Extending the Double-Tuned Circuit to Three Resonators

Here's an empirical design method for triple-tuned filters.

By Wes Hayward, W7ZOI

Although the most common LC band-pass filters used by radio amateurs are single and double-tuned circuits, there are situations where a higher-order filter is desired. The triple-tuned circuit, a band-pass filter with three resonators, is an especially useful example. It is easily designed and offers improved stop-band attenuation with little increase in insertion loss. This paper presents two simple methods that allow the VHF triple-tuned circuit to be adjusted and tuned with simple instruments and little more complication that a double-tuned filter.

7700 SW Danielle Ave
Beaverton, OR 97008
e-mail **w7zoi@teleport.com**

The Double-Tuned Circuit as a Step toward the Triple-Resonator Filter

Two filter schematics are shown in Fig 1. Both were designed for a Butterworth response and a center frequency of 110 MHz with a 3-dB bandwidth of 2 MHz. The N = 3 (three pole) filter has slightly higher insertion loss than the double-tuned circuit, but is more selective at high attenuation. The reader can calculate the responses with any of dozens of available computer programs.[1]

It is interesting to compare the two schematics. The coupling capacitors are identical for the same bandwidth. However, the end-section matching is slightly different, with the end Q being higher for the double-tuned circuit (DTC) than for the triple-tuned circuit (TTC). This leads us to ask what the performance would be for a DTC that has the same end designs as a TTC. This is shown schematically in Fig 2 with responses shown in Fig 3.

Experimental Methods

The introductory example presented above used computer generated and analyzed designs. This is all the preparation that is needed for lower-frequency filters where discrete reactances are large. This works well for filters up through 30 to 50 MHz with capacitor values of 1 pF or more and inductors of a couple hundred nanohenries or more. As we move into the VHF area, and higher, the components are not described well by

[1]Notes appear on page 46.

"printed" values. Stray reactances begin to dominate, encouraging us to use experimental methods.

I described the DTC in detail in a previous *QST* paper.[2] Experimental methods were emphasized in that tutorial, which described a method for building a double-tuned circuit without ever going through the numbers. The method entails adjusting the end loading on both resonators while also adjusting coupling. The resonators are tuned for maximum response after K and Q adjustment; the insertion loss is then measured. The reader is urged to study that paper if he or she is not very familiar with the procedure.

Perhaps the most important detail presented in the DTC tutorial was the need to perform a wide-band sweep to locate any double-humped response that might be present. A common and potentially disastrous error that the experimenter can make with the DTC is severe over coupling that produces two widely separated response peaks. It is easy to miss one of the two peaks if a wide sweep is not done.

With this background in mind, we can use the earlier observations to implement a triple-tuned circuit. The three-element filter is built with the middle resonator eliminated. The loading is kept identical at the two ends and is adjusted for a desired filter bandwidth. Coupling is set up between the first and *third* resonator and the combination is adjusted as a DTC. A wide-band sweep is done to find the double humped response, if present. It is then eliminated through further adjustment, if found. This is

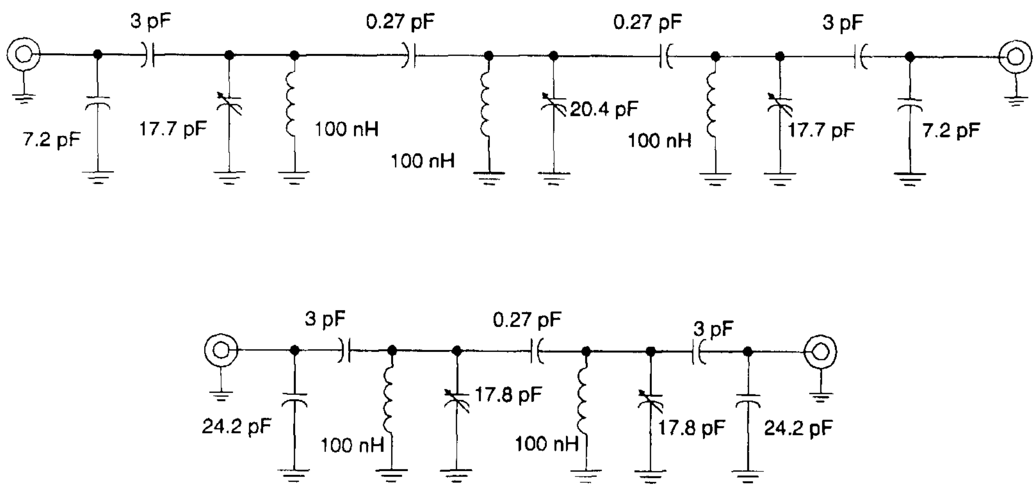

Fig 1—Butterworth LC Band-pass Filters with a 2 MHz bandwidth, centered at 110 MHz. The upper schematic is a triple-tuned circuit (N = 3), while the lower schematic is a double-tuned circuit.

