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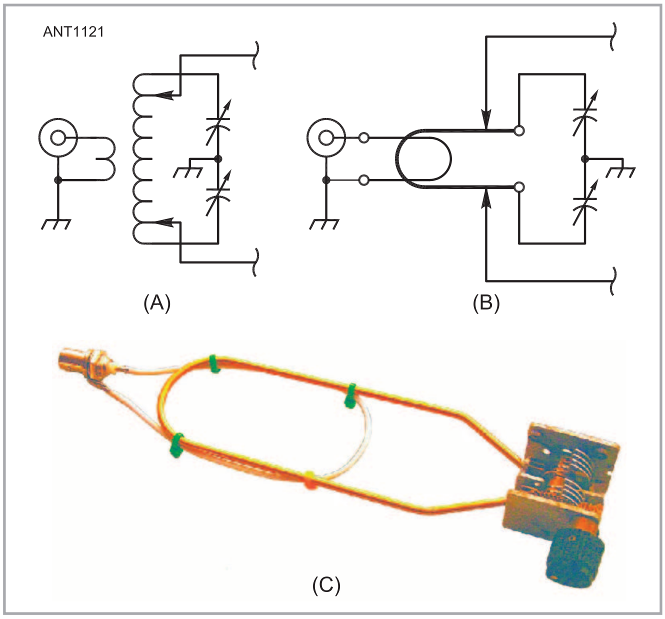


**Figure 24.8 — Balanced tuner configurations. At (A) conventional tapped coil based tuner, at (B) the hairpin equivalent. (C) shows a hairpin tuner for 144 MHz. The technique can be used from 10 meters through 70 cm.**

the additional components and the more complex mechanical arrangements to adjust more than one component at the same time with a single control.

The hairpin tuner configuration in **Figure 24.8** is a balanced tuner for use at VHF and UHF where solenoid-wound coils may have too much inductance. The tuner is described in the April 2009 *QST* article "Hairpin Tuners for Matching Balanced Antenna Systems" by John Stanley, K4ERO (the article is included on this book's CD-ROM).

### 24.2.6 Project: HIGH-POWER ARRL ANTENNA TUNER

Dean Straw, N6BV designed this antenna tuner with three objectives in mind: First, it would operate over a wide range of loads at full legal power. Second, it would be a high efficiency design, with minimal losses, including losses in the balun. This led to the third objective: Include a balun operating within its design impedances. For that reason this unit was designed with the balun at the input of the tuner.

This antenna tuner is designed to handle full legal power from 160 to 10 meters, matching a wide range of either balanced or unbalanced impedances. The network configuration is a high-pass T-network, with two series variable capacitors and a variable shunt inductor. See **Figure 24.9** for the schematic of the tuner. Note that the schematic is drawn in a somewhat unusual fashion. This is done to emphasize that the common connection of the series input and output capacitors and the shunt inductor is actually the subchassis used to mount these components away from the tuner's cabinet. The subchassis is insulated from the main cabinet using four heavy-duty 2-inch steatite (ceramic) stand-off insulators.

While a T-network type of tuner can be very lossy if care isn't taken, it is very flexible in the range of impedances it can match. Special attention has been paid to minimize power loss in this tuner — particularly for low-impedance

