Magnetic and dielectric properties of YIG/HDPE composites for high-frequency application

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A low loss high-frequency magnetic composite with $Y_3Fe_5O_{12}$ (YIG) ultrafine particles embedded in a high density polyethylene (HDPE) matrix was fabricated by using a simple low-temperature hot-pressing technique. The magnetic and dielectric properties of the as-prepared composites were investigated in details. The results indicate that as the volume of the ceramic fillers increase, the permittivity, permeability, dielectric and magnetic loss of the composite all increase. The cut-off frequencies of the composites are all above 700 MHz. Since the low resistivity of YIG, the dielectric losses of the composites are high and decrease with frequency in lower frequency range. Good frequency stability of the permittivities and permeabilities, and low dielectric and magnetic losses within the measurement range has been observed.

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1. Introduction

Ferrites find extensive applications in making useful devices like inductor cores, circulators, isolators, refrigerator door seals, EMI shields, storage media, etc. [1, 2]. Polycrystalline ceramic ferrite powders can be incorporated into various elastomer matrixes to produce polymer-based ferrite composites [3, 4]. Polymer-based composites with high permeability [5-7] have been proposed due to their flexibility, compatibility with printed wiring board (PWB), and advantage of mouldability into complex shapes, which is not easily possible by conventional ceramic magnets.

$Y_3Fe_5O_{12}$ (YIG), a ferromagnetic material known as microwave ferrite, has been widely applied in passive microwave devices, such as circulators, oscillators, and phase shifters, because it possesses controllable saturation magnetization, low dielectric loss tangent (tanδ) in microwave region, and small linewidth (ΔH) in ferromagnetic resonance [8, 9]. Compared to the dielectric loss, the cut-off frequency of YIG is low and the magnetic loss is high in microwave range. Incorporating YIG powder into polymer matrix can increase the cut-off frequency and lower the magnetic loss of YIG in microwave range.

In this paper, novel low loss high-frequency magnetic composites were achieved by introducing YIG fillers into a high density polyethylene (HDPE) matrix. The magnetic and dielectric properties of the composites were investigated in detail. Such magnetic composites, possessing very low loss, could be used in high-frequency communications for the inductor integrating devices such as electromagnetic interference filters and antennas.

2. Experimental

The HDPE (density: 0.95 g/cm^3, M_w:100000) powders were used as matrix. The YIG filler was fabricated by conventional oxide mixing method and ground into powders, with the grain size of about 500 nm. To make the powders possess an active surface, they were fully mixed with 2 % oleic acid solution. Then the surface modified ceramic powders and the HDPE powders were mixed together, following by a low-temperature hot-pressing at 180 ^{o}C for 5 min under the pressure of 10 MPa. The magnetic and dielectric measurements were carried out by a HP4291B impedance analyzer with a HP16454L magnetic material test fixture and a HP16453A dielectric material test fixture, respectively. The frequency ranges were 10 MHz ~ 1 GHz and 1 MHz ~ 1 GHz, respectively. The magnetic hysteresis loop of the composites were measured with a LDJ9600 type of VSM.

3. Results and discussion

Fig. 1 shows the magnetic hysteresis loops of the composites with the same matrix volume but different volume fractions of YIG. The saturated magnetization (Ms), remnant magnetization (Mr) and coercivity (H_C) were determined from the hysteresis loops, as shown in Table 1. As it can be seen in Table 1, the magnetic properties of the composites clearly depend on the ferrite loading. It can be found that the saturation magnetization (Ms) and remnant magnetization (Mr) increase with the increasing of YIG content, as expected, since these parameters depend on the total mass of the magnetic material. The reduction of the values may be caused by noncolinearity of the magnetic moments at the surface of the YIG particles, resulting in a decrease of the saturation magnetization for a lower YIG content [10]. The coercivity (H_C) nearly keeps constant as the variation of YIG content, which shows all the samples have very similar microstructure.

Table 1. Magnetic parameters of YIG/HDPE composites with different volume of YIG.

