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Design and evaluation of noise suppression sheet for GHz band utilizing magneto-elastic effect

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ABSTRACT

Feasibility of realizing a noise suppression sheet (NSS) coping with the low SHF band such as the 5 GHz band was investigated, which was composed of soft magnetic metal flakes dispersed in a polymer. For suppressing noises, the higher frequency one of the bimodal frequency dispersion (lower frequency one: Dispersion DII, higher frequency one: Dispersion DIII) seen in the imaginary permeability (μ''; magnetic loss component) spectrum of the NSS was aimed to utilize. Referring to the previous finding that Dispersion DIII is originated from a magneto-elastic effect, several magnetic composite sheets were prepared using various alloy flakes with different saturation magnetostriction (λ_s), and their frequency ($f_{r(DIII)}$) and magnitude ($\mu''_{(DIII)}$) of Dispersion DIII were investigated. It was found that the NSS containing flakes with higher λ_s exhibited higher $f_{r(DIII)}$ and higher $\mu''_{(DIII)}/\mu''_{(DII)}$, which was ratio of $\mu''_{(DIII)}$ to the magnitude of Dispersion DII ($\mu''_{(DII)}$). The $f_{r(DIII)}$ for the NSS having the highest λ_s containing Fe-Co alloy flake reached 7.45 GHz and μ'' in the 5 GHz band was approximately twice as high as the conventional NSS containing Fe-Si-Al alloy flake. For transmission attenuation power ratio (R_{tp}) when an NSS was placed on a microstrip line with characteristic impedance of 50 Ω, NSS with larger $f^2_{r(DIII)} \cdot \mu''_{(DIII)} \propto M_s^2$ (M_s: saturation magnetization), which theoretically gave the frequency limit of imaginary permeability for a thin film, exhibited larger R_{tp} in the low SHF band. These results suggested that an NSS containing a magnetic flake material with both large λ_s and M_s was suitable for suppressing low SHF band noises.

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1. Introduction

We previously proposed the noise suppression sheet (NSS), which was composed of a Fe-Si-Al flake powder and a polymer, coping with electromagnetic interference (EMI) problems of quasi-microwave band [1,2]. The NSS is widely used for suppressing high frequency EMIs inside electronic devices such as mobile phones often followed by receiving sensitivity degradation, where high frequency magnetic loss characteristics of the composite magnetic sheet are utilized. To cope with the recent rapid increase of mobile traffic, upper limit of the communication frequency band is expected to be expanded from 2 GHz to 5 GHz (low SHF band), as LTE-A (LTE-Advanced) and LTE-U (LTE in unlicensed spectrum) are to be operated. Since a plurality of antennas and active elements are mounted with high density in a small space inside a cellular phone, it is concerned that EMI problems occur at higher frequencies than ever. Therefore, NSS is in great need of which electromagnetic noise suppression effect is large in the 5 GHz band, that is, a material of which a dispersion of imaginary part of complex permeability ($\mu = \mu'\text{-}j\mu''$) appears and μ'' is high in the 5 GHz band. However, conventional NSSs cannot cope with frequencies above the 2.4 GHz band.

We revealed that the frequency spectrum of permeability of the composite magnetic sheet is composed of two dispersions in the case where the flake thickness is smaller than the skin depth. One is due to in-plane shape anisotropy of the flake (Dispersion DII). The other is due to magneto-elastic effect that happens near the flake surface (Dispersion DIII) [2,3]. By positively utilizing the magnetoelastic effect, which should be the origin of Dispersion DIII, it is expected that an NSS having large μ'' in the 5 GHz band can be obtained, which has been difficult to be realized. According

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Abbreviations: NSS, noise suppression sheet; μ'', imaginary part of complex permeability; R_{tp}, transmission attenuation power ratio; Dispersion DII, permeability dispersion appearing at a higher frequency of the bimodal dispersion which an NSS exhibits; Dispersion DIII, permeability dispersion appearing at a higher frequency of the bimodal dispersion which an NSS exhibits; $\mu''_{(DII)}$, peak value of μ'' for Dispersion DII; $\mu''_{(DIII)}$, peak value of μ'' for Dispersion DIII; $\mu''_{(DIII)}/\mu''_{(DII)}$, ratio of $\mu''_{(DIII)}$ to $\mu''_{(DII)}$; $f_{r(DII)}$, resonance frequency corresponding to Dispersion DII; $f_{r(DIII)}$, resonance frequency corresponding to Dispersion DIII; λ_s, saturation magnetostriction; M_s, saturation magnetization; SHF, super high frequency.

