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Combination of perovskite and magnetic inverse spinel structures to improve microwave absorption properties

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ABSTRACT

In this work, nanocomposites were prepared by filling polyester matrix with $SrTiO_3$ by using some spinel ferrites such as magnetite, cobalt ferrite, manganese ferrite, and polyaniline (PANi) as fillers. These nanocomposites were synthesized by the hydrothermal and co-precipitation and hydrothermal and interfacial polymerization. Radar absorption parameters were measured in the X-band range by the transmission line method by using a straight rectangular waveguide. X-ray diffraction analyzer, scanning electron microscope, and vector network analyzer were used to characterize the materials. The Taguchi method was used to optimize and study the effects of the weight ratios of fillers, type of spinel ferrite, and thickness on the radar absorption properties of nanocomposites by the total weight ratio of fillers of only 5%. The optimal conditions were a nanocomposite of manganese ferrite as the magnetic filler with a weight ratio of 2:1 for both spinel ferrite/$SrTiO_3$ and spinel ferrite + $SrTiO_3$/PANi at 1-mm thickness. All the prepared nanocomposites had a broadband reflection loss spectrum less than −20 dB over the entire X-band.

1. Introduction

Daily increase in the usage of electromagnetic (EM) waves for commercial and warlike purposes has caused extra demand for EM absorbing materials, because of the barricade against EM identification and EM interference removal. The demand in X-band is higher than that in other frequency ranges because of the more civil and military utilities in this band. More accurately, the demand to achieve a thinner microwave absorber with a broadband absorption is high. These promoted absorbers absorb EM energy and then convert it to heat energy, through both magnetic and dielectric losses mechanism [1,2].

Radar absorbing materials (RAMs) are made of electric and magnetic materials, and the physical principles of optics are applied to design their structures and advanced techniques are applied to optimize the absorption parameters [3].

The conventional RAMs have larger density, inferior environmental stability, narrow effective absorption bandwidth, and weak absorption capacity. These disadvantages have severely limited their future applications, and absorbers with relatively strong absorption capacity at a wide band and low weight are in high demand at present. Therefore, researchers are continuing to find novel types of EM absorbers to cope with different EM radiations [4].

In addition, studies on EM absorbers are expensive and require a large number of experiments and a long time for each experiment [5,6]. Furthermore, the current optimization methods, such as artificial neural networks and genetic algorithms, have disadvantages including computer and complex mathematical calculations. Such methods optimize the reflectivity, thickness, and weight. Among these methods, the Taguchi optimization method was used as a tool for discovering less parameter space for probing the interaction and sensitivity of parameters, and as an experimental design method, it can suggest the optimal conditions [3]. In this manner, parameters were chosen according to the physical principle of optics that determined the reflection process from the surface (Section 2.1).

Recently, hybrid magnetic and dielectric composites have been used in microwave applications, because of their versatility and flexibility of properties to tune and couple with electric and magnetic fields. Conventional magnetic materials are limited to three types, namely, hexaferrites, spinel ferrites, and garnets, because of the corrosion problem. Among these materials, spinel ferrites as soft magnetic materials can make the absorbers broad bond in a wide frequency range (1–100 GHz) [7]. Various dielectric

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materials have also been studied, among which strontium titanate with perovskite structure has been rarely, although it has good dielectric properties [8,9].

Poly aniline (PANi) has been widely studied because of its environmental stability and controllable electrical conductivity [5]. In the current study, it was also chosen for these advantages.

In our previous [5,6] and parallel works to discover novel radar absorbing compositions, it was accidentally found that perovskite structures with spinel ferrites have a synergy to reduce the reflected power from a surface and attenuate radar waves. These advantages were achieved by simple mechanical mixing method, without the requirement of any complex mixing methods such as coupling, doping, or core-shell structures. In addition, these compositions can be prepared using low-cost conventional materials by simple synthesis and mixture methods. The ideal reflection loss (RL) value for an ideal microwave absorber is −20 dB at a wide frequency range. The conventional monolayer absorbers have an RL value less than −20 dB at a weak band width or an RL value more than −20 dB at a narrow band width by using the quarter wave model. To the best of our knowledge, these compositions have extra tendency to produce higher broadband absorption than every monolayer absorber, which are intrinsically comparable to the multilayer absorber over the X band range. In the current study, the radar absorption properties of $SrTiO_3$ (a cubic perovskite structure) compositions with some spinel ferrites are characterized in the X band frequencies.

