Reduction of Proximity Effect in Coil Using Magnetoplated Wire

Tsutomu Mizuno[1], Shigemi Enoki[2], Takashi Asahina[1], Takayuki Suzuki[1], Masahiro Noda[1], and Hiroki Shinagawa[2]

[1]The Faculty of Engineering, Shinshu University, Nagano 380-8553, Japan
[2]Shinkawa Sensor Technology Inc., Higashi-Hiroshima 739-0153, Japan

The upgrading of the efficiency of transformers and increase in the quality factor of inductors are required. For this purpose, it is necessary to reduce copper loss. Reducing the winding AC resistance is one method of reducing copper loss. Therefore, we propose the use of magnetoplated wire (MPW) for coil windings. An MPW is a copper wire (Cu wire) whose circumference is plated with a magnetic thin film. The resistances due to the proximity effect of Cu wire and MPW coils at a frequency of $f = 1$ MHz, which have a diameter of $D = 4.54$ mm, a wire diameter of $d = 0.09$ mm, and a number of turns of $N = 102$, are 4.2 Ω and 2.1 Ω, respectively; thus, the proximity effect decreases by half.

***Index Terms*—AC resistance, copper wire, magnetoplated wire, proximity effect, skin effect.**

I. Introduction

The upgrading of the efficiency of transformers and increase in the quality factor of inductors are required. For this purpose, it is necessary to reduce copper loss [1]. Reducing the winding AC resistance is one method of reducing copper loss.

We proposed the use of magnetoplated wire (MPW) for coil winding [2]. An MPW is a copper wire whose circumference is plated with a magnetic thin film. An advantage of using the MPW is that its proximity effect decreases to a lower level than that in the case of copper wire (Cu wire) [3]. Therefore, the AC resistance of an MPW coil is lower than that of a Cu wire coil.

It is necessary to quantitatively that show the proximity effect is reduced by the use of MPW. Thus, we measured the resistance of Cu wire and MPW coils, and compared the measured values with calculated values obtained by the finite element method (FEM) [4]. In addition, the reduction in the proximity effect is clarified by comparing the resistance with that of the Cu wire coil. The following points concerning the reduction of the proximity effect by the use of the MPW are discussed:

1) comparison of measured and calculated values;
2) comparison of resistances due to proximity effect.

II. Structure and Magnetic Characteristics of MPW

A. Structure of MPW

Fig. 1 shows the structures of a Cu wire and an MPW. The MPW has a copper core plated with magnetic thin films (Fe and Ni) [3]. The thicknesses of the Fe and Ni thin films are 1 μm and 0.05 μm, respectively, as shown in Fig. 1(b). The Ni film is plated for ease of soldering.

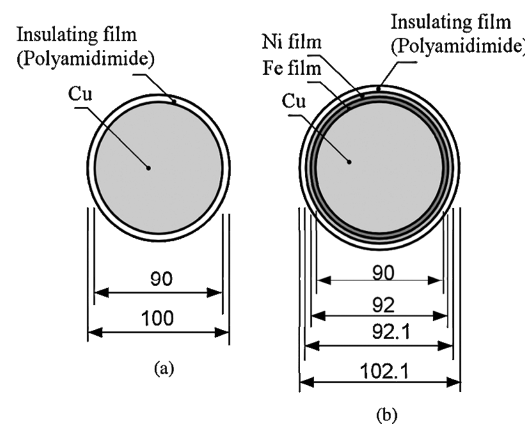

Fig. 1. Structures of Cu wire and MPW (unit: μm). (a) Cu wire. (b) MPW.

B. Magnetic Characteristic of MPW

Fig. 2 shows the B–H loop of MPW. We measured the B–H loop of MPW having 10 mm length with the vibrating sample magnetometer (Riken Denshi BVH-55). The magnetic field is affected MPW longitudinally. The maximum value of the field strength obtained by FEM affected MPW is 100 A/m under the condition of the measurement of the coil resistance. In this study, MPW was affected the magnetic field of ±80 A/m that was the most approximate to ±100 A/m from the specification of BVH-55. We assumed the following two matters.

