Magnetic loop antenna according to DL5MCC

A new concept for magnetic antennas, for frequency tuning without a variable capacitor

Klaus Finkenzeller, DL5MCC, klaus@dl5mcc.de

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A constant problem when building magnetic loop antennas is the procurement of a suitable, voltage-resistant variable capacitor with the appropriate capacitance range. The following article describes a new type of magnetic loop antenna, which does not require a variable capacitor at all. The frequency adjustment within a band is done by changing the magnetic coupling between two loops which aren't galvanically connected. Changing frequency band is accomplished by switching fixed capacitors. The basic concept of the antenna as well as first simulation and practical results are presented here. Even though the article is not a construction manual, simple hints for self-construction and adjustment of the antenna are given.

Basic concept of the antenna

Antennas with a small, compact design are enjoying increasing popularity. No wonder, as the ever increasing density of construction in cities, the growing hostility towards technology and "fear of radiation", anonymous neighbourhoods and in new housing estates even general bans on antennas, have led to the problem that antenna construction is often the dominant obstacle for amateurs to build their own radio station. The construction of a classic long-wire antenna is often simply impossible.
Magnetic loop antennas (MLA) have an extremely compact design and are therefore a good alternative to long-wire antennas. An MLA consists of a mostly circular or square conductor loop as inductor and a capacitor. The loop and the capacitor together form an electrical parallel resonant circuit. In practice, the circumference of the loop is usually between one third and one tenth of the wavelength, with the largest possible surface area. MLAs primarily generate a magnetic field in the near field, which then changes into an electromagnetic wave at the transition to the far field.
In order to enable a high efficiency of the antenna, correspondingly high currents must be generated in the loop, which requires a high Q-factor in the parallel resonant circuit. In addition, an MLA must always be operated in resonance, which means that the antenna has to be constantly tuned when the frequency changes. In common practice, variable capacitors are used for this purpose in order to be able to adjust the resonance frequency continuously.
However, the high Q-factor of the MLA now also leads to a very high voltage at the variable capacitor during transmission. At a typical transmission power of 100 W, several kilovolts of voltage can easily occur at the variable capacitor. When choosing a suitable variable capacitor, besides the capacitance range, a sufficient dielectric strength has to be considered, which can only be solved by a large distance between the capacitor plates. The well-known formula for the capacitance of a (plate) capacitor

$$C = \varepsilon \cdot \frac{A}{d}$$

forces at large plate separation *d*, at constant capacity *C* a correspondingly large surface *A* of the plates. This leads to very large and mechanically complex designs of the variable capacitors.
Even a reduction of the transmission power does not help much. Due to

$$U = \sqrt{P \cdot R}$$

a difference of 1:100 in the transmission power, results in a difference of only 1:10 in the applied voltage.
Our dilemma: Because standard variable capacitors as used in receivers cannot be used in transmission mode. Voltage-resistant variable capacitors however are difficult to obtain and usually very expensive. A large part of construction projects for an MLA, probably failed from the outset because suitable variable capacitors were unavailable or too expensive.
The presented MLA after DLM5CC uses a completely different concept for frequency tuning and does not require a variable capacitor.

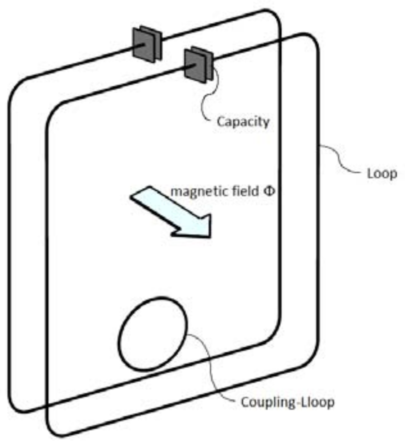

Figure 1: Basic principle of the MLA designed by DL5MCC.

The common magnetic flux Φ through both loops results in a magnetic (transformer) coupling between the two loops, expressed by the coupling factor k, which can assume values between 0 and 1. A coupling factor of 1 means that the magnetic field generated in the first loop flows through the second loop entirely. A coupling factor of 0, on the other hand, means that a magnetic field generated in the first loop does not flow through the second loop at all, or is cancelled out in direction (and thus in effect).
With large loops within a few centimetres of distance from each other, degrees of magnetic coupling between

