

A Simple Wireless Power Charging Antenna System: Evaluation of Ferrite Sheet

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We report a simple wireless power charging (WPC) antenna system (50 mm × 40 mm × 0.1 mm) for use in simulating power transfer efficiency (η) with and without ferrite and a metallic object (battery case), thereby identifying suitable magnetic parameters and ferrite sheet thickness. The simulation results suggest that magnetic loss tangent ($\tan \delta_\mu$) and permeability (μ') need to be less than 0.05 and higher than 125 at 13.56 MHz, respectively, to achieve at least 75% of the transfer efficiency ($\eta_{\max}$) of the WPC antenna without ferrite and the metallic object. Accordingly, we have fabricated $\text{Ni}_x\text{Zn}_{0.85-x}\text{Cu}_{0.15}\text{Fe}_2\text{O}_4$ ($x = 0.32 - 0.38$) spinel ferrites using a one-step sintering process and obtained relatively high μ' of 169 and low $\tan \delta_\mu$ of 0.1 with a nickel (Ni) concentration of 0.38. This magnetic loss is still too high to achieve 75% of the $\eta_{\max}$ value. In order to further reduce the magnetic loss, a two-step sintering process was used. The two-step sintered $\text{Ni}_{0.38}\text{Zn}_{0.47}\text{Cu}_{0.15}\text{Fe}_2\text{O}_4$ shows μ' of 132 and a $\tan \delta_\mu$ of 0.03 at 13.56 MHz, respectively. Therefore, this ferrite meets criteria identified by the transfer efficiency simulation and is a good candidate for 13.56-MHz wireless power transfer charging antenna system. In addition, our designed WPC system is capable of evaluating other magnetic materials that are suitable for WPC antenna applications.

Index Terms—Ni–Zn–Cu ferrite, power transfer efficiency, wireless power charging (WPC) system.

I. INTRODUCTION

RECENTLY, wireless power charging (WPC) systems using inductive coupling have been of great interest due to increased safety and convenience [1]. A WPC system transfers power wirelessly via the magnetic field generated by a coil. In such a WPC system, magnetic sheets are employed to the backside of the transmitting and receiving coil antennas to enhance the transfer efficiency and suppress electromagnetic field (EMF) noise [2]. With the presence of any metallic object underneath a WPC antenna, the power transfer efficiency significantly degrades due to the magnetic field from the coil generating eddy currents on the metallic component. To alleviate the eddy current effect, magnetic isolation is required, which can be realized by magnetic field convergence with a high permeability (μ') and electrical resistivity magnetic sheet. Moreover, the low magnetic loss is essential at the operation frequency (13.56 MHz) of WPC systems. In an effort to investigate low magnetic loss, high permeability, and high resistivity materials, Ni–Zn–Cu spinel ferrites have been widely studied [3]–[7]. For instance, Co-doped Ni–Zn–Cu ferrite shows a permeability of 154 and a magnetic loss tangent ($\tan \delta_\mu$) of 0.03 at 13.56 MHz [3] but is composed of four components, including expensive Co.

Although WPC has been known for more than a century, to the best of our knowledge, there is no report on the evaluation of shielding ferrite by a simple WPC system for optimal dynamic properties and ferrite thickness.

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In this paper, we have designed a simple WPC antenna system to identify the most desired parameters of a ferrite sheet, i.e., magnetic properties and thickness, for efficient wireless power transfer at 13.56 MHz. In addition, this WPC system can be useful in the evaluation of any magnetic sheet. Based on the thickness and magnetic parameters confirmed by power transfer efficiency simulations, we have also designed and synthesized Ni–Zn–Cu spinel ferrites. The synthesized Ni–Zn–Cu ferrites meet the optimal magnetic parameters.

II. SIMULATION OF WIRELESS POWER TRANSFER EFFICIENCY

Fig. 1 shows our designed WPC system for simulation of the wireless power transfer efficiency (η) of the antenna. ANSYS HFSS (version 16) was employed for the simulation. The WPC consists of two coil antennas, A_1 (considered as a charger) and A_2 (considered as a charging device). Each antenna consists of a coil, polyethylene (PE) and ferrite sheet, and matching circuit, as shown in Fig. 1(a). Each coil has three turns with a 0.3-mm gap between traces ($W = 0.6$ mm) and is attached to a PE sheet (50 mm × 40 mm × 0.1 mm), which has a smaller area than a typical commercial smartphone battery. The ferrite sheet is located underneath the PE sheet with an equivalent area. Ferrite sheet thickness (t) is varied from 0.1 to 0.9 mm, and the matching circuit is designed to meet 50 Ω at 13.56 MHz, which is the frequency of interest for WPC applications.

