)=4*A(K-1)*A(K)/(B(K-1)*G(K-1))
1860 NEXT K
1870 NN=N/2
1880 NNN=(N+1)/2
1890 REM IF NNN-NN<0 THEN AG1=1 ELSE IF NNN-NN=0 THEN AG1=2 ELSE AG1=3
1900 ON (2+SGN(NNN-NN)*1) GOTO 1910,1910,1930
1910 G(N+1)=((EXP(BETA/2)+1)/(EXP(BETA/2)-1))^2
1920 RETURN
1930 G(N+1)=1
1940 RETURN
1950 END
1960 REM SUB FOR BUTT
1970 REM
1980 REM
1990 REM
2000 REM
2010 POV2=1.57079633#
2020 FOR K=1 TO N
2030    G(K)=2*SIN(POV2*(2*K-1)/N)
2040 NEXT K
2050 G(N+1)=1
2060 RETURN
2070 END
```

number of elements	ripple dB	bandwidth MHz	loss at 440 dB	loss at 445 dB
2	0.25	2	1.2	21.6
2	0.25	3	0.8	14.4
3	0.25	2	2.5	41.4
3	0.25	3	1.7	30.5
3	0.25	4	1.3	22.6
4	0.50	1	7.9	88.8
4	0.50	3	2.7	50.0
4	0.25	3	2.4	46.8
6	0.25	3	4.2	79.4
6	0.25	4	3.2	63.4

fig. 3. Program tests various configurations for the 440-MHz bandpass filter. For comparison, all are for 0.38 inch diameter rods between groundplanes 1 inch apart, and all have a center frequency of 440 MHz.

a step further, he showed how to determine these tap locations. A computer program, described below, is developed around this design approach.

program description

The BASIC listing is given in **table 1**. This program follows in loose form a program originally written in Fortran IV by Rook and Taylor.[3] We translated into BASIC, modified it for use on a personal computer, and added additional plotting output. The program uses an interactive approach to request design information from the user, and then calculates the expected electrical performance and computes the mechanical dimensions of the filter. It is written in BASIC in its IBM PC™ version, but it is structured so that conversion into other versions of BASIC for different computers should not be difficult.

The first portion of the program sets up the required variable dimensions and types. Next, an interactive question sequence collects the input data for the design. Once the required data are available to the program, it computes the expected electrical performance and gives details of the filter's mechanical construction. Finally, the program prints a graph of the passband and rejection skirts of the filter.

Two different examples of filters for two different ham bands are given. Each example gives general mechanical details of construction techniques which have been proven to give good results. The examples are just that, examples, and serve as guides to help the reader design and build filters which are optimized for his own particular application. The explanations of these techniques give enough information so that the examples themselves can be duplicated without too much difficulty.

440 MHz bandpass filter

The first example is a front-end filter for a 440 MHz FM receiver in a linear translator system. A linear translator, like a repeater, retransmits what it receives on a frequency 5 MHz (the 440 MHz spacing) away from the input channel. In order to prevent receiver overload or excessive intermodulation distortion in the presence of the strong transmitted signal, the rejection of the near-by repeater transmitter at 445 MHz must be approximately 50 dB. At the same time, the filter's passband loss should be moderate, less than about 3 dB, or the receiver sensitivity will be degraded excessively. These two considerations dictate the choice of filter type and design.

An interdigital bandpass filter turns out to be a good choice for this application. It can be simply and inexpensively built, and has relatively low passband losses together with good out-of-band rejection. And while it is true that a cavity diplexer filter of the sort often seen in amateur repeaters can give still lower losses and greater rejection, its good electrical performance can be accomplished only at the expense of increased mechanical complexity, larger size, and higher cost. Here, the required performance does not absolutely dictate the use of a multiple cavity diplexer, so we should definitely consider using the much simpler interdigital filter. If still less skirt rejection and somewhat greater loss can be tolerated, a helical resonator filter might be a good choice, for it would provide less rejection and probably would have higher passband losses, but it would also be much smaller mechanically than an equivalent interdigital bandpass filter. This size reduction is possible because the inductances in a helical filter are coils and because the inter-element couplings are not dependent only on the physical spacing of elements.

The first step in the choice of filter parameters is to determine the required passband loss limit, passband ripple, and out-of-band rejection that can be tolerated. An interactive computer-aided design program makes these tradeoffs considerably simpler to evaluate. The designer begins by entering a first estimate, or guess, of the approximate number of elements and passband ripple. From these inputs, the computer program quickly determines the approximate loss and plots the pass and reject bands. In the course of a few minutes' work, several different configurations can be tried out. From these it is easy to select the optimum design.

As an example of this interactive optimization, **fig. 3** lists a number of different 440 MHz filter configurations tested by the program. These designs differ mainly in the number of elements and in their passband widths. Filters with from 2 to 6 elements and ripple bandwidths of from 1 to 4 MHz are compared. In each case, the loss at the center frequency, 440 MHz, and at the transmitter frequency to be rejected, 445 MHz, are listed for comparison.

