A Transmitting Loop Antenna for the 40M Band

by

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21 September 2008

Introduction

Loop antennas are of interest to a wide range of users, from shortwave listeners (SWLs) and radio amateurs to designers of direction-finding receiver systems. SWLs and radio amateurs living in confined areas such as apartments or in communities having antenna restrictions find loop antennas and especially active loop antennas to be a practical solution as they can offer directional performance similar to that of a dipole antenna while taking up a considerably smaller space, and their small size makes them readily adaptable to mechanical rotation.

However, the high inductive reactance of the loop antenna impedance is detrimental to wideband performance, and remote tuning is often employed for achieving good performance and enjoying the highly desireable magnetic field response, which provides some degree of immunity from electric field noise from sources such as lightning discharges, faulty mains transformers, and fluorescent lighting.

Remotely tuned receiving loop antennas are easily implemented by way of using varactors for the remote tuning function (1, 2, 3), but transmitting loop antennas often require a motor-driven variable capacitor. Most designs employ a high voltage variable capacitor, often an expensive vacuum variable, at the top of the loop opposite the feed point.

Feedline coupling is often accomplished by way of a gamma match element or an inductive Mini-Loop, both of which are effective but are somewhat demanding in terms of adjustment. High ratio wideband transformers are also seen in some designs, but the low impedance of the loop antenna at resonance often causes these transformers to be lossy.

The design approach presented herein seeks to resolve these problems and offer an alternative design that is less demanding in terms of adjustment and construction as well as being far less expensive while at the same time improving the overall performance of the transmitting loop antenna.

Loop Antenna Impedance

Before we address the design of remotely tunable matching networks, we need to gain an understanding and appreciation of the impedance of loop antennas, the nature of which precludes the design of wideband matching networks. It is well known that the loop antenna impedance consists of a small real part R_{ant} (consisting of the radiation resistance plus bulk and induced losses) in series with a large inductance L_{ant}, which renders the loop antenna as being a high Q source (4):

$$Q_{ant} = \frac{\omega L_{ant}}{R_{ant}} \qquad (1)$$

where ω is the frequency in radians per second.

There is more than enough literature available about loop antennas that the basic theory really does not need to be repeated here, and very thorough treatments are available from King (5), Kraus (6), Terman (7) and Padhi (8). Most authors provide little discussion about the impedance of the loop antenna, other than to demonstrate that the impedance is dominated by a large series inductance and is a cascade of parallel and series resonances (9). A few go further and show that the loop antenna impedance can be seen as a shorted transmission line. Terman (7) makes use of this method, which is usable for frequencies below the first parallel resonance.

An IEEE paper published in 1984 (10), provides a very useful means for estimating the real and imaginary parts of the loop antenna impedance, the latter of which is a refinement of the method proposed by Terman, and which the authors of that paper further refine by providing scalar coefficients for use with a wide

Configuration	$L/\lambda \leq 0.2$		$0.2 \leq L/\lambda \leq 0.5$	
	a	b	a	b
Circular	1.793	3.928	1.722	3.676
Square (side driven)	1.126	3.950	1.073	3.271
Square (corner driven)	1.140	3.958	1.065	3.452
Triangular (side driven)	0.694	3.998	0.755	2.632
Triangular (corner driven)	0.688	3.995	0.667	3.280
Hexagonal	1.588	4.293	1.385	3.525

Table 1 - Coefficients to be Used with Equation 2

variety of geometries that are commonly used in the construction of loop antennas. In their approximation, the radiation resistance is determined by:

$$R_{ant} = a\, tan^{b}\left(\frac{k_0\, L}{2}\right) \qquad (2)$$

where L is the perimeter length of the loop antenna and the wave number k_0 is defined as:

$$k_0 = \omega\sqrt{\mu_0\, \varepsilon_0} \qquad (3)$$

where μ_0 is the permeability of free space ($4\pi\, 10^{-7}$ H/m), and ε_0 is the permittivity of free space ($8.8542\, 10^{-12}$ F/m). The coefficients *a* and *b* in Eq. 2 are dependent on the geometry and the perimeter length of the loop antenna, a list of values being provided in Table 1.

