A Varactor-Tuned
Indoor Loop Antenna

by

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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.

Loop antennas incorporating remote tuning can be a bit demanding in terms of mechanical construction, especially those intended for transmitting that require motor-driven variable capacitors. Antennas intended for receiving are less demanding, but at the same time those intended for outdoor installations require that the assembly be weather-proof. Antennas intended for indoor usage or that are placed outdoors when needed are far simpler, and the design to be described herein is one such example.

Loop Antenna Impedance

Before we address the design of tunable loop antenna 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 (1):

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

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 (2), Kraus (3), Terman (4) and Padhi (5). 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 (6). A few go further and show that the loop antenna impedance can be seen as a shorted transmission line. Terman (4) makes use of this method, which is usable for frequencies below the first parallel resonance.

An IEEE paper published in 1984 (7), 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 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:

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

Configuration	$L/\lambda \le 0.2$		$0.2 \le L/\lambda \le 0.5$	
	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

where μ_0 is the permeability of free space (4π 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 (8) 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 to measured data, especialy when designing matching networks.

Fig. 1 shows the measured terminal impedance of a 1m diameter loop made with 0.25" copper tubing. In order to ensure that the loop antenna is properly balanced, a 1:1 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 (9).

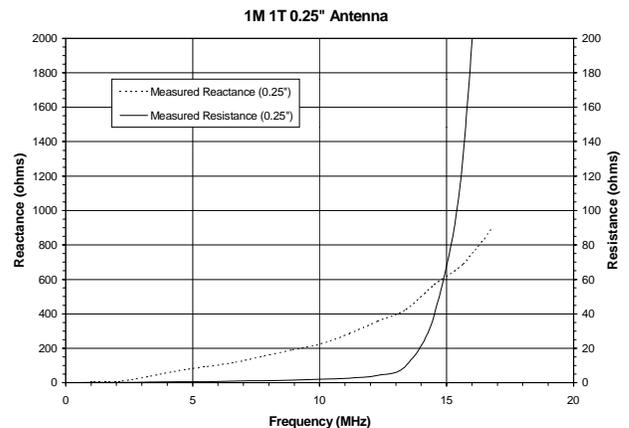In the process of designing matching net-

Fig. 1 - Measured Impedance of 1 meter Diameter Loop Antenna made with 0.25" Copper Tubing
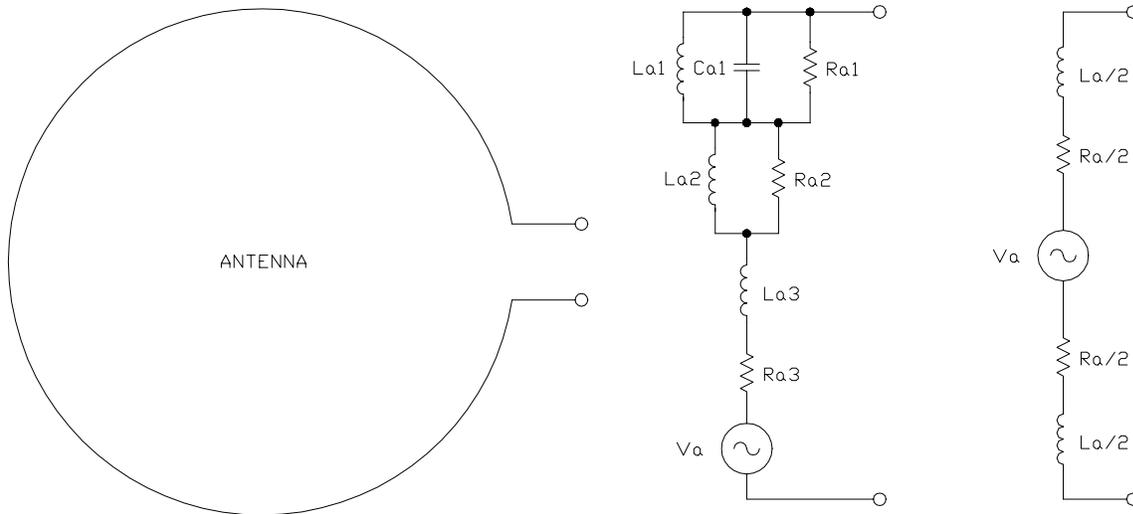
Fig. 2 - The Loop Antenna (left) Together with Detailed (centre) and Simplified (right) Lumped Element Impedance Equivalent Models.

works 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 (10), but they would serve little purpose here as the application here is focused on frequencies below the first resonance.