roughly 0.75 and approximately 1 are obtained, which means that the two resonant circuits form a common resonance frequency, even if the individual resonance frequencies of both loops are not the same. We can use this circumstance very elegantly to switch the frequency band, as we will see later.
The resulting common resonance frequency is always lower than the resonance frequency of an oscillating circuit alone, and depends on the strength of the magnetic coupling. **If we change the strength of the magnetic coupling, we can change the frequency of the common resonance frequency.**
In addition to the common lower resonance frequency f1, a second, higher resonance frequency f2 is formed. This is clearly visible in the simulation and also in the impedance measurement, but is unfortunately unusable for practical radio operation. At frequency f2 the currents in both loops flow in push-pull. Therefore no power is radiated, the radiation resistance of the antenna is close to zero.
To adjust the magnetic coupling and thus the resonance frequency of the antenna, it is sufficient to change the mechanical arrangement of the two loops in relation to each other. With the patterns built so far, one of the loops is simply tilted with respect to the other loop. An adjustment of the tilt angle between 0° and about 15°, for example, is completely sufficient to be able to tune over the entire 20 m or 40 m band.

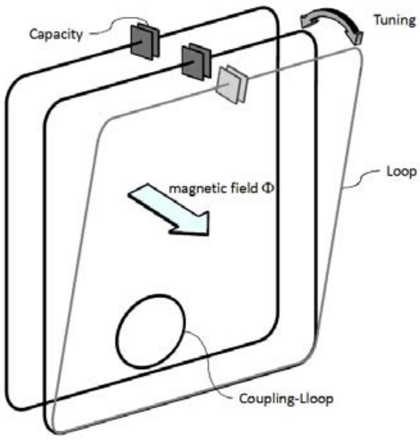

Figure 2: Simple setting of the resonance frequency with an MLA according to DL5MCC

Other ways of tuning the resonance frequency would be, for example, to shift the loops laterally relative to each other, or to change the distance between the loops on the common coil axis.
Due to the use of at least two loops in resonance, as well as the alignment by a modified magnetic coupling, this antenna is also called "**D**ual **L**oop **M**agnetic **C**oupling **C**alibrated" (DL-5-MCC).

HF feed of the antenna

The RF feed of the antenna is exactly the same as known from the classic MLA, either via a coupling loop, gamma adjustment or any other feed suitable for MLAs. It is sufficient to feed into only one of the loops, the second loop is automatically excited as well. The coupling can therefore be realised and dimensioned in the same way as with classic loop antennas. Since there are numerous articles and websites on the subject of coupling in MLAs that deal with this topic in detail, this article will not go into the calculation of coupling loops in detail. A suitable tool for the calculation of the RF coupling is for example the magnetic antenna calculator [2] by DG0KW.

Theoretical background

In order to understand how the antenna works a little bit better, we first have to deal with the theory of coupled oscillating circuits.
For the sake of simplicity, we will consider two MLAs with the same dimensions, i.e. corresponding to the same resonance frequency. As soon as we bring the two loops of the MLA close to each other, a magnetic coupling occurs. This means that a part of the magnetic field generated in the first loop also penetrates the second loop and induces an electric voltage. The resulting current in turn creates its own magnetic field, which acts back on the first loop. In this way, an interaction between the two antenna resonant circuits is created, which is expressed by the mutual inductance L_M (mutual inductance) or the coupling factor k.
Figure 3b shows a simple equivalent circuit diagram of the two antenna resonant circuits. Since we assume the same dimensions, both loops have the same inductance L and the two capacitors have the same capacity C. The common, lower frequency resonance frequency f1 then results in

$$f_1 = \frac{1}{2\pi\sqrt{\left(L + L_M\right)\cdot C}}$$

with $L_M = k\cdot L$

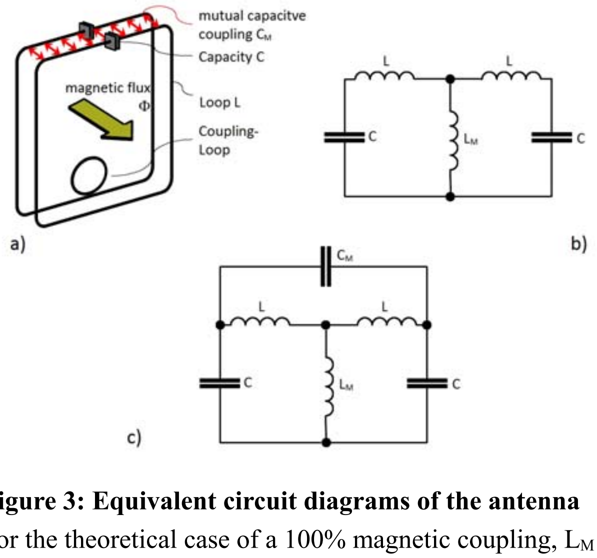

Figure 3: Equivalent circuit diagrams of the antenna

For the theoretical case of a 100% magnetic coupling, $L_M = k\cdot L$, so that as common resonance frequency f1, we will get a value of

$$f_1 = \frac{1}{2\pi\sqrt{\left(L + L\right)\cdot C}} = \frac{1}{\sqrt{2}\cdot 2\pi\sqrt{L\cdot C}}\ .$$

