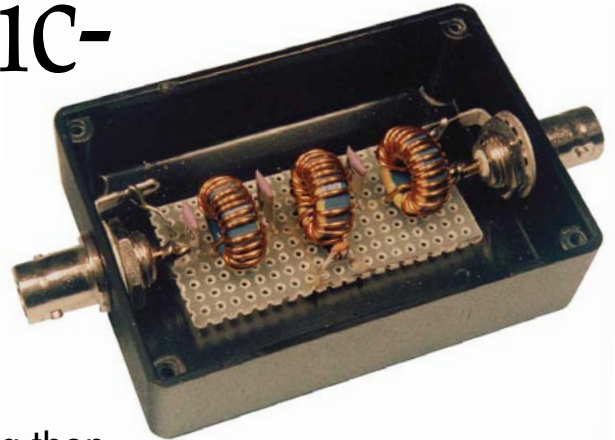By Ed Wetherhold, W3NQN

Second-Harmonic-Optimized Low-Pass Filters

Sometimes we need a little more output filtering than traditional designs offer. Look at a new filter that can give you that extra boost.

Introduction

The FCC requires transmitter spurious outputs below 30 MHz to be attenuated by 40 dB or more for power levels between 5 and 500 W (Ref 1). Radio amateurs usually attempt to satisfy this requirement by placing a seven-element standard-value capacitor (SVC) low-pass filter (LPF) after the final amplifier. This procedure was demonstrated by Dave Benson, NN1G, in his *QST* article discussing a 3-W PEP QRP SSB transceiver for 20 or 75 meters (see Ref 2). The seven-element Chebyshev LPF is adequate for Benson's application because spurious signals must be attenuated by only 30 dB at power levels less than 5 W.

For power levels greater than 5 W, the typical second-harmonic attenuation (40-dB) of a seven-element Chebyshev LPF is marginal. An additional 10 dB of attenuation is needed to assure compliance with the FCC requirement (Ref 3).

If the standard seven-element Chebyshev SVC LPF could be slightly modified to obtain an additional 10 dB of stop-band loss at the second-harmonic frequency without significantly decreasing its passband return loss (RL), the problem would be solved. The minimum passband RL of Benson's 20-meter LPF is about 21 dB, and this minimum RL level is suitable to use as a guide for an acceptable return loss after the filter design modifications have been completed.

We can easily increase the 20-meter SVC LPF second-harmonic attenuation at 28 MHz by adding a capacitor across the center inductor to form a resonant circuit. If this is done, however, the 20-meter passband RL decreases to an unacceptable level, less than 12.5 dB. We need a way to add the resonant circuit, while maintaining an acceptable RL level over the 20-meter passband.

The typical LPF used by Benson (and the Chebyshev SVC designs listed in *The*

Above: A QRP 20-meter CWAZ low-pass filter installed on a piece of perf board in a small (1×2⁷⁄₈×2-inch, HWD) plastic box available from Farnell (Ref 4), order #645-680, $1.56 each. The toroidal cores are Micrometals (Ref 5) T50-17. The capacitors shown are Philips 683 series, low-k, 100 V dc, with a 2% tolerance. Some of those shown have a 0.2-inch lead spacing, which is no longer available from Farnell. For new construction, use Philips 680, low-K series having 0.1-inch lead spacing. The Philips 680 series is good for all QRP filtering because of its 2% tolerance.

ARRL Handbook) all have maximum SWR (equivalent to a minimum RL level) specifications that extend from the filter ripple-cutoff frequency down to dc. For the usual Amateur Radio application, however, we need an acceptable minimum RL only over the amateur band for which the LPF is designed. If the passband RL below the amateur band (where it is not needed) could be exchanged to improve the RL only in the passband—while simultaneously increasing

the stop-band loss at the second-harmonic frequency—it would be practical to resonate the center inductor at the second harmonic. Our problem would be solved.

