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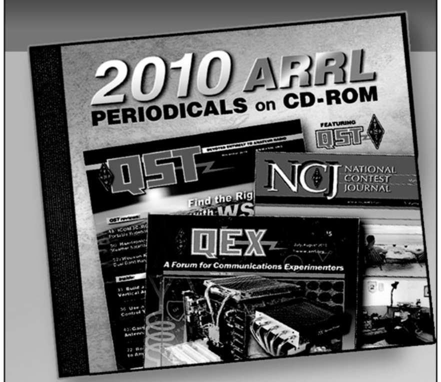

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By Luiz Duarte Lopes, CT1EOJ

Designing a Shortened Antenna

Loading coils can be used to shorten an antenna, but how do you design the coils and what linear spacing do you use?

Many amateurs cannot install the antennas they'd like because the physical space they have available is simply not large enough. Erecting a classic half-wave dipole for 40 meters, which requires approximately 20 meters of wire length, may prove to be difficult for many hams. One solution could be the installation of a so-called "shortened antenna."

There are several ways to shorten an antenna (the half-wave dipole will be considered here) and the techniques to use in each case have been covered before. No new antenna is presented here; this article focuses only on the way in which a shortened dipole can be tailored to fit available space.

The antenna we are going to design is a horizontal half-wave dipole, which is shortened with loading coils. Although the subject has been covered before in some detail[1,2] the purpose here is to clarify the basics behind the use of loading coils to do that job.

Current Distribution

In the classic half-wave dipole, at resonance, the current distribution along the antenna wire is sinusoidal—the maximum value is at its center (the feed point) and the minimum (almost zero) is at its ends. This fact assumes that the wire diameter is very small in relation to its length. At this point we won't consider the end-effect; we will assume the current at the extremities of the antenna wire is zero. The maximum current is determined by the amount of power delivered to the antenna and its *radiation resistance*—the antenna's ability to transfer power to free space—and its efficiency.

Let's assume the antenna wire is divided into very small segments. Consider that the signal strength at any particular point in space is the sum of the radiation coming from each of these small segments, and the final result comes mainly from the elements at the center of the antenna, where the current is greatest. The contribution from the segments with currents very near zero is negligible. As the reduction of the antenna length is based on the replacement of part of the antenna wire by a coil, the question is: What part(s) of the antenna are we going to remove?

The physical length of a horizontal half-wave dipole is equivalent to an electrical length of π radians (2π radians equal 360°) or 180°. If we consider this antenna divided into six parts of 30° each, as shown in Figure 1, and remembering what we said previously, it is evident that the parts making the least contribution to the total radiated power are the two labeled C. Although we could be tempted to remove them, their replacement by a coil at each extremity of the antenna wire is not feasible, because it would require a very large, practically infinite inductance. [As the electrical distance (in degrees, β) to the antenna's end approaches 0°, the cotangent of that distance becomes very large, thus increasing the reactance (hence inductance) needed. This will become more evident later.—*Ed.*]

On the other hand, the two parts of the antenna at A, where the RF current is both maximum and near maximum, should not be touched, as they are responsible for the greatest part of the radiated power. In fact, the amount of power radiated by the two parts at A is equal to the power radiated by the remaining four parts, B and C, taken together.

As a good compromise, the part that should be removed from each side of the antenna (to be replaced by a coil) should be part B. We then will arrive at an antenna length that is 2/3 of the full half