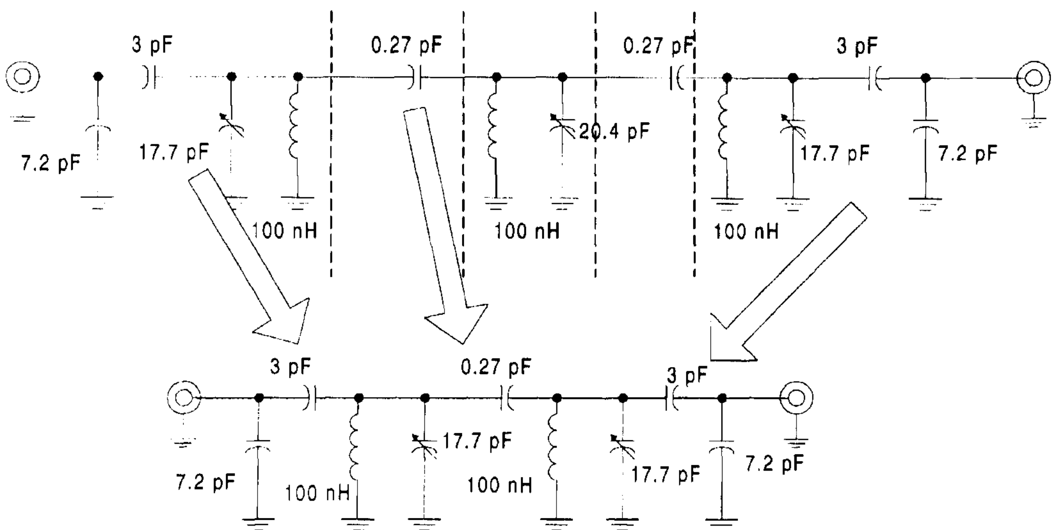

Fig 2—A TTC is designed "on paper" and is mentally segmented into end resonators, a middle resonator, and coupling elements. A DTC is then fabricated consisting of the two end resonators and a coupling element. The response of the DTC, and the parent TTC are shown in Fig 3.

repeated until the desired bandwidth is achieved in a DTC.

With a working DTC now in hand, the coupling is examined and duplicated as the third, middle resonator is added. The coupling from resonator 1 to 2 should be the same as that from 2 to 3. The TTC is then tuned and measured, performing a wide-band sweep to confirm the absence of extra peaks. The final bandwidth should be close to that of the intermediate DTC with a slightly higher insertion loss.

The filter shown in Photos A and B was built for use as the first IF of a spectrum analyzer. Filter design began with selection of an inductor. Values around 100 nH are practical at 110 MHz. The inductor was built with a 6.0 inch piece of #18 enameled wire. The ends were stripped and five turns of the wire were wound on the shank of a 1/4 inch drill bit.[3] The unloaded Q was assumed to be around 200, a value later confirmed with measurements. This inductor resonates at 110 MHz with a capacitor of about 21 pF, realized in the filter with combinations of fixed and glass trimmers. The predicted coupling capacitor value is 0.27 pF for each of the two components. A computer design is useful to provide guidance during construction, even if some components are less than practical.

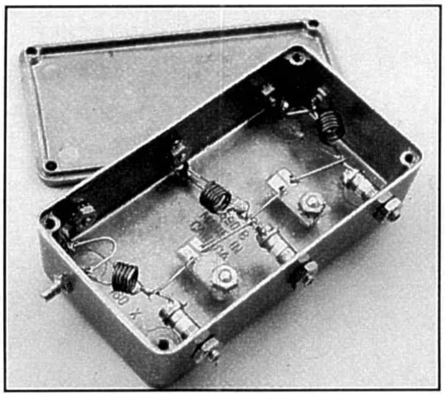

Photo A—A TTC filter for 110 MHz.

