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Dual-feed and Dual-Tuned "magnetic" loops

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Summary

So-called "magnetic" loops are used frequently for EMC, measurement and reception/transmitting. Many users think they are sensitive to the magnetic field only. There is however a sensitivity for the E-field also. This E-field sensitivity increases with circumference over lambda ratio. The E-field sensitivity may introduce systematic measurement errors.

A dual-feed loop (also called double feed gap loop) reduces E-field sensitivity significantly, enabling larger loops with better sensitivity/efficiency while maintaining the figure-of-eight radiation pattern.

This document discusses how the "magnetic" loop interacts with the Electromagnetic field, discusses far field radiation patterns and the idea behind the dual-feed loop. Design information is given and a design example of a 440 MHz tuned loop is included.

Content

1. Introduction

So-called “magnetic” loops are used by many people:

- tuned or wide band receive loops
- tuned transmitting loops,
- small loops for EMC troubleshooting,
- Loops as part of sensors
- loops for (EMC/noise) measurement,
- loops for direction finding and radio fox hunting

Figure 1.1 shows two examples.

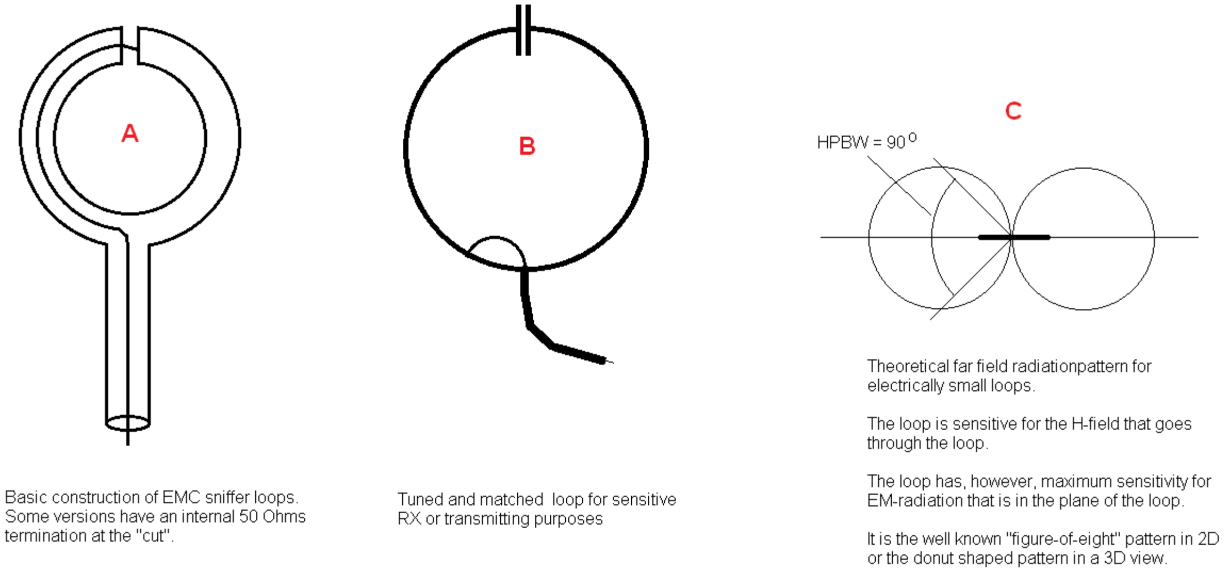


Figure 1.1: basic loops and far field radiation pattern

In the A figure, the EMF develops across the single gap in the top, so this is a single-feed loop. When looking into the gap, the geometry of the left and rights side towards the coaxial line leaving the loop, is identical. So this loop is fully balanced without the need of a balun. It is not uncommon to see ferrite chokes around the coaxial feed line to suppress common mode current.

In the B figure, geometry left and right of the tuning capacitor is also (near) identical. Hence a balun isn’t required. There is some negligible unbalance due to the feeding loop that provides coupling and matching.

As such loops are balanced circuits, a counterpoise provision is not required.
This is one of the mayor advantages of a loop as a detector or transmit antenna. Its near field performance doesn’t depend on a ground (compared to E-field sensors).
Note that the far field radiation pattern still depends on ground conductivity, especially for vertically polarized loops.

The C figure shows the theoretical far field radiation pattern for an electrically small loop (that is circumference < 0.1λ) with a single feed. When signals are relatively strong, and the wave front is plane, the notch in the pattern can be used to accurately determine the azimuth of the radiation. This works well at HF and below, but at VHF and higher, propagation is different. The “figure-of-eight” pattern is also used to suppress a single dominant interferer or noise.

It should be noted that the figure-of-eight pattern holds only when the loop is vertical, and for vertically polarized waves.

Experiments

Many people experimented with loops. During experiments, it appeared that the deep notch property sometimes wasn’t present, despite well balanced construction and presence of a plane wave front. Further experiments showed that when examining vertically polarized signals, and the loop is with the feed (or tuning capacitor) horizontally, the deep notch is gone, even in an obstacle free situation (wooden tripods, common mode decoupling, no people close to the loop, etc).

The reason for the absence of the deep notches became clear: E-field sensitivity for certain orientation of the loop with respect to the arriving EM-field.

A new question arrived: does the E-field sensitivity reduce the supposed “noise suppressing” properties? In some cases it can, but in many cases the “magnetic” loop has no noise suppressing properties, even if it would not be sensitive to E-field. Only in the near field or in case of a single interferer, there can be noise suppressing properties. This is also valid for a dipole. So the noise suppressing properties are more or less a myth, especially at HF and higher.

People may observe better S/N performance compared to monopole antennas. This may be because of common mode interference on the feed line in case of monopole antennas.

1.1. Efficiency

When amplifier/receiver noise is a limiting factor, efficiency becomes important. Efficiency depends on:

- Ohmic and dielectric losses, mostly modeled as a single resistance (R_{Loss}) in series with the loop
- Apparent loss due to radiation of energy, mostly modeled as a single resistance R_{rad}.

The additional resistance due to radiation (R_{rad}) can be calculated with:

$$R_{rad} \approx 31.2k \cdot \left(\frac{A}{\lambda^2}\right)^2 \approx 3.85 \cdot 10^{-30} \cdot A^2 \cdot f^4$$

This formula underestimates Rrad [Ohms] with increasing rt(A/λ^2) ratio for standard single-feed loops.
For rt(A/λ^2) = 0.05, actual Rrad is 10% higher compared the “small Loop” formula. For a circular loop that means circumference = 0.18·λ.

$$Efficiency = \frac{R_{rad}}{R_{rad} + R_{Loss}}$$

To get near 100% efficiency, ignoring the super conducting case, the loop circumference generally needs to be more than 0.15 lambda.

1.2. Induced EMF

No-load output voltage for single-turn small loops.

$$EMF\,[V] = \frac{d\Phi}{dt} = \mu 0 \cdot \omega \cdot A \cdot H = 7.9 \cdot 10^{-6} \cdot f \cdot A \cdot H$$

All in base units (so Hz, m^2, A/m). For the AC case: when using amplitude for H, the EMF is peak voltage (so amplitude). $B = \mu_0 \cdot H$

The H-field should be perpendicular to the plane of the loop, otherwise correct with cos(α). Where α is the angle between the actual direction of the H-field and the line perpendicular to the loop. When H is in the plane of the loop, output is zero.

With increasing circumference, actual EMF increases due to transmission line effects.

1.3. Inductance for single turn loop

Knowing the inductance is useful for calculating the actual output voltage into certain load, or for calculation of the tuning capacitance.

$$L[H] = \quad 2\cdot\pi\cdot D\cdot 10^{-7}\cdot\left(\ln\left(\frac{8\cdot D}{d}\right)-2\right)$$

In case of using strip, d = 0.5·(strip width). Formula is valid for the HF case, so skin depth << wire diameter.

In case of a square loop with width = D, actual inductance is about 19% higher than calculated with this formula.

1.4. Increasing loop size

Increasing loop size means increasing circumference/λ ratio, or increasing rt(A/λ^2) ratio.

In case of relative strong signals (close to a source, or lower part of HF and MF), small loops can be used. That means circumference/λ ratio < 0.1.

With increasing frequency, noise levels decrease, hence one will encounter smaller signals. In such case the loop size must be increased to get more EMF, or to get better efficiency in case of tuned and well matched loops.

Here problems will arrive:

- Formulas for radiation resistance show large deviation (can be corrected).
- E-field sensitivity increases (output due to conservative E-field component in the total Field)
- Loss of “figure-of-eight” radiation pattern for certain orientation and field polarization.

Don’t panic, we can push the limits.

2. Electric and Magnetic fields

The solution is in the fields. The treatment uses transmission lines to help understand EM-waves.

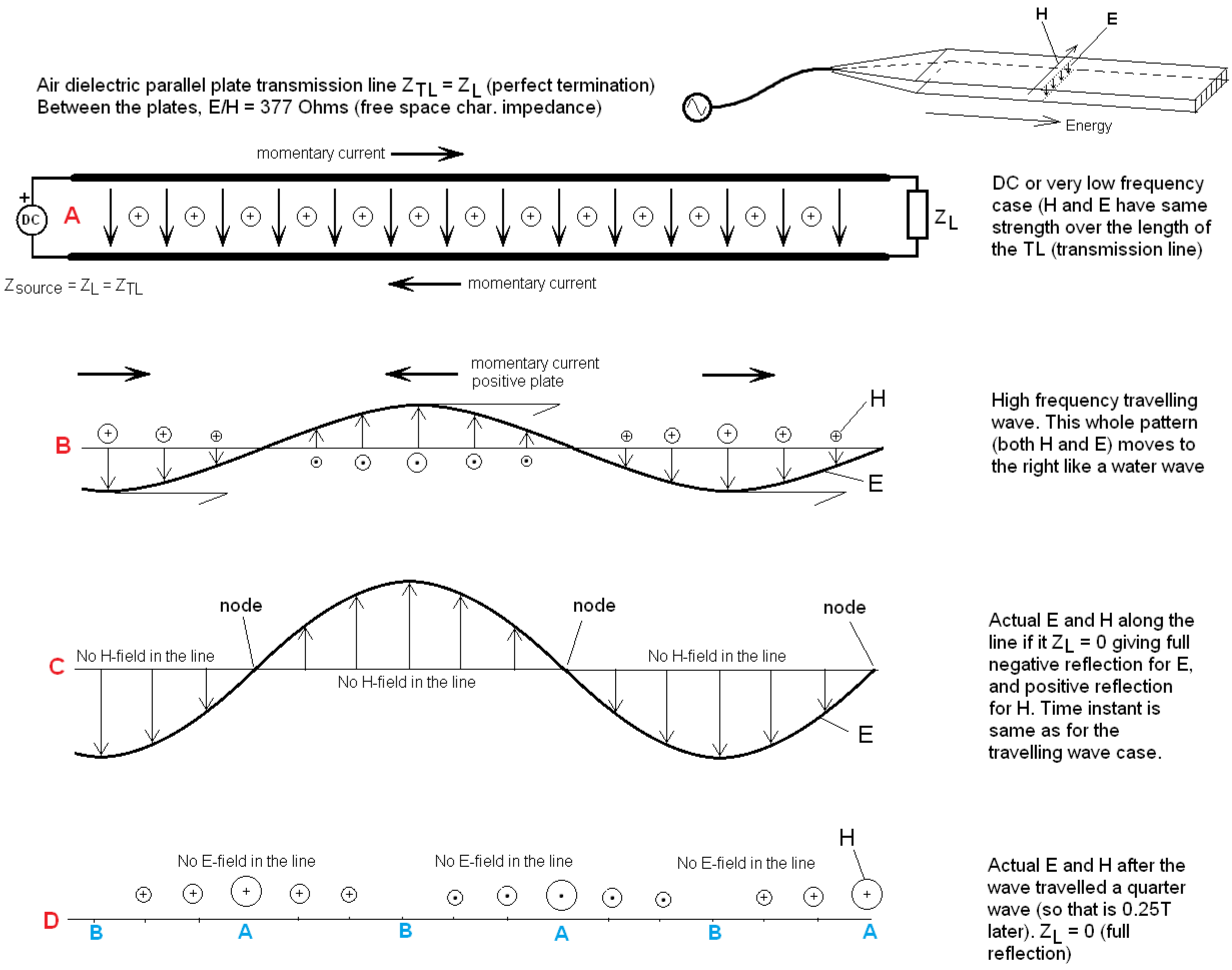
Figure 2.1.A, shows a 3D drawing of a wide parallel strip transmission line. When the width is large compared to distance, the field between the strips is near uniform. Energy goes from left to right, and both the electric field (E) and the magnetic/magnetizing field (H) are perpendicular to the direction of energy flow.

