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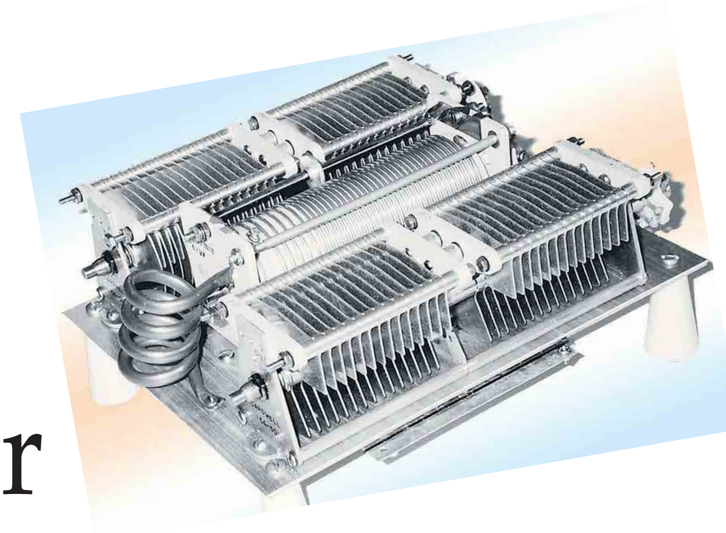
On the Quest for an Ideal Antenna Tuner



This discussion of optimum antenna tuners for feeding antennas through balanced lines will clear up some common misconceptions.

Introduction

The function of an antenna system tuning unit (ASTU) is to transform the impedance at the input end of the transmission line to the 50 Ω impedance required by the transmitter, and so establish a conjugate match for maximum power transfer to the antenna system. Over the years, radio amateurs have devised many circuits for doing this. At one time, when open wire transmission line was in common use, transmitters had link coupled tuned circuits to provide the balanced output needed to feed a balanced antenna system such as a ladder line-fed multiband dipole.

Coaxial cable feed lines are now more commonly used, and most commercial and homebrew antenna tuners use unbalanced networks. Thus, to feed an antenna system, such as a multiband dipole, a balun is required at the point where the coaxial cable connects to the balanced antenna system. If open wire transmission line is used, the balun is usually placed between the ASTU and the balanced line, where the VSWR can be high. This stresses the balun, and could lead to balun failure. In addition, power loss can be considerable.

Most commercial ASTUs used by amateurs employ a high-pass T network. Dean Straw, N6BV (and others) have developed computer simulation programs that make it possible to estimate matching range, internal losses and peak RF voltages for T, π and L section networks. This program is provided with recent editions of *The ARRL Antenna Book,*[1] and example calculations are given, in aid of selecting the most practical tuner. The high power tuner designed and built by N6BV is a T section matching network.[2] James Garland, W8ZR, using the ARRL program, describes a very professional looking automatic T network-based tuner in his *QST* article series.[3]

The principal differences between N6BV's tuner and W8ZR's tuner are as follows:

- N6BV has constructed his tuner so that the "ground" terminal of the unbalanced T network can be isolated from chassis ground. That is, the chassis is not hot but the unbalanced RF network can be floated with respect to the chassis and transceiver ground. Hence, a balun can be inserted at the input to the ASTU (between the transmitter and the tuner), and the output terminals are in effect balanced with respect to ground. W8ZR's tuner is the more usual unbalanced network arrangement, and so to feed a balanced transmission line a balun is inserted between the tuner and the transmission line (where the VSWR can be high); and,
- W8ZR has automated his tuner, which is certainly an accomplishment that I could not do. The inductor in his circuit will certainly have a Q factor that is high compared with the compact commercial automatic tuners, which are less efficient when used to tune antenna systems that have a large capacitive input impedance.[4]

Simplifying the Network

W8ZR's three part article begins with a brief review of antenna system tuning units and follows with a description of versions of the T network. He decides in his quest for the "ideal tuner" to base his design on the popular T network. A consideration of the L network is provided in the following comment in a footnote:

"For tuners dedicated to specific antennas, many amateurs swear by the simple L network. However, the L network cannot match both low and high impedance loads without changing the configuration, and this shortcoming makes it unsuitable for a general purpose antenna tuner."

