Audio Filters for EN 55020 Testing

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Introduction

The objective of the European Norm (EN) 55020 is to define the immunity test requirements for television broadcast receivers, sound broadcast receivers and associated equipment intended for use in the residential, commercial and light industrial environment.[1] Portions of EN 55020 provide specifications for a 15-kHz lowpass filter and a .5 k – 3 kHz bandpass filter, but the diagrams showing how the filters are integrated within the test systems are incomplete, and an example given in EN 55020 of a bandpass filter is incorrect.

This article will discuss the design, construction and installation of a suitable 15-kHz lowpass filter and a .5 k – 3 kHz bandpass filter that will meet the attenuation specifications as given in Annex B, p. 35 of EN 55020. But before beginning with the discussion concerning design, construction and installation of the filters, several portions of EN 55020 must be clarified so the inexperienced tester is not misled into incorrectly installing the filters.

Filter Impedance

When discussing "impedance" relative to passive filters, the term should be understood to refer to the source and load resistances (always equal unless otherwise stated) as seen by the filter. When the filter is terminated in its design impedances, it will provide the attenuation versus frequency response for which it was designed. The term "characteristic" impedance as used in Para. B1 of EN 55020 with reference to the 15-kHz lowpass filter impedance is incorrectly applied in this case.

The term "characteristic" is associated with the Zobel image parameter filter design procedure (based on transmission line theory) that was widely used prior to 1950.[2, 3] Filters are now designed based on modern network synthesis to obtain special attenuation responses such as the Chebyshev or Cauer (also known as "elliptic"). These modern filters are intended to be terminated in their design (not "characteristic") impedance.

Figure 2 of EN 55020 (audio power-output measurement, p. 9) indicates the FR audio filter is to be inserted between the rated load impedance R_L (typically 8 ohms) of the EUT or amplifier audio output port and an audio-frequency voltmeter of unspecified impedance. Although speaker crossover networks are widely used in high-fidelity sound systems and are designed for an 8-ohm impedance level, the attenuation response of these networks is not selective enough for EN 55020 testing application. The more selective filters required to comply with the EN 55020 specification need a much higher impedance level than 8 ohms so that the filter inductance and capacitance values will be reasonable. This impedance transformation is most easily accomplished with audio-frequency transformers, as will be demonstrated shortly.

The audio output of an amplifier is usually designed to be terminated in a speaker load having an impedance between 4 and 16 ohms. Although the speaker output port is commonly referred to as an "8-ohm port," this should not be confused with the actual source impedance seen looking into the output port. Actually, the "8-ohm" refers to the load for which the amplifier was designed to be terminated, and the actual source impedance is usually less than 8 ohms. This fact must be considered when defining the source impedance to be presented to the filter via a transformer.

Although the attenuation versus frequency specification for the lowpass and bandpass filters are appropriate as given in paragraphs B1 and B2 of EN 55020, the important passband return loss specification is missing. A filter may appear to be quite satisfactory based only on its passband and stopband attenuation responses, but unless the return loss or the standing wave ratio (SWR) response is included, it cannot be confirmed that the filter will perform as expected unless it is specifically designed to do so.[4,5]

Commercial filter manufacturers usually specify a maximum passband SWR of 1.5, which is equivalent to a minimum passband return loss of about 14 dB. However, a return loss of about 20 dB is preferable to minimize reflective losses and to make the filter less sensitive to impedance termination and component tolerance variations. For the purpose of EN 55020 and the filter responses that are required, a maximum passband SWR of about 1.3 or a minimum passband return loss of 17.7 dB appears appropriate without seriously compromising the filter selectivity.

The example of a .5 k – 3 kHz bandpass filter (BPF) referred to in Para. B2, p. 35 and shown in Figure B1, p. 36 of EN 55020 should be ignored. Instead, use the BPF recommended in this article to satisfy EN 55020 test requirements. The previously mentioned aspects of filter design, construction and installation will now be considered in the following paragraphs.

Filter Impedance — What Should it Be?

An acceptable impedance level for audio frequency filtering up to 3 or 4 kHz can range from a minimum of about 50 ohms to a maximum of about 1000 ohms. The impedances of the 15 – kHz lowpass and the .5 k – 3 kHz bandpass filters recommended in this article will be such that the designs can use inexpensive commercial audio transformers. To make it easy to install these two filters in EN 55020 test setups, the filters will be designed so they can use the same impedance matching transformers. The two transformers can be a permanent part of a test jig with the two filters arranged to be plug-in interchangeable between the transformers.

From previous experience in designing speech BPFs,[6] the author has learned that an impedance level of about 200 ohms is suitable for the .5 k – 3 kHz BPF. A satisfactory impedance for the 15-kHz lowpass filter (LPF) will be inversely proportional to the ratio of the bandwidth centers of the LPF and BPF. (The geometric bandwidth centers of the 15-kHz LPF and the .5 k – 3 kHz BPF are equal to the SQR (15) and SQR (.5 • 3) = 3.87 and 1.22, respectively. The inverse ratio of these bandwidth centers is 1.22/3.87 = .315.) Therefore, a suitable impedance for the 15-kHz LPF is 200 • .315 or about 63 ohms.