Figure 2.1.A also shows a side view and a DC (or low frequency) source. As the positive terminal is at the top plate, E points down and H goes into the paper (circles with cross, you look to the tail of an arrow). The strip transmission line is terminated with its characteristic impedance, hence the E and H field satisfy free space conditions.

These are:

- E perpendicular to H
- Both E and H perpendicular to the energy propagation direction
- E and H in time phase
- E/H = 377

H and E-field in a parallel strip Transmission Line



The short circuit at the right end gives full standing wave behavior for both E and H. At the A positions, there is an H-field only. E is zero, but there is maximum Curl (Rotation) in the E-field. H is twice as high compared to the travelling wave condition.

At the B positions, E oscillates up and down, but in the top of the sine the curve is flat, hence the field is conservative (no Curl / Rotation), so there is no H-field at the B positions. E is twice as high compared to the travelling wave condition.

Summary: in the full standing wave situation, there is only a magnetic field at the E-field zero crossings (nodes), but there is no H-field at the positions of maximum E-swing (antinodes).

Figure 2.1: E- and H-fields between a wide parallel plate transmission line

2.1. Travelling waves

Figure 2.1.B shows the same transmission line, perfectly terminated (free from reflections), but now with an HF source. The “image” is a freeze photo. The free space conditions still apply. Because of perfect termination the waveform (both E and H) move from left to right with c_0 (3e8 m/s). The thick arrows show the momentary current flow in the upper strip of the transmission line. Circles with dots means H-field out of paper (arrow points towards observer).

Signals and Noise

A propagating wave has both E and H (E/H = 377). It doesn’t matter whether the wave is an intended signal, or noise. The believed “noise suppression” of so-called “magnetic” loops is therefore very limited.

The advantage of the small loop for vertically polarized reception is in the notch. One can rotate the loop for best S/N ratio. In addition common mode interference that couples with the coaxial cable, doesn’t couple with the loop. Monopoles (both passive and active) suffer from conducted interference reaching the antenna via the coaxial braid. Of course this can be avoided.

For horizontally polarized reception a well-designed (short) dipole also has a notch, and is also not sensitive for conducted interference on the coaxial braid (provided a real Balun is used).

Only very close to an unintended radiator (reactive field zone) or close to obstacles, a well oriented loop can behave differently from a well oriented dipole. So in case of interference, first test/experiment with both antenna types, before buying.

2.2. Standing wave situation

In figure 2.1.C, the transmission line is short circuited. This causes RC = -1 for the voltage/E-field wave and RC = +1 for the current/H-field wave. The freeze photo is taken at the same time as in figure 2.1.B. Due to full reflection, E-field at the termination is zero and the E-field doubles at the Antinodes.

There is something special happening:

> For those that are familiar with **differential vector calculus** and the **Maxwell equations:**
>
> The E-field swings up and down, but doesn’t move to the right. Though the E-field swings heavily, the field is always conservative at the antinodes. In other words the field has no Curl (Rot) at the antinodes. Hence there is no time varying B field. As B = µ·H, there will also be no H-field.
>
> A theoretical “magnetic” loop positioned at an antinode of the E-field should produce no output no matter the orientation.

At the zero crossings (nodes, figure 2.1.C), dE/dx is maximum, giving large Curl (Rot). Now we have a time varying magnetic field (as Rot(E) = -dB/dt). With correct orientation, a magnetic loop should generate an EMF that is in phase with E versus time.

Easy to absorb view
A short circuit has RC = +1 for current, so at a quarter wave (+n*0.5 lambda) from the short circuit, there is no current versus time, hence there is no time varying magnetic field (so you don't need dif. Vector calculus here).

Figure 2.1.D shows a freeze photo taken 0.25T seconds after freeze photo 2.1.C. Now E is zero everywhere and the H-field is maximum, but there will never be H-field at the E-field antinodes.

So it is possible to "generate" a magnetic field with zero E and an electric field with zero H.

The free space case
A horizontally or vertically polarized wave front that hits a metallic wall perpendicularly has no E-field close to the wall. The H-field however equals twice the incident H-field. So close to the metal, a H-field sensor may provide best output. This property is used in for example "on-metal" Gen 2, UHF 868 MHz RFID tags. These are actually flat resonant loops.

At a quarter wave distance from the vertical metallic wall, there will be twice the incident E-field, but zero time varying H-field. Such wave propagation phenomena can be used to test sensors.

Though beyond the scope of this document, the field decay versus distance from large media interfaces can also be used to determine the properties of the media. The procedure is similar to the measurement of complex impedance using a slotted transmission line (wave guide or coaxial line).

3. “magnetic” loop response

3.1. The intended response for the H-Field

Figure 3.1.A to C (C included) shows various orientations of the loop with respect to a magnetic field only. The loop’s center is at the voltage node, hence the average E-field the loop experiences, is zero. The H- (or B-) field is maximum.

The direction of the H-field is parallel to the Y-axis. A free space, vertically polarized wave coming from the left or the right (that is along the negative or positive X-axis) produces this H-field. A wave arriving from positive or negative Z-axis does the same.

The behavior is as expected. A small “magnetic” loop has maximum output when the H-field goes straight through the loop. If so, D = 1.76 dBi (factor 1.5). When the loop is vertically oriented, it is sensitive for vertically polarized waves only. The direction of energy flow for maximum output must be in the plane of the loop (see figure 1.1.C for the radiation pattern).

When the loop is oriented horizontally (figure C), (that is in the XY-plane), there is no sensitivity for vertically polarized waves. For horizontally polarized waves, the radiation pattern is omnidirectional (with D = 1.76 dBi (factor 1.5))

Note on isotropic gain (G_i) and directivity D:
D is the isotropic gain in dBi if there were no losses and a perfect match to the source. When the antennas efficiency is 0.1 (that is –10 dB), the maximum gain would be:

$$G_i = D + eff = 1.76 - 10 = -8.2 \text{ dBi}$$

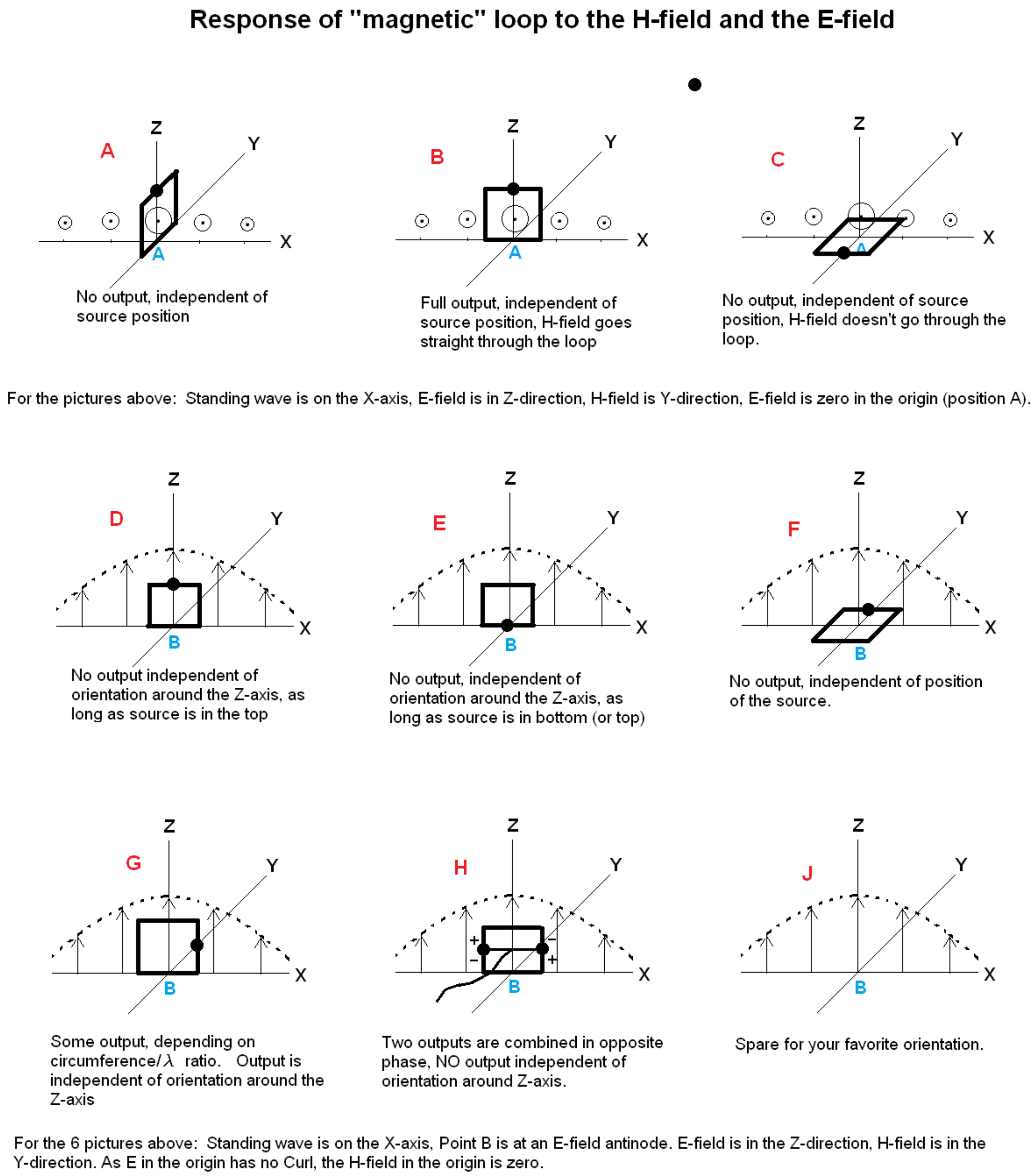


Figure 3.1: Response of small magnetic loop to the H- and E-field

3.2. *Unintended behavior of the "magnetic" loop*

Though it is frequently called a magnetic loop, under some circumstances it is sensitive for the E-field component of an EM wave.

Figure 3.1.D to J show various loop orientations towards the E-field. The loop is at an antinode of the E-field, so there is no net magnetic field passing the loop, no matter its orientation.

Of course left and right of the voltage maximum in the antinode there is Curl in the E-field (so an H-field), but the circulation of E along the circumference of the loop is zero, hence there is zero net H-field passing through the loop.

It goes wrong when the output (or feed in case of transmit) is in one of the vertical conductors of the loop (3.1.G). the loop will generate some voltage due to the E-field, independent of orientation around the Z-axis.

Why this is happening?

