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Investigation of electrical and magnetic properties of ferro-nanofluid on transformers

Tsung-Han Tsai¹, Ping-Hei Chen^{1*}, Da-Sheng Lee² and Chin-Ting Yang³

Abstract

This study investigated a simple model of transformers that have liquid magnetic cores with different concentrations of ferro-nanofluids. The simple model was built on a capillary by enamel-insulated wires and with ferro-nanofluid loaded in the capillary. The ferro-nanofluid was fabricated by a chemical co-precipitation method. The performances of the transformers with either air core or ferro-nanofluid at different concentrations of nanoparticles of 0.25, 0.5, 0.75, and 1 M were measured and simulated at frequencies ranging from 100 kHz to 100 MHz. The experimental results indicated that the inductance and coupling coefficient of coils grew with the increment of the ferro-nanofluid concentration. The presence of ferro-nanofluid increased resistance, yielding to the decrement of the quality factor, owing to the phase lag between the external magnetic field and the magnetization of the material.

Introduction

In coming decades, new generations of electronic products such as mobile phones, notebooks, and e-paper will be developed with the primary goals of mobilization and miniaturization. New CMOS fabrication technology will be applied to fabricate the miniaturized IC of electronic products on silicon substrates, including on-chip micro-transformers. Several issues of on-chip micro-transformers have been investigated for many years [1-21]. Some researches focused on the material of the magnetic core [1-10] and the geometry of the transformer [11-14]. Some papers discussed the parasitic effect of the conductive substrates. Transformer losses become dramatic at high frequencies and limit the performance of the transformers. Previous studies have discussed in detail the causes of transformer losses such as parasitic capacitance, ohmic loss, and substrate loss [15-18]. Core loss from the solid magnetic core significantly affected the performance of the transformers. The solutions for the solid magnetic core loss were proposed [19-21].

Consequently, only a few studies addressed transformers with liquid magnetic cores. The liquid magnetic core, ferro-nanofluid, with its distinguishing features of low electric conductivity and super-paramagnetism is

regarded as a solution to the core losses of eddy current and hysteresis. In this study, a ferro-nanofluid was applied as a liquid magnetic core in a transformer. The performance of the transformer with the ferro-nanofluids was measured, simulated, and compared with that of a transformer with an air core.

Experiment

The ingredients of ferro-nanofluid used in this study were Fe₃O₄ nanoparticles, oleic acid, and diesel oil. The oil-based Fe₃O₄ nanofluid was synthesized by co-precipitation, surface modification, nanoparticles dispersing, and base-fluid phase changing [10].

The shape and size of the Fe₃O₄ nanoparticles was examined by a transmission electron microscope (TEM). Figure 1 shows the TEM photo of the Fe₃O₄ nanoparticles. The average diameter of the nanoparticles was approximately 10 nm. The crystalline phases of Fe₃O₄ nanoparticles were determined by X-ray diffraction, as shown in Figure 2. The magnetic properties of Fe₃O₄ nanofluid were measured by a vibrating sample magnetometer (VSM). The magnetized curve of the Fe₃O₄ nanofluid measured by a VSM is shown in Figure 3. The measured results illustrate that the synthesized ferro-nanofluids have the characteristic of super-paramagnetism. The saturated magnetizations of 0.25, 0.5, 0.75, and 1 M Fe₃O₄ nanofluids were 3.75, 8.85, 12.7, and 16.7 emu/g, respectively.

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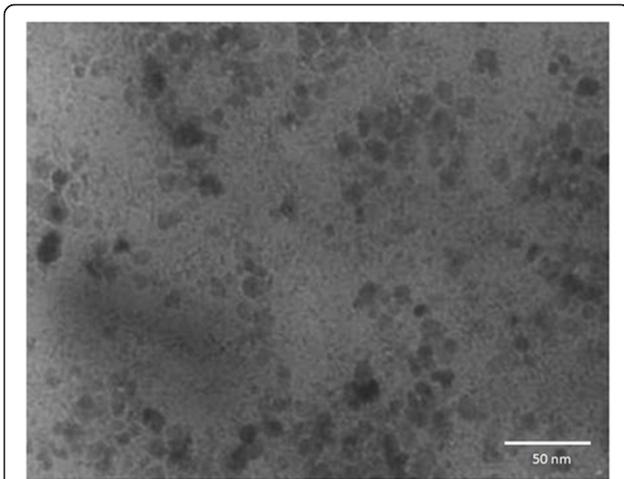


Figure 1 The TEM photo of Fe_3O_4 nanoparticles.