This problem of significantly increasing the second-harmonic attenuation of the seven-element Chebyshev LPF while maintaining an acceptable RL over the amateur passband has been solved by Jim Tonne, WB6BLD. With Jim's approval and encouragement, I am using this article
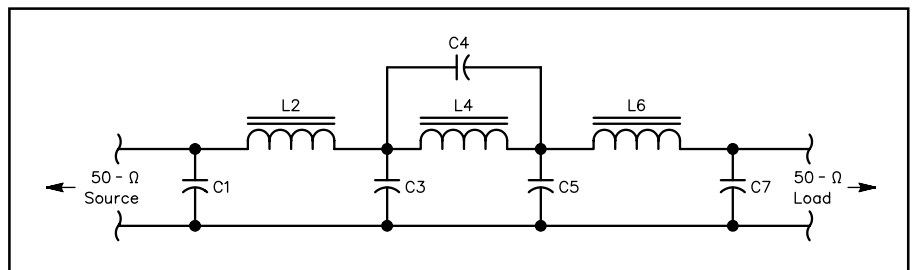

Figure 1—Schematic diagram of a CWAZ low-pass filter designed for maximum second-harmonic attenuation. See Table 1 for component values of CWAZ 50-Ω designs. L4 and C4 are tuned to resonate at the F4 frequency given in Table 1. For an output power of 10 W into a 50-Ω load, the RMS output voltage is $\sqrt{10 \times 50} = 22.4$ V. Consequently, a 100 V dc capacitor derated to 60 V (for RF filtering) is adequate for use in these LPFs if the load SWR is less than 2.5:1. For QRP filtering, use Philips 680 low K (high Q), 100 V dc ceramic capacitors, mainly for their close tolerance (2%). This capacitor is available from Farnell/Newark in values up to 330 pF and is listed on page 62 of the March/September 1998 Farnell catalog (Ref 4). For QRP filtering, the Micrometals T37, T44 or T50 cores of materials –2 (red), –6 (yellow) or –17 (blue/yellow) are suitable (Ref 5). These cores are available in small quantities from Amidon (Ref 6).

Table 1
CWAZ 50-Ω Low-Pass Filters

Designed for second-harmonic attenuation in amateur bands below 30 MHz.

Band (m)	Start Frequency (MHz)	C1,7 (pF)	C3,5 (pF)	C4 (pF)	L2,6 (µH)	L4 (µH)	F4 (MHz)
—	1.00	2986	4556	680.1	9.377	8.516	2.091
160	1.80	1659	2531	378	5.21	4.73	3.76
		1450 + 220	2100 + 470				
		1500 + 150	2200 + 330	330 + 47			3.78
80	3.50	853	1302	194	2.68	2.43	7.32
			1150 + 150				
		470 + 390	1200 + 100	150 + 47			7.27
40	7.00	427	651	97.2	1.34	1.22	14.6
		330 + 100	330 + 330	100			14.4
30	10.1	296	451	67.3	0.928	0.843	21.1
		150 + 150	470	68			21.0
20	14.0	213	325	48.6	0.670	0.608	29.3
		220	330	47			29.8
17	18.068	165	252	37.6	0.519	0.471	37.8
		82 + 82	100 + 150	39			37.1
15	21.0	142	217	32.4	0.447	0.406	43.9
		150	220	33			43.5
12	24.89	120	183	27.3	0.377	0.342	52.0
		120	180	27			52.4
10	28.0	107	163	24.3	0.335	0.304	58.5
		100	82 + 82	27			55.6

NOTE:

The CWAZ low-pass filters are designed for a single amateur band to provide more than 50 dB attenuation to the second harmonic of the fundamental frequency and to the higher harmonics. All component values for any particular band are calculated by dividing the 1-MHz values in the first row (included for reference only) by the start frequency of the selected band. The upper capacitor values in each row show the calculated design values obtained by dividing the 1-MHz capacitor values by the amateur-band start frequency in megahertz. The lower standard-capacitor values are suggested as a convenient way to realize the design values. The middle capacitor values in the 160- and 80-meter-band designs are suggested values when the high-value capacitors (greater than 1000 pF) are on the low side of their tolerance range. The design F4 frequency (see upper value in the F4 column) is calculated by multiplying the 1-MHz F4 value by the start frequency of the band. The lower number in the F4 column is the F4 frequency based on the suggested lower capacitor value and the listed L4 value.

ply divide the first-row C and L values (for 1 MHz) by the start frequency of the desired band. For example, C1, 7 for the 160-meter design is equal to 2986/1.80 = 1659 pF. The other component values for the 160-meter LPF are calculated in a similar manner.