The antennas in Fig. 1(b) are separated by 30 mm. Furthermore, metals, which are assumed to be batteries or other electronics, with a dimension of 70 mm × 50 mm × 3 mm, are placed on the backside of the antennas. Only antenna A_1 is externally excited with 1 W in the

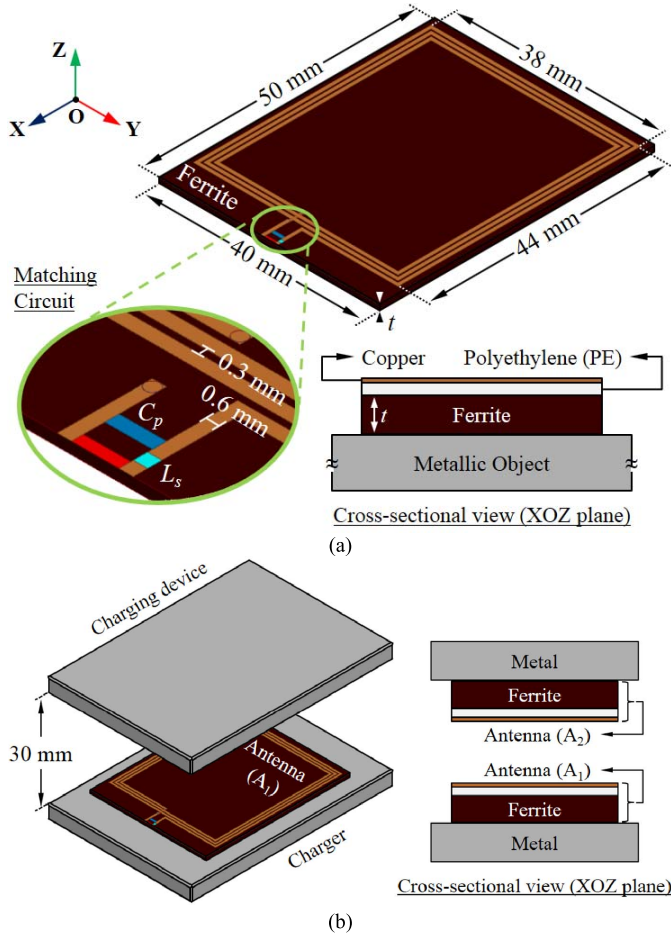


Fig. 1. Geometry and dimensions of (a) single antenna and (b) pair of antenna with metal for WPC applications.

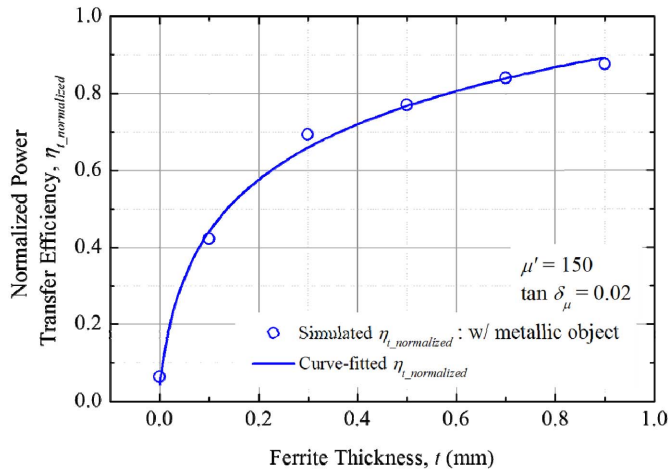


Fig. 2. Simulated and normalized power-transfer efficiency as a function of ferrite sheet thickness.

simulation of power transfer efficiency. We first simulated the efficiency ($\eta_{\max}$) of the WPC system without ferrite and the metallic object and used this efficiency to normalize the efficiency of the WPC antenna with ferrite and metallic object.