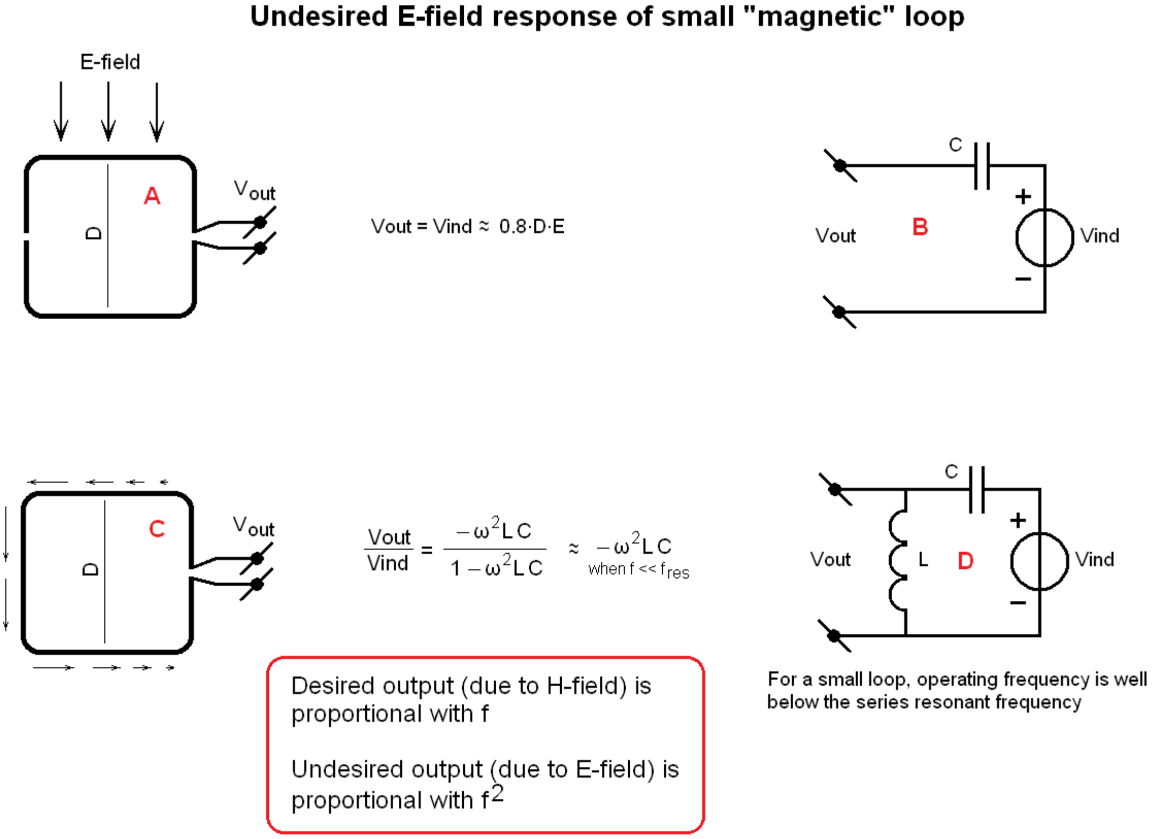


Figure 3.2: reason for undesired E-field response

When we cut the loop in the middle of the two vertical arms, we get two structures that have a certain capacitance (figure 3.2.A). The E field induces a voltage between the now open ends. It will be about

$$V_{ind} = 0.8 \cdot E \cdot D$$

D = vertical distance between the horizontal arms.

This electrically induced voltage acts on the capacitance between the upper and lower half (C). A circuit model is given in figure 3.2.B.

Now we short circuit the left vertical arm (figure 3.2.C). Current will flow through the left side of the square loop. However this current experiences inductance, so a voltage develops across the output terminals of the loop. The actual electrically induced V_{out} is a voltage division between the capacitance of the square loop halves, and the wire inductance (about half the loop inductance). The model is in figure 3.2.D. Resistive and radiation loss is ignored, as these are small compared to the impedance of L and C.

For short loops, $Z_L << Z_C$, that means $f << f_{res}$. When doubling the frequency (that is halving the wavelength), impedance of the inductor doubles, and impedance of the capacitance halves. So given the same E-field, the electrically induced output voltage (V_{out}) increases 4 times. Note that the H-field sensitivity increases 2 times when doubling the frequency.

This behavior can also be found by doubling the size of the loop.

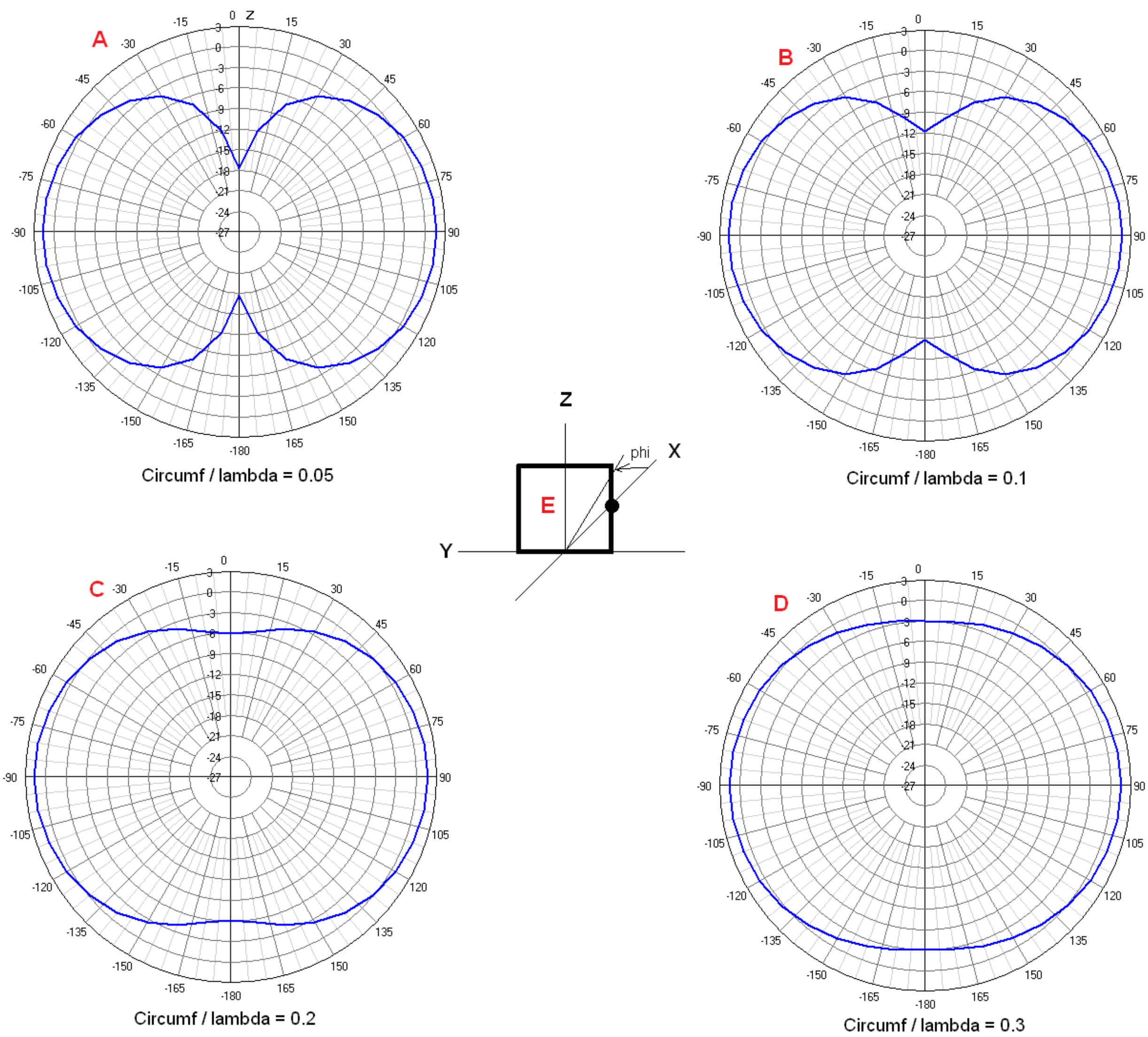
When doubling the size of the loop, A (encircled area) increases with factor 4, so desired output due to the H-field increases with factor 4.

However: the capacitively induced voltage doubles, because D doubles). The construction becomes larger, both capacitance and inductance increase with factor two. So the voltage division increases with factor 4. As we already had double induced voltage. Doubling the loop size gives 8 times more undesired output due to capacitive induction from the E-field.

We can conclude that with increasing circumference/λ ratio the undesired (capacitive) output due to E-field in the end outruns the desired (inductive) output when the output is taken from a vertical arm.

The effect on the radiation pattern is given in figure 3.3 (NEC2D, 4NEC2 software by Arie Voors).

Directivity for vertically polarized wave of magnetic loop with feed in a vertical arm



These far field patterns are Azimuth Directivity patterns for vertically polarized waves with the antenna in position E. There is only vertical polarization. Directivity is plotted for increasing phi with theta = 90^{o} (that is zero elevation). It can be seen that Dmax/Dmin ratio decreases with 6 dB each doubling of frequency (or each doubling of circumference / lambda ratio). Maximum gain up to Circumf / lambda = 0.3 is only 0.2 dB less compared to small ratio.

When the loop is rotated so that the feed is in the top (or bottom), but still in the YZ plane, the ideal figure-of-eigth behavior appears for pure vertical polarization. However when looking to the total gain (that is including the horizontally polarized component), the patterns are as shown above. At phi = 0 and 180^{o}, polarization is horizontally only. These are the direction where you look straight through the loop.

Figure 3.3: radiation patterns of loops with feed in one of the vertical arms

Figure 3.3 shows the Directivity for vertical polarization with the feed/output in a vertical arm. Even with circumference/λ = 0.1, that is generally considered a small loop, the discrimination is just 13 dB (that are just two S-points on a communications receiver). As expected from theory, doubling the size of the loop doubles the unintended behavior compared to the intended behavior (6 dB).

For circumference/λ = 0.2, the discrimination is 7.5 dB and this is poor.

One would say: well, let's use the loop only with the feed/output in the top or bottom. That is a good thing for pure vertically polarized waves. This statement is fully correct however, now you have sensitivity for horizontally polarized waves that are in the plane of the loop. Therefore the total Directivity patterns for top or bottom feed are the same as given in figure 3.3. "total" means total directivity for combined horizontal and vertical polarization.

When you use your loop for direction finding at VHF and up, polarization change in ground propagation is caused by obstacles (reflection, diffraction, etc). So the loop orientation can be such that for the vertical component you are in a "null", but the horizontally polarized component has maximum coupling, masking the "null".

3.3. Conclusion

A so-called magnetic loop with a single feed (single gap) has sensitivity for a conservative E-field also. Normally spoken this isn't a problem in an HF receive situation, unless you want to "notch" a single interferer. Receive loops are typically installed with the feed in the top or bottom as this gives the best figure-of-eight pattern for pure vertical polarization, and the balance is not disturbed by the coaxial feed or the mast. However when the interference has dominant horizontal polarization, even a 0.1·lambda loop has limited figure-of-eight performance (13.5 dB).

In case of measurement purpose, or EMC sniffing, care must be taken with relative large loops. One should orient the loop so that there will be no E-field component across the feed. When using the loop as a current measurement device for a cable, the actual feed (the gap) or cable entry, should "see" the cable. Positioning a non-fed side towards the cable, results in output due to H-field and E-field. This particularly happens when measuring current at voltage antinodes in constructions carrying standing waves (such as antennas). Common mode suppression (chokes) do improve the performance, but doesn't remove E-field sensitivity as discussed here.

It makes no difference whether or not the loop is shielded. An open loop with a well-balanced 1:1 balun (so not a CM choke) works as well as a shielded loop as shown in figure 1.1.A.

4. Reducing undesired behavior

4.1. *Basic operating principle*

The sensitivity for the conservative E-field component can be reduced significantly by using dual outputs. The basic idea is given in figure 3.1.H. The output of both right and left arm are added, but check the +, - signs at the fat dots.

When the E-field is positive, it induces a positive voltage at the top half of the loop. The left output experience a positive EMF, but the right output experiences a negative EMF as it has reversed polarity. When adding the outputs observing the polarity as in figure 3.1H, the sum will be zero. So the electrically induced voltage will not result in output.

The magnetically induced EMF now splits across the two outputs. When the left output experiences a positive EMF, the right output will also experience a positive EMF. When adding both outputs, the EMF will be the same as for a single output.

The dual feed system or double gap system enables larger loops maintaining the “figure-of-eight” radiation pattern. Larger loops generally are more sensitive (generate more EMF and/or efficiency increases, hence less thermal noise). When efficiency goes beyond say 40%, increasing loop size will reduce the antenna Q-factor (due to increased radiation losses). This gives more bandwidth (can be beneficial, but also undesired).

In addition, but not treated in detail here, the R_{rad} formula holds better now as the current becomes more uniform, and is equal for opposite arms.

