



Frequency and field dependent dynamic properties of $\text{CoFe}_{2-x}\text{Al}_x\text{O}_4$ ferrite nanoparticles



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ABSTRACT

Aluminum doped $\text{CoFe}_{2-x}\text{Al}_x\text{O}_4$ ($0 \leq x \leq 0.9$) nanoparticles were synthesized via auto-combustion. Formation of single phase cubic spinel structure was confirmed by X-ray diffraction (XRD) analysis. XRD analysis suggests a linear decrease in lattice cell parameters and grain size (90–55 nm) with the increase in Al^{3+} content. The saturation magnetization of samples decrease with increasing Al^{3+} content due to magnetic dilution effect. A concomitant linear reduction in coercivity was also observed mainly due to decrease in magnetic anisotropy. Frequency and field dependent dynamic properties of nanoparticles were studied by ferromagnetic resonance (FMR) technique. The resonance frequency increases linearly with magnetic field for all nanoparticles. Magnetic field dependent experimental absorption data (S_{21} vs. frequency) were compared with effective medium theory considering an effective demagnetization field and was observed to be in good agreement with each other. High Al^{3+} content reduces the Gilbert damping parameter thus making $\text{CoFe}_{2-x}\text{Al}_x\text{O}_4$ as an attractive material for high frequency applications.

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1. Introduction

Among family of ferrites, Cobalt ferrite (CoFe_2O_4), an inverse spinel, is industrially promising material due to its strong magnetic anisotropy, high coercivity (5.40 kOe) at room temperature, moderate saturation magnetization (80 emu/g) and good mechanical hardness and chemical stabilities [1–4]. As per the application, additional changes in magnetic and electrical properties of spinel ferrite is achieved by doping magnetic and non-magnetic atoms. Depending upon the valence, the substitution ion distribute on tetrahedral (A) and/or octahedral (B) sites which eventually affects ferrite physical properties [5–9]. Among various ions substitution, Al^{3+} substitution decreases magnetic hardness while increases electrical resistivity which finds application in power transformers and telecommunication applications [10,11].

Ferrites are the choice of material for microwave applications such as circulators, isolators, phase shifters, absorbers, etc. During the last decade magnetic properties, especially dynamical

properties of magnetic materials have attracted a lot of attention due to their application in the development of new devices for spintronics. The miniaturization and fast time scale applications of these devices are a new topic of research. A distinctive property of such devices is the magnetization relaxation rate characterizing the time scale on which a system being deviated from the equilibrium returns to it, or how fast the device can be switched from one state to another. Magnetic relaxation, a time dependent phenomenon, is an approach of a magnetic system to an equilibrium or steady-state condition as the magnetic field is changed. The properties of ferromagnetic and antiferromagnetic materials in high-frequency electromagnetic fields depend substantially on magnetic relaxation. Magnetic relaxation plays a role in the processes of magnetization and determines the width of magnetic ferromagnetic resonance lines. The study of magnetic relaxation is important as it affects number of technologies, including computer, microwave, to medical applications. Ultimately, the physical limitation of any technology which incorporates magnetic materials calls for the precise knowledge of the relaxation time of the magnetic material being used.

Among other methods, there have been many attempts to employ microwave techniques to study magnetic nanoparticles

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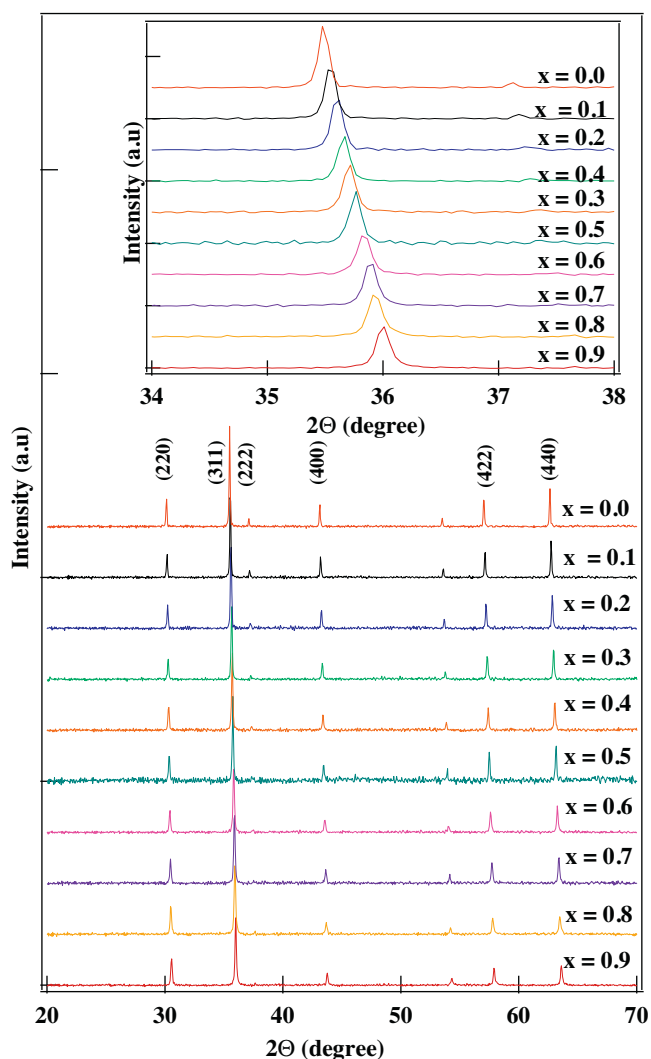


Fig. 1. The X-ray diffraction patterns of the $\text{CoFe}_{2-x}\text{Al}_x\text{O}_4$ as function of Al^{3+} content. The inset show expanded view of XRD patterns between 34 and 38° 2θ values.

