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Microwave properties of ferromagnetic composites and metamaterials

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Abstract

In this paper, we present our work on ferromagnetic composites for microwave applications [Lebourgeois, R., *et al.*, New ferromagnetic composites for radio-frequency applications. *J. Magn. Magn. Mater.*, 2003, **254–255**, 608–611; Adenot, A.L., *et al.*, Tuneable microstrip device controlled by a weak magnetic field using ferromagnetic laminations. *J. Appl. Phys.*, 2000, **87**(8), 6914–6916]. The metallic character of ferromagnetic materials led us to use them as inclusions in a composite. We worked on three topologies of composites: laminate, wire and sphere composites. We show the microwave permeability measured on samples representative of these topologies, elaborated from ferromagnetic thin films, glass coated microwires, and polyol powder. Then, we focus on metamaterials, which is a new approach in the field of electromagnetic materials. We illustrated the striking properties of these composites on wire and laminate composite samples. The metamaterial approach is a very efficient tool to control the resonance frequency of the composite material.

Keywords: Composites; Nanocomposites; Magnetic properties; Metamaterials; Soft magnets

1. Introduction

The very high induction saturation of ferromagnetic materials (up to 2.15 T for iron) makes them attractive for a wide range of applications.[1,2] However, their high electrical conductivity (metallic behavior) prevents them to be used in a bulk form. The higher the frequency, the thinner must be the ferromagnetic foil in order to allows penetration of the electromagnetic wave. At GHz frequencies, the penetration depth is about 1 μm. As a consequence we used a composite approach by mixing ferromagnetic materials with a micrometer sized characteristic length and the insulating properties of polymers. We worked on three topologies: the laminate composite, the wire composite, and the sphere composite.[3–5] The microwave permeability and permittivity of these composites are related to the properties of the constituents by homogenization laws.[3,6]

The design of composite materials with original microwave behavior has been enriched recently by the metamaterial approach. Metamaterials are a large class of artificial materials which includes the left-handed materials or negative index materials.[7–9] In all these materials, the electromagnetic properties are obtained through the patterning of metallic material. They are aimed at finding applications like "superlens" (lens without diffraction) in the extremely high frequency range (optics).[10] In this approach, magnetic properties are generally obtained using conducting materials conformed into inductive patterns (loops, split rings,). However, they do not possess a significant level of microwave permeability out of the vicinity of the resonance, on the contrary to classical magnetic materials. To amplify the inductive behavior of the pattern without narrowing the width of the resonance peak, it is then necessary to use magnetic materials. In our applications the inductive pattern is a copper helix with a varying number of loops wound around a core of a ferromagnetic composite material. We applied it in the case of the laminate and the wire composite.

2. Composite approach on ferromagnetic materials

2.1. The laminate composite

This basic topology is sketched in Fig. 1. Because of a strongly anisotropic topology, the composite is very efficient only in one polarization of the incident electromagnetic wave. The ferromagnetic layers consist in amorphous ferromagnetic thin films deposited by magnetron sputtering on flexible polymer substrate (insulating layer). The thin films are characterized by Bs = 0.5 T, and an uniaxial anisotropy field Ha = 2000 A/m.

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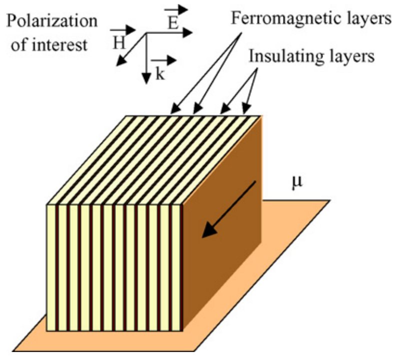

Fig. 1. Sketch of the laminate composite with his polarization of interest: direction of the permeability μ is perpendicular to the direction of the magnetization (in-plane uniaxial anisotropy).

The thin films are stacked and glued together to make the composite. In measurement purpose, the flexible thin film is wound with glue into a torus.[3] The sample is then suitable for measurement in a APC7 coaxial line setup from 50 MHz to 18 GHz. A network analyzer HP8720 has been used to measure the reflection/transmission on/through the sample. The effective permittivity and permeability μ_{eff} of the sample are determined from this measurement and the intrinsic permeability μ_{int} can be retrieved through inversion of the following mixing law:

$$\mu_{\mathrm{eff}} = q\mu_{\mathrm{int}} + 1 - q$$

where q is the ferromagnetic volume fraction.

In Fig. 2 is presented the microwave permeability of laminate composite using a 1 μm thick CoFeSiB thin film deposited on a 23 μm PET substrate (ferromagnetic volume fraction 7%). The permeability has been set into arbitrary units.