I have used L networks for 50 years[5] to match antenna systems, for ease of matching and to allow visualizing what I am doing. The procedure that I use is to resonate the antenna by a series reactance, and then use an L network to match the resistive component of the antenna's impedance to the required 50 Ω impedance. If the antenna's resistance is less than 50 Ω, a two element L-C network will do the trick. If the antenna's impedance is greater than 50 Ω, a reversed L network must be used, and so the two element L network then becomes a three element network, or a T network. A rearrangement of the circuit elements can usually provide a match using a two element L network for almost any antenna system impedance (see below).

With the L network or the reversed L network referred to by W8ZR, the so-called "shortcoming" is not really a problem. A single pole double throw switch can be used to change the configuration, as shown in Figure 1. When impedance matching, the user of the T has to tune three knobs to match while an L matching network requires only two (and one less variable RF component). In the words of my Newfoundlander colleague Joe Craig, VO1NA, "the user of a T wastes

[1]Notes appear on page 39.

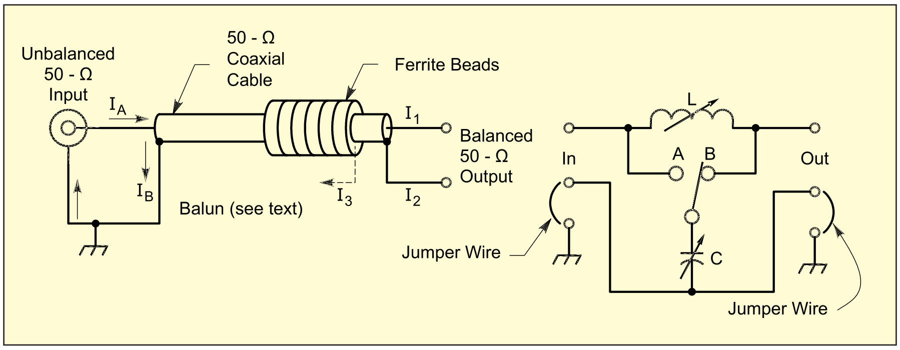


Figure 1—A simple reversible L matching network. Typical values for the inductor and capacitor: L = 30 mH, C is a dual-section 19-202 pF/section (Cardwell-Johnson 153-503-1), arranged so that it can be operated as a single section or with the two sections in parallel to keep the minimum capacity as low as possible (see Figure 2 and text).

time mucking about with a 'useless knob,' since an L network is just as useful for getting a low VSWR."[6]

To tune balanced loads, the "ground" connection for the network (normally connected to chassis ground) needs to be isolated from chassis ground. See Figure 1. The tuner input terminals could be a standard female chassis mount coaxial connector, mounted on a small square piece of Plexiglas so it can be isolated from chassis ground. The jumper connections provide the necessary connections at the input and output terminals to chassis ground, as required for tuning unbalanced antenna systems. A 1:1 W2DU type current balun, ferrite beads over the coaxial cable, is shown in the figure. This balun is in fact an integral part of the coaxial line connecting the tuner to the transmitter.

A Case Study

I have for many years[7] been making the case that the best method to feed a multiband dipole is to use a balanced transmission line having the necessary length to reach from antenna terminals to transceiver, not as Louis Varney, G5RV, did (see the Appendix). To illustrate the usefulness of the simple L network, using component values given in Figure 1, I have used the *EZNEC pro* antenna modeling program *NEC 4D* provided by Roy Lewallen, W7EL, combined with the ARRL *TLA* Transmission Line Matching program. I have shown that indeed this network (with the switch in Position B) can be used to match a 102 foot (30.1 meter) dipole, popularly called a G5RV dipole, fed with 450 Ω windowed twin lead, on all amateur bands 3.5 MHz to 29.7 MHz. The dipole height is 40 feet (12.2 meters) and for my numerical model this is the length of the transmission line [Editor's note: The 19th and later editions of *The ARRL Antenna Book* bundled a *Windows* version called *TLW* (Transmission Line for *Windows*). *TLW* gives a more sophisticated set of values for nominal 450 Ω line compared with *TLA*.]

The results of this case study are tabulated in Table 1. Note that for 3.75 MHz the maximum capacitance of the 153-503-1 capacitor is perhaps just enough (including distributed capacitance), and clearly a low minimum capacitance is also required for the higher frequencies.

The computed tuner losses (including the loss in the transmission line) using the default values of the ARRL program are a dB or less.

