TUTORIAL: TRANSMITTER (PA) OUTPUT FILTERS

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The PA output filter serves two major purposes:
1. Impedance matching from the PA (RL') to the load (RL)
2. Rejection of harmonics and spurious emissions to meet FCC compliance standards (-30dBc for 5W transmitters). This is usually in the form of band-pass or low-pass filters.

Filter configurations to meet the above requirements are nearly endless. Therefore, the filter designs that follow are based on the following assumptions, typical for QRP PA's:
1. PA output circuit per **Fig. A1;** Pout = 5W; RL'=13W
2. Output load is 50W (antenna or dummy load)
3. PA-to-50W impedance match is primarily due to T1, a 10T bifilar wound T50-43 toroidal core for 1:4 impedance ratio
4. Output filters will be of the low-pass filter (LPF) type.
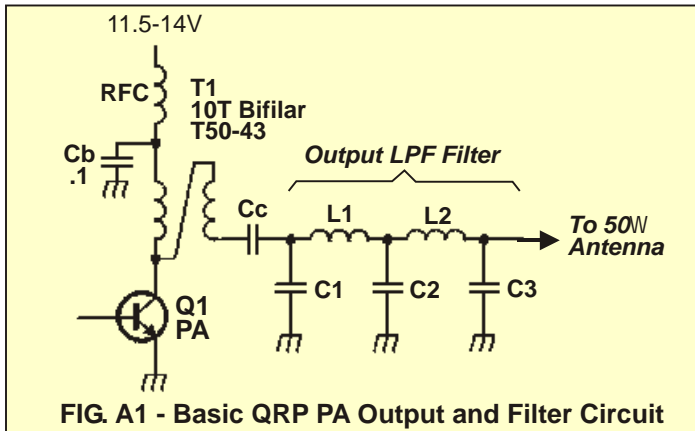
FIG. A1 - Basic QRP PA Output and Filter Circuit

The typical 5W QRP transmitter above has an estimated output impedance (RL') of:

$$RL'=\frac{(Vcc-Vce)^2}{2Po} = \frac{(12V-0.5)^2}{2x5W} = 13W$$

where Vce= 0.5v collector-emitter voltage typical, or as measured on an oscilloscope.

Transformer T1 is a bifilar wound toroid, for an impedance ratio of 1:4. Zp=RL'=13W. Zs (secondary) is 4 times Zp, or Zs=Zp x 4 = 52W, or very close to 50W. Thus, this is the component that performs the 50W conversion in this PA output scheme. This allows us to use **50W reciprocal filters**, which means the filters "sees" 50W on both input and output ends. Other filter designs will convert the 13W input to 50W output directly, but this adds another level of calculations or exhaustive tables to interpret. Reciprocal filters are the easiest to design. Since the impedance matching requirement for the output filter has been performed by T1, the output filter then is simply choosing and designing a constant impedance (50W) low pass filter -- for which the following examples are based.

RFC is used for the storage of dc current. To do this properly, it must have a higher impedance than that of the PA and the load. The XL of RFC is usually set to be 5-10 times RL.

   XRFC = 10RL =10x50W=500W

For 14MHz, this equates to L=17uH (15uH would be fine). RFC can be a fixed inductor or wound on a T35-43 toroid. The value is not overly critical. It's job is to dump current into the filter while the

PA is turned off to sustain output power. A much larger value than calculated would cause the RFC to still be dumping current when the PA turns on again - lowering the efficiency of the PA and altering the PA output impedance.