Any recent Mouser Electronics catalog[7] has a listing of audio transformers that are suitable for use in EN testing. A series of 0.4-watt, 8-ohm transformers are available with high-impedance windings of 48, 120, 200, 500, 800, 1k and 1.2 k ohms. The 8/48-ohm transformer, Mouser Stock No. 42TU048, is closest to the 63-ohm impedance approximated for the LPF, and therefore this transformer will be used. By taking advantage of an input/output connection option available with the BPF, the 8/48-ohm transformer can also be used for the BPF if the design impedance of the BPF is made equal to 4 • 48 = 192 ohms. For these reasons the lowpass and bandpass filters will be designed for 48 and 192 ohms.

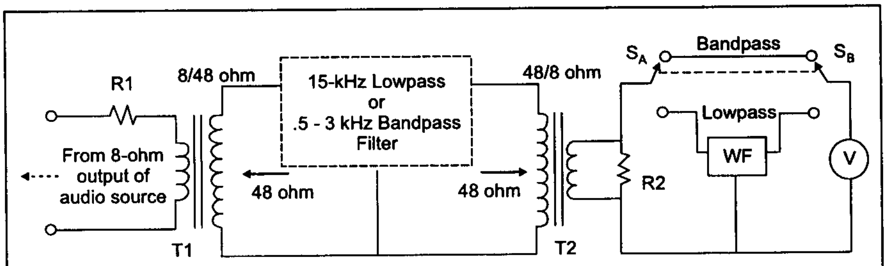
Figure 1 shows the proposed 8/48-ohm impedance matching circuit for both the 15-kHz LPF and the .5k – 3 kHz BPF. The matching circuit is identical for both filters with the only difference being that the LPF uses a weighting filter (WF) in front of the voltmeter while the bandpass filter does not. EN 55020 provides no description of the WF circuit and the reader must refer to CCIR Recommendation 468 for details. Switch S in Figure 1 inserts or removes the WF from across the voltmeter.

The value of R1 is selected so the impedance looking into the high-impedance winding of T1 is within 5% of 48 ohms. This can be confirmed by applying a 1-kHz signal to the EUT/amplifier so a voltage of about 4 volts appears across the open-circuited 48-ohm winding of T1. Select an R1 value so the T1 voltage drops by 6 dB (to half of its open-circuited voltage) when a 48-ohm resistor is connected across the high-impedance winding. After the 48-ohm resistor is removed, the transformer will provide the proper input impedance termination for the filter. The filter output is terminated by the 48 ohms reflected through T2 from R2.

15-kHz Lowpass Filter

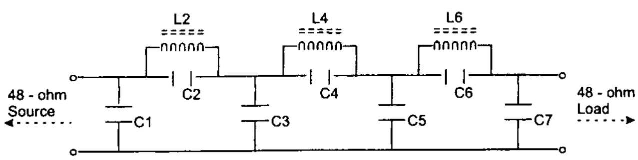
Figure 2 shows the schematic diagram and component values of the 15-kHz LPF that is recommended for use with EN 55020. This design is calculated for an impedance of 48 ohms and is referred to as a 7th-order Cauer lowpass filter with a reflection coefficient of 9.77%, a ripple-cutoff frequency of 15.032 kHz, and a 51.25-dB stopband frequency of 18.73 kHz. This particular design is unique in that L4 and L6 have the same value to simplify realization of the filter.[8, 9] Design details are in Appendix A.

EN 55020 specifies this filter to have not more than a 3-dB loss at 15 kHz and not less than a 50-dB loss at 19 kHz (see Para. B1, p.35 of EN 55020); however, there is no loss specification



Notes:
1. R1 = 1/4-watt resistor, 1-to-5 ohms. See text for value.
2. T1,T2 = Audio transformers, Part #42TU048, 8/48-ohms center-tapped, EI-24 core, 400-mW maximum output.
3. R2 = 1-watt, 5%, 8-ohm resistor to serve as the rated load impedance of the EUT audio output.
4. WF = Weighting filter according to CIR Recommendation 468 as specified in Para. 7.2, p. 8 of EN 55020 for the 15-kHz lowpass filter. When the .5k - 3kHz bandpass filter is used, the WF is omitted.
5. S_{AB} = DPDT switch for WF insertion or removal.
6. V = Audio frequency voltmeter.

Figure 1. *Proposed 8/48-ohm Impedance Matching Circuit for the Lowpass and Bandpass Filters Used in EN 55020 Testing.*



LOWPASS FILTER SPECIFICATIONS AND COMPONENT VALUES

Description: 7th-order Cauer lowpass filter

Ripple cutoff frequency, FA_p = 15.032 kHz
Stopband frequency, FA_s = 18.73 kHz
Minimum stopband attenuation, A_s = 51.25 dB
Minimum passband return loss = 20.2 dB
Reflection coefficient = 9.77%
Source and load impedance = 48 ohms

C1 = 196 nF		
C2 = 30.7 nF	L2 = 649 uH	F2 = 35.7 kHz
C3 = 312 nF		
C4 = 151 nF	L4 = 464 uH	F4 = 19.0 kHz
C5 = 276 nF		
C6 = 113 nF	L6 = 464 uH	F6 = 22.0 kHz
C7 = 138 nF		

Notes:
1. All capacitors are Mylar and rated at 100 or 200 VDC.
2. The odd-numbered and even-numbered capacitors are selected to be within 5% and 2%, respectively, of their design values.
3. All inductors are hand-wound on moly-perm cores, Magnetics MPP Part No. 55206, u=125, or equivalent; OD=.80", ID=.50", HT=.25".
4. L2 is wound with approx. 102 turns from a 92" length of #24 film-insulated wire. The inductor Q is 40 at 15 kHz.
5. L4 and L6 are each wound with approx. 86 turns from 78" lengths of #24 wire. The inductor Q is 28 at 15 kHz.
6. The number of turns on each inductor is adjusted until the inductor resonates with its capacitor at the specified frequency.

