Inexpensive Construction Techniques For 50-Ohm Signal Line Filters

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Simple and inexpensive construction techniques expedite the assembly of passive LC filters for use in the 1-kHz to 5-MHz range.

INTRODUCTION

The testing of communication systems in accordance with a certain test specification familiar to most ITEM readers requires the use of many different passive inductor/capacitor (LC) filters for defining the 6-dB bandwidths of non-tunable detection systems. These filters are also useful for providing preselection in front of low-level, broadband preamplifiers used with tunable detection systems. Although many articles have been published on the simplified design of suitable filters,[1-4] relatively few articles have been published on the simplified construction of these filters. For example, an ITEM 1982 article provided examples of filter construction using small tinned steel boxes.[5] Unfortunately, the box manufacturer needs several weeks for fabrication and delivery, and quantities of 250 or more must be ordered to be cost-effective. This article will demonstrate a quicker, simpler and less expensive construction technique where only several scrap pieces of one-sided printed-circuit board (PCB) are needed for the mounting of the filter parts.

In many instances, the more complex filter assemblies involving boxes with partitions or microstrip lines on PCBs are unnecessary, and the simpler and less expensive procedure of securing the filter components with a few dabs of RTV (silicone rubber) on a PCB is adequate. This is especially true in the 1-kHz to 5-MHz frequency range, where the inductors and capacitors are small enough so they do not need special mounting arrangements. Also, below 5 MHz, satisfactory lowpass filter stopband performance and highpass filter passband performance are possible without partitions or microstrip lines, respectively. Thus, in the 1-kHz to 5-MHz range, simpler construction is quite practical using cheap PCB material as a base, and this article will demonstrate some techniques that may be used. In addition, suitable capacitor and inductor types and convenient sources will be recommended to facilitate obtaining the parts for filter construction.

By using the construction techniques and recommended components discussed in this article, passive LC filters can be assembled faster, easier and cheaper than before. Consequently, building these filters for non-stringent applications may become a more attractive alternative as compared to buying them from commercial filter manufacturers.

FILTER DESIGN SELECTION

The choice of a suitable lowpass or highpass filter design depends on either calculating the 6-dB frequencies in accordance with the instructions provided in the test specification being used or selecting the 6-dB cutoff frequencies for a particular application. Once the 6-dB cutoff frequencies are known, the precalculated filter design tables in one of the first four references can be searched for designs having cutoff frequencies closest to the desired cutoff frequencies. However, because these tables do not include the 6-dB frequencies, an approximation must be made by using the tabulated 3-dB frequencies. Although this procedure will usually suffice, filter tables with the 6-dB frequencies are preferable, and lowpass and highpass tables with the 6-dB frequencies are listed in Appendix A.

Appendix A lists 48 7-element 50-ohm Chebyshev computer-calculated designs, with 24 designs for lowpass filters and 24 designs for highpass filters. Seven-element designs were used for a skirt selectivity of better than 42 dB per octave, and only designs having VSWRs (voltage standing wave ratio) less than 1.2:1 were tabulated so that lowpass and highpass filters could be cascaded for a bandpass response with minimum interaction. In addition to the ripple cutoff frequency (F-co) and 3-, 20- and 40-dB frequencies, the 6-dB frequency and the minimum return loss for each design are also listed. Only the E12 capacitor values are tabulated to minimize the number of designs.

Although the tabulated designs cover only the 1 to 10-MHz decade, the same tables may be used for the 1 to 10-kHz decade by changing all frequencies to kHz and the C and L values to nF and mH, respectively. The VSWR and return loss values remain unchanged. The component values for other frequency decades may be read directly from the tables by inspection. For example, to change the 1 to 10-MHz tables to 0.1 to 1-MHz or 0.01 to 0.1-MHz, the listed frequencies are divided by 10 or 100 and the capacitor and inductor values are multiplied by the same number. For example, the C and L values for a 6-dB, 0.121-MHz lowpass filter are 27000 pF (0.027 µF), 109 µH, 56000 pF (0.056 µF) and 126 µH.

In many instances, the more complex filter assemblies involving boxes with partitions or microstrip lines on PCBs are

To find a suitable filter design with a specific 6-dB cutoff frequency, the 6-dB frequency column of Table A1 or A2 is scanned and the corresponding capacitor and inductor values are read. The components are connected together as shown in Figures A1 or A2.

Choosing a suitable design is the easy part! Selecting and ordering appropriate capacitors and toroidal cores for the inductors, followed by correctly winding the cores and then assembling the filter is much more difficult. The remainder of this article will provide sufficient details so this aspect of filter construction will be as easy as choosing a design.

RECOMMENDED COMPONENT TYPES AND SOURCES

After deciding to build instead of buy a filter, the problem of finding suitable components can be quite confusing. For example, in addition to finding capacitors with suitable performance characteristics, a distributor must be found who has a wide selection of capacitor types and values and who is

Continued on page 154

CAPACITANCE RANGE (F)	DESCRIPTION AND PANASONIC TYPE NO.	TOLERANCE (%)	VOLTAGE (V)	DIGI-KEY PART NO.	COST/10 ($)
6.8 µ	Miniature Metallized	10	100	EF1685	21.75
0.1 µ	Polyester Film	10	100	EF1104	2.05
	Type ECQ-E(F)				
0.10 µ	Stacked Metallized Film	5	100	P4725	2.23
0.01 µ	V-Series	5	100	P4713	1.76
0.01 µ	Polypropylene	2	50	P3103	4.37
0.001 µ	P-Series	2	50	P3102	4.37
820 p	Polypropylene	5	50	P3821	2.04
270 p	P-Series	5	50	P3271	2.04

NOTES: 1. All capacitors are manufactured by Panasonic and distributed by Digi-Key Corp., P.O. Box 677, Thief River Falls, MN 56701-0677. 1-800-344-3439.

2. The above Panasonic capacitor types are recommended for the construction of lowpass and highpass filters based on the capacitance ranges given in the first column.

