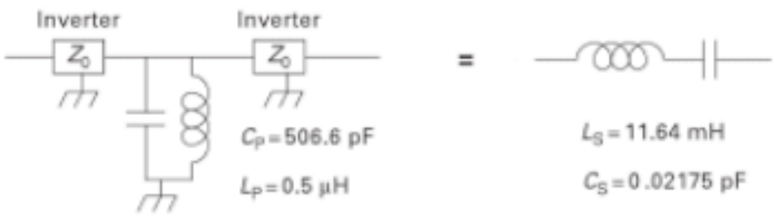

Figure 13.14. Inverters transform a 0.5-µH shunt inductor into a 11.644-mH series inductor.

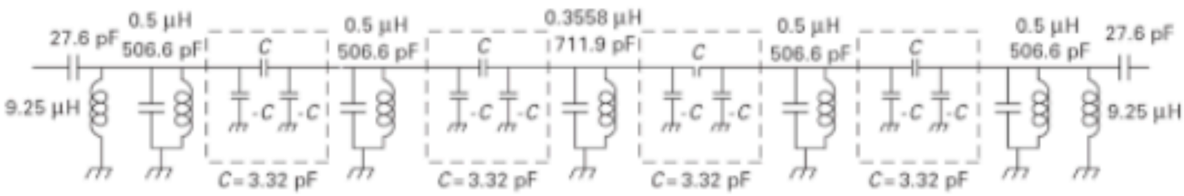

Figure 13.15. Coupled-resonator version of previous bandpass filter.

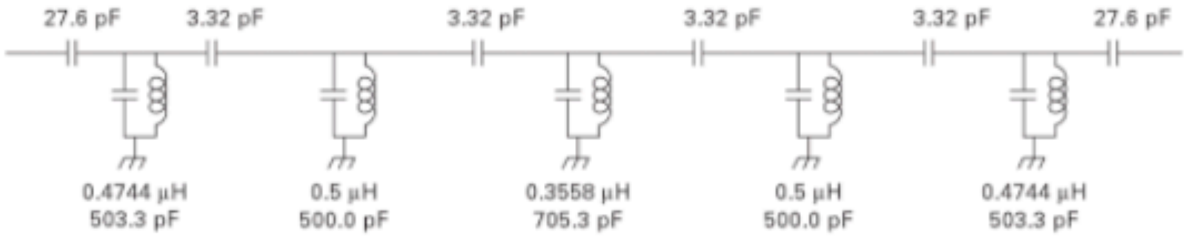

Figure 13.16. Finished coupled-resonator filter.

For this type of inverter, we had seen that $Z_0 = X_C$, so $C = 3.32$ pF. We now have our coupled-resonator filter but since it works at 6705 ohms we will add L-section matching networks at each end to convert it back to 50 ohms. The filter, at this point, is shown in Figure 13.15. All the resonators are now parallel resonators. (In other situations we might use inverters to convert series resonators into equivalent parallel resonators to make an all-series-resonator filter – see Figure 13.1.)

The final clean-up step is to absorb the − 3.32 pF capacitors into the resonator capacitors and combine the matching section inductors with the end-section resonator inductors as shown in Figure 13.16.

The response of the finished filter is shown in Figure 13.17 and is almost identical to the response of the prototype filter of Figure 13.11. The difference, a fraction of a dB, occurs because the inverters work perfectly only at the center frequency.

13.4 Tubular bandpass filters

A popular bandpass filter design, the "tubular filter" is produced by many filter manufacturers. Figure 13.18 shows the construction of a three-resonator tubular filter.

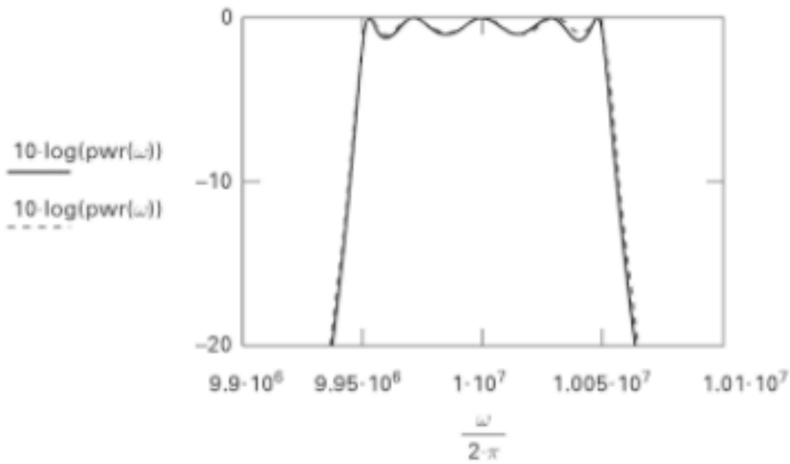

Figure 13.17. Calculated response of the filters of Figure 13.16 (pwr) and Figure 13.11 (pwr).

The only standard electronic components are the coaxial connectors at the ends. There are also (in this example) three inductors (wire coils), four metal cylinders, two dielectric spacers, two (or one long) dielectric sleeves, and a tubular metal body. Figure 13.19 shows how a coupled-resonator filter design, of the type we have discussed, is transformed into the tubular filter design. You can verify that Figure 13.19(d) is the circuit diagram of the tubular filter. The three-capacitor π-sections are formed by the capacitance between the adjacent faces of the metal cylinders and the capacitors are formed between the outside surfaces of the cylinders and the tubular body.