2.2. The wire composite

The wire composite is sketched in Fig. 3. Here we used the original magnetic properties of CoFeSiB amorphous glass coated microwires produced by the Taylor Ulitovsky technique. A high level of stresses in the microwire arises from the difference between the dilatation coefficient of the glass and of the metal. The magnetostriction coefficient through the magneto elastic coupling allows the engineering of the magnetic properties. When the magnetostriction coefficient of the amorphous alloy is negative, the bamboo-type domain structure results in high microwave permeability parallel to the axis of the microwire.[11] A wire composite consists in an assembly of many parallel microwires maintained together with glue. We performed APC7 coaxial line measurements on toroidal sample of microwire wound with glue.[5]

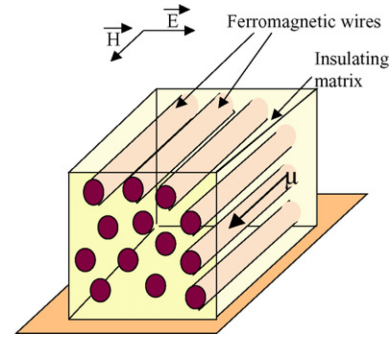

Fig. 3. Sketch of a wires composite in the polarization of interest: direction of the permeability μ is locally perpendicular to the direction of the magnetization (circumferential anisotropy in negative magnetostriction glass coated microwires).

A 4 μm metallic core diameter and 8 μm total wire diameter (including the glass cover) wire was used to elaborate such wire composite. Fig. 4 shows the microwave permeability of such a composite with 7% ferromagnetic volume fraction.

2.3. The sphere composite

The sphere composite consists in a dispersion of a ferromagnetic powder into an insulating matrix. The powder are constituted by spherical particles with a size ranging from a few nanometers to several micrometers and a narrow size distribution (with a standard deviation lower than 10% of the mean diameter).[4] The particles are elaborated through the polyol process in the Co_xNi_{100-x} and $Fe_z[Co_xNi_{100-x}]_{(1-z)}$ systems. The imaginary part of the dynamic permeability of these particles dispersed in an insulating matrix (or coated by a manganese dioxide layer and compressed) exhibits several behaviors according to the size range[12–14] (Fig. 5). In the micrometer size range, the permeability presents a broad and damped peak. On the contrary, in the submicrometer size range, the permeability exhibits an original behavior with the occurrence of several narrow peaks. The resonance frequencies of these peaks are shifted

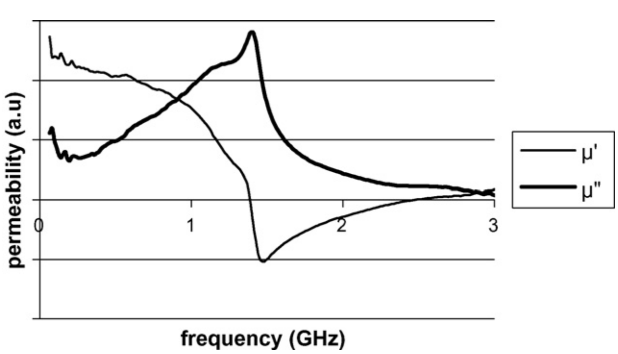

Fig. 2. Microwave permeability of a laminate composite with ferromagnetic volume fraction of 7%.

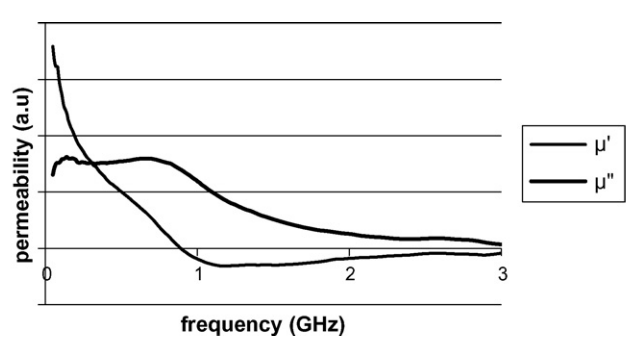

Fig. 4. Microwave permeability of a wire composite with 7% ferromagnetic volume fraction.

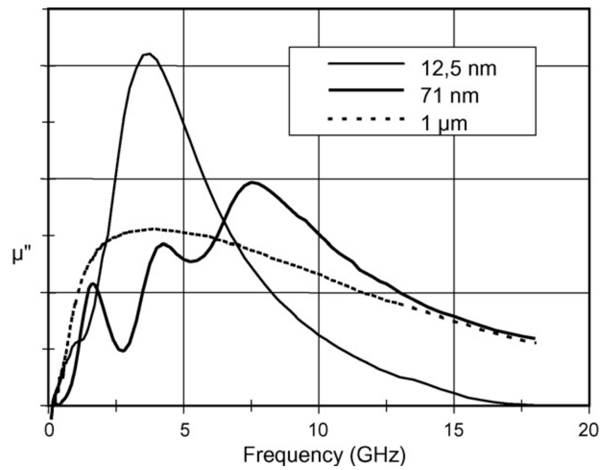

Fig. 5. Microwave permeability of spherical particles in the nanometer, submicrometer and micrometer size ranges.