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to our finding that conducted noise suppression effect when the composite magnetic sheet is placed in the vicinity of a transmission line is proportional to the product of μ'' and frequency (f), it is effective to utilize Dispersion DIII in the case where $\mu''\cdot f$ for Dispersion DIII is larger than that for Dispersion DII.

In this study we attempted to confirm the feasibility of utilizing Dispersion DIII appearing at a higher frequency than Dispersion DII and clarify the measure to control DIII, in order to achieve large magnetic loss in 5 GHz band. Several metal materials with different saturation magnetostriction (λ_s) and saturation magnetization (M_s) were flattened to have fine flake shapes and the obtained flakes were mixed with polymers, thus we obtained the magnetic composite sheet samples. The permeability characteristics were analyzed in detail, and the conducted noise suppression effects for the composite sheets in 5 GHz band were examined.

2. Experimental procedure

2.1. Measurements of saturation magnetization and magnetostriction constant

The alloy ingots shown in Table 1 were obtained using a high frequency induction heating furnace, where the Fe-9.8mass%Si-6.4mass%Al and the other alloy ingots were obtained by melting and molding the raw materials (Fe, Si and Al) and the atomized powders [4] of each composition, respectively. Saturation magnetization was measured using a vibrating sample magnetometer applying magnetic field of 796 kA/m along the in-plane direction for samples of 7 mm × 7 mm × 2 mm in size. Saturation magnetostriction was measured by attaching a strain gauge under the magnetic field of 796 kA/m for samples of 10 mm × 10 mm × 1.5 mm in size, which was obtained through electric discharge machining.

2.2. Preparation of magnetic flakes and composite sheet samples

The Fe-9.8mass%Si-6.4mass%Al ingot was crashed into a powder smaller than 150 μm. The other alloy powders smaller than 150 μm were obtained by the atomization method. These alloy powders were micro-forged with 2-propanol solvent using a slurry re-circulation media agitating mill, and the flake samples shown in Table 2 were obtained. Magnetic paste was obtained by mixing 88 mass% of magnetic flake and 12 mass% (by solid content) of acrylic polymer solved in toluene. The magnetic paste was applied repeatedly onto a base material to have 0.1 mm thickness using the doctor blade method, thus the composite magnetic sheet samples with density (d), surface resistivity (ρ_s) shown in Table 3 were obtained.

Note that the composite magnetic sheets prepared in this study contains as-forged flakes without heat treatment, and the flakes are aligned parallel to the in-plane direction caused by a shear stress generated during the application process.

Table 1
Saturation magnetization and saturation magnetostriction of raw alloy materials. M_s is saturation magnetization at 796 (kA/m). λ_s is magnetostriction at 796 (kA/m).

Magnetic alloy	M_s (kA/m)	λ_s
Fe-9.8 mass%Si-6.4 mass%Al	755	6.6×10^{-6}
Fe-6.5 mass%Si-4.5 mass%Cr	1243	17×10^{-6}
Fe-0.5 mass%Si	1590	20×10^{-6}
Fe-3.5 mass%Si-4.5 mass%Cr	1372	26×10^{-6}
Fe-14 mass%Al	920	62×10^{-6}
Fe-50 mass%Co	1721	72×10^{-6}

Table 2
Magnetic flakes prepared in this study. D_{50} is median size in the flakes plane. S is specific surface area of flakes.

