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Double negative electromagnetic property of granular composite materials in the microwave range

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ABSTRACT

The double negative (DNG) electromagnetic property, i.e. the simultaneous negative permittivity and permeability, of granular composite materials has been studied in the microwave frequency range. The negative permittivity spectrum can be realized by the low frequency plasma oscillation which is generated in the percolated metal particle chain as well as the dielectric resonance of the induced dipole in the isolated metal particle clusters. Meanwhile, the negative permeability spectrum can be obtained by the magnetic resonance of the embedded ferromagnetic particles in the granular composite structure. By combining these negative electromagnetic properties, the DNG characteristics can be produced in the granular composite material. The DNG properties of the Cu/Yttrium Iron Garnet (Cu/YIG) granular composite materials under external magnetic field will be presented; the negative refractive index of the Cu/YIG composite material will also be discussed.

1. Introduction

Double negative materials (DNMs) or Left-handed metamaterials (LHMs), which simultaneously have negative permittivity and permeability (DNG: Double negative) spectra in the microwave or optical frequency range, are in a novel class of materials; they have been the subject of great interest in this decade. The LHM was introduced by Veselago [1] and shows the peculiar electromagnetic properties such as the negative refraction of electromagnetic waves or the inverse Doppler effect [2]. A periodic structure composed of the Split Ring Resonator (SRR), which shows the Mu negative (MNG), and the Long Metal Wire Array (LMWA), which indicates the Epsilon negative (ENG), was proposed as a LHM, and a negative refraction of the electromagnetic (EM) wave was observed in this medium [3,4]. By use of the SRR or MWA the electromagnetic compatibility (EMC) materials such as the perfect EM wave absorber [5,6] or the frequency selective microwave shielding device [7] can also be fabricated.

On the other hand, the development of the DNG composite materials using magnetic, dielectric or metallic compounds or alloys has also been the subject of considerable interest and a number of studies have been devoted to realize the DNM composed of real materials [8–11]. The MNG characteristic can be achieved by the magnetic resonance of ferromagnetic materials [12,13]. Meanwhile, the ENG property in the microwave range has been investigated by the dielectric resonance of metallic fibers in the dielectric host materials; the Lorentz type frequency dispersion of permittivity having the ENG characteristic was reported [14,15]. Furthermore, the low frequency plasma oscillation, which produces a finite negative permittivity value in the microwave range, can be formed in the granular composite materials by the percolation of embedded metallic particles or particle clusters. A metallic state having the low conduction electron density has been investigated in the metal granular composite materials; the Drude type permittivity dispersion was observed in several granular composites indicating the low frequency plasmonic state [16,17]. Recently, several DNMs in the radio wave (RF) to microwave frequency range have been developed using the low frequency plasmonic property and ferromagnetic resonances [10,11,18].

In this work, the electromagnetic properties of the granular composite materials including metallic and ferromagnetic particles have been studied to realize the DNG property in the microwave frequency range. In this paper, the experimental results for a low frequency plasmonic state in the coagulated Cu particle composite and the ferromagnetic resonance of Yttrium Iron Garnet (YIG) granular composites under external magnetic field will be presented. We will discuss the Double negative property of Cu/YIG granular composite in the microwave range and the refractive index spectrum determined from the complex permeability and permittivity data of Cu/YIG composites.

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2. Mechanisms of the negative permittivity and permeability in the random composite structure

The conceivable mechanisms to generate ENG and MNG i.e. the single negative (SNG) characteristics in the granular composite structure are shown in Fig.1(a) as well as the schematic diagram of the structure of the DNG composite (b). In granular composite materials, the ENG characteristics can be realized by the dielectric resonance of the polarization P which is produced in the metallic clusters or fibers. Further, the ENG property can be achieved by the low frequency plasma oscillation of conduction electrons in the percolated metal particle clusters in the microwave range, too. Meanwhile, the MNG properties of granular composite material can be produced by the magnetic resonance which is originated by the domain wall vibration or the gyromagnetic spin rotation in the embedded magnetic particles.

As shown in Fig.1(b), the dielectric polarization P can be formed in the isolated metal clusters or metal fibers embedded in the insulating host under external electric field. The external electric field E changes the polarity of P and the polarization resonates with the E. As a result, the Lorentz type frequency dispersion is formed in the permittivity spectrum [14,19]; negative permittivity can be obtained in the resonance frequency band.