CWAZ Versus Seventh-Order SVC Chebyshev

The easiest way to demonstrate the superiority of a CWAZ LPF over the Chebyshev LPF is to compare the RL and insertion-loss responses of these two designs. As an example of a Chebyshev design, we will use the 20-meter SVC LPF design used by NN1G for filtering the output of his 20-meter QRP SSB transceiver.

Figure 2 shows the computer-calculated return- and insertion-loss responses of a seven-element Chebyshev SVC LPF commonly used for attenuating the harmonics of a 20-meter RF amplifier. The plotted responses were made using Jim Tonne's *ELSIE* filter design and analysis software. This DOS-based program is available from Trinity Software (Ref 7). The component values, obtained from the LPF schematic diagram shown in Figure 1 on page 30 of NN1G's *QST* article, were used by *ELSIE* in plotting the Chebyshev SVC LPF responses. A sketch of the filter topology with component values is included in Figure 2.

Figure 3 shows the computer-calculated return- and insertion-loss responses of a CWAZ LPF intended to replace the seven-element 20-meter Chebyshev SVC LPF. The stop-band attenuation of the CWAZ LPF in the second-harmonic band is more than 60 dB and is substantially greater than that of the Chebyshev LPF. Also, the pass-band RL of the CWAZ LPF is quite satisfactory, at more than 25 dB. The disadvantages of the CWAZ design are that an extra capacitor is needed across L4, and several of the designs listed in Table 1 require paralleled capacitors to realize the design values. Nevertheless, I believe these disadvantages are minor in comparison to the increased second-harmonic stop-band attenuation that is possible with a CWAZ design.

LC Filter-Design Demo Software is Available

Those involved in passive LC filter design on an amateur and semiprofessional basis may experience the capabilities of *ELSIE* through a demo disk that is available from Jim Tonne. I use *ELSIE* V 1.11 with a 386SX CPU operating at 20 MHz. Although the plotting response of this computer is slow, I can evaluate the return- and insertion-loss responses of a design in less than 10 seconds, by using the minimum number of data points for preliminary plots. V 1.11 requires less than 1 Mb of hard disk space, while a more recent V 1.23 requires about 1.1 Mb. *ELSIE* requires a hard disk.

The *ELSIE* demo disk is restricted to LC filters of the third-order or less, but one can still explore all the capabilities of *ELSIE* in the design and analysis of filters. For ex-

as a means of describing this LPF design advancement for the benefit of the Amateur Radio fraternity.

A New Type of Low-Pass Filter

This article introduces a new eight-element LPF having a topology similar to that of the seven-element Chebyshev LPF, with two exceptions: The center inductor is resonated at the second harmonic in the filter stop band, and the component values are adjusted to maintain a more than acceptable RL across the amateur passband. To distinguish this new low-pass filter from the familiar SVC Chebyshev LPF, I propose that this new filter be named the "Chebyshev with Added Zero" LPF or a "CWAZ" LPF design. With this designation, you should understand that these LPFs are *output filters for single-band transmitters*. They provide optimum second and higher harmonic attenuation while maintaining a suitable level of return loss over the amateur band for which they're designed.

Figure 1 shows a schematic diagram of a CWAZ LPF design. Table 1 lists suggested capacitor and inductor values for all amateur bands from 160 through 10 meters. These tabulated values were derived from the normalized values provided to me by Jim Tonne for use in this article. If you want to confirm my tabulated values or calculate the CWAZ values for different bands, sim-

Figure 2 — component listing:

```
Qinductors: 100     Qcapacitors: 1000
Source — Input termination: 50.00
   C            150.00 pF
   L            0.68000 µH
   C            330.00 pF
   L            0.78000 µH
   C            330.00 pF
   L            0.68000 µH
   C            150.00 pF
Load — Output termination: 50.00
```