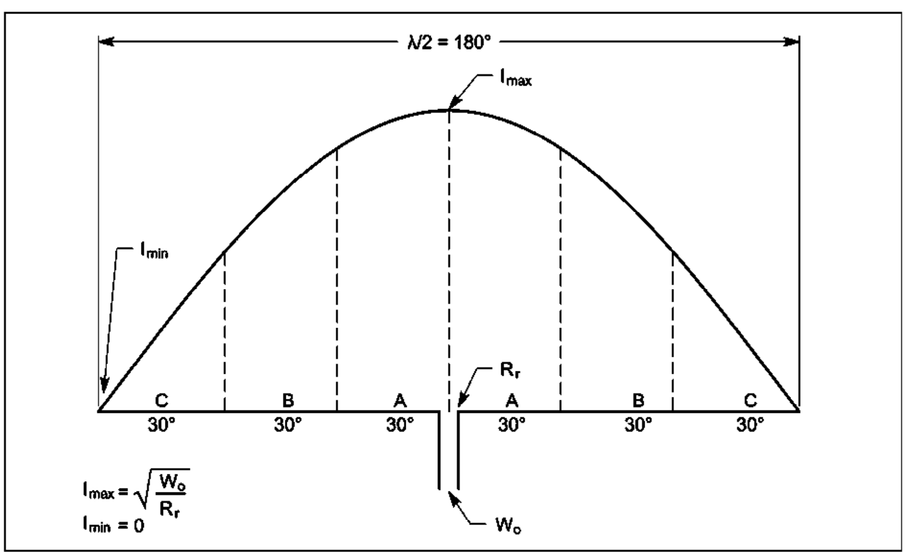

Figure 1—A half-wave dipole divided into 6 elements of 30° each. The sinusoidal current distribution is shown above the antenna.

[1]Notes appear on page 32.

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wavelength. If this length reduction won't be enough, we'd also have to consider removal of a part of C (not all) and, eventually, of part of A. The final decision depends on the particular space occupied by each segment and the practicality of the coil inductance used. In any case, it would be best to keep part A untouched.

Reactance Along the Antenna Wire

Suppose we intend to have an antenna shortened to ²/₃ the length of a half-wave dipole and the coils are to be located just in the middle of each antenna half. As an example, for a frequency of 7.070 MHz, such an antenna is represented in Figure 2.

First of all, by analogy with transmission line theory,[3] we will use Equation 1 to determine the reactance in both extremities of the piece of wire that will be replaced by the coil:

$$X = -j\, Z_0 \cot \beta \qquad \text{[Eq 1]}$$

where

X is the reactance we are looking for,

β is the distance in electrical degrees from the extremity of the antenna wire to the point under consideration, and

Z_0 is the characteristic impedance of a one-wire transmission line using the same wire diameter and height above ground as the antenna.

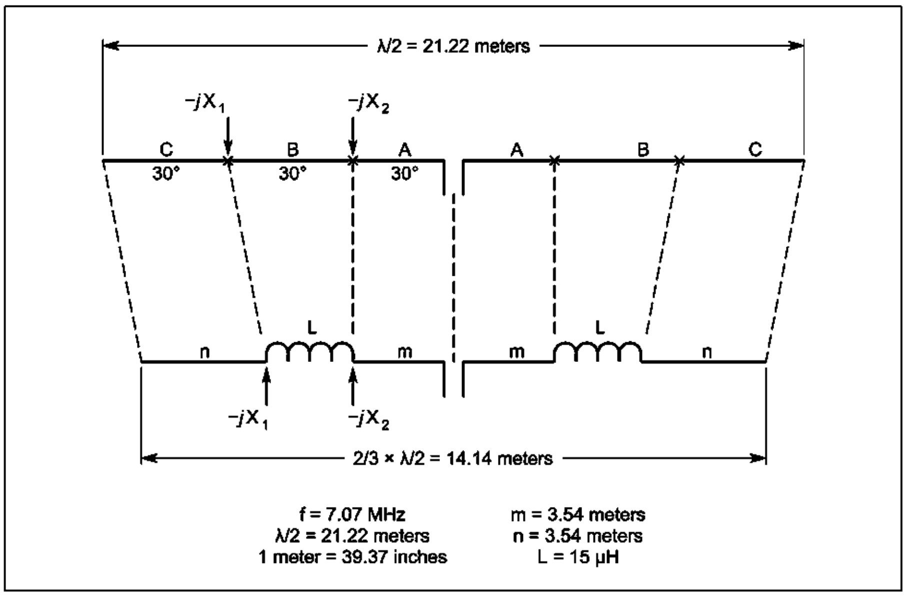

Figure 2—The first shortened example. A half-wave dipole reduced to ²/₃ of its normal length.