The inductive reactance of the loop antenna impedance is determined by:

$$X_{ant} = j\, Z_0\, tan\left(\frac{k_0\, L}{2}\right) \qquad (4)$$

where Z_0 is the characteristic impedance of the equivalent parallel wire transmission line, defined as:

$$Z_0 = 276\, ln\left(\frac{4\, A}{L\, r}\right) \qquad (5)$$

where A is the enclosed area of the loop antenna and r is the radius of the antenna conductor.

A highly detailed report from the Ohio State University Electroscience Laboratory in 1968 (11) provides a thorough analytical means for estimating the real and imaginary parts of the impedance of single and multi-turn loop antennas, as well as the antenna efficiency.

Computer simulation routines such as EZNEC also provide a useful means for estimating the loop antenna impedance. Together with papers and reports such as those mentioned herein, they allow the designer to gain an understanding of the nature of the loop antenna impedance. They are not, however, suitable substitutes for actual measurements and the designer should always rely on measured data, especialy when designing matching networks.

Fig. 1 shows the measured terminal impedance of a 1.5m diameter loop made with

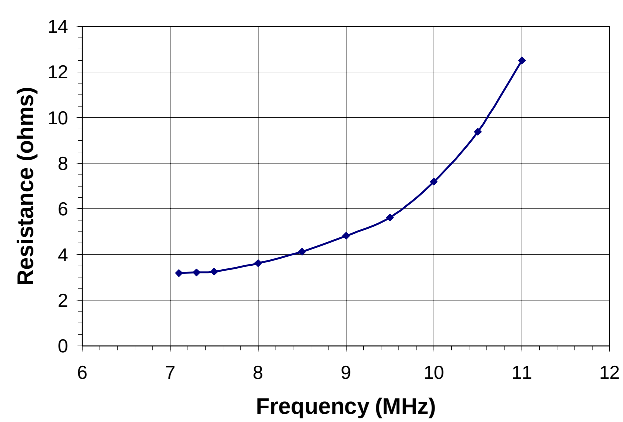

Fig. 1 - Measured Resistance of 1.5 meter Diameter Loop Antenna made with 1/2" Copper Tubing

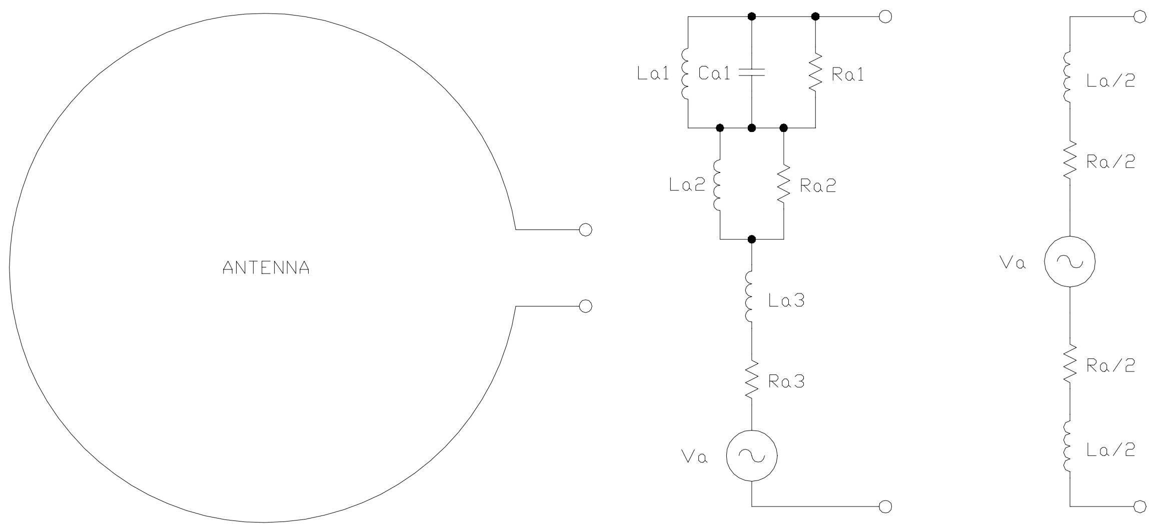

Fig. 2 - The Loop Antenna (left) Together with Detailed (centre) and Simplified (right) Lumped Element Impedance Equivalent Models.

1/2” copper tubing. In order to ensure that the loop antenna is properly balanced, a 1:1 balanced-to-unbalanced (BalUn) transformer is used to interface the loop antenna with the impedance bridge. Loop antennas that are fed unbalanced have dramatically different impedance characteristics and radiation patterns from those that are fed balanced (1).