4.2. *Practical implementation of the dual-feed loop*

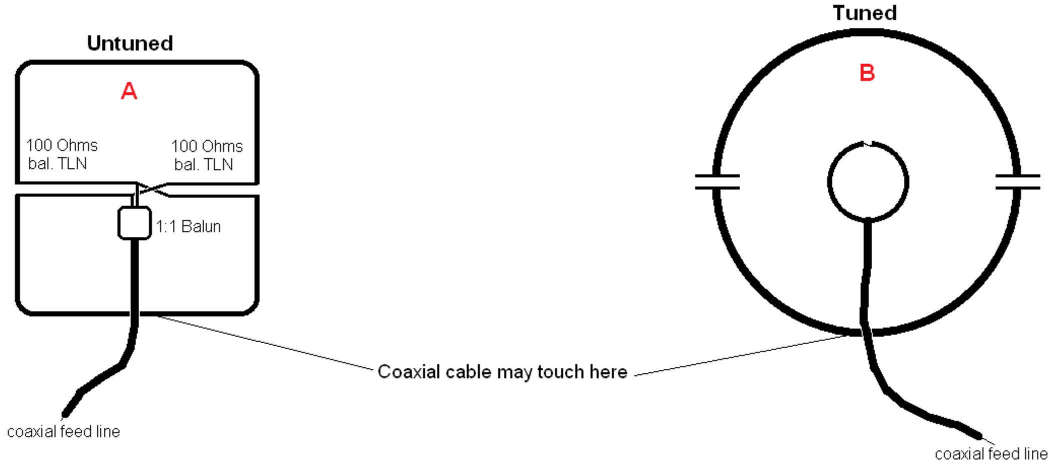
4.2.1. Non-tuned loops

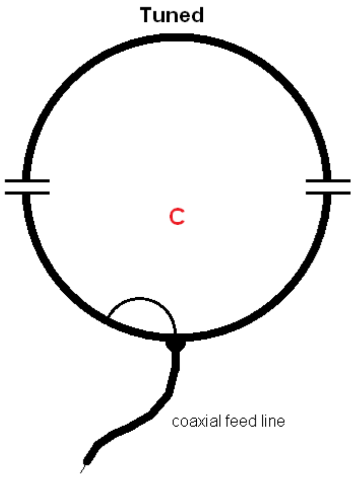
Figure 4.1.A shows a non-tuned implementation where the outputs are added by means of paralleling.

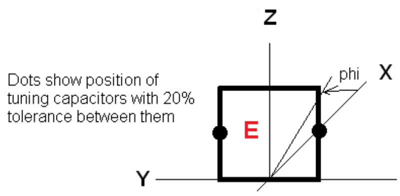
The outputs are transferred to the center of the loop via two balanced 100 Ohms transmission lines. However one of the lines has a 180^0 twist to get the right polarity. They are placed in parallel and can now be fed directly into a 50 Ohms 1:1 balun. The coaxial cable may electrically touch the upper or lower arm in the middle as there is zero potential in the vertical plane through the loops center. There is also zero potential in the horizontal plane!

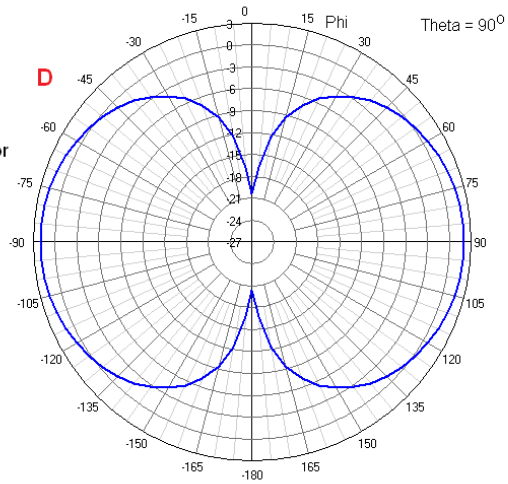
Due to the paralleling of outputs, the EMF halves, but the load as seen by the inductance is 200 Ohms now instead of 50 Ohms. One should take this into account when converting EMF to output voltage.

Dual-Feed "magnetic" loops









Total Azimuth Directivity is shown for Circumf/lambda ratio = 0.3, and deliberate 20% unbalance in the tuning capacitors.

Dmax/Dmin > 21 dB.

In the Z direction, gain is 0.3 dB more then in the Y direction.

Despite the circumf/lambda ratio and the capacitor unbalance, the figure-of-eight pattern is good.

Figure 4.1: dual-feed loops

4.2.2. Tuned loops

Figure 4.1.B shows a tuned loop with two gaps and therefore also two capacitors. It is important to have same capacitance on both sides. This is the difficult thing in implementing this concept.

The coupling loop couples with the upper and low half, so the structure is fully symmetrical/balanced. The only asymmetry is in the coupling loop itself. However, that loop is generally small compared to the magnetic loop, and it doesn't resonate. Therefore induced EMF because of E-field in the small coupling loop will be negligible compared to the induced EMF from the small loop.

Normally spoken Q factor of resonating loops is relatively high (above 100), so it is acceptable to use the coupling as shown in figure 4.1.C. This makes adjustments for matching easier.

In case of loops with low Q-factor, the coupling loop may be no longer small compared to the loop itself, or a good match is no long possible. In such cases one may add a series capacitor in the coupling loop to counteract some of its inductance. Always start with a capacitor well above the value for series resonance (of the coupling loop). Reduce the value gradually. Do a frequency sweep and observe SWR or Smith Chart. When the curve doesn't reach the origin of the Smith Chart, capacitance should be reduced.

Effect of capacitor deviation

Figure 4.1.D shows the azimuth radiation pattern for the loop in figure 4.1.E. The unbalance in the capacitors is 20%. Though the loop circumference is $0.3 \cdot \lambda$, there is excellent figure-of-eight behavior of over 22 dB (about 3.5 S-units on a communications receiver).

When tuning capacitors have exact equal values, notches are infinitely deep.

Dual-Feed with single capacitor

Within the amateur community, there is a dual circular loop design sometimes used for VHF (6m and 2m). It is a single capacitor tuned antenna. Its intention is to get more bandwidth due to the paralleling of the inductors and the somewhat destructive mutual coupling.

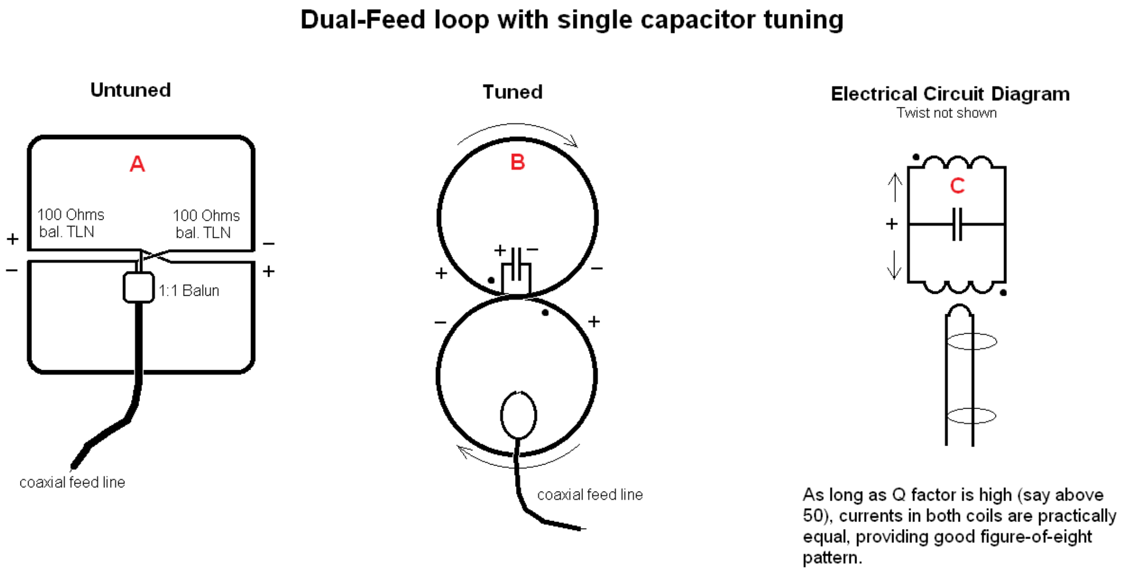


Figure 4.2: dual-feed, single capacitor tuned loop

Figure 4.2 shows the conversion from a dual feed untuned loop into the dual-feed single capacitor tuned loop.

Figure 4.2.A shows the untuned loop with parallel circuit addition of the left and right feed points. In figure 4.2.B, the feed lines are converted to be part of two circular loops. Note the crossing where the loops “touch”!

When the capacitor is positive on its left side, and discharges via the loops, the currents act as it is one large loop. Observe the curved arrows indicating current and the dots indicating winding direction/starting point.

The equivalent circuit diagram is in figure 4.2.C. As long as the voltage across the capacitor is large compared to the induced voltage from the coupling loop, current in both loops is virtually equal, giving good figure-of-eight performance. This condition is met for Q > 50 (not too critical).

When Q drops, the coupling loop should couple to both loops. In that case the coupling loop should be larger, and positioned at the wire crossing. A series capacitor in the coupling loop is generally required to get a good match.

5. Design example of a 440 MHz tuned loop (70 cm band)

5.1. Goal

This is just an experiment to see whether such a loop can be used for finding unintended emissions (radiated emission from equipment, or intruders). It will never beat the 2 and 4 element reflector arrays, but a magnetic loop for this frequency range is really small, lightweight and you don't get to much attention.

It doesn't need to cover the full EU 70 cm band (430..440 MHz), as long as it can be tuned across that band. Radiation efficiency should be around 50% or better, and it should be small.

Though this loop is generally used for reception only, It may be used in combination with a portable transceiver. Transmitting power will be 4 W maximum.

5.2. Design

The design is influenced by available materials. There is some very old stock of aluminum strips with 20*3 mm^2 and 30*3 mm^2 cross section. This enables easy construction of a square loop. When performance is good, it can be made out of sheet material to further reduce its weight.

We just make a start: 80*80 mm^2 outer measures. That fits in a pocket. This is shown in figure 5.1.

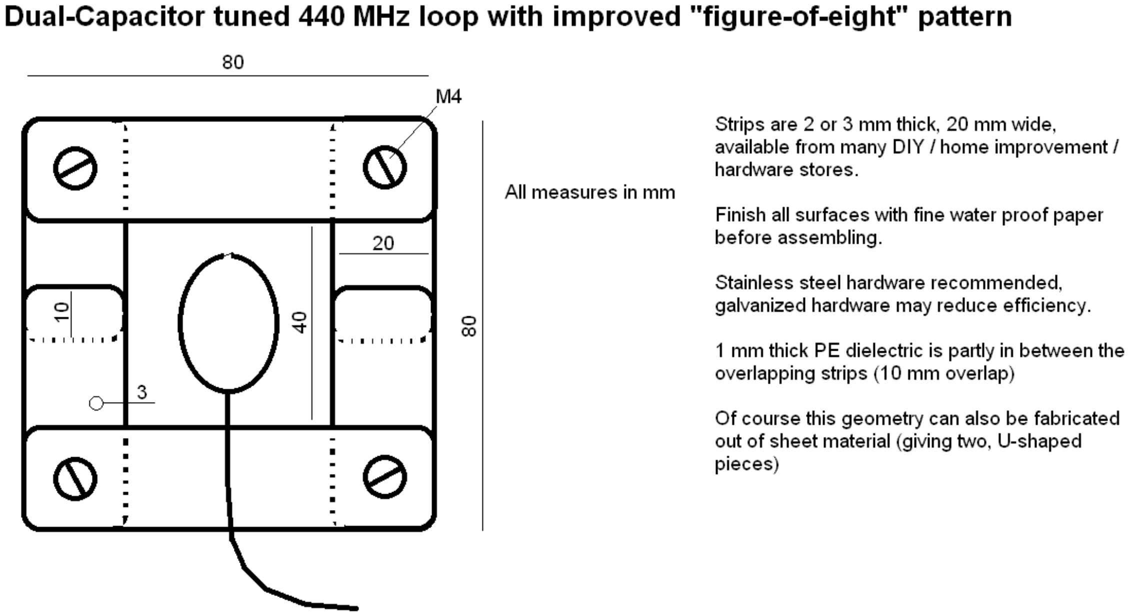


Figure 5.1: example dual-feed 440 MHz loop.

When using the 20 mm wide strip, inner measures will be 40*40 mm^2.

The large outer/inner size ratio give some problems in calculation, so below are just ballpark calculations. If the outcome is far from expectations, adjustment of loop size is required.

Effective square side length

*$Le_{side.eff}$ = rt(80*40) = 57 mm,*

Area (A) = 3.2e-3 m^2.

Geometric mean gives generally better results than arithmetic means. This is due to that RF current concentrates to the inner side of the loop.