TABLE 1. Capacitors Suitable for 50-ohm Filter Construction, 1 kHz to 5 MHz.

capable of supplying small quantities within seven to ten days. In the case of inductors, toroidal cores will be hand-wound to get the exact design inductance values, and therefore it is necessary to obtain cores that not only have the proper magnetic characteristics but also are available in small quantities.

The components and distributors discussed in this article have been found to be suitable when constructing simple passive LC filters intended for non-stringent application. Of course, minor changes may be necessary to suit individual situations.

Choosing a suitable design is the easy part! Selecting and ordering appropriate capacitors and toroidal cores for the inductors, followed by correctly winding the cores and then assembling the filter is much more difficult.

CAPACITORS

Capacitors are available with a wide variety of values, dielectrics, voltage ratings, temperature coefficients, physical construction, prices, etc. Choosing a suitable capacitor and distributor can be difficult and time consuming. To assist the inexperienced filter constructor, a summary of selected capacitor values and types available is given in Table 1. A brief description of the characteristics of each capacitor type follows:

Miniature metallized polyester film features a dual-sided metallized polyester film with high dielectric constant and large C-values in small dimensions at low cost. The standard capacitance tolerance is ten percent with a one-percent maximum dissipation factor.

Stacked metallized film offers high volumetric efficiency, a maximum dissipation factor of one percent and a five-percent tolerance, and is usually suitable for replacing monolithic ceramic capacitors.

Polypropylene is available in two- or five-percent tolerances, depending on capacitance. It has a low temperature coefficient and a lower dissipation factor than the polyester types (0.1 percent compared to one percent) which makes the polypropylene type preferable for filter applications at the higher cutoff frequencies (up to 10 or 20 MHz). Because of increasing cost for higher capacitance values, this capacitor type is preferred for values less than 0.01 μF.

The capacitors in Table 1 are grouped into types that are most suitable for the capacitance ranges in the first column. For example, the metallized polyester film type should be used for those designs requiring capacitors between 0.1 μF and 6.8μF. For the smaller capacitance ranges of 0.10 - 0.01 μF, 0.01 - 0.001 μF and 820 - 270 pF, the listed types are more suitable than the miniature metallized film type because of a tighter capacitance tolerance and lower dissipation. All the capacitor types are available from Digi-Key in the E12 series of preferred values, that is, values of 10, 12, 15, 18, 22, 27, 33, 39, etc., and their decade multiples. The last two columns of Table 1 list the Digi-Key part numbers with prices for quantities of ten. To use Table 1, scan the first and second columns to find the recommended capacitor type based on the capacitance range, and note the tolerance, voltage rating and price. Then obtain the catalog part number for the particular E12 value needed and order the part. All capacitors will be suitable for applications where the expected maximum rms voltage level is less than one-tenth of the capacitor voltage rating.

To assure that the actual filter cutoff frequency will be close to the design value, capacitors having a two- or five-percent tolerance should be used. This is no problem with capacitors of less than 0.1 μF, which have tolerances of two or five percent; however, capacitors larger than 0.1 μF have a ten-percent tolerance. If the larger-valued ten-percent capacitors are measured and found to be too low by more than five percent of the design value, they should be paralleled with a smaller capacitor to bring the paralleled value to within five percent of the design value. Digital capacitance meters suitable for making these measurements cost less than $150.

INDUCTORS

Unlike capacitors, the inductors recommended for filter construction are not bought ready to use, but must be first hand-wound on toroidal cores and then checked for proper inductance before installation. The toroidal winding configuration is used because the magnetic field is contained almost entirely within the toroid shape, and leakage inductance

(A) LOWPASS FILTERS									
FREQUENCY RANGE (Hz)	INDUCTANCE RANGE (H)	CORE MATERIAL & MANUFACTURER	OUTSIDE DIA (IN)	MFG. PART NO.	PERM. (µ)	L/100T (H)	NO. OF TURNS (Lmax	Lmin)	WIRE SIZE (AWG)
F (6 dB)									
1 k-4 k	15 m -3 m	Moly-permalloy Powder Cores	0.90	55305-A2	300	2.16 m	264	118	(Note 1)
4 k-10 k	3.8 m-1.3 m	Magnetics	0.90	55210-A2	125	900 µ	205	120	(Note 1)
10 k-40 k	1.5 m-300 µ	P.O.Box 391	0.90	55312-A2	26	190 µ	281	118	(Note 1)
40 k-100 k	380 m -130 µ	Butler, PA 16003 (412)282-8282	0.90	55313-A2	14	99 µ	196	115	(Note 1)
100 k-500 k	150 µ- 30 µ	Iron Powder Cores	0.94	T94-1 (Blu)	20	160 µ	97	43	22-26
500 k-1 M	35 µ - 13 µ	Micrometals, Inc.	0.80	T80-2 (Red)	10	55 µ	80	49	22-26
1 M-2 M	15 µ - 6 µ	1190 N. Hawk Circle	0.68	T68-7 (Wht)	9	52 µ	54	34	24-26
2 M-5 M	8 µ- 2 µ	Anaheim, CA 92807 (800)356-5977	0.50	T50-7 (Wht)	9	43 µ	43	22	24-26

(B) HIGHPASS FILTERS									
FREQUENCY RANGE (Hz)	INDUCTANCE RANGE (H)	CORE MATERIAL & MANUFACTURER	OUTSIDE DIA (IN)	MFG. PART NO.	PERM. (µ)	L/100T (H)	NO. OF TURNS (Lmax	Lmin)	WIRE SIZE (AWG)
F (6 dB)									
1 k-4 k	5 m -1 m	Moly-permalloy Powder Cores	0.90	55305-A2	300	2.16 m	152	68	(Note 1)
4 k-10 k	1.2 m -400 m	Magnetics	0.90	55210-A2	125	900 µ	115	67	(Note 1)
10 k-40 k	500 µ -100 µ	P.O.Box 391	0.90	55312-A2	26	190 µ	162	73	(Note 1)
40 k-100 k	120 µ -40 µ	Butler, PA 16003 (412)282-8282	0.90	55313-A2	14	99 µ	110	64	(Note 1)
100 k-500 k	47 µ - 8 µ	Iron Powder Cores	0.80	T80-1 (Blu)	20	115 µ	64	26	20-24
500 k-1 M	10 µ - 4 µ	Micrometals, Inc.	0.68	T68-2 (Red)	10	57 µ	42	27	22-26
1 M-2 M	5 µ - 2 µ	1190 N. Hawk Circle	0.50	T50-7 (Wht)	9	43 µ	34	22	24-26
2 M-5 M	2.5 µ - .8 µ	Anaheim, CA 92807 (800)356-5977	0.44	T44-7 (Wht)	9	46 µ	23	1324-26	

