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Impedance Matching of Electrically Small Antenna with Ni-Zn Ferrite Film

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We demonstrate that a partial loading of $Ni_{0.5}Zn_{0.5}Fe_2O_4$ (Ni-Zn ferrite) film remarkably improves impedance matching of electrically small $Ba_3Co_2Fe_{24}O_{41}$ (Co_2Z) hexaferrite antenna. A 3 μm thick Ni-Zn ferrite film was deposited on a silicon wafer by the electrophoresis deposition process and post-annealed at 400 °C. The fabricated Ni-Zn ferrite film has saturation magnetization of 268 emu/cm^3 and coercivity of 89 Oe. A partial loading of the Ni-Zn ferrite film on the Co_2Z hexaferrite helical antenna increases antenna return loss to 24.7 dB from 9.0 dB of the Co_2Z antenna. Experimental results show that impedance matching and maximum input power transmission to the antenna without additional matching elements can be realized, while keeping almost the same size as the Co_2Z antenna size.

Keywords : electrophoresis deposition, Ni-Zn ferrite film, impedance matching, electrically small antenna, Co_2Z hexaferrite

1. Introduction

Integration and miniaturization of antenna are becoming important issues for mobile electronics applications [1-3]. Therefore, antenna size and impedance matching are recent research subjects to study. Monopole antenna length is proportional to $\lambda_{eff}/4$, where the λ_{eff} is the effective wavelength. The effective wavelength is given by the equation (1):

$$\lambda_{eff} = \frac{c}{f_r\sqrt{\mu_r \varepsilon_r}} = \frac{\lambda_0}{\sqrt{\mu_r \varepsilon_r}}, \quad (1)$$

where f_r is the antenna resonant frequency, c is the velocity of light, and λ_0 is the wavelength in air. Ferrite possesses both relative permeability (μ_r) and permittivity (ε_r) greater than unity [4]. Therefore, antenna size can be short by both permeability and permittivity of the ferrite. Furthermore, ferrite is electrically an insulator, thereby reducing eddy current loss at high frequency [5]. All these facts imply that electrically small and efficient antenna can be realized with ferrite.

However, electrically small antenna has a high quality factor (Q) because of Chu's limit [6]. High Q leads to poor antenna impedance matching. According to the equation (2), antenna impedance matching can be improved by a combination of ferrite thickness t, μ_r, and ε_r [7].

$$Z_{in} = Z_0\sqrt{\frac{\mu_r}{\varepsilon_r}}\tanh\left[j\frac{2\pi ft}{c}\sqrt{\mu_r \varepsilon_r}\right], \quad (2)$$

where Z_{in} is the input impedance and Z_0 is the characteristic impedance of the air. In order to improve impedance matching for hexaferrite RF antenna, we have partially covered a Co_2Z ($Ba_3Co_2Fe_{24}O_{41}$) hexaferrite antenna with ferrite film rather than bulk ferrite. The film form of ferrite has advantages over bulk ferrite [7, 8]. This is because the Snoek's limit of ferrite film is increased by a factor of $\sqrt{(\mu_r - 1)}$ according to the equation (3):

$$(\mu_r - 1)\cdot f_{FMR} = \frac{4\pi M_s}{H_k}\cdot \gamma\sqrt{4\pi M_s H_k} = \gamma \cdot 4\pi M_s\sqrt{(\mu_r - 1)}, \quad (3)$$

where γ is the gyromagnetic constant, H_k is the magnetic anisotropy field, and M_s is the saturation magnetization.

In this paper, we demonstrate that partially loaded $Ni_{0.5}Zn_{0.5}Fe_2O_4$ (Ni-Zn ferrite) film remarkably improves impedance matching of Co_2Z hexaferrite helical antenna in the very high frequency (VHF) range.