Fig. 2 shows the simulated and normalized power-transfer efficiency, $\eta_{t_normalized} = \eta_t / \eta_{\max}$, as a function of ferrite thicknesses. η_t is the simulated power-transfer efficiency at

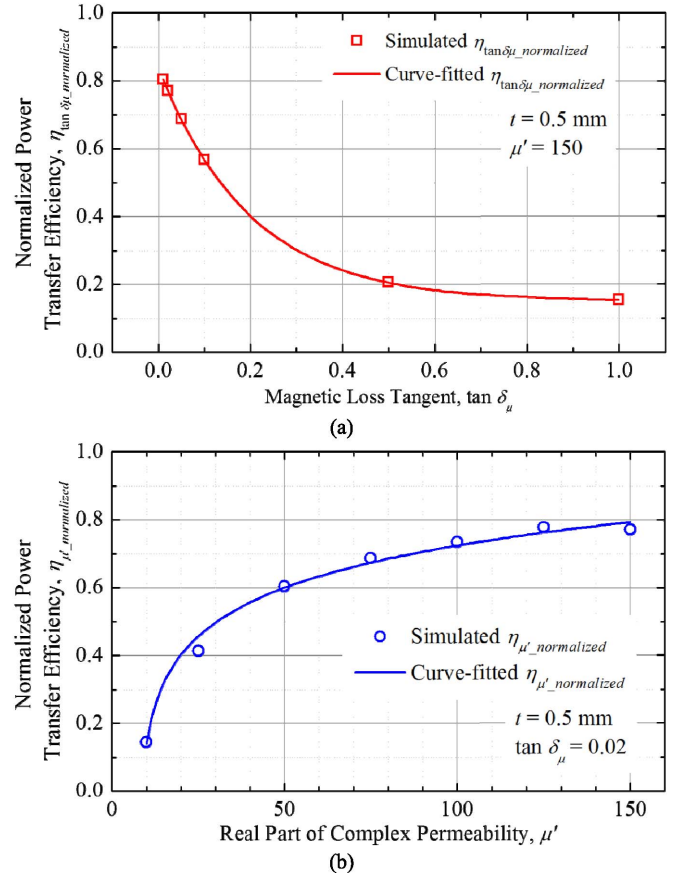


Fig. 3. Simulated and normalized power-transfer efficiency as a function of (a) magnetic loss tangent and (b) real part of complex permeability.

different ferrites t with the metallic object, and $\eta_{\max}$ (63%) is the simulated efficiency of the coil antennas. Surprisingly, $\eta_{t_normalized}$ drops to 0.064 when the metallic object is placed on the backsides of the antennas without ferrite sheets. Therefore, loading of the ferrite sheet is indispensable to the increase of η by magnetically isolating the metallic object from the antenna. $\eta_{t_normalized}$ is increased from 0.42 to 0.88 as t increases from 0.1 to 0.9 mm when the ferrite sheet has a permeability (μ') of 150 and a magnetic loss tangent ($\tan \delta_\mu$) of 0.02. The simulated efficiencies in Fig. 2 can be fit to the following empirical equation: $\eta_{t_normalized} = a + b \times \ln(t - c)$, where $a = 91.2$, $b = 22.2$, and $c = 0.02$. $\eta_{t_normalized}$ gradually increases with the t value but starts to saturate when t reaches 0.5 mm. Accordingly, a t value of 0.5 mm was used for subsequent simulations, since the thinner sheet is favorable in real applications.

Fig. 3(a) shows the simulated and normalized power-transfer efficiency ($\eta_{\tan \delta_\mu_normalized} = \eta_{\tan \delta_\mu} / \eta_{\max}$, where $\eta_{\tan \delta_\mu}$ is the simulated η at different $\tan \delta_\mu$ values), and $\eta_{\mu'_normalized}$ ($= \eta_{\mu'} / \eta_{\max}$, where $\eta_{\mu'}$ is the simulated η at different μ' values) is shown in Fig. 3(b). $\eta_{\tan \delta_\mu_normalized}$ remarkably decreases as the $\tan \delta_\mu$ value increases in Fig. 3(a). Noticeably, $\eta_{\tan \delta_\mu_normalized}$ decreases 14.6% with the small increase in the $\tan \delta_\mu$ value from 0.01 to 0.05. On the other hand, $\eta_{\mu'_normalized}$ at $t = 0.5$ mm and $\tan \delta_\mu = 0.02$ gradually increases with μ' , and then begins to saturate when μ' is greater than 125 as seen in Fig. 3(b). The increase in the transfer efficiency with t and

