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Performance Evaluation of a Very Small Magnetic Core Loop Antenna for an LF Receiver

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***Abstract* — This paper describes a method for evaluating the performance of a magnetic core loop antenna (MCLA) used for receiving time standards via long wave radio signals. The antenna is intended for the use in radio controlled watches, wherein miniaturization and loss of sensitivity are trade-offs. Using a magnetic field simulator, we analyzed and searched for an optimum MCLA design. In addition, the performance of a radio controlled watch with the influence of a metal case is presented.**

***Index Terms* — magnetic core loop antenna, LF, time standard, antenna factor, magnetic field simulation.**

I. Introduction

By receiving standard radio waves, radio controlled watches or clocks can provide precise date and time. However, radio controlled watches tend to have a larger size than conventional watches, because of the additional antenna and receiver inside the watch. To achieve a relatively better size and design, antenna miniaturization is also needed.

Magnetic core loop antennas (MCLAs) are widely used in radio controlled watches. The conventional design procedure consists of the trial production and the sensitivity measurement. The typical length of MCLAs used in the watch is about 20 mm, even though the wavelength of the radio wave is several kilometers. For such electrically extremely small antennas, it is not appropriate to use an electromagnetic simulator used in the simulation of ordinary antennas. Instead we use a magnetic field simulator based on finite element method as we consider such MCLAs as a magnetic field sensors. The magnetic field simulator is a part of software used for electromechanical analysis [1]. Such a simulator can handle the magnetic material and the eddy current in the LF region.

This paper is organized as follows. Section II introduces the basic characteristics of the MCLA. In section III, the simulation model and the measurement method of the MCLA antenna factor is explained. Section IV describes the optimization of an amorphous metal core loop antenna. In section V, the simulation results considering the influence of the metal case is provided. Finally, conclusion is given in section VI.

II. MCLA for Radio Controlled Watches

Figure 1 shows a picture of a loop antenna module with a magnetic core used in radio controlled watches. The antenna length is 16 mm, and the number of turns is 1107. The copper wire, which forms the coil, has a diameter of 0.08 mm. The magnetic body is covered with plastic for reinforcement. In the figure, a flexible printed circuit (FPC) was used to implement a tuning capacitor that is connected to the antenna. The permeability of the core is 8000.

Amorphous metals are also used for the magnetic core. In recent years, amorphous metal cores are used more than ferrite cores for reliability and strength. The characteristics of ferrite and amorphous metal cores are shown in Table I.

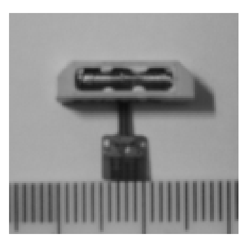

Fig. 1. The MCLA used in radio controlled watches.

TABLE I
CHARACTERISTICS OF THE CORE MATERIALS

Magnetic core	Strength	Structure
Ferrite	Fragile	Bulk
Amorphous metal	Strong	Sheet lamination

III. ANTENNA FACTOR OF THE MCLA

We evaluated the receiving sensitivity of an MCLA by the antenna factor. Considering an antenna receiving plane wave of frequency *f*, the antenna factor (*AF*) can then be defined as the ratio of the electric field strength (*E*) to the received voltage (V_0) of the antenna as follows:

$$AF(f) = \frac{E(f)}{V_0(f)}. \quad (1)$$

Note that an antenna factor is an easier and a more realistic parameter than the antenna gain for an MCLA, as the impedance is not usually matched between the receiver IC and the antenna in such a low frequency system.

We measured the antenna factor of the MCLA by using a substitution method. The measurement flow is as follow: 1) measure the electric field strength (*E*) at the receiving position by using a standard loop antenna for EMC measurement; 2) measure the received voltage (V_0) of MCLA at the same receiving position as the standard loop antenna was located; 3) obtain the antenna factor using Eq. (1).

Figures 2 and 3 show the measurement setup. A continuous wave of 40 kHz, 50 kHz and 60 kHz was used in the measurement from the signal generator. The low-frequency wave is transmitted by the loop antenna on the right, and received by the standard loop antenna on the left as shown in Fig. 2. Actually, as the loop antenna detects a magnetic field, the electric field strength is obtained by multiplying the wave impedance and the magnetic field strength.

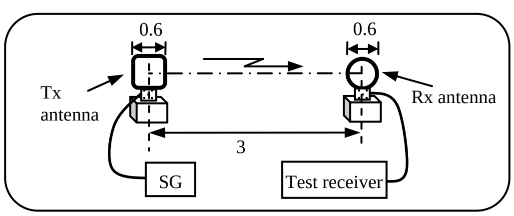

Fig. 2. Measurement setup using standard loop antenna.