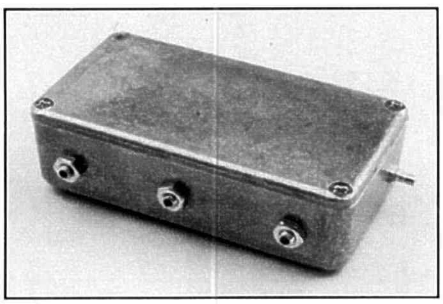

Photo B—An outside view of the TTC in its cast box.

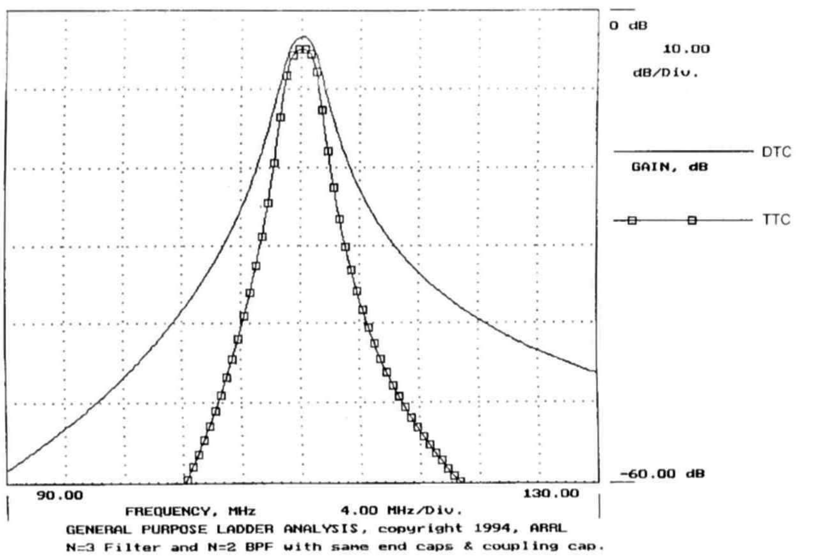

Fig 3—Response of a TTC and a DTC derived from it. Both have approximately the same bandwidth.

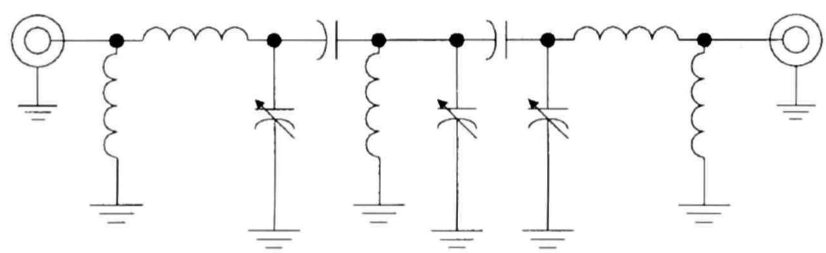

Fig 4—Filter form used with a band-pass circuit shown in photograph A.

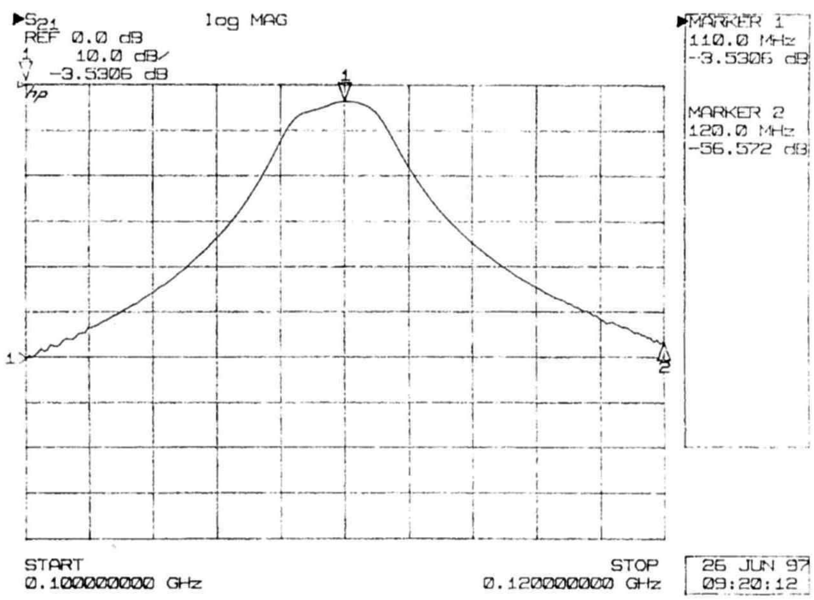

Fig 5—Experimental results with an example triple-tuned filter.