The common (coupled) resonance frequency f1 of two identical antenna resonant circuits with the resonance frequency f0 (uncoupled) can thus theoretically assume the frequency f0/√2 as the smallest value at maximum magnetic coupling. By changing the magnetic coupling between two identical antenna resonant circuits, the resonance frequency of the antenna can therefore theoretically maximally be tuned in the range between f0/√2 and f0. In practice, however, a second effect comes into play. An additional capacitive coupling C_M (mutual capacity) is effective between the two parallel loops, as shown in Figure 3a. An equivalent circuit diagram is shown in Fig. 3c. The common resonance frequency f1 is now calculated as

$$f_1 = \frac{1}{2\pi\sqrt{(L+L_M)\cdot(C-C_M)}} .$$

If we bring the two loops closer together, the values of L_M and C_M increase equally. Because of the opposite sign (subtraction), the capacitive coupling counteracts the magnetic coupling (addition) with regard to the frequency shift, so that the adjustment range for the resonance frequency will always be (significantly) smaller than 1/√2 in practice.
The size of the capacitance C_M depends strongly on the mechanical construction of the antenna, for example the cross-section of the loop or the distance between the loops.
A larger distance between the loops or an unequal geometry of the two loops (e.g. unequal diameter) reduces the maximum coupling factor, but also the capacitive coupling between the two loops. In general, this leads to a smaller frequency adjustment range and thus represents a kind of band-spreading. The exact behaviour as well as the dimensioning of the antenna can best be determined by simulation, e.g. with 4NEC2.
The tuning range of the presented MLA typically covers 0.5 to 2 MHz with fixed capacitances and can therefore only be used in one band.

Comparison with dual-circuit band filters

The behaviour of our MLA in the frequency domain corresponds largely to the behaviour of a dual-circuit band filter. The critical coupling frequency response, known from dual-circuit band filters occurs at magnetic coupling levels in the range of k=0.055 ... 0.015, above which the range of supercritical coupling begins with the formation of two bumps [1], the two resonant frequencies f1 and f2. To see critical coupling in MLAs, however, the two loops would have to be several meters apart. With magnetic coupling levels well above 0.1 as used here, the two bumps are already completely separated from each other. As the magnetic coupling factor k increases, the two resonant frequencies of the loop diverge further and further (Figure 4). For our Dual Loop we have to use the lower resonance frequency f1. At the upper resonance frequency f2, the currents in the two loops flow in opposite directions, so that there is no radiation, since the fields generated cancel each other out in the far field.
For the frequency of the humps (we only use the lower one with f1) it is irrelevant whether the two individual resonant circuits (i.e. our loops) are tuned to the same frequency or even a few MHz apart, due to the strong magnetic coupling. The mutual influence is so strong that common resonance frequencies are always formed between the loops.

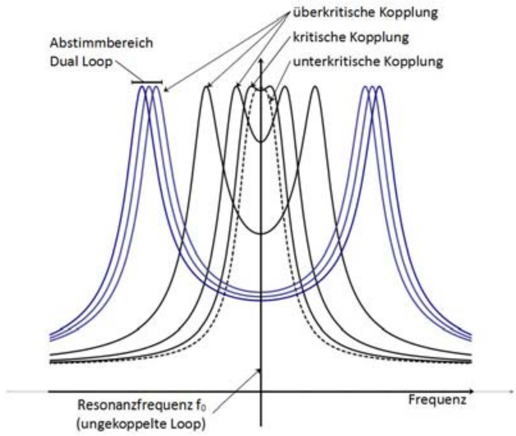

Fig. 4: The MLA presented here behaves like a dual-circuit band filter with highly supercritical coupling.

Switching the frequency band

By connecting additional capacitors in parallel, the MLA can be switched to bands of lower frequency, even if the two antenna resonant circuits are wired with different capacitances. This is very convenient for us, because in this way it is sufficient to alternately connect another capacitor in parallel to one of the loops to realise several bands. A square MLA with an external dimension of 1 m x 1 m serves as an example. Table 1 lists the capacitance values required for frequency band switching by alternately adding capacitors. C1 is assigned to loop 1 and C2 to loop 2. The values were determined for a tube diameter of 22 mm. Since double pipe clips from a hobby story were used, the minimum distance between tube centre to tube centre is 4.2cm
If, as described below, coaxial cables are used as capacitors, the core of the individual coaxial cables can be connected to one end of the loop if necessary, to add the capacity required for a specific band. The shielding can remain permanently connected and does not interfere.