The results of this scan of various possible designs

```
# OF ELEMENT $ P-P RIPPLE IN PASSBAND (DB)? 4,.25
INPUT FILTER CENTER FREQ.(GHZ),BW(MHZ)&LOAD IMPEDENCE ZO? .440,3,50
INPUT GROUND PLANE SPACING , ROD DIAMETER
& DISTANCE TO CENTER OF FIRST AND LAST ROD? 1,.38,.5
NO. OF FREQ. REJECTION PTS AND STEP SIZE (MHZ)? 38,.5
DESIGN DATA FOR 4 POLE INTERDIGITAL FILTER .BAND PASS RIPPLE .25 DB
CENTER FREQ.  .44 GHZ
CUTOFF FREQ.  .4385  (GHZ) AND  .4415   GHZ
RIPPLE BW.    3.000021E-03 GHZ
3 DB BW.      3.419328E-03 GHZ
FRACTIONAL BW. 6.81823E-03
FILTER Q   128.6803
EST QU     1459.315
LOSS BASED ON THIS QU   2.422713   DB
DELAY AT BAND CENTER  294.6652 NANOSECONDS
FREQUENCY REJECTION INFORMATION
                                                                * .4305  69
                                                                * .431   67
                                                                * .4315  65
                                                              *   .432   63
                                                            *     .4325  61
                                                         *        .433   58
                                                       *          .4335  56
                                                    *             .434   53
                                                 *                .4345  50
                                             *                    .435   46
                                         *                        .4355  42
                                     *                            .436   38
                                *                                 .4365  33
                          *                                       .437   27
                  *                                               .4375  19
        *                                                         .438   9
*                                                                 .4385  0
*                                                                 .439   0
*                                                                 .4395  0
*                                                                 .44    0
*                                                                 .4405  0
*                                                                 .441   0
*                                                                 .4415  0
        *                                                         .442   9
                  *                                               .4425  19
                          *                                       .443   27
                                *                                 .4435  33
                                     *                            .444   38
                                         *                        .4445  42
                                             *                    .445   46
                                                 *                .4455  50
                                                    *             .446   53
                                                       *          .4465  56
                                                         *        .447   58
                                                            *     .4475  61
                                                              *   .448   63
                                                                * .4485  65
                                                                * .449   67
QUARTER WAVELENGTH = 6.706136 INCHES
THE LENGTH OF INTERIOR ELEMENTS = 6.418164  INCHES
LENGTH OF END ELEMENTS = 6.438183  INCHES
GROUND-PLANE SPACE = 1       INCHES
ROD DIAMETER  = .38  INCHES
END PLATES .5  INCHES FROM C/L OF END ROD
TAP EXTERNAL LINES UP  .2294638  INCHES FROM SHORTED END
LINE IMPEDANCES: END ROD 67.31341  ,OTHER  72.49873  , EXT. LINES  50 OHM
DIMENSIONS
EL. NO.       END TO C       C TO C       G(K)         Q/COUP
0                                         1             1.570873
1               .5                        1.378239      .6633376
                             1.894495
 2              2.394495                  1.269327      .5431323
                             1.969942
 3              4.364437                  2.055808      .6633376
                             1.894495
 4              6.258931                  .8509719      1.570873
 5                                        1
                6.758931
```

fig. 4. Computer printout for the 440-MHz filter.

quickly reveals some expected trends. For instance, it is clear that filters that are too narrow (i.e., filters that have passband widths well under 1 percent of their center frequency) have increasingly higher passband losses. Also, filters with wide passbands have lower loss at the center frequency but decreased out-of-band rejection. These are fundamental tradeoffs. Next, it is also apparent that increasing the number of elements increases both the passband loss and the desired rejection of out-of-band signals, and that a filter with a relatively wide passband and many elements will have low in-band losses and good rejection. However, the number of elements cannot be increased arbitrarily because experience has shown that filters with many elements are less easily built and tuned, and that for Amateur construction and tuning techniques it is best to avoid the use of more than about five or six elements.

With all this in mind, we selected a four-section filter with passband ripple of 0.25 dB (VSWR = 1.62) and a bandwidth of 3 MHz. For our application, these choices resulted in approximately the desired loss and rejections, namely 2.4 dB loss at 440 MHz and a rejection of about 46.8 dB at 445 MHz. Note that this rejection is relative to the passband loss, so that the filter's total loss at 445 MHz is estimated to be approximately 49.2 dB.

computer output

The computer program's output for this filter design is shown in **fig. 4**. The printout contains information on both the electrical performance estimates as well as mechanical information in detail sufficient to fully describe the filter.

After the "RUN" command is entered, the program asks for some electrical design information such as the number of sections, or elements, in the filter and the passband ripple in decibels. Enter these two numbers, separated by a comma, followed by the "return" key, and the computer will respond with the next questions. These are the center frequency, expressed in gigahertz, the ripple bandwidth of the filter in megahertz, and the desired load impedance in ohms (usually 50). As before, these three entries should be separated by commas and followed by a return.