In the process of designing matching networks for adverse impedances such as those of loop antennas, it is very useful to devise lumped element equivalent models as some analysis and optimization routines, such as PSpice, do not have provisions for including tables of measured data for interpolation. Fig. 2 illustrates two rudimentary lumped element models, the first being usable up to and slightly beyond the first parallel resonance and the second being usable to the point prior to where the impedance becomes asymptotic, or about 25% below the first parallel resonance. Far more detailed models can be devised that include subsequent resonances and anti-resonances (12), but they would serve little purpose here as the application here is focused on frequencies below the first resonance.

Matching Network Design

Even by way of casual observation, the simplified equivalent model in Fig. 2 readily suggests that adding a capacitor in series with each antenna terminal would provide a good match. This approach, illustrated in Fig. 3 provides for suberb signal-to-noise performance in receiving systems as the loop antenna can be matched properly to the load (2, 4). In addition, the magnetic field performance of the loop antenna can be thoroughly enjoyed, reducing the effects of noise from electric field sources,

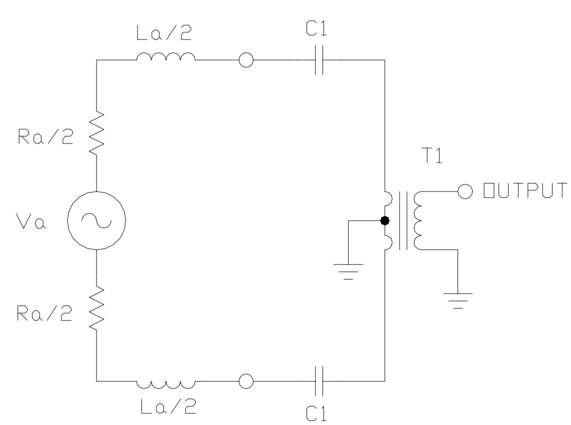

Fig. 3 - Basic Passive Series Tuning

though not to the degree as would be experienced with a shielded loop antenna.

Once the reactance portion of the loop antenna impedance is adequately tuned, the impedance of the antenna seen at the output terminal of Fig. 3 becomes a very small resistance, which can be less than an ohm for small loop antennas made with large radius conductors such as 1/2" copper tubing. These low impedances represent a significant problem in the realization of matching networks, specifically with respect to the design of transformer T1. Since the typically high turns ratio often precludes the twisting of wires or even the use of parallel wires, a significant portion of the linking flux is coupled to the magnetic core material, where the high flux density results in significant losses in the core material. In a receiver system, these losses result in an increase in the overall antenna noise temperature and the noise figure (NF) of the receiver system. In a transmitting system, these losses result in a decrease in system power efficiency as well as excessive heating of the transformer and subsequent component failure.

This problem can be overcome if the antenna element is chosen such that the real part of its impedance is some convenient integer ratio of the feedline impedance, which would then allow for the usage of one or more transformers that can be realized by way of bifilar and/or trifilar windings. Such an approach is shown in Fig. 4, where the loop element is chosen to have a resistance of 3.125 ohms, which will allow for matching to a 50 ohm feedline by way of a pair of 1:4 transformers. The first of these, T1, is the familiar Guanella 1:4 balanced-to-balanced (BalBal) impedance transformer (13, 14, 15), while the second, T2, is a 1:4 BalUn current transformer.

Making a 1:4 Guanella transformer such as T1 in Fig. 4 that will have good symmetry around the grounded centre tap is primarily a matter of good construction practices. At the same time, dual variable capacitors are not easily matched for a variety of reasons, and their usage in the matching network of Fig. 4 can result in a voltage imbalance to the loop antenna, which in turn will disturb the radiation pattern. This potential problem can be circumvented by moving the capacitors to the point between T1 and T2, as shown in Fig. 5. Since the secondary winding of the 1:4 current BalUn T2 is floating with respect to ground, the balance to the loop antenna is determined by the symmetry of transformer T1, which again is a matter of good construction practices.