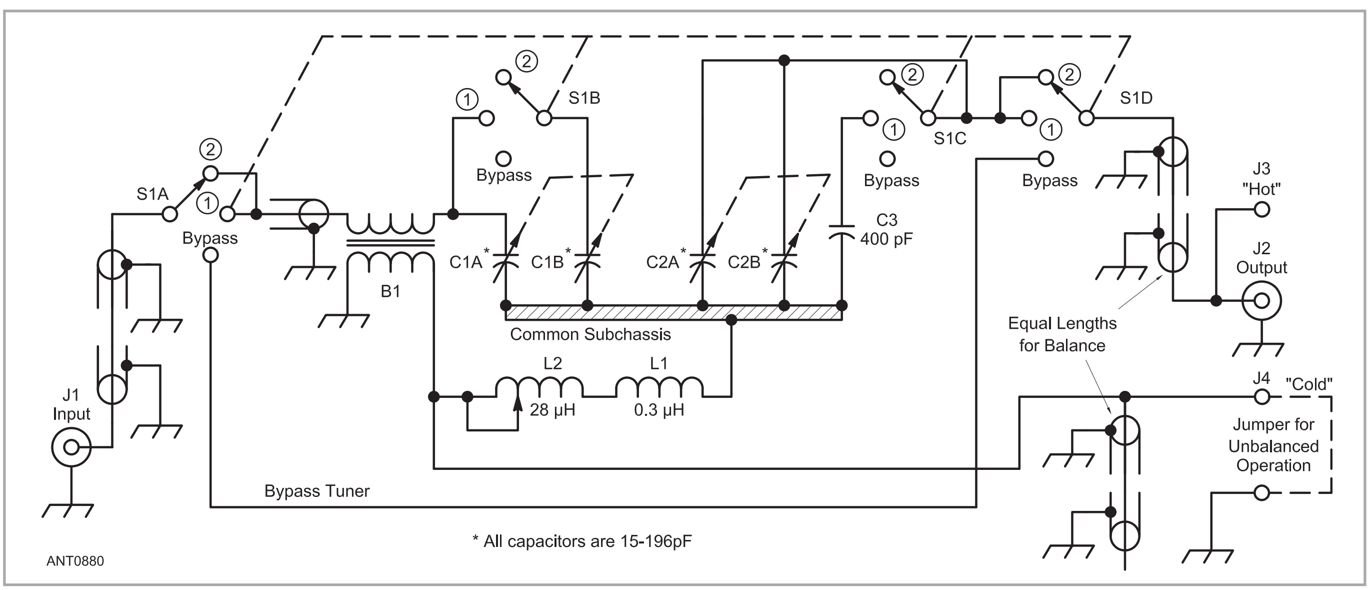


**Figure 24.9 — Schematic diagram of the ARRL Antenna Tuner.**

**B1 — Balun, 12 turns bifilar wound #10 AWG Formvar wire side-by-side on 2.4-inch OD Type 43 core, Amidon FT240-43. C1, C2 — 15-196 pF transmitting variable with voltage rating of 3000 V peak, such as the Cardwell-Johnson 154-507-1 (www.cardwellcondenser.com).**

**C3 — Home-made 400 pF capacitor; more than 10 kV voltage breakdown. Made from plate glass from a 5 × 7-inch picture frame, sandwiched in between a 4 × 6-inch, 0.030-inch thick aluminum plate and the electrically floating subchassis that also forms the common connection between C1, C2 and L1.**

**L1 — Fixed inductor, approximately 0.3 μH, 4 turns of ¼-inch copper tubing formed on 1-inch OD tubing.**

**L2 — Rotary inductor, 28 μH inductance, Cardwell 229-203-1, with steatite coil form (www.cardwellcondenser.com).**

loads on the lower-frequency amateur bands. Preventing arcing or excessive power dissipation for low-impedance loads on 160 meters represents the most challenging conditions for an antenna tuner designer. To see the computed range of impedances it can handle, look over the tables in the ASCII file called TUNER.SUM on this book's CD-ROM. The tables were created using the program *AAT*, described in an article on this book's CD-ROM.

For example, assume that the load at 1.8 MHz is 12.5 + *j* 0 Ω. For this example, the output capacitor C3 is set by the program to 750 pF. This dictates the values for the other two components. At 1.8 MHz, for typical values of component unloaded Q (200 for the coil), 7.9% of the power delivered to the input of the network is lost as heat. For 1500 W at the input, the loss in the network is thus 119 W. Of this, 98 W ends up in the inductor, which must be able to handle this without melting or detuning. The T-network must be used judiciously, lest it burn itself up or arc over internally.

One of the techniques used to minimize power lost in this tuner is the use of a relatively large output capacitor. (The output variable capacitor has a maximum capacitance of approximately 400 pF, including an estimated 20 pF of stray capacitance.) An additional 400 pF of fixed capacitance can be switched across the output variable capacitor on 80 or 160 meters. At 750 pF output capacitance at 1.8 MHz and a 12.5-Ω load, enough heat is generated at 1500 W input to make the inductor uncomfortably warm to the touch after 30 seconds of full-power key-down operation, but not enough to destroy the roller inductor.