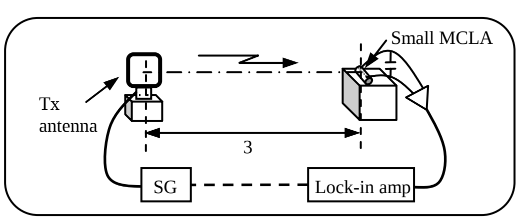

Fig. 3. Measurement setup using the MCLA.

After measuring the equivalent electric field strength, we replaced the receiving loop antenna with the MCLA at the same position as shown in Fig. 3. The axis of the ferrite core was placed normal to the plane of the transmitting loop antenna with the center of the ferrite core in the plane of the transmitting loop [2]. A buffer amplifier was used between the antenna and the instruments to avoid the influence of the cables. The receiving voltage was measured with a lock-in amplifier. A lock-in amplifier is used for very small signals with poor SNR. Its main function is to synchronize the input signal with the transmitted signal, and to filter the signal to a very narrow bandwidth. The received voltage of the MCLA is obtained by dividing the output of the lock-in amplifier by the gain of the buffer amplifier.

Figure 4 shows the simulation model of the MCLA used in the product (radio controlled watch). Figure 5 shows the measured values and the simulation results of the antenna factor within the 40 kHz to 60 kHz frequency range. The maximum difference between the simulation results and the measured values is 2 dB. This value confirmed that our method in obtaining the antenna factor is reasonably accurate. From the results, the antenna factor at 60 kHz is smaller than that at 40 kHz, because the Q-factor at 60 kHz takes larger values than that at 40 kHz.

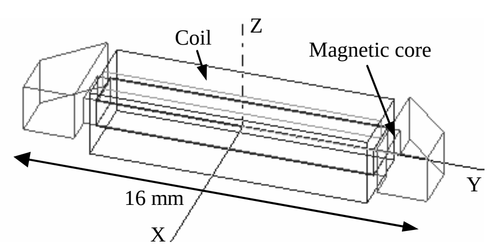

Fig. 4. Simulation model of the MCLA.

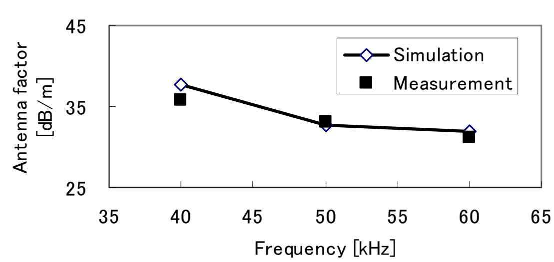

Fig. 5. Antenna factor of the MCLA.

IV. Optimization for Amorphous Metal Core Loop Antenna

As we mentioned in section II, amorphous metal can also be used as a magnetic core for MCLAs. Very thin films are laminated to construct such a core. Those films are molded with resin. Figure 6 shows how this amorphous laminate structure may look like in the MCLA considered. An electromagnetic simulation of such laminate structure is difficult, because the aspect ratio is too large, and accordingly, it demands huge memory. So we modeled the laminate structure by an equivalent bulk structure, and set the material characteristics as anisotropic.

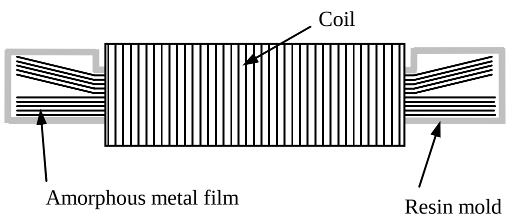

Fig. 6. Structure of amorphous metal core loop antenna.

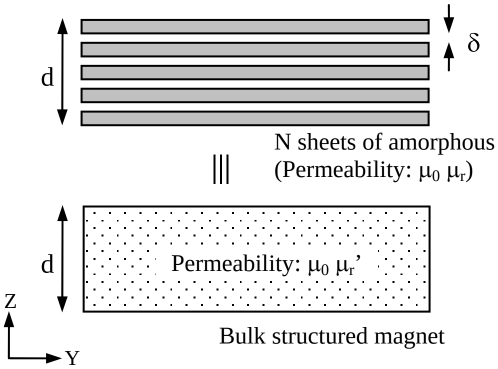

Fig. 7. The magnetic body with the equivalent bulk structure.

As shown in Fig. 7, assuming Z-component reluctances of both magnetic bodies are equal,

$$\frac{d-(N-1)\delta}{\mu_0\mu_r S}+\frac{(N-1)\delta}{\mu_0 S}=\frac{d}{\mu_0\mu_r' S}. \qquad (2)$$

Correspondingly, the relative permeability of equivalent bulk structure can be written as

$$\mu_z'=\frac{\mu_r d}{d-(N-1)\delta+\mu_r(N-1)\delta}. \qquad (3)$$

By similar calculation X- and Y-axes, the X- and Y-components of relative permeability is expressed as follows,

$$\mu_x'=\mu_y'=\frac{d-(N-1)\delta}{d}\mu_r. \qquad (4)$$

To improve the receiving sensitivity, both ends are V-shaped. To concentrate more magnetic flux, it is effective to widen the cross sectional area of a magnetic body for a planar loop [3]. However, a very wide opening of V-shape lowers the sensitivity because the length of magnetic core is shortened at the same time. Therefore, the most suitable opening angle seems to exist to maximize the receiving sensitivity.