Labels: 20 meter Pass Band; Insertion Loss; Second – Harmonic Stop Band; Return Loss. Axes: Insertion and Return Loss (dB) vs Frequency (MHz).
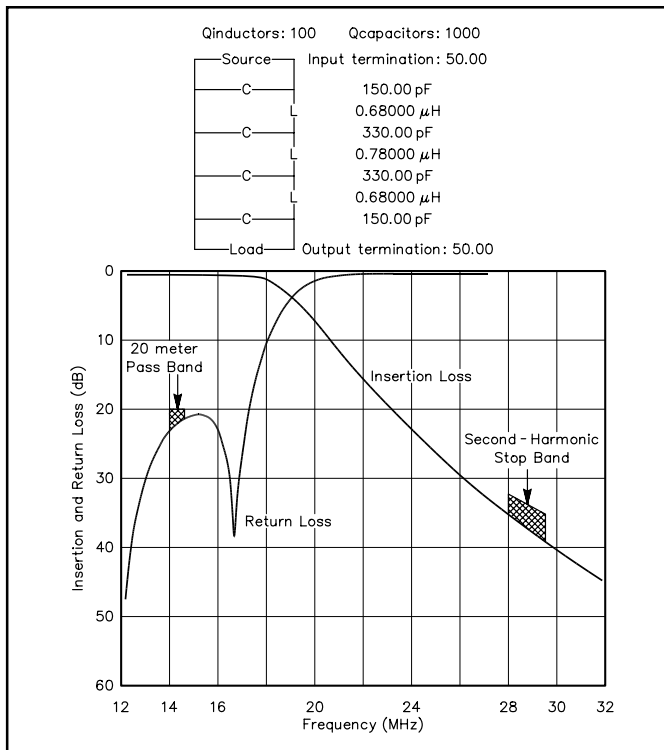
Figure 2—The plots show the *ELSIE* computer-calculated return- and insertion-loss responses of the seventh-order Chebyshev SVC low-pass filter used in the April 1997 *QST* article to attenuate second-harmonic signals. The 20-meter passband RL is about 21 dB, and the insertion loss over the second-harmonic frequency band ranges from 35 to 39 dB. A listing of the component values is included.
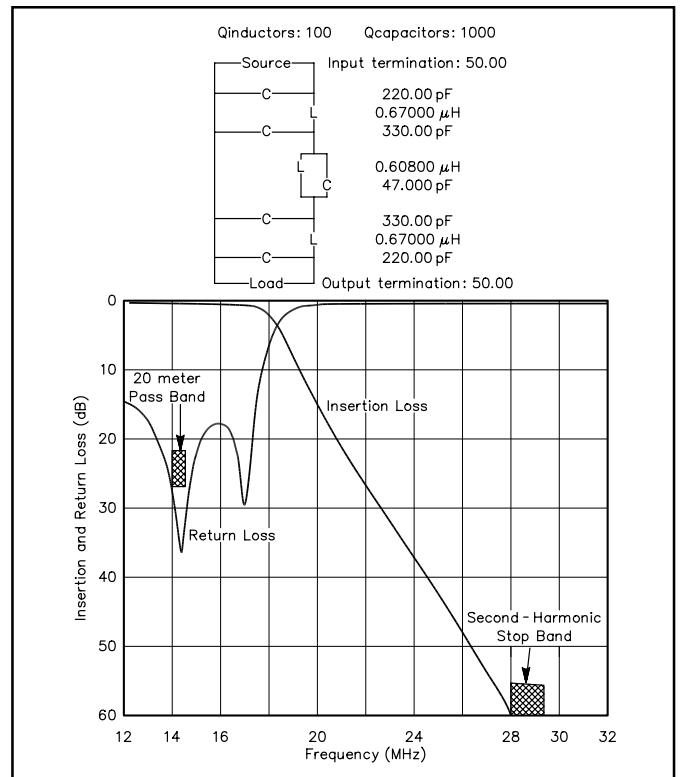
Figure 3 — component listing:

```
Qinductors: 100     Qcapacitors: 1000
Source — Input termination: 50.00
   C            220.00 pF
   L            0.67000 µH
   C            330.00 pF
   L            0.60800 µH
   C             47.000 pF
   C            330.00 pF
   L            0.67000 µH
   C            220.00 pF
Load — Output termination: 50.00
```

Labels: 20 meter Pass Band; Insertion Loss; Second – Harmonic Stop Band; Return Loss. Axes: Insertion and Return Loss (dB) vs Frequency (MHz).

Figure 3—The plots show the *ELSIE* computer-calculated return- and insertion-loss responses of the eight-element low-pass filter using the CWAZ capacitor and inductor values listed in Table 1 for the 20-meter low-pass filter. Notice that the calculated attenuation to second-harmonic signals is greater than 60 dB, while RL over the 20-meter passband is greater than 25 dB.

ample, you can use the tune option to adjust the component values of a Cauer third-order band-pass filter until the transmission zeroes fall in the centers of the adjacent ham bands for optimum RF selectivity. This would be impractical with tables of normalized values, but *ELSIE* can evaluate many different designs in a relatively short time.