For a variable capacitor used in a T-network tuner, there is a trade-off between the range of minimum to maximum capacitance and the voltage rating. This tuner uses two identical Cardwell-Johnson dual-section 154-507-1 air-variable capacitors, rated at 3000 V. Each section of the capacitor ranges from 15 to 196 pF, with an estimated 10 pF of stray capacitance associated with each section. Both sections are wired in parallel for the output capacitor, while they are switched in or out using switch S1B for the input capacitor. This strategy allows the minimum capacitance of the input capacitor to be smaller to match high-impedance loads at the higher frequencies.

The roller inductor is a high-quality Cardwell 229-203-1 unit, with a steatite body to enable it to dissipate heat without damage. The roller inductor is augmented with a series 0.3 µH coil made of four turns of ¼-inch copper tubing formed on a 1-inch OD form (which is then removed). This fixed coil can dissipate more heat when low values of inductance are needed for low-impedance loads at high frequencies. Both variable capacitors and the roller inductor use ceramic-insulated shaft couplers, since all components are hot electrically. Each shaft goes through a grounded bushing at the front panel to make sure none of the knobs is hot for the operator.

The balun allowing operation with balanced loads is placed at the input of this antenna coupler, rather than at the output where it is commonly placed in other designs. Putting the balun at the input stresses the balun less, since it is operating into its design resistance of 50 Ω, once the network is

The 400-pF fixed capacitor is constructed using low-cost plate glass from a 5 × 7-inch picture frame, together with an approximately 4 × 6-inch flat piece of sheet aluminum that is 0.030-inch thick. The tuner's 10-½ × 8-inch subchassis forms the other plate of this homebrew capacitor. For mechanical rigidity, the subchassis uses two ¹⁄₁₆-inch thick aluminum plates. The ¹⁄₁₆-inch thick glass is epoxied to the bottom of the subchassis. The 4 × 6-inch aluminum sheet forming the second plate of the 400-pF fixed capacitor is in turn epoxied to the glass to make a stable, high-voltage, high-current fixed capacitor. Two strips of wood are screwed down over the as-

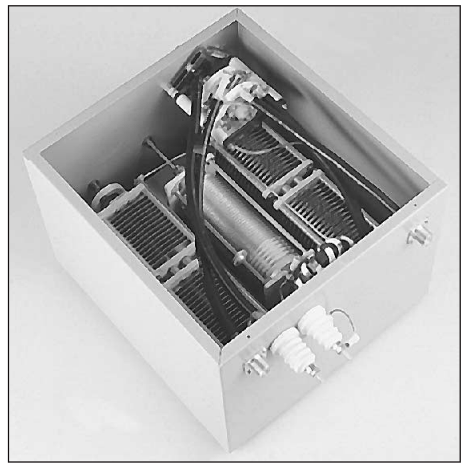

**Figure 24.10 — Interior view of the ARRL Antenna Tuner. The balun is mounted near the input coaxial connector. The two feedthrough insulators for balanced-line operation are located near the output coaxial unbalanced connector. The Radioswitch Corporation high-voltage switch is mounted to the front panel. Ceramic-insulated shaft couplers through ground ¼-inch panel bushings couple the variable components to the knobs.**

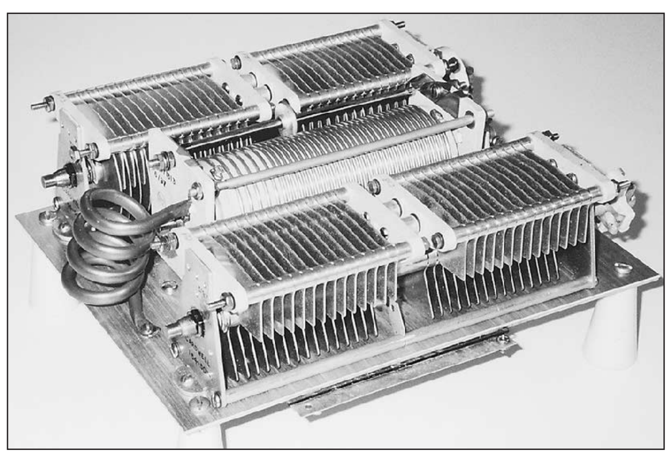

**Figure 24.11 — Bottom view of the subchassis, showing the four white insulators used to isolate the subchassis from the cabinet. The homemade 400-pF fixed capacitor C3 is epoxied to the bottom of the subchassis, sandwiching a piece of plate glass as the dielectric between the subchassis and a flat piece of aluminum.**