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2. Experiment

2.1. Electrophoretic Ni-Zn ferrite film deposition

Low temperature electrophoretic deposition (EPD) technique [9, 10] was used to fabricate Ni-Zn ferrite film on a silicon wafer. Ni-Zn ferrite particles (100-200 nm in size) were dispersed in deionized water, and pH of the solution was adjusted to 2.6-3. As shown in Fig. 1, positively charged ferrite particles in a colloidal suspension migrate under an electric field towards the negatively charged Au-sputtered silicon substrate. As-deposited ferrite film was post-annealed at 400 °C. The prepared Ni-Zn ferrite films were characterized with a vibrating sample magnetometer (VSM, MicroSense EV9) and X-ray diffractometer (XRD) for magnetic properties and phase identification. Furthermore, scanning electron microscopy (SEM) and atomic force microscopy (AFM) were used to characterize microstructure and surface topology of the ferrite films.

2.2. Fabrication of electrically small Co_2Z hexaferrite helical antenna

A helical antenna was designed and fabricated on a Co_2Z hexaferrite substrate having a volume of 42 × 10.5 × 2.5 mm^3. The Co_2Z hexaferrite has real part of permeability of 7.2 and magnetic loss tangent of 0.02 at 200 MHz. The antenna radiator has 9.5 helical turns, and consists of a 1 mm width copper strip with a 3 mm gap between the coils. It is noted that the resonant frequency (f_r) of air-core helical antenna shifts to lower frequency by loading a ferrite according to the equation (4):

$$f_r = \frac{1}{2\pi\sqrt{LC}}, \quad (4)$$

where L is the inductance and C is the capacitance. Inductance $L = \mu_0\mu_r N_2 A/l$, where N is the number of turns, A is the cross-sectional area, and l is the length of an antenna. Inductance L increases with relative permeability of ferrite, thereby decreasing antenna resonant frequency. A double-sided copper laminated FR4 board (100 × 50 × 1.6 mm^3) with ground of 80 × 50 mm^2 was prepared with a precision milling machine (LPKF ProtoMat S62) for a testing board to hold the antenna. Fig. 2(a) and (b) show Co_2Z helical antenna and Co_2Z helical antenna partially covered with Ni-Zn ferrite film (20 × 11 × 0.003 mm^3)/Au-sputtered silicon wafer, respectively. A 50 Ω coaxial cable was used to excite the antenna. Three types of antenna were characterized with a vector network analyzer (Agilent N5230A) for return loss. The three antennas are Co_2Z ferrite, silicon wafer covered Co_2Z, and Ni-Zn ferrite/silicon wafer covered Co_2Z antennas.

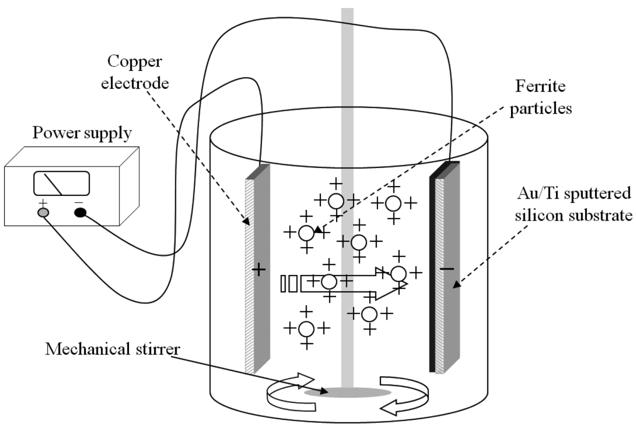
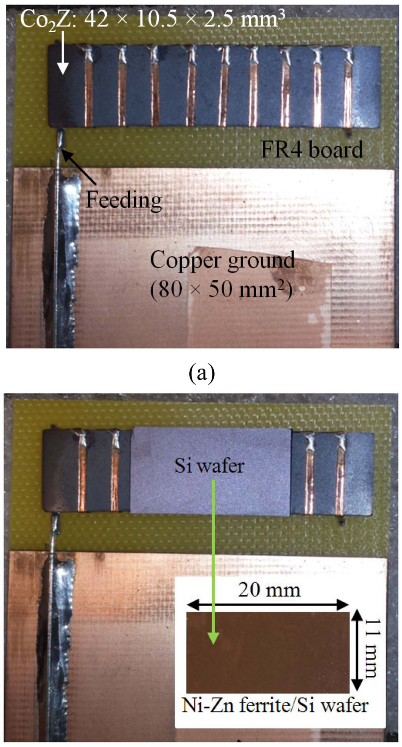