Band	Frequency	C1	C2	dBi (dBd)	CU-CL
17m	18.068-18.168	12,8 pF	12,8 pF	1,60 (-0,55)	0,958 m
20m	14.000-14.350	12,8 **+ 19,6 pF**	12,8 pF	1,05 (-1,1)	0,913 m
30m	10.100-10.150	12,8 **+ 19,6 pF**	12,8 **+ 49.5 pF**	-0,33 (-2,48)	0,927 m
40m	7,000-7,200	12,8 **+ 19,6 + 107pF**	12,8 **+ 49.5 pF**	-3,7 (-5,85)	1,017 m
60m	5,3515-5,386	12,8 **+ 19,6 + 107pF**	12,8 **+ 49.5 + 157pF**	-6,6 (-8,75)	1,14 m

Table 1: Required capacitance values for frequency band switching at the described 1m by 1m dual loop. (CU-CL = circumference of the coupling loop)

Construction of the MLA

The MLA shown here can easily be assembled with materials from a hardware stores. The loops are constructed from copper pipes as used for water installations. Common diameters are for example 15, 18 or 22 mm. Square or hexagonal loops can be constructed with 90° or 45° elbows. Permanent electrical and mechanical connection between pipes and elbows can be achieved by using a soldering iron or torch. Fitting solder from a hardware store or commercially available electronic solder is used for this purpose.

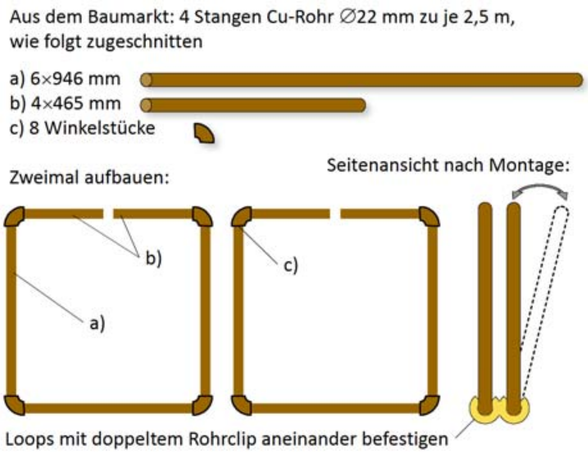

Figure 5: Dimensions of the components and individual loops from Table 1: Two identical loops are required to build the antenna

In order to be able to realise the required voltage-resistant capacitors cost-effectively with any capacitance values, we use common coaxial cables. The commonly used 50 W coaxial cables, such as RG58 or RG213, have a capacitance of 101 pF per meter of length, so that we can adjust the required capacitance over the length of the cable sections.

Figure 6: Coaxial cables are used as voltage-resistant capacitors.

The cables are prepared in such a way that they can later be attached to the loop at one end with core and shielding with eyelets. The other end of the coaxial cables remains open. To avoid high voltage flashovers later during operation, the inner conductor of the open end can be additionally insulated against the shield with a piece of heat-shrinkable tubing. When building the loops, leave a gap of about one centimetre on one side of the loops, where we can attach the capacitors, for example with a screw connection. The core and shielding of the coaxial cable capacitors are connected to opposite ends of the loop (Fig. 7).
If the inner diameter of the copper tubes used is large enough, the coaxial cables can be inserted into the copper tubes so that they are out of the way. If there is not enough space for this, or if you want to experiment, the coaxial cables can also be attached to the outside of the copper tubes (e.g. with cable ties) and run parallel to the tubes. When doing so, it is essential to ensure that the coaxial cables are laid on the same side of the loop, the shielding of the cable was connected to, otherwise an undesirable parasitic capacitance will occur between the coaxial cable and the loop.

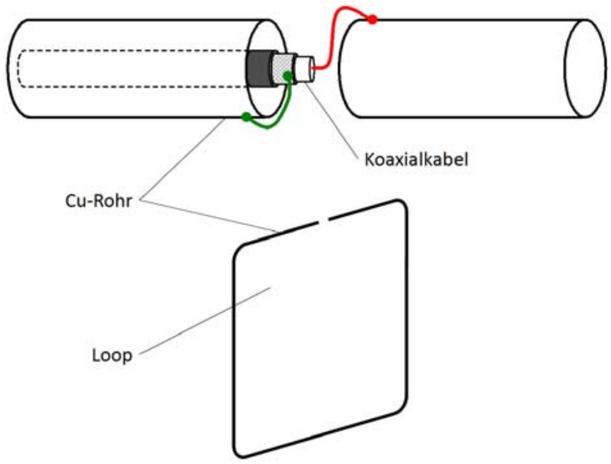

Figure 7: Core and shielding of the coaxial cable capacitors are attached to opposite ends of the loop.

