A systematic investigation of structural, optical and magnetic properties of pristine 
BaFe$_2$O$_4$, Mg and Mg, Cs co-doped in BaFe$_{2-x}$Mg$_x$O$_4$ and Ba$_{1-x}$Cs$_x$Fe$_{2-y}$Mg$_y$O$_4$ 
spinel nano ferrites

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The oxygen annealed barium nano ferrites have been synthesized by the chemical co-precipitation technique integrated with microwave treatment. The effects of doping on structural, optical and magnetic properties have been studied in detail. Powder XRD of the Mg doped and Mg, Cs co-doped BaFe$_2$O$_4$ shows large variation in the crystallite size especially due to the impact of alkali (Mg) and alkali earth metal (Cs) doping in octahedral and tetrahedral sites of the orthorhombic spinel structure. The appropriate atomic compositions and functional groups have been confirmed by the EDX and FTIR spectrums. The structural transformation of substantial nanoparticles to marginal nanorods explicit in the SEM micrograph and the evolution of high band gap have been obtained from the UV-Vis spectra. The magnetic hysteresis in the field range of ±1.5 T at room temperature has revealed the hard ferromagnetic characteristics with large coercivity and remanence for Mg, Cs co-doped BaFe$_2$O$_4$ than other spinel systems.

Keywords: Magnetic materials, Chemical synthesis, X-ray diffraction, Magnetic properties, Optical properties

1 Introduction

Magnetic nanoparticles holds a solid ground in diverse fields of applications particularly in permanent magnets, magnetic recording media components, high frequency applications, coherent spin FET, ceramic pigments, microwave absorbers, photocatalysts and magnetic sensors$^{1-8}$. These materials in the nanoscale with remarkable finite size effect and exotic surface effect can be synthesized by various frequent techniques such as chemical co-precipitation, thermal decomposition, micro emulsion, hydrothermal synthesis, sol-gel method and sonochemical synthesis$^{9,10}$. According to Lu et al.$^9$, chemical co-precipitation method surpasses the others by being the simplest experimental procedure under ambient conditions with low reaction temperature, short time period, narrow particle size distribution and high yield of desired size of crystallites and particles. It has also been evidenced that it is the most preferred method of synthesis especially for the magnetic nanomaterials derived from an iron and metallic oxide precursors$^{10}$. Among the big sort of magnetic materials in nanometer range, ferrites particularly would contribute a larger portion under the active applications due to its high coercivity than Alnico magnets, differential response to temperature variation, low cost and good chemical stability$^2$.

The barium ferrites (BaFe$_2$O$_4$) are one of the very interesting and promising spinel materials (AB$_2$O$_4$) in comparison to other ferrites (Co, Ni, Sr, Cu, Zn, Mn, Al and Mg) because it has high Curie temperature, strong magnetic anisotropy field effect and large energy efficiency, which is mostly used for fast magnetic memory storage devices$^2$. These ferrites are more sensitive when a small change induced by an inclusion of foreign atom, heat treatment or external stabilizing by capping agent induces a remarkable change in the magnetic domain alignment, crystalline phase and both optical and electrical band gap$^{3,12}$. For a speedy and complete evaporation of solvent using the microwave treatment with a better surface stabilizing agent such as PEG gives a good crystallinity with lower amount of secondary elements than other heating methods$^{13}$. Further, the barium ferrite nanoparticles were annealed in oxygen atmosphere at 700 °C for 6 h to improve the mechanical strength and get defect free crystallites of barium nano ferrites. We have fabricated the pristine
BaFe$_2$O$_4$ and have doped it with Mg in Fe site, and Mg, Cs simultaneously in the place of Fe and Ba sites in BaFe$_{2-x}$Mg$_x$O$_4$ and Ba$_{1-x}$Cs$_x$Fe$_{2-y}$Mg$_y$O$_4$ for the first time using a chemical co-precipitation method with suitable capping agent. Hence, the most important objective is to find the impact of alkali and alkali earth metal on the structural, optical and magnetic properties of BaFe$_2$O$_4$ in nanoscale.