Using variable capacitors as series-tuned network elements can be mechanically demanding and subsequently expensive when matters of insulation and remote operation are brought into the picture. To overcome this difficulty, an additional transformer is added to the matching network that allows for the usage of

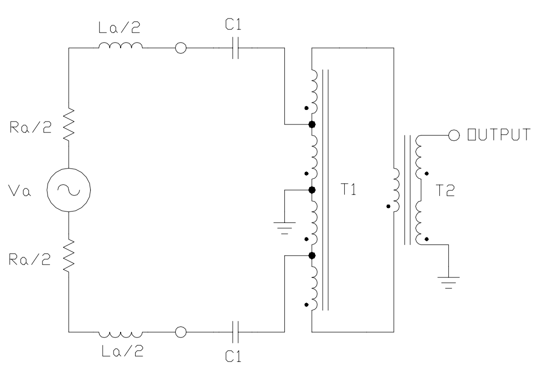

Fig. 4 - Passive Series Tuning with 1:4 Transformers

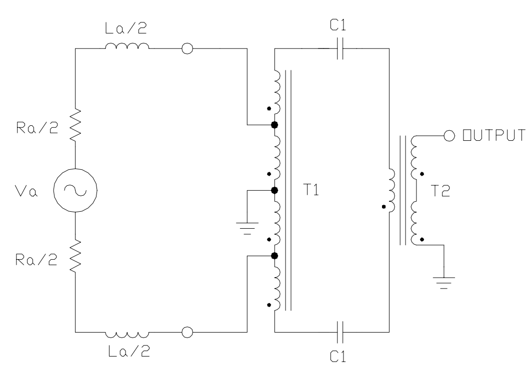

Fig. 5 - Passive Series Tuning with Relocated Series Capacitors

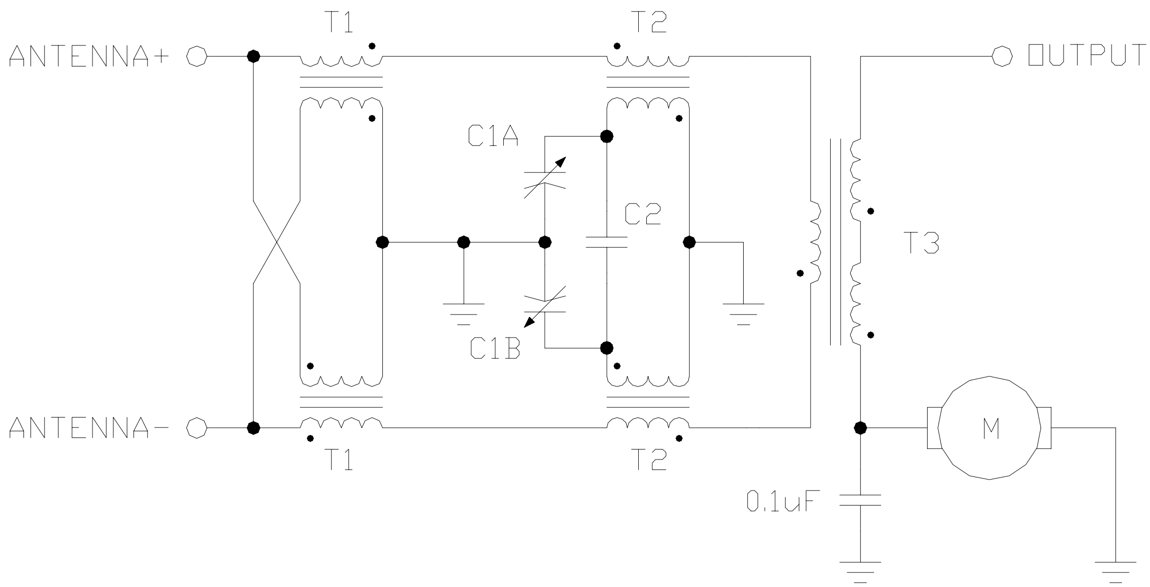

Fig. 6 - Transmitting Loop Antenna Tuner Schematic

dual variable capacitors that have a common shaft, which is usually attached to the mounting frame. As shown in the schematic of the tuner in Fig. 6, this transformer consists of a pair of 1:1 windings on a single magnetic core, which helps to maintain the balance through the network. The fixed capacitor C2 is added here to provide for centering the frequency range of the tuner.

The design now becomes a matter of devising a series of good quality wideband transformers that have low loss characteristics at the low impedances seen by T1 and T2 and which also have good wideband characteristics so that the tuner may be used for a variety of frequency bands without having to do anything more serious than changing the loop antenna element and perhaps changing the padding capacitor C2.

