

# How to Tune an L-network Matchbox

*W8MQW describes a non-iterative two-step matching for an L-network.*

A very common matchbox design is the L-network of Figure 1. It is certainly the most common design among autotuners. Manually tuning such matchboxes is an iterative process, where an initial guess is made for the  $L$  and  $C$ , then by watching SWR, refinements are made alternately to  $L$  and  $C$  until SWR has been lowered to an acceptable level. Some autotuners employ simple bisection searches for minimal SWR, or at the other extreme, some use sophisticated frequency sampling equation solving predictor/correctors. But tuning an L network need not be an iterative process — it can in theory be done in two simple steps if a second parameter in addition to SWR is observed during tuning.

## Two-step Matching

Let us first develop these two steps for the special case of matching a pure resistance  $R$  greater than  $50\ \Omega$ . The impedance  $Z$  of Figure 1 presented to the transmitter is, by the standard arithmetic of series and parallel impedances,

$$Z = \frac{RX_C^2}{R^2 + X_C^2} + jX_L - j\frac{R^2 X_C}{R^2 + X_C^2} \tag{1}$$

So the obvious approach is to proceed in two simple non-iterative steps.

*Step 1.* Adjust the capacitor to bring the real part of  $Z$  to  $50\ \Omega$ .

That is, choose  $X_C$  so that

$$\frac{RX_C^2}{R^2 + X_C^2} = 50 \tag{2A}$$

This is mathematically possible since the left hand side of [EQ 2A], as an increasing function of  $X_C$ , takes on each value between 0 and  $R$  exactly once. As an aside, this shows that an L-network has at most one possible matching solution.

*Step 2.* Adjust the inductor  $L$  to bring the reactive part of  $Z$  resulting from Step 1 to zero. That is, choose  $X_L$  so that

$$X_L = \frac{R^2 X_C}{R^2 + X_C^2} \tag{2B}$$

## But is This Doable?

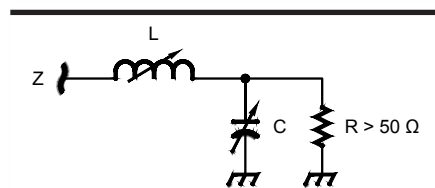
The second step is easy once the first is completed. Merely adjust the inductor for zero return power, i.e., SWR = 1. But is there a method to steer the tuning of the capacitor to accomplish Step 1? Can we, or a CPU, observe some voltage that we may null to achieve Step 1?

Think of the left end of the network of Figure 1 as the beginning of a  $50\ \Omega$  transmission line of length zero. If  $V_f$  and  $V_r$  are the forward and reflected voltages on this line, then because the value of  $Z$  is the quotient of the net voltage across it divided by the net current through it, and because the reflected current travels in the reverse direction<sup>1</sup>,

$$Z - 50 = \frac{V_f + V_r}{V_f/50 - V_r/50} - 50 = \frac{100V_r}{V_f - V_r} \tag{3}$$

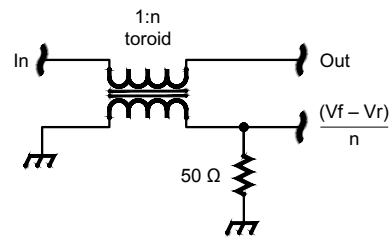
Thus  $Z - 50$  is purely reactive exactly when the two voltages  $V_f$  and  $V_f - V_r$  are in quadrature.

So the crucial voltage to null in order



QX1609-MacCluer01

Figure 1 — A common L-network matchbox that transforms  $R$  to  $Z$ .



QX1609-MacCluer02

Figure 2 — Forward and reflected currents subtract in this current sampler.

to achieve Step 1 is the dc phase voltage from a phase detector that compares  $V_f$  to  $V_f - V_r$ . This dc voltage will be zero only at a 90-degree phase shift. The reflected voltage  $V_r$  is of course obtainable from the reflected port of a tandem coupler, while the difference voltage  $V_f - V_r$  is obtainable from a current sampler, such as in Figure 2.

## Matching reactive loads

Almost certainly, a matchbox will be asked to match loads with both resistive and reactive parts. Thinking of such a load in its

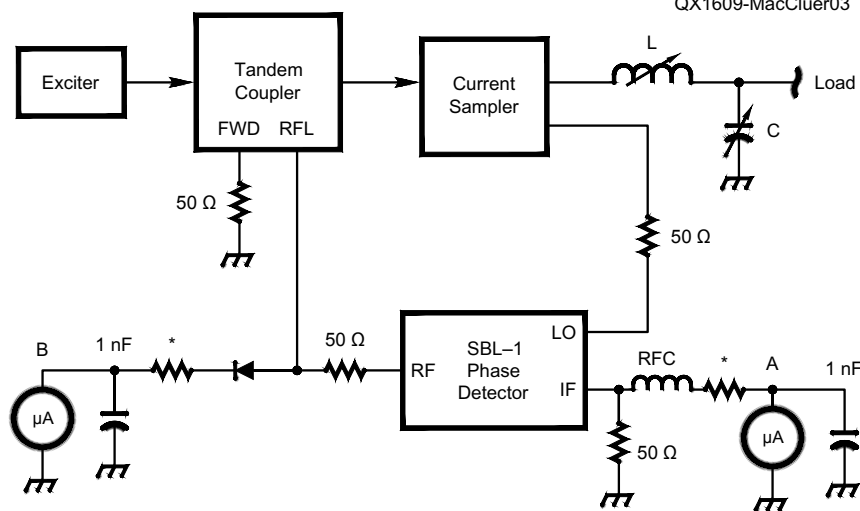


Figure 3 — The matchbox in block form. The user (or CPU) zeros meter A phase voltage by adjusting C, then zeros meter B reflected voltage by adjusting L. Attenuators (not shown) reduce the sampled voltages when operating high power.