Figure 2. *Schematic Diagram and Component Values of the Recommended 15-kHz Lowpass Filter Required for Use in EN 55020 Testing.*

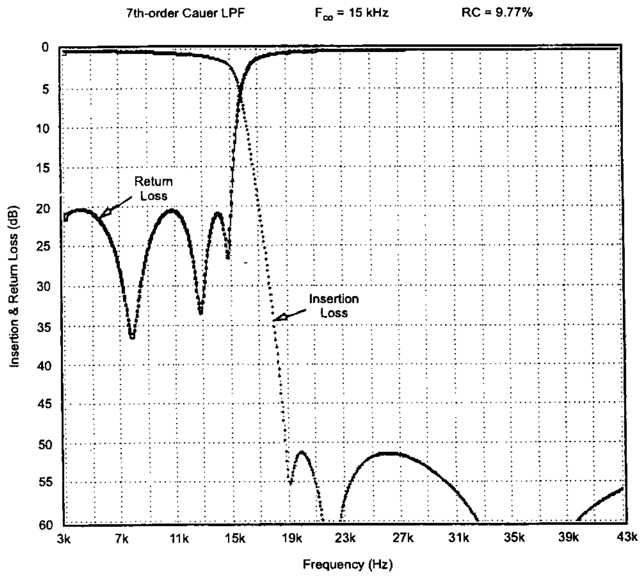


Figure 3. *The Two Plots Depict the Computer-calculated Responses of the 48-ohm, 15-kHz Lowpass Filter. When the assembled lowpass filter shown in Figure 4 was tested in a 48-ohm system, the measured responses were essentially identical with the computer-calculated responses shown above.*

above 19 kHz. When the author designed this filter for this article it was assumed that the intent of the specification was to have the 50-dB stopband continue well above 19 kHz, and this is what the stopband was designed to do. The 50-dB loss requirement at 19 kHz probably is related to the need to suppress a 19-kHz pilot tone referred to in Para. 14.1.2, p. 21 of EN 55020. To provide maximum attenuation at 19 kHz, the cutoff frequency was chosen so L4 and C4 of the filter are parallel resonant at 19 kHz for maximum attenuation.

The EN also specifies the passband attenuation up to 10 kHz to be not more than 0.5 dB. To achieve this relatively low level of attenuation, it is necessary that high-Q inductors be used for L2, L4 and L6. For those interested in winding their own inductors, the author can provide molybdenum-permalloy powder (MPP) toroidal cores suitable for hand-winding to obtain the inductance values required by the lowpass filter design. See the notes in Figure 2 for details.

The lowpass filter was assembled in accordance with the design details given in Figure 2 and both the measured attenuation and return loss responses were virtually identical with the ELSIE computer-calculated response plots shown in Figure 3.[10] Note that all EN 55020 attenuation requirements for the 15-kHz LPF are satisfied with the proposed design in Figure 2.

Figure 4 is a photograph of the filter assembled on a breadboard so its performance could be measured in a 48-

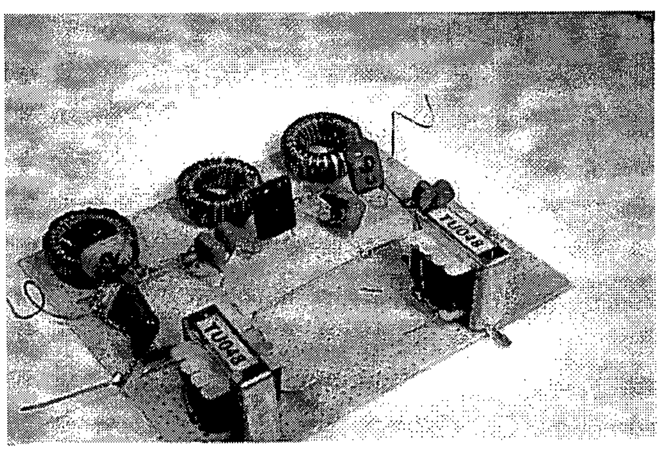


Figure 4. *Photograph of the 15-kHz Lowpass Filter with its Components Mounted on a Piece of Perf-board. The 8/48-ohm transformers were not used during the filter insertion loss measurement and are included in the photo only for reference.*

ohm system. The filter itself has a maximum passband loss of 0.3 dB up to 10 kHz and 1.7 dB loss at 15 kHz. The 8/48-ohm transformers are shown in the photo for reference but they were not included when the filter loss was measured. When the two transformers are included, they will contribute another 2.5 dB of loss.

.5 k – 3 kHz Bandpass Filter

Figure 5 shows the schematic diagram and component values of the bandpass filter that is recommended for use with EN 55020. This design is referred to as a 3rd-order Chebyshev bandpass filter with a reflection coefficient of 10%, a 3-dB bandwidth of 3.3 kHz and a center frequency of 1.20 kHz. The design is calculated for an impedance of 192 ohms, but by using the center taps of L1 and L3, the filter may be terminated in 48 ohms for use in the impedance matching circuit shown in Figure 1.