2. Theoretical aspects

2.1. Physical principles

To minimize the reflection on an absorber surface, awareness of physical equations, which demonstrate the process of reflection, would be beneficial. In the RAM literature, three terms exist that lead to reflectivity minimization from the surface of the absorber. The first term explains the reflection coefficient on a surface (transmission line theory).

$$\Gamma = \frac{Z_M - Z_0}{Z_M + Z_0} \tag{1}$$

where, Γ and Z are the reflection coefficient and the impedance of propagating media, respectively. (Subscript 0 represents free space and M represents the incident medium for absorber). If Z_M equals Z_0, then Γ equals to zero. In other words, the impedance of material from a layer is matched to the incident media (first condition). The intrinsic impedance of the free space is given by

$$Z_0 = \frac{\mathbf{E}}{\mathbf{H}} = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 377 \text{ ohms} \tag{2}$$

where H and E are the magnetic and electric field vectors and μ_0 and ε_0 are the permeability and permittivity of the free space, respectively. If the incident medium is a free space, the absorbers with an impedance of 377 ohms will not backscatter microwaves. The impedance is calculated by the following formula:

$$Z_M = Z_0\sqrt{\frac{\mu^*}{\varepsilon^*}}\tanh\left(j\frac{2\pi t}{\lambda}\right)\sqrt{\mu^*\varepsilon^*} \tag{3}$$

where Z_M is the input impedance associated with the impedance of free space and $\varepsilon_r^* = \varepsilon' - i\varepsilon''/\varepsilon_0$ and $\mu_r^* = \mu' - i\mu''/\mu_0$. The prime and the double prime demonstrate the real and imaginary parts of complex permeability and permittivity of absorbers, respectively. λ and t are the wavelength and the thickness of the absorber.

Furthermore, perfect impedance matching can be realized, if the magnetic permeability and the electric permittivity are equal. This can be considered as the second term that leads to a minimization in the reflection coefficient. By using this term, Eq. (1) can be rewritten as follows:

$$\Gamma = \frac{\frac{Z_M}{Z_0} - 1}{\frac{Z_M}{Z_0} + 1} \tag{4}$$

In addition, the intrinsic impedance can be normalized as follows:

$$\frac{Z_M}{Z_0} = \sqrt{\frac{\mu_r^*}{\varepsilon_r^*}} \tag{5}$$

If free space is the same as the incident media and the reflectivity equals to zero, it can be confirmed that $\mu_r^* = \varepsilon_r^*$. This implies that if the imaginary and real parts of permeability and permittivity are equivalent, the reflection coefficient will be zero.

The third condition demonstrates the attenuation of EM waves when they propagate into an absorbing media. The wave power decays exponentially with the increase in the distance x, by a factor of $e^{-\alpha x}$. Here, α is the attenuation constant of the material and can be represented as follows:

$$\alpha = -\sqrt{\varepsilon_0\mu_0}\,\omega\left(a^2 + b^2\right)^{1/4}\sin\left(\frac{1}{2}\tan^{-1}\left(-\frac{a}{b}\right)\right) \tag{6}$$

where $a = (\varepsilon_r'\mu_r' - \varepsilon_r''\mu_r'')$ and $b = (\varepsilon_r'\mu_r'' - \varepsilon_r''\mu_r')$. To achieve high attenuation at smaller thickness, α and following it, $\varepsilon_r', \varepsilon_r'', \mu_r' and \mu_r''$must be larger. Third condition must be moderated with the first and second conditions. Where a high permeability and permittivity would lead to a higher reflection coefficient, the reflection coefficient can be expressed in decibels as follows:

$$RL(dB) = -20log \tag{7}$$

where RL is the reflection loss [3].

2.2. EM loss mechanisms

In radar frequency range, reflection reduction can be achieved by both absorption and cancellation mechanisms. During cancellation, destructive interference due to multiple reflections from various interfaces can annul the backscattered signals. Absorption is the process of transferring EM wave's energy into materials that have fundamental parameters. These parameters can be expressed by complex numbers. These materials can dissipate the incident wave's energy into heat. The EM loss mechanisms are based on the assigned permittivity and permeability for the materials. To express complex permeability and permittivity, their relative values (μ_r^* and ε_r^*) are used by normalizing them with free space amounts (μ_0 and ε_0). The complex symbolization of the relative permittivity and permeability is normally expressed as follows.

$$\varepsilon = \varepsilon' - j\varepsilon'' = \varepsilon_0(\varepsilon_r' - j\varepsilon_r'') \tag{8}$$

$$\mu = \mu' - j\mu'' = \mu_0(\mu_r' - j\mu_r'') \tag{9}$$

where the imaginary and real components are shown by double prime and single prime symbols, respectively, which represent the loss and energy storage parts, respectively. In microwave frequency, the molecules and ionic structures can absorb EM energy and then transfer it into heat energy, similar to ohmic loss in conductors. By transferring the wave energy into the material, dielectric and magnetic dipoles start to oscillate. The imaginary components, the loss values, of the permeability and permittivity or loss tangents are both determined in a similar way. The loss tangents can be expressed as follows:

$$\tan\ \delta_\varepsilon = \frac{\varepsilon''}{\varepsilon'} \tag{10}$$