■ ED WETHERHOLD W3NQN PRESENTS A SERIES OF LOW-PASS FILTERS FOR AMATEUR-BAND APPLICATIONS, WITH

Filters - Cutting

Minimise those harmonics from your signal with a new low-pass filter with even lower second harmonic output.

In a recent *Practical Wireless* article‡1, The rev. **George Dobbs G3RJV**, explained the importance of including low-pass filters on the outputs of amateur-band transmitters to attenuate harmonics. The filters he recommended were 7-element Chebyshev designs selected from a listing of 30 designs published in a *Short Wave* magazine article‡2. These designs are preferred because only standard-value capacitors are needed, and for that reason, they are called 'SVC' designs.

The SVC series of passive filter designs have been widely published in Amateur Radio handbooks and electronics trade and professional journals over the past 17 years‡3-8. Although these designs are, for the Radio Amateur, convenient to use for harmonic reduction, the designs are not optimised for this application. For example, of the designs listed by G3RJV in his Table 1, all but two, provide less than 42dB attenuation at the second harmonic.

To increase the second-harmonic attenuation, the simplest way would be to place a capacitor across the middle inductor and resonate this inductor to twice the centre frequency of the amateur band. I've shown this proposed configuration in **Fig. 1**, and I've named it the 'WB6BLD low-pass filter' for reasons I'll explain later. However, if L4 is resonated while still using the original component values, the resulting pass-band s.w.r. becomes unacceptably high.

An explanation of the component numbering of the layout of the circuit in Fig. 1 may be in order at this point. It is 'usual' to label the inductors and capacitors of a filter according to the notional 'pole' (broadly the number of components) occupied within the filter. The filters described here are '7-pole' types so, have capacitors in sections 1, 3, 4, 5 and 7 and inductors in sections 2, 4 and 6. In the previous designs there would not have been a capacitor in section 4, only an inductor. (G1TEX)

To maintain an acceptable pass-band s.w.r. of preferably less than 1.2:1, different component values must be used. Although s.w.r. was used in the listed references as an indication of filter pass-band performance, another related parameter called 'return loss' is more commonly used. Return loss is easier to measure more accurately than s.w.r., and most computer analysis software uses return loss to characterise filter pass-band response.

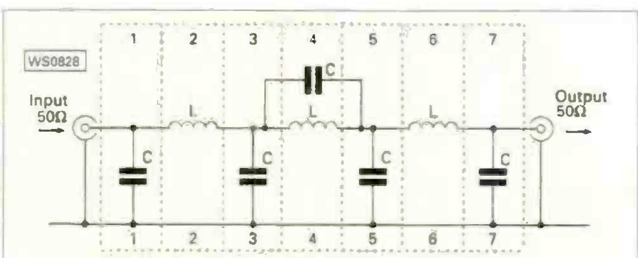


Fig. 1: The generalised circuit layout of the of the WB6BLD designed filter. See text for component numbering and values.

Band (m)	Freq. (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
		1659	2531	378			3.76
160	1.80	1450+220	2100+470		5.21	4.73	
		1500+150	2200+330	330+47			3.78
		853	1302	194			7.32
80	3.50		1150+150		2.68	2.43	
		470+390	1200+100	150+47			7.27
		427	651	97.2			14.6
40	7.00				1.34	1.22	
		330+100	330+330	100			14.4
		296	451	67			21.1
30	10.1				0.928	0.843	
		150+150	470	68			21.0
		213	325	48.6			29.3
20	14.0				0.670	0.608	
		220	330	47			29.8
		165	252	37.6			37.8
17	18.068				0.519	0.471	
		82+82	100+150	39			37.1
		142	217	32.4			43.9
15	21.0				0.447	0.406	
		150	220	33			43.5
		120	183	27.3			52.1
12	24.89				0.377	0.342	
		120	180	27			52.4
		107	163	24.3			58.6
10	28.0				0.335	0.304	
		100	82+82	27			55.6

Table 1 WT0830

The factors of s.w.r. and return loss (RL) are related by the following equations:

$$RL(dB) = -20 \times Log_{10}\left(\frac{s.w.r. - 1}{s.w.r. + 1}\right)$$

and

$$s.w.r. = \left(\frac{1 + p}{1 - p}\right)$$

where $p = 10^{\frac{-RL}{20}}$ (RL is the dB figure)

As an illustration, if you have an s.w.r. of 1.222:1, the corresponding return loss is 20dB. In the remainder of this article, I'll use return loss as an an indication of pass-band response.