Figure 4 — The L-network matchbox with stepper-driven vacuum capacitor and roller inductor.

parallel equivalent, its reactive part can be thrown onto the shunt capacitive reactance of C, and the algorithm proceeds in two steps as before, as long as the series resistive part exceeds 50 Ω.

To extend the capabilities of any L-network to handle resistive parts less than 50 Ω, the shunt capacitor must of

course be switched from the antenna to the transmitter side of the network. In this case, the algorithm is as before: phase voltage is zeroed by the capacitor, return voltage by the inductor.

### Proof of Concept

To verify this simple two-step algorithm, I

built a simple L-network tuner with the block diagram of Figure 3. Referring to this figure, the algorithm therefore becomes:

Step 1. Null out the center-zero meter A by adjusting C.

Step 2. Null the meter B by adjusting L.

Again note that this is a simple two-step process, *not* an iterative process.

### The Construction Project Sketched

A 28 μH roller inductor was obtained from Palstar. The capacitor used was a Jennings 1000 pF vacuum variable. Each is turned by a small 28 oz-in stepper motor from Adafruit. The two steppers are directed by an Arduino UNO R3 and an Adafruit motor shield. The Arduino reads the user's intent from two panel-mounted 10 kΩ potentiometers, see Figure 4. These two CPU-controlled stepper motors were used in anticipation of eventually implementing automatic tuning.

The tandem coupler used was the inestimable design by Larry Phipps, N8LP.<sup>2</sup> The tandem and current sampler of Figure 3 were built in separate cast-aluminum boxes, see Figures 5 and 6.

The phase detector employed was a Mini-Circuits SBL-1, see Figure 7. All the sampled forward and return voltages from the coupler and current sampler are of a level that no active devices are required when tuning with 10 W. Not shown in the block diagram of Figure 3 are attenuator pads that lower sample levels during normal operation after tuning is completed.

### Theory Collides with Practice

Alas, in actual operation, the L and C controls interact somewhat, especially on higher frequency bands. On 160 and 80 practice closely matches theory, with the two-step algorithm yielding a match with little post adjustment. But as the frequency rises, the real-world stray L/C/R of the components and wiring begin to induce interaction. Another cause of this divergence from theory is that theoretical performance is predicated on the source being a perfect 50 Ω voltage source, while during matching the reflected currents disturb the characteristics of the source. But the dominant source of this interaction is that phase difference reported by the phase detector depends not only upon the phases, but upon the amplitudes of the two inputs to the detector. To obtain true two-step tuning would require the use of a logarithmic amplifier such as the AD8302 to swamp out this effect from the input amplitudes. When the matching process is observed as a Lissajous display, ( $V_r$  against  $V_f - V_r$ ), convergence to a match follows theory.

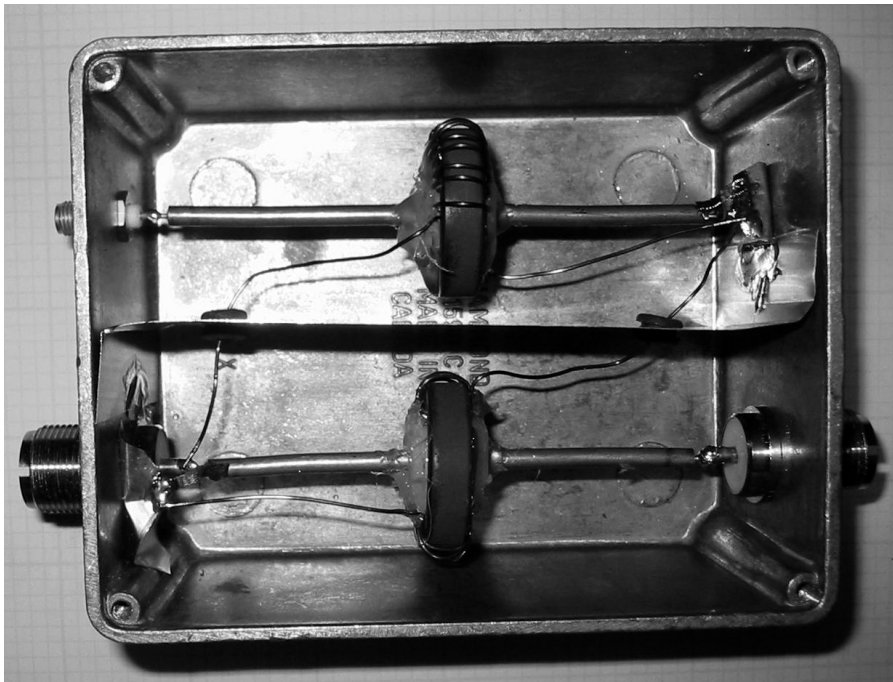


Figure 5 — Tandem coupler design by Larry Phipps, N8LP.

