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Self-biased cobalt ferrite nanocomposites for microwave applications

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ABSTRACT

Oriented $CoFe_2O_4$ nanoparticles, dispersed in polymethyl methacrylate (PMMA) matrix, were fabricated by magnetophoretic deposition of functionalized nanocolloidal cobalt ferrite particles into porous alumina membrane. Their magnetic behavior exhibits an out-of-plane easy axis with a large remanent magnetization and coercitivity. This orientation allows high effective internal magnetic anisotropy that contributes to the permanent bias along the wire axis. The microwave studies reveal a ferromagnetic resonance at 46.5 and 49.5 GHz, depending on the filling ratio of the membrane. Ansoft High Frequency Structure Simulator (Ansoft HFSS) simulations are in good agreement with experimental results. Such nanocomposite is presented as one of the promising candidates for microwave devices (circulators, isolators, noise suppressors etc.).

1. Introduction

Recently, nanocomposites based on magnetic nanostructures embedded into Anodic Aluminum Oxide (AAO) membrane are becoming increasingly important for developing circulators [1] magnetic photonic band gap materials [2], isolators [3] and noise suppressors [4]. For example, most circulators use the non-reciprocal properties of ferrite materials for obtaining the circulation effect [5]. Their technological applications concern essentially wireless communications as mobile phone systems, satellite links, radar duplexers and military applications [6]. However, the main disadvantages of conventional circulators, widely used in microwave devices, are that the ferrite needs to be biased by an external dc magnetic field to show a ferromagnetic resonance, as well as the geometry of bulk ferrite, difficult to integrate on future miniature planar circulators. Thus, in order to work in high-frequencies (>40 GHz) and reduce the circulators size by removing the permanent magnet needed for biasing the ferrite crystal, many research works were done to fabricate unbiased microwave circulators using hexaferrite [7,8] or ferromagnetic nanowires [9]. These features present an interesting alternative way to bulky ferrite materials. Indeed, by using a self-biased ferrite nanocomposite based on ferrite inclusions (nanoparticles) in dielectric host matrix, one can control the key physical parameters determining the performances of circulators, namely, anisotropy coefficient K, damping parameter α, saturation magnetization M_s and particle shape [10]. Another important fact is that the choice of dielectric matrix with low dielectric losses is necessary for reduction of the insertion losses (PMMA [11] and AAO [12] for example).

In this paper, we report an original approach that combines the highest saturation magnetization and magneto-crystalline anisotropy of preformed functionalized $CoFe_2O_4$ nanoparticles [13,14] and the high-aspect ratio nanostructure offered by AAO template. We focus on the investigation of morphological, magnetic and microwave properties of oriented $CoFe_2O_4$ nanoparticles prepared by magnetophoretic deposition of cobalt ferrite nanoparticles into porous alumina template using Scanning Electron Microscope (SEM), Superconducting Quantum Interference Device (SQUID) magnetometer and Vector Network Analyzer (VNA), respectively.

2. Experimental details

2.1. Synthesis of nanocolloidal CoFe2O4 nanoparticles

Ferrofluid based on cobalt ferrite nanoparticles was prepared by dispersion of cobalt ferrite nanoparticles in toluene solution. First, nanoparticles with a spherical shape, an average diameter ranging from 18 to 20 nm and a spinel crystal structure (Fig. 1), were synthesized by an alkaline coprecipitation of cobalt hydroxide and iron hydroxide followed by an hydrothermal decomposition treatment (200 °C, 24 h) [15]. The precipitate obtained was isolated and dispersed in an aqueous solution of nitric acid. BNE surface agent was then added. At the end of this process, the