Fig. 1. Schematic illustration of electrophoresis deposition of $Ni_{0.5}Zn_{0.5}Fe_2O_4$ ferrite film on a silicon substrate.



(a) (b)

Fig. 2. (Color online) Fabricated Co_2Z hexaferrite helical antenna (a) without and (b) with $Ni_{0.5}Zn_{0.5}Fe_2O_4$ film on silicon wafer.

3. Results and Discussion

Both as-deposited and annealed Ni-Zn ferrite films are well indexed to the spinel ferrite with a minor phase of Au seed layer as shown in Fig. 3. Fig. 4 shows magnetic hysteresis loops for as-deposited and annealed N-Zn ferrite films. Both films are magnetically soft, and the annealed

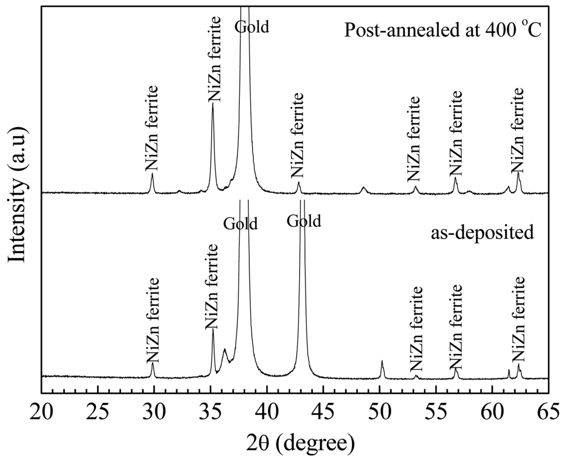


Fig. 3. X-ray diffraction patterns of as-deposited and post-annealed $Ni_{0.5}Zn_{0.5}Fe_2O_4$ films.

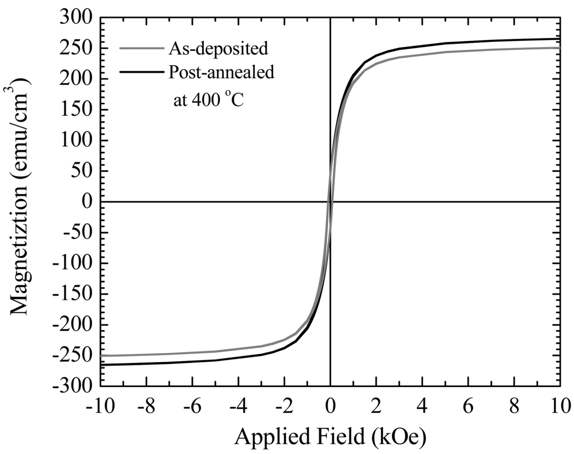


Fig. 4. Magnetic hysteresis loops of as-deposited and post-annealed $Ni_{0.5}Zn_{0.5}Fe_2O_4$ films.

film has about 270 emu/cm^3. Fig. 5 shows SEM and AFM images. The thickness of the film is about 3 μm, and the root-mean-squared (rms) roughness is 321 nm.