In general, I use the more detailed model for PSpice simulations and the simpler one for illustrations such as those to be used here later. For the 1m diameter loop made from 0.25" copper tubing, the element values are roughly:

$Ra_1 = 5k$ ohms $\qquad La_1 = 0.4uH$
$Ca_1 = 300pF$

$Ra_2 = 0.6$ ohm $\qquad La_2 = 0.05uH$

$Ra_3 = 1.0$ ohm $\qquad La_3 = 2.2uH$

These values were used in the evaluation of a wide variety of passive matching networks suitable for adaptation to remote tuning, the goal being to devise a varactor-tuned matching network that could be coupled directly to a coaxial cable having an impedance of 50-ohms or to a subsequent amplifier stage or stages of comparable impedance.
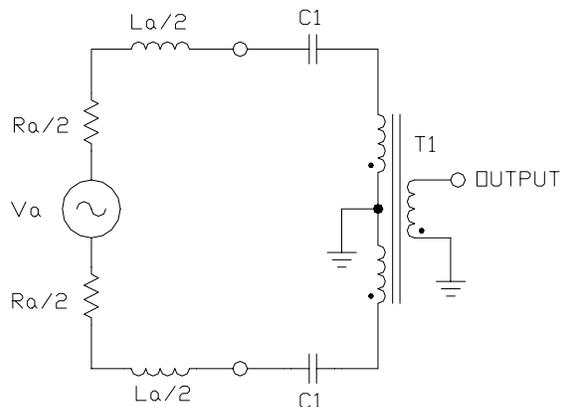

Fig. 3 - Passive Series Tuning

In the overall scheme, balanced networks a prefered as they allow for the supression of common-môde interference signals such as lightning discharges, faulty mains transformers, fluorescent lighting, as well as nearby high-power broadcasting stations, many of which are serious noise sources for indoor antennas.

Simple Matching Networks

At first glance, 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 as the loop antenna can be matched properly to the load (1, 11). In addition, the magnetic field performance of the loop antenna can be thoroughly enjoyed, reducing the effects of noise from electric field sources, 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 resist-ance, which can be less than an ohm for antennas made with large radius conductors such as 1/2" copper tubing. The design now becomes a matter of devising a series of good quality wideband transformers so as to provide a good match between this low resistance and the characteristic impedance of the feed line, which is usually 50-ohm coaxial cable.

Matching Network Design

Many designs for matching loop antennas make us of a single transformer between the feed line and the antenna. In such approaches, the coupling coefficient between the primary and secondary windings is generally poor due to the high turns ratio between the two windings and the low impedance of the tuned loop. In transmitting applications, the lower coupling coefficient results in loss of radiated power and heating of the magnetic materials used in the transformer core. In receiver applications, the lower coupling coefficient and subsequent power loss results in a higher antenna temperature and receiver system noise figure (NF).

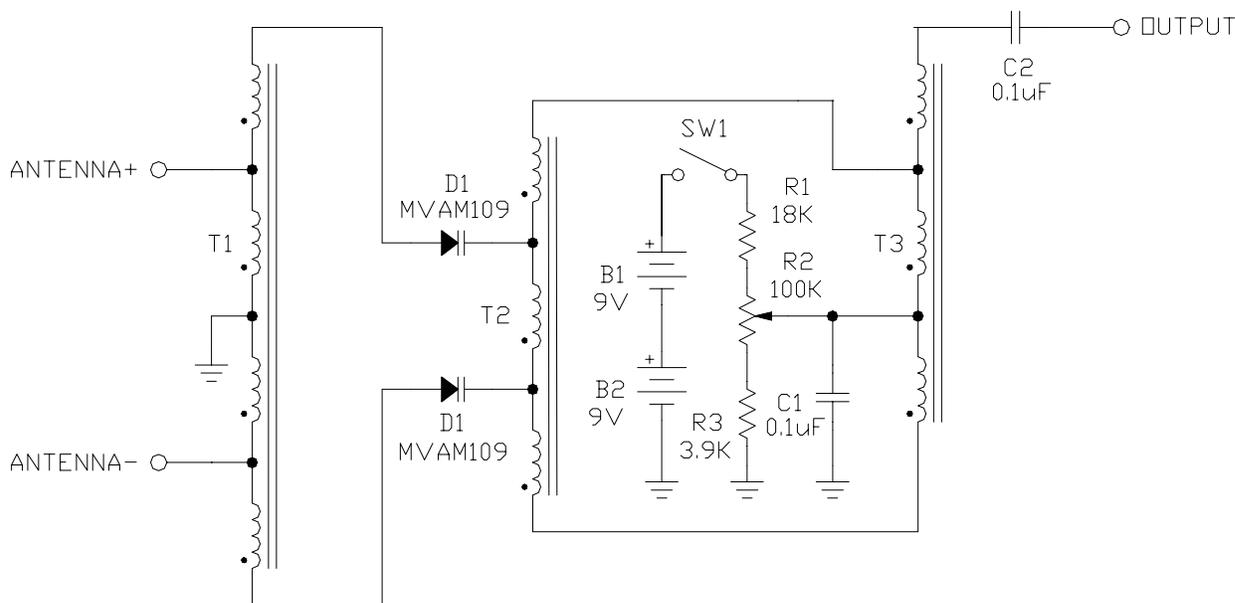Twisted bifilar and trifilar wires typically