Next, the program requests some mechanical information. The spacing between the top and bottom ground planes, the diameter of the resonant rods and the desired spacing between the end of the filter and the first rod are entered in response to the questions. All of these dimensions should be entered in decimal inches because the design formulas within the program contain constants in inches.

The third and last section of input data concerns the plotter output. The operator must specify how many plot points and the spacing in megahertz between each point. The maximum number of plot points is 40. It is usually convenient to specify a step size of somewhat smaller than the passband width to give a good picture. In this example, the filter is 3 MHz wide and the plot with a one-half MHz resolution shows the rejection skirts clearly.

After these last bits of information are entered, the computer program proceeds without further intervention. It first prints out some of the calculated parameters of the filter. Then the computer graphically plots the pass and reject bands on the screen and on a printer if one is selected.

The last block of computer printout gives the mechanical details of the filter. The quarter wavelength listed is the inside dimension of the filter cavity. The length of the interior elements is listed, followed by the length of the two end elements. All of the interior elements have the same length, but the two end elements may have a different length from the end rods. The tap point is the point on the end element at which the external connection is made, and it is measured from the "cold" or grounded end of the rods. A tabular summary of the filter's dimensions appears at the end of the printout. It lists the end to center dimensions, the element center to center dimensions, and two coupling coefficients. The mechanical dimensions are easily translated into a sketch of the filter. Naturally, the designer must have certain dimensions and construction materals in mind before the computer program can be run. The ground plane spacing and rod diameter must be entered as constants to permit the completion of the design. These variables depend on the materials used to build the filter, and on the construction technique.

construction

Now that the computer program has been used to select an optimized filter and it has printed the mechanical dimensions of the filter's structure, it is time to consider how to translate the filter design into a form that can be realized. The mechanical structure must be sufficiently sound to produce the expected performance.

The table of numbers at the end of the computer printout, **fig. 4**, gives fairly complete information on the dimensions of the filter structure. The first column gives the element number, with zero indicating the first edge of the filter and a number one greater than the total number of rods denoting the other edge of the structure. The second column gives dimensions in inches from the end of the housing to the center of the rod indicated. For example, in our design, the second element is to be located a distance of 2.39 inches from the end of the housing. The total length of the filter will be the dimension listed opposite the final entry which is, in this case, 6.759 inches (17.168 cm).

Although the printout gives information on how to size the filter, it is probably a good idea to make a drawing to fix in your mind just how the box is to be assembled. **Figure 5** is a mechanical sketch of the 440 MHz filter. It is clear that the dimensions on this drawing have been taken directly from the computer printout, but the sketch also shows how the walls of the box are to be joined together. The dimensions on the printout are for the electrical housing, which consists of the copper conductor inside the box, and not the outside, mechanical dimensions. Keep in mind that the external dimensions of the box are not the critical factors.

One of the more popular amateur construction materials is copper clad printed circuit board. It is widely available at low cost, is strong and stable, and it can be easily joined together by regular soldering techniques to make boxes and circuit housings of any given size. It can be cut with a sheet metal shear or tin snips to fairly close tolerances, and so it is a good choice as the basic "building block" material for a custom bandpass filter. Furthermore, copper is one of the best conductors for use at high frequencies as its electrical resistivity is quite low. Of the more common materials, only silver has better high-frequency conductivity, and it is considerably more expensive.

To construct the filter housing of this example, we used 1/16 inch double-clad fiberglass epoxy board throughout. The top, bottom, sides and end pieces of the filter's housing were cut to shape with a sheet metal shear, drilled to accept the resonator rods, and soldered together with "tack" joints, that is with small flows of solder at intervals along the edges of the pieces to be joined. The pieces need not be soldered with a continuous seam, but a soldered tack should be used about every inch. This dimension corresponds to only about 5 percent of a wavelength, and so it ensures good electrical interconnection at all points along the copper.

The most critical dimensions of the housing are the width of the filter, which is usually a quarter wavelength, and the inside height of the cavity. A small piece of wood or metal with perpendicular faces is a good "jig" to help solder the housing walls accurately. If you work carefully, you should be able to build a housing that's both nearly square and accurate enough to take advantage of the custom design made possible with the computerized design aid described in this article.

Because we want to hold all of the parts of this filter together with regular tin-lead solder, all of the parts obviously should be solderable. A good material for the filter rods is common copper tubing which is available in a number of sizes in hardware and plumbing supply stores. For the design of this 440 MHz filter we chose 3/8 inch tubing. The "3/8 inch" refers to the outside dimension of the tubing, so the filter rod diameter measures approximately 0.375 inches.