We calculated the magnetic flux linkage for a given opening angle by magnetic field simulation. Figure 8 shows the opening angle of the amorphous metal core. From the simulation results, the behavior of the magnetic flux and inductance is plotted as shown in Fig. 9. In the model that we evaluated, the flux linkage takes the maximum aperture angle of about 30 degrees.

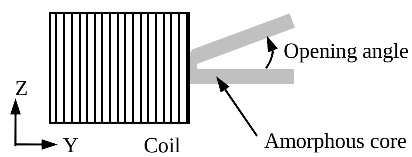

Fig. 8. Aperture angle of the amorphous metal core.

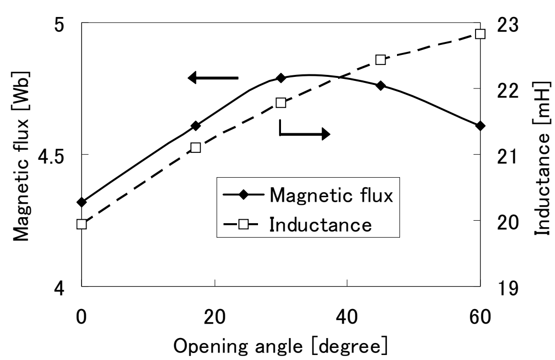

Fig. 9. Magnetic flux and inductance results.

V. Simulation Results for MCLA Considering the Metal Case

Radio controlled watches with fully-integrated antennas are highly desired to relatively improve the overall design. However, such integration causes a degradation of the receiving sensitivity, because the shielding effect and eddy current loss are increased when a metal case is used.

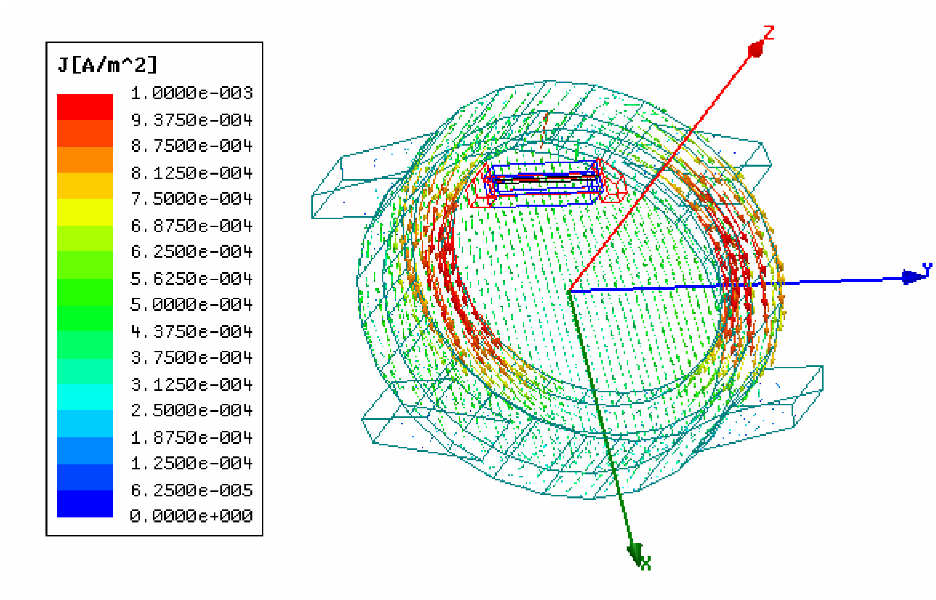

Fig. 10. Current density generated in a metal case.

We investigated these eddy currents that are generated in a metal case by magnetic field simulation. The fully-integrated antenna model is put in a magnetic field of 40 kHz. Figure 10 shows the electric current density vector from the simulation. The primary observed result is that eddy currents are stronger near the antenna and at both sides of the bezel. Further miniaturization of the MCLA was seen to contribute more in optimizing the overall design.

VI. Conclusion

In this paper, we discussed a method of evaluating the performance of a very small MCLA. We explained the simulation model and the measurement procedure in order to obtain the performance. The simulation results agree with the measurement results.

An amorphous metal antenna consists of laminating sheets. It can be modeled an equivalent bulk structure that is handled in the simulator by setting anisotropic characteristics. We also investigated eddy currents generated in a metal case which include the MCLAs.

Acknowledgement

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