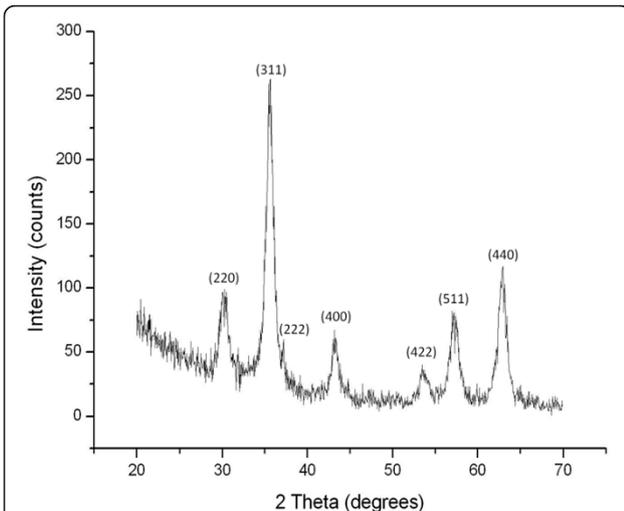


Figure 2 The crystalline phases of Fe_3O_4 nanoparticles.

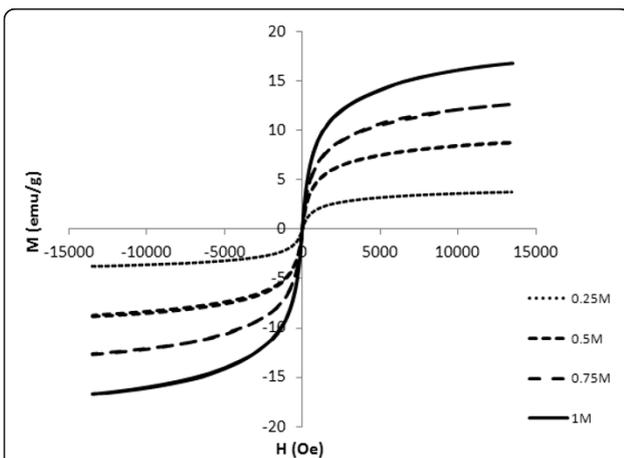


Figure 3 The magnetized curve of the Fe_3O_4 nanofluid measured by a VSM.

A liquid magnetic core of a transformer was used in this study; the capillary served as a container in which the Fe_3O_4 nanofluid was loaded. The coils of the transformer were made by winding enamel-insulated wires on a capillary. Figure 4 shows the transformer on a capillary, which loads the oil-based Fe_3O_4 nanofluid. The diameter of the enamel-insulated wire used was 0.45 mm, and the thickness of the enamel layer was approximately 0.05 mm. The primary and secondary windings had 20 turns. The outer and inner diameters of the capillary were 3.2 and 2.3 mm, respectively, and the capacity of the capillary was 100 μL .

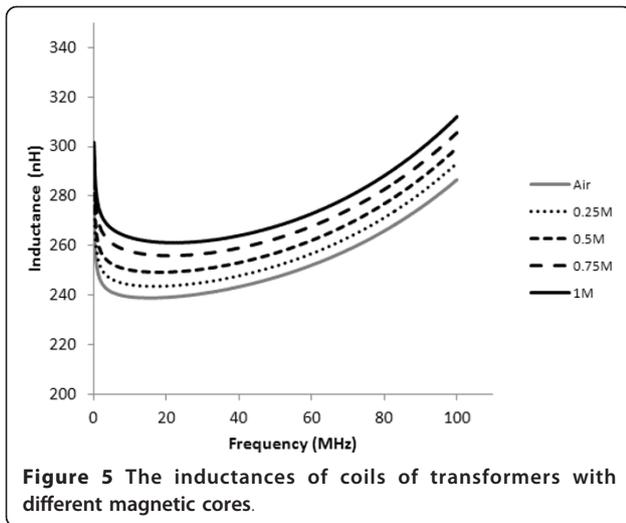
Results and discussion

Different magnetic cores, air, and Fe_3O_4 nanofluids of 0.25, 0.5, 0.75, and 1 M were applied as the magnetic core of transformers. The inductance (L), coupling coefficient (K), resistance (R), and quality factor (Q) were measured by an Agilent 4294A Precision Impedance Analyzer. In this study, the simulation of the transformer was also established with HFSS 3D Full-wave Electromagnetic Field Simulation. By applying measured permeability, permittivity, and magnetic tangent loss and setting exciting sources, the impedances will be calculated by the finite element method. Both the frequencies of measurement and simulation range from 100 kHz to 100 MHz.