Cb places the "top" of T1 primary at rf ground. For this purpose, values from .001uF to 0.1uF are used. It also acts with RFC to keep RF out of the power supply. For better power supply regulation, often a large electrolytic is placed in parallel with Cb. Values of 22uF to 100uF is sufficient.
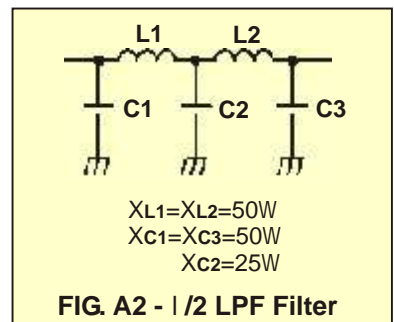
FILTER 1:
THE 50W HALF-WAVE (λ/2) FILTER

The *half-wave filter* is the easiest low-pass filter to design. It is so called because it produces a 180° phase shift from input to output -- or, equivalent to a half-wave section of transmission line. Referring to **Fig. A2**, it is the filter C1-L1-C2-L2-C3. This is a *5-pole filter* (n=5) since it consists of five reactive elements. A simpler version would be a *3-pole filter* (n=3), looking much like a "pi" filter, consisting only of C1-L1-C2. As you increase the number of reactive elements, the steeper the attenuation slope, as shown in **Fig. A3**. A n=3 filter provides about 24dB attenuation at 2f, while a n=5 filter about -30dB. Therefore, an n=5 filter is the minimum recommended to meet the -30dBc FCC requirement (shown on the charts).

Filter design is quite simple. For the desired cut-off frequency, you simply calculate the value of L and C such that XL and Xc equals 50W. By transposing the equation for XL and Xc, this yields:
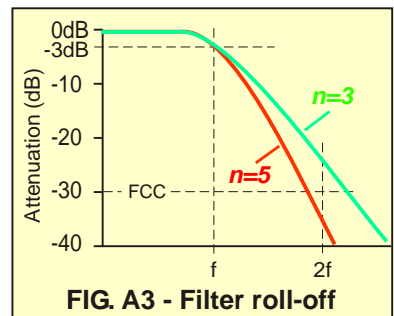
$$L=\frac{XL}{2pfc}$$

$$C=\frac{1}{2pfcXc}$$

Note that C2 is shared by both L1 and L2 sections, such that it's effective impedance will be 25W. The calculated values for the filter is shown in **Fig. A4**

$XL1=XL2=50W$
$Xc1=Xc3=50W$
$Xc2=25W$

FIG. A2 - λ/2 LPF Filter

FIG. A3 - Filter roll-off

The above calculates the **f3dB**, the frequency where the attenuation is 3dB *(half-power).* A filter with f3dB= 14MHz will attenuate half of your 5W signal. Keep this in mind. The cut-off frequency for most filters (except Chebychev) are based on the 3dB frequency. To compensate for this, select the f3dB to be at least 1.2 times your operating frequency. For a 14MHz output filter, calculate the filter for fc=1.2x14.1MHz=17MHz. However, this also reduces the attenuation curve at 2f about 6dB. This means you need a filter with -36 attenuation at 2f (2x17=34) to attenuate the 2x14 harmonic by 30dB. The n=5 half-wave filter just barely does this. These concepts are illustrated in **Fig. A4**.

FIG. A4 - Output filter response at f and 1.2f for the n=5 l/2 LPF
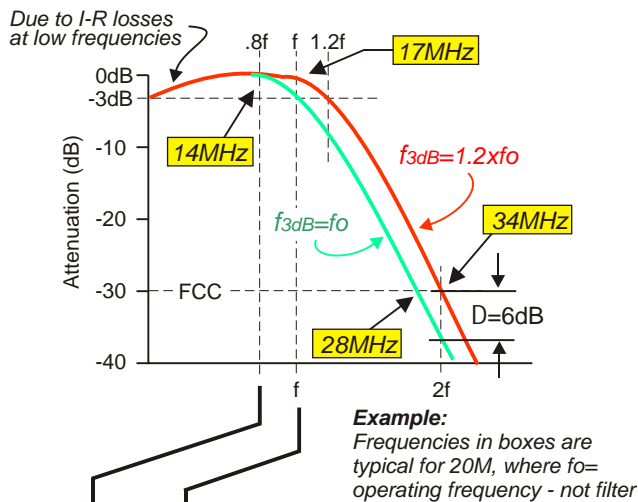
BAND	MHz	F3db	L1,L2 (uH)	C1,C3 (pF)	C2 (pF)
80M	3.5	4.2MHz	1.90	758	1516
40M	7.1	8.4	0.95	379 (390)	758 (680)
30M	10.1	12.1	0.66	263 (270)	526 (560)
20M	14.1	16.8	0.47	190 (180)	380 (390)
15M	21.0	25.2	0.32	126 (120)	158 (150)
10M	28.0	33.6	0.24	95 (100)	190 (180)

Values in ( ) are nearest standard values.