2 Experimental

Aqueous solutions of 0.5 M pure BaCl$_2$·2H$_2$O (Merck) and anhydrous FeCl$_3$ (Merck) with 100 mL distilled water were stirred constantly for 1 h and then 0.5 M NaOH (70 mL, Merck) was added drop by drop using the burette until the pH of 10 - 12 was reached and maintained. The resulting colloidal solution was further heated at 60 °C and in addition, a few drops of polyethylene glycol (PEG) 400 (Merck) were poured into that mixture to avoid destabilization and particle agglomeration in the colloidal solution. The precipitate collected finally was washed in hot distilled water, ethyl alcohol and acetone to remove the excess of salt (NaCl) produced as a byproduct in the BaFe$_2$O$_4$ chemical precipitation. Then, the salt free precipitate was thoroughly dried using microwave oven (750 W, 10 min) which leads to the formation of powdered BaFe$_2$O$_4$ nanoferrites. Similarly, BaFe$_{1.9}$Mg$_{0.1}$O$_4$ and Ba$_{0.9}$Cs$_{0.1}$Fe$_{1.9}$Mg$_{0.1}$O$_4$ nanoferrites were synthesized using same procedure with the addition of 0.5 M MgCl$_2$·6H$_2$O (100 mL) and CsCl (100 mL) in the initial colloidal solution. Finally as prepared BaFe$_2$O$_4$, BaFe$_{1.9}$Mg$_{0.1}$O$_4$ and Ba$_{0.9}$Cs$_{0.1}$Fe$_{1.9}$Mg$_{0.1}$O$_4$ nanoferrites powder from the chemical co-precipitation method were annealed under oxygen atmosphere at 700 °C for 6 h using the eight segmented tubular furnace (Model: VBCC/FUR/1000 °C-112). The phase identification with corresponding crystalline parameters were investigated by the Powder X-Ray Diffractometer (PXRD, Model: Rigaku Dmax/2C, Japan with Cu Kα radiation; α = 1.5405 Å). The FTIR (Model: spectrum RX I, Perkin Elmer) and SEM with EDX (Model: FEI Quanta FEG 200) studies were carried out to confirm the presence of appropriate functional groups, the exact percentage of elemental compositions and to see the surface morphology of BaFe$_2$O$_4$ system in detail. UV-Vis Spectroscopic analysis (Model: Lambda 35, Perkin Elmer) was done and corresponding optical band gap energy of the ferrites were calculated. The isothermal magnetization (M vs H) for synthesized barium nanoferrites were studied using Vibrating Sample Magnetometer (Model: 7404, Lakeshore, UK with an applied external magnetic field of ±1.5 T.

3 Results and Discussion

The powder X-Ray diffraction peaks of pristine BaFe$_2$O$_4$, BaFe$_{2-x}$Mg$_x$O$_4$ (x = 0.1) and Ba$_{1-x}$Cs$_x$Fe$_{2-y}$Mg$_y$O$_4$ (x = y = 0.1) are displayed in Fig. 1. The observed strong diffracted beam intensity with 20 peak of Mg free and Mg doped samples are closely matched with a standard JCPDS card no. 77-2337. Further, we found a large amount of amorphous phase from all the samples and it evolves with an orthorhombic (α = 17.30Å, b = 9.43Å, c = 10.83Å for as synthesized) spinel crystal system at room temperature with a space group of Pmcm. It can be clearly seen that the sample annealed at 700 °C is peculiar causative factor for the absence of non-identified intermediate phases and the crystal system equilibrium restoration as previously reported by Candeia et al. and Castro et al. The small amount of secondary α-Fe$_2$O$_3$ phase (20–63°) appeared for all the samples with diffraction pattern, which usually undergoes a magnetic inversion aiding in the formation of ferrites above 680 °C. Also, 20 at 30° denotes the presence of Cs$_2$O phase in the Mg, Cs co-doped sample.

