Magnetic Loop Antenna: Five Misconceptions

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The Magnetic Loop Antenna has been used in amateur radio for 40 years now, but unrealistic expectations are still raised regarding the efficiency and gain of the MLA. This is partly due to misunderstandings of some RF technical terms and their relationship. Here is an attempt of clarification.

After moving to an apartment on the second floor, there was initially no possibility to put up an antenna. A long wire for the shortwave bands across the street in front of the house was successfully tried, but had to be dismantled immediately, as the use of public space is not permitted. Since the apartment has a second, small balcony, a *Magnetic Loop Antennaa* (MLA) came into consideration as an alternative. After some preliminary tests with double- and triple-loops of different sizes, the proven single-loop design according to Ch. Käferlein, DK5CZ was selected: A ring with a diameter of 1.7 m was bent from a 22 mm thick copper tube and the open ends were connected to a motor-driven butterfly rotary capacitor (modified kit from TA1LSX). In Fig.1 you can see the antenna in front of the balcony railing; the rotary capacitor sits weather-protected in a piece of HT tube and at the lower end you can see a symmetrical shielded coupling loop to connect to the coax line to the transceiver in the shack.

Fig.1: MLA on the balcony

Well-known formulas applied incorrectly?

For the dimensioning of *Magnetic Loop* antennas, there have been dimensioning formulas since the 1970s. In 1983 the release of DL2FA /1,2/ appeared in the CQ DL, which coincided with the development and production of the "**A**bstimmbare **M**agnetische **A**ntenne" (AMA) by DK5CZ. The most widely used are the formulas of W5QJR, which were first included in the ARRL Antenna Handbook 15th Edition /3/; these or similar formulas were later widely used and repeated in many contributions, see the bibliographies with German-language contributions in /4/ and international contributions in /5,6/. When dimensioning my antennas, however, I largely used simulation with EZNEC+, which is based on the proven field calculation for wire antennas of the "Electro-Magnetic Code" (NEC). The reliability of this software (within its defined limits) and its applicability in MLA calculations were first assured by comparison to results of the formulas for a few quite loop dimensions, where satisfactory agreement between EZNEC and formula results was found. With the help of the simulation, measurements on the antenna could be better understood and important insights into the functionality and characteristics of the MLA could be gained. A detailed description of the procedure for the simulation and measurement on the realized antenna and the conclusions can be found in /7/.

Looking through the many dedicated contributions on the MLA, online and in print, I noticed some serious misconceptions about dimensioning formulas in connection with some basic terms of RF technology, which can lead to greatly exaggerated expectations of the MLA. Some of these misunderstandings have already been corrected in various online contributions by radio amateurs and in scientific publications, but this, as far as can be seen, has not yet become widely accepted. In particular, information on the efficiency and gain of MLAs is still frequently given, which at least in the case of realizations with amateur means, often are in stark contradiction to the measured impedance bandwidths of the antennas. This article tries to clarify these misunderstandings and to explain the relationship between the measured bandwidth and Q-factor, gain and efficiency.

What Q-factor and what Bandwidth?

It is ordinary understanding that the large ring conductor of an MLA is actually a high-Q RLC resonant circuit operated at the resonance frequency. The inductance L is essentially determined by the diameter of the ring and the necessary capacitance C of a variable capacitor is determined by L and the desired resonance frequency. The resonant circuit oscillations are attenuated by the resistance R, which consists of a "radiation resistance" R_R which can be calculated precisely and a "loss resistance" R_L. The radiation resistance represents the power emitted by radiation to the far field but is not an "ohmic" resistance of the ring conductor that heats the ring conductor. Unlike the loss resistance, which represents the RF power that is converted into heat (dissipated) in the ring conductor and is thus lost to the radiation; in /3/ and many calculations derived from it, the loss resistance is only related to the current dissipation loss in the ring conductor and is calculated with the formula for the "skin effect" resistance.