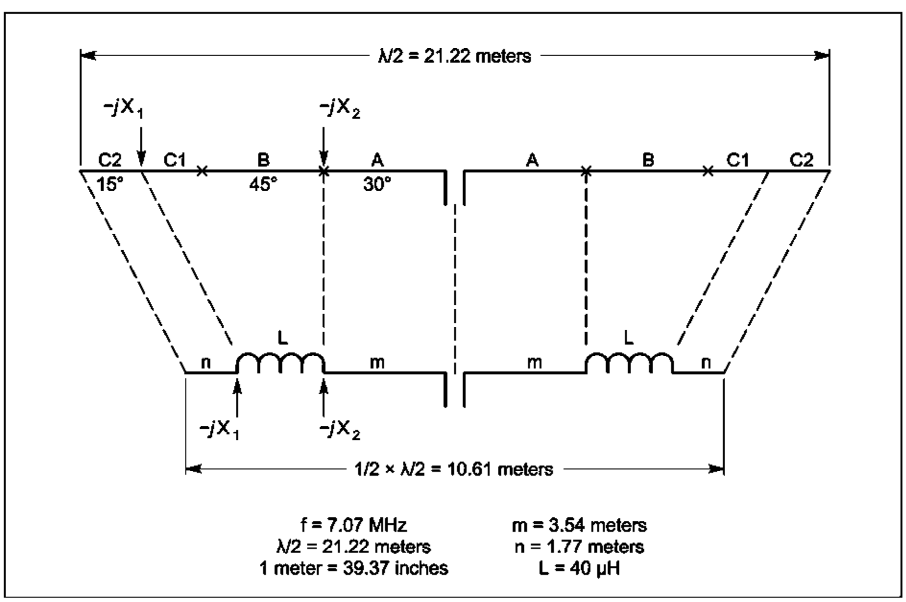

Figure 3—Example two. A half-wave dipole reduced to half its normal length.

We obtain two values: X_1 (at the junction of C with B) and X_2 (at the junction of B with A). In each arm of a half-wave dipole, β is always less than 90° ($\lambda/4$) and we obtain two negative values: $-jX_1$ and $-jX_2$ (see Figure 2). The coil reactance, X_L, to be introduced in each arm of the antenna, comes from Equation 2:

$$X_L = X_2 - X_1 \qquad \text{[Eq 2]}$$

or

$$X_L = -jX_2 - (-jX_1)$$

and

$$X_L = jX_1 - jX_2$$

As the quantity X_1 is always greater than the quantity X_2 [X_1 is closer to the end of the antenna than X_2, β is smaller and thus cotan β is larger.—*Ed.*], the value of X_L is positive ($+j$), which corresponds to a coil, as we expected. (Remember that positive reactance is inductive.)

For the expression in Equation 1 we still need the value of Z_0. We will use Equation 3.[4]

$$Z_0 = 138 \log (4h / d) \qquad \text{[Eq 3]}$$

where h and d are the antenna height above ground and the wire diameter, respectively, in the same units.

In practice, the value of h is not easy to know accurately. In the majority of situations, the value we can measure with a measuring tape is not equal to the real electrical height. It is affected by the nature of the soil and, mainly, by the close proximity of other objects and antennas. Typically the electrical height is smaller than the physical height, but the physical height will be used for the approximate value of h.

A First Example

Using the antenna of Figure 2, we can now determine the coil inductance and the wire lengths, with 7.070 MHz as the antenna's resonant frequency. The antenna wire diameter will be 2.0 mm (12 gauge) and 6 meters (20 feet) will be the estimated height to the ground. This height value looks small but, as previously discussed, we have to be aware of not only the distance to ground but also the distance to nearby objects and other conductors.

Using Equation 4, with the frequency f in MHz, we obtain the length l in meters of the horizontal half-wave dipole before being shortened:

$$l = 150 / f \qquad \text{[Eq 4]}$$

$$l = 150 / 7.07 = 21.22 \text{ meters}$$

As stated previously, we are ignoring the usual reduction of this length due to the end effect. Antenna trimming (with an RF analyzer) at 7.070 MHz

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will take care of that later.