The generality of these methods allows great flexibility. Any of several coupling methods can be used for end-section loading. Even though the schematic shows capacitive taps for attachment between end resonators and the 50 Ω loads, other methods could just as well be applied. For example, the filter shown in the photos used end loading realized with the circuit of Fig 4, where the grounded end of the inductor is lifted from ground and attached to a coaxial connector. Then, a small inductor is attached from the connector to ground. The size of this inductor is varied to establish the end Q. Even though the physical details are different, the measurement schemes and results are not.

Figure 5 shows experimental results, a plot for the experimental filter. The evaluation measurements were performed with an HP-8510B network analyzer. However, the sophisticated instrument was not used for any of the adjustments.

Filter Adjustment with a Return-Loss Bridge

A second useful method is available to the experimenter with a return-loss bridge in his or her laboratory. This instrument, which has often been described in the literature[4], is an impedance bridge where the error, or unbalance signal serves as a measure of reflection coefficient (or SWR) looking into a load. Fig 6 is the schematic for a filter where the input reflection coefficient is to be measured. This analysis was performed with the evaluation version of the popular *PSpice*.[5] The use of a pair of voltage sources at the input generates a voltage, shown as "gam," which *is* the voltage reflection coefficient.[6] Return loss relates to Gamma through

$$Return\ Loss = -20 \cdot Log(\Gamma) \qquad \text{(Eq 1)}$$

Figure 7 shows the gain and magnitude of S11 versus frequency for the complete filter. The match plot dips down to a return loss of 20 dB at the filter center frequency.

Figure 8 shows a modification where the match is calculated for an end resonator that is no longer coupled to the rest of the filter. The result is shown in Fig 9. This match, now only 6.5 dB at resonance, is not nearly as good as the complete filter. If the unloaded resonator Q was much higher, the return loss would be even less. Hence, it is important that the unloaded Q value be reasonably accurate during this simulation.

We eventually wish to use this as an aid to measurements. This was to be a measure of impedance at resonance, but we have not obtained enough information to establish an impedance. Two different resistive loads can provide a 6 dB return loss, just as two different pure resistances can provide a 3:1 SWR. This dilemma is solved with the computer simulation shown in Fig 10, where the single resonator is swept several times with different values of matching inductor with each sweep. A return loss of 6 dB occurs with matching inductor values of 4 nH and 10 nH. Yet only the higher, 10 nH, value produces the desired filter response.

The information from the simulations can now be used to tune our circuit. The TTC filter is built, but the center resonator is either short circuited, or removed. One end is driven at 110 MHz by a return-loss bridge and the resonator is tuned for best return loss, occurring with the largest dip. The matching (grounded) inductor is then varied and retuned until a return loss of about 6 dB is measured. The matching inductor should have a total wire length of about an inch, corresponding to an inductance of about 10 nH using the rule-of-thumb that a

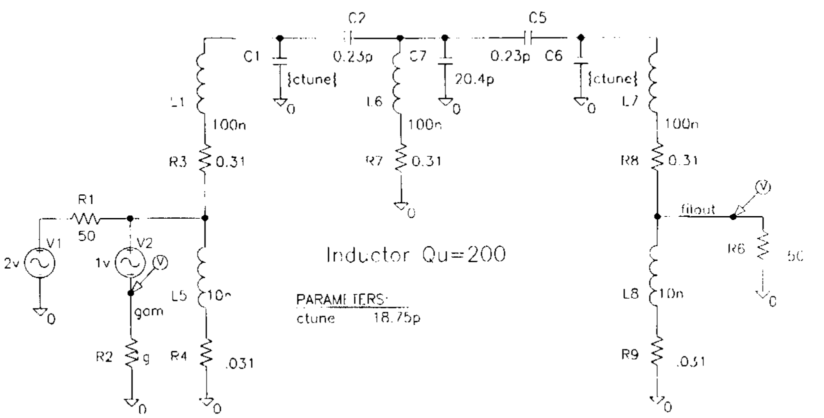

Fig 6—Schematic for practical version of the filter, set up for analysis in *PSpice*.