tuned. For unbalanced (coax) operation, the common point at the bottom of the roller inductor is grounded using a jumper at the feedthrough insulator at the rear of the cabinet. In the prototype antenna tuner, the balun was wound using 12 turns of #10 AWG Formvar insulated wire, wound side-by-side in bifilar fashion on a 2.4-inch OD core of type 43 material. After 60 seconds of key-down operation at 1500 W on 29.7 MHz, the wire becomes warm to the touch, although the core itself remains cool. We estimated that 25 W was being dissipated in the balun. Alternatively, if you don't intend to use the tuner for balanced lines, you can delete the balun altogether.

In our unit, a piece of RG-213 coax is used to connect the output coaxial socket (in parallel with the "hot" insulated feedthrough insulator) to S1D common. This adds approximately 15 pF fixed capacitance to ground. An equal length of RG-213 is used at the "cold" feedthrough insulator so that the circuit remains balanced to ground when used with balanced transmission lines. When the cold terminal is jumpered to ground for unbalanced loads (that is, using the coax connector), the extra length of RG-213 is shorted out and is thus out of the circuit.

### Construction

The prototype antenna tuner was mounted in a Hammond model 14151 heavy-duty, painted steel cabinet. This is an exceptionally well-constructed cabinet that does not flex or jump around on the operating table when the roller inductor shaft is rotated vigorously. The electrical components inside were spaced well away from the steel cabinet to keep losses down, especially in the variable inductor. There is also lots of clearance between components and the chassis itself to prevent arcing and stray capacitance to ground. See **Figures 24.10** and **24.11** showing the layout inside the cabinet of the prototype tuner. **Figure 24.12** shows a view of the front panel. The turns-counter dial for the roller inductor was purchased from Surplus Sales of Nebraska.

sembly underneath the subchassis to make sure the capacitor stays in place. The estimated breakdown voltage is 12,000 V. See **Figure 24.13** for a bottom view of the subchassis.

Note: The dielectric constant of the glass in a cheap ($2 at Wal-Mart) picture frame can vary. The final dimensions of the aluminum sheet secured with one-hour epoxy to the glass was varied by sliding it in and out until 400 pF was reached, while the epoxy was still wet, using an Autek RF-1 antenna analyzer as a capacitance meter. Don't let epoxy slop over the edges — this can arc and burn permanently!

S1 is bolted directly to the front of the cabinet. S1 is a special high-voltage RF switch from Radio Switch Corporation, with four poles and three positions. It is not inexpensive, but we wanted to have no weak points in the prototype unit. A more frugal ham might want to substitute two more common surplus DPDT switches for S1. One switch would bypass the tuner when the operator desires to do that. The other would switch the additional 400-pF fixed capacitor across variable C3 and also parallel both sections of C1 together for the lower frequencies. Both switches would have to be capable of handling high RF voltages, of course.

### Operation

The ARRL Antenna Tuner is designed to handle the output from transmitters that operate up to 1.5 kW. An external SWR indicator is used between the transmitter and the antenna tuner to show when a matched condition is attained. Most often the SWR meter built into the transceiver is used to tune the tuner and then the amplifier is switched on. The builder may want to integrate an SWR meter in the tuner circuit between J1 and the arm of S1A.

Never *hot switch* an antenna tuner, as this can damage both transmitter and tuner. For initial setting below 10 MHz, set S1 to position 2 and C1 at midrange, C2 at full mesh. With a few watts of RF, adjust the roller inductor for a decrease in reflected power. Then adjust C1 and L2 alternately for the


**Figure 24.12 — Front panel view of the ARRL Antenna Tuner as built by Lee Jennings, ZL2AL. Lee used vacuum-variable capacitors in the construction of his tuner.**