But even with the minor interaction of the  $L$  and  $C$  controls, convergence to match is much quicker because of the added information available from the phase voltage. If phase voltage is negative, decrease  $C$ ; if phase voltage is positive, increase  $C$ . Thus the  $50\ \Omega$  real part is matched immediately. Then proceed in the usual way to a one-to-one match by adjusting  $L$ .

### Some Final Thoughts

To save space, the current sampler of Figures 2 and 6 could possibly be incorporated into the tandem coupler of Figure 5 by adding its toroid as a second toroid on the through line. I did not try this.

Both meter  $A$  and  $B$  can be any  $100\ \mu\text{A}$  or smaller ammeters. The meter  $A$  must be a center-zero meter since the phase detector reports both positive and negative voltages. Select by trial and error the current limiting resistors, marked “\*”, for your particular meters. As a starting point try  $1\ \text{k}\Omega$ .

The fortuitous levels of the sampled voltages require no active devices. This permitted all signals to be piped about with my favorite coax, RG402 semi-rigid coax with SMA connectors, lending a microwave look to the construction.

This algorithm is valid for any  $L$  network

matchbox, whether it is a balanced network preceded by a balun or an unbalanced network followed by a balun.

It would be easy to add an outboard current sampler and phase detector plus meter to existing manual L-network tuners to achieve expedited two-step tuning.

Displaying  $V_r$  (horizontal input) against  $V_i - V_r$  (vertical input) as an oscilloscope Lissajous diagram is an exceptionally efficient aid in finding a match — one adjusts  $C$  to rotate the ellipse vertical, then  $L$  to shrink the ellipse to a vertical line.

An outboard current sampler/phase detector/meter might also speed  $T$ -match tuning.

The above matchbox construction details were merely sketched. Instead the thrust of this note is to reveal that *tuning an L network need not be a tedious iterative process*. It can in theory be done in two steps by carefully observing two simple-to-measure voltages.

### Acknowledgements

This project grew from a challenge from Gary Adamowicz, WA1OXT, who is developing a competing approach. I thank Mike Blake, K9JRI, and Chuck Hawley, KE9UW, for their many helpful comments and suggestions.

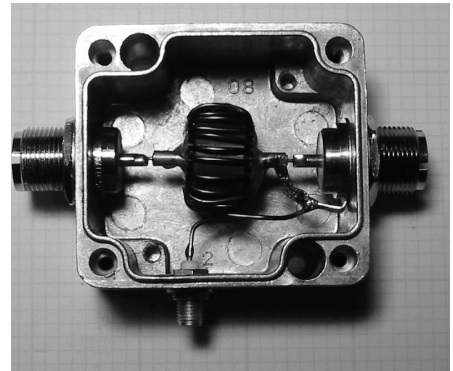


Figure 6 — The current sampler used to sample the difference between forward and reflected voltage.

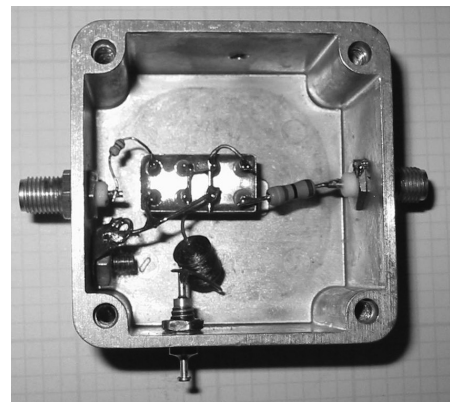


Figure 7 — A phase detector employing a MiniCircuits SBL-1.

*Chuck MacCluer, W8MQW, was first licensed in 1952 with the novice call sign WN8MQW, and progressed to Amateur Extra license. He has been very active in EME on 432 and 1296 MHz, and recently is active on SSB, CW, and digital modes on 160, 80, and 40 meters. Chuck received a PhD in Mathematics in 1966 from the University of Michigan and is now Professor Emeritus of Mathematics at Michigan State University. Chuck is a Life member of ARRL, IEEE, SIAM, and ASHRAE.*

### Notes

<sup>1</sup>The intermediate quotient of [EQ 3] is the core computation that underlies the Smith Chart. ARRL item no. 0413, available from your ARRL dealer, or from the ARRL Store, Telephone toll-free in the US 888-277-5289, or 860-594-0355, fax 860-594-0303; [www.arrl.org/shop/](http://www.arrl.org/shop/); [pubsales@arrl.org](mailto:pubsales@arrl.org).

<sup>2</sup>L. Phipps, N8LP, “The LP-100 Wattmeter”, *QEX*, Jan/Feb 2006.