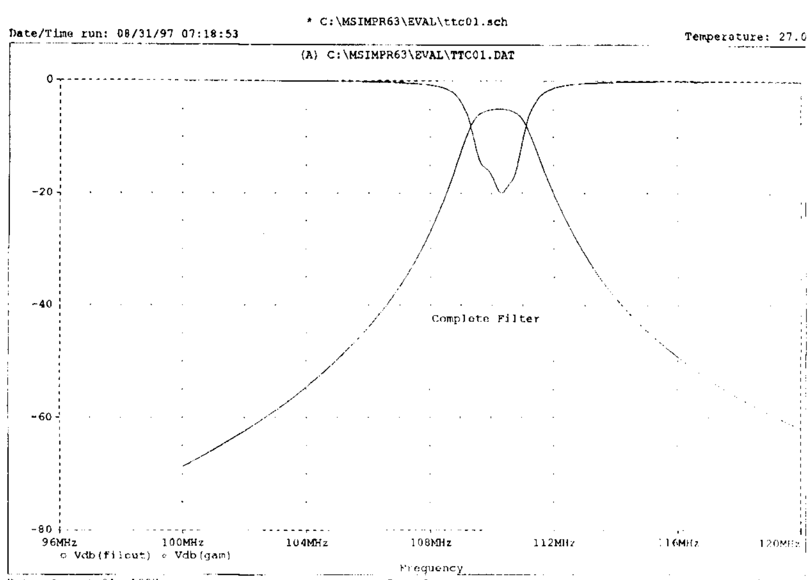

Fig 7—Transfer function and impedance match for complete filter. The return loss looking into the filter is about 20 dB at band center.

wire has L = 0.5 nH per millimeter of wire length. This procedure is repeated for the other end of the filter.

Having established the end Q, the center resonator is added to the circuit. Equal valued coupling capacitors are added between resonators, always keeping the values as small as "seems" reasonable. The three resonators are tuned at 110 MHz as the coupling caps are adjusted. A wide-band sweep is performed during the process to guarantee that overcoupling is not producing extra response peaks. If extra peaks appear, the coupling capacitors are reduced until the desired band-pass shape and bandwidth are obtained.

Some Practical Considerations

Band-pass filters are critical elements in most RF systems and should be built with care. Shielding is often needed; not only is it important to shield the resonators from the outside

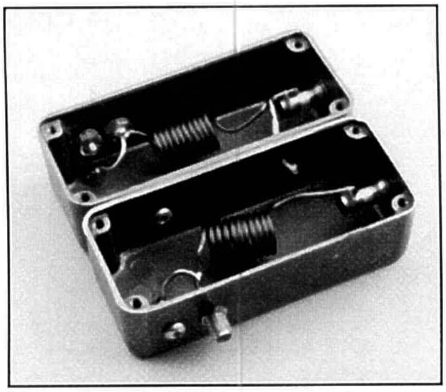

Photo C—This DTC is mounted in *two* boxes to improve isolation.

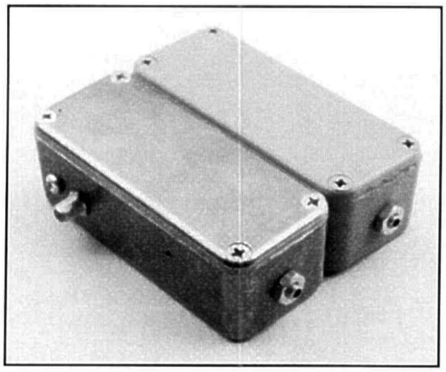

Photo D—An outside view of the DTC in two boxes.

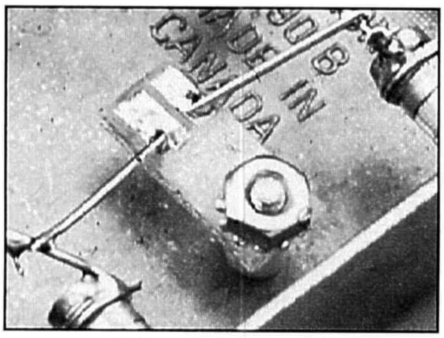

Photo E—This enlargement from Photo A shows one method to achieve tiny coupling capacitances. This method of capacitively coupling two conductors is sometimes called a "gimmick" capacitor. See text.