Twisted bifilar and trifilar wires typically used in small signal wideband transformers provide high coupling coefficients that approach unity (16, 17, 18). However, parallel wires are a far better option for applications where larger gauge wire is called for in higher power applications (19). In actuality, there is little difference in the performance between the two methods (19). Generally, twisted wires will provide a better coupling coefficient for small gauge wires such as are used when constructing wideband transformers for small-signal applications (19, 20, 21).

Transformers T1 and T2 are both constructed with a pair of six-turn windings of parallel #22 AWG wire on Micrometals T106-6 toroidal cores. Extensive experimentation showed that using ferrite materials in these two transformers resulted in significant losses and lower tuning Q, therefore powdered iron cores were chosen.

The opposite was true for T3, which performed best when constructed on Fair-Rite 5943001401 and 5961001401 toroidal cores, the former being used for frequencies from 100kHz to 10MHz and the latter for frequencies up to 30MHz. The windings consist of 12 turns of #22 AWG wire for the primary and 24 turns of #22 AWG wire for the secondary, the latter going twice around the core so as to allow both windings to be pressed firmly against the core body. Twisted trifilar #24 AWG wires were used earlier in the design, but proved to be a bit difficult to contend with mechanically.

Tuner Construction Details

As shown in Fig. 7, the tuner is constructed on a baseplate made from a 2" by 8" piece of 1/8" thick aluminum plate. Brackets for supporting the variable capacitor, gearhead motor, and SO-239 connector are made from 1/8" thick aluminum angle stock and are attached to the baseplate with #6 hardware. The shaft coupling between the gearhead motor and the variable capacitor is made from 1/2" diameter brass stock 3/4" long. Although this part was made on a screw lathe, it could very carefully be made using a drill press where the brass rod stock is held in the drill press chuck and the drill bits (and possibly chucking reamers) are held in a drill press vise which is securely mounted to the drill press table.

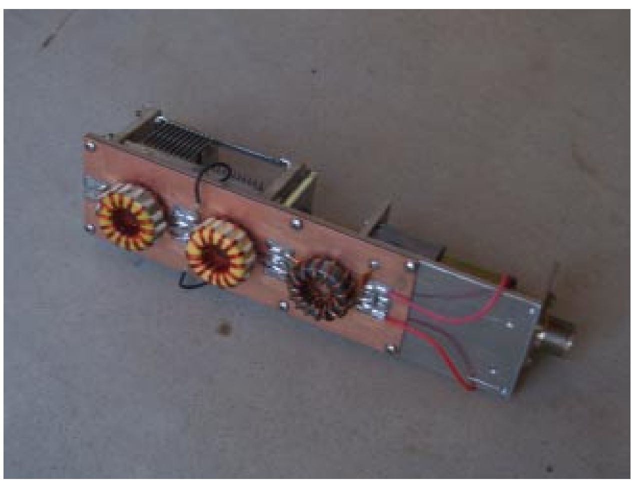

Fig. 7 - Tuner Mechanical Details

The variable capacitor shown in Fig. 7 is a dual 50pF with 800V spacing made by Johnson. A similar part is available from Cardwell (HFAD-50B). The gearhead motor came from Electronics Goldmine (#G15492). It develops more than sufficient toque at 3RPM using 6VDC and draws less than 100mA under load.

The transformers are assembled on a 2.0" by 6.0" piece of 1/16" thick PC board material. Pads were cut out using a Dremel tool, and the pads were kept large so as to better withstand the stresses that result from repeated soldering during experimentation. The PC board is attached to the baseplate using #4 hardware.

Masthead Construction Details

The mechanical construction of the weatherproof masthead assembly for the tuner and for mounting the loop antenna element requires nothing more than PVC plumbing components and other commonly available hardware items.