Fig. 4 - Varactor-Tuned Loop Antenna Matching Network Schematic

Fig. 5 - Construction Details
for Transformer T1

used in wideband transformers provide high coupling coefficients that approach unity (12, 13, 14). However, the high turns ratio of the primary and secondary windings of the single transformer approach shown in Fig. 3 precludes the use of combining both windings as a single grouping of twisted wires.

Fig. 4 illustrates a matching network that can be realized using a pair of hyper-abrupt vaaractors and three wideband transformers made with bifilar and trifilar twisted wires. A pair of 9V batteries provide the needed power supply, which eliminates the concern of noise that might be introduced by way of a regulated power supply such as a wall transformer.

Although the earlier description of a se-ries-tuned matching network in Fig. 3 would suggest a mechanical dual capacitor for the tun-
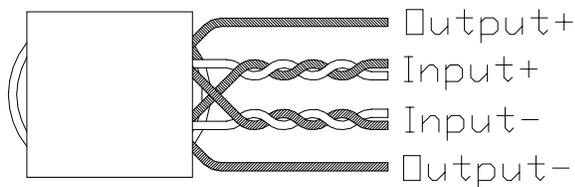
ing, such devices are very costly and typically have a common connection that requires an ad-ditional transformer for coupling to the match-ing network. Such an arrangement is neces-sary for transmitting antennas where power lev-els would preclude the usage of varactors, whereas for receivng antennas the use of varactors is more cost-effective.

In Fig. 4, transformer T1 is a Guanella 4:1 impedance balanced-to-balanced (BalBal) transformer (15, 16, 17) made with two bifilar pairs of twisted wire on a single core of mag-netic material. Under most circumstances, such a transformer would be constructed on a ferrite core such as a Fair-Rite 2843002402 binocular core, however the low impedances at this point in the circuit requires that an alter-nate form of construction be used. Shown in Fig. 5, transformer T1 is constructed as two windings of twelve turns each of #30 AWG bifilar wire on a Micrometals T44-6 powdered iron core.

Parallel wires could be used in the con-struction of transformer T1, however there is lit-tle difference in the performance between the two methods (18). In general, twisted wires will provide a better coupling coefficient for small gauge wires such as are used here and are very convenient when constructing wideband transformers for small-signal applications (18, 19, 20). Parallel wires are a far better option for applications where larger gauge wire is called for in higher power applications (18).

Using a 4:1 impedance transformer at the
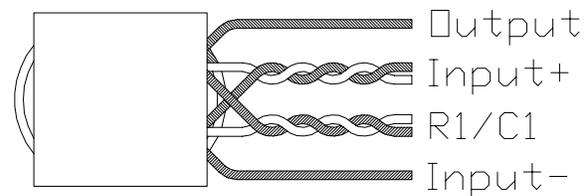