[12–14]. Ferromagnetic resonance (FMR) is a powerful and well-established dynamic technique to investigate magnetic materials and to determine magnetic properties, such as magnetic anisotropy, effective magnetization, magnetic damping, etc. Our earlier studies have shown that the complex dynamics of magnetic nanoparticles are reflected in FMR spectra [12,13]. To our knowledge, there have been few detailed studies on Al^{3+} substituted $\text{CoFe}_{2-x}\text{Al}_x\text{O}_4$. And in addition, the high frequency dynamic studies are limited too [14]. In this paper, we report the static and dynamic properties of $\text{CoFe}_{2-x}\text{Al}_x\text{O}_4$ nanoparticles. The non-magnetic Al^{3+} substituted $\text{CoFe}_{2-x}\text{Al}_x\text{O}_4$ show reduction in magnetic parameters but demonstrate remarkable energy absorption properties at a high-frequency and magnetic field.

2. Experimental

Aluminum doped cobalt-ferrites with nominal compositions $\text{CoFe}_{2-x}\text{Al}_x\text{O}_4$ ($x = 0.1, 0.2, \dots, 0.9$) were synthesized by auto-combustion chemical synthesis technique. Nitrate salts of $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ and $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ were used to synthesize $\text{CoFe}_{2-x}\text{Al}_x\text{O}_4$ nanoparticles. The stoichiometric amounts of precursors were dissolved in a beaker with 30 ml of distilled water. Citric acid was added with the molar ratio of 1:1 according to the total amount of metal ions in the solution. The solution was

Table 1

Structural parameters derived from X-ray diffraction pattern refinement.

x	"a" (Å)	"V" (Å ³)	Particle size (nm)
0.0	8.382	589.018	82.23
0.1	8.370	586.385	76.45
0.2	8.356	583.596	72.91
0.3	8.343	580.875	70.35
0.4	8.332	578.613	67.12
0.5	8.321	576.159	70.68
0.6	8.305	572.863	60.09
0.7	8.291	570.067	62.46
0.8	8.282	568.225	54.72
0.9	8.267	565.142	58.37

continuously sonicated to make it homogeneous. Then the pH of the solution was adjusted to 6.5 with ammonia hydroxide. The solution was kept on the hot plate at 300°C . The ignited gel resulted in black powder. The powder was collected and was calcined up to 950°C for 10 h.

The structural and phase purity of the samples was assessed using X-ray diffractometer (Bruker Inc.) using $\text{CuK}\alpha$ radiation. The magnetic characterization was performed on compacted powders at room temperature using vibrating sample magnetometer (VSM) in fields up to 1.2 T. Microwave resonance studies were performed using a broad-band FMR system in the frequency range from 1 to 55 GHz and magnetic field from 0 to 10 kOe. Network Analyzer systems was used to perform ferromagnetic resonance (FMR) in transmission mode [12]. A flip-chip technique was used with a coplanar waveguide transmission line structure to study the dynamic response of nanostructures in the broad-band FMR system. To do this, thin layer of nanoparticles suspended in binder was spin coated on a clean glass substrate. The nanoparticle coated glass slide was flipped on to top of a coplanar waveguide. The

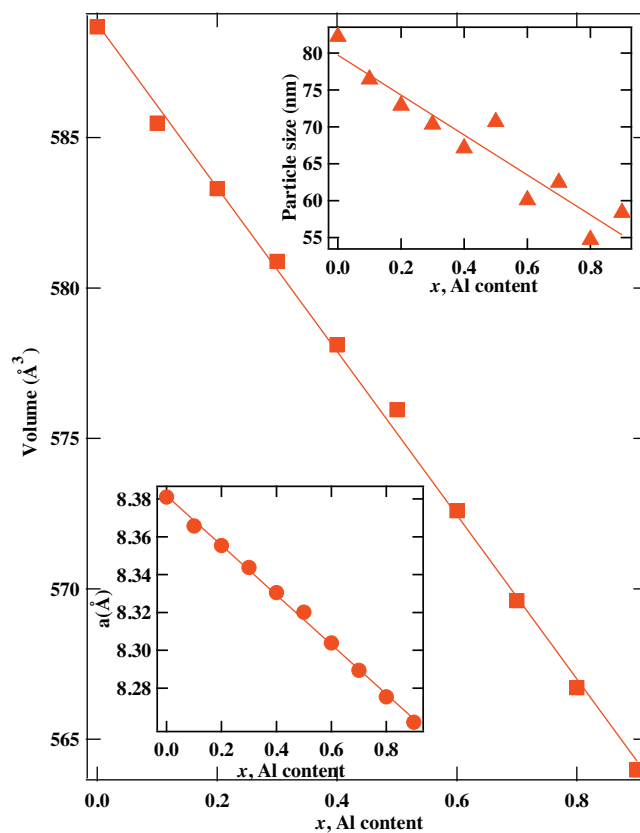


Fig. 2. Lattice parameters a , and V , and particle size as a function of Al^{3+} content, x , in $\text{CoFe}_{2-x}\text{Al}_x\text{O}_4$.

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