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The Response of a Magnetic Fluid to Radio Frequency Electromagnetic Field

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Electromagnetic pollution generated by the electrical devices has been regarded as a new form of pollution, harmful to the society as air and water pollution. The operation of electronic devices in a polluted electromagnetic environment has caused electromagnetic interference to become important concerns. Devices that are vulnerable to interference must often be shielded to protect them from the effects of electromagnetic interference. In this work we describe an interaction of a magnetic fluid based on transformer oil with alternating magnetic field. The magnetic fluid was composed of a transformer oil and dispersed magnetite nanoparticles coated with oleic acid. Among the wide range of topics covered, we pay attention to an important field related to the absorption of electromagnetic field by magnetic fluid as a suitable candidate for applications where it is necessary to electrically isolate, remove excess of heat, and to shield electromagnetic fields. We present a method for the determination of shielding effectiveness of the magnetic fluid under high-frequency excitation conditions from 750 MHz to 3 GHz by means of magnetic near field measurements and analysis. Herein, we report the effect of magnetic volume fraction in the magnetic fluid and the effect of the sample thickness on the shielding effectiveness. We have found that the magnetic fluid has a frequency dependent "windows", characterized that either absorb the magnetic field, or facilitate penetration of the magnetic field through the barrier.

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1. Introduction

Production and extended use of electronic devices in the world results in the generation of an electromagnetic interference (EMI) and radio frequency interference (RFI), also called electromagnetic (EM) pollution. Most EMI is caused by frequencies falling between 1 kHz and 10 GHz. The EMI could disturb or jam sensitive components, destroy electric circuits, and prompt explosions and accidents. The increased number of EMI sources is closely related to the increased number of communication instruments and rapid development of commercial, military and scientific electronic devices [1–3].

The sources of EMI and RFI act on living organisms too. At frequencies from 10 MHz to 300 GHz, heating is the major effect of absorption of EM energy. Temperature rises of more than 1-2 °C can have adverse health effects [3–5]. The mentioned facts result in increased interest in the development of materials having good shielding characteristics [6].

2. Theoretical background

Attenuation is one of the main indicators for measuring the effectiveness of EMI shielding. The determination of the level of attenuation for an EMI shield can be complex, and the methods used to obtain the results often differ depending on the particular shielding application. Some of the common techniques for testing SE include [7, 8]:

- open field test,
- shielded room test,
- coaxial transmission line test,
- shielded box test.

There are experimental techniques in which the dielectric permittivity and magnetic permeability are firstly measured to determine the reflection coefficient R and the transmission coefficient T [9–11]. The common definitions of the electric SE_e and magnetic SE_m shielding effectiveness at an arbitrary point P within the shielded domain are given by

$$SE_e = 20\log\left(\frac{\boldsymbol{E}_{us}}{\boldsymbol{E}_s}\right), \quad SE_m = 20\log\left(\frac{\boldsymbol{H}_{us}}{\boldsymbol{H}_s}\right), \quad (1)$$

respectively. In Eq. (1) the numerators represent the amplitudes of the time-harmonic electric (magnetic) field intensities, measured at P in the absence of the shield, while the denominators contain their values in the shielded case at the same locations. When the meter readings V_{us} and V_s are, respectively, proportional to E_{us} and E_s (H_{us} and H_s), a more convenient form for Eq. (1) is

$$SE_e = 20\log\left(\frac{V_{us}}{V_s}\right), \quad SE_m = 20\log\left(\frac{V_{us}}{V_s}\right), \quad (2)$$

and the SE_e in (2) can be expressed in decibel scale as

$$SE_{e[\mathrm{dB}]} = V_{us[\mathrm{dB}]} - V_{s[\mathrm{dB}]}. \quad (3)$$

Similarly, the SE can be calculated by measuring of the

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magnetic field. SE can be broken into the product of three terms: reflection loss R, absorption loss A and multi-reflection M as follows:

$$SE_{[\mathrm{dB}]} = R_{[\mathrm{dB}]} + A_{[\mathrm{dB}]} + M_{[\mathrm{dB}]}. \qquad (4)$$

When discussing SE it is necessary to consider two radiation zones: the near field and the far field zones. The distinction between them lies in the distance from the source of EMI. If the distance from the source to shielding is less than $\frac{1}{6}$ of the free path wavelength of the EMI to be shielded, the radiation is described as a near field zone. Above this zone it is in the far field zone.

3. Materials and methods

The investigated magnetic fluid (MF) consists of the magnetite nanoparticles dispersed in the inhibited mineral oil (Mogul Trafo CZ-A, PARAMO). The saturation magnetization of the originally prepared ferrofluid sample obtained by a superconducting quantum interference device magnetometer is 23.15 $\mathrm{A\,m^2\,kg^{-1}}$, and the estimated dc magnetic susceptibility is 0.75. Dynamic light scattering measurements yielded the average hydrodynamic particle diameter of 33.28 nm. Three samples of the MF with volume fraction equal to 0.5%, 1.5% and 6.6% were prepared for the experiment [12].

To study the MF response to radio frequency EM field, we used two calibrated broadband (30 MHz to 1 GHz) magnetic antennas (Agilent 11940A close-field probe) arranged in one line at a distance of 3.3 mm, which is much smaller than the limit of the near field zone at a frequency of 3 GHz, and mutually oriented towards each other. The manufacturer declares that the antenna works well above 1 GHz. The measurement was carried out in the absence of an external static magnetic field. At the beginning of the experiment the response of the measurement setup without the sample was measured in the frequency range from 750 MHz to 3 GHz. Subsequently, the analyzed sample was placed between the antennas and the signal level was measured again. The measured response of the holder without the sample was subtracted from the measured response of the holder with the sample for each thickness. As a sample holder, we used a small Petri dish. The thickness of the test sample was 0.5, 1, and 1.5 mm, respectively.