A desireable feature of this design was to make it such that a variety of antenna elements could be used which would allow for experimentation as well as using antenna elements that are optimized for specific frequency bands. Using a method suggested by Roberto Craighero (22), the familiar SO-239 UHF connector is used on the masthead for attaching the antenna elements. These are mounted on opposite sides of a 3" PVC end cap which is used for the upper housing assembly. As shown in Fig. 8, flat areas are first machined on opposite sides of the end cap of sufficent size for mouting the connectors, after which a 5/8" diameter hole is bored through along with the constellation of four 9/32" holes to match those of

Fig. 8 - Upper Housing Assembly Details

the SO-239 flange. The mounting holes on the connector flange should also be drilled to this diameter so as to accept #6 mounting hardware. A hole is then bored into the top of the end cap to accomodate a 1 1/4" to 1" PVC bushing, which is then cemented into the hole and held securely by adding a ring of PVC pipe material to the back side.

The lower housing assembly is made in a similar fashion but does not require the SO-239 mounting features. As shown in Fig. 9, a 3" PVC end cap is bored to accept a 1 1/4" PVC pipe adapter, which is then cemented into the hole and held securely by adding a ring of PVC pipe material to the back side.

Fig. 9 - Lower Housing Assembly Details

Fig. 10 - Housing Body Details

As shown in Fig. 10, the housing body is made from a 10" long section of 3" PVC pipe and has notches cut into the top end to accomodate the hadware used to mount the SO-239 connectors to the upper housing assembly.

To provide the electrical connection between the SO-239 connectors and the tuner assembly, a "spider" consisting of four #6 solder lugs is assembled with the aid of an SO-239 connector, four 1/4" spacers, and four sets of 1/2" long 6-32 machine screws and nuts. Arranged as shown in Fig. 11, the four solder lugs are attached to a 4" piece of finely stranded

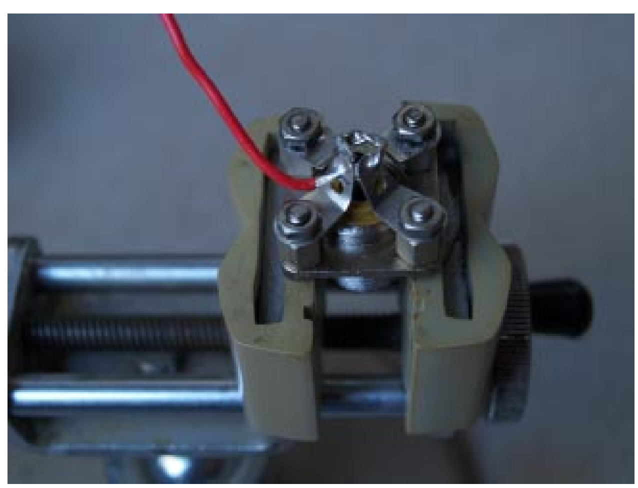

Fig. 11 - Spider Assembly Details

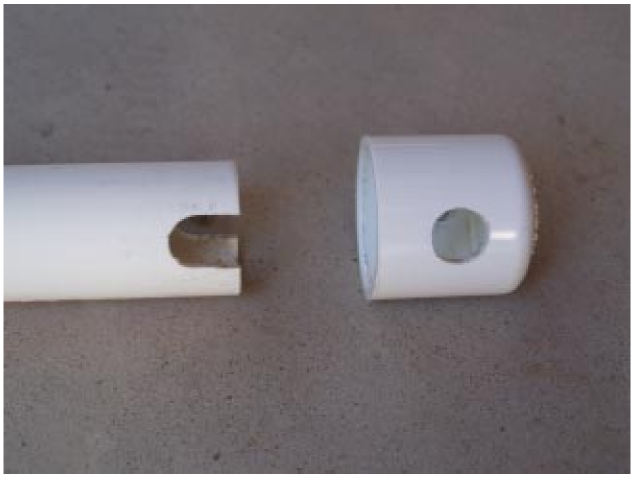

Fig. 12 - Support Mast Details

#12 AWG wire, passing the wire through one hole of each solder lug and then firmly soldered. Tined copper braid may also be used to provide a low resistance connection between the loop antenna element and the tuner.

The connectors and spiders are then mounted to the PVC portion of the upper housing assembly using 1/2" long 6-32 machine screws and nuts, and a layer of silicone sealant should be applied under the connector flange to provide a weatherproof seal.

Finally, a support mast is made from 1" PVC pipe and a 1" PVC end cap. As shown in Fig. 12, the end cap has a pair of holes drilled through to accomodate the loop antenna element, while the pipe has a pair of slots cut into the top end to pass around the loop antenna element. The length of the 1" PVC pipe used will depend upon the diameter of the loop antenna element.