It is advisable to devise a mechanical construction keeping the two loops at a defined distance from each other. Single and double pipe clips can be used to fix the antennas in place. In the construction according to Fig. 10, the pipe clips also serve as a pivot point for the second loop, so that it can be tilted away from the first loop.

Setup and adjustment of the antenna

When the antenna is put into operation for the first time, the coaxial cable capacitors must be adjusted to the appropriate capacity, i.e. shortened to the correct length. For this purpose the MLA is adjusted to the highest possible magnetic coupling. The antenna in Fig. 10 should therefore be completely "closed". It is recommended to fix the coaxial cables with cable ties along the loop, so that they do not hang uncontrolled in the middle of the loop.
We start the adjustment with the lowest frequency of the highest band, in the example from table 1 at 18.068 MHz. For this purpose, both loops are connected to the 12.8 pF capacitors only. Using an antenna analyzer or a VNA (vector network analyzer), we measure the resonance frequency of the antenna. The measured resonance frequency should ideally be some 10 to 100 kHz below the lower end of the intended frequency band. If the frequency is too low, it can now be raised by shortening (pinching) the cable at the open end by centimetres. When assembling the antenna, the coaxial cable capacitors should therefore

always be left a little longer than indicated in the calculation or the assembly instructions, so that there is still the possibility of adjustment. If the frequency of the antenna is already too high in the "closed" state, the coaxial cable capacitors are already too short, i.e. the capacity is too small.
By changing the magnetic coupling, i.e. by opening the antenna in Fig. 10, we can check the frequency range of the antenna with the antenna analyzer during the adjustment.

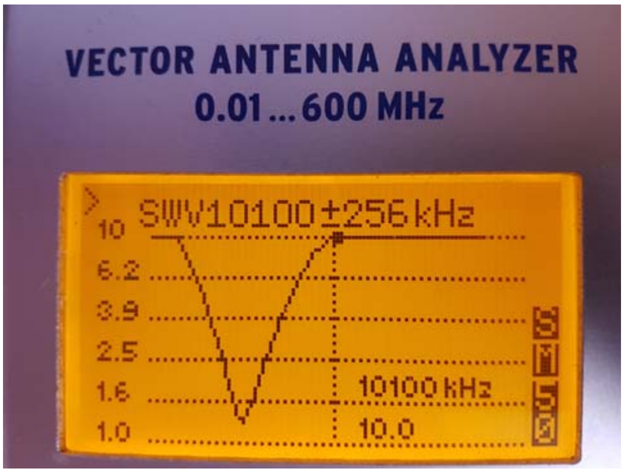

Figure 8: Measurement of the resonance frequency with an antenna analyzer, by measuring the minimum SWR.

Once the highest frequency band of the antenna has been tuned to our satisfaction, we now add the additional coaxial capacitor required for the next lower band to one of the two loops. In the example of table 1 this would be 19.6 pF to reach the 20 m band. We again set the highest possible magnetic coupling and try to set the frequency slightly below the lower end of the band by pinching off the coaxial cable centimetre by centimetre. We then repeat this procedure step by step, with the lower bands, by successively switching on and then adjusting the required capacitors. For each lower band, one more capacitor is connected in parallel to the ones already connected.

Figure 9: After frequency alignment the coaxial cable capacitors can be stowed inside the tubes. It is essential to ensure that the cables are plugged into the same side where the shielding is connected.

If the adjustment of the antenna was successful, the resonance frequency in the entire band can be adjusted by reducing the magnetic coupling, e.g. by opening the antenna. The "trimmed" coaxial cable capacitors can be hidden in the copper tubes after adjustment (Figs. 7 and 9), or fixed permanently parallel to the tubes on the outside with cable ties.

Figure 10: Prototype of the antenna with 65 cm side length. The antenna is slightly opened.