NOTES: 1. Use AWG #24 bifilar wire, MWS Part #B-2242111, for winding in one or two layers. After winding, connect the green start lead to the red finish lead and measure the inductance between the other two leads. Remove or add turns as required until the measured inductance is within three percent of the design value.

2. For cutoff frequencies above 2 MHz, use a single layer winding for best Q. Remove or add turns to get near the design value and then squeeze or spread the turns for the final adjustment.

***TABLE 2.** Toroidal Cores Suitable for 50-ohm Filter Construction, 1 kHz to 5 MHz.*

and stray capacitance are very small. Because of this, several toroidal inductors may be placed close together without any spurious coupling problems. It therefore is possible to assemble small, compact filters that would not be practical with the more common solenoid-wound inductors.

The first step in assembling a toroidal inductor is to choose a core appropriate for the inductance and frequency range. After a core is chosen, a suitable wire type and size is selected to facilitate the hand-winding process. All of the variables associated with this process have been considered and a suitable selection of cores and wire sizes is summarized in Table 2.

Table 2 is divided into two sections, (A) and (B), for lowpass and highpass filters, respectively. Each section is divided into two parts -- the upper part lists moly-permalloy cores and the lower part lists iron powder cores. Both tables have ten columns of interrelated parameters with appropriate column headings.

The frequency range is listed in the first column and is broken into eight ranges between 1 kHz and 5 MHz, with corresponding core manufacturers and part numbers that are optimum for a particular frequency range. The inductance values in the second column were chosen by referring to Table A1 (Lowpass) in Appendix A to find the maximum and minimum inductance values corresponding to the lowest and highest 6-dB cutoff frequencies of each frequency range in the first column. For example, for the first range, 1k - 4k, Design A1-22 has a 6-dB cutoff frequency of about 1 kHz with a corresponding maximum inductance (L4) of about 15 mH. The 6-dB 4-kHz cutoff frequency is best met by design A1-13 with a minimum inductance of about 3 mH. The other column headings are self-explanatory.

An example demonstrates the use of Table 2 for selecting a toroidal core appropriate for building a lowpass filter. A lowpass filter is assumed to have a 6-dB cutoff frequency of about 5 MHz. Referring to Table A1, design #15 has a 6-dB cutoff frequency of 5.36 MHz which is close enough to be satisfactory. The recommended core for this design (as indicated by Table 2) is a Micrometals powered iron core, Part No. T50-7. Based on the L/100 turns for 43 μH, the number of turns for the design inductance values of 3.01 and 2.43 μH are calculated using the following equations:

$N(L4) = 100\sqrt{3.01/43} = 26$ turns wound with AWG #24 or 26,

$N(L2,6) = 100\sqrt{2.43/43} = 24$ turns wound with AWG #24 or 26.

Thus, once the 6-dB cutoff frequency is known, a suitable core is easily selected and then the proper number of turns is calculated.

SOURCES FOR MAGNETIC CORES AND WIRE

The source from which magnetic cores are obtained will depend on the number of filters built and whether this filter building capability will be a long-term responsibility. If only a few filters are needed, the most convenient procedure is to obtain the cores from a manufacturer distributor who will accept small orders.

For small quantity purchases (less than 20) of powdered iron cores, the best known distributor of Micrometals cores is Amidon Associates, Inc., located in Dominquez Hills, California.[6]

If the building of these passive LC filters are planned on a continuing basis for use in several test systems, then it is much more convenient and cost-effective to invest two or three hundred dollars and purchase a large number of cores from the manufacturers. Both Magnetics and Micrometals have catalogs available providing useful information on the winding and application of their cores.[7-8]

WINDING OF TOROIDAL CORES

The hand-winding of toroidal inductors requiring less than 50 turns is easily done using standard film-insulated magnet wire. Polyurethane insulation is recommended because it is solderable and requires no scraping. The appropriate wire sizes are given in Table 2. For frequencies above 2 MHz, a single wire layer is recommended for best Q. Below 2 MHz, two or three layers may be needed to get the required number of turns on the core.

First, the length of wire to be used is estimated based on the number of turns and the length of one turn. A few inches is added for both leads. A length of magnet wire is cut and half of the wire is pulled through the core. The builder starts by winding half of the wire, and when the first half is nearly all on the core, continues winding the core with the second half. Winding only half of the total wire at a time minimizes the length of wire that needs to be pulled through the core.

Although a heavier wire than listed in Table 2 can be used in winding the toroidal cores, the recommended wire should be used. By winding with a smaller diameter wire, sufficient open space will be left on the core to allow the turns to be squeezed together or spread apart for the final adjustment of inductance. If a heavier wire would be used, there would be no room to allow for final adjustment. The paragraph on construction techniques discusses a procedure for tuning the three inductors in the lowpass and highpass filters.

When an inductor requires more than 50 or 60 turns, the winding process becomes more difficult and tedious because of the increased number of turns and the much longer length of wire that must be handled. The difficulty of winding many turns can be reduced by half by using a length of bifilar magnet wire consisting of two parallel-bonded lengths of different colored wires. The bifilar wire handles like a single strand, but winds twice as fast as a single strand because for every turn of bifilar wire, two turns are actually being put on the core. After the core is wound, the proper ends of the winding are soldered together to connect the two windings in series, aiding to give the required inductance.