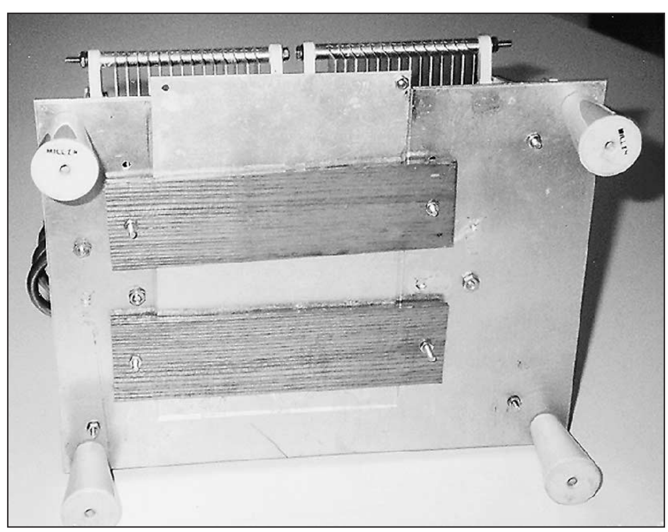

**Figure 24.13 — Bottom view of subchassis, showing the two strips of wood ensuring mechanical stability of the C3 capacitor assembly.**

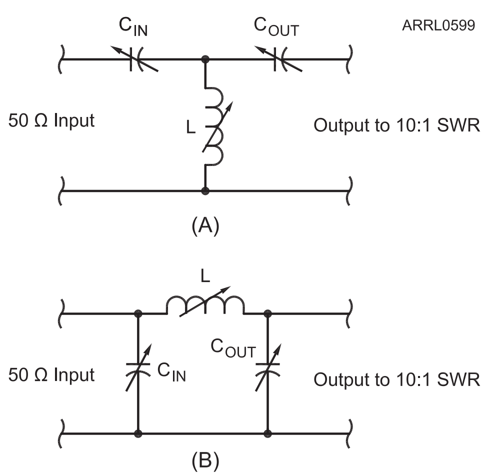


**Figure 24.14 — Schematic diagrams of a high-pass T-network (A), pi-network (B), and a low-pass L-network (C). Tables 24.3 to 24.5 give component values at 1.8, 3.5, and 30 MHz to match different values of load impedances to 50 Ω.**

**Table 24.3**
**Component Requirements for High-Pass (Shunt L) T-Network Antenna Tuners at 10:1 SWR**

| *Frequency/Z (Ω)* | *Capacitor* | | *Inductor (µH)* | *Capacitor Voltage ($V_P$)* | | *Efficiency (%)* |
|---|---|---|---|---|---|---|
| *1.8 MHz* | *Input (pF)* | *Output (pF)* | | *100 W* | *1500 W* | |
| 5 | 1136 | 3000 | 2.1 | 180 | 710 | 96 |
| 500 | 548 | 500 | 13.9 | 323 | 1250 | 98 |
| 25 + *j*100 | 343 | 300 | 10.3 | 790 | 3070 | 92 |
| 25 – *j*100 | 170 | 300 | 20 | 1040 | 4030 | 86 |
| 250 + *j*250 | 308 | 200 | 10.5 | 380 | 1470 | 98 |
| 250 – *j*250 | 337 | 300 | 16.9 | 525 | 2030 | 96 |
| *Frequency/Z (Ω)* | *Capacitor* | | *Inductor (µH)* | *Capacitor Voltage ($V_P$)* | | *Efficiency (%)* |
| *3.5 MHz* | *Input (pF)* | *Output (pF)* | | *100 W* | *1500 W* | |
| 5 | 563 | 1500 | 1.1 | 190 | 720 | 96 |
| 500 | 265 | 200 | 7.3 | 343 | 1330 | 98 |
| 25 + *j*100 | 275 | 200 | 3.5 | 613 | 2373 | 95 |
| 25 – *j*100 | 104 | 200 | 8.6 | 880 | 3403 | 88 |
| 250 + *j*250 | 333 | 100 | 5.6 | 381 | 1475 | 98 |
| 250 – *j*250 | 136 | 100 | 10.8 | 670 | 2600 | 94 |
| *Frequency/Z (Ω)* | *Capacitor* | | *Inductor (µH)* | *Capacitor Voltage ($V_P$)* | | *Efficiency (%)* |
| *30 MHz* | *Input (pF)* | *Output (pF)* | | *100 W* | *1500 W* | |
| 5 | 79 | 200 | 0.12 | 160 | 640 | 96 |
| 500 | 29 | 50 | 0.77 | 370 | 1470 | 97 |
| 25 + *j*100 | 91 | 30 | 0.24 | 400 | 1560 | 98 |
| 25 – *j*100 | 24 | 100 | 0.46 | 440 | 1710 | 93 |
| 250 + *j*250 | 36 | 100 | 0.9 | 300 | 1150 | 98 |
| 250 – *j*250 | 29 | 100 | 0.6 | 360 | 1410 | 97 |