Using Equation 3, we can calculate the characteristic impedance (Z_0):

Z_0 = 138 log [4 (6000/2.0)]

[6000 mm is about 20 feet and 2.0 mm is about the diameter of 12 gauge wire. —*Ed.*]

Z_0 = 138 (4.08)

$Z_0 \approx 563\ \Omega$

Now, with Equation 1, we can determine the values of X_1 and X_2 (see Figure 2). The distance, β, from the extremity of the antenna to the junction of the segment C with B and to the junction of B with A is 30° and 60°, respectively.

Then,

$X_1 = -j563(\cot 30°) = -j563(1.732)$

$X_1 = -j975$

And

$X_2 = -j563(\cot 60°) = -j563(0.577)$

$X_2 = -j325$

Finally, using Equation 2, we have:

$X_L = -j325 - (-j975)$

$X_L = +j650$

With the frequency *f* in MHz, the value of the coil L, in µH, is obtained with Equation 5:

$X_L = 2\pi f L$ [Eq 5]

$L = 650 / [2\pi (7.07)]$

$L = 14.63\ \mu H \approx 15\ \mu H$

Then, with the insertion of one coil with an inductance of 15 µH in the middle of each arm of the dipole, the antenna length will be reduced from 21.22 meters to 14.14 meters, or 2/3 of its classic length. The end effect will reduce this even more.

A Second Example

We consider the previous antenna, but this time shortened to half of its classic length. We start by dividing each element C of the dipole into two elements C_1 and C_2 of 15 electrical degrees each, as shown in Figure 3. As the central elements, A should be preserved as much as possible; the elements to remove are now B and C_1, that is 30° + 15° = 45° on each side of the dipole.

We already know, from the previous example, that:

$Z_0 \approx 563\ \Omega$ and

$X_2 = -j325$

We need a new value for X_1. Using Equation 1 for β =15°, we have:

$X_1 = -j563 (\cot 15°) = -j563 (3.732)$

$X_1 = -j2101$

From Equation 2:

$X_L = -j325 - (-j2101)$

$X_L = +j1776$

And, from Eq 5:

$L = 40\ \mu H$

The total length of the horizontal dipole has thus been reduced from 21.22 meters to 10.61 meters. That is half its normal length, but this reduction does require greater inductance and hence larger coils (40 µH).

One may consider that 40 µH coils are physically too large. Because of that, we present a third example, for an antenna reduced to half the classic size, but using smaller coils.

The Third Example

Keeping the antenna half size, but looking for smaller coils implies that we have to move each coil to a position closer to the center of the antenna. This is shown in Figure 4, where the full length of the dipole is divided into 8 segments of 22.5° each. The values of X_1 and X_2 are now calculated for 22.5° and 67.5°, respectively.

Doing the calculations as in the previous examples, we get the following results:

$X_1 = -j1359$

$X_2 = -j233$

$X_L = +j1126$ and finally,

$L = 25\ \mu H$

The size of the coil is now smaller than it was in the second example. But this was only possible because we jeopardized part A of the dipole, reducing it from its original 30° length to 22.5°. The question is: Can we use this 25 µH coil without touching part A of the antenna? The answer is presented in the next, and final, example.

The Fourth Example

Figure 5 illustrates the final example, with A equal to 30° and L = 25 µH. How long should C_2 be? We already know that:

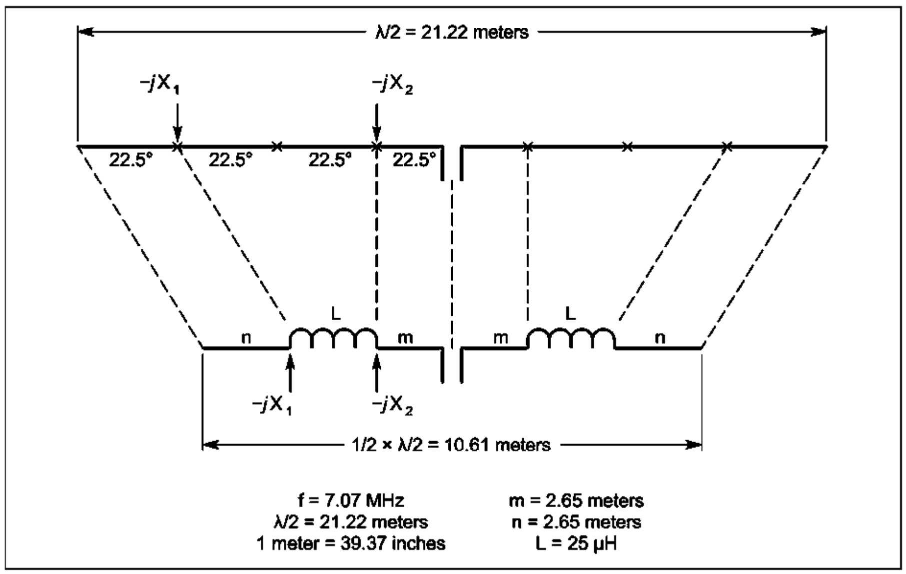

Figure 4—The third example. A half-wave dipole half its normal length, but with smaller coils. The lower inductance coils must be moved closer to the center of the antenna. The dipole is divided into 8 segments of 22.5° each.

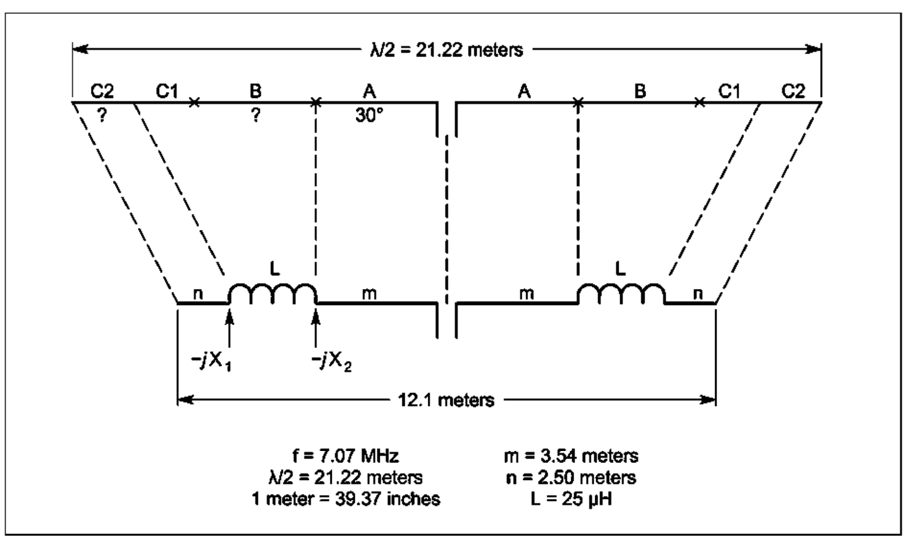

Figure 5—Example four. The dipole is slightly longer than half its classic length, but the coils are now moved so that the critical length A is not affected. Segment A is the area of maximum radiated current that we want to avoid by the loading coils.

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$X_2 = -j325$ (from example 1)
$X_L = +j1126$ (from example 3)
Then:
$X_1 = X_2 - X_L$
$X_1 = -j325 - j1126$
$X_1 = -j1451$
As
$X_1 = -jZ_0 \cot \beta$
$\cot \beta = 1451/563 = 2.577$
And
$\beta = 21.20°$
Then:
$C_2 = 21.20\ (21.22/180) = 2.50$ meters

The antenna now has a total length of about 12.1 meters, which is a little bit longer than half the classic half-wave, but part A of the dipole is untouched and is left with its original electrical length of 30°. The end effect and the trimming of the antenna will allow us to have a final length very near 10.6 meters (half of the half-wave length).