The bifilar magnetic wire recommended for winding more than 50 or so turns on a toroidal core is available from MWS Wire Industries, Part #B 2XX2111. The B-2 designation in the MWS part number refers to multifilar magnet wire consisting of two conductors. The third and fourth digits (XX) indicate the AWG wire size. The next digit (2) signifies a heavy insulation thickness. The three "ones" signify the insulation type (polyurethane), color coded conductors (1=red/green) and the bonding film (polyvinyl butyral). Other combinations of wire numbers, insulation thickness, insulation type, colors and bonding films are specified in a General Product Information sheet available from MWS.[9]

SIMPLIFIED CONSTRUCTION TECHNIQUES

The simplified construction techniques discussed in this article are suitable for the assembly of lowpass and highpass filters having cutoff frequencies of less than five or six MHz. In these cases, the simpler open construction on a PCB is satisfactory because the passband or stopband performance of the filter in the decade or so above the cutoff frequency is relatively unaffected as compared to filters having much higher cutoff frequencies. An example of the assembly and testing of a lowpass and highpass filter will demonstrate this simplified construction technique, and plots of the passband and stopband responses will demonstrate the performance that may be expected.

LOWPASS FILTER ASSEMBLY AND RESPONSES

A 7-element lowpass filter having a 6-dB cutoff frequency of 5.36 MHz (Design #15 from Table A1) was assembled and tested to demonstrate the simplified assembly procedure and the stopband and passband attenuation performance that can be expected when using simplified construction.

Figure 1 shows the lowpass filter components assembled on a single-sided piece of PCB. BNC connectors were fastened to the ends of the boards by soldering their ground lugs to the copper-clad underside of the PCB. The capacitors and toroidal inductors (wound on Micrometals T50-7 cores) were laid on the top of the board and their leads soldered in accordance with the schematic diagram shown in Figure A1. Because of the shortness and stiffness of the capacitor leads, they provide sufficient support for the inductors so additional support is not needed; however, a few dabs of silicone rubber (RTV) around each inductor will make the whole assembly more secure and less likely to be damaged by handling. If necessary, additional protection can be added by wrapping the filter assembly with a layer of plastic tape.

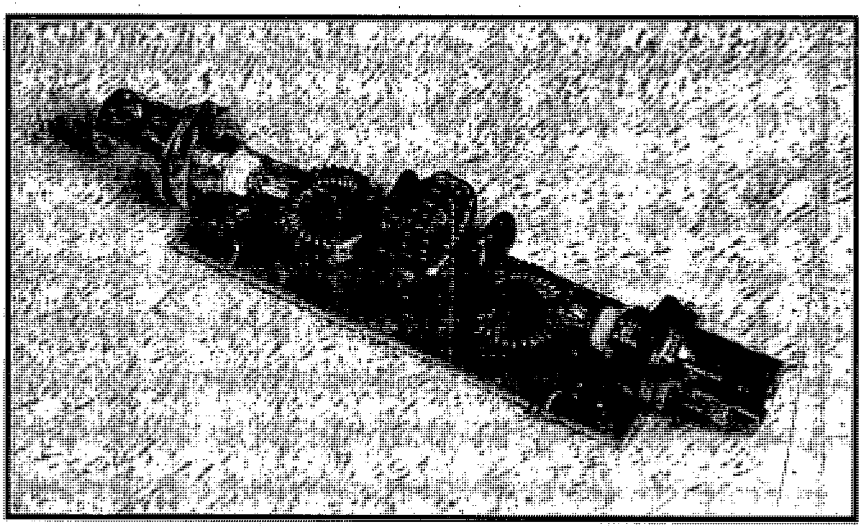

FIGURE 1. *The 5.4-MHz, 7-element Lowpass Filter. It is assembled on a small piece of single-sided PCB to simplify construction. Solder lugs on both BNC connectors are soldered to the copper foil on the underside of the board. In spite of the open construction, the filter stopband of 70 dB or more extends to 140 MHz.*

Normally, such a simple form of assembly is not acceptable, but this filter is assumed to be for personal use in a test laboratory where the quick response to a testing requirement is more important than obtaining a professionally assembled filter that will meet all kinds of stringent environmental specifications. As long as the filter passband and stopband performance are in accord with individual requirements and the components are securely fastened to a base, the filter assembly will be satisfactory.

Figure 2 shows three plots depicting the 5-MHz lowpass filter stopband, transition band and passband responses that were measured with a spectrum analyzer and tracking generator. The stopband attenuation response was measured up to 200 MHz and is shown in Figure 2(A). The stopband response is greater than 70 dB up to about 100 MHz, after which the attenuation gradually drops to about 50 dB at 200 MHz. Even with the open construction, the filter stopband is quite satisfactory for more than a decade above the cutoff frequency. This stopband performance clearly demonstrates that this simplified form of construction is quite practical. The stopband performance will, of course, be poorer for filters having substantially higher cutoff frequencies.

Figure 2(B) shows the filter transition response between 4 and 9 MHz. The 6-dB, 20-dB and 40-dB measured frequencies are within one percent of the design frequencies, indicating that the capacitor values are correct and the inductors were properly tuned. With care in assembly, similar agreement between the measured and design frequencies should be expected with all similar filters of this type.

Figure 2(C) shows the filter attenuation and return loss in the 1 to 5-MHz passband. The passband attenuation and return loss curves have vertical scales of 1 and 10 dB, respectively. As expected, the filter passband is less than one dB up to about 4.2 MHz, after which the attenuation gradually starts to rise. Over most of the same range, the return loss is greater than 30 dB with three peaks.