The low frequency plasmonic state is the basic concept of the ENG in the artificial left-handed structure such as the LMWA. In metals, the conduction electrons have a vibrational motion under the electric field; this is called the plasma oscillation. The plasma angular frequency ω_p is given by

$$\omega_p = \sqrt{\frac{n_e q^2}{m_e \varepsilon_0}}, \tag{1}$$

where q and m_e are the charge and mass of an electron, ε_0 is the permittivity of vacuum. Generally, the metallic material has a large n_e in the order of 10^{23} mol^{-1}; hence the ω_p locates about 10^{15} s^{-1}. In the frequency below ω_p, external electric field E is canceled by the conduction electron motion (plasma oscillation). This plasma oscillation produces the dielectric flux density D opposite to E; the permittivity ε_r becomes negative. However, since the ε_r rapidly decrease to minus infinity with decreasing frequency, the negative permittivity value in the microwave range is almost minus infinity. In the LMWA complex, since the electric current flow is restricted along the separated long thin wires, the effective conduction electron density n_e is reduced and the ω_p shifts to microwave range [3]. As a result, the LMWA has a finite negative permittivity value in the microwave range. In the metal granular composite, the metal particles and their clusters produce a low electron density metallic state in the composite structure above a certain volume fraction of the particle (percolation threshold φ_c). The electrical current I can flow along the percolated metal particle chain under the external electric field E as shown in Fig. 1(b); the plasma oscillation of conduction electrons can produce the electrical flux density D having the opposite direction of the E and the permittivity can be negative. The negative permittivity spectrum caused by the low frequency plasmonic state has also been observed in several metal granular composite materials [17,20]. Effective permittivity spectra of plasmonic state including isolated dipole moment P can be described by the following formula using the Drude and Lorentz type frequency dispersion [21].

$$\varepsilon_r = \varepsilon_r' - i\varepsilon_r'' = 1 - \chi_D + \chi_L = 1 - \frac{\omega_p^2}{\omega^2 - i\Gamma_D\omega} + \frac{K}{\omega_L^2 - \omega^2 + i\Gamma_L\omega} \tag{2}$$

where χ_D and χ_L indicate the Drude and Lorentz type electrical suscepbitility, K is a constant, Γ_D and Γ_L indicate damping factors for Drude and Lorentz model, respectively. The χ_D gives negative permittivity ε_r' below a characteristic angular frequency $\omega_0 = \sqrt{\omega_p^2 - \Gamma_D^2}$ and the resonance type permittivity dispersion is given by the χ_L.

The MNG in the granular composite materials can be achieved by the magnetic resonance including domain wall (DW) and gyromagnetic spin resonances [22],

$$\mu_r = 1 + \chi_{dw} + \chi_s = 1 + \frac{\chi_{d0}\omega_{dw}^2}{\omega_{dw}^2 - \omega^2 + i\beta\omega} + \frac{\chi_{s0}(\omega_s + i\alpha\omega)}{(\omega_s + i\alpha\omega)^2 - \omega^2}, \tag{3}$$

where χ_{dw} and χ_s are the magnetic susceptibilities for DW and spin motions, $\omega_{dw}=2\pi f_{dw}$ and $\omega_s=2\pi f_s$ are the resonance angular frequencies, χ_{d0} and χ_{s0} are the static magnetic susceptibilities of each component, α and β are their damping factors, and $\omega=2\pi f$ is the angular frequency of the applied electromagnetic field. Though the two magnetic resonances, DW and Spin, are able to make MNG spectrum, the gyromagnetic spin resonance is essential to make MNG in the microwave range. From the previous studies of the magnetic composite materials, the magnetic particle content should be increased in the composite structure to realize the relatively high magnetic permeability and the magnetic resonance spectra with negative μ_r region [22,23]. Hence the ferromagnetic metals such as Fe-Ni, Fe-Co, or Fe-Al-Si alloy are useful for the magnetic granular composites. However, the magnetic permeability is reduced by the eddy current in the microwave range [24]. Accordingly, the surface treatment of embedded particles has been studied to decrease the eddy current effect in the metal granular

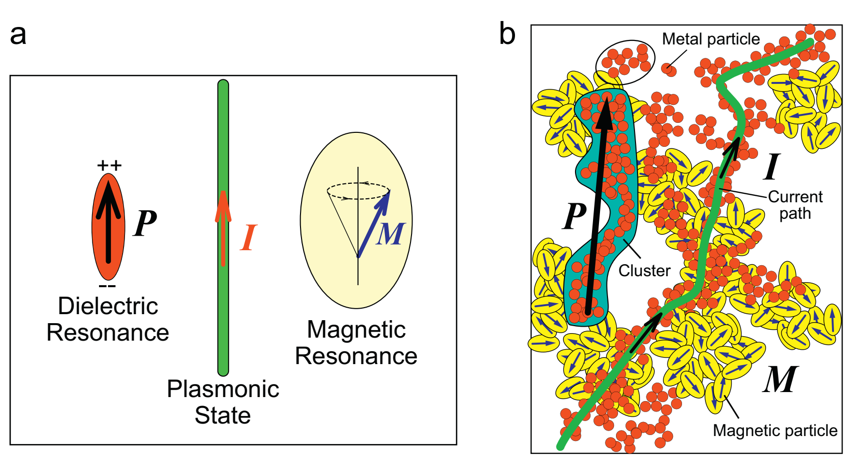

Fig. 1. Possible mechanisms to generate ENG and MNG characteristics in the granular composite structure (a) and the schematic diagram of the structure of the DNG granular composites (b).