1) Fe thin film is isotropy.
2) The diamagnetic field is disregarded because the demagnatiging factor of MPW that has the diameter of 92 μm and the length of 10 mm is 10^{-3} or less [5].
   The relative permeability of MPW, μ_r, was 100 shown in Fig. 2.

.

III. Method of Calculation

A. Structure of Coils

Fig. 3 shows the structure of Cu wire and MPW coils. They are made of the wires shown in Fig. 1. They have an air coil and a coil diameter of $D = 4.54$ mm and a number of turns of $N = 102$.

B. Condition of FEM Analysis

Table I lists the conditions of FEM [4], [6]. We analyzed the model of coil shown in Fig. 3 using Maxwell ver. 11. The number of elements of MPW coil was 500 000 to analyze the eddy current in the Fe thin film in detail.

Digital Object Identifier 10.1109/TMAG.2007.893716

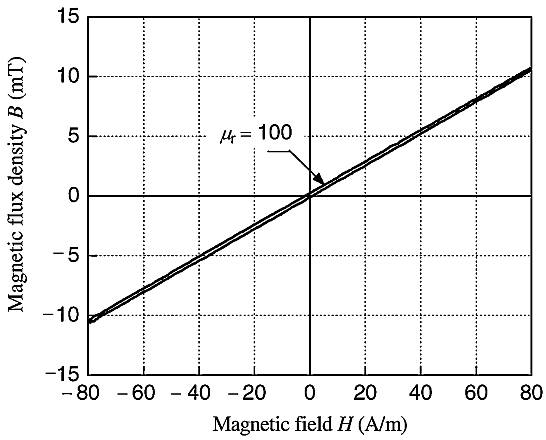

Fig. 2. B-H loop of MPW (measured with Riken Denshi BHV-55).

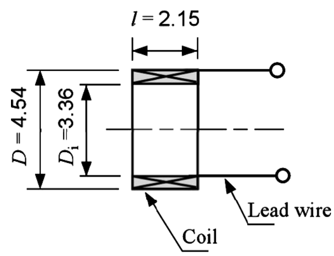

Fig. 3. Structure of coil (unit: mm).

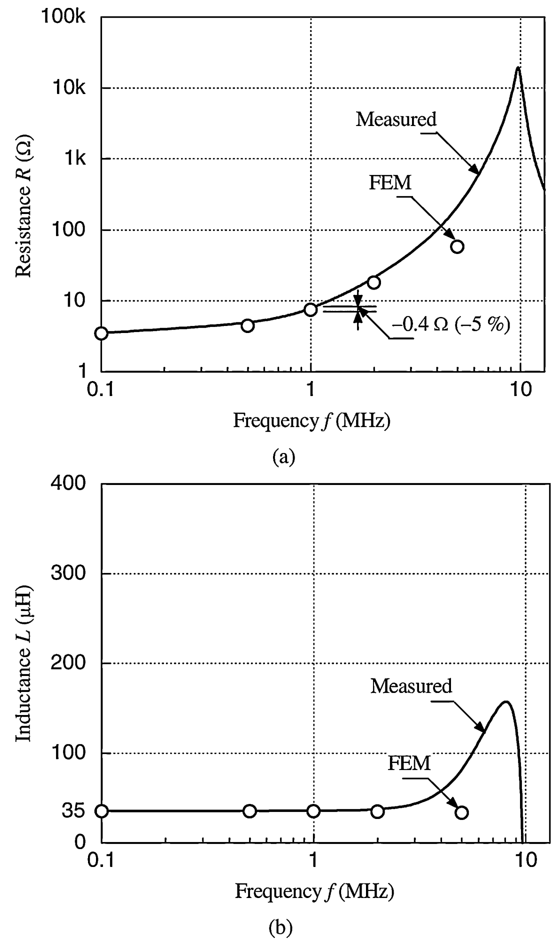

Fig. 4. Comparison between measured and calculated resistances and inductances of Cu wire coil. (a) Resistance. (b) Inductance (measured with HP 4192 A, $\mu_r = 0.999991$, $\rho = 0.0172\,\mu\Omega\cdot$m).