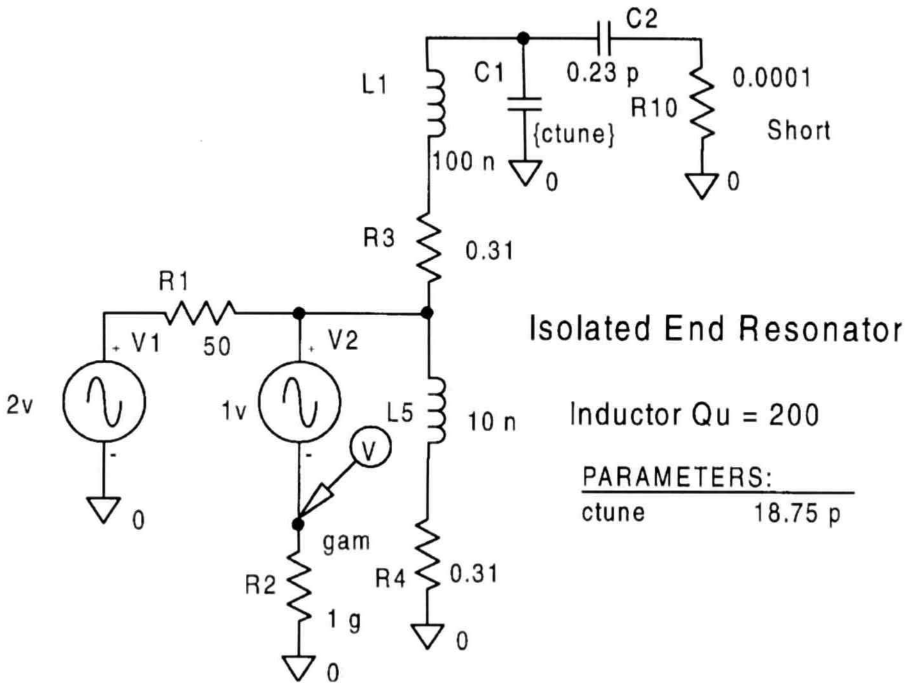

Fig 8—Calculation of reflection when looking into an end resonator without other coupled resonators.

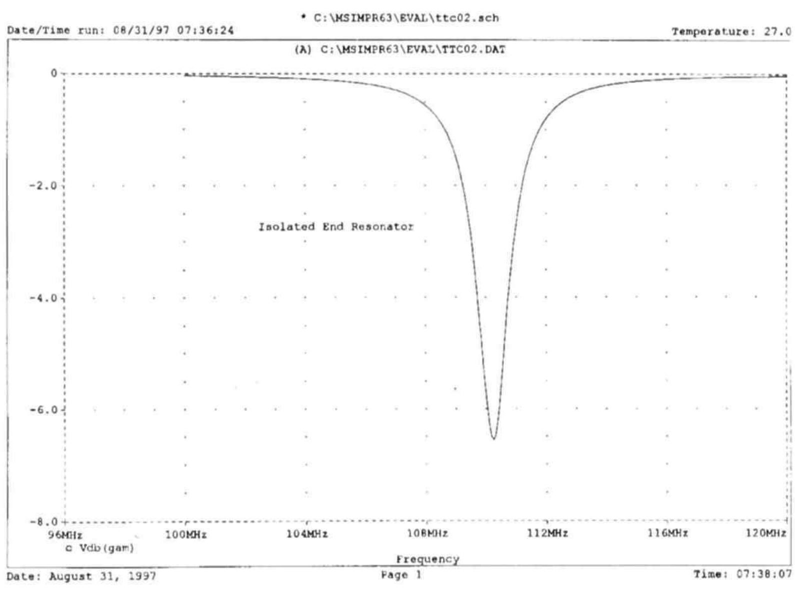

Fig 9—Reflection looking into the isolated resonator.

world, but shielding between resonators is often required. The 110 MHz example TTC is built in a single cast-aluminum box. (See Photos A and B.) Small-diameter coils were picked specifically to minimize interaction between resonators, eliminating the need for internal shields. Photos C and D show a double-tuned circuit built in two cast-aluminum boxes that have been bolted together. Large, higher Q inductors are used. This scheme can be expanded to numerous filter elements. It is often worthwhile to flip adjacent boxes so that lids alternate, side to side to accommodate cast boxes with nonparallel sides.