μ' in Figs. 2 and 3 is due to the cancellation of the magnetic flux through the coil, thereby reducing eddy currents on the metal objects [2]. In Fig. 3, the red and blue solid lines are fit curves given by $\eta_{\tan\delta\mu_normalized} = d \times \exp(-\tan\delta\mu/e) + f$ and $\eta_{\mu'_normalized} = g \times \ln(\mu' - h)$, respectively, where $d = 68.8$, $e = 0.2$, $f = 14.9$, $g = 16$, and $h = 7.6$. The simulation results suggest that ferrite with $\tan\delta\mu < 0.05$ and $\mu' > 125$ is desired to achieve 75% of the η_{max} value of the coil antennas. Therefore, we have designed and synthesized spinel ferrites to meet a μ' value of 132 and 0.03 of $\tan\delta\mu$ at 13.56 MHz.

III. EXPERIMENT

Spinel $Ni_xZn_{0.85-x}Cu_{0.15}Fe_2O_4$ ($x = 0.32-0.38$) ferrites were prepared using the sol-gel and sintering processes. The precursors $[Ni(NO_3)_2 \cdot 6H_2O, Zn(NO_3)_2 \cdot 6H_2O, Cu(NO_3)_2 \cdot 2.5H_2O, Fe(NO_3)_3 \cdot 9H_2O]$ and citric acid of Ni-Zn-Cu ferrites were dissolved in 50 mL of deionized (DI) water with the appropriate stoichiometric ratio, named Solution I. Citric acid was dissolved in 300 mL of DI water, named Solution II. Then, Solution I was dropped into Solution II while stirring under an O_2 atmosphere. The mixed solution was then dried in an oven, and the dried powder was collected and annealed at 750 °C. The annealed powder was ground and pressed into a toroidal ring (inner diameter: 3.2 mm, outer diameter: 7.0 mm, and thickness: 2 mm) to characterize the dynamic magnetic properties. One-step sintering was carried out at 850 °C or 900 °C for 4 h, and two-step sintering at 900 °C for 1 min, followed by sintering at 830 °C for 4 h.

We have used an X-ray diffractometer (XRD: Cu $K\alpha$ -1.54 Å) and vibrating sample magnetometer (VSM: MicroSense EV9) to characterize the annealed $Ni_xZn_{0.85-x}Cu_{0.15}Fe_2O_4$ powders for crystalline phases and static magnetic properties. To measure dynamic magnetic properties of the sintered toroidal rings, an impedance/material analyzer (IA: Agilent E4991A) with a material test fixture (Agilent 16454A) was used in the range of 1 MHz–1 GHz. We have characterized the sintered ferrites by a field emission scanning electron microscope (FE-SEM: JEOL 7000 FE) for their microstructures.

IV. RESULTS AND DISCUSSION

Fig. 4 shows the XRD patterns of $Ni_xZn_{0.85-x}Cu_{0.15}Fe_2O_4$ ($x = 0.32-0.38$) powders with the standard diffraction patterns of Ni-Zn spinel ferrite. All powders show a cubic spinel phase with no secondary phases. To estimate the average crystallite size (D) of the ferrite powder, we have used Scherrer's equation with the (3 1 1) diffraction peak

$$D = 0.89\lambda/(\beta \cos \theta) \quad (1)$$

where λ is the wavelength of the X-ray, β is the full width at half maximum angle, and θ is the diffraction angle [8]. The measured average crystallite size increases from 33 to 50 nm as x (Ni content) increases from 0.32 to 0.38. This can be understood by an enthalpy of the compound. The enthalpy of $NiFe_2O_4$ ($\Delta H_{970K} = -1.22 \pm 0.22$ kcal/mole) is higher than that of $ZnFe_2O_4$ ($\Delta H_{970K} = -2.67 \pm 0.23$ kcal/mole), suggesting less liberation of heat with an increase of x ; consequently, nickel (Ni) enhances the crystallite growth [9], [10].