TABLE I
CONDITIONS OF FEM

Item	Content
Software	Maxwell ver. 11 (Ansoft co. Ltd)
Analysis condition	Cylindrical coordinate
	Eddy current solver (I = 1 mA)
Analysis space	R 70 × Z 60 mm
Error	0.5 % or less
Number of elements	50,000 (Cu wire), 500,000 (MPW)
Material properties	Copper (ε_r = 1, ρ = 0.0172 μΩ·m, μ_r = 0.999991)
	Fe (ε_r = 1, ρ = 0.098 μΩ·m, μ_r = 100)
Circumference	Air (ε_r = 1, ρ = ∞ μΩ·m, μ_r = 1)

IV. COMPARISON OF PROXIMITY EFFECT

A. Comparison Between Measured and Calculated Resistances

Fig. 4 shows the comparison between the measured and calculated resistances and inductances of Cu wire coil, and Fig. 5 shows the comparison between the measured and calculated resistances and inductances of MPW coil. We measured the resistance and inductance vs. frequency characteristics with the impedance analyzer (HP 4192 A). The resistance R and the inductance L of the coil were measured with the compensation of R and L of the lead wire shown in Fig. 3. The resonant frequencies of Cu wire and MPW coils were approximately 10 MHz shown in Figs. 4(b) and 5(b). In this study, we compared between measured and calculated values at a frequency of $f = 1$ MHz, because it is sufficiently different from the resonant frequency.

The calculation errors of the resistances of the Cu wire and MPW coils at a frequency of $f = 1$ MHz were -5% and -12%, respectively; thus, the calculation error of the MPW coil was larger than that of the Cu wire coil. The calculation accuracy will be higher if the hysteresis loss of the Fe film is considered in the calculation of MPW coil resistance.

B. Comparison of Resistances Due to Proximity Effect

The coil resistance R is given by

$$R = R_{\rm dc} + R_{\rm s} + R_{\rm p} \quad (\Omega) \tag{1}$$

where $R_{\rm dc}$ is the DC resistance (Ω), R_s is the resistance (Ω) due to the skin effect, and $R_{\rm p}$ is the resistance (Ω) due to the proximity effect.

The resistance of the MPW coil in the frequency range from 0.5 to 2 MHz was decreased by 13%–45% compared with that of the Cu wire coil, as shown in Figs. 4 and 5. We compare the proximity effect in the MPW coil with that in the Cu wire coil

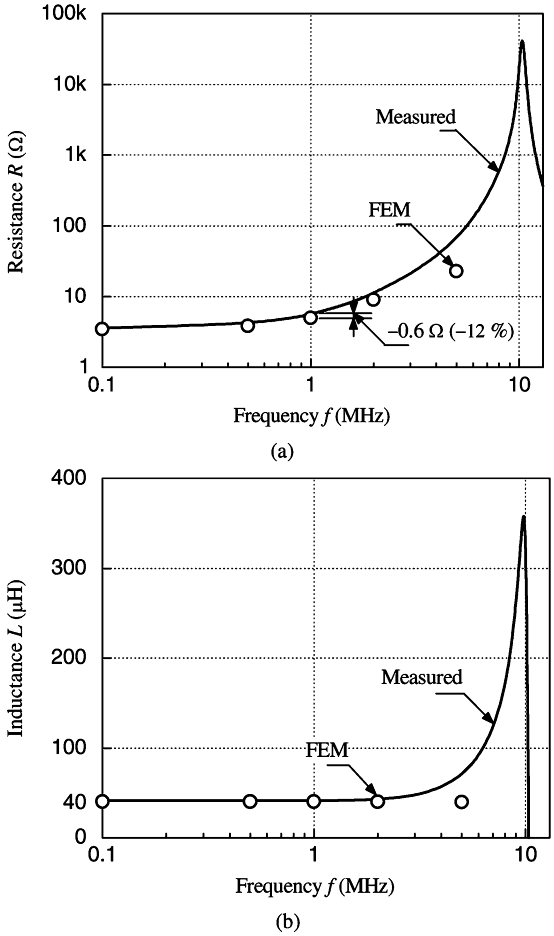

Fig. 5. Comparison between measured and calculated resistances and inductances of MPW coil. (a) Resistance. (b) Inductance (measured with HP 4192A, $\mu_r = 100$, $\rho = 0.098\ \mu\Omega\cdot$m).