Radiation Resistance
Using the R_{rad} formula from chapter 1, for lambda = 0.7m gives:

$$R_{rad} \approx \quad 31.2k \cdot \left(\frac{A}{\lambda^2} \right)^2$$

Rrad = 1.33 Ohms

Inductance
Using the width of 20 mm to say d = 10 mm, is not right here. The strip thickness is 3 mm and at the corners the thickness is even 6 mm due to the overlap. So decided (just a guess) to use strip width = 23 mm.

We use the formula for a circular loop, and add 19% inductance after the calculation.

D = 57 mm, d = 0.5*23 mm, circumference/lambda = 0.33. It is fully clear that in this case single capacitor tuning would give bad total figure-of-eight performance (see figure 3.3).

$$L[H] = \quad 2 \cdot \pi \cdot D \cdot 10^{-7} \cdot \left(\ln\left(\frac{8 \cdot D}{d} \right) - 2 \right)$$

L = 60 nH

Add 19% because of square instead of round geometry

L = 72 nH X_L = 199 Ohms @ 440 MHz

Q factor in case of super conductive loop
Q factor due to radiation loss

$Qsc = X_L/R_{rad} = \omega \cdot L/R_{rad} = 199/1.33$

Qsc = 150 (at 440 MHz)

Efficiency
This requires knowing the loss resistance. Due to the skin effect, current flows at the circumference of the cross section of the aluminum (20*3 mm^2). Half-hard aluminum has about 40% conductivity of copper (so ρ is 2.5·(copper resistivity))
Copper resistivity is 0.0176e-6 Ohm·m, μ_0 = 1.2566e-6 H/m. The formula below is for materials where the conduction current density is well above the capacitive current density (that means $J \gg J_D$, $J_D = dD/dt$, with D = dielectric displacement in As/m^2 or C/m^2).

$$\delta[m] = \sqrt{\frac{2 \cdot \rho}{\mu \cdot \omega}}$$

Skin depth = 5 um

So cross section for current = 5u * 0.046 = 2.3e-7 m^2.

Resistance = ρ·le/A = 2.5*0.0176e-6·0.23 / 2.3e-7 = 0.044 Ohms

In a flat strip, current distribution isn't uniform. This normally gives twice the calculated AC resistance. As Douter/Dinner is no longer very large, current concentrates at the inner side of the square loop. To be save, the guess is that the resistance is 4 times the calculated resistance.

R_{loss} = 0.175 Ohms

That means efficiency will be

Efficiency = $R_{rad}/(R_{loss} + R_{rad})$ = 1.33/(1.33 + 0.18)

Efficiency = 0.88

Depending on the capacitor, efficiency may decrease. As the loop Q factor is around 1100, it is unlikely that a partly air/PE dielectric capacitor reduces the Efficiency significantly. PE dielectric has Q=3000. As part of the E-field path in the capacitor goes through air, the capacitor Q factor will be > 4000. This would yield an overall resonator Q excluding radiation loss of about 860, giving slightly less efficiency.

Some notes on Q factor:
An inductor Q of 1100 seems unrealistically high. It isn't. Measurements on aluminum HF and VHF loops showed Q factors in this range when circumference/lambda ratio are > 0.1. When one would use a round geometry (both loop and wire) and use copper, Q-factors will exceed 1500.

Required capacitance and voltage handling
72 nH has j199 Ohms impedance, so total tuning capacitance will be 1.8 pF. As we have two capacitors in series, each capacitor must by 3.6 pF.

When using 1 mm thick PE dielectric, required capacitor area will be: 1.6 cm^2. Actual required area will be less, as there will be field fringing. As the strips are 20 mm wide, the overlap were dielectric will be between the strips, will be < 8 mm. So our loop should have about 10 mm overlapping metal that will be separated by 1 mm thick PE. The PE should be movable to create a partial air gap for tuning.

Voltage rating

4 W into 1.33+0.175 Ohms develops 2.65 A in the resistances (R_{loss} + R_{rad}).

Inductive reactance is 199 Ohms, so

U_{Loop} = 199·2.65 = 530 Vrms

V_{pk} = 750 Vp

Half of this voltage is across each capacitor. So capacitor voltage handling will be:

V_{cap} = 375 Vp

Dielectric is 1 mm thick, air gap is at least 1mm, and all strips have rounded edges. probability of (partial) discharge is zero. Very likely this loop can handle 15 W without any problem.

Bandwidth for VSWR = 2

As efficiency = 0.88, and Qsc = 150, the actual Q factor will be in the range of:

$Q_{ant} = Q_{sc} \cdot eff = 150 \cdot 0.88$

$Q_{ant} = 132$

$Bandwidth_{-3dB} = f_{center}/Q_{ant} = 440M/132 = 3.3\ MHz$

$Bandwidth_{SWR=2} = 0.707 \cdot Bandwidth_{-3dB}$

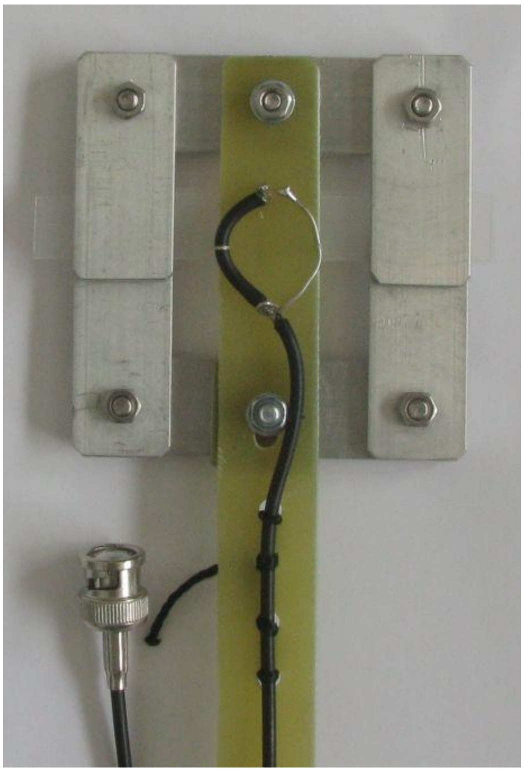
$\mathbf{Bandwidth_{SWR=2} = 2.4\ MHz}$

This finishes the ballpark design calculations.

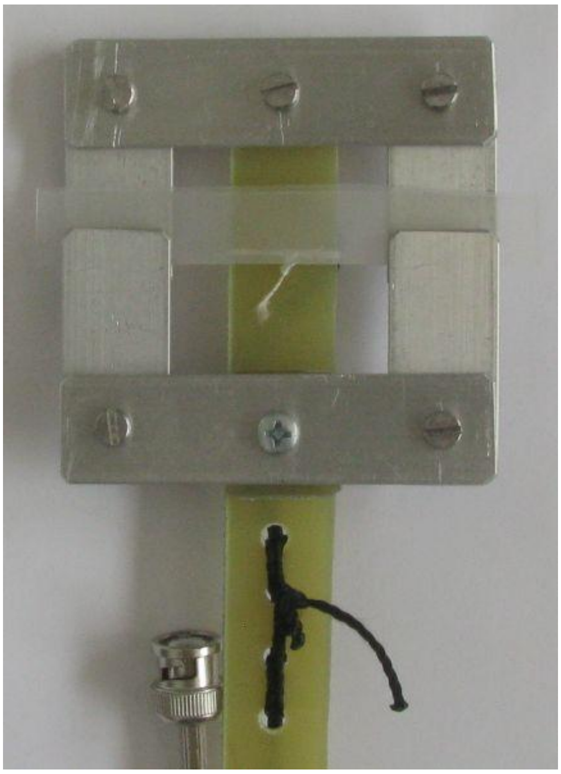
5.3. Actual implementation

Three pictures of the actual loop are shown below:

1



2



3

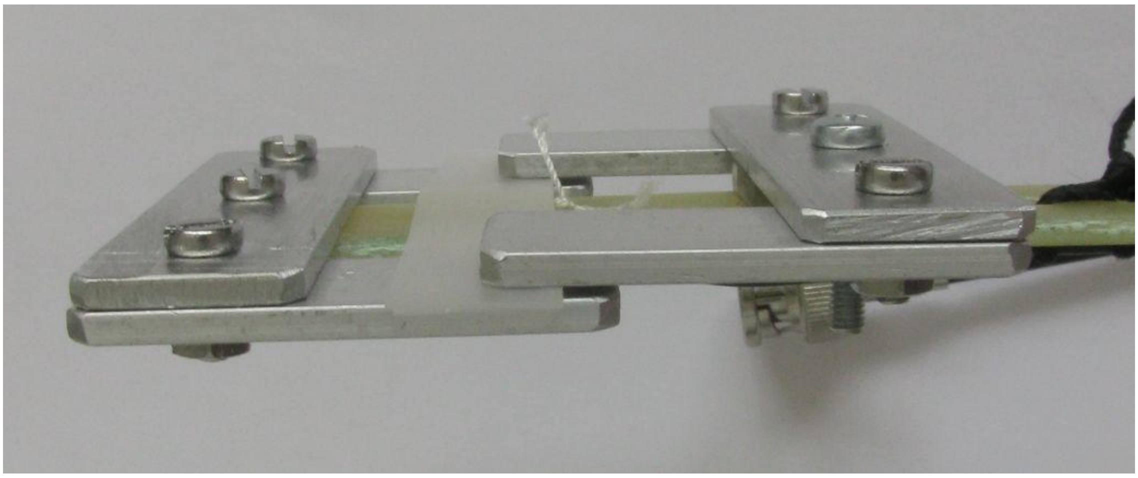


Figure 5.2: pictures of actual implementation of 440 MHz dual-feed loop

Some construction notes
You may use 1.5 or 2 mm thick material. The thinner material (1.5 mm) only if you have relative hard aluminum, otherwise it will bend (plastic deformation).

Make sure to finish all aluminum with fine waterproof paper prior to assembly. This assures good electrical contact.

Even better contact is possible by slightly bending the strips at a line that goes through the center of the drilled holes for the M4 bolts/nuts. Such bend gives a slightly concave surface acting like a curved spring washer. This gives better mechanical stability and better electrical contact, however this requires good experience with the material. Too much and the alignment of the overlap goes bad, introducing unbalance in the capacitors.

Other option is to mill/grind away some metal to get a concave surface, it takes more time, but the risk on bad alignment of the overlaps is near zero.

All mounting hardware is Stainless steel. After assembly, you may put a drip of machine oil at the joints. This oil should not be inside the overlaps.

Strain relieve
There are several ways to fix the cable. When using rope (as done here), do not tighten too much. Polyethylene shows creep under constant pressure. This may lead to short circuit between the center conductor and the braid. When using rope, you may add some flexible sealant. If so, scratch the cable sheet and plastic support before assembly. Otherwise sealant adhesion will be bad.

The capacitors
The third picture shows the overlap of about 10 mm and the 1 mm thick dielectric. Moving the dielectric to the left (photo 3) raises the tuning frequency.

The coupling loop is just determined by experimentation. It is a balanced coupling loop as in picture 1.1.A. The loop couples with the upper and lower half of the loop (photo 1 and 2).

Photo 1 shows a groove in the 3 mm thick FR4 grip. This enables to modify the overlap to get a relative wide tuning range for other applications. The dielectric thickness can be reduced to further widen the tuning range. As one can see (photo 3), two layers of 0.5 mm dielectric are used here.

The coupling loop gives a good match around the center (435 MHz) of the 70 cm band. Optimum match is around 445 MHz.

5.4. *Does it do its job?*

Figure-of-eight pattern
This has been checked in the Bethune Polder in Maarssen (near Utrecht) with reception of several 70 cm repeaters (locations are precisely known).

This is an open area with good flatness. Scattered obstacles (shrubs, undergrowth) > 100 m away. Large trees > 300 m away. Horizon elevation towards source < 2.5^0 (due to trees).

The PI2NOS repeater system is used as test signal (430.125 MHz, emitted from the Gerbrandy tower in IJsselstein).

Usability has been tested on a practical basis, absolute measurements will be done later.

In combination with an AOR AR 8200 portable receiver, notch is deep, independent of loop orientation (that means tuning capacitors in top and bottom, or in the vertical arms). Direction of Notch (and maximum signal) is as expected (almost South for the PI2NOS repeater system).