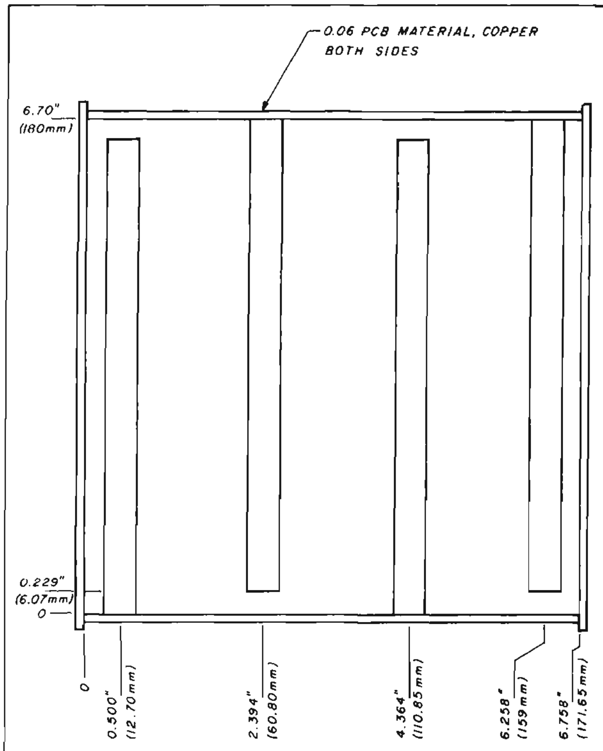

fig. 5. Sketch showing the top view of the 440-MHz filter. The end walls are deliberately cut longer so they can be soldered to both sides of the side walls.

The choice of rod diameter is not entirely arbitrary, although it is not very critical, either. As a rule of thumb, the rod diameter should be roughly 1/3 the housing height. In general, large diameter rods have lower losses than smaller rods. This is because skin effect losses predominate at radio frequencies. A larger diameter rod has greater surface area and, hence, less resistive loss than a smaller diameter rod. However, using a larger rod diameter can lead to mechanical difficulties. In this filter, for example, it was difficult to solder the large 3/8 inch diameter copper rods. These rods have fairly large masses and good thermal conductivity, so a regular soldering iron, intended for lighter duty circuit board work, just wouldn't provide enough heat. In the end, it took the greater heat of a propane torch to solder the rods to the copper walls.

The rods should be cut a bit longer than the correct length given by the printout. Then they are fit through holes drilled in the housing wall and soldered on both sides of the double clad circuit board, as shown in **fig. 6**. A good solder joint on each side increases the mechanical strength and improves grounding. The interior lengths of the rods and the center-to-center spacings between the rods are among the most critical dimensions affecting the frequency response of the filter, so measure them as carefully and precisely as possible. In spite of all the care you use in construction, however, it will almost certainly be necessary to peak tune the filter response.

One simple way to tune the filter rod lengths is to load their open-circuited ends with variable capacitors. If the rods are just a bit shorter than the design calls for, then the small capacitance of a tuning screw at the open end will tune that element's resonant frequency. This tuning compensates for the minor inaccuracies which inevitably occur in construction.

These tuning screws need good grounds at the points where they penetrate the wall. It is important to realize that it is the inside grounded surface that matters most, because the inside copper cladding forms the conductive boundary that contains the filter's electric fields. For this reason the tuning screws are supported by brass nuts soldered to the inside surface of the box. These nuts are visible in the overall photograph of the filter and especially in the close-up view, **fig. 7**. The nut makes a simple threaded support for the screw and serves as the low impedance path from the screw body to the ground plane. On the outside of the filter housing a second nut holds the screw firmly in place. This nut is tightened after all of the filter tuning is completed, and it ensures that the screw is tightly bound to the soldered-down nut and prevents it from moving and thereby detuning the filter.

The computer program also lists the tap point distance, which is the position at which the external connectors pass through the walls and are coupled to the filter. The distance is given relative to the shorted

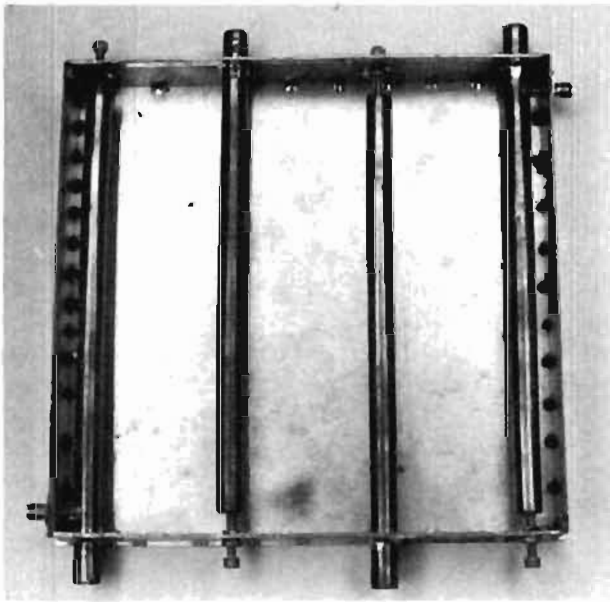

fig. 6. An overall view of the 4 section 440-MHz bandpass filter. The top cover has been removed to show the internal detail.