Sample	M_S	M_r	H_C
10%YIG/90%HDPE	8.5	0.2	40.5
20%YIG/80%HDPE	13.9	1.4	41.8
30%YIG/70%HDPE	18.1	1.9	42.2
40%YIG/60%HDPE	23.5	2.5	43.5

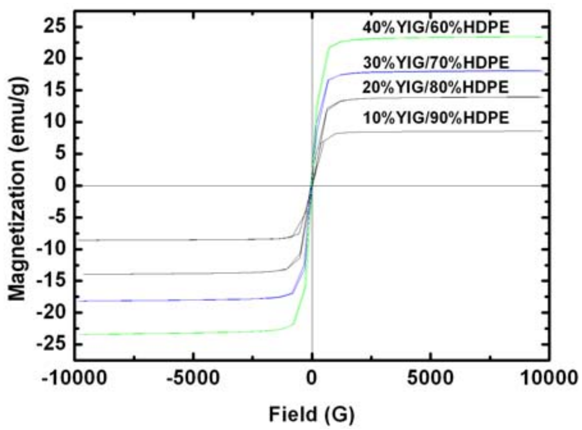

Fig. 1. Magnetic hysteresis loops of the composites with different volume fractions of YIG.

Fig. 2 shows the frequency dependence of the magnetic properties of the composites with different volume fractions of YIG. It can be seen that with the increasing of YIG the permeability and magnetic loss increase. According to Rikukawa [11], for either domain wall movement or spin rotation, the initial permeability is proportional to M_s^2. It is known that with the increasing of YIG content of the composites, M_s increases. With the increasing of frequency, the permeabilities of all the composites nearly keep constant and the magnetic losses show dispersion and increase slightly only in high frequency range. It is also found that the cut-off frequencies (i.e., the frequency where the μ' value reach half of the starting value) of the composites are all above 700 MHz. And it can be assumed that with the decreasing of YIG content, the cut-off frequency increases. According to Snoek's law [12], the product of the initial susceptibility and cut-off frequency is a constant for a ferromagnetic material, i.e., $(\mu_i-1)f_r=\gamma/(2\pi M_s)$, where f_r is the cut-off frequency, γ is the gyromagnetic ratio, M_s is the saturation magnetization and μ_i is the initial permeability. The decreasing of YIG content may cause the decrease of M_s. Accordingly, the increase of cut-off frequency can be expected. Additionally, the magnetic losses of the composites are all very low. This is probably due to the fact that the insulating matrix wrapps the YIG particles, which drastically increases the resistance and reduces the eddy-current loss of the composites.

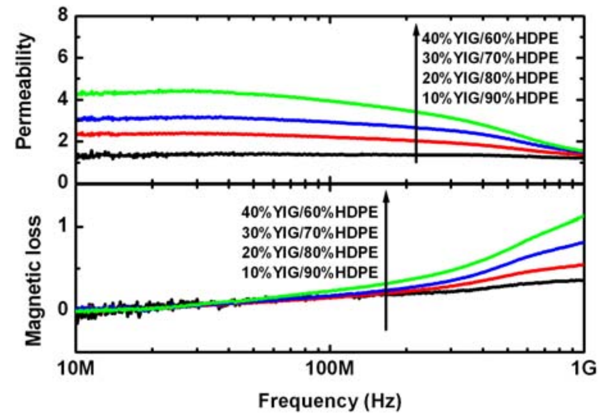

Fig. 2. Frequency dependence of the magnetic properties of the composite with different volume fractions of YIG.

Fig. 3 shows the comparison of magnetic properties for the bulk YIG ceramic and the 20%YIG/80%HDPE composite. It can be seen that the bulk YIG ceramic shows a resonance at about 20 MHz whereas the resonance frequency of the two-phase composite shifts to a much higher frequency beyond the HP4291B measurement range, which indicating that the two-phase composite possesses an advantage of much wider working frequency range.