A More Versatile Tuner

One can certainly find impedances that this simple circuit will not match. This difficulty can usually be overcome by interchanging L and C. For optimum performance the circuit shown in Figure 2 could be used, since this arrangement permits by switch selection the full range of versatility available with the L network. Switch S1 is used (as in Figure 1) to switch the shunt element from the input to the output terminals. Switch S2 is a four pole, three position switch that interchanges C and L or bypasses the tuner. Switch S3 selects either a single section of a dual section capacitor, or parallels the two sections. This arrangement is used to minimize the minimum capacity setting for the capacitor C. If C were a vacuum variable this switch would not be needed. This switch should be a multi-position switch to connect fixed capacitors across C (or external fixed capacitors could be added by means of connection to banana plugs mounted on a Plexiglas strip), which may be needed for the lower bands (40 meters and up).

The ground circuit arrangement should be as indicated in Figure 1. To make the tuner even more versatile, a 4:1 balun could be used[8] as an aid in matching some impedances. This is because, in effect, the balun is an integral part of the coaxial cable connecting the transceiver to the ASTU. Thus, the tuner will then match to 200 Ω, instead of 50 Ω (see below).

Some Aspects of the Balun Problem

I have, see above, and in published articles,[7,9] said that the place to put a balun is on the tuned side of an ASTU where the VSWR is 1:1. I have experimented with two versions of tuners feeding a system of off center fed dipoles—an antenna system that presents an unbalanced load to the balanced transmission line—because the arms of the dipole are different lengths. Each conductor of the transmission line sees a different impedance with respect to virtual ground. This antenna system makes an interesting load for an ASTU. I used (1) a balanced network with a voltage balun on the input "tuned side," and (2) an unbalanced network with a current balun on the output side (high VSWR).

Feeder currents I_1 and I_2 were monitored (by means of current transformers) at the input terminals of the balanced transmission line. The balanced transmission line was, in fact, two coaxial lines; we in effect had a center tap to measure

Table 1
Case Study by Simulation
98 foot 9 inch (30.1 meter) dipole height 40 feet, feeder 40 feet of 450 Ω windowed twin lead, average ground.

Frequency (MHz)	*Dipole Impedance (Ω)*	*Input Impedance of Antenna System (Ω)*	*Network Values*	*Transmission Line Loss (Tuner Loss)*
3.75	29 – *j*334.6	25.75 + *j*172.96	9.9 µH, 413.6 pF	0.8 dB (0.15 dB)
7.15	533.3 + *j*1244	56.23 + *j*22.47	0.6 µH, 325.6 pF	0.18 dB (0.02 dB)
14.15	114.8 – *j*54.5	154.13 + *j*243.56	1.7 µH, 98.9 pF	0.15 dB (0.09 dB)
18.1	2066 + *j*1573	65 + *j*21.6	0.3 µH, 122 pF	0.25 dB (0.02 dB)
21.15	289.3 – *j*1048	863.1 + *j*1681.2	3.3 µH, 20.5 pF	0.41 dB (0.24 dB)
24.925	201.1 + *j*313.9	477.9 + *j*600	1.5 µH, 31.9 pF	0.14 dB (0.13 dB)
29.0	2108 – *j*1502	67.4 + *j*21.35	0.2 µH, 75.1 pF	0.29 dB (0.02 dB)