Filter values in the table **Fig. A4** are calculated for the HF ham bands (except 160M and 17M). Inductances can be wound on a T37-6 toroid, or fixed inductors. A 5-pole half-wave filter just barely meets FCC compliance at -30dB. Additional attenuation can be achieved by adding another section. The new inductor will be the same value as L1-L2. The input and output capacitor will remain at Xc=50W, while the two "inside caps" are Xc=25W. Adding another L-C section will add about another 12dB of attenuation (about 6dB per reactive component).

Summary. The half-wave filter is the easiest to design and adapt to any frequency. However, it has marginal attenuation at 2f. The attenuation steepness shown above is ideal. Actual results can have less attenuation by 2-3dB than shown due to circuit losses.

Filter 2: The Butterworth Low Pass Filter

The next type of PA output filter to consider is the Butterworth filter. The Butterworth is another "middle-of-the-road" medium Q filter, suitable for transmitter output filters. It also provides about -30dBc at 2f, the 2nd harmonic. The attenuation response is very similar to the l/2 filter, except very flat across the passband as shown in **Fig. A5.** The extremely flat pass band is one of the important features of this filter, also called the *maximally-flat* filter. This is not necessarily a requirement for transmitter output filters, however. Butterworth filters are *not* based on making the components 50W, but rather a polynomial solution that makes the overall network *appear* to be a certain impedance - 50W in our case. This results in some complicated math to determine the component values. This is why pages of filter tables are often found on Butterworth filters for calculating L and C for a host of variables (freq., impedance, poles, etc.). However, for PA output filters, we know we want 50W and the

number of poles will generally be 3, 5 and 7. This greatly simplifies the table information we need to know, and therefore greatly simplifies calculating the component values for L and C as will follow.

$$A(dB) = 10\log\left[1 + \left(\frac{fx}{f3dB}\right)^{2n}\right]$$

where *f3db* is the cut-off frequency of the filter, *fx* the frequency you want to calculate attenuation at, and *n* the number of poles in the filter. Since the ratio of fx/f3db is raised to the power of 2 times n, it is obvious the attenuation increases dramatically as the number of poles increase. That is, a 5-pole filter will have significantly more attenuation than a 3-pole filter. This equation can be calculated on a spreadsheet program, with the results sent to a charting utility to plot the attenuation of the filter. The attenuation for a filter with 3, 5 and 7 poles is plotted in **Fig. A5**.
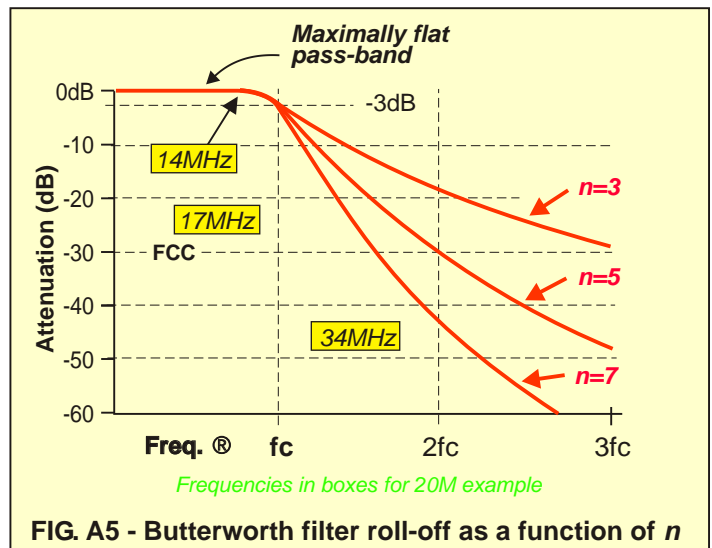
FIG. A5 - Butterworth filter roll-off as a function of *n*

The cut-off frequency for the Butterworth is based on the 3db frequency. Therefore, like the half-wave filter, fco should be calculated to be at least 1.2xfo, or at least 17MHz for a 20M filter.