Best performance is when holding the loop above your head. This is likely due to reflections on your own body. When holding the loop above your body, the capacitors are in vertical arms.

The figure-of-eight patterns enables to make relative good bearings of azimuth of the incoming wave front (of course having an uncertainty of 180^0).

Bandwidth, SWR=2
Bandwidth (SWR=2) is measured without correction for the 1.30m of RG174. The cable loss is 0.85 dB. So correction is required.

SWR=2 equals a reflection coefficient (RC) = 0.33. The test signal from the VNA travels twice the distance. So total loss is 1.7 dB (that is voltage gain of 0.82).

So actual measurements should look to the points were RC = 0.82*0.33 = 0.274. This equals VSWR = (1+0.274)/(1-0274) = 1.75. Marking these points actually determines the frequency points were SWR=2, referenced at the antenna.

This gives a BW = 2.3 MHz at 445 MHz. So

$$\mathbf{BW_{(SWR=2)} = 2.3\ MHz}$$

This is agrees with the expected 2.4 MHz. So efficiency is very likely around the expected 88%. As efficiency is not that importance (as long it is above 50%), efficiency is not further investigated.

Reason for using 445 MHz instead of 435 is that at 445 MHz the S11 curve goes through the origin. At 435 MHz, the curve goes a bit around the origin, making the measurement less accurate.

Note on the tuning
This is done by moving the PE dielectric more or less inside the overlap. As the relative useful BW is small, only small adjustments should be made. Think of 0.3 mm on each side. Always check that overlap on both sides is equal, and coverage of the dielectric inside the overlap is equal. If not, you introduce too much capacitor unbalance, reducing the depth of the notches in the figure-of-eight pattern.

When almost all of the dielectric is under the overlap, then it is best to increase the overlap somewhat, this allows to get more air in the overlap (increasing Q-factor).

5.5. "Scouting" Style implementation"

A very minimalistic and lightweight implementation is possible using copper or aluminum wire and a support made from a PE cutting board. Everything is hold in place using 1 mm nylon rope using an asymmetrically sliding knot. Once everything is fine, some better fixing is required as detuning due to mechanical shock is very likely.

For construction reasons the tuning capacitance is in the top and bottom arms. As the support is in the field of the capacitance between the overlapping wires, one should use low loss dielectric (PE, PP, but not FR4 epoxy/glass laminate).

As the effective area is large compared to the metal strip implementation, radiation resistance is significantly higher. Though inductance is higher (thin wire), Q factor is less (around 80). Distance from coupling loop towards the loop is significantly more resulting is low coupling factor. This would require a coupling loop almost as large as the loop itself. This is not desired as the coupling loop becomes a receiver on its own.

Here the series capacitor trick does its job (start with $Xc<XL_{coupling}$). The capacitor is a 25 pF Teflon (PTFE) capacitor. The Teflon is just because that trimmer capacitor was in stock, Teflon dielectric is not mandatory.

Below are two pictures of the front and back side. Loop width (center-center) is about 80 mm.

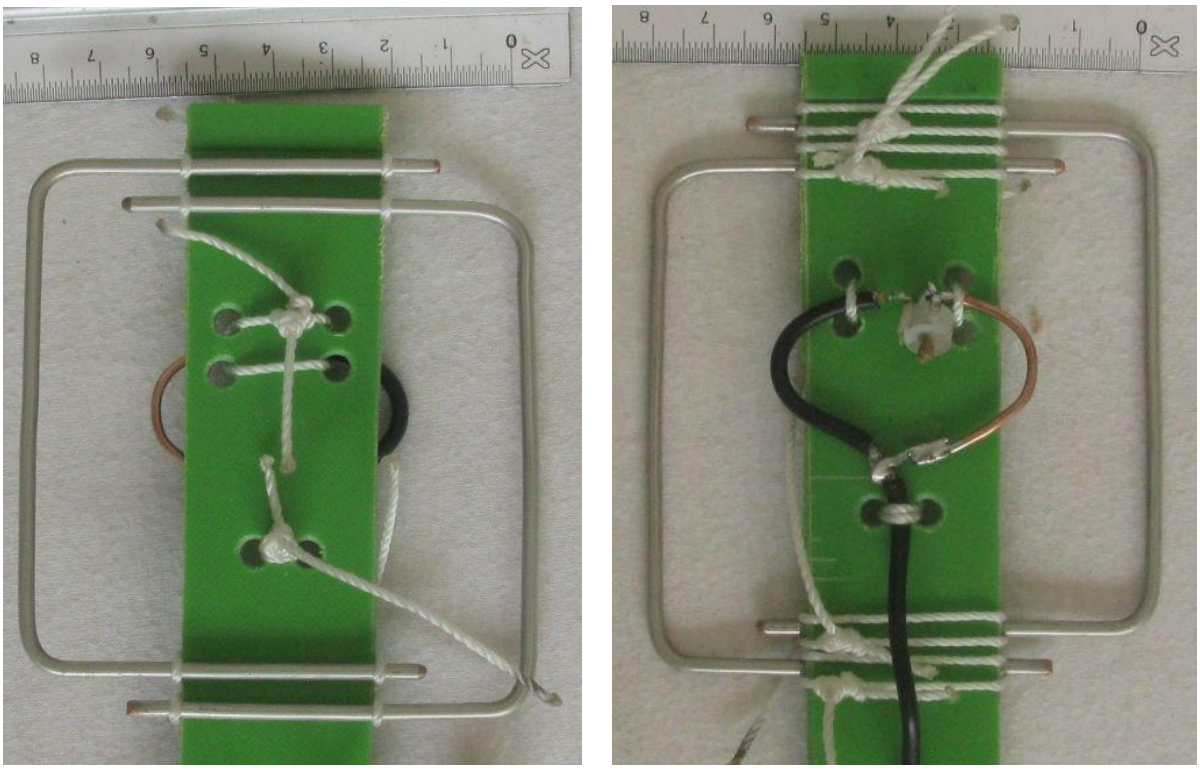


Figure 5.3: "Scouting style" implementation of dual-feed 440 MHz loop.

The coaxial cable bridges the lower capacitance and is in the fringe field.

Detail not shown on the right image. To reduce coupling between braid and lower capacitance, the coaxial cable "jumps" over the 4 ropes. Distance between cable and green support (between the middle two wires) is about 8 mm. As the support has a thickness of 3 mm, there is sufficient clearance so that coupling is negligible.

The nylon rope is in the high field zone. The volume compared to the air volume between the overlapping wires is small, so the effect on Q-factor is negligible. However…., when the rope becomes wet, performance drops significantly. Options is to use thin wire (for example 0.5 mm nylon or polyester and impregnate it with cosmetic grade pure petroleum jelly), or make sure the wire doesn't become wet.

This loop has been tested also at the Bethune Polder, and performance is comparable to the "metal strip" implementation.

Note on directivity
This loop is no longer small compared to wavelength (circumference/lambda = 0.46). The current in the vertical sections is more than the current in the horizontal sections. Therefore when the loop is in the position as shown on the pictures (green support vertically), directivity in the horizontal plane is somewhat more compared to when the green support is positioned horizontally.

The asymmetrically sliding knot.
The image below shows how to make the knot that is used for fixing the parts to the green support.

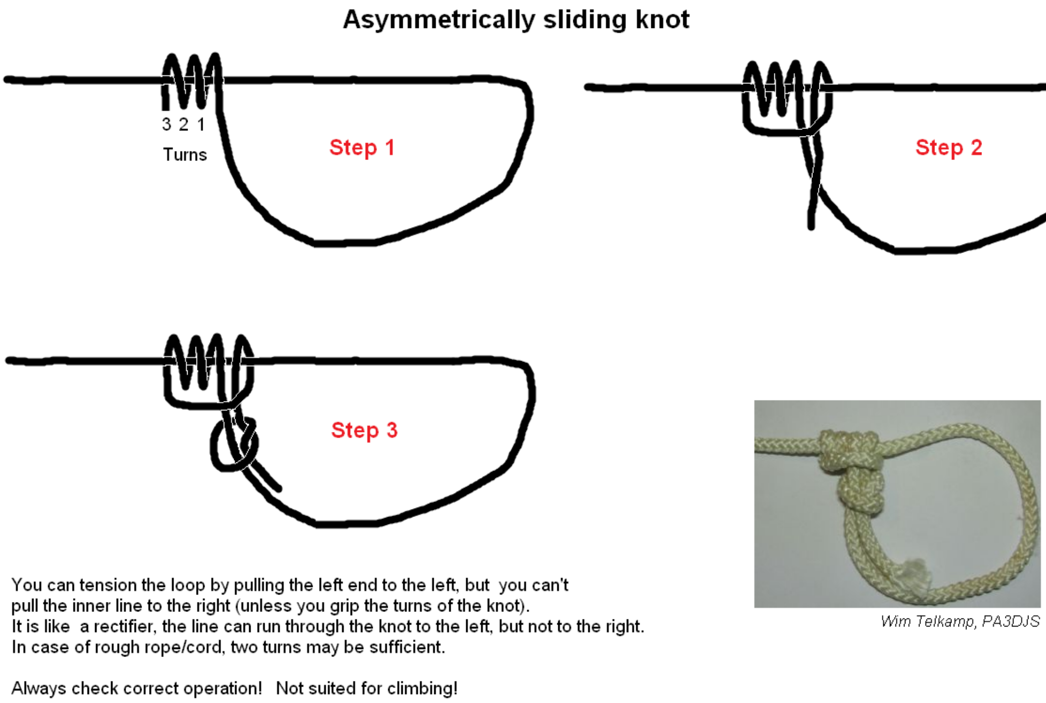


Figure 5.4: Adjustable loop with friction knot.

6. Design example 145 MHz loop (2 m band).

Added February 2019

6.1. Goal.

Verification of the loop design procedure and some approximate formulas. The loop will be used for fox hunting and interference location.

Though simple loops don't provide front to back ratio, they have a very useful pattern for signals/interferers with a dominant vertically polarized component.

The antenna has to be mounted on regular non-conducting material (think of wood), therefore the Scouting Style 70 cm design cannot be used.

6.2. Design.

Normally ideas are first simulated, however this one was first built based on approximate formulas, and simulated afterwards. Only the capacitor was simulated first in ATLC2.

The Scouting Style 70 cm antenna (on green cutting board strip) relies on the low loss dielectric as part of the E-field goes through the green strip. For this and other designs, the two capacitors use an intermediate ground plate that functions as a shield between the two extremities and a lossy supporting structure.

One would say: "put the capacitors in the vertical arms, then the there is no E-field near the vertical supporting structure". This is correct, however in case of no longer electrically small loops, the gain in the plane of the capacitors goes down.

Figure 6.1 shows a drawing of the proposed capacitor.

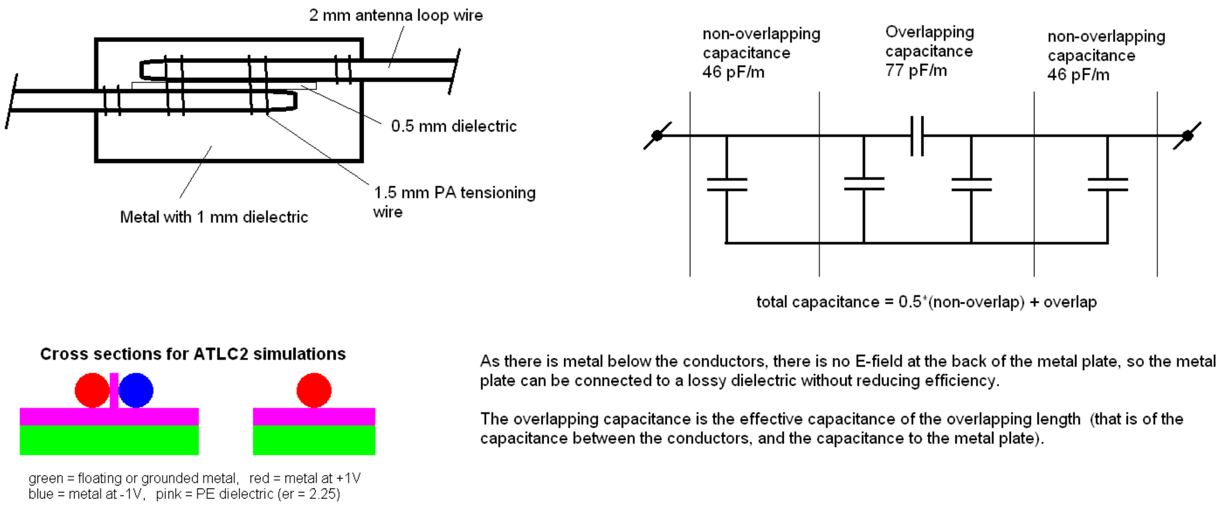


Figure 6.1: semi-shielded experimental capacitor

There is dielectric between the rods and ground (0.5 mm), and between the overlapping parts (0.5 mm).