Fig. 6 - Construction Details
for Transformer T2

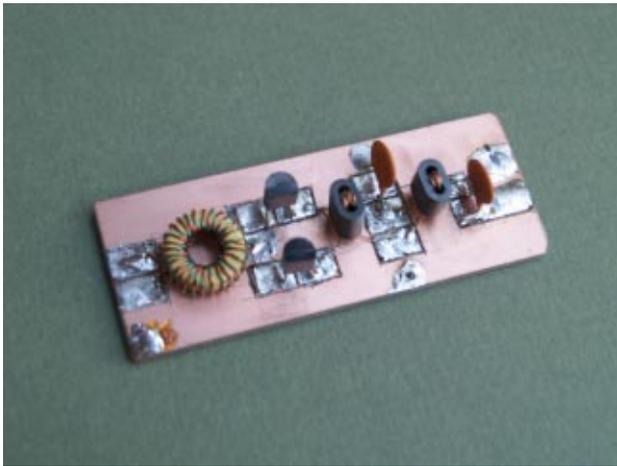Fig. 7 - Construction Details
for Transformer T3

Fig. 8 - Prototype Circuit Assembly

input stage of the network provides a somewhat better operating point for the MVAM109 varactors D1 and D2 that are used here for the tuning. Used at this point, the equivalent series resistance of the varctors results in little signal loss and they can provide almost two octaves of tuning range with loop antenna elements made with 1/4" copper tubing.

Transformers T2 and T3 are both constructed with four turns of #30 AWG trifilar wire through the holes of a Fair-Rite 2843002402 binocular core. Fig. 6 and Fig. 7, respectively, illustrate how the wires are grouped together for the various connections.

The matching network shown in Fig. 4 is not the only form that may be used for matching loop antennas in this manner. The input transformer T1 provides a good first stage for interfacing with the tuning varactors D1 and D2, and the output BalUn transformer T3 is mandatory for converting the balanced tuning and matching network to the unbalanced coaxial cable. The interstage transformer T2 may be any combination of 1:4 and 1:9 impedance transformers that provides the impedance ratio needed to attain a good wideband match, and the combination will depend very much on the size of the antenna conductor used. For instance, if

1/2" copper tubing is to be used for the antenna, then the single 1:9 transformer shown for T2 in Fig. 4 would be better if replaced with a pair of 1:4 transformers.

A prototype for this circuit was constructed on a 1.0" by 2.5" piece of 1/16" thick PC board material and is shown in Fig. 8. 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.

Antenna Base Construction Details

The mechanical construction of the antenna base assembly for the tuning network and for mounting the loop antenna element requires nothing more than a plastic enclosure, a couple of 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 (21), the familiar SO-239 UHF connector is used on the antenna base assembly for attaching the antenna elements. These are mounted on opposite ends of the plastic housing, as shown in Fig. 10.

To provide the electrical connection between the SO-239 connectors and the circuit 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. 9, the four solder lugs are attached to a 6" piece of finely stranded #12 AWG wire, passing the wire through one hole of each solder lug and then firmly soldered.
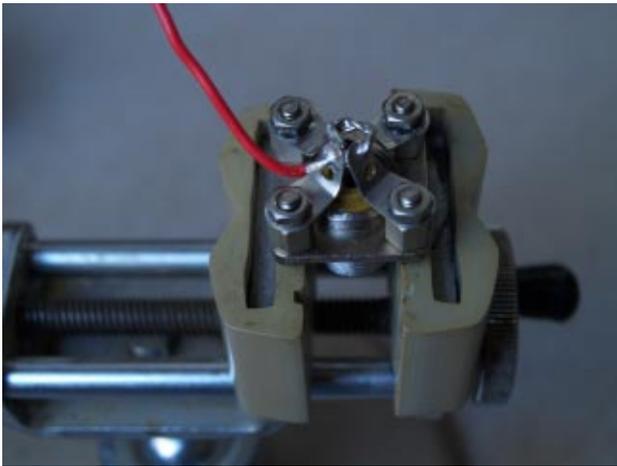
The connectors and spiders are then

Fig. 9 - Assembling the
Connector "Spider"

Fig. 11 - PL-259 Reducers Attached to 1/4"
(left) and 1/2" (right) Copper Tubing

mounted to the plastic housing using 1/2" long 6-32 machine screws and nuts. A mounting socket for a supporting mast is added to the centre of the top of the plastic housing, consisting of a 3/4" PVC plug and a 1/2" PVC coupling, also shown in Fig. 10.

Antenna Element Assembly

The antenna elements are made from either 1/4" or 1/2" flexible copper tubing. 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 oprimization.