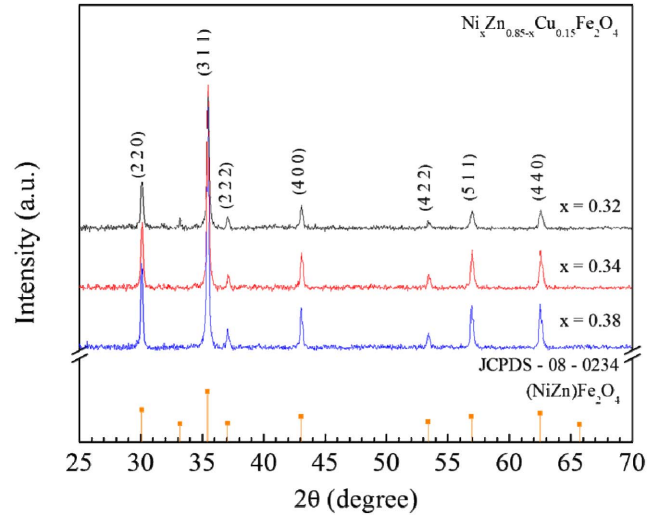


Fig. 4. X-ray diffraction patterns of $Ni_xZn_{0.85-x}Cu_{0.15}Fe_2O_4$ powders with various Ni concentrations.

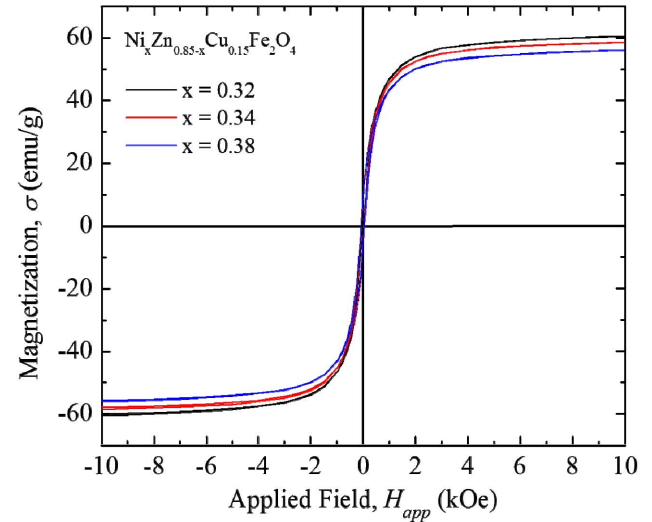


Fig. 5. Magnetic hysteresis loops of $Ni_xZn_{0.85-x}Cu_{0.15}Fe_2O_4$ powders with various Ni concentrations.

Fig. 5 shows the magnetic hysteresis loops of $Ni_xZn_{0.85-x}Cu_{0.15}Fe_2O_4$ ($x = 0.32-0.38$) powders, all of which appear magnetically soft. As the Ni concentration increases from 0.32 to 0.38, the saturation magnetization (σ_s) decreases from 60 to 56 emu/g. This is because the magnetic Ni^{2+} cations preferably occupy octahedral sites, which leads to a reduction in the total net magnetization [6], [11].

Fig. 6(a) and (b) shows Ni concentration dependence of the measured complex permeability spectra and $\tan\delta\mu$, respectively, of $Ni_xZn_{0.85-x}Cu_{0.15}Fe_2O_4$ ($x = 0.32-0.38$) ferrites. These ferrites were sintered at 900 °C, i.e., one-step sintering. It is found that μ' decreases to 169 from 274 at 13.56 MHz, and $\tan\delta\mu$ decreases to 0.1 from 0.47 as the Ni content increases from 0.32 to 0.38. This is because the ferromagnetic resonant frequency shifts to a higher frequency according to Snoek's effect. The decrease of μ' is attributed to a decrease of M_s ($=\rho \times \sigma_s$, where ρ is the density) [6]. A $\tan\delta\mu$ of 0.1 for $Ni_xZn_{0.85-x}Cu_{0.15}Fe_2O_4$ ($x = 0.38$) is still too high to achieve 75% of the η_{max} value.