The outer two capacitors of the circuit diagram (fig. 6.1.) represent the capacitance of the non-overlapping part to the metal plate. They are “half effective” as they are in series. The Overlap increases the capacitance, as that capacitance is 100% effective. ATLC2 simulation graphs are provided. Note that ATLC2 does not need a closed ground along the full edge of the bitmap (compared to the original ATLC program).

The dielectric layers are made of semi-transparent hard plastic document folders (bought at the local HEMA). The dielectric thickness is about 0.5 mm, the material is hard Polyethylene. Do not use the flexible sheet protectors or flexible folders, as the material is very thin. Mylar overhead projector sheets are also not suitable because of the dielectric loss.

The tensioning cord is transparent nylon cord available at many hardware / DIY stores. It is recommended to avoid black cord as that may contain carbon black. The friction knot is shown in chapter 5.5.

Figure 6.2 shows various simulation results.

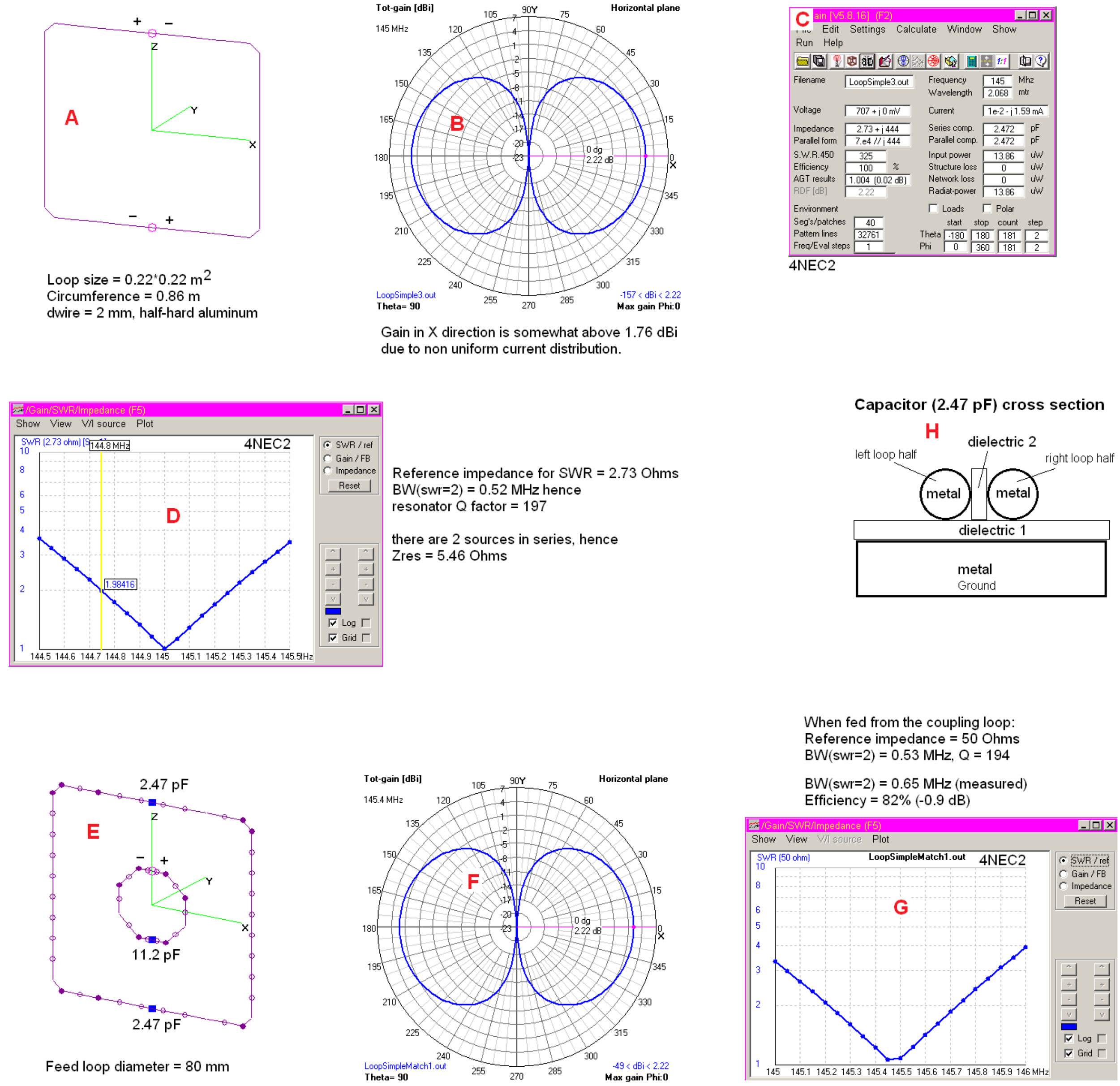


Figure 6.2: 4NEC2 simulation of dual feed / double gap loop only, and loop with coupling loop

Figure A, B and C are for the loop alone, with a voltage feed in both the top and bottom. Check the polarity of the sources, the null should be perpendicular to the loop (that is in y direction). Figure D shows the SWR when a capacitor (LD card) is put in series with the loop. The reference impedance is 2.73 Ohms. Figure H shows the capacitor construction that provides about 2.7 pF capacitance.

Figure E shows the complete loop, with coupling loop. Individual segments are shown. The coupling loop has D = 80 mm, main loop has W = H = 0.22 m.

When doing your own simulation, run the Average Gain Test with < 5 degree resolution for the 3D far field pattern. It should be close to zero dB (or 1 as a number).
When > +/- 0.5 dB, you may need to change your model.

Key data:

Rs = 5.46 Ohms (sum of both feeds, loop only)

Required capacitance, 2.47 pF/gap (so effective total = 1.24 pF).

Capacitor voltage @ 10W input: 850V for each capacitor.

The gain in the plane of the loop (figure 6.2.F.) is 2.22 dBi, though a small loop has Gi = 1.76 dBi. This isn't a simulation error, but because of the non-uniform current distribution. The vertical legs carry more current.

The simulated bandwidth for SWR = 2 (figure G) is just 530 kHz.

6.3. Implementation

Figure 6.3. shows the assembled loop

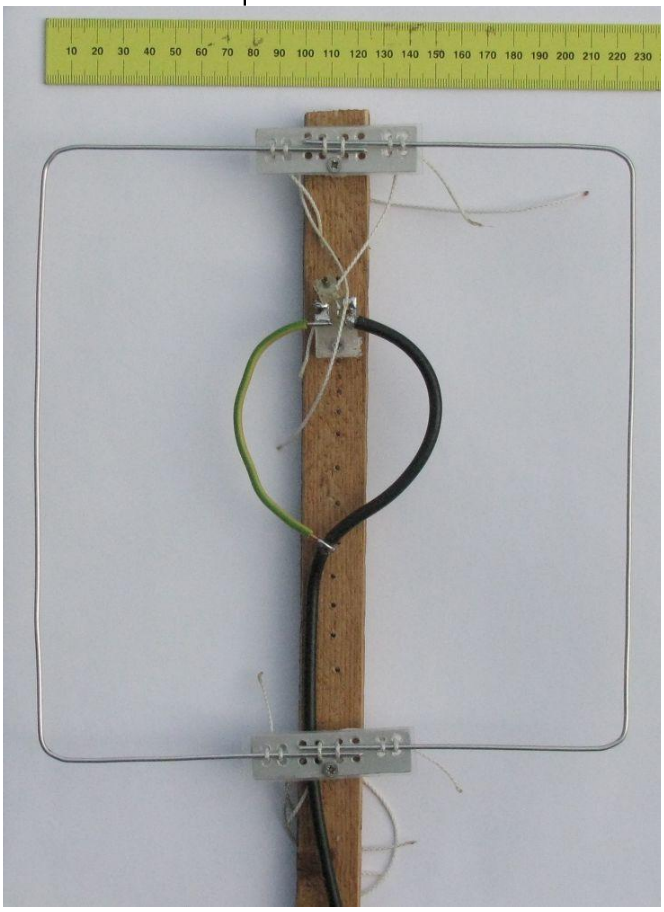


Figure 6.3: Complete loop on wooden support

The loop wire is 2 mm aluminum electrical fencing wire. Start with two straight pieces of 0.46 m, and place marks 0.12 m from the extremities to mark the corners. Bending radius is about 10 mm. The coaxial cable is just RG58. The left half of the coupling loop is green/yellow 2.5 mm^2 Cu-wire, and is soldered onto the braid.

The capacitor is an old Philips Teflon 18 pF trimmer capacitor. A low Q trimmer capacitor is also good as the loaded Q factor of the coupling loop isn't high.

Tuning capacitors.

Tuning capacitors are shown below. The dielectric between the two extremities is clearly visible. The aluminum plate serves as the screen avoiding that E-field reaches the wooden support. The unused holes are for fixing the extremities in case of larger overlap. Length of metal strip is 60 mm, overlap is about 25 mm for 0.5 mm dielectric

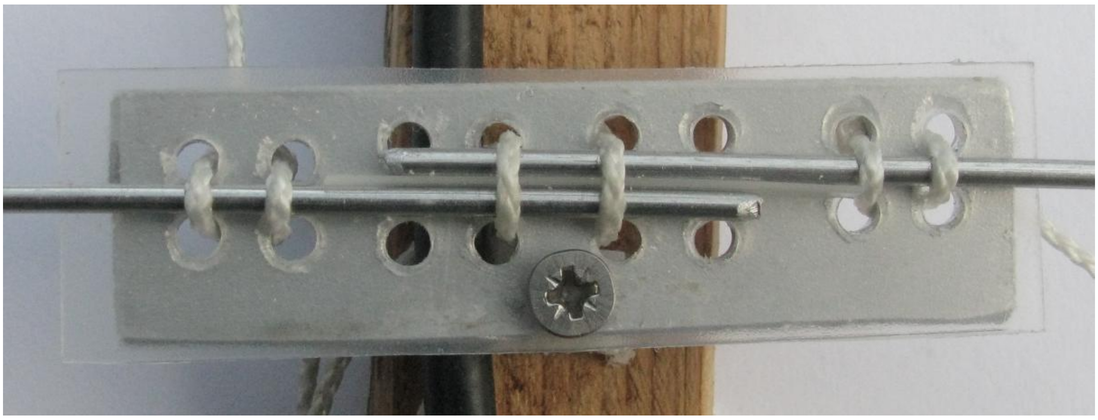


Figure 6.4.A: detail of capacitor

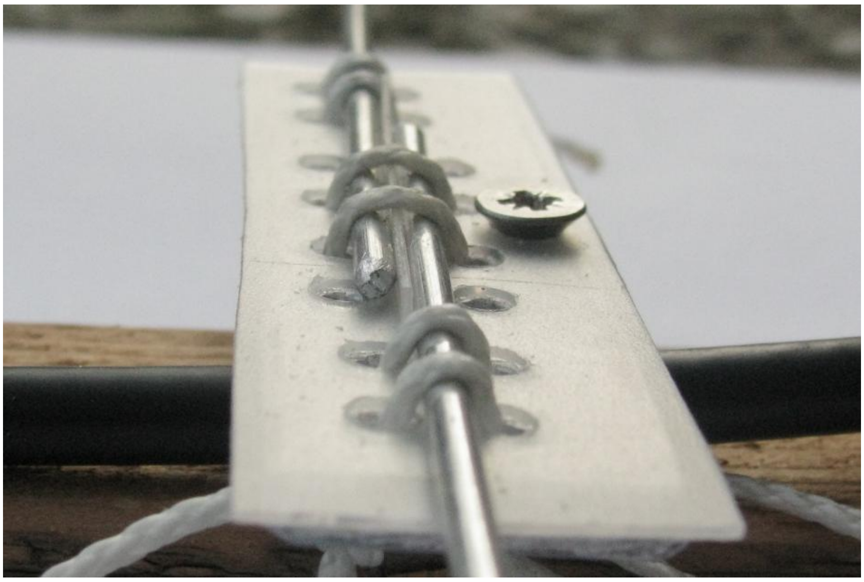


Figure 6.4.B: detail of the capacitor

The coupling loop
The coupling factor (k, coupling coefficient) between the radiating loop and the coupling loop is low (in order of $k < 0.05$). Together with the limited Q factor of the radiating loop a 50 Ohms match is impossible. A series inductance remains. Adding a series capacitor in the coupling loop cancels this inductance (partly).