Composition of flake	D_{50} (μm)	S (m^2/g)
Fe-9.8 mass%Si-6.4 mass%Al (for NSS-A)	27	1.31
Fe-6.5 mass%Si-4.5 mass%Cr (for NSS-B)	32	1.47
Fe-0.5 mass%Si (for NSS-C)	14	2.31
Fe-3.5 mass%Si-4.5 mass%Cr (for NSS-D)	32	1.82
Fe-14 mass%Al (for NSS-E)	39	1.23
Fe-50 mass%Co (for NSS-F)	19	2.71

2.3. Measurement of high frequency permeability of composite magnetic sheets

In-plane complex permeability of the magnetic sheets was determined with Nicolson-Ross method [5] by measuring S-parameters at frequencies between 10 MHz and 9 GHz for ring-shaped samples with outer diameter of 7.0 mm and inner diameter of 3.04 mm, using a network analyzer ENA5080A (KEYSIGT TECHNOLOGY) and coaxial tube CSH2-APC7 (KEAD).

Conducted noise suppression effects for the composite magnetic sheets were evaluated by transmission attenuation power ratio (R_{tp}) [6]. The R_{tp} was determined with Eq. (1) by measuring S-parameters when the composite magnetic sheet (width: 2 mm, length: 50 mm) was placed on a microstrip line (line width: 2 mm, line length: 70 mm, characteristic impedance: 50 Ω) connected to a network analyzer ENA5080A (KEYSIGT TECHNOLOGY).

$$R_{tp} = -10\log_{10}\frac{10^{\frac{S_{21}}{10}}}{1-10^{\frac{S_{11}}{10}}} \tag{1}$$

3. Results and discussion

Table 3 shows electromagnetic properties for the prepared six NSS samples A-F to be applied for noise suppression sheet for GHz band. All of the samples had sufficiently high surface resistivity of 1.9×10^6–4.2×10^8 Ω/sq. Fig. 1. shows permeability spectra for NSS-A, NSS-E and NSS-F. Every sample exhibited Dispersion DII and Dispersion DIII at frequencies $f_{r(\mathrm{DII})}$ and $f_{r(\mathrm{DIII})}$ where $\mu''_{(\mathrm{DII})}$ and $\mu''_{(\mathrm{DIII})}$ had the maximum, respectively, and showed a tendency that both $f_{r(\mathrm{DII})}$ and $f_{r(\mathrm{DIII})}$ became higher with increasing λ_s.

The $f_{r(\mathrm{DIII})}$ for NSS-F containing Fe-Co alloy flake with the highest λ_s reached 7.45 GHz, of which μ'' was about 2 times higher in the 5 GHz band and 4.2 times higher at 7.45 GHz than NSS-A containing the conventional Fe-Si-Al flake.

Fig. 2 shows relationship between λ_s of magnetic flake and $\mu''_{(\mathrm{DIII})}/\mu''_{(\mathrm{DII})}$ of the NSS. It is found that $\mu''_{(\mathrm{DIII})}/\mu''_{(\mathrm{DII})}$ increases with increasing λ_s of magnetic flake. These results support our previous finding[3] that Dispersion DIII of the μ'' spectrum has close relationship with magnetoelastic effect.

In order to verify the effectiveness of using dispersed DIII of NSS for noise suppression, it is compared with the effective noise suppressor in the GHz band which has been reported so far. The thin film obtained by the ferrite plating method exhibits high μ'' even in the GHz band exceeding so-called Snoek's limit, which is the frequency limit for bulk ferrites [7], and thus exhibits a conducted noise suppression effect up to 10 GHz [8]. Therefore, we compared the complex permeability dispersion of NSSs in this study and the ferrite-plated thin film.

Fig. 3 shows cross-sectional SEM images for NSS-A, NSS-E and NSS-F. Average thickness of the flat powder was 0.28 μm for NSS-A, 0.38 μm for NSS-E, 0.15 μm for NSS-F, and aspect ratio of the flat powder was 97 for NSS-A, 104 for NSS-E, and 127 for NSS-F. Thus the demagnetizing field along the in-plane direction

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