Figure 6 shows return loss for the three different types of antenna, which were studied in this paper. The resonant frequency (f_r) and return loss (RL) of the Co_2Z helical antenna are 228 MHz and 9.0 dB, respectively. The Co_2Z hexaferrite substrate significantly reduces the antenna size compared to dielectric and air-core antennas [11]. It is noted that the size (i.e. diagonal length = 43.3 mm) of fabricated Co_2Z antenna is about 0.033λ (λ = 1315 mm at 228 MHz). Therefore, this antenna is electrically small [12]. When a silicon wafer is partially loaded, the f_r shifted to 202 MHz from 228 MHz of Co_2Z ferrite antenna. This is due to large permittivity of 11.9 of the silicon wafer. The RL is 7.8 dB at f_r of 202 MHz, which is slightly lower than that of the Co_2Z antenna, implying poorer impedance matching than the Co_2Z antenna. However, good impedance matching and miniaturization were achieved by partially covering the Co_2Z hexaferrite antenna with Ni-Zn ferrite/Silicon substrate. The antenna f_r decreases to

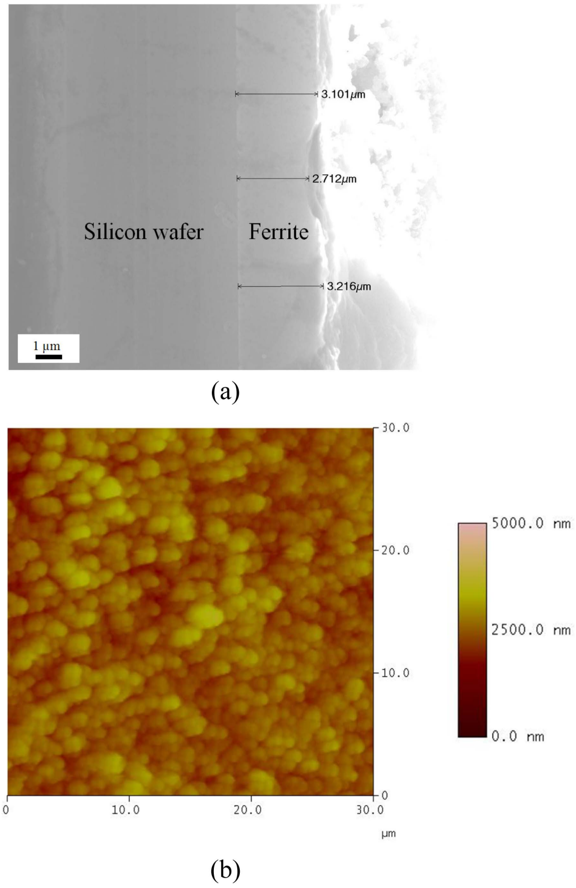


Fig. 5. (Color online) (a) Cross-sectional SEM and (b) surface AFM images of EPD processed $Ni_{0.5}Zn_{0.5}Fe_2O_4$ film on silicon wafer.

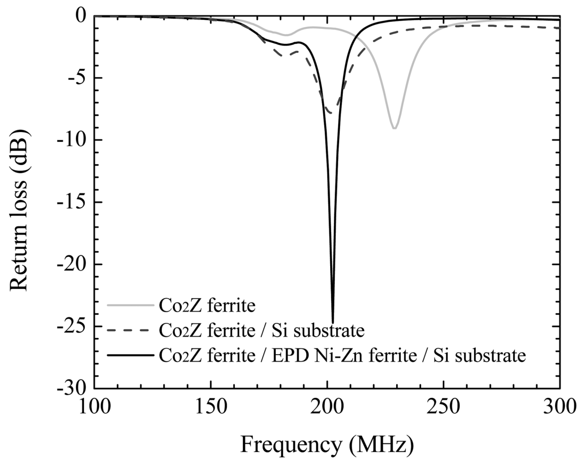


Fig. 6. Measured return losses of the Co_2Z hexaferrite helical antenna with and without EPD processed $Ni_{0.5}Zn_{0.5}Fe_2O_4$ film.