From a practical point of view, the coupling capacitor creates a continuously adjustable coupling factor without changing the size or position of the coupling loop.

Gradually decreasing the coupling loop capacitor value increases the apparent coupling coefficient. Start from a capacitor value that is well above the value for series resonance. That means the series resonant frequency of the coupling loop / capacitor combination must be below the operating frequency.

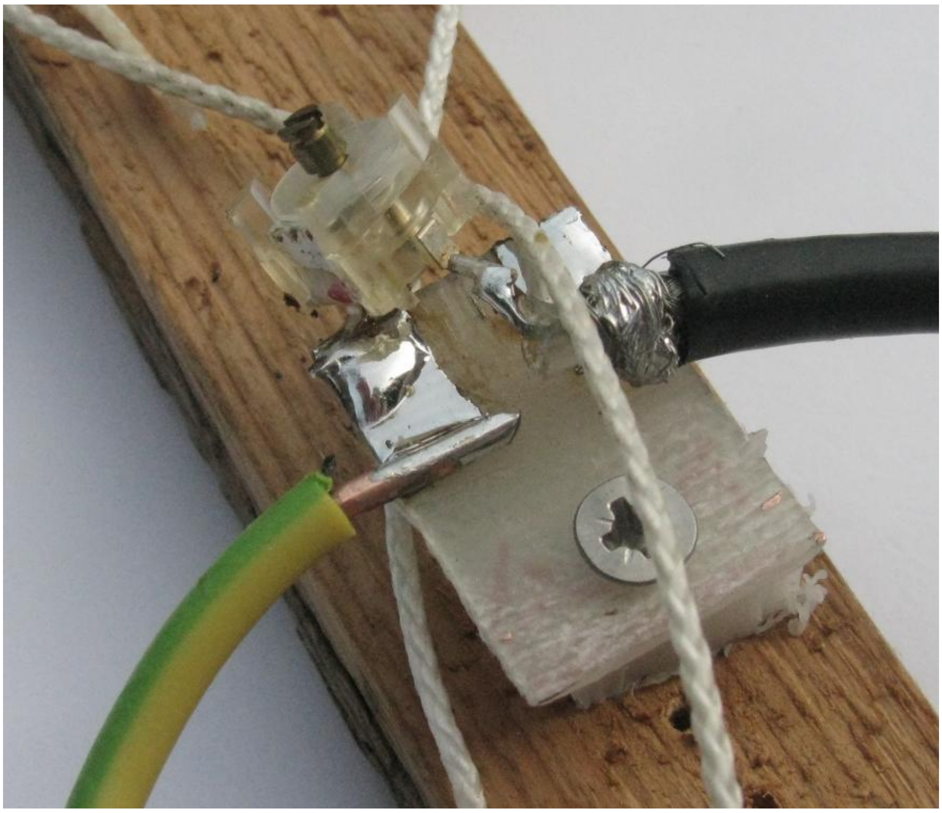


Figure 6.5: detail of the coupling loop capacitor

Figure 6.5 shows the coupling loop capacitor. It is connected between the yellow/green Cu wire and the center conductor of the RG58 coaxial cable.

Tuning and practical results

You need a means for measuring SWR, S11 or return loss. Most convenient is a graphic analyzer. Instructions below are for a scalar graphic analyzer.

- Adjust overlap on bottom and top capacitor to about 25 mm, tighten nylon cord and set trimmer capacitor to its maximum value.
- Measure SWR or S11. When SWR dip is below center frequency, reduce the overlap on top and bottom capacitor. Keep overlap the same for bottom and top, and centered around the vertical center line of the aluminum strip.
- Slightly reduce coupling loop trimmer capacitance and observe SWR until SWR is 1. Note that center frequency moves somewhat, therefore a graphical analyzer is very useful.
- Adjust top and bottom overlap to bring best SWR to required center frequency.
- You may need to repeat the above steps once.

When using a single frequency measurement, and you change the coupling loop capacitor, you need to change the measurement frequency to find the frequency for lowest SWR.

Bandwidth for SWR=2 should be about 650 kHz or less. This equals an antenna efficiency of > 82%.

Though the loop is primary made for reception (locating interference and fox hunting), it can be used as a low power transmitting antenna. Though the antenna survived 10 W CW during 1 minute, it is not recommended. Capacitor voltage is 850 Vp, and creepage paths are small, so tracking may occur. This can be accelerated when operating in humid environment.

When finished, impregnate the friction knots with glue or resin, and cut excess wire after curing.

This construction isn't waterproof. A single drop of water at the high voltage areas (metal to dielectric junctions) will leave the loop useless.

6.4. Modifications

The bandwidth is small (650 kHz at SWR = 2). Using thicker conductors for the main loop will increase bandwidth. When using thicker radiators, there is no benefit of using copper. When using about 8..10 mm thickness, efficiency reaches near 100% and 1 MHz useful bandwidth is possible.

Using a larger loop will increase the bandwidth, but not as strong as expected based on the Rs formula and loop inductance. This is because of the non-uniform current distribution. That becomes even more non-uniform with increasing loop size. Gain in X-direction will increase, but gain in Z direction reduces.

When using a larger main loop, the coupling loop diameter must increase, otherwise you can't get a 50 Ohms match anymore. As a guideline

$$D_{coupling.loop} = 0.33...0.45*(\text{main loop width})$$

Do not make it larger then necessary, as it will affect the depth of the notch in the radiation pattern.

When the coupling loop size increases, inductance increases also, hence the loaded Q-factor. When using a large loop, it is recommended to use a good trimmer capacitor in series with the coupling loop.

Example for a rectangular loop:

Loop width = 0.3 m, Loop height = 0.4 m, tube diameter = 8 mm,
Top and bottom tuning capacitance about 1.22 pF
Coupling loop diameter = 0.14 m, coupling loop tuning capacitance = 4.5 pF

Center frequency = 145 MHz, bandwidth (VSWR = 2) = 2 MHz
Gain = 3.2 dBi, notch depth > 23 dB below max. gain (including the contribution of the coupling loop).

Due to the smaller capacitance and thicker tubing, overlap is likely not required.

7. Dual-feed EMC sniffer loop

7.1. Introduction

The small single gap (figure 1.1.A) loop is good for many EMC sniffer applications. Undesired current in wires can be demonstrated and the effect of ferrite can easily be determined.

When current in a conductor is relatively low, but voltage is high, E-field sensitivity may become non-negligible. This happens in showing current in antenna conductors during antenna courses and instructions. Current in antinodes of transmission lines with very high SWR are less deep than expected. Loop orientation is very important.

In case of large loops, the approach shown in figure 4.1.A can be used, but this is troublesome in case of small loops. Would it be possible to make something based on the single gap loop (as this already has a balun function). Yes it is possible!

7.2. Evolution from single gap to dual gap EMC sniffer loop

Figure 7.1 shows the evolution from a single gap loop towards a double gap loop (dual-feed loop).

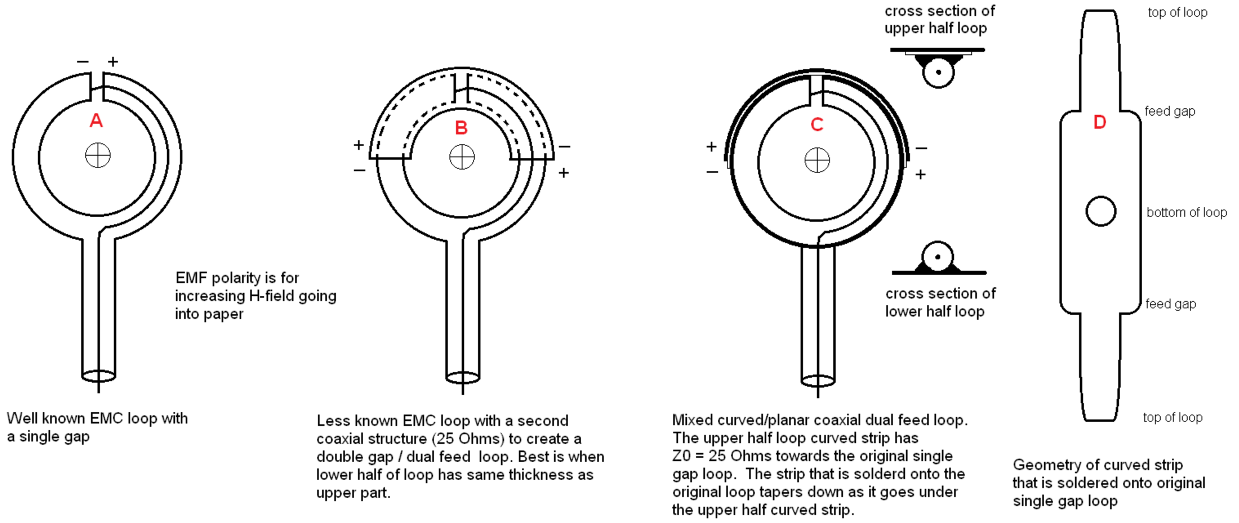


Figure 7.1: From single-gap EMC sniffer loop towards curved planar dual-feed loop

Figure 7.1.A shows the single gap EMC sniffer loop. The center conductor coming out of the right half loop connects to the left half loop. The induced signal across the gap travels via the coaxial structure inside the right half loop towards the connector (not shown).

When the H-field that goes into the paper increases (so positive dH/dt), the polarity is as indicated in the figure.

Another coaxial structure is added in the B figure. As seen from the top gap, the coaxial structures are in series, so to maintain good match, the new coaxial structure should have 25 Ohms characteristic impedance (assuming 50 Ohms cable impedance).

The double gap EMC sniffer loop is there!

To get maximum balance, the lower part of the loop should be thickened to the same diameter as the added upper half loop. The induced signal across the two new gaps travel upward via the added coaxial structure to the original gap. They add to produce the same signal compared to the single gap loop.

Besides better suppression of the non-rotational E-field component, the path length halved. The first parallel resonant frequency doubles compared to the single gap loop. This enables H-field measurement at twice the frequency without correction for transmission line effects in the loop.

7.3. Dual gap curved quasi planar loop example

Construction of the full coaxial loop is troublesome, but of course possible. A quasi-planar construction is possible shown in figure 7.1.C. A practical implementation is shown in figure 7.2. The loop diameter is 40 mm, strip width is 10 mm. PTFE coax is used. The plastic jacket is removed before soldering.

Figure 7.2: detail of Quasi (curved) planar dual-feed loop

First a sheet pattern is cut as shown in figure 7.1.D. This is bent into a loop and (semi rigid, PTFE) coaxial cable is soldered onto the inside of the right half of the strip loop. Now a single gap EMC loop is present, but the upper half of the loop has about half the strip width. This can be seen in figure 7.2 (inner side of loop).

When looking to figure 7.2, the non-used coax inside the left half loop is not present. This is allowed as long as the strip width is large compared to coaxial diameter. The upper half of the loop (figure 7.1.C) is covered with a dielectric sheet (for example PE tape). Another half loop made from strip material is mounted onto the dielectric. The narrow part of the single gap loop forms a microstrip. The inner side of the outer half loop functions as ground for the microstrip.

Two feed gaps are present now. Figure 7.1.C also shows cross sections of the lower half and the upper half of the loop.

The example in figure 7.2 shows the upper half loop at the right side. Three layers of PE tape are visible at one of the feed gaps. Total dielectric thickness is about 0.5 mm. The narrow part of the loop is also visible.

A rope loop with a friction knot (figure 5.4) is used to press the upper half loop (left half loop in graph 7.2) onto the inner loop. The coating is applied afterwards.

Even without common mode decoupling, E-field rejection is outstanding and improves the transmission line and antenna current instruction.