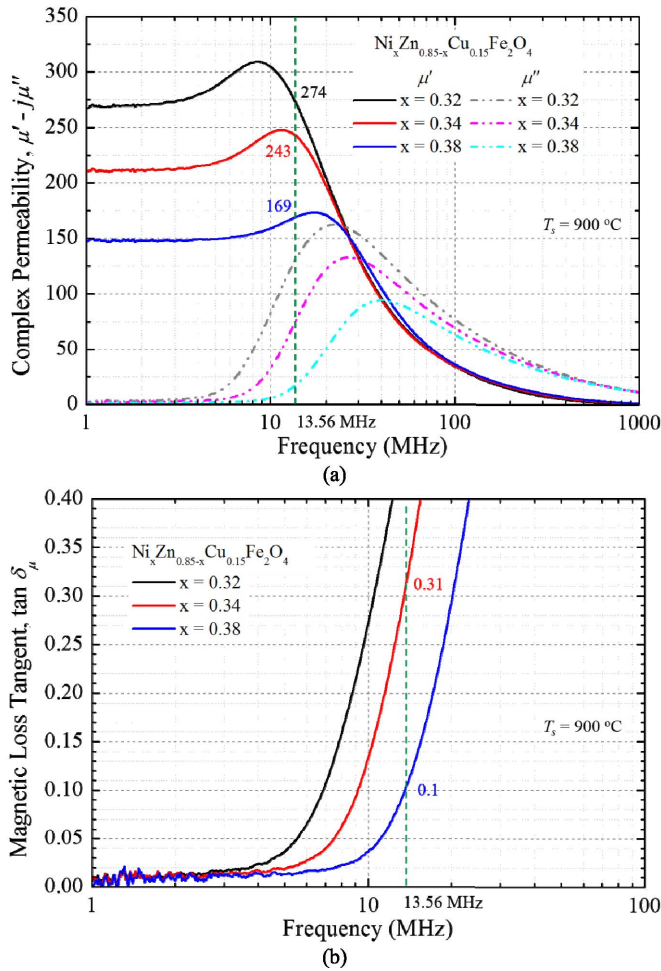


Fig. 6. Ni concentration dependence of (a) complex permeability and (b) magnetic loss tangent for $\text{Ni}_x\text{Zn}_{0.85-x}\text{Cu}_{0.15}\text{Fe}_2\text{O}_4$ ferrite sintered at 900°C .

Therefore, we have redesigned the microstructure of the ferrite ($x = 0.38$) by modifying the single-step sintering profile, i.e., a two-step sintering route. This is because the dynamic complex permeability of ferrite is highly affected by its microstructure [12], [13]. Fig. 7(a) compares the measured complex permeability of $\text{Ni}_{0.38}\text{Zn}_{0.47}\text{Cu}_{0.15}\text{Fe}_2\text{O}_4$ ferrite sintered by the two-step sintering process (900°C and 830°C) to that of one-step sintered ferrites. The two-step sintered ferrite shows a μ' of 132 and a $\tan \delta_\mu$ of 0.03 at 13.56 MHz. This μ' is lower than that of the one-step sintered ferrite at 900°C and marginally higher than that of the one-step sintered ferrite at 850°C . This is because the average grain size of two-step sintered sample is 660 nm, which is smaller than that (980 nm) of the one-step sintered sample at 900°C and slightly larger than that (590 nm) of the one-step sintered sample at 850°C , as shown in Fig. 8. However, the $\tan \delta_\mu$ value (0.03 at 13.56 MHz) of the two-step sintered ferrite is much lower than the one-step sintered ferrites (0.05 and 0.10 at 13.56 MHz), which is shown in Fig. 7(b). This low $\tan \delta_\mu$ can be attributed to the higher density of the two-step sintered ferrite ($\rho = 4.37 \text{ g/cm}^3$) than that of the one-step sintered sample (850°C , $\rho = 4.28 \text{ g/cm}^3$). We compared the magnetic loss tangent of the developed ferrite with commercial ferrites [14], [15] in Fig. 7. It is observed that the developed ferrite shows a low