The examples we have shown so far are only four possible cases that may be encountered. In the real world there are many different situations and the use of loading coils could be a satisfactory solution to shorten an antenna. The procedure we've shown can be used for any one of those possible cases. [A program for calculating the loading coil inductances, **K1TD.EXE**, can be found at the ARRL Web site **www.arrl.org/files/qst-binaries/lopes1003.zip**. This will simplify the calculations considerably.—*Ed.*]

Building the Antenna

To confirm the calculations, an antenna was constructed using the parameters of the fourth example. The antenna was built with ordinary plastic insulated 12 gauge copper wire, commonly used for electrical house wiring. The final lengths, after trimming, are shown in Figure 6. The values were very close to those calculated, although they do have some uncertainty in a couple of parameters (antenna height and end effect).

Building the loading coils was the most difficult part of the job. [An inductance bridge or a Q meter would be a big help here.—*Ed.*] For the forms, white PVC tubing of 10 cm length and 46.5 mm outside diameter were used, on which was wound 33 turns of 12 gauge enamel wire. The length of the coil was 70 mm. The number of turns was determined with the aid of Equation 6.[5]

$$L = [(a^2)(n^2)] / (18a + 40b) \qquad \text{[Eq 6]}$$

where
L is in µH
a and b are the diameter and the length (in inches) of the coil, respectively, and n is the number of turns

Using the values found earlier, a 25 µH coil was made. A piece of Plexiglas was introduced inside the coil to support the tension of the antenna wire. Figure 7 details the coil construction and Figure 8 shows the completed coil before the Plexiglas wire support was installed.

The Results

The receiving and transmitting performance of the antenna was very good. During several contacts the reports received were very similar, or slightly lower than the reports with my main antenna (a W3DZZ type). The difference did not exceed –3 dB (half an S unit), principally because the short antenna was tested at a lower height. In theory, if the losses in the coil are small, the amount of radiated energy is very close to the energy radiated by a full-length half-wave dipole. However, a short antenna has a lower radiation resistance; this is the main reason for the reduction in efficiency.

Efficiency

In free space, the radiation resistance of a classic (full-length) half-wave dipole is about 73 Ω. In actuality, near ground, the radiation resistance depends on the height above ground and, in most cases, it is closer to 50 Ω, as the antenna is usually relatively low.[6]

When we reduce the length of a dipole in relation to its half-wave length, the radiation resistance decreases, which, in a loss-free world would be of no significance. In fact, with the same amount of power delivered to the antenna, the antenna current would increase in such a way that the radiated power would be the same as with a full-length half-wave dipole.

In the real world, losses in the antenna system do exist. They are in the conductors, the insulators and the ground and they are also in associated items, such as baluns, transmission lines and antenna tuners.

The antenna system efficiency is the ratio between the radiated power and the power delivered to the antenna system and is determined by the following equation:

$$\eta = [R_r / (R_r + R_t)] \times 100\% \qquad \text{[Eq 7]}$$

or

$$\eta = [1 / (1 + R_t / R_r)] \times 100\% \qquad \text{[Eq 8]}$$

where
η is the antenna system efficiency,
R_r is the radiation resistance and
R_t the equivalent resistance of all the losses in the antenna system.

Assuming that the total losses R_t remain the same, this last equation shows that the decrease in the radiation resistance R_r implies the increase of the ratio R_t / R_r and, consequently, the decrease of the antenna efficiency η.

For example, we can assume that a half-wave dipole antenna with a radiation resistance of 50 Ω and a total loss resistance of 5 Ω has an efficiency of 50 divided by 55, that is, 91%. A short version of this dipole may have 25 Ω of radiation resistance and, assuming no change in the loss resistance, the efficiency would be 25 divided by 30, or 83%.

Actually, the introduction of the loading coils implies some increase in the antenna losses due to the resistance of the coil wire. Additionally, an antenna tuner (adding further loss) would probably be used with the shortened dipole. If we thus consider a higher value of 10 Ω rather than 5 Ω for the loss resistance (including the tuner loss), the efficiency would be 25 divided by 35, which is 71%. How important is this efficiency reduction? In fact, it corresponds to a decrease of only 1 dB.