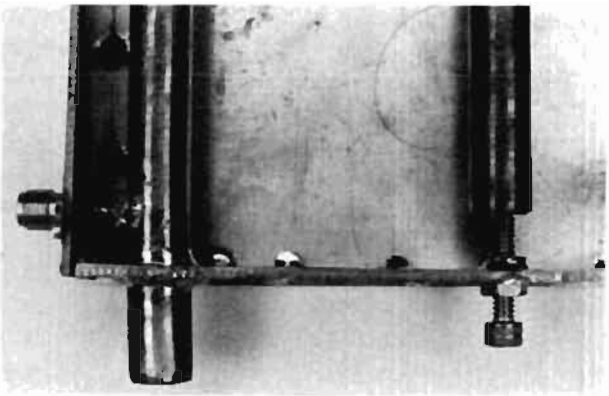

fig. 7. Close-up view of the 440-MHz filter showing details of the 50-ohm coaxial connector tap and of a tuning screw.

end of the rods. This junction should be by a short length of wire or cable. The closeup view shown in **fig. 7** shows how the connector's center pin has been joined to the end rod with a short length of solid wire. The actual tap point distances may need to be adjusted for best performance, but if the design value is used it will serve for most cases without change.

tuning

After the filter has been fully assembled, which means after all of the soldered joints are fully completed and the top is well secured electrically to the sides, it is time to test and tune.

Tuning microwave filters can be done in a number of ways. Several methods are described in reference 1, but the simple procedure of "sight tuning," or tuning by eye, is adequate for amateur filters, especially for filters with fewer than five or six sections. The basic principle involved is to tune for maximum signal at the center frequency, a process sometimes called synchronous tuning. The tuning is interactive, which means that one adjustment affects the tuning of adjacent elements, so it is necessary to return to each element once or twice to achieve peak performance.

A basic test set that can be used to peak the performance of any of the filters described here is shown in **fig. 8**. Inject a signal at the center frequency of the filter, detect or monitor the output power level, and tune for maximum. If the center frequency is within the ham bands, the input signal can be a transmitter or exciter. A signal generator can also be used. Harmonics of lower frequency sources or crystal oscillators can be useful as well. For example, the third harmonic of a 2-meter transmitter falls within the 420 to 450 MHz band and could be used to tune this filter. The signal detector can be a receiver with a signal level meter, a diode detector, a sensitive power meter or signal analyzer. Reference 6 describes many good low-cost UHF test methods in detail.

fig. 8. Simple test set block diagram. The signal source produces an output at the filter's center frequency. The filter is then tuned for maximum signal at the detector.

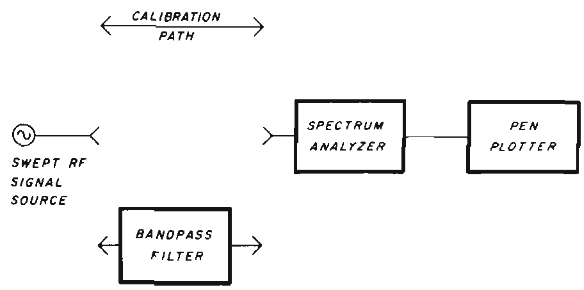

fig. 9. Test set used to produce the filter frequency response charts.

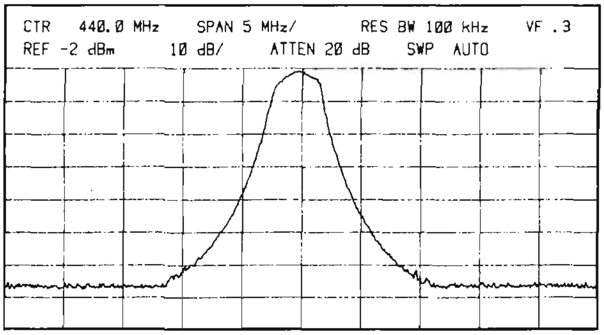

fig. 10. Swept frequency response of the four section 440-MHz filter. The horizontal scale is 5 MHz per division and the vertical scale is 10 dB per division. The spectrum analyzer settings were recorded automatically at the top of the plot.

Apply the test signal to one of the filter's connectors and connect the signal detector to the other and tune each of the screws to achieve the maximum output signal. The tuning range of this type of filter design is rather limited, which helps prevent tuning to the wrong harmonic, as can happen with broadly resonant circuits. This is a useful feature if the simple test set, with its potentially low spectral purity, is to be used.

If the filter is properly designed and carefully constructed, the slight tuning range afforded by the tuning screws should be sufficient. Each tuning screw should show a definite maximum. If it does not, this is an indication that the element which you are tuning is not properly resonant. In such a case, the rod length must be corrected before the filter will operate properly.