Note that the calculated attenuation tends to be a bit low compared to what is usually seen in "the real world." A 5-pole filter calculates -30dB at 2f, while in most QRP output filters, the measured value will be about -36dB. This is due to the higher Q when using toroidal inductors (i.e., T37-2) and the effect of the PA output capacitance in series with L1.

Filter Design. The normalized component filter values for a Butterworth filter are shown in **Table 1** for n=3, 5 and 7 filters. These values (C1', L1', C2', etc.) are used in the equations below the table for calculating the proper values of L and C for the desired frequency. **Table 2** shows the calculated values for the HF ham bands.

In **Table 1**, note the column labeled **Rs/RL** Rs is the source resistance, which is the RL' of the PA transistor calculated previously (13W for 5W) and RL is the 50W load (antenna). For all the examples used in this article, where impedance transformation from the PA is made via the 1:4 toroid, the input to all of these filters is approximately 50W, so Rs/RL = 1.0 is used for the calculations. The other popular QRP transmitter approach is to use only an RFC in the collector and coupling directly to the output filter via a 0.1uF dc blocking capacitor, Cc, as shown in **Fig. A8 .** In this case, the output filter must also

perform the impedance conversion from 13W Rs to the 50W RL load. Therefore, Rs/RL = 13W/50W = .26 (or, 0.3 on the table for **Fig. A 8** configuration). This Rs/RL ratio is equivalent to the 1:4 impedance transformation needed.

TABLE 1 - Normalized values for Butterworth Filters

n=	Rs/RL	C1'	L1'	C2'	L2'	C3'	L3'	C4'
3	1.0	1.00	2.00	1.00	---	---		
5	1.0	.62	1.62	2.00	1.62	.62		
7	1.0	.45	1.25	1.80	2.00	1.80	1.25	.45
3	0.3	1.84	.44	5.63	---	---		
5	0.3	1.09	.29	4.84	.54	5.31		

How to calculate FILTER VALUES:
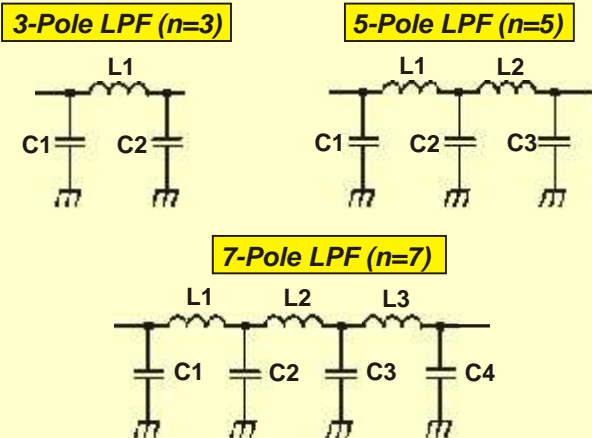
$$L1 = \frac{RLL1'}{2pfc} \qquad L2 = \frac{RLL2'}{2pfc} \quad (etc.)$$

$$C1 = \frac{C1'}{2pfcRL} \qquad C2 = \frac{C2'}{2pfcRL} \quad (etc.)$$

Example: For 17MHz (20M) n=5 LPF

$$C1 = \frac{C1'}{2pfcRL} \qquad C1 = \frac{.62}{6.28 \times 16.8MHz \times 50W} = 118pF$$
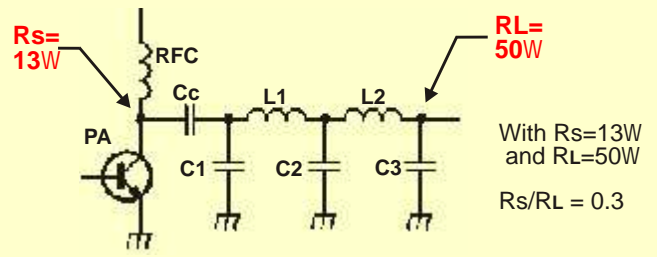
FIG. A7 - Butterworth Filter Values