The small valued coupling capacitors needed in band-pass LC filters are often difficult to realize. One scheme that I have applied is sometimes called a gimmick capacitor (shown in Photo E). Two small, isolated pads are fabricated on a scrap of single sided circuit board material. (Double-sided board has excessive capacitance related to the board material.) Wires are then run from the "hot" ends of the resonators to the pads. The wires are kept a bit longer than required to reach the pads. The excess ends can then be bent close to each other, as needed, to adjust the capacitance. In the example filter, the excess wire lengths were completely trimmed away, for the stray pad-to-pad capacitance provided the needed coupling.

The measurements outlined are best done with the best instrumentation available. This may be elegant commercial gear, or simple home built tools. It is quite possible to build and adjust a TTC with a signal generator and a home-brew power meter, such as the unit recently described by K7OWJ.[7] Once the filter is finished, it can be integrated into a spectrum analyzer, an instrument that will then simplify the adjustments the next time a TTC is needed.

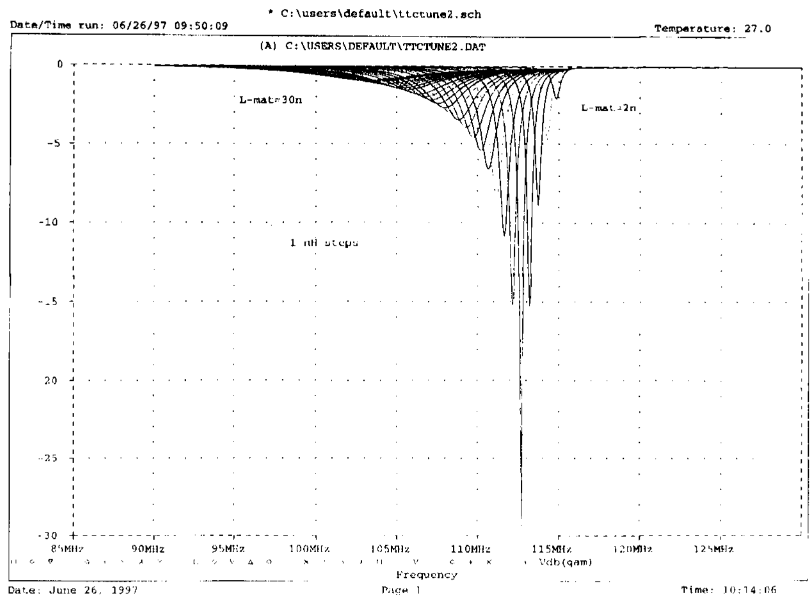

Fig 10—Reflection looking into an isolated resonator with the matching inductor changed in 1 nH steps.

References:

[1]The filters were designed with *DTTC*, a program offered with the ARRL version of "*Introduction to Radio Frequency Design*," ARRL Order No. 4920. The analysis of Fig 3 was generated with *GPLA*, also offered with the text. *ARRL Radio Designer* is also suitable for analysis of filters of this sort. *PSpice* is a program offered by MicroSim, 20 Fairbanks, Irvine, CA 92718. Also, see **www.microsim.com**. The evaluation version of *PSpice* is a very effective, yet affordable tool. ARRL publications are available from your local ARRL dealer or directly from ARRL. Mail orders to Pub Sales Dept, ARRL, 225 Main St, Newington, CT 06111-1494. You can call us toll-free at tel 888-277-5289; fax your order to 860-594-0303; or send e-mail to **pubsales@arrl.org**. Check out the full ARRL publications line on the World Wide Web at **http://www.arrl.org/catalog**.

[2]Hayward, "The Double-Tuned Circuit," *QST*, Dec. 91, pp 29-34.

[3]See IRFD (See Note 1). The coils are designed with a program on the disk, *COILS.EXE*.

[4]The return-loss bridge is described in IRFD, in *Solid-State Design for the Radio Amateur*, (Newington: ARRL, 1977; ARRL Order No. 0402) and in several editions of the *ARRL Handbook (ARRL Order No. 1786)*, as well as numerous articles.

[5]See information on MicroSim presented in Note 1.

[6]Hayward, "Reflections on the Reflection Coefficient," *QEX*, Jan 1993, p 10-12.

[7]Bramwell, "The Microwatter," *QST*, June 1997, pp 33-35.