The return loss peak and valley frequencies can be calculated relative to the ripple cutoff frequency because the normalized values are already known and are the same for all 7-element Chebyshev filters. For example, the normalized return loss peak frequencies for a 7-element Chebyshev design occur at 0.9749, 0.782, and 0.434 times the ripple cutoff frequency. Because the ripple cutoff frequency of filter design #A1-15 is 4.13 MHz, the return loss curve in Figure 2(C) should have peaks at 4.03, 3.23, and 1.79 MHz. In a similar way, the return loss valley frequencies should occur at 0.901, 0.6235 and 0.223 times 4.13 MHz, or at 3.72, 2.58 and 0.92 MHz. Also, the return loss theoretically should be not less than 35 dB. Examination of Figure 2(C) shows the theoretical return loss response is approached but not achieved. For example, although there are three return loss peaks, they differ quite a bit from the theoretical peak frequencies. Also, the return loss should dip to a minimum of 35 dB, but at 1 MHz, the minimum is about 31 dB and at 2.6 and 3.6 MHz, the return loss minimum is about 39 dB.

The plotted return loss response was obtained with a return loss bridge connected to one end of the filter with the other end of the filter terminated in a 50-ohm load. The detector output of the bridge was connected to the input of a spectrum analyzer while a tracking generator was connected to the source input of the bridge. When the inductor tuning was first started by squeezing and spreading turns, only two return loss peaks were observed, and the first peak closest to the cutoff frequency was completely absent. While tuning the coils, the first peak appeared, and after a suitable return loss was obtained over most of the passband, further tuning attempts were stopped. If the fixed capacitors could also have been adjusted, the exact theoretical response of the filter could have been duplicated; however, for the intended filter application, it was concluded that additional tuning was not necessary.

When making final adjustments to a filter, the passband return loss response provides much better indication of correct filter tuning than does the passband attenuation response. This is because passband return loss is a much more sensi-

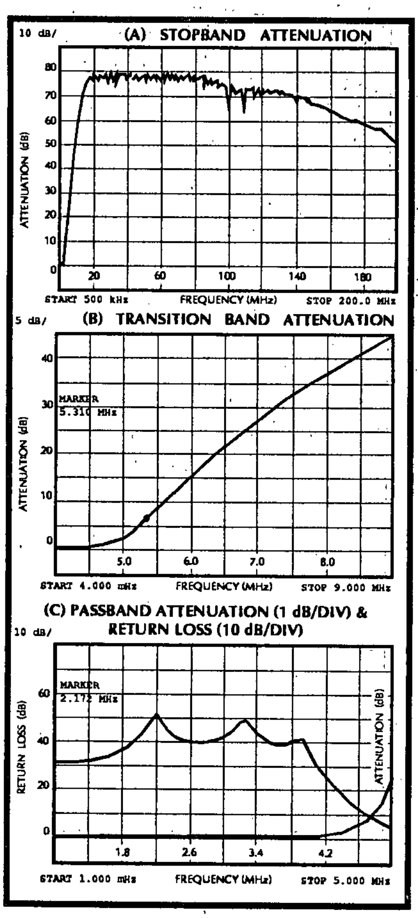

FIGURE 2. *Attenuation and Return Loss Responses of Lowpass Design #A1-15, F-co = 4.13 MHz, F6 = 5.36 MHz.*

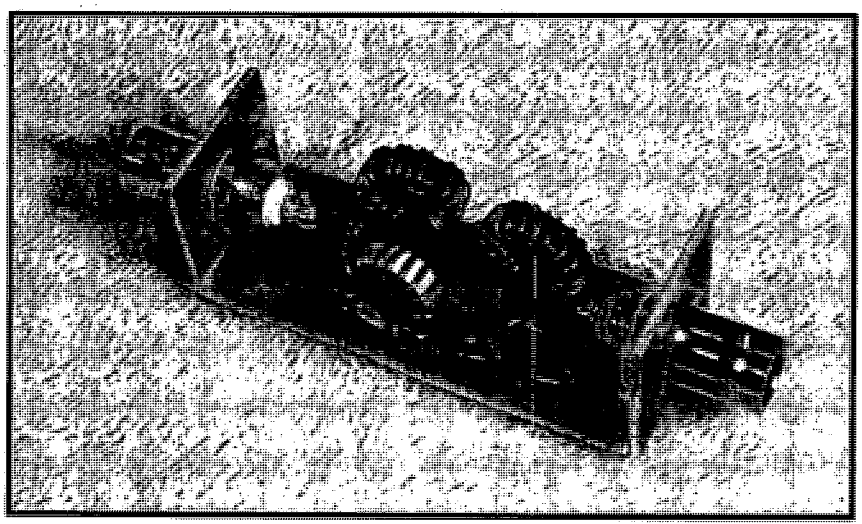

FIGURE 3. *The 4.8-MHz, 7-element Highpass Filter. It is assembled on a small piece of single-sided PCB to simplify construction. In spite of the simple construction, the filter passband return loss of 27 dB or more extends to 42 MHz, indicating that up to this frequency, more than 99 percent of the input power is transmitted through the filter to its 50-ohm load.*

tive indication of correct tuning than is the passband attenuation response. For example, passband attenuation changes of a few hundredths of a dB are hardly discernable, whereas the corresponding change of several dB of return loss is easily observed.

HIGHPASS FILTER ASSEMBLY AND RESPONSES

A 7-element highpass filter having a 6-dB cutoff frequency of 4.75 MHz (Design #19 from Table A2) was assembled and tested to demonstrate the simplified assembly procedure and to demonstrate the stopband and passband attenuation responses that can be expected when using simplified construction.

Figure 3 shows the highpass filter components assembled on a single-sided piece of PCB. Small rectangular pieces of PCB, each with a hole for a BNC connector, were soldered at right angles to each end of the base. BNC connectors were mounted in the holes and the capacitors and inductors were installed between the connectors in accordance with the highpass filter schematic diagram in Figure A2. There is no advantage in this method of BNC connector mounting over the method used in the lowpass filter assembly. For satisfactory high frequency passband response in highpass filters, microstrip construction is usually required; however, because the cutoff frequency of this particular design example is low enough, the passband response is satisfactory up to a decade above the 6-dB cutoff frequency of 4.75 MHz. Consequently, it may be concluded that the simplified construction technique is suitable.