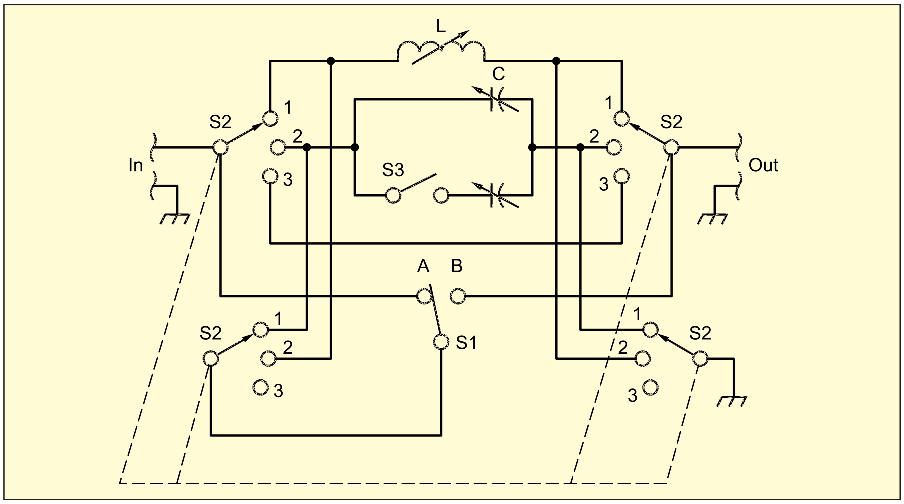


Figure 2—A versatile L matching network. This circuit is basically the same as shown in Figure 1 (see text for details), but the component arrangement can be changed.

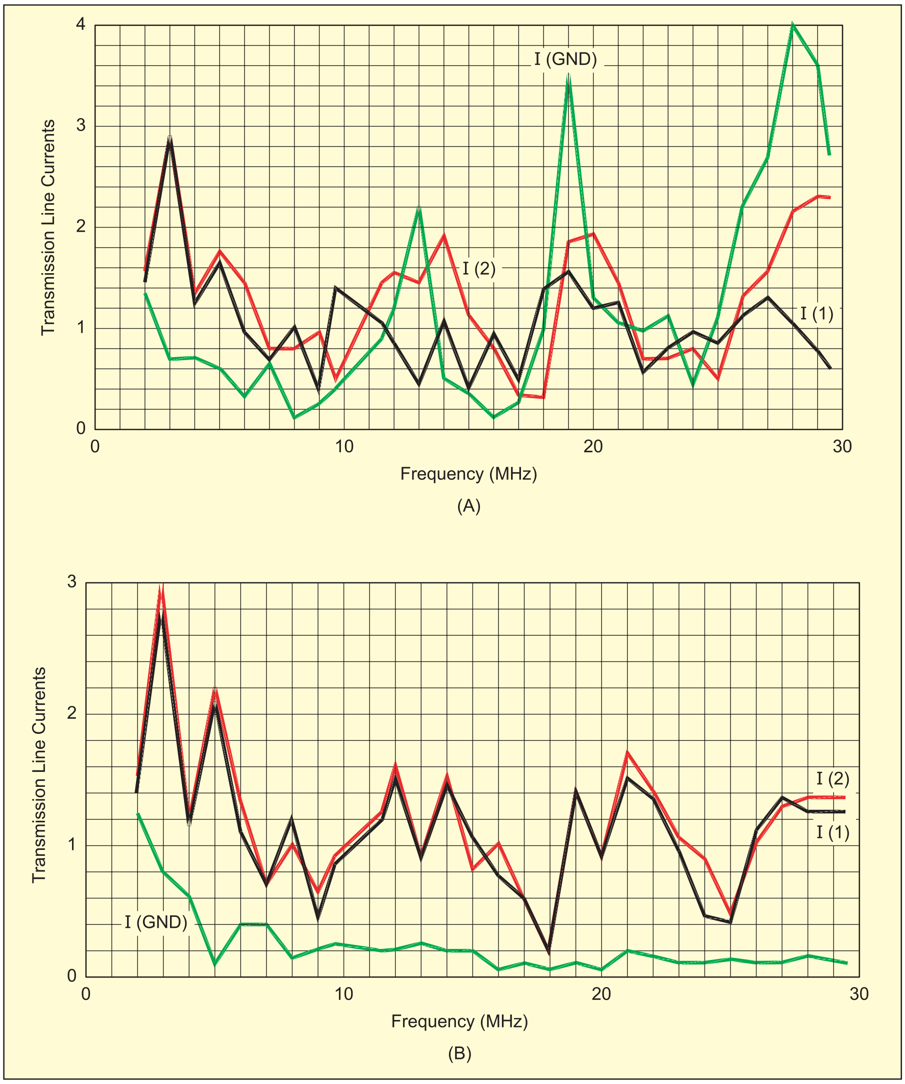


Figure 3—At A, transmission line currents (peak values shown for 100 W transmitter output power) for an off center fed dipole, tuned by a balanced tuner and a voltage balun on the input side of the tuner. At B, transmission line currents (peak values for 100 W transmitter output power) for the same antenna, tuned by an unbalanced T network and a ferrite bead choke (W2DU) current balun (balun on the output end of the tuner). This illustrates that a current balun will indeed "force" the currents to be equal better than will a voltage balun. [This test did not directly address the issue of where the balun should be placed—at the input or at the output of a tuner.—*Ed.*]