Once you've adjusted each tuning screw to yield the maximum output signal, go back and readjust each screw again slightly to peak the filter. If the filter response is not as calculated, and if the passband losses seem high even though each of the resonators gives a good peak tuning point, it may be necessary to adjust the tap points at the two end resonators. If no means of carefully measuring the losses is available, it is probably better to stay with the calculated tap dimensions. At this point the tuning is done.

A more sophisticated measuring system is useful for measuring the actual performance of the filter. **Figure 9** is a diagram of the test set which produced the swept frequency response of the filter examples. The input signal from a sweep generator scans across the frequency range in regular sweeps. A spectrum analyzer measures the output signal from the bandpass filter, and provides a graphic plot of the filter's output signal across the frequency range swept by the signal generator. Because the power from the generator to the filter input is constant, the spectrum analyzer's display is a direct representation of the filter's attenuation at various frequencies.

Figure 10 is the response of the 440-MHz filter. This graph is the plotter output from the test set described above. The filter was tuned using the simple single-frequency method of peaking all adjustments for maximum signal at 440 MHz. With the aid of such sophisticated test equipment it is possible to tune for improved passband flatness or for more precise centering if desired, but this clearly was not necessary in this case.

In summary, the 440 MHz bandpass filter example fully met its design goals of low cost, simple construction and easy adjustment, and it produced the desired electrical performance. The filter is physically small enough and sufficiently sturdy to be used in a fixed base system, although mechanical improvements would be needed for mobile service. This general construction technique using copper clad board and tubular copper or brass resonators has been applied to successfully build filters for the amateur bands from 440 to 2304 MHz.

1296 MHz filter

The second example of the use of this program is a bandpass filter centered at 1296 MHz with a desired ripple bandwidth of 20 MHz, a passband ripple of 0.25 dB and rejection points of 35 dB and 50 dB specified. Using these data, a few iterations with the program revealed that a four-section filter would again meet the requirements.

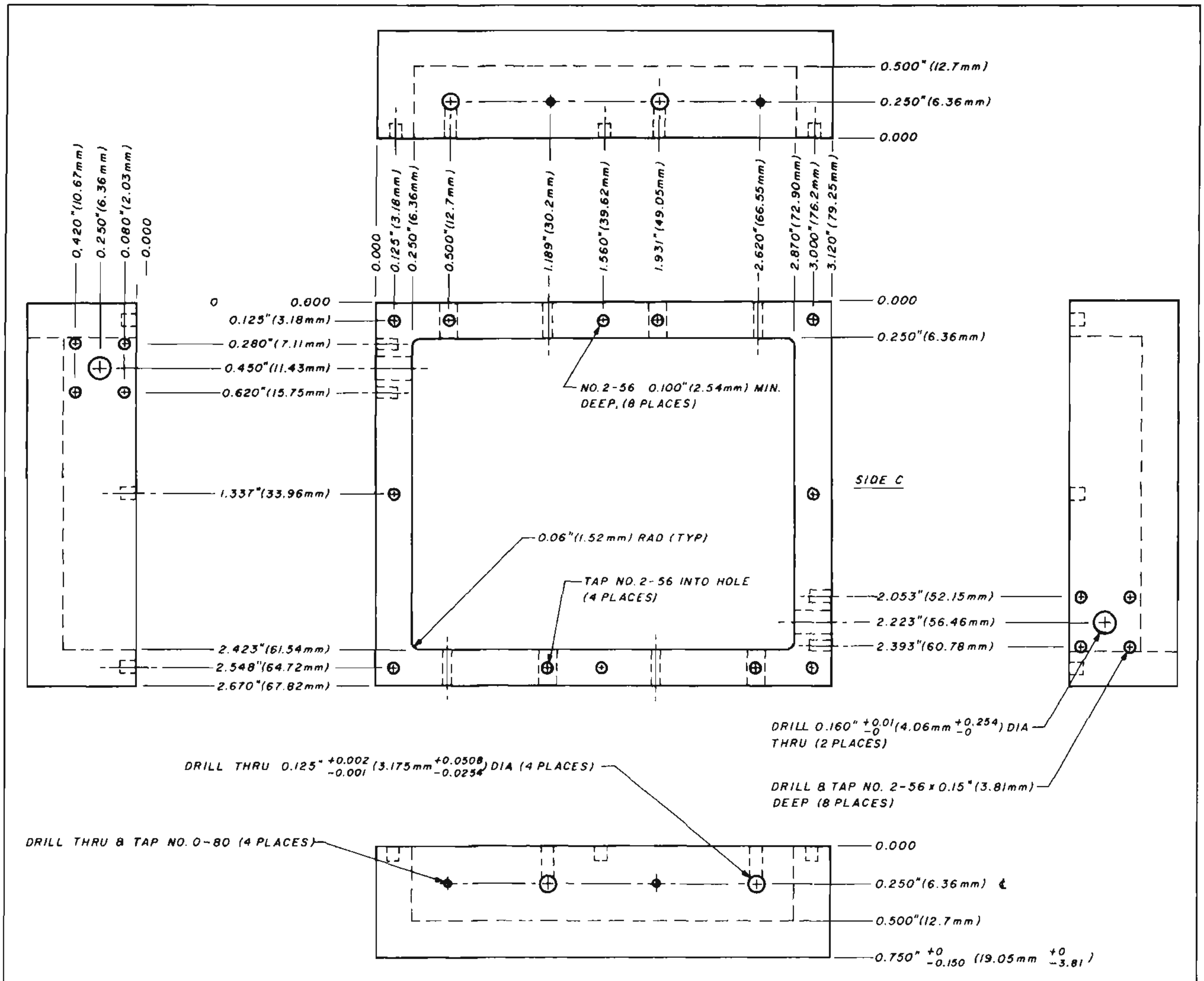

fig. 11. Mechanical details of the 1296-MHz filter housing. This housing is machined from aluminum stock. The top cover, not shown, is made from 0.06 sheet aluminum.