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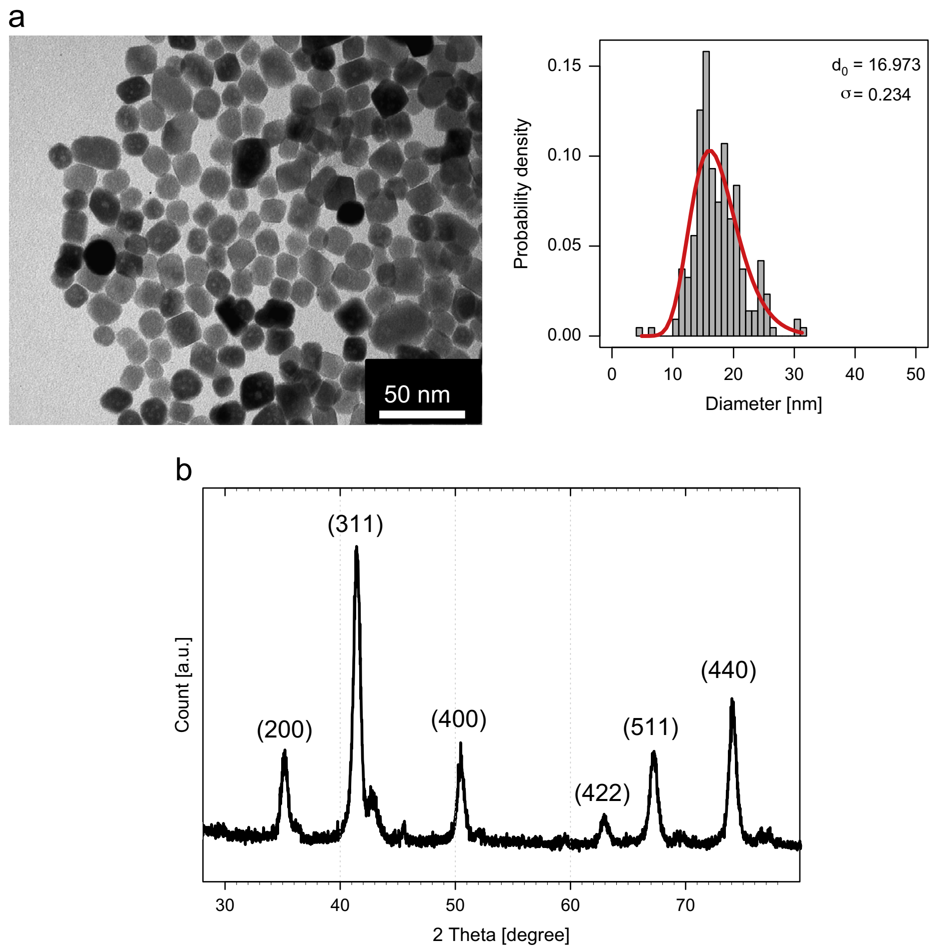

Fig. 1. (a) TEM image and corresponding histogram and (b) XRD pattern of $CoFe_2O_4$ nanoparticles prepared by the hydrothermal process.

precipitate was dispersed in toluene, producing a stable colloidal dispersion of nanoparticles with magnetic concentraion of 1%. Next, the nanocomposite suspension was obtained by dissolving a 0.01 g of PMMA in 10 ml of cobalt ferrite ferrofluid under vigorous stirring. Thus, the deposition of this nanocolloidal suspension on a substrate under an external magnetic field can allow an oriented ferrite cobalt nanoparticles tightly fixed by PMMA after evacuating of toluene at room temperature and solidification of PMMA. In these conditions, the volume fraction of cobalt ferrite nanoparticles is estimated at around 90%.

2.2. Fabrication of coplanar waveguide (CPW) transmission lines

The template used for fabricating the device is a porous commercial anodic aluminum oxide (AAO) membrane, which has porosity (*P*) of 50% and an array of holes with a size of 60 μm in length and 200 nm in diameter (Whatman Anodisc). Prior to cobalt ferrite nanoparticles deposition, the 72 μm coplanar waveguide (CPW) transmission lines (72 μm and 40 μm are the width of the central signal line and the gap between the central line and the ground one, respectively) were fabricated on top of the alumina template. A thick layer of Cu ≈ 5 μm was deposited by radio frequency cathodic sputtering. Cleanroom photolithography and etching techniques were used to define CPW line structure. The lines were designed for a 50 Ω characteristic impedance.

2.3. Magnetophoretic deposition into AAO template

It is well known that in the case of colloidal magnetic nanoparticles, particle alignment and chaining phenomenon, occurred by interaction of the dipole moment, can be induced by the application of a homogeneous magnetic field, allowing a high anisotropic structure [16,17]. On the other hand, with an inhomogeneous field, the gradient can be used to control the transport of magnetic nanoparticles. This phenomenon, called magnetophoresis [18,19], is used, for example, in separation technology [20] as well as in biomedical applications [21–23]. Indeed, by using an inhomogeneous magnetic field, we can align the magnetic nanoparticles and control their movement to regions of higher flux density. This phenomenon is called magnetophoresis. In the case of naocolloidal particles, the force induced by a magnetic field gradient in the *z*-direction is given by:

$$F_z = \frac{\pi M_s d^3 \mu_0}{6} \frac{\delta H}{\delta z} \quad (1)$$

where d is the particle diameter, M_s is the bulk saturation magnetization of particle material, μ_0 is the permeability of vacuum and $\delta H/\delta z$ is the gradient magnetic field.

Experimentally, we have used NdFeB circular permanent magnet. The magnetic field, created in the *z*-direction, is characterized by a maximum intensity of 0.5 T at the center of the pole faces. This value varies as the distance from the pole. In the near of the center of the two poles, the gradient magnetic field is ≈ 80 mT/mm. For magnetophoretic deposition, the AAO template with CPW lines is placed in the center of the north pole face of the permanent magnet, then droplets of the magnetic nanofluid were deposited onto AAO surface. Consequently, the gradient magnetic field drive the cobalt ferrite nanoparticles toward interface AAO/permanent magnet where they are collected, leading the filling of the AAO membrane. Thus, by evacuating toluene and solidification