current in the center tap lead to ground, I_{gnd}. That is, the shields of the coaxial cables are connected at the transmitter end and at the antenna end and, at the transmitter end, the shields connect to chassis ground. The results of this experiment are shown in Figure 3. This experiment tells us that even though a balanced tuner was used, it is necessary to use a current balun to force almost equal currents into the two conductors of the balanced line. For our transmission line, if the currents are not exactly equal, there will be a difference current flowing in the ground lead that connects the braids of the two coaxial cables to the tuner ground. Peak I_{gnd} currents are less (except for one value) for the case where the balun is on the output side of the tuner (high VSWR) and, although the balun is certainly doing its job (equal currents into an unbalanced two conductor load), the balun losses are increased.

In other experiments with baluns placed at the output terminals of an unbalanced tuner, in cases where the VSWR can be high, we can have problems with baluns. The W2DU type balun (ferrite beads over coax) gets very hot at kW power levels. Increasing the number of beads from 100 to 300 helped the heat problem, but we still had excessive balun power loss. Various versions of the bifilar wound choke type balun[10] on a ferrite toroid failed (blue flame and smoke) during testing (carbon burns damaged the insulation because of arcing between turns), and I even cracked the ferrite core of a so-called commercial 10 kW balun.

Providing the VSWR is not too high, it does not matter where the balun is located (input or output end), but power loss will be smaller if the balun is on the input side.

Finally, I will comment on using a tuner with an unbalanced network, but with a "floating ground," compared with using a balanced tuner. In my view there is no circuit performance difference, excepting that the balanced network component values are different, and at least three components are needed rather than two. The current balun insures equal transmission line conductor currents in both cases. Stray capacitance will also be slightly different.[11]

Finally, looking again at Web discussions, it should be noted that an unbalanced network with a "floating ground" means the so-called "ground end" of the network is not connected to chassis ground. The chassis is not "hot," the chassis is grounded, but the network is floating.

Concluding Remarks

The L matching network that I describe, using a switch arrangement to provide different circuit arrangements, is indeed a very versatile tuner. It is not, however, *an* *innovative design that can provide performance better than any homebrew ASTU ever created*. It can be designed to handle antenna systems having a high reactance. It has so far proven to be just as useful for getting a 1:1 VSWR as other tuners I have used, for example T matching networks made by Vectronics and by MFJ; and a π matching network made by R. L. Drake (I still have and use the performance proven Drake MN-1000).

A final comment on power loss in the ASTUs. From the point of view of resistance match, the L network can be used to provide a low loss (typically less than a dB) resistance match to almost any load resistance (from a few ohms to thousands of ohms). Tuner loss when using the T network increases with decrease in load resistance, and tuner loss becomes significant for load resistances less than the desired match load resistance (50 Ω). See, for example, Figure 3 in Part 1 of the article by W8ZR. Both types of tuners (T or L) suffer increasing loss when the decrease in the resistive component of the load impedance is associated with an increase in the capacitive reactance of the load (for example, tuning electrically small antennas). But this loss is unavoidable, since the capacitive reactance of the load has to be canceled by a conjugate inductive reactance provided by the tuner.

Let me consider, for point of illustration, a case study—the matching an impedance of $Z_a = 5 - j400\ \Omega$ at a frequency 3.75 MHz. Tuner loss (using default values for the ARRL program) for the L section network is 2 dB (according to *TLA*). Tuning the same load with a T matching network yields a loss of 4.1 dB to 2.1 dB, depending on the setting of the output series capacitor (100 pF to 800 pF, respectively). This example illustrates that for the T there can be a range of settings that lead to a 1:1 VSWR and that some settings are better than others.

In other words, a low resistance high capacitive reactance is not good for anybody's tuner. That is why electrically short antennas should be tuned by a high Q (low loss) base loading coil.

Dean Straw, N6BV, noted, on reading an earlier version of this article, that if I had used a longer transmission line (62 feet instead of 40 feet) for my G5RV dipole, I would have to match a different impedance at 3.75 MHz, $59 + j600\ \Omega$ (instead of $26 + j173\ \Omega$). He noted that a high-pass T network with the maximum output series capacity of 400 pF will match this impedance, and the loss will be 0.09 dB. My L network will match this impedance (series L on the input side, shunt C) but the loss is 0.33 dB. The T network is better?