The design procedure and reason for selecting this particular 3rd-order Chebyshev bandpass design are explained in Appendix B. Appendix B also provides sufficient information so the reader may confirm the correctness of the proposed design and also calculate other more or less selective bandpass designs if desired.

Figure 6 shows the ELSIE computer-calculated attenuation and return loss plots of the BPF that will result when the filter is tested in a 192-ohm system. The bandpass filter was assembled in accordance with the design details given in Figure 5 and both the measured attenuation and return loss responses were found to be virtually identical with the ELSIE computer-calculated plots shown in Figure 6. Note that all the attenuation requirements of EN 55020 for the BPF are satisfied with the proposed design in Figure 5.

Figure 7 shows the BPF assembled on a breadboard so its performance could be measured in a 48-ohm system using the center taps of L1 and L3 for the filter input/output connections. The filter by itself had a passband loss of not more than 0.5 dB between 1 and 2 kHz and less than 3-dB loss at .5 kHz and 3 kHz as required by the EN 55020 specification.

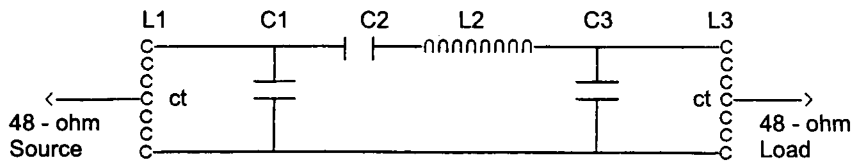
The satisfactory performance of this BPF is primarily due to using high-Q toroidal inductors that were obtained as scrap material by the author many years ago from the C&P Telephone Co. of Maryland. The author will be happy to provide inductors to those explaining their application and including $5 to cover costs of packing and shipping. The inductors are easily modified from their original 88/22-mH value to the values given in Figure 5 by removing turn-pairs until the design values are reached. Because the inductors are bifilar wound, the windings can be connected either in series or parallel, aiding to obtain inductances ranging from 88 to 50 mH in the series connection or from 22 to 13 mH in the parallel connection while keeping the inductor Q to slightly less than its original value of 50 at 1 kHz.[11]

All engineers and technicians having a genuine test application for these high-quality toroidal inductors are encouraged to take advantage of this offer. It is the author's intent to demonstrate that the average technician or engineer is capable of designing and constructing their own passive LC filters that are similar to the lowpass and bandpass filters used in EN 55020. If any readers know of other simple passive LC filter requirements for which a design is needed, please consult the author to obtain an appropriate design. Please include a stamped, self-addressed envelope for a reply.

Summary

Portions of the European Standard 55020

Continued on page 262



BANDPASS FILTER SPECIFICATIONS AND COMPONENT VALUES

Description: 3rd-order Chebyshev bandpass filter

Minimum passband return loss = 20.0 dB
Reflection coefficient = 10.0%
Source and load impedance = 192 ohms

Component Values

C1,3 = .33uF/100VDC ±2% Mylar
C2 = 1.12 uF/100VDC ±2% Mylar
L1,3 = 53.3 mH, center-tapped
L2 = 15.7 mH

Design Frequencies

F_C	=	1.20 kHz
B3	=	3.30 kHz
$F3_{LO}$	=	390 Hz
$F3_{HI}$	=	3.690 kHz
B30	=	9.306 kHz
$F30_{LO}$	=	152 Hz
$F30_{HI}$	=	9.458 kHz
B30/B3	=	2.82

Notes:

1. All inductors are surplus 88/22-mH bifilar-wound on moly-perm cores and are modified by removing turns until each inductor resonates with its capacitor at the bandpass filter center frequency of 1.20 kHz.
2. Inductor Q is greater than 50 at 1.2 kHz.
3. L1 and L3 are center-tapped so the bandpass filter can be terminated with source and load impedances of 48 ohms.

***Figure 5.** Schematic Diagram and Component Values of the Recommended .5 k – 3 kHz Bandpass Filter Required for Use in EN 55020 Testing.*