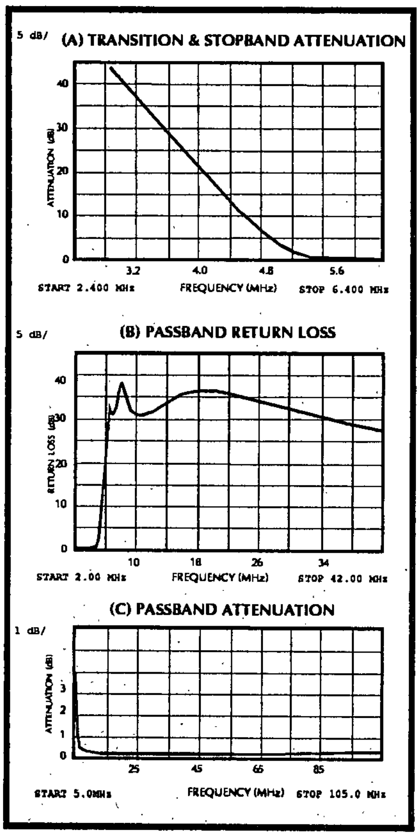

FIGURE 4. *Attenuation and Return Loss Responses of Highpass Design #A2-19, F-co = 6.07 MHz, F6 = 4.75 MHz.*

Figure 4 shows three plots depicting the 5-MHz highpass filter stopband/transition band, passband return loss and passband attenuation. These responses were measured using the same procedures as used in the lowpass filter evaluation. The frequencies of the measured stopband/transition band response shown in Figure 4(A) agree within two percent of the theoretical frequencies. The passband return loss shown in Figure 4(B) is also satisfactory, with the expected three peaks being present and with a return loss of greater than 27 dB up to 42 MHz. A return loss of greater than 20 dB at the filter input means that more than 99 percent of the input power to the filter is delivered to the load. Figure 4(C) shows that the passband attenuation is about one-tenth dB and remains relatively flat to 75 MHz, after which it begins to slowly increase.

In a manner similar to that used with the lowpass filter, the frequencies of the passband return loss peaks for the highpass filter can be calculated by multiplying the highpass filter ripple cutoff frequency (F-co = 6.07 MHz) by the reciprocals of the previously given lowpass normalized frequencies. Thus, for a lowpass normalized frequency of 0.9749, the corresponding highpass normalized frequency is 1.0257, and the frequency of the first peak is 1.0257*6.07 = 6.23 MHz. In a similar manner, the frequencies of the two other peaks can be calculated as 7.76 MHz and 13.99 MHz. Comparing these calculated peak return loss frequencies with the plotted frequencies shows varying degrees of agreement. As with the lowpass filter return loss response, if the highpass filter capacitors could have been adjusted in addition to the inductors, the measured return loss response could have been made identical to the theoretical response. However, for the intended application of this filter, it may be concluded that the passband and stopband responses are satisfactory and additional tuning is unnecessary.

INDUCTOR FINAL TUNING PROCEDURE

Even though inductors are wound with the calculated number of turns based on the manufacturer's value of L(µH)/100 turns, a final adjustment is advisable, either by removing or adding a turn or by squeezing or spreading the turns. If an inductance bridge is available, the final L2, L4 and L6 inductance values can easily be checked and the necessary adjustments made. However, if such instrumentation is not available, alternative methods must be used.

From about 1 kHz to 2 MHz, the simplest alternative inductor measurement method is to find the resonant frequency of the tuned circuit consisting of the inductor to be measured and one of the capacitors being used in the filter. This technique requires a frequency counter, a digital capacitance meter, a signal generator and a wideband ac VTVM (vacuum tube voltmeter). Once the capacity is known to an accuracy of one percent and the resonant frequency is known to the nearest Hz, the inductance can be calculated. Turns are removed or added to the inductor until a resonant frequency is obtained which indicates the inductance is correct. The measurement circuit consists of the signal generator and the ac VTVM both coupled to a parallel-resonant circuit consisting of the measured capacitor and the inductor being tuned. The coupling elements are two capacitors, each having a capacitance of about 0.002 or less times the resonating capacitance. The common junction of the two capacitors connects to the "hot" end of the resonant circuit. The other end of one of the coupling capacitors connects to the signal generator output and the end of the other capacitor connects to the VTVM. The ground end of the parallel-resonant circuit connects to the signal generator and VTVM grounds. Resonance is indicated by a sharp rise in voltage amplitude as the signal generator frequency is varied through the resonant frequency of the parallel-resonant circuit. For inductance-capacitance combinations having resonance above two megahertz, a different method using a dip meter is preferable.

A dip meter (also known as a "grid-dip meter" during the vacuum tube age) is a multipurpose battery-operated active device widely used by amateur radio operators for finding the approximate resonant and operating frequencies of either energized or de-energized circuits. By coupling the plug-in coil of the dip meter into the filter circuits, the resonance of a particular C/L combination can be found. If the resonant frequency is high relative to the calculated frequency based on the known C/L values, the inductance is increased, and if the reverse is the case, the inductance is decreased. For example, to check the values of L2 and L6 in the lowpass filter of design #15 in Table A1, inductor L4 is first removed. The dip meter coil is then coupled into the resonant circuit of C1, L2 and C3. The resonance of this circuit should be 5.56 MHz based on the series connection of the 470 and 1200 pF capacitors across the 2.43 μH inductor. A turn is added or removed to L2 and the turns are squeezed or spread until the resonant frequency becomes 5.56 MHz. The dip meter is then coupled to the circuit consisting of C5, L6 and C7 and the same procedure is repeated. The leads of L2 and L6 are disconnected from C3 and C5, and L4 is connected to C3 and C5. The dip meter is coupled to this new circuit having a 3.75-MHz resonant frequency and the procedure is repeated. In this way, all the inductors are made to resonate at known frequencies to obtain the correct inductance. The same procedure is used to adjust the highpass filter inductors.