The question mark—is it? If instead of asking the ASTU to match to 50 Ω, suppose we match to 200 Ω. An L network (shunt L, series C on the output side) will tune and match this antenna impedance, and the loss will be 0.04 dB.

Finally, I noted above that most commercial tuners use a T network, with the balun on the output side of the tuner. At least two tuners (but I have seen and used only one) employ an L network. One is a tuner made a number of years ago by UPC (Unique Wire Products), their "Unique Wire Tuner" (I have one). The other is the Ten-Tec Model 238B, a high power tuner in current production that utilizes an L network.[12] This L network has a series inductance with a switching arrangement to move the combination fixed and variable capacitors between input and output to match high and low impedances.

Professional (Laboratory type) L matching networks that I have used for high-power work-related projects all used quality components: Jennings vacuum variable capacitors and silver plated edge wound inductors made by Gates (Q factor 500 compared with 200, the default value for the ARRL program). In my experience, antenna engineers usually employ the L matching network to tune antenna systems. The T and π matching networks are used (on the tuned side) for phased array antenna systems, since a resistance match (to control current) can be realized for the required phase lag needed for the directional pattern. The phase lag for the L matching network is what it turns out to be, depending on the impedances to be matched.

I will be interested to hear from anyone who might construct my versatile L matching network shown in Figure 2. A comment for those who do: matching some impedances on some bands may appear (at first) to be a bit tricky, since tuning the knobs may initially have no observable effect on VSWR. This may be because you are using the wrong network configuration. There are four configurations. Sometimes more than one configuration will tune the antenna, sometimes only one. With the correct network configuration tuning will be very precise, and a VSWR of 1:1 will be achievable. Each time you tune to a new band, log the switch positions, and the capacitor and inductor dial settings, for convenience when returning to the same frequency or band.

Notes

1 *The ARRL Antenna Book*, 20th edition, available from your local dealer or the ARRL Bookstore for $39.95 plus shipping. Order number 9043. Telephone toll-free in the US 888-277-5289, or 860-594-0355; **www.arrl.org/shop/**; **pubsales@arrl.org**.

2 *The ARRL Antenna Book*, 20th edition, Chapter 25, pp 15-18.

3 J. Garland, "The EZ Tuner—Parts 1, 2 and 3," *QST*, Apr 2002, pp 40-43, May 2002, pp 28-34 and Jun 2002, pp 33-36.

4 J. Belrose, "Automatic Antenna Tuners for Wire Antennas," *QST* (Technical Correspondence), Apr 1994, p 84.

5 J. Belrose, "Short Antennas for Mobile Operation," *QST*, Sep 1953, pp 30-35, 108.

6 J. Craig, "Notes on the 'RL' (Reversible L) Impedance Matching Network," *VO News*, Feb 1987. (Out of print.) Copies are maintained by the Marconi Radio Club of Newfoundland.

7 J. Belrose, and P. Bouliane, "On Center-Fed Multiband HF Dipoles," *ARRL Antenna Compendium Volume 4*, 1995, pp 103-111.

8 J. Belrose, "Transforming the Balun," *QST* Jun 1991, pp 30-33.

9 J. Belrose, and P. Bouliane, "The Off-Center-Fed Dipole Revisited: A Broadband, Multiband Antenna," *QST*, pp 28-33, Aug 1990.

10 J. Sevick, *Understanding, Building and Using Baluns and Ununs*. Available from the ARRL Bookstore for $19.95 plus shipping. Order number 8982. Telephone toll-free in the US 888-277-5289, or 860-594-0355; **www.arrl.org/shop**; **pubsales@arrl.org**.

11 To use *TLA* to analyze a balanced network, change the default value for the input impedance to 25 Ω (instead of 50 Ω). We want to match half the antenna's impedance to half the desired input impedance. TLA tells us that the loss for this network is the same (in dB) as that for the unbalanced network, but do not get confused. This loss in dB is a power loss for half the transmitter power, so the total loss is identical.

12 J. Parise, "Product Review—*QST* Reviews Five High-Power Antenna Tuners," *QST*, Feb 2003, pp 69-75.

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