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 this design . 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

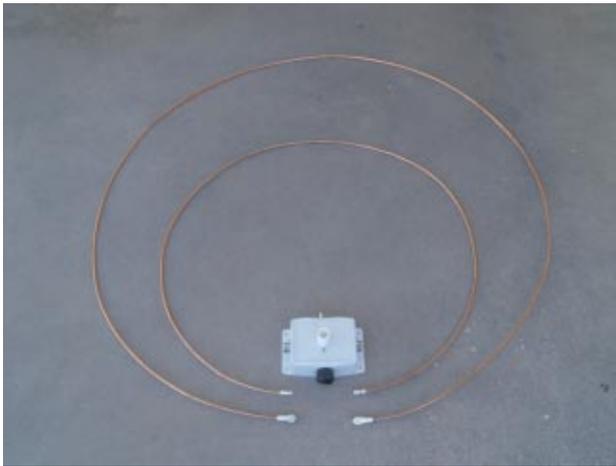Fig. 10 - Varactor-Tuned Indoor Loop Antenna Base

Fig. 12 - A Variety of Antenna Elements

to the copper tubing, the PL-259 is simply screwed on to complete the assembly. Fig. 11 shows the reducer as attached to both 1/4" and 1/2" copper tubing, and Fig. 12 shows a variety of antenna elements made in this manner.

Prototype Evaluation

A prototype of the matching network of Fig. 4 was constructed and evaluated with a 1m and a 64cm diameter loop element, each made with 1/4" copper tubing. Surprisingly, there was virtually no harmonic interference from nearby AM BCB stations, which may very likely be a benefit of the balanced nature of the
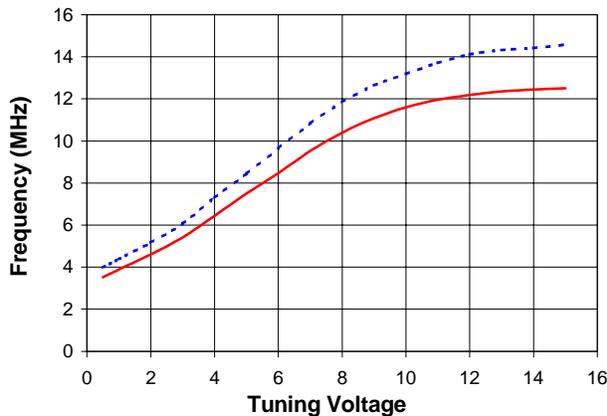
tuning. The chart of Fig. 13 describes the tuning range of the two antenna elements used in the evaluation.

WIth the 1m diameter element, the 3dB bandwidth was a fairly constant 200kHz over the entire tuning range. The S/N ratio is very good, owing in no small part to the passive nature of the network and the voltage gain that accompanies the impedance matching between the very low loop impedance and the 50-ohm coaxial cable impedance.

A photograph of the completed indoor loop antenna assembly appears in Fig. 14.

Closing Remarks

There are many benefits to be realized in applying simple impedance matching and rseries tuning techniques to loop antennas. The design described herein has a generous tuning range of almost two octaves together with a very good S/N due to the impedance matching which precludes the need for amplification. 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.

Fig. 13 - Tuning Characteristics of 64cm (dashed line) and 1m (solid line) Diameter Antennas made with 1/4" Copper Tubing

Fig. 14 - Fully Assembled Varactor-Tuned Indoor Loop Antenna

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Part Resources

      Most of the parts used in the matching network (Fig. 4), as well as one or two in the bias tee (Fig. 16) and control unit (Fig. 18) are not widely available from commercial distributors. Items such as toroid and balun cores, as well as the MVAM109 varactors, are available from specialty parts dealers and various hobby outlets. Fortunately, all such parts used in the design are available from Dan's Small Parts (http://www.danssmallpartsandkits.net), allowing for a few substitutions, and can be conveniently obtained in a single purchase. Those items are as follows:

Item	Source	Part Number or Description
MVAM109 Varactor	Dan's Small Parts	MVAM109 Varactor
	eBay	
T44-6	Amidon	
substitute T50-6	Dan's Small Parts	T50-6
Fair-Rite 2843002402 Balun Core	Dan's Small Parts	BLN43-2402 2 Hole Balun Core
#34 AWG magnet wire	various	
substitute #32 AWG	Dan's Small Parts	No. 32 25 Feet
substitute #36 AWG	Dan's Small Parts	No. 36 25 Feet
Fair-Rite 2843000102 Balun Core		
substitute 2843000202	Dan's Small Parts	BLN43-202 2 Hole Balun Core
#26 AWG magnet wire	Dan's Small Parts	No. 26 25 Feet