The dip meter is a most useful and versatile test instrument and belongs in all laboratories involved in EMI/RFI work and other similar types of testing. A dip meter, Model 90651A, covering the 1.7 to 300-MHz range, is available from James Millen Electronics for $385.00.[10]

RETURN LOSS BRIDGE

The usefulness of the return loss bridge (RLB) in making final adjustments to lowpass and highpass filters while observing the passband return loss response was briefly discussed earlier in this article. Two return loss bridges (RLB) from Eagle were used in making the plots shown in Figures 2 and 4.[11] Eagle also provides an interesting application note, "High Performance VSWR Measurements," at no charge. The final paragraph of this application note provides a nice summary of the RLB capabilities and is paraphrased as follows: The RLB is useful for making low power VSWR measurements and most bridges yield a 40-dB directivity which is equivalent to a 1.02 VSWR. Performance in excess of this is only possible using slotted line techniques. RLBs can be used for characterizing passive networks, antennas and low-power amplifiers. Because of its small size, low cost, high performance and ease of use, the RLB should be a standard piece of test equipment in the RF laboratory.[12]

SUMMARY

The design and assembly of simple but effective 7-element Chebyshev lowpass and highpass filters using a piece of PCB as a base was shown to be feasible as long as the cutoff frequency was not much greater than about 5 MHz; consequently, the more complicated assemblies involving closed boxes with partitions between filter sections (for lowpass filters) or microstrip lines (for highpass filters) were concluded to be unnecessary.

Two tables of computer-calculated designs using standard-value capacitors were provided to simplify the design selection. A listing of capacitors and toroidal inductor cores including the names of several parts distributors was also provided to allow those unfamiliar with filter components to quickly and conveniently select and order appropriate capacitors and cores. How to hand wind the toroidal cores and fine tune the inductors was explained so the beginner could obtain a filter having a measured response that closely agreed with its calculated response.

By using the simplified techniques discussed in this article, the inexperienced electronics test technician will be able to quickly and conveniently design, assemble, and tune passive LC filters specifically designed for use in his or her test work, thereby avoiding the two-or three-week delay that is usually experienced when similar filters are ordered from commercial sources.

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APPENDIX A

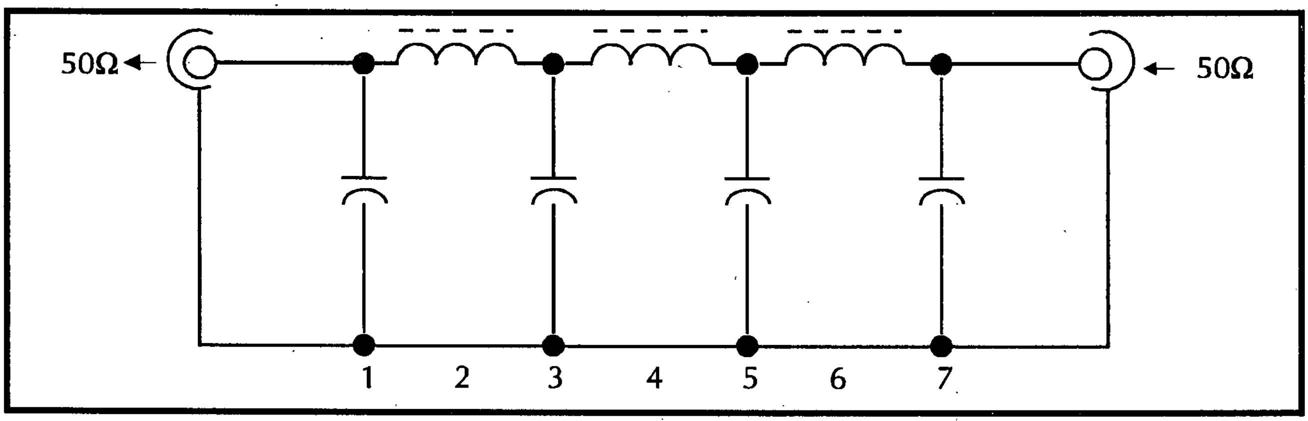

FIGURE A1. *Schematic Diagram of the 7-element Lowpass Filter. Each component is identified by number at the bottom of the diagram. See Table A1 for the capacitor and inductor values.*

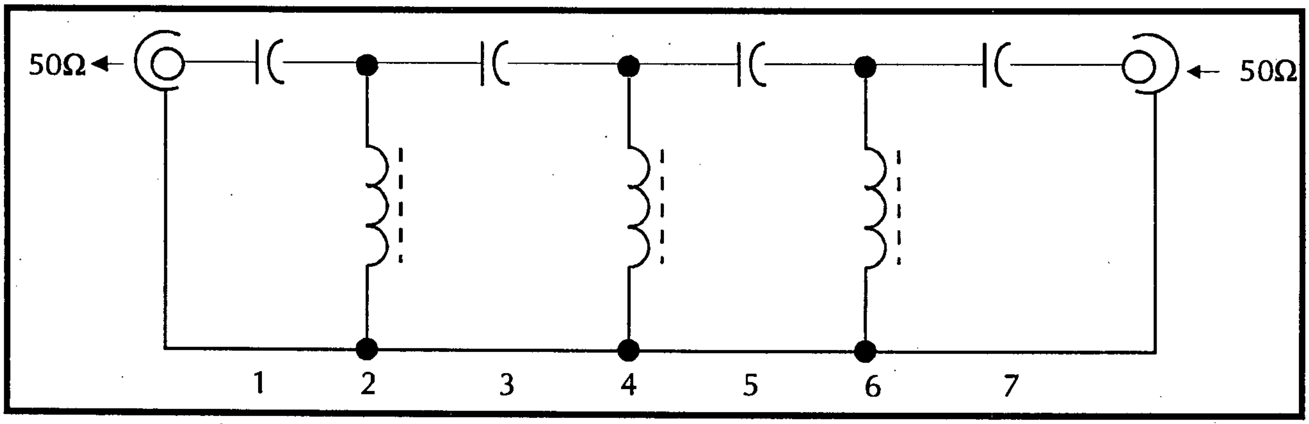

FIGURE A2. *Schematic Diagram of the 7-element Highpass Filter. Each component is identified by number at the bottom of the diagram. See Table A2 for the capacitor and inductor values.*

APPENDIX A:
SEVEN-ELEMENT 50-OHM CHEBYSHEV E12 SVC-FILTER DESIGNS FOR VSWR <1.20.