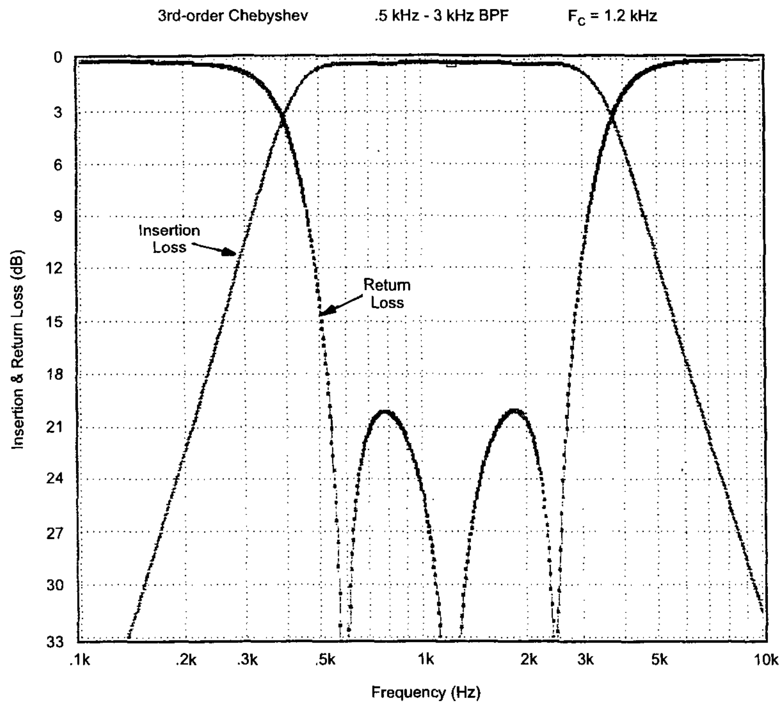


Figure 6. *The Two Plots Depict the Computer-calculated Responses of the 48-ohm, .5 k – 3 kHz Bandpass Filter. When the assembled bandpass filter shown in Figure 7 was tested in a 48-ohm system the measured responses were essentially identical with the computer-calculated responses shown above.*

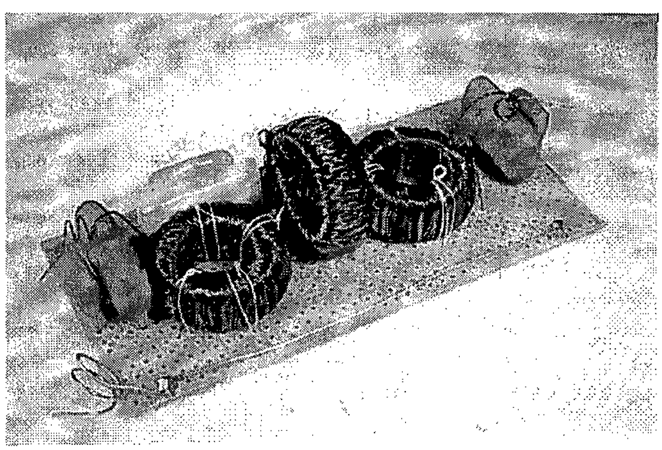


Figure 7. *Photograph of the .5 k – 3 kHz Bandpass Filter with its Components Mounted on a 1.8 x 4-inch Piece of Perf-board. The center-taps of the two horizontally-mounted toroidal inductors (L1 and L3 in Figure 5) serve as the filter input/ output leads.*

relating to audio filters and how they should be integrated into the test systems were discussed. Some parts of the Standard regarding a 15-kHz lowpass filter and a .5k – 3 kHz bandpass filter required for some of the tests were concluded to be misleading or incomplete. Because the Standard provided no suggestion of how the 15-kHz lowpass filter requirement might be met, an appropriate lowpass filter was designed, and details were discussed of its design, construction and integration into the test system.

To replace the inappropriate example of a bandpass filter given in the Standard, a simpler .5 k – 3 kHz bandpass filter was also designed with details of the design procedure included so other filters having different selectivity requirements could be calculated. The termination impedances of the bandpass and lowpass filters were made to be identical so both filters could be integrated into the test systems using the same pair of audio transformers.

To facilitate the construction of these two filters, the author offered to provide the high-Q toroidal inductors required for constructing the bandpass filter and the toroidal cores required for constructing the lowpass filter with the intent of demonstrating that it is possible for the average test engineer or technician to design and assemble passive LC filters similar to those required in the European Standard 55020.

References

1. BS EN 55020: 1995; Electromagnetic Immunity of Broadcast Receivers and Associated Equipment; Prepared by Subcommittee GEL/210/5, it is the English version of EN 55020: 1994. The portions applicable to passive LC filters are: Paragraph 7.2 and Figure 2, Audio Power-output Measurement, pp. 8, 9; Annex B and Figure B1, pp. 35, 36.
2. H.H. Skilling, Electric Transmission Lines, (New York, McGraw-Hill Book Co., 1951), p. 229n.
3. E. Wetherhold, "Practical LC Filter Design, Part 1," *Practical Wireless*, Vol. 60, No. 7, Issue 928, July 1984.
4. E. Wetherhold, "Design and Construction of a 9-kHz Highpass Filter and Assembly of a Return Loss Bridge for Filter and PLISN Testing," *ITEM 1993*, p. 220.
5. E. Wetherhold, "Construction of a Low-frequency RLB with a Changeable Impedance Level," *ITEM Update 1993*, p. 58.
6. E. Wetherhold, "CW and SSB Audio Filters Using 88-mH Inductors," *QEX* 82, published by the ARRL, December 1988.
7. Mouser Electronics, Inc., Santee, CA, Purchasing Manual #592. Telephone Mouser at (800) 346-6873 to request a catalog.
8. E. Wetherhold, "Simplified Elliptic Filter Construction Using Surplus 88-mH Inductors," *Radio Communication*, Vol. 59, No. 4, published by the Radio Society of Great Britain, April 1983.
9. E. Wetherhold, "Elliptic Lowpass Audio Filter Design," *Ham Radio*, February 1984 p. 20.
10. ELSIE Filter Design and Analysis Program from Trinity Software, 7801 Rice Dr, Rowlett, TX 75088. Tel: (972) 475-7132.
11. E. Wetherhold, "Inductance and Q of Modified Surplus Toroidal Inductors," *QST*, September 1968.