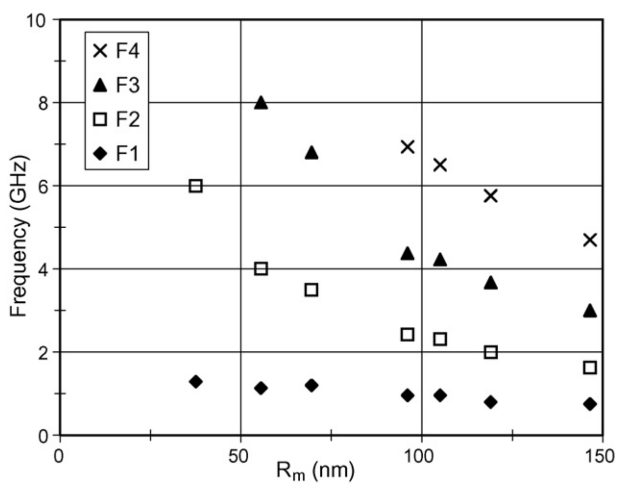

Fig. 6. Resonance frequencies f1 to f4 (f1 is the fundamental mode) vs. mean radius of submicrometer sized $Co_{50}Ni_{50}$ particles for sphere made composites.

to the high frequencies when the particles size decreases (Fig. 6). The original behavior was explained from the calculations of the exchange resonance modes by Aharoni[15] and through numerical treatments by Levy.[16] For the finest sizes, only one peak remains whose resonance frequency is constant and this mode corresponds to the fundamental one.

3. Metamaterial approach

3.1. Experimental details

We apply the metamaterial approach on the laminate and the wire composite previously described and corresponding to Figs. 2 and 4. Measurements of the microwire permeability are performed on 2 mm thick toroidal samples in a 40 mm external diameter coaxial line from 50 MHz to 3 GHz. Corrected measurements for the reduction of the sample size are detailed in Ref. [17] The samples are composed of periodically spaced metamaterial blocks so that the sample complies with the symmetry and the field configuration of the measurement setup (details in Fig. 7). The inductive pattern is a copper helix (50 μm diameter of the copper wire) round on the composite core. The external shape of the metamaterials blocks induces a strong demagnetizing field. However, the coupling effect between the blocks tends to reduce this effect. The effective demagnetizing field has to be taken into account. In this purpose, we compared measurements on continuous and periodic samples and deduced the effective demagnetizing field fitting the spectra by a gyromagnetism model.

A complex theoretical model has been developed to describe the microwave permeability $\mu_{xx} = 1 + \chi_{xx}$ of the metamaterial and is to be published. We performed a parametric study of χ_{xx} and obtained the following simple result: $F_r \propto 1/\sqrt{LC}$, where F_r is the resonance frequency. L and C are characteristics parameters of the electromagnetic behavior of the helix copper, which has been described as a solenoid in a very rough approach.

4. Results

In Fig. 8 are reported the measured imaginary part of the intrinsic permeability of the metamaterial of wire samples with varying numbers of loops from 4 to 16. The figure included also the measured permeability of the sample “no loops” (i.e. the peri-

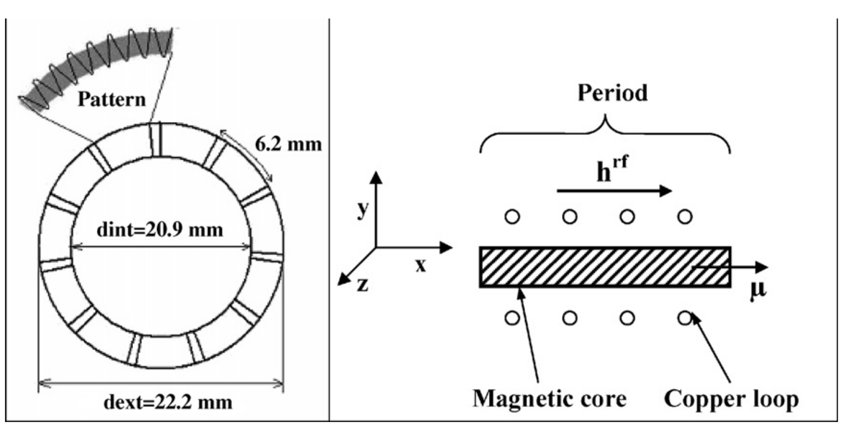

Fig. 7. Schematic view of a sample with 11 patterns and configuration of fields during measurement of sample: direction of the permeability for wire or laminate composite magnetic core is sketched.