This is the first misunderstanding: In practice, the capacitor with its "Equivalent Series Resistance" (ESR) can easily cause the same losses as the ring conductor itself and thus cause an additional loss resistance in the resonant circuit. If large-surface area contact of the capacitor to the ring conductor is not ensured, considerable undesirable transition resistance can occur. Further resistances occur especially in the "inside" of a rotary capacitor due to contact resistances in the capacitor plate packages or due to dielectric losses in the insulating attachments of the plate packages and the rotor. Unfortunately, another loss-maker of often even greater importance is added: An MLA that is **not in "free space"** is surrounded by "material" that can have a finite conductivity and a dielectric loss factor. In my antenna projects it is the building with the house wall only 85 cm away from the ring conductor; in most cases, it will be the ground. As long as the "material" is still within the area around the antenna known as the reactive near-field zone (e.g., a radius of about 6 m in the 40-m band), the material is heated by the RF near-fields of the antenna, like in a microwave oven. This heat generation is withdrawn from the RF power of the antenna and can no longer contribute to the radiation. We then model the effect as a further additional loss resistance in the resonant circuit; note that this additional resistance does not heat the ring conductor, but only stands for the heating of the environment. With an MLA, placed below one meter above the ground, the additional loss resistance can be even greater than the other loss resistances and the radiation resistance together; only at a height of about 4 m in the 40-m band can one expect that the additional loss resistance is approximately on par with the radiation resistance and at a bit higher altitude one can then assume conditions as in "free space" /8/.

Since in the formula for the efficiency of the antenna $\eta = R_R / (R_L + R_R)$ the decisive loss resistance is in the denominator, all calculations of the efficiency (and the antenna gain derived from it) are over-optimistic, if the losses in the antenna "system" are not fully accounted for and unrealistically small values for R_L are assumed; e.g., if the MLA in the garden is just above the ground and not at a height of 10 m.

The second misunderstanding lies in determining the Q-factor of the MLA. According to the formula given in /3/, the quality factor of the antenna is the reactive impedance X_L of the inductor divided by twice the resistance R in the circuit (which should be realistically large, see above): $Q=X_L/(2R) = 2\pi f_{res}L/(2R) = f_{res}/\Delta f$. This calculation of the Q-factor applies to the so-called "loaded Q" Q_L, which is measured when the resonant circuit is loaded with a resistor; in the case of impedance match of the resonant circuit to, e.g., a receiver, $Q_L = Q/2$, where Q is the so-called "Intrinsic quality" of the resonant circuit. Therefore, the bandwidth Δf calculated in the formula is also the bandwidth at which the noise power received by an Rx drops by 3 dB from the maximum value. This is seen in the plot of Figure 2, which was recorded with my balcony MLA. However, if the external reception noise in normal operation is not sufficient this type of determination of the bandwidth is only possible with the help of a noise generator which radiates noise power into the antenna from close by. Instead of the noise bandwidth, the impedance match bandwidth at the antenna terminals is usually measured using a VSWR meter, directional coupler, or Vector Network Analyzer (VNA). In this measurement, we usually take the bandwidth at a VSWR of 2.0.

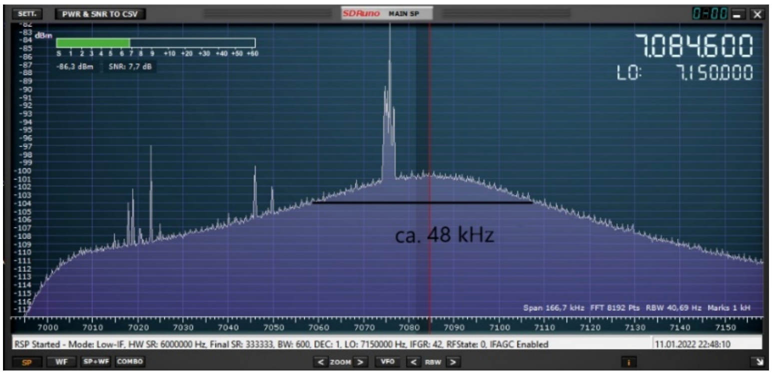

Figure 2: Measurement of the "noise bandwidth" of the MLA in the 40-m band with the SDRplay and irradiation by a noise generator. The bandwidth measured at the -3 dB frequencies is about 48 kHz.