![Fig. 1 — Powder X-ray diffraction peaks for the (a) pristine, (b) Mg and (c) Mg, Cs co-doped BaFe$_2$O$_4$ spinel nanoferrites.](image)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Lattice parameters</th>
<th>Crystallite size (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a (Å)</td>
<td>b (Å)</td>
</tr>
<tr>
<td>JCPDS (77-2337)</td>
<td>17.34</td>
<td>9.33</td>
</tr>
<tr>
<td>BaFe$_2$O$_4$</td>
<td>17.30</td>
<td>9.43</td>
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<tr>
<td>BaFe$<em>{1.9}$Mg$</em>{0.1}$O$_4$</td>
<td>17.27</td>
<td>9.37</td>
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<td>Ba$<em>{0.9}$Cs$</em>{0.1}$Fe$<em>{1.9}$Mg$</em>{0.1}$O$_4$</td>
<td>17.21</td>
<td>9.28</td>
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Table 1 — The calculated geometrical factors (lattice parameters, unit cell volume and crystallite size) of different BaFe$_2$O$_4$ ferrites
The lattice parameters, unit cell volume and crystallite size corresponding to the orthorhombic pristine BaFe$_2$O$_4$, BaFe$_{1.9}$Mg$_{0.1}$O$_4$ and Ba$0.9$C$_{0.1}$Fe$_{1.9}$Mg$_{0.1}$O$_4$ were listed in Table 1. The Mg$^{3+}$ (1.45 Å) substitution in the place of Fe$^{3+}$ (1.56 Å) having greater ionic radii along the tetrahedral cation site is confirmed by the reduction of $a$ and $b$ lattice parameter values (Table 1). On the other hand, the strain induced by this shrinkage may lead to the expansion of $c$ lattice representing the octahedrally coordinated Fe$^{3+}$ as anticipated$^{16}$. Similarly, the doping of larger Cs$^{1+}$ in the place of Ba$^{2+}$ site shows contraction in the $c$ axis lattice parameter with respect to size of the constituent atomic radius. Hence, the total decreasing of unit cell volume from $1766.79$ Å$^3$ to $1747.21$ Å$^3$ for as-prepared BaFe$_2$O$_4$ and simultaneous doping in the place of Ba and Fe sites of the BaFe$_2$O$_4$ ferrites can also be observed. The crystallite size ($D$) was determined using the Debye Scherrer's equation,

$$D = \frac{k \lambda}{\beta \cos \theta}$$

and their comparisons to the crystalline parameters are shown in the Table 1. Here, $k$ is the dimensionless shape factor ($k = 0.94$), $\lambda$ is the wavelength of the incident x-ray, $\beta$ is the full width at half maximum value and $\theta$ is the Bragg’s diffraction angle. Large variation in the grain size especially for the Mg, Cs co-doped BaFe$_2$O$_4$ sample could be due to high lattice strain with shrinkages than other samples, which is also further confirmed by a drastic reduction in the unit cell volume changes.

The IR spectrums recorded in the ranges between 4000-400 cm$^{-1}$ of nanoferrites are shown in Fig. 2. The common occurrence of $v_1$ (600 cm$^{-1}$) and $v_2$ (400 cm$^{-1}$) band seen in ferrites is due to the stretching vibration of tetrahedral and octahedral group complex Fe-O respectively$^{17,18}$. Here, the presence of intrinsic stretching vibrations of tetrahedral and octahedral group complexes were found at $471.31$, $434.05$, $438.17$ cm$^{-1}$ and $693.93$, $580.90$, $581.32$ cm$^{-1}$, respectively for the pristine, Mg doped, Mg, Cs co-doped barium ferrites, which confirms the ferrite nature of the synthesized materials. The absorption bands corresponding to the $v_3$ band assigned to the stretching vibrations of Fe$^{3+}$ and O$^2-$ in the tetragonal complexes decreases while inclusion of Mg in the place of Fe$^{3+}$ site. Similarly, the absorption band corresponding to the $v_3$ band assigned to the stretching vibrations of Ba$^{2+}$ and O$^2-$ in the octahedral complexes decreases due to the substitution of Cs and Mg in the place of Ba and Fe simultaneously. It has also been noted that the C=O vibration exists due to the vibrational spectra ranging between 1621-1600 cm$^{-1}$ for all the samples. Then, free hydroxyl bands of –OH stretching lies between 3783-3695 cm$^{-1}$ in each sample. The transmittance IR band of –OH in plane bending also occurs due to the addition of PEG, especially in the 1413 cm$^{-1}$ band spectra region$^{19}$. Also, the presence of 2925 cm$^{-1}$ and 2927 cm$^{-1}$ band spectra represents the antisymmetric CH$_2$ vibrations of the carbon only observed from Mg doped and Mg, Cs co-doped BaFe$_2$O$_4$ nanoferrites.