The antenna in Fig. 10 was additionally equipped with a handle to eliminate the influence of the hand capacitance during adjustment. For this purpose a plastic pipe from the electrical installation was attached to the loop with simple pipe clips.
If no usable SWR can be achieved at the set resonance frequency, this indicates an incorrectly dimensioned coupling loop size. The SWR can be improved by enlarging or reducing the size of the coupling loop, which is basically trial and error, though. If you have the possibility to do so, you should measure the input impedance of the antenna over a range of frequencies and plot the locus curve in the Smith chart. To achieve an SWR of 1:1, the locus curve must run exactly through the centre of the Smith chart.
Figure 11 shows locus curves as calculated with 4NEC2 for different sized coupling loops. The impedance locus (i.e. the impedance curve over the selected frequency range) is represented by the red curve, which forms a circle here. The diameter of the purple circle is a measure of the mismatch at 50 Ω (centre of the Smith chart) and intersects the locus curve at the point with the best matching.
In the Smith chart at the top of figure 11, an SWR of 3:1 is achieved at best (violet circle). The centre of the Smith chart is located within the locus (red circle). This indicates that the diameter of the coupling loop is too large.
In the middle Smith chart, no better SWR than 3:1 can be achieved either. Now the centre of the chart is outside the locus curve, which indicates that the coupling loop is too small. In the Smith chart at the bottom of figure 11, the location curve runs almost exactly through the centre of the chart. Here the selected size of the coupling loop fits perfectly, an SWR of 1.1:1 can be achieved.

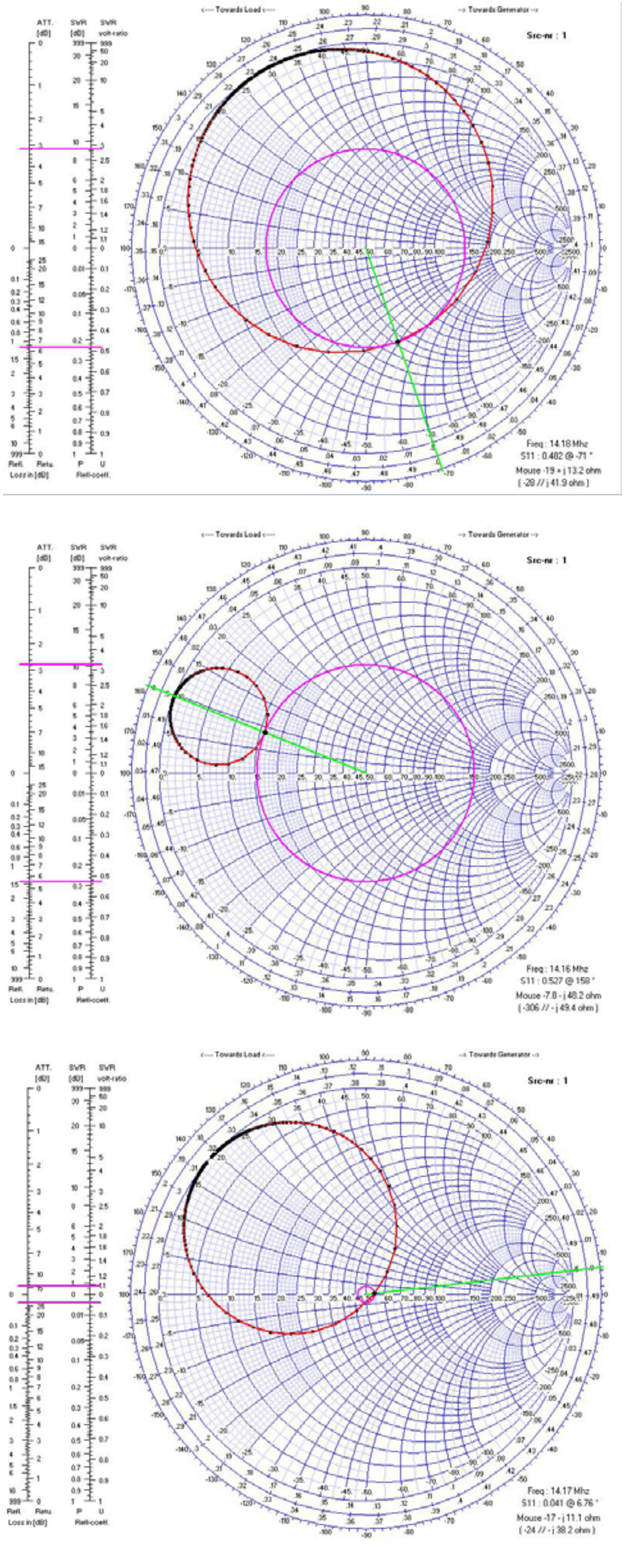

Figure 11: Locus curve of the input impedance S11 for different sizes of the coupling loop.