Several calculations and tests were run to determine the radiation resistance of this antenna. Using specific formulas from different sources[7,8] a value of about 25 Ω was calculated. Finally, with a noise bridge and a computer to solve the *transmission line equation*,[9] a similar result was achieved. The SWR goes up to 2.0

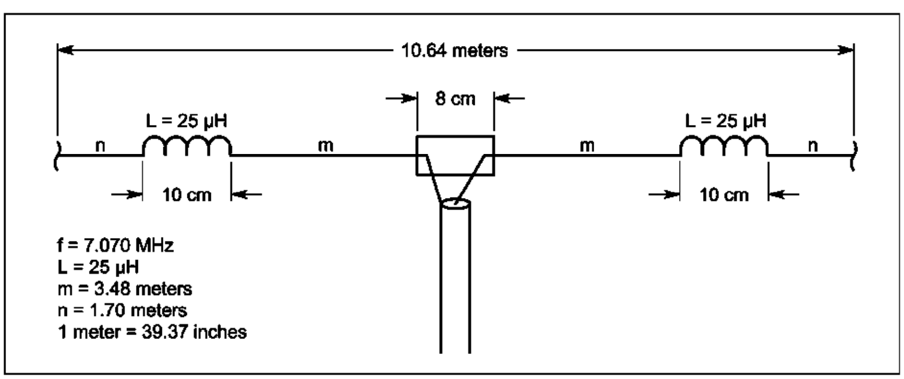

Figure 6—The completed shortened half-wave dipole after frequency trimming at 7070 kHz.

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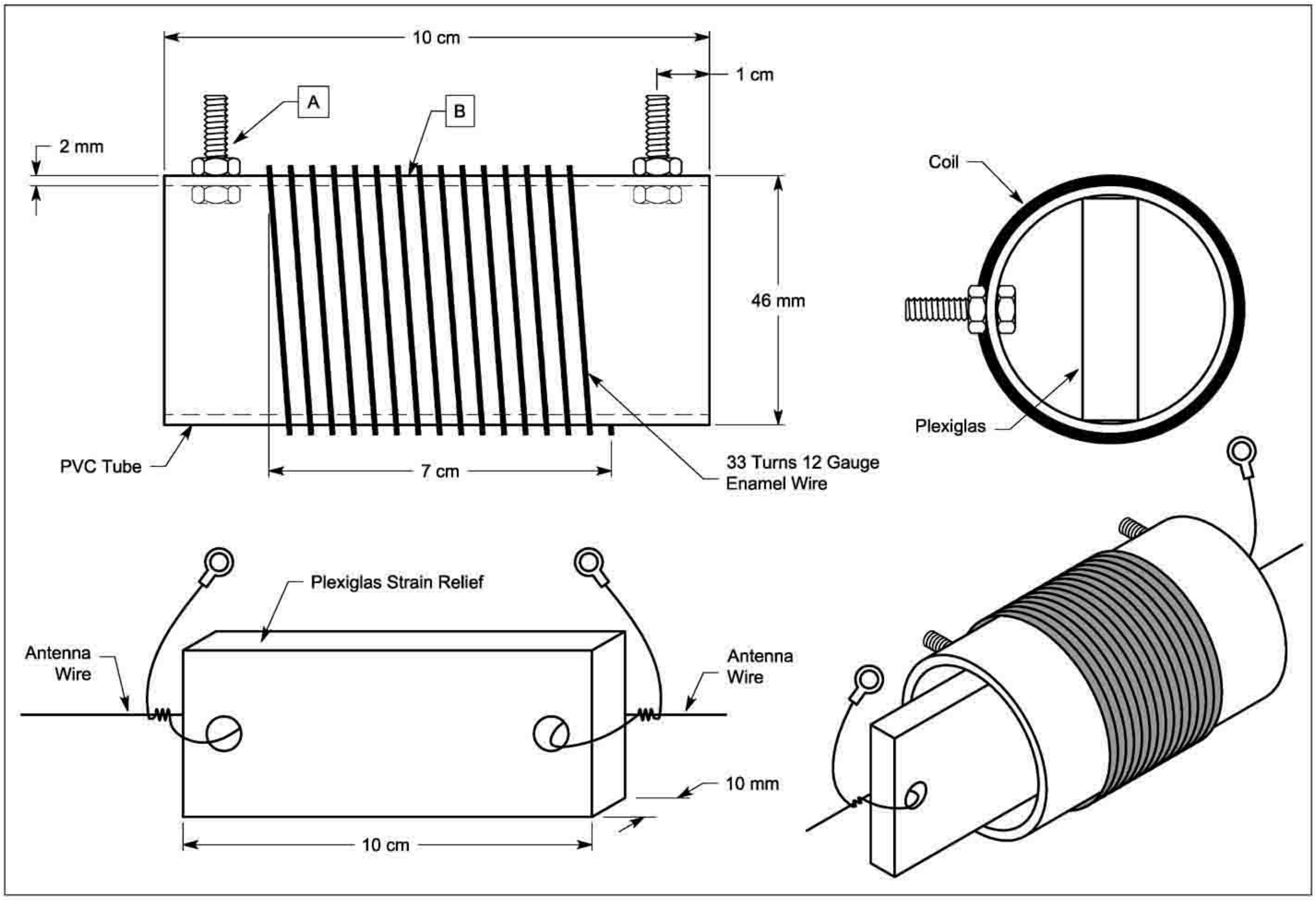