If the construction techniques used to build the 440-MHz filter seemed spartan, then this 1296 MHz filter is by contrast decidedly upscale. In order to prove that close tolerance construction could give good agreement with the computed data, a machined aluminum housing was used for this filter. Machining a housing using a metal milling machine gives precise control of the housing dimensions. This housing is considerably more accurate than the hand-made structure described in the first example.

The mechanical data supplied by the program were used to make a sketch, shown in **fig. 11**, of a housing that could be manufactured simply on a metal milling machine. The elements, machined from 0.125 inch brass rod stock (a standard size) were tightly "press fit" into holes in the housing walls. The rods are held tightly in position with a small setscrew once the exact interior lengths were determined. At the input and output ends of the filter SMA type connectors were installed so that their center pins contacted the rods at the tap point calculated by the computer program. Small diameter tuning screws were installed in the threaded holes in the walls opposite the open circuit end of each resonator rod. These screws, as in the 440-MHz filter, make it possible to fine-tune the filter passband. A top cover of 0.06-inch aluminum sheet was attached by eight screws that go into the threaded holes along the top edge of the housing. The photographs of this filter, **figs. 12** and **13**, show the construction details clearly. (Note: while 0-80 screws are specified in the construction drawings, 2-56 screws could be used as well.)

The housing was manufactured by machinists in a small shop, working from a simple sketch of the housing and cutting the aluminum stock with hand-operated machinery. In order to reduce costs, we

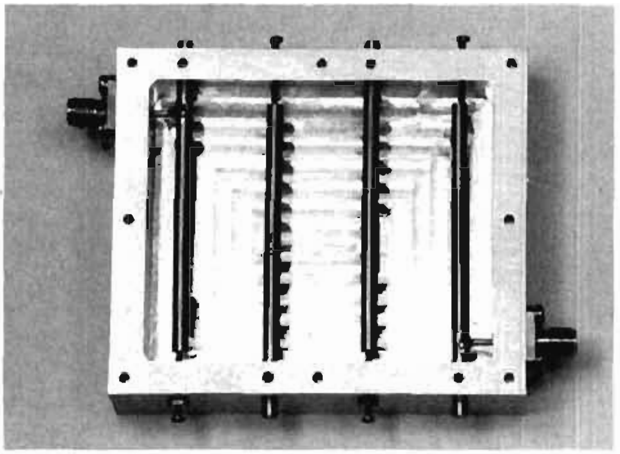

fig. 12. An overall view of the machined 1296-MHz filter. The sheet metal cover has been removed to show the internal cavity and the 4 resonator rods.

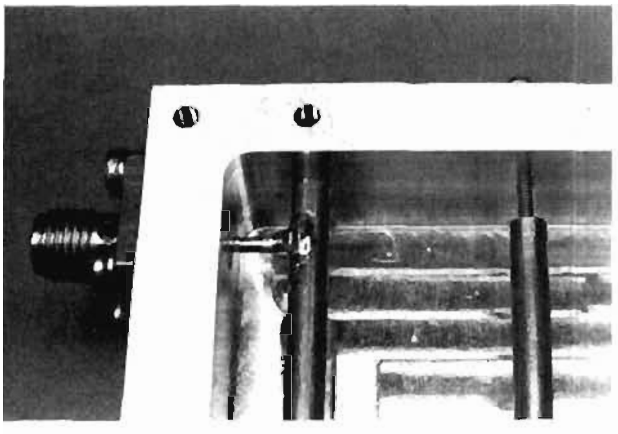

fig. 13. Close-up details of the 1296-MHz filter. The SMA connector center pin is clearly visible where it passes through the housing wall and contacts the end resonator rod. The small tuning screw at the end of the second resonator is also seen.