Commercial filters are frequently advertised as having a maximum s.w.r. of 1.5:1, which corresponds to a minimum return loss of 13.98dB. However, a minimum return loss of 20dB (s.w.r. of 1.222:1) is preferable to minimise reflection loss. For example, a filter with a pass-band return loss of 20dB will cause only one percent of its incident power to be lost due to mismatch between the source and filter.

For maximum second-harmonic attenuation, it's preferable that any low-pass filter used has a minimum return loss of 20dB. Though, over the limited range of an amateur band it's possible to trade poorer return loss outside the amateur pass-band (where it is not needed) in exchange for increased attenuation within the filter stopband. This 'trade-off' can be realised by making C4/L4 resonate at the second-harmonic frequency while using specially selected component values that cause the filter pass-band within the amateur band to have a return loss of 20dB or more.

The normalised component values for the special low-pass filter designs were determined by **Jim Tonne, WB6BLD**, of Rowlett, Texas. He used his *ELSIE* filter design and analysis software to find the special filter component

The Edge

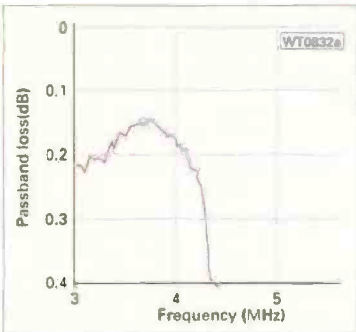


Fig 2a: Pass-band loss for the 3.5MHz band filter is less than 0.2dB within band.

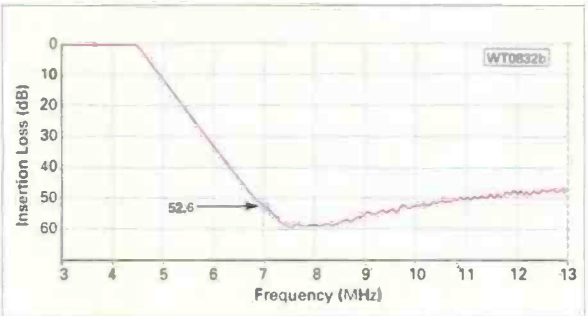


Fig. 2b: Through loss for the 3.5MHz version is at 52.6dB at 7MHz.

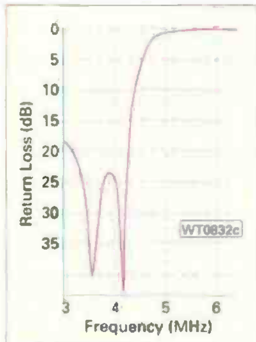


Fig. 2c: Return loss curve for the 3.5MHz band filter. (See text for an explanation of its significance).

values that provides the desired filter performance. Jim currently distributes his *ELSIE* software through his company of which he is president‡9. Because of Jim's efforts in making this special low pass filter design available to the amateur radio fraternity, it is appropriate to refer to this design as the 'WB6BLD design' to distinguish it from other similar ladder configurations such as the Butterworth, Bessel, Chebyshev, etc.

A summary of the WB6BLD 50Ω low-pass filters (l.p.f.) designed for second-harmonic attenuation in all the amateur bands below 30MHz is shown in **Table 1**. The first row of which (white background) shows the component values for a filter 'normalised' for 1MHz that Jim Tonne provided for me (and this article). By dividing these 1MHz values by the start frequency of the required band (in MHz), the values for any of the amateur bands can be independently calculated.

Band (MHz)	Turns L2 & 6	Turns L4	F_x (MHz) C1 & L2	F_y (MHz) C1 & L4	Core No.	Wire Size mm	Wire Size s.w.g.	Length (mm)
1.81	31+	30	1.717	1.802	T50-2	0.50	25	560
3.5	22	21	3.437	3.610	T44-2	0.50	25	430
7.0	17	16	6.63	6.949	T44-6	0.56	24	330
10.1	14	13	9.54	10.01	T44-6	0.71	22	280
14.0	17+	17	13.11	13.76	T50-17	0.71	22	330
18.068	15	14	17.25	18.11	T50-17	0.71	22	295
21.0	14+	14	19.44	20.39	T50-17	0.80	21	280
24.89	13	12+	23.7	24.84	T50-17	0.80	21	260
28.0	12	11	27.5	28.87	T50-17	0.80	21	240

Table 2 WT0831

To derive a filter for a particular band, divide all of the various capacitor and inductance values by the starting frequency of the amateur band required. The calculated capacitor values are not all that critical and all can be realised with one (or two parallel) standard-value capacitors. For example, in Table 1 the value for C1, and C7, of 853pF in the 3.5MHz band filter is suggested as a parallel combination of 470 and 390pF capacitors. If however, the 390pF value is not available, a 330pF value may be substituted with no discernable effect on the filter performance.