If you are seriously interested in passive LC filter design and analysis, but cannot afford the high-priced software used by professional filter designers, contact Jim Tonne at Trinity Software (see Ref 7) about the *ELSIE* demo disk.

Summary

The seven-element SVC Chebyshev low-pass filter is commonly used to attenuate the second and higher harmonics of QRP RF transmitters to comply with FCC requirements. Using *ELSIE,* I've demonstrated that the second-harmonic attenuation provided by a seven-element Chebyshev SVC low-pass filter is marginal. I introduced a new filter that provides maximum attenuation at the second-harmonic frequency while simultaneously maintaining an acceptable return loss in the filter pass band. This is accomplished by forming a resonant circuit (the center inductor and capacitor) and using special values of inductance and capacitance to restore the passband return loss. A table of precalculated 50-Ω CWAZ LPF designs is presented for all the amateur bands. I evaluated an example 20-meter CWAZ LPF design to demonstrate how the harmonic attenuation is improved over that of a standard Chebyshev LPF while still maintaining an acceptable pass-band return loss.

Whether or not these new CWAZ LPFs will eventually supersede the more familiar seven-element Chebyshev SVC LPFs remains to be seen. I encourage you to try these new CWAZ designs and report your experience with them.

References

1. Dean Straw, N6BV, Ed., *1998 ARRL Handbook for Radio Amateurs*, 75th Ed, (Newington: ARRL, 1997) Figure 29.3, p 29.7. (Because of WRC-97, new, more-stringent emission standards will take effect over the next few years. For details see Technical Correspondence (*QST*, Jun 1998, pp 61-62) and Larry E. Price, W4RA, and Paul Rinaldo, W4RI, "WRC-97—An Amateur Radio Perspective," *QST*, Feb 1998, pp 31-34.—*Ed.*)
2. Dave Benson, NN1G, "A Single-Board QRP SSB Transceiver for 20 or 75 Meters," *QST*, Apr 1997, p 29.
3. These filters are most useful with single-band, single device transmitters. Common medium-power multiband transceivers use push-pull power amplifiers because such amplifiers inherently suppress the second harmonic. This suppression then permits the use of octave-related low-pass filters (eg, 2, 4, 8, 16 and 32 MHz) rather than a separate filter for each band.—*Ed.*
4. *Farnell Electronic Components Catalog*, copyright 1998 by Newark Electronics, Chicago, IL 60640; tel 800-718-1997, fax 800-718-1998; http://www.farnell.com.
5. Iron-powder cores catalog RF Applications, Issue F, Sep 1996. Micrometals, 5615 E La Palma Ave, Anaheim, CA 92807; tel 800-356-5977; **http://www.micrometals.com**.
6. Amidon Associates, Inc, 240 Briggs Ave, Costa Mesa, CA 92626; tel 800-898-1883, fax 714-850-1163.
7. Trinity Software, 7801 Rice Dr, Rowlett, TX 75088, (Jim Tonne, President); tel 972-475-7132.

Ed Wetherhold, W3NQN, received a degree in Radio Engineering from Tri-State University, Angola, Indiana, in 1956. From 1962 to 1992, he was employed at the Annapolis Signal Analysis Center of Alliant Techsystems, Inc (Alliant Techsystems was formerly the Defense Division of Honeywell, Inc), as a communications systems test engineer and as a certified TEMPEST Professional Level II.

Ed obtained his Amateur Radio license in 1947, while serving in the Air Force as a radio mechanic instructor at Scott AFB, in Illinois. For the past 22 years, he has been a technical advisor to the ARRL on passive LC filters. Ed's many articles on simplified filter design have been published in the electronics trade and Amateur Radio journals, such as Interference Technology Engineers' Master *(ITEM),* QST, QEX, CQ *and* Practical Wireless, *and in professional EMC journals. The* 1998 ARRL Handbook *contains Ed's SVC filter design tables and an explanation of how to design passive LC filters.*

While not working on filters, Ed is active as a tournament tennis player and is ranked Number 1 in the Men's 70 doubles in the USTA's Middle Atlantic section. You can contact Ed at 1426 Catlyn Pl, Annapolis, MD 21401-4208; tel 410-268-0916, fax 410-268-4779.