in this section. Fig. 6 shows a comparison of coil resistances between the Cu wire and MPW coils at $f = 1$ MHz. The calculated values of $R_{\rm dc} + R_s$ are shown in this figure. The wire diameter, d, was 90 μm; therefore, the R_s at $f = 1$ MHz was approximately 0 Ω. The coil resistances of the Cu wire and MPW coils at $f = 1$ MHz were 7.9 Ω and 5.7 Ω, respectively; thus, the resistance of the MPW coil decreased by 15% compared with that of the Cu wire coil. In addition, the resistances due to the proximity effect, $R_{\rm p}$, of the Cu wire and MPW coils were 4.2 Ω and 2.1 Ω, respectively; thus, the $R_{\rm p}$ of the MPW coil was reduced in comparison with that of the Cu wire coil by half.

V. Conclusion

The reduction of the proximity effect in an MPW coil was calculated.

A. *Comparison Between Measured and Calculated Values*

The calculation errors of Cu wire and MPW coils were -5% and -12%, respectively; thus, the calculation error of the MPW coil was larger than that of the Cu wire coil, as shown in Figs. 4 and 5.

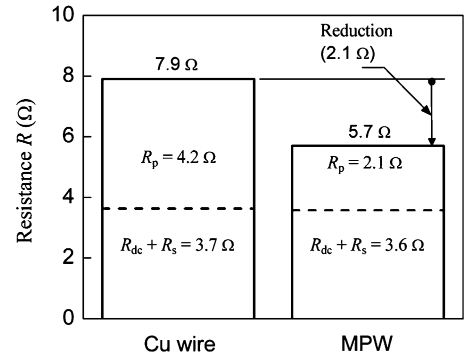

Fig. 6. Comparison of resistances due to proximity effect between Cu wire and MPW coils ($f = 1$ MHz).

B. *Comparison of Resistances Due to Proximity Effect*

The coil resistances of the COW and MPW coils at $f = 1$ MHz were 7.9 Ω and 5.7 Ω, respectively. In addition, the resistances due to the proximity effect, $R_{\rm p}$, of the Cu wire and MPW coils were 4.2 Ω and 2.1 Ω, respectively; thus, the $R_{\rm p}$ of the MPW coil was reduced in comparison with that of the COW coil by half, as shown in Fig. 6.

Acknowledgment

The authors sincerely thank Dr. K. Takeshita of Hitachi High-Tech. Electronics Engineering Co., Ltd., and Dr. S. Kishimoto for helpful discussions.

References

[1] J. D. Lavers and V. Bolborici, "Loss comparison in the design of high frequency inductors and transformers," *IEEE Trans. Magn.*, vol. 35, no. 5, pp. 3541–3543, Sep. 1999.
[2] T. Mizuno, T. Hayashi, F. Komeno, T. Asahina, S. Enoki, H. Shinagawa, H. Yamada, S. Watanabe, S. Uehara, T. Kishimoto, and K. Takeshita, "Eddy current displacement sensor using magnet-plated wire," in *Technical Meeting on Magnetics, IEE Jpn.*, 2004, vol. MAG-04-185, pp. 19–24.
[3] S. Yoshimura, S. Yoshihara, T. Shirakashi, E. Sato, and K. Ishii, "Characteristics of high-Q coils composed of Fe-plated Cu wire," in *Proc. 1st Magneto Electronics Int. Symp.*, 1994, pp. 485–487.
[4] Maxwell 2D Version 11, Ansoft Co., Ltd.
[5] Y. Yamamoto and H. Yamada, "Novel analytical equation on magnetic flux distribution and demagnetizing factor of cylindric magnetic core," *Trans. IEE Jpn. A*, vol. 102, no. 5, pp. 255–262, 1982.
[6] Japan Industrial Standards Committee, "Resistance of copper materials for electrical purposes," JSI C 3001, 3 p., 1981.

Manuscript received October 31, 2006 (e-mail: mizunot@gipwc.shinshu-u.ac.jp).