This leads to the <u>third misconception</u>, the measurement of bandwidth. When measuring the impedance of the MLA at the terminals of a coupling loop, the reflectometer or better the VNA "sees" a parallel RLC resonant circuit without additional load. Accordingly, the Q-factor of the resonant circuit is the "intrinsic quality factor" and the corresponding bandwidth Δf is half of the noise bandwidth measured from the Rx noise spectrum. The VNA measurement plot shown in Figure 3 also is based on my balcony MLA. However, this bandwidth is defined by the difference of the frequencies at which a VSWR = 2.62 is achieved; a measurement of the bandwidth at VSWR = 2.0 is 0.707 times below this value. Interestingly, twice this band width is found at the VSWR = 5.8, and that at these frequencies the antenna reflects 50% or 3 dB of the transmit power; this fits together with the drop in the noise level in the Rx by 3 dB at these frequencies. The above VSWR values only apply to a perfectly matched antenna. For mismatched antennas you can determine the appropriate values with Owen Duffy's Online Calculator /9/ (Attention: The case distinction between over- and under-critical coupling is to be reversed).

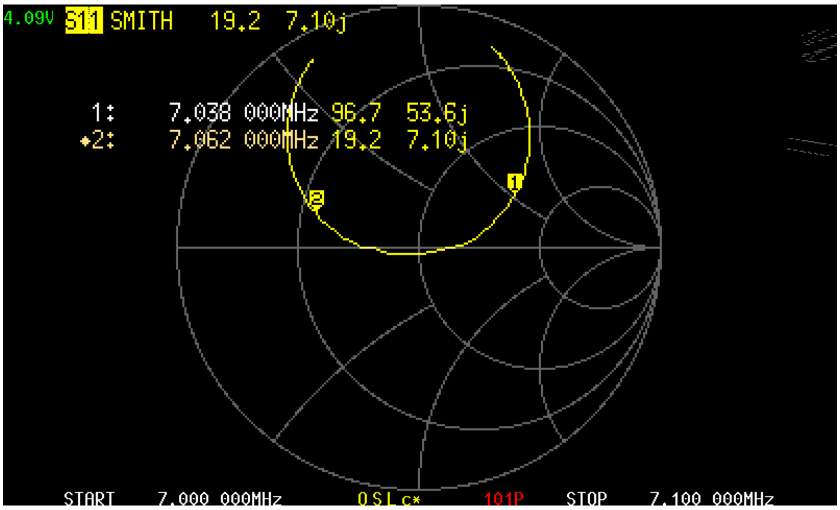

Figure 3: Reflection factor of the balcony MLA from 7.0 to 7.1 MHz in the display of the NanoVNA-F. The impedance match bandwidth at VSWR=2.6 is about 24 kHz.

What else was noticed

A fourth misconception concerns the importance of metallic conductors in the environment of the MLA. Contrary to widespread belief, good to moderately good conductors are not a major problem for the efficiency of the MLA, even if they are designed as conductor loops. As long as no significantly large currents are induced into these conductors in relation to the **extremely large currents** in the large conductor loop of the antenna and the conductors do not have considerable "ohmic" resistance, little power is lost; however, the resonance frequency of the antenna easily can be detuned due to interceptions of the reactive near-field of the MLA. The reason is that the power converted into heat in conductors drops with the square of the current. At a current of 8 A in the ring conductor and the highest current found at 50 mA in a conductor of the balcony railing near the MLA and the same conductor resistances assumed, the power dissipation of the conductor is already five orders of magnitude below that of the ring conductor: for the radiation efficiency a completely negligible quantity. You can easily use an EM simulation (with EZNEC or similar) to recognize that it only becomes critical when conductors or conductor loops come into resonance, so that the MLA also induces similarly high currents through its near-fields as in the ring conductor itself. If conductors are located at a greater distance, outside the near-field radius of the antenna, their effect will mainly be a distortion of the radiation pattern due to a partial reflection of the emitted wave or a "secondary" radiation, but hardly influence the efficiency of the antenna.