NO.	--- FREQUENCY (MHz) ---					MAX.	MIN.	C1,7	L2,6	C3,5	L4
	F-co	3-dB	6-dB	20dB	40dB	VSWR	RL(dB)	(pF)	(uH)	(pF)	(uH)
1	1.04	1.16	1.21	1.40	1.79	1.142	23.6	2700	10.9	5600	12.6
2	1.03	1.30	1.36	1.63	2.15	1.030	36.7	1800	9.52	4700	11.9
3	1.21	1.37	1.42	1.66	2.13	1.119	25.0	2200	9.27	4700	10.8
4	1.25	1.57	1.65	1.97	2.59	1.031	36.4	1500	7.90	3900	9.85
5	1.44	1.64	1.71	1.99	2.56	1.109	25.7	1800	7.73	3900	9.04
6	1.68	1.93	2.01	2.35	3.03	1.099	26.5	1500	6.58	3300	7.72
7	1.75	2.25	2.37	2.84	3.75	1.023	39.1	1000	5.45	2700	6.89
8	2.02	2.34	2.44	2.86	3.70	1.086	27.7	1200	5.41	2700	6.40
9	2.16	2.76	2.91	3.49	4.60	1.024	38.6	820	4.44	2200	5.61
10	2.52	2.89	3.01	3.52	4.54	1.099	26.5	1000	4.38	2200	5.15
11	2.67	3.38	3.56	4.26	5.61	1.027	37.6	680	3.64	1800	4.57
12	3.09	3.54	3.69	4.31	5.55	1.100	26.4	820	3.59	1800	4.21
13	3.17	4.05	4.26	5.12	6.75	1.024	38.5	560	3.03	1500	3.82
14	3.69	4.24	4.42	5.17	6.66	1.097	26.7	680	2.99	1500	3.52
15	4.13	5.11	5.36	6.39	8.38	1.035	35.2	470	2.43	1200	3.01
16	4.72	5.35	5.57	6.49	8.34	1.116	25.2	560	2.37	1200	2.76
17	4.93	6.12	6.43	7.67	10.1	1.034	35.5	390	2.03	1000	2.51
18	5.69	6.44	6.70	7.80	10.0	1.122	24.8	470	1.97	1000	2.29
19	6.17	7.52	7.88	9.36	12.2	1.043	33.4	330	1.66	820	2.04
20	7.01	7.89	8.20	9.53	12.2	1.131	24.2	390	1.61	820	1.86
21	7.36	9.04	9.48	11.3	14.8	1.039	34.3	270	1.38	680	1.70
22	8.58	9.59	9.96	11.6	14.8	1.148	23.3	330	1.32	680	1.52
23	8.86	11.0	11.5	13.7	18.0	1.036	35.0	220	1.14	560	1.40
24	10.4	11.6	12.1	14.0	17.9	1.142	23.6	270	1.09	560	1.26

***TABLE A1**. Lowpass E12 SVC-filter Designs.*

NO.	--- FREQUENCY (MHz) ---					MAX.	MIN.	C1,7	L2,6	C3,5	L4
	F-co	3-dB	6-dB	20dB	40dB	VSWR	RL(dB)	(pF)	(uH)	(pF)	(uH)
1	1.00	.880	.845	.724	.563	1.109	25.7	3900	5.67	1800	4.86
2	1.16	.922	.878	.734	.558	1.030	36.7	4700	5.55	1800	4.45
3	1.22	1.06	1.02	.871	.676	1.099	26.5	3300	4.70	1500	4.01
4	1.39	1.11	1.05	.880	.670	1.031	36.4	3900	4.63	1500	3.71
5	1.55	1.34	1.28	1.09	.845	1.086	27.7	2700	3.74	1200	3.16
6	1.82	1.59	1.53	1.31	1.01	1.099	26.5	2200	3.14	1000	2.67
7	2.15	1.67	1.59	1.32	1.00	1.023	39.1	2700	3.10	1000	2.45
8	2.22	1.94	1.86	1.59	1.24	1.100	26.4	1800	2.57	820	2.19
9	2.61	2.03	1.93	1.61	1.22	1.024	38.6	2200	2.54	820	2.01
10	2.69	2.34	2.25	1.92	1.49	1.097	26.7	1500	2.13	680	1.81
11	3.10	2.45	2.33	1.94	1.47	1.027	37.6	1800	2.10	680	1.67
12	3.19	2.82	2.71	2.32	1.81	1.116	25.2	1200	1.77	560	1.52
13	3.81	2.98	2.83	2.36	1.79	1.024	38.5	1500	1.73	560	1.37
14	3.79	3.35	3.22	2.76	2.15	1.122	24.8	1000	1.49	470	1.28
15	4.35	3.52	3.35	2.81	2.14	1.035	35.2	1200	1.45	470	1.17
16	4.52	4.02	3.86	3.32	2.59	1.131	24.2	820	1.24	390	1.07
17	5.27	4.24	4.04	3.39	2.58	1.034	35.5	1000	1.20	390	.969
18	5.26	4.71	4.53	3.91	3.05	1.148	23.3	680	1.06	330	.924
19	6.07	4.98	4.75	4.00	3.06	1.043	33.4	820	1.02	330	.829
20	6.46	5.77	5.55	4.78	3.74	1.142	23.6	560	.867	270	.752
21	7.50	6.11	5.82	4.89	3.74	1.039	34.3	680	.831	270	.675
22	8.11	7.16	6.89	5.91	4.60	1.119	25.0	470	.697	220	.599
23	9.28	7.51	7.16	6.00	4.58	1.036	35.0	560	.677	220	.548
24	10.0	8.80	8.45	7.24	5.63	1.109	25.7	390	.567	180	.486

***TABLE A2**. Highpass E12 SVC-filter Designs.*

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He obtained his amatuer radio license, W3NQN, in 1947 and for the past 10 years has been a technical advisor to the American Radio Relay League. (301)266-1769.