The number of turns needed to make the various inductance values with Micrometals toroidal cores is shown in **Table 2**. By using the design information contained in Tables 1 and 2, a low pass filter with the maximum second-harmonic attenuation can be assembled for any amateur band.

To confirm the correctness of the design data in Tables 1 and 2, low pass filters for the 3.5 and the 7MHz bands were assembled and then measured with an H-P Network Analyzer And Plotter (provided and operated by **John Brosnahan W0IUN**), LaSalle, Colorado. (A photo of John's antenna towers appeared on the

Fig 3a: Pass-band loss for the 14MHz band filter is less than 0.2dB within band.

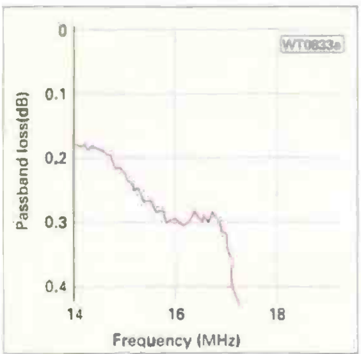


Fig. 3b: Insertion loss for the 14MHz version of the WB6BLD filter.

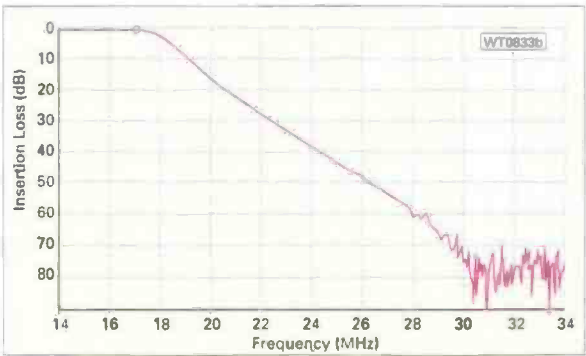
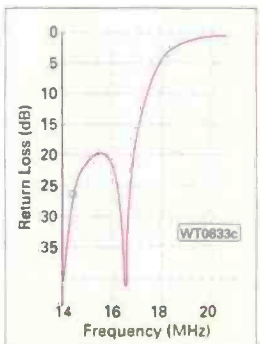


Fig. 3c: Return loss curve for the 14MHz band filter. (See text for an explanation of its significance).



front cover of the April 1996 issue of *Practical Wireless*.)

Copies of the plots are shown in **Fig. 2** and **Fig. 3**, illustrating the pass-band and stopband insertion loss and the pass-band return loss of the prototype filters. In both cases, the pass-band insertion loss is less than 0.2dB and the return loss is greater than 24dB, while the stopband insertion loss peaks near the second harmonic frequency. Similar satisfactory responses may be expected for all the other l.p.f.s listed in Table 1. The increase in second harmonic attenuation over that of the standard 7-element Chebyshev design can range from 14 to 25dB.

The photographs shows the filters assembled on pieces of perf-board. Shown in **Fig. 4**, a 3.5MHz l.p.f.and the 7MHz l.p.f. is shown in **Fig. 5**. I later installed my prototypes in an aluminium mini-box, in the case of the 3.5MHz filter, and in a miniature plastic

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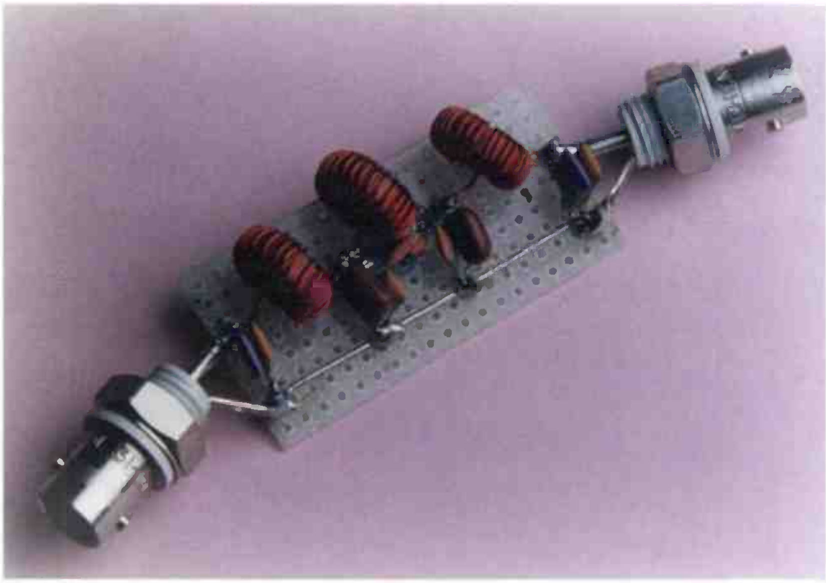


Fig. 4: The 3.5MHz version of the filter built up on perf-board.