Fig. 13 - PL-259 Reducers Attached to 1/4" (left) and 1/2" (right) Copper Tubing

Antenna Element Assembly

The antenna element is made from either 1/4" or 1/2" flexible copper tubing, though 1/2" tubing is preferred as it will have a lower loss resistance. A pair of PL-259 UHF connectors with reducers are used to attach the antenna elements to the masthead assembly, providing a very convenient means for changing the antenna element for experimentation and optimization.

The PL-259 reducer, which is made for the purpose of using the smaller diameter RG-58 and RG-59 cable with the PL-259 connector, is a very fortunate item for the design of loop antennas . First, the inside diameter is slightly more than 1/4", which allows for easily sweat soldering them to 1/4" copper tubing. And the outside diameter of the boss at the one end is such that it will fit very snugly inside 1/2" copper tubing, though some slight amount of effort may be required and some small holes should be drilled at the end of the tubing to allow for more secure soldering. After the reducers are attached to the copper tubing, the PL-259 is simply screwed on to complete the assembly. Fig. 13 shows the reducer as attached to both 1/4" and 1/2" copper tubing.

Fig. 14 shows the completed housing assembly while Fig. 15 shows the entire transmitting loop antenna assembly with a 1.5m diameter loop antenna element made from 15 feet of 1/2" flexible copper tubing attached.

Tuning Control Assembly

The tuner control voltage is sent up the coaxial cable feedline, and the source need not

Fig. 14 - Completed Housing Assembly

Fig. 15 - Completed Transmitting Loop Antenna Assembly

be any more complicated than a suitable source of 6VDC power, a DPDT centre-off switch, and a simple bias tee, such as the circuit depicted in the schematic of Fig. 16. Here, the transformer T1 is made with two windings of 18 turns of #22AWG wire on a Fair-Rite 5943001401 or 5961001401 toroidal core, although any other core that fulfills the purpose may be used.

Prototype Evaluation

The prototype of the transmitting loop antenna shown in the accompanying photos was tested for tuning bandwidth and return loss.

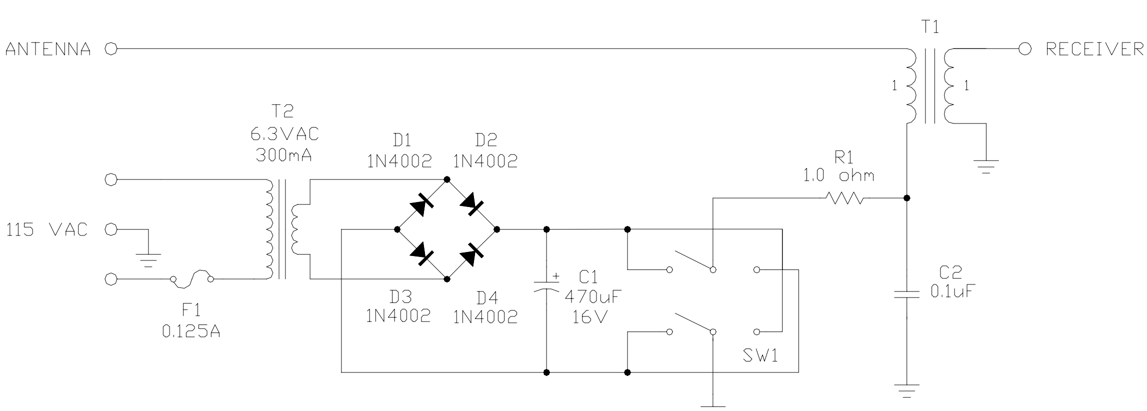

Fig. 16 - Simple Control Unit Schematic (see terxt)

Using a padding capacitor (C2 in Fig. 6) of 220pF, the 1.5m diameter loop could be tuned from 6.9 MHz to 7.5 MHz, providing more than sufficient coverage for the 40M band. The return loss over the band was better than 20dB. This could be improved further by removing a few inches from the antenna element, but it is doubtful if this degree of precise matching is of any real benefit.

Closing Remarks

There are many benefits to be realized in applying simple impedance matching and remote tuning techniques to loop antennas. The design described herein has a tuning range that adequately covers the 40M band together with a very good return loss. The mechanical design uses readily available hardware items and allows for interchanging the antenna elements as may be desired for optimizing performance for specific bands of interest.

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