lowest possible SWR, also adjusting C2 if necessary. If a satisfactory SWR cannot be achieved, try S1 at position 3 and repeat the steps above. Finally, increase the transmitter power to maximum and touch up the tuner's controls if necessary. When tuning, keep your transmissions brief and identify your station.

For operation above 10 MHz, again initially use S1 set to position 2, and if SWR cannot be lowered properly, try S1 set to position 3. This will probably be necessary for 24 or 28-MHz operation. In general, you want to set C2 for as much capacitance as possible, especially on the lower frequencies. This will result in the least amount of loss through the antenna tuner. The first position of S1 permits switched-through operation direct to the antenna when the antenna tuner is not needed.

### Comments

Surplus coils and capacitors are suitable for use in this circuit. L2 should have at least 25 µH of inductance and be constructed with a steatite body. There are roller inductors on the market made with Delrin plastic bodies but these are very prone to melting under stress and should be avoided. The tuning capacitors need to have 200 pF or more of capacitance per section at a breakdown voltage of at least 3000 V. You could save some money by using a single-section variable capacitor for the output capacitor, rather than the dual-section unit we

**Table 24.4**
**Component Requirements for Low-Pass (Series L) L-Network Antenna Tuners at 10:1 SWR**

| Frequency/Z (Ω) | Capacitor | | Inductor (μH) | Capacitor Voltage ($V_P$) | | Efficiency (%) |
|---|---|---|---|---|---|---|
| 1.8 MHz | Input (pF) | Output (pF) | | 100 W | 1500 W | |
| 5 | 5254 | n/a | 1.34 | 100 | 390 | 98 |
| 500 | n/a | 536 | 13.5 | 310 | 1210 | 98 |
| 25 + *j*100 | n/a | 1408 | 12 | 290 | 1120 | 98 |
| 25 – *j*100 | 1760 | n/a | 11 | 100 | 390 | 97 |
| 250 + *j*250 | n/a | 713 | 13 | 310 | 1210 | 98 |
| 250 – *j*250 | n/a | 359 | 13 | 310 | 1210 | 98 |
| *Frequency/Z (Ω)* | *Capacitor* | | *Inductor (μH)* | *Capacitor Voltage ($V_P$)* | | *Efficiency (%)* |
| 3.5 MHz | Input (pF) | Output (pF) | | 100 W | 1500 W | |
| 5 | 2700 | n/a | 0.69 | 100 | 400 | 98 |
| 500 | n/a | 275 | 6.8 | 310 | 1200 | 98 |
| 25 + *j*100 | n/a | 720 | 6.2 | 290 | 1120 | 98 |
| 25 – *j*100 | 926 | n/a | 5.6 | 100 | 390 | 97 |
| 250 + *j*250 | n/a | 367 | 6.8 | 310 | 1210 | 98 |
| 250 – *j*250 | n/a | 184 | 6.8 | 310 | 1210 | 98 |
| *Frequency/Z (Ω)* | *Capacitor* | | *Inductor (μH)* | *Capacitor Voltage ($V_P$)* | | *Efficiency (%)* |
| 30 MHz | Input (pF) | Output (pF) | | 100 W | 1500 W | |
| 5 | 315 | n/a | 0.08 | 100 | 390 | 98 |
| 500 | n/a | 32 | 0.79 | 310 | 1210 | 98 |
| 25 + *j*100 | n/a | 85 | 0.72 | 290 | 1120 | 98 |
| 25 – *j*100 | 140 | n/a | 0.58 | 100 | 390 | 97 |
| 250 + *j*250 | n/a | 43 | 0.79 | 310 | 1210 | 98 |
| 250 – *j*250 | n/a | 22 | 0.79 | 310 | 1210 | 98 |