The fifth misconception concerns the function of the small coupling conductor loop for the impedance transformation of the MLA. An equivalent circuit diagram for the complete MLA with both conductor loops is rarely found in the many Amateur contributions to the MLA. But sometimes the coupling between the large conductor loop and the small coupling loop is assumed to be an inductive transformer with the winding ratio 1 : 1. This seems obvious, since it is a single conductor loop on the primary and secondary sides. On closer inspection, however, it becomes clear that there is a very loose magnetic coupling, as the magnetic flux of one loop flows only to a small extent effectively through the second loop. Therefore, a simplified (therefore only approximately valid) equivalent circuit diagram in Fig. 4 shows a winding ratio of 1 : N, where in our example N = 85 applies to the large ring conductor and 1 for the small conductor loop (explanation in /7/). The transformer is connected with the large number of turns to the resonant circuit, which represents the large ring conductor. On the "low-impedance" side of the transformer, the inductance of the small conductor loop is added. This inductance is connected in series so that the reactive impedance rotates the reflection factor circle of the large ring conductor clockwise in the Smith Chart (as can be seen in Figure 3).

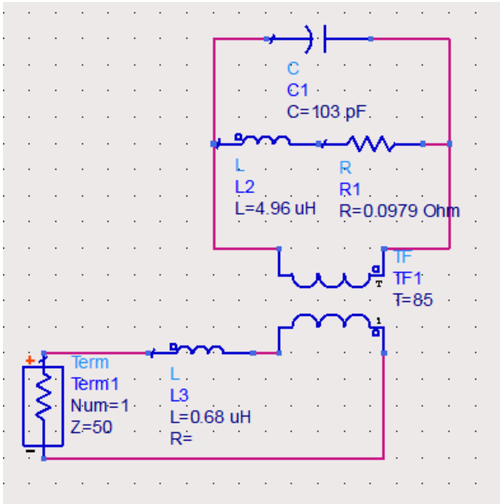

Figure 4: Equivalent circuit diagram of the MLA with large ring conductor and small coupling conductor loop. Values of R1, T and L3 apply to the MLA without additional loss resistance at 7 MHz.

Expectations are disappointed

The disappointment has only to do with the first three misunderstandings: In many individual contributions to the design and realization of MLAs, the formulas according to /3/ are misinterpreted by first ignoring the additional loss contributions and grossly underestimating the actual loss resistance in the antenna. On top, the unrealistic theoretical bandwidth from these formulas is interpreted as an impedance match bandwidth for a VSWR=2. In this way, you can hardly make a meaningful comparison between theory and measurement.

However, it should be particularly disappointing for the user that the efficiency and thus also the antenna gain is significantly worse than is claimed in many tables, data sheets and calculation proposals, because any additional losses are ignored, or an installation of the MLA in "free space" is assumed. In our (but particularly blatant) case of the self-constructed balcony MLA, the efficiency in the 40-m band drops by even 8 dB. In addition to the lower antenna gain, the poorer efficiency has other effects in connection with a given transmission power: The additional resistance causes a decrease in the resonance currents of the ring conductor, exactly according to the decrease in the intrinsic quality factor. Proportionally, the voltage at the capacitor becomes smaller, i.e., the plate spacing calculated with the formulas assuming no additional resistance appears unnecessarily oversized. Similarly, the electric and magnetic fields in the near-field range become smaller in proportion to this, resulting in a smaller safety distance to be kept than without additional resistances. In our case of the balcony MLA, at 50 W input power, the RF current in the simulation drops from 21 A (without additional resistance) to 8 A and the calculated safety distance in the axis perpendicular to the conductor loop (at H_{max} = 0.1 A/m) drops from 4.4 m to about 3 m. Remarkable: The prediction of the simulation was verified by an H-field measurement! In addition, this safety distance fits well with the measurement results of an earlier publication /10/. However, this is not at all the case with the calculation results from WattWächter /11/ when we select the AMA82,as the antenna which is also 1.7 m in size (manufactured by WiMo); note that this calculation program obviously assumes a completely lossless antenna (the antenna gain is given as 1.4 dB!) and it offers no other way to specify the efficiency than to reduce the Tx power or to specify the transmission line losses in dB by exactly the amount of the assumed efficiency in dB (with a positive sign!) .