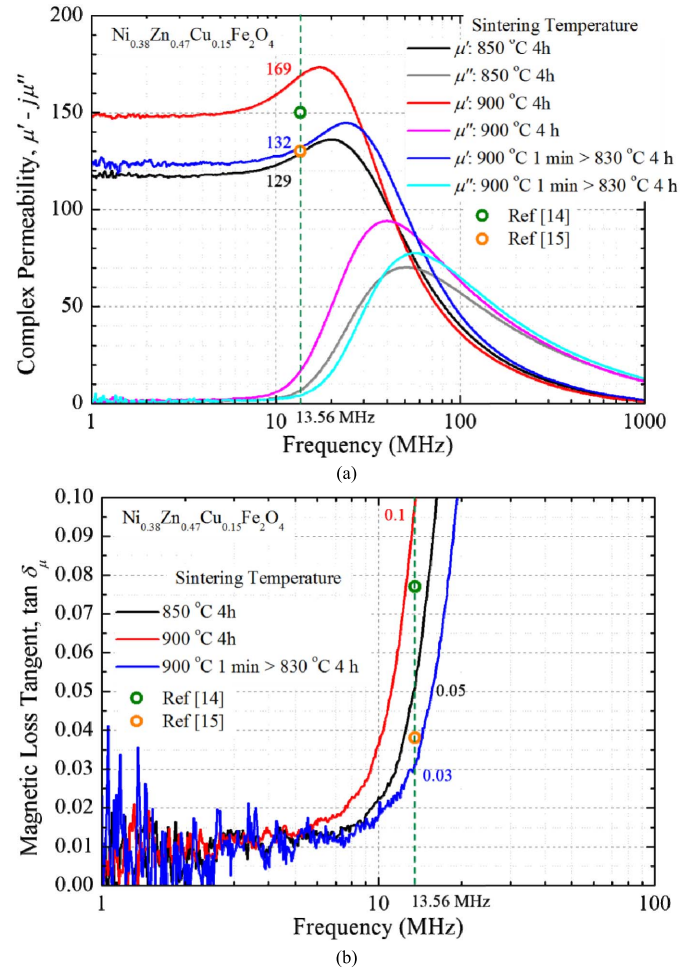


Fig. 7. Effects of sintering condition on (a) complex permeability and (b) magnetic loss tangent for $\text{Ni}_{0.38}\text{Zn}_{0.47}\text{Cu}_{0.15}\text{Fe}_2\text{O}_4$ ferrite.

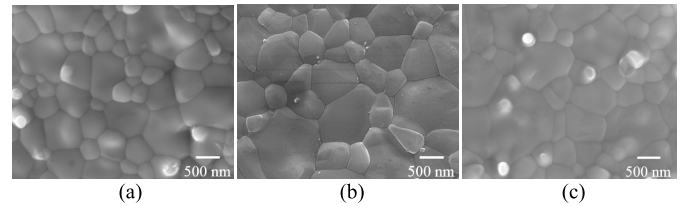


Fig. 8. Microstructures of sintered $\text{Ni}_{0.38}\text{Zn}_{0.47}\text{Cu}_{0.15}\text{Fe}_2\text{O}_4$ ferrites. (a) $T_s = 850^\circ\text{C}$ for 4 h. (b) $T_s = 900^\circ\text{C}$ for 4 h. (c) $T_{s1} = 900^\circ\text{C}$ for 1 min and $T_{s2} = 830^\circ\text{C}$ for 4 h.

magnetic loss with relatively high permeability compared with the commercial ferrite sheets.

The two-step sintered ferrite meets magnetic parameters identified by WPC simulation to achieve higher than 75% of the $\eta_{\max}$ value. We have found that our designed simple WPC system can be useful for the evaluation of any magnetic sheets and used to get necessary information for the design of shielding ferrite.

V. CONCLUSION

Power transfer efficiency simulations of a WPC system identified the magnetic parameters of a ferrite sheet suitable for achieving higher than 75% of the transfer efficiency ($\eta_{\max}$).

of the WPC coil antenna system without ferrite and a metallic object. The ferrite sheet needs to have a permeability (μ') of at least 125 and a magnetic loss tangent ($\tan \delta_\mu$) less than 0.05 at 13.56 MHz to achieve 75% of the $\eta_{\max}$ value. $\text{Ni}_x\text{Zn}_{0.85-x}\text{Cu}_{0.15}\text{Fe}_2\text{O}_4$ ($x = 0.38$) ferrite, prepared by a one-step sintering, shows a relatively high μ' of 169 and a low $\tan \delta_\mu$ of 0.1. However, the loss is still too high to achieve 75% of the $\eta_{\max}$ value. Alternatively, a two-step sintering processed $\text{Ni}_{0.38}\text{Zn}_{0.47}\text{Cu}_{0.15}\text{Fe}_2\text{O}_4$ ferrite ($x = 0.38$) has a μ' of 132 and a $\tan \delta_\mu$ of 0.03 at 13.56 MHz, which achieves more than 75% of the $\eta_{\max}$. Therefore, this ferrite is a good candidate for WPC antenna applications.

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