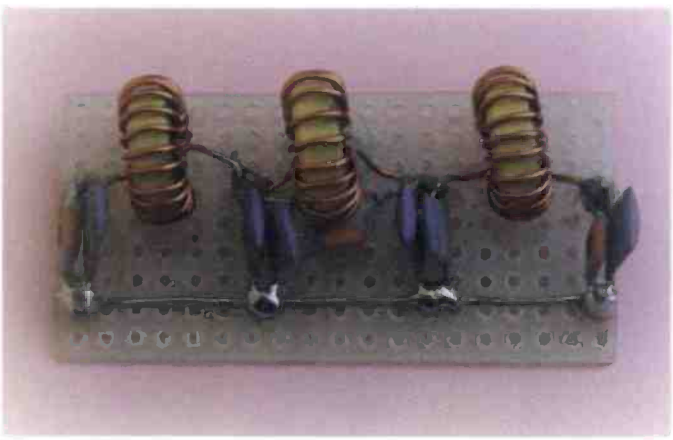
box available from Farnell. The powdered-iron cores used in the filter assembly are listed in Table 2. The capacitors (470pF and less) used are from the Philips 683 Series: ceramic, NP0 low K with a 100 V(d.c.) rating and a two-percent tolerance. Because the 390pF value is not available in the Philips 638 series, the 330pF value can be substituted for the 390pF value with no noticeable effect on the filter performance.

The lead spacing of 5mm (0.20in) of many modern low value capacitors, makes it convenient to install these capacitors in the 0.1-inch grid of the perf board. For capacitance values greater than 470pF, the WIMA FKP2 polypropylene film series or the Panasonic polypropylene film capacitors (used in the 3.5MHz l.p.f. construction and obtained from DIGI-KEY) are recommended because of their excellent high-frequency performance and small size. They both have a 5mm lead spacing.

The WIMA series of capacitors have a 100 Vdc (63 Vac) rating with a tolerance of ±5%. The values that are available above 470pF are 680, 1000, 1500 and 2200pF. These capacitors should be adequate for power levels up to 20W. Both the Philips ceramic and WIMA film capacitor types are listed in the Farnell components catalogue.

The inductance ratings of the Micrometals cores, also known as the 'AL' values, are listed in Table 2 of George's article for the '-2' and '-6' mixes. These core ratings may be used to find the approximate number of turns to put on a core to obtain a particular inductance. However, the my experience has been that when using these ratings the number of calculated turns is usually one more than actually required. For example, to get the L4 value of 4.73µH for the 1.8MHz band design, the calculated number of turns using the T50-2 AL rating of 0.49µH-per-10 turns is: $10\sqrt{(4.73/0.49)}$ or 31 turns. However, when a more precise method of calculating the required turns is used, the number of turns required is one less, at 30 turns, as is listed in Table 2.

Fig. 5: The 7MHz version of the filter built up on perf-board.



Tuning Procedure

Here's a tuning procedure I've found that works. The procedure I used to obtain a more precise turn count for a particular inductance is to form a parallel-resonant circuit using a known capacitor and the inductor to be adjusted. Place the parallel-tuned circuit between a 50Ω variable-frequency signal source (the attenuated output of your transmitter may be suitable for the signal source) and a 50Ω detector having an output level indicator. Tune the signal source frequency for a sharp null at the detector output.

Note the frequency of the signal source and calculate the inductance using the equation:

$$L(\mu H) = \frac{25330}{C \times F^2}$$

where C is in pF and the frequency, F, is measured in MHz. See Table 2 for suggested values of C and F to find the number of turns required to obtain L2 and L4. C1, F_x and C1, F_y are used to find the number of turns on L2 and L4, respectively. For example, if C1 = 1650pF (1500+150) and F_x = 1.717MHz, then L2 = 5.21µH. If the null frequency is above or below the F_x or F_y frequency, then add or remove, or squeeze together (or spread apart) the turns

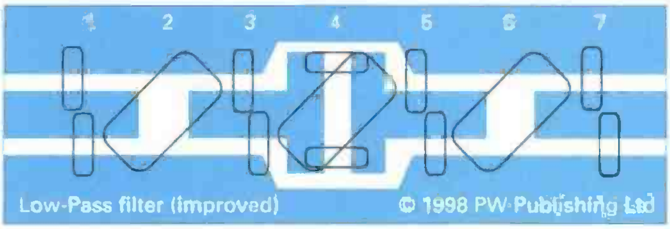


Fig. 6: Using a small p.c.b. can make construction of the filter much easier and neater.

on the core until the null frequency equals the F_x or F_y frequency. When this occurs, the inductor value must be equal to the design value.