The SEM micrographs show hard agglomeration of particles, which are revealed in two distinct ranges of 3 µm and 1 µm as shown in Fig. 3(a, b and c). In BaFe$_{1.9}$Mg$_{0.1}$O$_4$ and Ba$_{0.9}$C$_{0.1}$Fe$_{1.9}$Mg$_{0.1}$O$_4$, two types of aggregates such as substantial nanoparticles and marginal nanorods were noticeable in the some figures. Though, there is a structural morphology transformation of spherical particles into marginal rod shape may be induced by doping of magnesium in place of Fe site, which also has been visible in Cs and Mg co-doped BaFe$_2$O$_4$ SEM pictures. This structural morphology changes due to Mg doping was consistent with SEM results reported by Manu Sharma et al.$^{20}$. The chemically analyzed spinel nanoferrites by the energy dispersive absorption spectra recorded in the range of 0-9 keV with a resolution of 30 µm were also shown in Fig. 3. The matrix of the EDX spectra shows effective Ba, Fe, O peaks and also the additional visible Mg peak located at 1.3 keV. The weak Cs peaks were observed at 3.8 keV and for the Mg doped and Mg, Cs co-doped barium nanoferrites (BaFe$_2$O$_4$) the observed peak at 5.6 keV ascribed the Mg element. It is also confirmed that Mg and Cs are substituted along with the Fe and Ba sites successfully.

![Fig. 2 — IR spectra of the pristine, Mg doped and Mg, Cs co-doped barium nanoferrites.](image-url)
within general form of $\text{Ba}_{1-y}\text{Cs}_y\text{Fe}_{2-x}\text{Mg}_x\text{O}_4$ as shown in the Fig. 3. In addition, the final molar ratio for all the samples of barium ferrite were calculated from (the final molar ratio = mole fraction of the element = weight percentage of the element/molecular weight of the element) empirical formula$^{21,22}$.

The samples were scanned at the rate of 960 nm/min by ultraviolet radiations (UV) and the multi-curve plots of the absorption and transmission peaks obtained are shown in Fig. 4(a). The minimum absorption peak is found at 219 nm for the microwave treated pristine $\text{BaFe}_2\text{O}_4$ particles. The observed shift in the fundamental absorption edge of UV-Visible spectra can be correlated with the optical band gap and thus calculated from the Tauc’s expression given by:

$$(\alpha h\nu)^2 = B (h\nu - E_g)$$

... (1)

where $\alpha$ is the absorption coefficient corresponding to the fundamental absorption edge, $h\nu$ is the photon energy and $B$ is the constant of proportionality. Then, the relation between absorption co-efficient and absorption wavelength is given by:

$$\alpha = 2.303 \times \frac{A}{T}$$

... (2)

where $A$ is the absorption wavelength in nanometer and $T$ is the thickness of the sample in meter. The values of optical band gap $E_g$ can be deduced from the intercept of the linear fitted lines in the plots of $(\alpha h\nu)^2$ versus $h\nu$, as shown in Fig. 4(b). By extrapolating the slope lines to $\alpha = 0$, the corresponding band gap of both absorption and transmission of the material was determined and the same has been manually calculated, which is also listed in Table 2. Surprisingly, the optical band gap of pristine, Mg and Mg, Cs co-doped Ba ferrites has enhanced up to ~6 eV, which is effectively higher than $\text{BaFe}_2\text{O}_4$ (~1.9 eV in 652 nm range) and $\text{MgFe}_2\text{O}_4$ (~2.0 eV) band gap.
energy values\textsuperscript{7,23}. It might give the importance of alkali and alkali metal in BaFe\textsubscript{2}O\textsubscript{4} spinel system by chemical co-precipitation with microwave heating resulting in extensive optical phenomenon in this case.