**Table 24.5**
**Component Requirements for Low-Pass Pi-Network Antenna Tuners at 10:1 SWR**

| Frequency/Z (Ω) | Capacitor | | Inductor (μH) | Capacitor Voltage ($V_P$) | | Efficiency (%) |
|---|---|---|---|---|---|---|
| 1.8 MHz | Input (pF) | Output (pF) | | 100 W | 1500 W | |
| 5 | 5256 | 500 | 1.4 | 100 | 390 | 98 |
| 500 | 2602 | 1000 | 9.6 | 310 | 1200 | 96 |
| 25 + *j*100 | 966 | 1500 | 12.5 | 280 | 1110 | 97 |
| 25 – *j*100 | 3410 | 500 | 7.5 | 280 | 1100 | 96 |
| 250 + *j*250 | 1931 | 1000 | 11.3 | 310 | 1210 | 97 |
| 250 – *j*250 | 1284 | 500 | 12.9 | 310 | 1210 | 97 |
| *Frequency/Z (Ω)* | *Capacitor* | | *Inductor (μH)* | *Capacitor Voltage ($V_P$)* | | *Efficiency (%)* |
| 3.5 MHz | Input (pF) | Output (pF) | | 100 W | 1500 W | |
| 5 | 2706 | 500 | 0.7 | 100 | 390 | 98 |
| 500 | 1287 | 500 | 5.1 | 310 | 1200 | 96 |
| 25 + *j*100 | 643 | 800 | 6.2 | 280 | 1110 | 97 |
| 25 – *j*100 | 1886 | 300 | 3.7 | 280 | 1430 | 95 |
| 250 + *j*250 | 934 | 500 | 6.0 | 310 | 1200 | 97 |
| 250 – *j*250 | 859 | 300 | 6.2 | 310 | 1200 | 97 |
| *Frequency/Z (Ω)* | *Capacitor* | | *Inductor (μH)* | *Capacitor Voltage ($V_P$)* | | *Efficiency (%)* |
| 30 MHz | Input (pF) | Output (pF) | | 100 W | 1500 W | |
| 5 | 321 | 200 | 0.08 | 100 | 390 | 98 |
| 500 | 118 | 50 | 0.7 | 310 | 1200 | 97 |
| 25 + *j*100 | 103 | 100 | 0.7 | 290 | 1100 | 97 |
| 25 – *j*100 | 205 | 30 | 0.5 | 285 | 1100 | 96 |
| 250 + *j*250 | 71 | 50 | 0.8 | 310 | 1200 | 97 |
| 250 – *j*250 | 77 | 30 | 0.8 | 310 | 1200 | 97 |

used. It should have a maximum capacitance of 400 pF and a voltage rating of 3000 V.

Measured insertion loss for this antenna tuner is low. The worst-case load tested was four 50-Ω dummy loads in parallel to make a 12.5-Ω load at 1.8 MHz. Running 1500 W key down for 30 seconds heated the variable inductor enough so that you wouldn't want to keep your hand on it for long. None of the other components became hot in this test.

At higher frequencies (and into a 50-Ω load at 1.8 MHz), the roller inductor was only warm to the touch at 1500 W key down for 30 seconds. The #10 AWG balun wire, as mentioned previously, was the warmest component in the antenna tuner for frequencies above 14 MHz, although it was far from catastrophic.

### 24.2.7 GENERAL PURPOSE TUNER DESIGNS

Several antenna tuner designs were created by Joel Hallas, W1ZR, for the book *The ARRL Guide to Antenna Tuners*. The *TLW* program was used to determine component values for a set of common load impedances and three popular antenna tuner circuits shown in **Figure 24.14**. **Tables 24.3** to **24.5** show the required component values to match those load impedances at 1.8, 3.5 and 30 MHz, the extremes of HF operation for antenna tuners.

## 24.3 TRANSMISSION LINE SYSTEM DESIGN

The previous sections of this chapter looked at system design from the point of view of the transmitter, examining what could be done to ensure that the transmitter load is its design load of 50 Ω. In this section, we will look at antenna system design from the point of view of the transmission line.