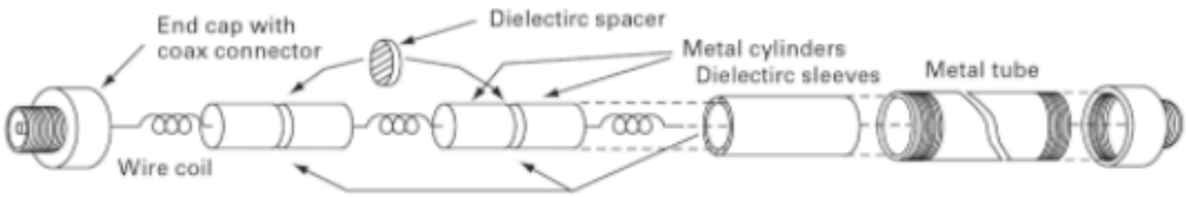

Figure 13.18. Tubular bandpass filter.

Beginning with Figure 13.19(a), we have a standard coupled-resonator bandpass filter using series resonators. In the canonical prototype for this filter, the middle section is a parallel resonator, but this has been replaced by a series resonator sandwiched between two impedance inverters. In (b), the center capacitor has been replaced by two capacitors (each of twice the value of the original capacitor so that, in series, the total series capacitance is the same). The capacitors have been shifted slightly in (c) to identify a T-section capacitor network at each side of the central inductor. Finally, in going from (c) to (d), these T-networks are replaced by equivalent π-networks, to arrive at the circuit of the tubular filter. Any

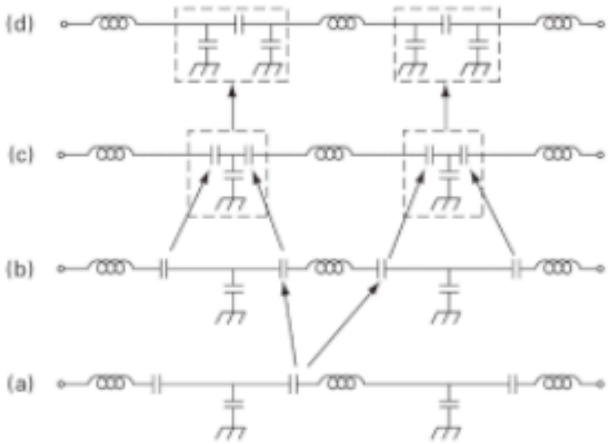

Figure 13.19. Tubular bandpass filter evolution.

$$Z_1 = \frac{Z_a Z_b}{Z_a + Z_b + Z_c} \qquad Z_a = \frac{Z_1 Z_2 + Z_2 Z_3 + Z_3 Z_1}{Z_3}$$

Figure 13.20. Equivalent π-section and T-section networks.

T-network has an equivalent π-network and vice versa (Problem 13.5). These transformations, also known as T$-\pi$ and $\pi-$T are shown in Figure 13.20. Formulas are given for one element in each network; the others follow from symmetry.

13.5 Effects of finite *Q*

These calculated filter responses assume components of infinitely high Q. We can calculate the effects of finite Q by paralleling the (lossless) inductors in our model with resistors equal to Q times the inductor reactances at the center frequency. If, for example, the Q is 500 (quite a high value for a coil), we would parallel the inductors in the filter of Figure 13.15 with resistors of about 15 000 ohms. Reanalyzing the circuit response, we would find that the filter will have a midband insertion loss of 7 dB and that the flat (within 1 dB) passband response becomes rounded. The effect will be somewhat less for a filter with more gradual skirts, e.g., a 0.01 dB Chebyshev or a Butterworth filter. But the real problem is still the small fractional bandwidth. For a filter with small fractional bandwidth to have the ideal shape of Figure 13.17, the resonators must be quartz or ceramic or other resonators with Qs in the thousands. An approximate analysis predicts that the midband loss per section in a bandpass filter will be on the order of

$$\frac{\text{power transmitted}}{\text{power incident}} = \left(1 - \frac{L_0/2}{Q \cdot \text{fractional bandwidth}}\right) \tag{13.7}$$

where L_0 represents the inductor value in the normalized lowpass prototype filter. For our five-section filter we can take L_0 to be about 1.5 henrys. If the inductor Q is 500, the predicted transmission of the five-section filter is $5 \times 10 \log[1-(1.5\ /2)/(500\cdot(1/100))] = -10$ dB, which is roughly equal to the actual value of −7 dB.

13.6 Tuning procedures

Filters with small fractional bandwidths and sharp skirts are extremely sensitive to component values. In the filter of Figure 13.16, for example, the resonators must be tuned very precisely or the shape will be distorted and the overall transmission will be lowered. (The values of the small coupling capacitors – all that remains of the impedance inverters – are not as critical.) Usually each resonator is adjustable by means of a variable capacitor or variable inductor. All the adjustments interact and, if the filter is totally out of tune, it may be hard to detect any transmission at all. A standard tuning procedure is to monitor the input impedance of the filter while tuning the resonators, one-by-one, beginning at input end. While resonator N is being adjusted, resonator N+1 is short circuited. The tuning of one resonator is done to produce a maximum input impedance while the tuning of the next is done to produce a minimum input impedance. The procedure must sometimes be customized to account for matching sections at the ends.

13.7 Other filter types

The coupled-resonator technique is used from HF through microwaves. Not all RF bandpass filters, however, use the coupled-resonator technique. The IF bandpass shape in television receivers is usually determined by a SAW (surface acoustic wave) bandpass filter. SAW filters are FIR (finite impulse response) filters, whereas all the LC filters we have discussed are IIR (infinite impulse response) networks. This classification is made according