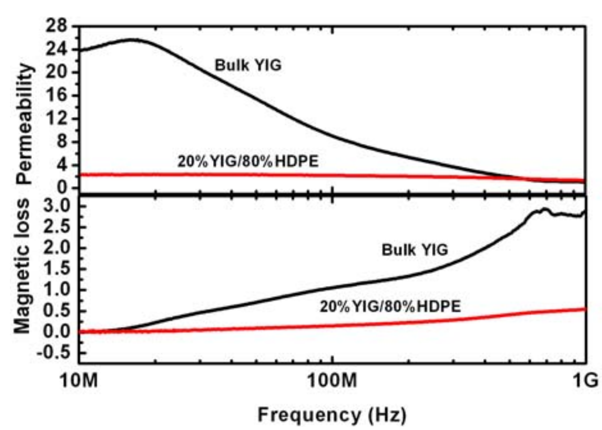

Fig. 3. Frequency dependence of the magnetic properties of the 0.4YIG/0.6HDPE composite and the bulk YIG.

Fig. 4 shows the dielectric properties of the composites with different volume fractions of YIG.

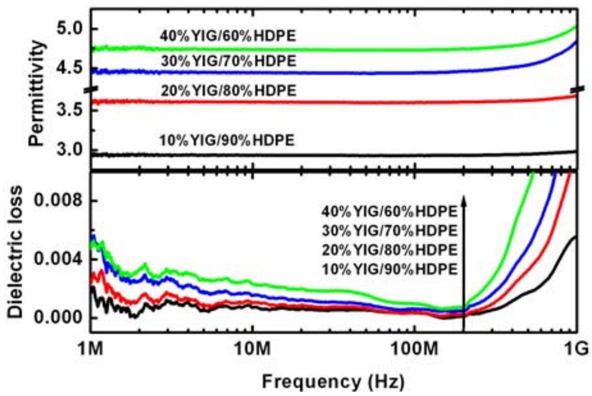

Fig. 4. Frequency dependence of the dielectric properties of the composite with different volume fractions of YIG.

It can be easily found that the permittivities and the dielectric losses increase with the increasing of YIG content, since the permittivity and dielectric loss of YIG are both higher than those of HDPE matrix. The dielectric losses of all the composites are very low in the high frequency range. The permittivities of all the composites nearly keep constant within the measurement frequency range. It also can be found that the dielectric losses of the composites are relatively high in the low frequency range. The dielectric losses decrease first and then increase with the increasing of frequency. This is attributed to the low resistivity of YIG and can be explained by the following formula [13]. When an alternating electric field is applied, not only polarization loss but also leakage loss generates. The dielectric loss is divided into two parts.

$$D = D_P + D_G = \frac{(\varepsilon_S - \varepsilon_\infty)\omega\tau}{\varepsilon_S + \varepsilon_\infty \omega^2 \tau^2} + \frac{\gamma}{\omega\varepsilon_0}\left(\frac{1}{\varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1+\omega^2\tau^2}}\right) \tag{1}$$

where D is the total dielectric loss tangent, D_P is the polarization loss tangent, D_G is the leakage loss tangent, γ is conductivity and τ is relaxation time. It can be deduced that at a certain temperature when frequency (ω) go to 0, i.e., static electric field, D_P go to 0. In such a case, the dielectric loss is almost attributed to the leakage loss. Thus when the frequency is very low, $\omega \cdot \tau << 1$, the dielectric loss can be described approximately as below.

$$D \cong \frac{\gamma}{\omega\varepsilon_0\varepsilon_S} \tag{2}$$

Hence the dielectric loss is inversely proportional to frequency in the low frequency range. As the frequency increasing, the D_P gradually increases and becomes predominant while the D_G decreases. In the higher frequency range towards the end of the measurement range of HP 4291B, a resonant peak would occur due to the LC resonance in the measurement circuit which caused the increasing of the measured dielectric loss.

4. Conclusions

YIG/HDPE magnetic composites with various volume fractions of ceramic fillers were prepared by using a simple low-temperature hot-pressing technique. With the increase of the volume of YIG, the permittivity, permeability, dielectric and magnetic loss of the composite all increase. The cut-off frequencies of the composites are all above 700 MHz. The permittivities and permeabilities of all the composites have shown good frequency stability and low dielectric and magnetic losses within the measurement range. Such magnetic composites are candidates for the capacitor-inductor integrating devices such as electromagnetic interference filters in RF communications.

Acknowledgements

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