### 24.3.1 TRANSMISSION LINE IMPEDANCE TRANSFORMATION

For the purposes of designing a transmission line system, the line can be also be used for its impedance transforming properties. A certain value of load impedance, consisting of a resistance and reactance, at the end of the line is transformed into another value of impedance at the input of the line. The amount of transformation is determined by the electrical length of the line, its characteristic impedance, and by the losses inherent in the line. The input impedance of a real, lossy transmission line is computed using the following equation

$$Z_{in} = Z_0 \times \frac{Z_L \cosh(\eta\ell) + Z_0 \sinh(\eta\ell)}{Z_L \sinh(\eta\ell) + Z_0 \cosh(\eta\ell)} \quad \text{(Eq 9)}$$

where

$Z_{in}$ = complex impedance at input of line = $R_{in} \pm j X_{in}$

$Z_L$ = complex load impedance at end of line = $R_l \pm j X_l$

$Z_0$ = characteristic impedance of line = $R_0 \pm j X_0$

$\eta$ = complex loss coefficient = $\alpha + j$ b

$\alpha$ = matched line loss attenuation constant, in nepers/unit length (1 neper = 8.688 dB, so multiply line loss in dB per unit length by 8.688)

$\beta$ = phase constant of line in radians/unit length (multiply electrical length in degrees by $2\pi$ radians/360 degrees)

$\ell$ = electrical length of line in same units of length as used for $\alpha$.

Solving this equation manually is tedious, since it incorporates hyperbolic cosines and sines of the complex loss coefficient, but it may be solved using a traditional paper Smith Chart or software that performs the Smith Chart operations. *TLW* can perform this transformation, but without Smith Chart graphics.

There are many devices available to amateurs that will measure the complex impedance at the input to a transmission line. Examples include the MFJ-259 family, the LP-100A wattmeter, the AIM-4170, or any VNA. Given the impedance in the series format, R + *j*X, *TLW* can make the transformations.

Let us go through an example. Use some of the values shown in the table for the 100-foot center-fed dipole in **Table 24.6**. Suppose we would like to use the antenna on 3.8 MHz. First of all, we should be feeding it with 450-Ω line as the losses with an SWR of 18.1:1 would be excessive with coaxial cable. After opening *TLW*, for the cable type select either of the 450-Ω Window Ladder Line options. (#551/#552 are used here) Set the length to 100 feet. Next enter the impedance value from the table, 39 – *j* 362. Other settings are: Frequency = 3.8, Source = Normal and select Load. At the bottom of the window, SWR at the line input is 14.86, the loss is 0.914 dB and the impedance at the line input is 203.19 – *j* 1024.75.

### 24.3.2 TRANSMISSION LINE SELECTION

Until you get into the microwave region where waveguides become practical, there are only two practical choices for transmission lines: coaxial cable and parallel-conductor lines such as open wire or ladder line, window line and twin-lead.

The shielding of coaxial cable offers advantages in incidental radiation and routing flexibility. Coax can be tied or taped to the legs of a metal tower without problem, for example. Some varieties of coax can even be buried underground. Coaxial cable can perform acceptably even with significant SWR. (Refer to information in the **Transmission Lines** chapter.) A drawback of coaxial line is its loss, particularly at moderate to high SWR. For example, a 100-foot length of RG-8 coax has 1.1 dB matched-line loss at 30 MHz.

**Table 24.6**
**Impedance of Center-Fed 100-Foot Flattop Dipole, 50 Feet High Over Average Ground**

| *Frequency MHz)* | *Antenna Feed point Impedance (Ω)* | *Loss for 100 ft 450-Ω Line (dB)* | *SWR* |
|---|---|---|---|
| 1.83 | 4.5 – *j* 1673 | 8.9 | 792.9 |
| 3.8 | 39 – *j* 362 | 0.5 | 18.3 |
| 7.1 | 481 + *j* 964 | 0.2 | 6.7 |
| 10.1 | 2584 – *j* 3292 | 0.6 | 16.8 |
| 14.1 | 85 – *j* 123 | 0.3 | 5.2 |
| 18.1 | 2097 + *j* 1552 | 0.4 | 8.1 |
| 21.1 | 345 – *j* 1073 | 0.6 | 10.1 |
| 24.9 | 202 + *j* 367 | 0.3 | 3.9 |
| 28.4 | 2493 – *j* 1375 | 0.6 | 8.1 |