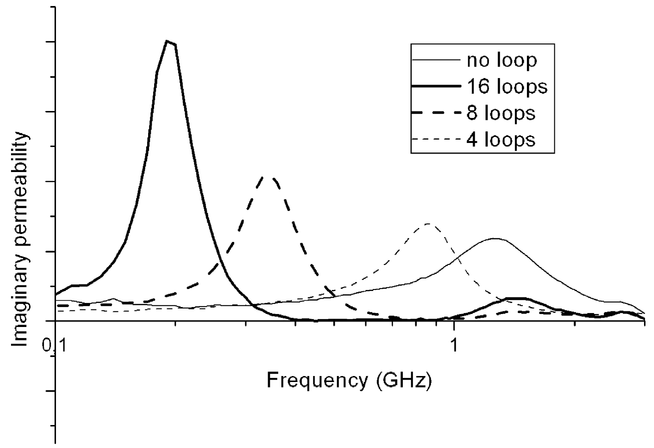

Fig. 8. Measured imaginary permeability of metamaterials vs. frequency for wire samples with different number of loops from 0 (no helices = magnetic composite alone) to 16 turn helices.

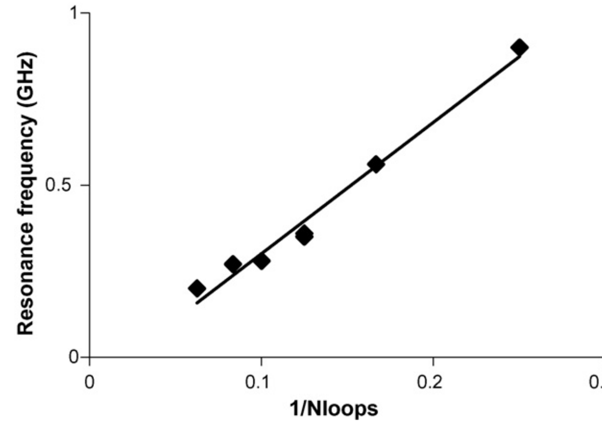

Fig. 10. Resonance frequency vs. 1/Nloops for both laminate and wire composite metamaterial samples.

odic magnetic core) for which we have $F_r = 1.3$ GHz. It differs from the continuous sample of Fig. 4 (F_r close to 1 GHz) because of the different shape of the samples, introducing demagnetizing effects. When the numbers of loops is varied from 4 to 16, the resonance frequency takes the following value: for 16 loops we obtain $F_r = 0.2$ GHz; 8 loops give $F_r = 0.35$ GHz and for the ones with 4 loops, it yields $F_r = 0.85$ GHz. This establishes clearly the critical role of the coiling on the resonance frequency. A second peak in the 4, 8, 16 loops samples is observed close to 1.3 GHz, which could be attributed to a residual response of the magnetic core alone.

In Fig. 9 is shown the real and imaginary permeability of the laminate composite with 12 loops of copper wire. Whereas in Fig. 2 the resonance frequency is of 1.5 GHz, it is only of 0.3 GHz on the metamaterial.

To go further in our study of the resonance frequency, we plotted in Fig. 10 the resonance frequency of both wire and laminate type of metamaterial samples versus the number of loops. It is noticeable that a very good linear interpolation is found. If we consider the relation between F_r and LC previously written this means that both L and C varies proportionally with Nloops. That confirms the solenoid approach of the coiling which exhibits that the inductance of a solenoid is proportional to Nloops and the capacitance is mainly due to an inter-loop contribution too.

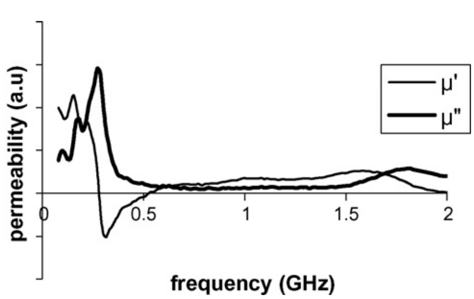

Fig. 9. Measured permeability of the metamaterial laminate composite with 12 loops of Cu wire, ferromagnetic volume fraction of 7%.

5. Conclusion

We first illustrated our approach on the dynamic permeability of ferromagnetic laminate, wire and sphere composites. We then presented our work on inductive metamaterials and demonstrated their great influence on the microwave permeability resonance frequency. We are going to perform the same kind of study on the level of maximum imaginary permeability, which may display the same kind of simple and strong dependence on the number of loop of the inductive pattern. Moreover, it should be very interesting to compare these results with an other type of magnetic material (ferrites, etc.) in the same conditions.

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