On the other hand, it also does not take much to calculate the efficiency. In order to determine the actual efficiency of the MLA in its respective placement situation, its **measured** impedance match bandwidth is decisive, without it having to be clear where exactly in the antenna system the additional losses are located: From the bandwidth Δf (at VSWR = 2.62) and the operating frequency f, the actual intrinsic quality $Q = f/\Delta f$ can be found in a first step. From the diameter of the large ring conductor both the inductance L and from it the reactance X_L as well as the radiation resistance R_R can be calculated. The actual resistance $R = (R + R_L) = X_L/Q$ in the resonance circuit results from the quality factor and the reactance and thus the efficiency η can be determined directly from the above-mentioned formula. If you do not want to calculate yourself, you can use the *calculator* by Owen Duffy /12/, which goes this calculation path. With the online calculator of DG0KW /13/ you can go the opposite way by increasing an "additional loss R" until the calculated bandwidth corresponds to the measured one.

Unfortunately, there are only a few individual contributions from other radio amateurs with information about measured impedance match bandwidths of realized MLAs. For example, Frank Dörenberg in /5/ shows an MLA with a diameter of 1 m, for which he measures 10 kHz bandwidth at VSWR=2, but which only comes to about 3 kHz in the simulation without additional resistance. In order to reach the measured bandwidth, an additional resistance of 0.18 Ω would have to be used in the simulation; the efficiency thus degrades by 5.5 dB. In /14/, Alan Boswell and colleagues also examine a 1-m dia. MLA on a professional antenna range and find a similar bandwidth, for which they blame an additional resistance of 0.25 Ω. An AMA 82 (design according to DK5CZ, manufacturer: WiMo) with a diameter of 0.8 m would have to have an additional resistance of 0.11 Ω in order to achieve the bandwidth of 10 kHz given in the data sheet as an empirical average. Thus, according to realistic calculations, about 6 dB in efficiency would be lost compared to the calculation with /3/.

As a conclusion, it appears that probably many realized MLAs are about one S-unit worse in their efficiency and gain than the calculations with the formulas according to /3/ and similar ones suggest - unless the MLA uses a particularly high-quality capacitor with a particularly low-resistance electrical connection to the ring conductor and the MLA is mounted 10 m above the ground without other RF absorbing environmental influences. Nevertheless, the MLA remains an excellent shortwave antenna for radio amateurs without a large garden. Presumably, most of these antennas will give satisfactory results in radio traffic compared to other antennas, since, especially in the lower bands, many comparison antennas also show weaknesses: in particular dipoles mounted low above the ground, with their steep upward radiation and power loss in the ground under the antenna.

References

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/2/ Hans Würtz, "DX-Antennen mit spiegelnden Flächen", cq-DL, 4/1983, pp. 170 – 171.

/3/ The American Radio Relay League (1988): "Small High Efficiency Loop Antennas for Transmitting". The ARRL Handbook, 15th Edition, pp. 5 – 11 to 5 – 17.

/4/ Rothammels Antennen Buch, Chapter "Magnetische Antennen", DARC Verlag.

/5/ Exciting reports on the design and manufacture of MLAs as well asa large collection of references regarding MLA can be found on the web page of Frank Dörenberg, N4SPP (as of 4 Febr. 2022): https://www.nonstopsystems.com/radio/frank_radio_antenna_magloop-small.htm

/6/ Theoretical and practical contributions to the design and evaluation of MLAs as well as a list of the few scientific publications on MLA can be found on the web page of Steve Yates, AA5TB (as of Feb. 4, 2022): http://www.aa5tb.com/loop.html

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/11/ WattWächter Afu: https://www.bundesnetzagentur.de/DE/Sachgebiete/Telekommunikation/Unternehmen_Institutionen/EMF/start.html

/12/ Owen Duffy, "Calculate small transmitting loop gain from bandwidth measurement", in (as of 4 Feb. 2022) https://owenduffy.net/calc/SmallTransmittingLoopBw2Gain.htm

/13/ https://www.dl0hst.de/magnetlooprechner.htm

/14/ Alan Boswell et al., "Performance of a small loop antenna in the 3 – 10 MHz band", IEEE Antennas and Propagation Magazine, vol. 47, no. 2, April 2005, p. 51 – 56.

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