Appendix A

Schematic diagram and attenuation response with normalized component values and other parameters used to calculate the 15-kHz lowpass filter

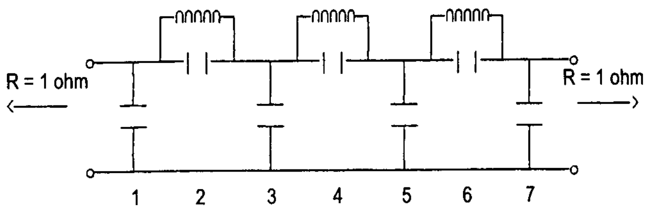


Figure A1. *Schematic Diagram of 7th-order Cauer Lowpass Filter. All components are numbered left to right and are listed in Table A1 with their normalized values.*

ORDER NUMBER AND TYPE = 7TH, CAUER NORMALIZED C AND L VALUES

Reflection Coefficient	= 9.77 %	C1	=	.1416 F
Minimum Return Loss	= 20.2 dB	C2	=	.02214 F
Max. Ripple Amplitude, A_p	= .04164 dB	L2	=	.2033 H
Normalized Cutoff Freq, FA_p	= 1.000 Hz	C3	=	.2252 F
Normalized Stopband Freq, FA_s	= 1.2458 Hz	C4	=	.1091 F
Min. Stopband Atten., A_s	= 51.25 dB	L4 & L6	=	.1452 H
F2	= 2.372 Hz	C5	=	.1993 F
F4	= 1.264 Hz	C6	=	.08165 F
F6	= 1.462 Hz	C7	=	.09931 F
L2/L4 Ratio	= 1.400			

Notes:
Calculate the filter component values, C' and L', by multiplying the normalized C and L values by the C_s and L_s scaling factors where R and FA_p are in ohms and Hz. R = 48 ohms and FA_p = 15.032 kHz.

Cs = 1/(R • FAp) = 1/(48 • 15.032k) = 1.386E-6
Ls = R/FAp = 48/15.032k = 3.193E-3
C'1 = .1416F(1.386E-6) = 196 nF. Calculate C'2-7 in a similar manner.
L'2 = .2033H(3.193E-3) = 649 uH. Calculate L'4,6 in a similar manner.
F'4 = 1.264Hz(15.032E+3) = 19.00 kHz. Calculate the other Fs in a similar manner.

Table A1. *7th-order Cauer Lowpass Filter Component Values and Frequencies Normalized for an FAp Cutoff Frequency of 1 Hz and 1-ohm Terminations.*

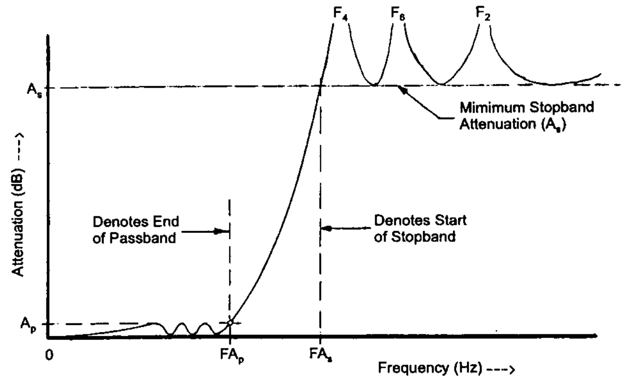


Figure A2. *Typical Attenuation Response of 7th-order Cauer Lowpass Filter.*

Appendix B

Lowpass Prototype Design and Lowpass-to-Bandpass Transformation Procedures

A 3-element (3rd-order) Chebyshev lowpass filter (LPF) is first designed as a prototype based on the given bandpass requirements. The LPF prototype is then transformed into the desired bandpass filter (BPF). Refer to Figures B1 and B2 for the LPF schematic diagram and its attenuation response curves. Use the following steps for calculating your EN Standard BPF:

(1) Determine the required 3-dB bandwidth (B3) of the BPF from the specification given in Para. B2, p. 35 of the EN Standard. According to this specification, the attenuation at .5 k and 3 kHz must be equal to or less than 3 dB. Therefore, the minimum B3 is 3k – .5k = 2.5 kHz; however, to provide a safety margin the B3 will be increased to 3.3 kHz. There is some freedom of choice in selecting B3, and if the first choice results in an inconvenient capacitance value for C1,3, another choice can be made that will give a more convenient value. As it turns out, the choice of 3.3 kHz for B3 will be shown to be satisfactory as it results in a standard-capacitor value for C1,3.

(2) Choose a center frequency, F_C, for the BPF. The F_C is calculated from the 3-dB upper and lower frequencies of the BPF specification using the equation:

$$F_C = \sqrt{(F3_{UP} \bullet F3_{LO})} = \sqrt{(3 \bullet .5)} = \sqrt{(1.5)} = 1.225 \text{ kHz};$$

however, an Fc of 1.20 kHz will be used instead. As with the 3-dB bandwidth selection, there is some freedom of choice with the F_C selection and another value may be used if desired. Later calculations will show if the choices of B3 and F_C are acceptable.