Summary

It is desirable, and a requirement, to minimise the harmonic output of radio transmitters, and the 7-element Chebyshev SVC low-pass filter is frequently used for this purpose because of the convenience of using standard-value capacitors. However, with some component value changes, and with the addition of a capacitor across the centre inductor, it's possible to optimise the attenuation at the second and higher harmonic frequencies of the amateur band being filtered.

I calculated 8-element low-pass filters, to the design described here, for each of the nine h.f. amateur bands. Although all the capacitors did not have standard values, this was shown not to be a problem as one or two paralleled capacitors could meet all the requirements in exchange for additional attenuation at the second and higher harmonic frequencies.

In addition to component values in this article, I've also suggested suitable capacitor and core types and provided coil winding information to simplify assembly of the filter for use in transmitters up to about 20W. Filters for the 3.5 and a 7MHz bands were assembled using the tabulated design information, and plots of the filter pass-band insertion and return loss and stopband insertion loss were made to verify that the performance of both filters was acceptable.

The Radio Amateur now has another series of low-pass filter designs to consider for providing better harmonic attenuation than was previously available with the standard Chebyshev designs. Whether or not these new designs will eventually replace the 7-element Chebyshev filters will depend on whether or not these new designs find acceptance within the Amateur Radio fraternity. I can only encourage you to try out these new designs and report on your experiences in building and using them.

REFERENCES

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‡2. Wetherhold, W3NQN, 'Low-pass Filters for Attenuating RF Amplifier Harmonics, Parts I and II,' *Short Wave Magazine*, December 1983 and January 1984.

‡3. Wetherhold, W3NQN, 'Practical LC Filter Design' Parts 1-3 of a 6-part series, *Practical Wireless*, July, August and September 1984.

‡4. Wetherhold, 'Low-pass Chebyshev Filters Using Standard-Value Capacitors,' Engineer's Notebook, *ELECTRONICS*, 19 June 1980.

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‡6. SAMS *Radio Handbook*, 23rd edition, edited by William I. Orr, W6SAI; Passive LC Filters, pp. 3-17 - 3-29; copyright 1987 by Howard W. Sams & Co., A division of Macmillan, Inc.

‡7. *Filters and Power Conditioning, Vol. 4*; Chapter 2, Electric Wave Filters for Communications Systems; published 1988 by Interference Control Technologies, Inc., Gainesville, VA.

‡8. *The ARRL Handbook*, 74th edition, Chapter 30, pp. 30.22 - 30.29, 'Passive LC SVC Filter design'; copyright 1996 by the American Radio Relay League, Newington, CT.

‡9. Trinity Software, 7801 Rice Dr, Rowlett, TX 75088; (972) 475-7132.

‡10. Philip J. Davis, *The Thread, A Mathematical Yarn*, 2nd edition, Harcourt Brace Jovanovich, Publishers, New York, copyright 1989, 1983; 124-page paperback, $10.95. A series of delightful yarns about mathematics and mathematicians with the spelling of Chebyshev's name used as the historical 'thread' to join the various yarns.

A SHORT HISTORY LESSON

I would like to correct an error that appeared at the bottom of p.48, second column, Part 1, of reference‡3 regarding the original application of the Chebyshev polynomials. Pafnuty Lvovitch Chebyshev (also spelled Tschebyscheff) (1821-1894) was a famous Russian mathematician and Academician. While touring Europe in 1852 to inspect various types of machinery, windmills, water turbines, railways, etc., he became interested in the mechanical linkage used in Watt's steam engine to convert the reciprocating motion of the piston rod into rotational motion of a flywheel that was needed to run factory machinery.

Chebyshev noted that Watt's piston had zero lateral discrepancy at three points in its cycle, and concluded that a somewhat different linkage would lead to a discrepancy of half of Watt's and would be zero at five points in the piston cycle. Chebyshev then wrote a paper, now considered a mathematical classic, that laid the foundation for the topic of best approximation of functions by means of polynomials. It is these same polynomials that were originally developed to improve the reciprocating to rotational linkage in a steam engine that now find application in the design of passive LC filters‡10! (W3NQN)