3-Pole LPF (n=3)   **5-Pole LPF (n=5)**

7-Pole LPF (n=7)

TABLE 2 - Component values for n=5 Butterworth

BAND	MHz	F3db	L1,L2	C1,C3 (pF)	C2 (pF)
80M	3.5	4.2MHz	3.6uH	564 (560)	1800
40M	7.1	8.4	1.5	235 (220)	758 (680)
30M	10.1	12.1	1.1	163 (150)	526 (470)
20M	14.1	16.8	0.8	118 (120)	379 (330)
15M	21.0	25.2	0.5	78 (68)	253 (220)
10M	28.0	33.6	0.4	59 (56)	190 (180)

Values in ( ) are nearest standard values.

Summary. The Butterworth filter is another good filter to use for the transmitter output filter. It is a bit more difficult to calculate the values, but the simplified tables above should make it relatively easy. Note that some of the standard values of capacitors are a fair ways from the values calculated. I use the *lower* standard value to *raise* the filter fc to keep the transmit frequency in the minimum attenuation zone. Tune by adding small capacitors (12-22pF) in parallel with the capacitors to note a decrease or increase in output power. Add value(s) that cause an increase. Often just C2 needs to be trimmed for a good SWR and increase in power to indicate filter alignment.


FIG. A8 - Case for using Rs/RL = 0.3

Filter 3:
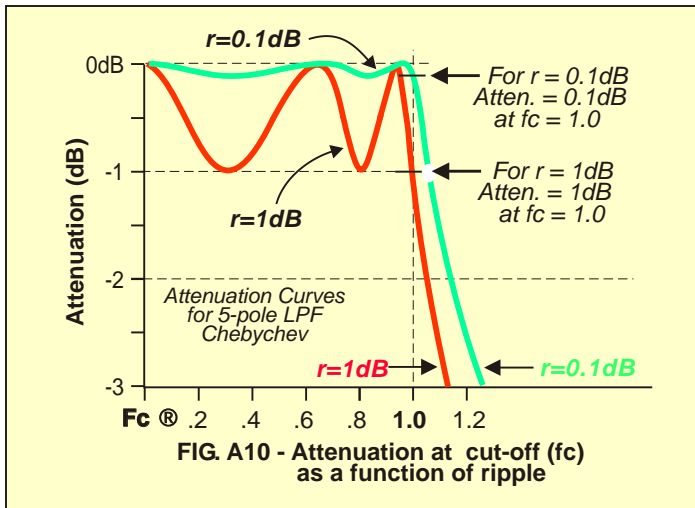## The Chebychev Low Pass Filter

The Chebychev low pass filter has the same schematic as the half-wave or Butterworth filter. However, it has an entirely different mathematical scheme to choose the component values, which is based on some rather tricky math. As in the Butterworth, only the values for n=3, 5, and 7 will be given to simplify using this very good filter. Chebychev filters give a much better attenuation for the same number of poles over the Butterworth, and thus are often preferred by homebrewer's for their enhanced harmonic rejection capabilities. A steep Chebychev filter comes with a price -- ripple in the passband. With passband ripples <2dB, it isn't really a concern for transmitter output filters, but is discussed since it is an important aspect of how these filters work.