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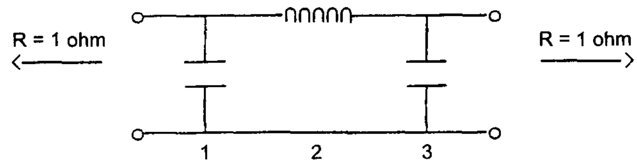

Figure B1. *Schematic Diagram of 3rd-order Chebyshev Lowpass Filter. The component values are numbered 1 to 3 from left to right. The C1 and C3 values are identical. See Table B1 for the normalized values for eight Chebyshev designs.*

(3) With B3 = 3.3 kHz and F_C = 1.20 kHz, calculate the expected lower and upper 3-dB frequencies of the BPF to confirm that the 3-dB specification will be satisfied. Use the equation:

$$F3_{LO} = -X + \sqrt{(F_C^2 + X^2)}$$

where

$$X = B3/2 = 3.3\ \text{kHz}/2 = 1.65\ \text{kHz};$$

$$F3_{LO} = -1.65 + \sqrt{(1.2^2 + 1.65^2)} = -1.65 + \sqrt{(4.1625)}$$
$$= -1.65 + 2.040 = 0.390\ \text{kHz}$$

$$F3_{UP} = F3_{LO} + B3 = .390 + 3.3 = 3.690\ \text{kHz}.$$

The chosen B3 and F_C frequencies are confirmed as being acceptable because the calculated lower and upper 3-dB frequencies are below and above the 3-dB frequencies specified in the EN Standard. Because of inductor losses, the actual lower 3-dB cutoff frequency of the assembled BPF may be 30 or 40 Hz higher than 390 Hz, and the upper 3-dB cutoff frequency may be slightly less than 3690 Hz, but in spite of this, the EN Standard BPF specification will still be satisfied.

Selection of a Lowpass Prototype Suitable for Transformation

The parameters of eight lowpass filters are listed in Table B1. One of these filters will be chosen as the lowpass prototype for transformation into a BPF that will satisfy the EN Standard attenuation specification. The LPF prototype schematic diagram and response curves are shown in Figures B1 and B2. The 3-dB bandwidth, B3, of the BPF is used as the bandwidth of the LPF prototype. The "B3" designation in Figure B2 indicates the LPF 3-dB cutoff frequency. Note that the bandwidth at any attenuation level in the LPF is identical to the bandwidth at the same attenuation level in the BPF after transformation. This means the specified 30-dB bandwidth of the BPF can be used to select a LPF having the same 30-dB bandwidth so when the selected LPF is transformed into a BPF, the required 30-dB bandwidth will result.

The "B30" line in Figure B2 indicates the 30-dB attenuation level and shows that each of the eight lowpass filters

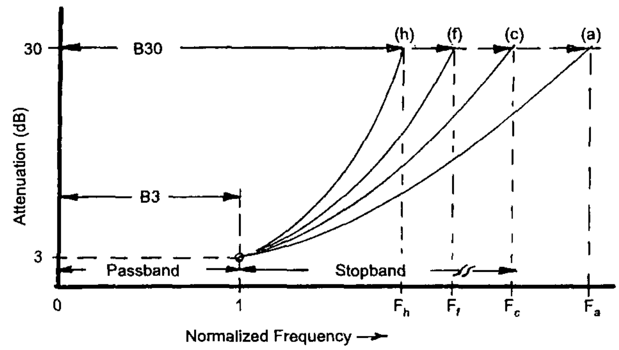

Figure B2. *Attenuation Responses of 3rd-order Chebyshev Lowpass Filters. See the B30 (Hz) column in Table B1 for the 30-dB bandwidths.*

reaches the 30-dB level at different frequencies. The most selective LPF has a reflection coefficient (R.C.) of 15.087% and it has the lowest 30-dB frequency (F_h) of all the LPFs. The least selective LPF with R.C. = 1.00% has the highest 30-dB frequency (F_a).

In order to meet the EN Standard attenuation specification of 30 dB or more at .1 kHz and 25 dB or more at 10 kHz, one of the LPF designs must be chosen that has an attenuation response of sufficient selectivity so it will satisfy the EN Standard specification after the LPF prototype is transformed into a bandpass filter. The normalized 30-dB frequencies listed in column B30 will be used to select a lowpass prototype that will satisfy the 30-dB attenuation requirement. Although the EN Standard gives two different attenuation levels of 30 and 25 dB at .1 kHz and 10 kHz, respectively, the 30-dB level will be used for both frequencies to simplify the calculations. If the 30-dB requirement is satisfied at 10 kHz, the 25-dB requirement is also satisfied.

The maximum permissible 30-dB bandwidth is 10 k - .1

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R.C. (%)	Min. Ret. Loss (dB)	C1, 3 (F)	L 2 (H)	B 30 (Hz)	Curve Reference
1.000	40.00	.1688	.3088	3.08	(a)
1.517	36.38	.1720	.3056	3.06	(b)
2.600	31.70	.1778	.2998	3.01	(c)
4.796	26.38	.1880	.2899	2.94	(d)
7.145	22.92	.1978	.2806	2.88	(e)
10.000	20.00	.2090	.2703	2.82	(f)
12.589	18.00	.2188	.2616	2.77	(g)
15.087	16.43	.2280	.2537	2.73	(h)

Table B1. *Third-order Chebyshev Lowpass Filter Component Values Normalized for a 3-dB Cutoff Frequency of 1 Hz and 1-ohm Terminations.*

k = 9.9 kHz. To provide a safety margin, the 30-db BW will be reduced to 9.4 kHz. The reduced 30-dB BW is then normalized relative to the previously selected 3-dB BW by dividing 9.4 kHz by 3.3 kHz = 2.85. Using this normalized 30-dB BW of the desired BPF as a reference, we examine the B30 column of Table B1 and select a LPF prototype that has its 30-dB BW closest to the desired BW. LPF designs (e) and (f) straddle the desired B30 value of 2.85, and (f) is selected because of its better selectivity. The LPF prototype has a reflection coefficient of 10% and a minimum passband return loss of 20 dB.