Simulation with 4NEC2

NEC (Numerical Electric Code) refers to a simulation method originally developed for the Navy for the analysis of wire antennas. 4NEC2 is a graphical user interface for easier operation. The antenna is divided into very short pieces = "segments". With 4NEC2, amazingly accurate simulations can be performed [4].

In order to find the appropriate capacitance values for band switching more easily, but also to better understand the properties of the antenna, numerous simulations were carried out in 4NEC2. For this purpose the square loop was defined with a conductor length of 1 m and duplicated at a given distance. By shifting the two loops to each other in the spatial coordinates, the tuning of the antenna can be easily simulated. The values found by simulation for the required capacitors are listed in table 1.

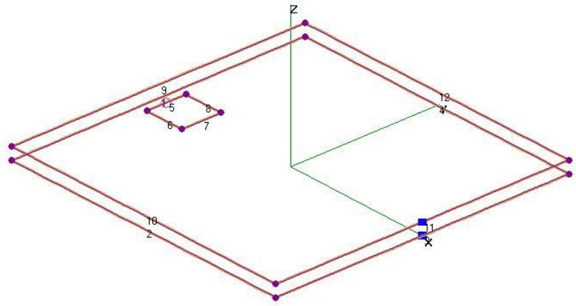

Figure 12: Geometry of the simulated antenna with parallel conductor loops.

The simulation nicely shows the detuning of the resonance frequency of the antenna via changing the magnetic coupling. Figure 12 shows the geometry of the antenna in closed state. The resonance frequency is just below the band limit of the 20 m band. Fig. 14 shows the geometry of the antenna in slightly open state. The distance between the conductor segments on the right side of the picture was increased by 5 cm. The resulting shifted resonance frequency can be seen in figure 13 (below). As tests have shown, the simulation here agrees so well with the practice, that 4NEC2 can also be used for the development and dimensioning of this antenna type. Especially the size of the required capacitors can be easily determined and optimised with 4NEC2 by trial and error.

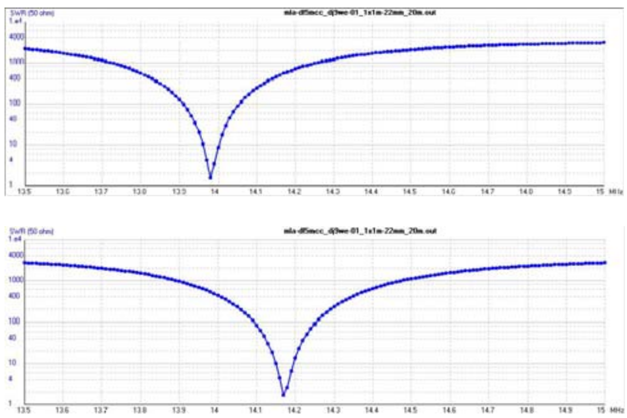

Figure 13: The shift in resonance frequency is clearly visible on the SWR curve at maximum coupling (top) and slightly opened (bottom).

The (3dB-) bandwidth and the gain of the antenna depend on the L/C ratio as well as on the ohmic losses in the loop. The gain of the antenna can be optimised by choosing a sufficiently thick Copper-tube. Loops made of enamelled copper wire are in the best case suitable for reception.

A comparison of the antenna gain between the MLA according to DL5MCC and a conventional MLA with one turn and a variable capacitor, both antennas with equal mechanical dimensions, shows that no surprise is to be expected here. Simulated with 4NEC2, the difference between both antenna is in ranges of roughly 0.25 dB and therefore negligible.

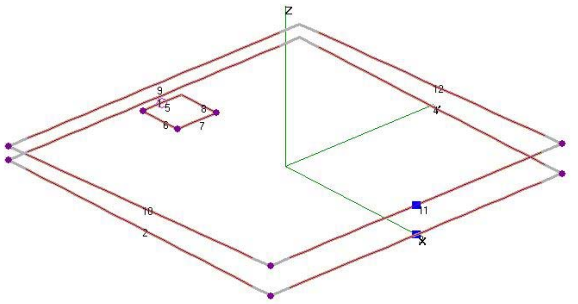

Figure 14: Geometry of the simulated antenna at an angle of about 10° between the conductor loops.

Additionally the radiation patterns (directional patterns) of the antenna do not differ from those of conventional MLAs. Figure 15 shows the antenna gain in the far field (E-field) in x and z direction as a 2D diagram.