Figure 7—Constructional details of the 25 µH loading coils.

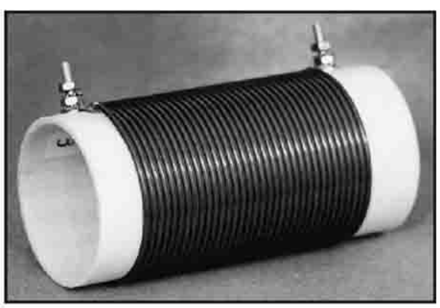

Figure 8—The completed loading coil before the addition of the tension support.

at this low value of radiation resistance. With the use of RG-58 (50 Ω) coaxial cable as a feed line, the use of an antenna tuner is strongly advised. [Two lengths of paralleled RG-58 (total Z_0 = 25 Ω) could be used to feed the antenna, however. This would bring the SWR close to 1.0 and would eliminate the need for a tuner, if your transmitter can handle the lower load impedance. In place of this, a quarter-wave transformer could be used, consisting of 27 feet of 2 lengths of RG-59 cable (70-75 Ω) in parallel (with a resulting effective impedance of about 35-37 Ω), the whole in series with the 50 Ω feed line, at the antenna. A further option would be a series matching section of 75 Ω coaxial line inserted into the 50 Ω feed line to match impedances and, again, get around the tuner requirement. [See *The ARRL Antenna Book* (19th edition, p 26-4) for design details on these useful matching techniques.[10]—*Ed.*]

Conclusion

The claim is not made that a shortened antenna with coils is as good as a classic half-wave dipole. Although the reduction in efficiency is low, the classic half-wave dipole is still a better solution, if you have enough space for its installation. That's a big "if," however, and we've shown that the loaded coil dipole offers an effective solution to that space problem. You should now be able to design to that solution for many requirements.

Notes

[1]J. Hall, K1PLP, "Off-Center Loaded Dipole Antennas," *QST*, Sep 1974, p 28.
[2]*The ARRL Antenna Book,* 19th edition, p 6-27.
[3]*The ARRL Antenna Book,* 19th edition, p 16-8.
[4]*The ARRL Antenna Book,* 19th edition, p 24-22.
[5]*The ARRL Handbook,* 80th edition, 2003, p 6-22.
[6]*The ARRL Antenna Book,* 19th edition, p 3-2.
[7]Laport, *Radio Antenna Engineering*, McGraw-Hill, 1952.
[8]*The ARRL Antenna Book,* 19th edition, p 16-6.
[9]*The ARRL Antenna Book,* 19th edition, p 24-11.
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