Figure 5 shows the inductances of the coils of the transformers with different magnetic cores. Figure 5 illustrates that the inductance grows linearly with the increase of Fe_3O_4 concentration. At frequencies ranging from 100 kHz to 15 MHz, the inductances decrease rapidly due to the skin effect of coils. At frequencies ranging from 15 to 100 MHz, the inductances increase gradually and approach the maximum inductance at the



Figure 4 The transformer on a capillary that loads the oil-based Fe_3O_4 nanofluid.



resonance frequency. Figure 6 shows the measured and simulated results of the coupling coefficients of the transformers with different magnetic cores. The coupling coefficients also increase with the increase of Fe_3O_4 concentration. It increases rapidly below frequencies of 5 MHz and increases gradually with frequencies over 5 MHz. These results show that the magnetic cores of nanofluids can improve the inductance and coupling coefficients.

Figure 7 shows that the resistance increases with the increase of Fe_3O_4 concentration, and it increases as a function of frequency. At 100 MHz, the resistances with the magnetic core of 0.25 and 1 M Fe_3O_4 nanofluids were two and five times the resistance as the air core. It is speculated that this is because of the phase lag on the material magnetization behind the external magnetic

field at high frequencies. When the relaxation times cannot keep up the alternate time of the magnetic field, the resistance of the coils will grow rapidly [10,22]. At high frequencies, the permeability should be regarded as a complex number. Rearranging complex permeability and the inductance of a solenoid-type inductor, the impedance equation is obtained as follows:

$$Z = R + j\omega L = R + \omega \frac{\mu'' N^2 A}{l} + j\omega \frac{\mu' N^2 A}{l} \quad (1)$$

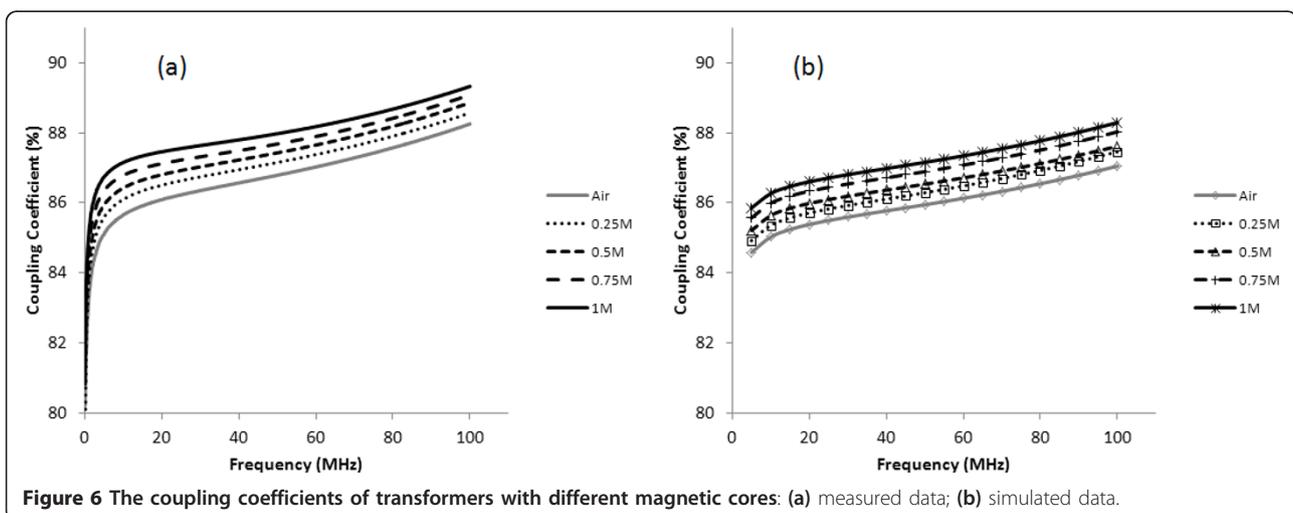
where ω is the angular frequency, N is the turns of coil, A is the cross-sectional area of solenoid, and l is the length of solenoid, μ' is the real part of complex permeability, and μ'' is the imaginary part of complex permeability. It can be observed that the imaginary part of complex permeability μ'' reflects on the real part of impedance, which is the cause of increasing resistance. Then, the quality factor Q , which is defined as the ratio of inductance to resistance, becomes [10]:

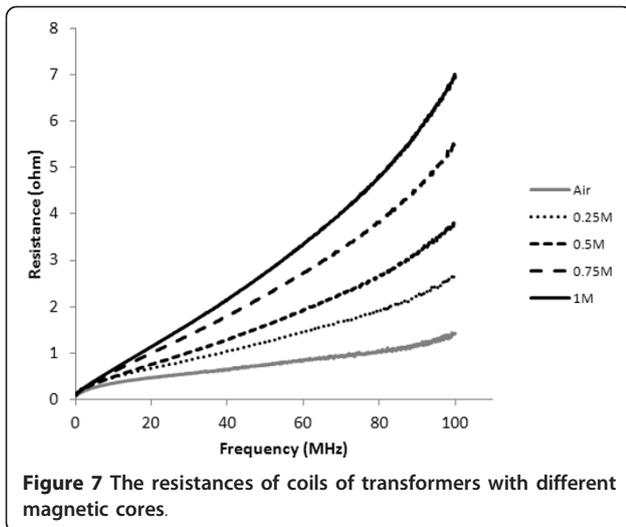
$$Q \equiv \frac{\text{Im}(Z)}{\text{Re}(Z)} = \frac{\omega \mu' N^2 A}{Rl + \omega \mu'' N^2 A} \quad (2)$$

Figure 8 shows the quality factor of coils of transformers with different magnetic cores. Owing to the fact that the increase of resistance is larger and faster than that of inductance with the presence of Fe_3O_4 nanofluids, the quality factor decreases when the Fe_3O_4 concentration rises. The simulated results show the same trend.

Conclusions

In this study, different concentrations of ferro-nanofluids were applied to the magnetic cores of transformers. The performance of transformers with magnetic cores of air





and Fe_3O_4 nanofluids of 0.25, 0.5, 0.75, and 1 M were measured, simulated, and compared. The experimental results indicated that the presence of Fe_3O_4 improved the inductance and the coupling coefficient of the coils. Due to phase lag on the material magnetization behind the external magnetic field at high frequencies, the resistance increased larger and faster than inductance, thus yielding a lower quality factor. For a micro-transformer, if a solid magnetic core is needed for higher inductance, it could be achieved by adding ferro-nanofluid and removing the base fluid repeatedly. This method has a lower thermal budget than the processes that sputtered or electroplated materials on chips. It is compatible with the MEMS process.

Abbreviations

TEM: transmission electron microscope; VSM: vibrating sample magnetometer.

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Authors' contributions

TH performed experimental investigations of electric and magnetic properties of ferro-nanofluids on transformers and prepared the draft, PH proposed the phenomena for investigation and revised the manuscript, DS suggested the theory for the explanation of measured results, and CT designed the experimental systems. All authors read and approved the final manuscript.

Competing interests

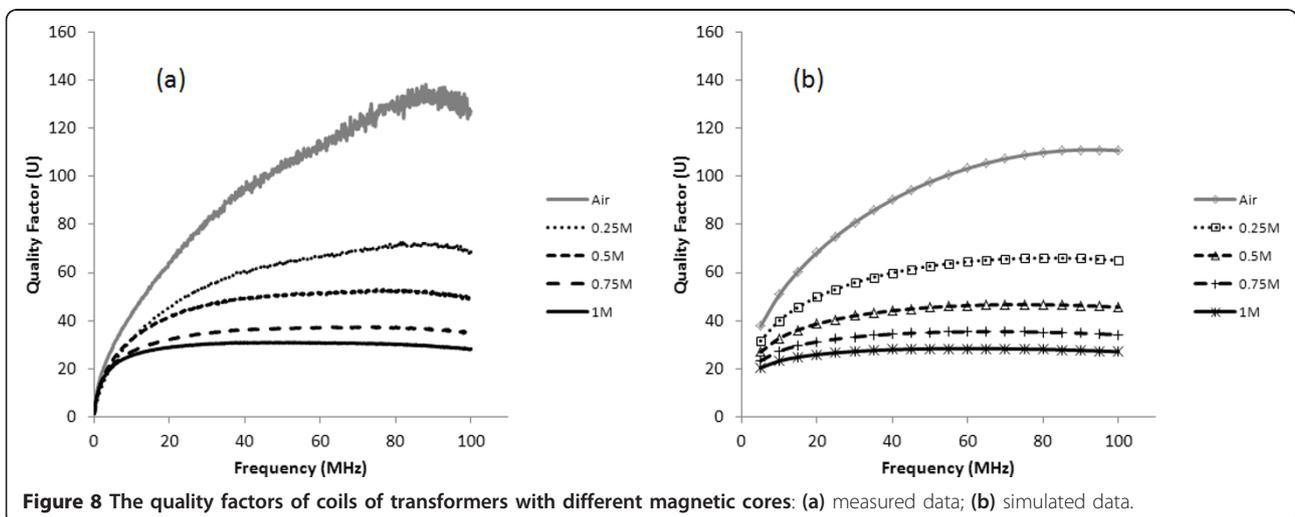
The authors declare that they have no competing interests.

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