The band gap is calculated using the Eq. (3) as follows:

\[ E = h\nu = \frac{hc}{\lambda} \]  \hspace{1cm} \text{(3)}

where \( h \) is the Plank’s constant (6.626 × 10\textsuperscript{-34} J s\textsuperscript{-1}), \( c \) is the velocity of light (3 × 10\textsuperscript{8} ms\textsuperscript{-1}) and \( \lambda \) is the cut off wavelength from the absorption spectra.

Table 2 — Optical band gap from the absorption and transmission UV spectra of the different barium nanoferrites

<table>
<thead>
<tr>
<th>Samples</th>
<th>From Absorption spectra (eV)</th>
<th>From transmission spectra (eV)</th>
<th>From Tauc’s plot (eV)</th>
</tr>
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<tbody>
<tr>
<td>BaFe\textsubscript{2}O\textsubscript{4}</td>
<td>5.42</td>
<td>5.44</td>
<td>5.50</td>
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<tr>
<td>BaFe\textsubscript{1.9}Mg\textsubscript{0.1}O\textsubscript{4}</td>
<td>5.74</td>
<td>5.77</td>
<td>5.81</td>
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<tr>
<td>Ba\textsubscript{0.9}Cs\textsubscript{0.1}Fe\textsubscript{1.9}Mg\textsubscript{0.1}O\textsubscript{4}</td>
<td>5.82</td>
<td>5.85</td>
<td>6.00</td>
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</table>

Fig. 4 — (A) UV-Visible absorption spectra for the spinel BaFe\textsubscript{2}O\textsubscript{4} nanoferrites. (B) Plots of \((\alpha h\nu)^2\) versus \(h\nu\) for the pristine (a), Mg doped (b) and Mg, Cs co-doped (c) BaFe\textsubscript{2}O\textsubscript{4} nanoferrites.

Fig. 5 — (A) and (B) Magnetic hysteresis loops for (a) BaFe\textsubscript{2}O\textsubscript{4}, (b) BaFe\textsubscript{1.9}Mg\textsubscript{0.1}O\textsubscript{4} and (c) Ba\textsubscript{0.9}Cs\textsubscript{0.1}Fe\textsubscript{1.9}Mg\textsubscript{0.1}O\textsubscript{4} nanoferrites measured in the external magnetic field ranges between ±1.5 Tesla. (C) Crystallite size depends on the magnetic saturation \((M_s)\) and remanent magnetization \((M_r)\) for pristine BaFe\textsubscript{2}O\textsubscript{4}, alkaline earth (Mg) and alkali metal (Cs) doped BaFe\textsubscript{2}O\textsubscript{4} spinel nanoferrites.