Attenuation of the Chebychev filter is a function of the number of poles, just as in the other filters. The higher number of reactive components, the steeper the attenuation. As shown in **Fig. A9** the steepness of the attenuation is also a function of the ripple in dB. Note that for a 0.5dB ripple (r=0.5dB) filter, attenuation at the 2nd harmonic (2f) is around -45dBc. This provides plenty of margin for meeting the -30dBc FCC compliance.
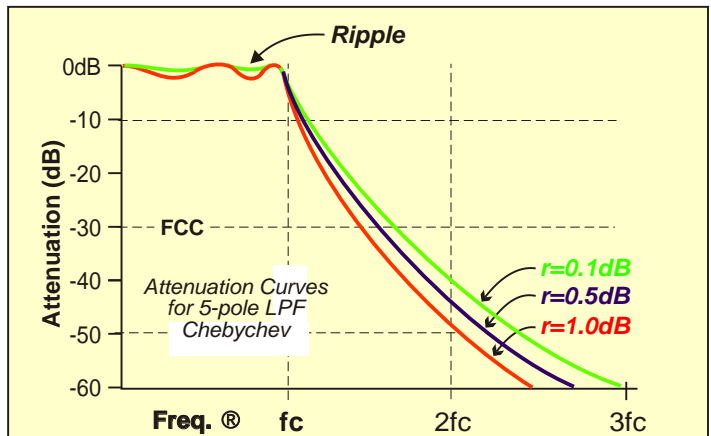
FIG. A9 - Chebychev LPF roll-off vs. ripple

LPF Cut-Off Frequency (fc). In the half-wave and Butterworth filters, fc is based on the 3dB frequency. In the Chebychev filter, however, fc is calculated closer to the actual "break point" of the filter, that is, where the attenuation first begins. Actually, the true fc is based on the frequency where the attenuation at fc equals the ripple. If you design a 1dB filter, then fc is the frequency where attenuation is 1dB. If you design a 0.1dB Chebychev filter, fc is the frequency where fc is equal to 0.1dB of attenuation. This is shown in **Fig. A10**.

r=0.1dB

0dB

For r = 0.1dB
Atten. = 0.1dB
at fc = 1.0

-1

For r = 1dB
Atten. = 1dB
at fc = 1.0

r=1dB

-2

Attenuation Curves
for 5-pole LPF
Chebychev

r=1dB → ← **r=0.1dB**

-3

Fc ® .2 .4 .6 .8 **1.0** 1.2

**FIG. A10 - Attenuation at cut-off (fc)
as a function of ripple**

Attenuation (dB)

FIG. A11 - Chebychev Low-Pass Filter Values

3-Pole LPF (n=3)

L1

C1 C2

5-Pole LPF (n=5)

L1 L2

C1 C2 C3

7-Pole LPF (n=7)

L1 L2 L3

C1 C2 C3 C4

TABLE 4 - Component values for n=5, r=1dB LPF

BAND	MHz	Fc	L1,L2 (uH)	C1,C3	C2
80M	3.5	3.7	2.4uH	1893 pF	2667 pF
40M	7.1	7.4	1.2	946	1334
30M	10.1	10.5	0.84	667	940
20M	14.1	14.5	0.60	483	681
15M	21.0	22.0	0.40	318	449
10M	28.0	29.0	0.30	242	340

Ripple is a function of the Q of the filter., where Q is the ratio of the series reactance (the inductances) to the 50W load. The higher the Q, the higher the ripple, and the steeper the attenuation. For PA output filters, r=0.5 to 1dB is equivalent to a loaded Q of 2-4, or the Q usually sought in most output filters using toroidal inductors. The 1dB ripple shown in **Fig. A10** is the *actual ripple* from a 5-pole 1dB Chebychev built for a 30M transmitter, and swept on a network analyzer to see where the ripple peaks in the passband fall. There will be a peak and a dip for each reactive element. For a n=5 filter, there will be 3 peaks and 2 dips (total 5) placed exactly where shown in the figure.

Filter Design. As with the Butterworth filter, the normalized filter values for the Chebychev are shown in **Table 3** for the 3, 5 and 7-pole filters, and for 3 different values of ripple. This greatly simplifies the mathematics involved in calculating the L and C values. The values from the table, C1', L1', C2', etc. are used in the equations below the table for calculating the proper values of L and C for the desired frequency ... which can be set only about 5% above the highest operating frequency.