All measurements were performed in the near field zone, wherein the magnetic field component was predominant, at room temperature. The transmitting antenna was supplied with a source of harmonic voltage Agilent N5183A. The received signal level was measured by using the spectrum analyzer R&S FSH8 with frequency range from 100 kHz to 8 GHz. Microclimate conditions during the measurements were as follows: ambient temperature from (23 ± 1) °C and relative air humidity (34 ± 3)%.

4. Results and discussion

As described above, the signal level was measured in dBμV at the terminal of the receiving antenna for various concentrations and thicknesses of the sample. By using Eq. (3) such measurements allow to calculate the frequency dependence of the SE within the range studied.

The calculated SE in the frequency range from 750 MHz to 1 GHz for the MF with concentration of 1.5% is shown in Fig. 1. As can be seen, the SE is approximately linearly dependent on the thickness of the measured sample. A negative value of SE for certain frequencies indicates that the magnetic component of the EM field "penetrates" through the shield. This phenomenon may be due to multiple reflection component $M_{[\mathrm{dB}]}$ due to the large skin depth.

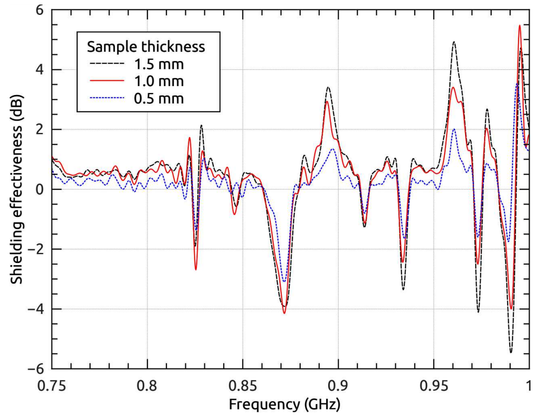

Fig. 1. The SE of the MF from 750 MHz to 1 GHz.

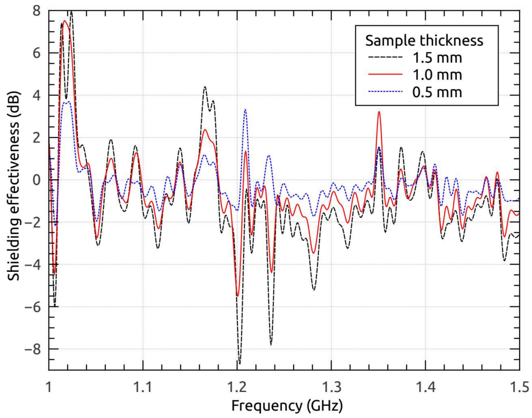

Fig. 2. The SE of the MF from 1 GHz to 1.5 GHz.

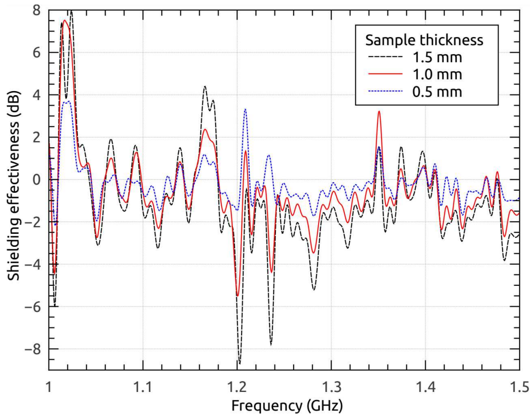

Fig. 3. The SE of the MF from 1.5 GHz to 2 GHz.

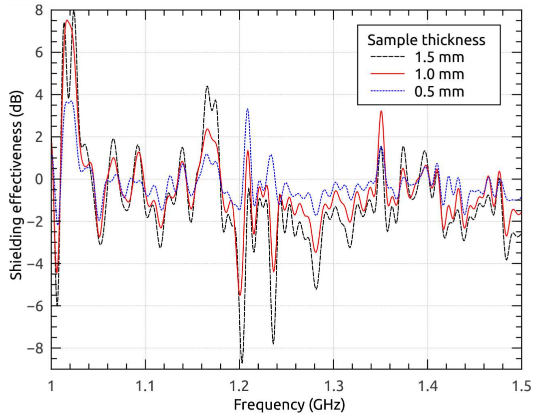

Fig. 4. The SE of the MF from 2 GHz to 3 GHz.

The maximum SE 7.98 dB at a frequency of 1.024 GHz and the minimum SE –8.7 dB at a frequency of 1.2 GHz can be seen in Fig. 2. The dependence of the SE on the thickness of the MF is evident in Fig. 3 with predominant negative value of the SE. Finally, SE for the frequency range from 2 GHz to 3 GHz with predominant negative values is presented in Fig. 4. By comparing the SE for the other concentrations of the MF (0.5% and 6.6%) it was found, that in the frequency range from 750 MHz to 3 GHz the SE decreases with increasing concentration. Negative SE has coherent frequency window from 1.48 GHz to 2.2 GHz.

5. Conclusions

Measurements of the shielding effectiveness of the MF based on transformer oil with the alternating magnetic field were performed. The results obtained by measuring the shielding effectiveness in the near field pointed to almost linear dependence on the thickness of the sample in the frequency range from 750 MHz to 3 GHz. Moreover, it was found that the shielding effectiveness of the magnetic fluid decreases with increasing concentration. We suppose that this phenomenon is caused by multiple reflection component $M_{[\mathrm{dB}]}$. Since the measurement was carried out in the absence of an external static magnetic field, we did not consider the ferromagnetic resonance.

Acknowledgments

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