Using the normalized B30 value (2.82) of the chosen prototype LPF, the 30-dB bandwidth in hertz is calculated by multiplying 2.82 by the 3-dB bandwidth: 2.82 X 3.3 = 9.306 kHz. The lower and upper frequencies at the 30-dB level are calculated using the same procedure used to calculate the lower and upper frequencies at the 3-dB level. The frequencies are: $F30_{LO}$ = .152 kHz and $F30_{HI}$ = 9.458 kHz. Because the $F30_{LO}$ is higher than .1 kHz and the $F30_{HI}$ is lower than 10 kHz, the EN Standard 30-dB specification is satisfied.

We are now ready to scale the normalized capacitor and inductor values (C1,3 and L2 in Table B1) to get the actual component values of the LPF prototype. The previously selected impedance level, R, of 192 ohms (see main text of this article) and the B3 cutoff frequency of 3.3 kHz are used to calculate the capacitance and inductance scaling factors. With R and B3 in ohms and Hz, respectively, the capacitance scaling factor, C_S, is equal to 1/(R • B3): C_S = 1/(192 • 3.3E+3) = 1.5783E-6. The C'1,3 capacitance value is calculated by multiplying the normalized C1,3 value of .2090F by C_S: C'1,3 = .2090F • 1.5783E-6 = .330 μF. This convenient standard value of capacitance is partly due to choosing a 3-dB bandwidth of 3.30 kHz.

The inductance scaling factor, L_S, is equal to R/B3 = 192/ 3.3k = 58.18E-3. The L'2 inductance is calculated by multiplying its normalized L2 value of .2703 by L_S: L'2 = .2703H • 58.18E-3 = 15.73 mH. The inductance need not be a standard value because it will either be hand-wound to the exact design value, or a previously wound inductor will be modified to the design value by removing turns. The two capacitors and one inductor are connected as shown in Figure B1. This completes the design of the 3rd-order Chebyshev lowpass prototype filter.

Lowpass-to-bandpass Transformation Procedure

The capacitors and inductor of the lowpass prototype in Figure B1 are resonated to the previously selected BPF center frequency of 1.20 kHz by connecting an inductance in parallel with C1 and C3 and a capacitance in series with L2. The values of L1,3 and C2 are calculated using the following equations where F_c, C and L are in kHz, uF and mH, respectively:

$$L1,3 = 25.33/(F^2 \bullet C1) = 25.33/(1.2^2 \bullet .33) = 53.3 \text{ mH};$$

$$C2 = 25.33/(F^2 \bullet L2) = 25.33/(1.2^2 \bullet 15.73) = 1.12\ \mu F.$$

The completed BPF with all design parameters is shown in Figure 5 and the computer-calculated responses of attenuation and return loss are shown in Figure 6. The manually-calculated bandpass attenuation response using the listed normalized data in Table B1 is shown in Figure B3. The manually-calculated attenuation response will be slightly different when compared with the measured response because the effects of inductor Q are not accounted for in the manual calculation procedure; however, if inductors having Qs of 50 or more are used in constructing the bandpass filter, the manually-calculated and the computer-calculated responses should both agree very closely with the measured attenuation response of the assembled filter.

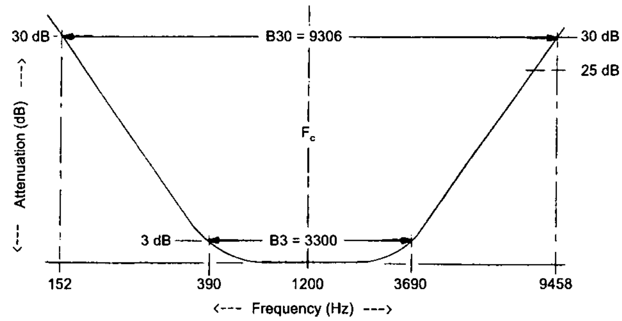

Figure B3. *The Curve Shows the Expected Attenuation Response of the Bandpass Filter after the Completion of the Lowpass-to-bandpass Transformation.*

Relationships

Equations showing the relationship between Return Loss, Reflection Coefficient, SWR and Passband Ripple Amplitude (Ap) are given:

$$\text{Return Loss (dB)} = -20 \bullet \log_{10}(\text{R.C.\%}/100)$$

$$\text{R.C.\%} = 100 \bullet 10^{-RL/20} \text{ where RL = Return Loss (dB)}$$

$$\text{SWR} = (1+p)/(1-p) \text{ where } p = \text{R.C. \%}/100$$

$$\text{Ap (dB)} = -10 \bullet \log_{10}(1-p^2)$$

For example, if R.C. = 10%, p = .10, Return Loss = 20 dB, SWR = 1.222 and Ap = .04365 dB.

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