202 MHz from 228 MHz of the Co_2Z hexaferrite antenna, and the RL remarkably increases to 24.7 dB, as shown in Fig. 6. This is because a loading of Ni-Zn ferrite film of μ_r counteracts large capacitive property of silicon substrate (ε_r of 11.9). Also, an additional magnetic tangent loss of the Ni-Zn ferrite decreases quality factor. Therefore, partially loading of Ni-Zn ferrite is significantly effective in improving impedance matching without additional matching elements, while maintaining almost the same antenna size.

Experimental results suggest that a loading of spinel ferrite film is beneficial and applicable to low-profile and miniature antenna applications. In addition, the EPD process has advantages of high deposition rate and low post-annealing temperature over sputter deposition [13], pulsed laser deposition [14], sol-gel process [15], and screen printing technique [16].

4. Conclusion

Electrically small Co_2Z hexaferrite antenna was characterized for return loss. Ni-Zn ferrite film has saturation magnetization of 268 emu/cm^3 and coercivity of 89 Oe. A partial loading of Ni-Zn ferrite on Co_2Z hexaferrite antenna increases return loss from 9.0 to 24.7 dB. Experimental results show that improved impedance matching and maximum input power transmission to the antenna can be achieved without additional matching elements and increase of antenna size. Therefore, a loading of Ni-Zn ferrite film is beneficial and applicable to low-profile and miniature antenna applications.

References

[1] J. Lee, Y. K. Hong, S. Bae, G. S. Abo, W. M. Seong, and G. H. Kim, IEEE Antennas Wirel. Propag. Lett. **10**, 603 (2011).

[2] H. Moon, G. Y. Lee, C. C. Chen, and J. L. Volakis, IEEE Antennas Wirel. Propag. Lett. **11**, 322 (2012).

[3] W. Lee, Y. K. Hong, J. Lee, D. Gillespie, K. G. Ricks, F. Hu, and J. Abu-Qahouq, IEEE Antennas Wirel. Propag. Lett. **12**, 765 (2013).

[4] Z. Zheng, H. Zhang, J. Q. Xia, and F. Bai, IEEE Trans. Magn. **49**, 4214 (2013).

[5] V. G. Harris, IEEE Trans. Magn. **48**, 1075 (2012).

[6] L. J. Chu, J. Appl. Phys. **19**, 1163 (1948).

[7] S. Bae, Y. K. Hong, and A. Lyle, J. Appl. Phys. **103**, 07E929 (2008).

[8] G. M. Yang, X. Xing, A. Daigle, O. Obi, M. Liu, J. Lou, S. Stoute, K. Naishadham, and N. X. Sun, IEEE Trans. Antennas Propag. **58**, 648 (2010).

[9] S. Hashi, N. Takada, K. Nishimura, O. Sakurada, S. Yanase, Y. Okazaki, and M. Inoue, IEEE Trans. Magn. **41**, 3487 (2005).

[10] S. Hashi, Y. Tokunaga, S. Yanase, Y. Okazaki, O. Sakurada, K. Nishimura, and M. Inoue, IEEE Trans. Magn. **40**, 2796 (2004).

[11] S. Bae, Y. K. Hong, J. J. Lee, W. M. Seong, J. S. Kum, W. K. Ahn, S. H. Park, G. S. Abo, J. Jalli, and J. H. Park, IEEE Trans. Magn. **46**, 2361 (2010).

[12] G. Breed, High Freq. Electronics **6**, 50 (2007).

[13] J. Prado, M. E. Gomez, P. Prieto, and A. Mendoza, J. Magn. Magn. Mater. **321**, 2792 (2009).

[14] O. F. Caltun, J. Optoelectron. Adv. Mater. **7**, 739 (2005).

[15] P. Gao, E. V. Rebrov, T. M. W. G. M. Verhoeven, J. C. Schouten, R. Lkeismit, G. Kozlowski, J. Cetnar, Z. Turgut, and G. Subramanyam, J. Appl. Phys. **107**, 044317 (2010).

[16] D. C. Kulkarni, U. B. Lonkar, and Vijaya Puri, J. Magn. Magn. Mater. **320**, 1844 (2008).