TABLE 3 - Normalized values for Chebychev LPF Filters

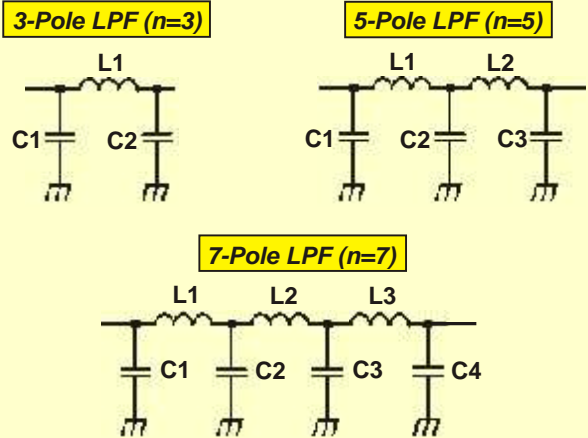| n=	r=	C1'	L1'	C2'	L2'	C3'	L3'	C4'
3	0.1dB	1.43	1.59	1.43				
5	0.1	1.30	1.56	2.24	1.56	1.30		
7	0.1	1.26	1.52	2.24	1.68	2.24	1.52	1.26
3	0.5dB	1.86	1.28	1.83				
5	0.5	1.81	1.30	2.69	1.30	1.81		
7	0.5	1.79	1.30	2.72	1.39	2.72	1.30	1.79
3	1.0dB	2.22	1.09	2.22				
5	1.0	2.21	1.13	3.10	1.13	2.21		

How to calculate FILTER VALUES:

$$L1 = \frac{R_L L1'}{2pfc} \qquad L2 = \frac{R_L L2'}{2pfc} \qquad \text{(etc.)}$$

$$C1 = \frac{C1'}{2pfcR_L} \qquad C2 = \frac{C2'}{2pfcR_L} \qquad \text{(etc.)}$$

Example: *For 14.3MHz (20M) n=5, r=0.5dB LPF*

$$C1 = \frac{C1'}{2pfcR_L} \qquad C1 = \frac{1.81}{6.28 \times 14.3MHz \times 50W} = 407pF \ (390pF)$$

Component Tolerances. One of the problems with the Chebychev filter values shown above is the capacitance values tend to fall quite a ways from the nearest standard value, except for 20M (470 and 680pF respectively). However, by using the normalized values (Table 3) in a spread sheet program to calculate L and C, you can piddle around with different ripple factors and find combinations more suitable for the band of your interest. Also, you can plot out the values on a chart and "guestimate" the normalized values for intermediate ripple values. However, in practice, it's not really that bad. By calculating the values for a given ripple, use the nearest standard capacitor values, and the effect will be a slight shift in fc and a higher or lower resulting ripple, which doesn't really effect the attenuation and impedance characteristics of the filter for a PA output filter. The largest concern is that the fc of the filter is *above* the highest transmit frequency to ensure you are not in the attenuation stop band portion of the filter, which will attenuate your output power by 0.5-1.0dB, or so. By selecting standard values *below* the values calculated, you are moving your fc *upward* in frequency for a measure of safety in this regard.

Alternatively, you can build the filter with the values calculated, using the nearest lower standard value, and adding small capacitors in parallel to achieve the exact value calculated. As with the Butteworth, often just trimming C2 will suffice in getting maximum power and minimum SWR from the filter. The chief advantage of using the Chebychev calculations for a PA output filter is the exceptional harmonic attenuation offered for a n=5 filter, giving you plenty of safety margin when you can not build it to the exact values calculated.

With all three filters presented here, it was the attempt of this article to serve as a reference guide for designing and building your own output filter, from the simple approach to a more detailed approach. If you calculate the values and use the next nearest standard values, you will have a very adequate filter with no further effort. However, if you have the test equipment and patience to "fine tune" your filter for maximum efficiency, you can perform that as well with the information within.