asked the shop to produce only a blank housing. They machined away the cavity to the precise 0.500 inch depth and drilled locating holes for the resonator rods, the tuning scews, the end connectors and the cover mounting screws, but they did not tap any of the holes. We were then able to finish the mechanical work by doing the time-consuming hand-tapping of all of the threaded holes. This reduced the cost of the housing by more than a third. Even so, the cost was in the $50.00 range, which may be justifiable only when precise results are essential.

However, the care and expense expended on the precise housing produced a filter that was nearly on frequency at first try, with precisely the initial resonator length settings that the computer predicted. Fine adjustments of the trimmer screws centered the passband precisely. **Figure 14** shows a plot of the swept RF response of the filter. Superimposed on the plot are circles that indicate the expected response calculated by the computer prediction. The calculated and actual values are in close agreement throughout the passband, and the rejection skirts are close to the computed values as well.

As before, the filter was peaked using the simple, single-frequency approach in order to illustrate the results obtainable with simple equipment. The test set used to make the swept frequency response plot was the same as that used in the 440 MHz filter tests.

This 1296 MHz filter, with its careful and precisely machined construction, shows the power and accuracy of the computer routine. The construction technique is a good one, and a simple metal milling machine, and perhaps even a drill press, can be used to make housings such as this one.

The use of 0.125 inch brass stock for the resonator rods was a bit of a compromise. It would have been better to use a somewhat larger diameter rod to reduce skin effect losses, but the 0.125-inch stock was on hand. Also, although brass rod is a good choice from a mechanical viewpoint, it is not a very good conductor of RF energy because its resistivity is about four times worse than copper's. Aluminum rods would be better than brass, because aluminum is both stronger and a better conductor, but with aluminum rods the tap point connections couldn't be easily soldered. Tradeoffs, as always, seemed to abound.

conclusion

This program is a powerful tool that greatly simplifies the selection and design of bandpass filters. The interdigital structure is useful from UHF to microwave frequencies, and provides good selectivity, low loss, small size, and an ease of construction that makes it suitable for many applications. The ease with which many different designs can be evaluated in software means that Amateurs can custom-design filters for specific applications and need not merely copy published designs that only approximate their re-

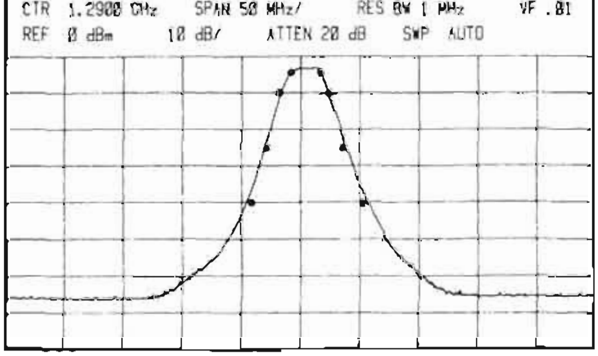

fig. 14. Frequency response curve of the 1296-MHz four section bandpass filter. The circles indicate the response computed by the program.

quirements. The widespread use of home computers together with software written specifically for Radio Amateurs should make possible a new generation of home-built equipment designs.

references

1. G. Matthaei, L. Young, and E.M.T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*, McGraw-Hill, New York, 1964.
2. M. Dishal, "A Simple Design Procedure for Small Percentage Bandwidth Round-Rod Interdigital Filters" *IEEE Transactions on Microwave Theory and Techniques*, MTT-13, Number 5, September, 1965, pages 696-698.
3. C.W. Rook, J.M. Taylor, "Intfil," 1970.
4. D.R.J. White, *A Handbook on Electrical Filters Synthesis, Design and Application*, Don White, Germantown, Maryland, 1963.
5. A.I. Zverev, *Handbook of Filter Synthesis*, John Wiley and Sons, New York, 1967.
6. K. Weiner, *The UHF Compendium*, Verlag Ruldolf Schmidt, Hof/Saale, West Germany, 1982.
7. L. Young, *Microwave Filters Using Parallel Coupled Lines*, Artech House, Dedham, Massachusetts, 1972.
8. V.P. Leonchenko, A.L. Feldstein, and L.A. Shepelyanskii, *Design of Interdigital Bandpass Filters*, Svyaz, Moscow, 1975, (in Russian).
9. E.G. Crystal, "Coupled Circular Cylindrical Rods Between Parallel Ground Planes," *IEEE Transaction on Microwave Theory and Techiques*, MTT-12, Number 4, July, 1968, page 428-439.
10. R. Fisher, "Interdigital Bandpass Filters for Amateur VHF/UHF Applications," *QST*, March, 1968, page 32.
11. L. Anderson, "Top Coupled Bandpass Filter," *ham radio*, June, 1977, page 34.
12. R. Cooper, "Interdigital Preamplifier and Combined Bandpass Filter for VHF and UHF," *ham radio*, August, 1970, page 6.
13. W. Hayward, W7ZOI, "The Peaked Lowpass: A Look at the Ultraspherical Filter," *ham radio*, June, 1984, page 96.

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