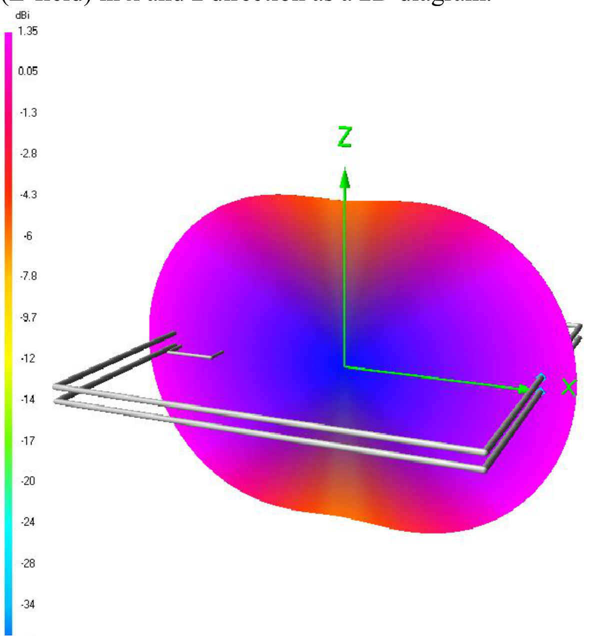

Figure 15: 2D directional diagram of the antenna presented in Table 1, in the 17m band in the far field (E-field).

Summary and outlook

The antenna presented here, developed by DL5MCC, is a variant of the magnetic loop, which works without a variable capacitor and is therefore particularly suitable for do-it-yourself construction. Tools for simple calculation of the antenna are still missing, but with 4NEC2 the required capacitors can be determined by a step wise optimisation. A detailed construction manual for the antenna is in work.

Since the antenna forms a common resonance frequency even if the capacitors on both loops are unequally dimensioned, band switching is easily possible. It is sufficient to alternately connect one capacitor to each of the two antennas (see Table 1).

With the prototype antenna shown in Figure 10, which is only 65 cm in size, extensive tests were carried out in the 40, 30 and 20 m band in FT8 mode. With only 4W transmit power it was possible to make FT8 connections with all of Europe without any problems.

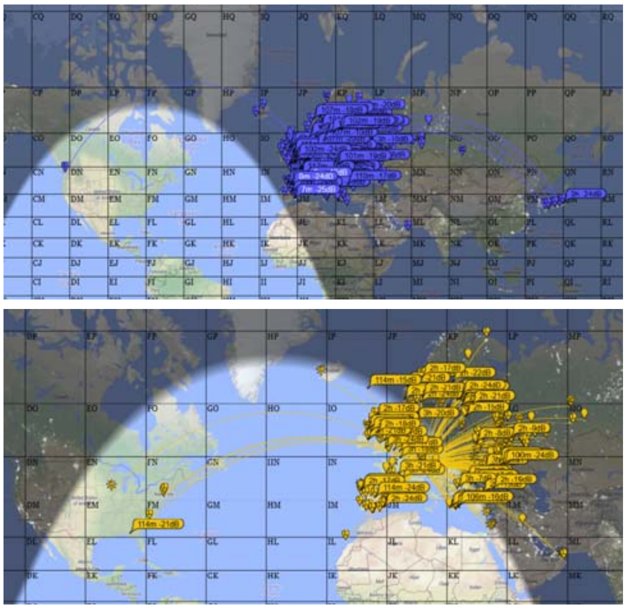

Figure 16: Operational tests with the 65cm MLA in FT8, with only 4W transmission power.
Above in the 40m band, below in the 20m band.

Literature

1] Dietmar Rudolf, The cusps at the dual-circuit belt filter, https://www.radiomuseum.org/forum/die_hoecker_beim_zweikreis_bandfilter2.html

2] Magnetic loop antenna calculator, http://www.dl0hst.de/magnetlooprechner.htm

3] Patent application file number DE 10 2018 008 510, "Adjustable magnetic antenna", 02.11.2018

4] Overview of 4NEC2, https://www.darc.de/der-club/distrikte/g/ortsverbaende/73/simulationen/4nec2/

[5] Dr. Aaron Scher, Positive coupling, negative coupling, and all that http://aaronscher.com/Circuit_a_Day/Impedance_matching/positive_negative_coupling/positive_negative_coupling.html

About the author

Klaus Finkenzeller, DL5MCC: Amateur radio licence since 1980, studied electrical engineering / communications engineering, working in the field of RFID/NFC. Special interests: Digital operating modes, DMR, SOTA activation.

Development of the software CPSProgrammer for DMR radio devices: http://dl5mcc.de/cpsprogrammer/

In 2000 QRV from Beijing (Beijing) as DL5MCC/BY1SK, during a longer professional stay in China: https://www.qsl.net/dl5mcc/by1sk.html

eMail: Klaus@dl5mcc.de

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