The magnetic properties of the BaFe\textsubscript{2}O\textsubscript{4}, BaFe\textsubscript{1.9}Mg\textsubscript{0.1}O\textsubscript{4} and Ba\textsubscript{0.9}Cs\textsubscript{0.1}Fe\textsubscript{1.9}Mg\textsubscript{0.1}O\textsubscript{4} nanoparticles has been investigated by the magnetic hysteresis curves measured at 300 K under the field ranges between ±1.5 T by using Vibrating Sample Magnetometer (VSM). Figure 5(a) shows the isothermal magnetic curves of
BaFe$_2$O$_4$, BaFe$_{1.9}$Mg$_{0.1}$O$_4$ and Ba$_{0.9}$Cs$_{0.1}$Fe$_{1.9}$Mg$_{0.1}$O$_4$ nanoparticles, which were annealed at 700 °C under oxygen atmosphere for 6 h. It could be clearly seen that the pristine BaFe$_2$O$_4$ has the magnetic saturation value of $M_s = 8.9897$ emu/g, which is comparatively smaller than the other two alkali metal doped samples (22.619 emu/g, 25.010 emu/g), respectively. The corresponding coercivity ($M_c$) was found to be $H_c = 2550.7$ Oe, 1890.4 Oe and 1711.7 Oe for BaFe$_2$O$_4$, BaFe$_{1.9}$Mg$_{0.1}$O$_4$ and Ba$_{0.9}$Cs$_{0.1}$Fe$_{1.9}$Mg$_{0.1}$O$_4$ samples, respectively. This indicates that a significant dopping of metals in the place of Fe and Ba sites could play an important role in deciding the magnetic property of BaFe$_2$O$_4$ spinel ferrites. Obviously, the magnetic properties of most metallic oxide nanosystems highly depend on the particle or crystallite size, and thermal treatments such as annealing, sintering, calcining temperature. This leads to significant change in the coercivity ($H_c$), saturation magnetization ($M_s$) and remanent magnetization ($M_r$) values. In addition, Fig. 5(a) indicates a hard magnetic hysteresis loop (large hysteresis area) and there is no indication of magnetic saturation under magnetic field up to 15000 Oe and zero coercivity. This implies that a substantial Fe magnetic moment interacts with alkali Mg metal and shows a large variation in $M_s$ value, in other words it may restrict the usual superparamagnetic particles with exact ‘$S$’ shaped $M$ vs $H$ hysteresis is observed from many spinel ferrites in nanometer range reported previously. Comparing the hysteresis loops of BaFe$_2$O$_4$, BaFe$_{1.9}$Mg$_{0.1}$O$_4$ and Ba$_{0.9}$Cs$_{0.1}$Fe$_{1.9}$Mg$_{0.1}$O$_4$ (Fig. 5(b)) it is found that the area of the hysteresis loop has enhanced for the alkali metal doped samples than pristine nanocrystallites. Also, the observed higher values of $M_s$ and $M_r$ for Mg and Mg-Cs co-doped compounds showed a hard ferromagnetic nature, which is completely different from other soft spinel nanoferrites.

Figure 5(c) depicts that the crystallite size depends on the magnetic properties of BaFe$_2$O$_4$, Mg and Mg-Cs co-doped BaFe$_2$O$_4$ compounds. When the crystallite size increases from 12 nm to 34 nm for BaFe$_2$O$_4$ to Mg and Cs co-doped BaFe$_2$O$_4$, the value of $H_c$ decreases from 0.25 to 0.17 Tesla as shown in Table 3. However, a profound increase in $M_r$ from 8.9 to 25 emu/g denotes a hard magnetic characteristic with respect to an externally applied magnetic field. This might be an effect of small magnetic crystalline anisotropy changes and the arrangement of spins in the surface core of alkali metal nanoparticles becomes more ordered under high applied magnetic field. An absence of ‘$S$’ (zero $H_c$ and $M_r$) shaped superparamagnetic curve denotes that the doping of alkali and alkali earth metal in the place Fe and Ba sites has enhanced the ferromagnetic hysteresis, which is useful for commercialized magnetic memory devices. So, the comparison of the magnetic characteristics of BaFe$_2$O$_4$ with alkali and alkali earth metal inclusions of this study might further help to enhance the hard magnetic nature of large spinel family compounds, and enable the making of superior magnetic storage devices based on such spinel nanoferrites investigated so far.

Table 3 — Comparison of the effect of crystallite size on the magnetic properties of BaFe$_2$O$_4$ spinel nanoferrites

<table>
<thead>
<tr>
<th>Samples</th>
<th>Crystallite size (nm)</th>
<th>Saturation magnetization $M_s$ (emu/g)</th>
<th>Coercivity $H_c$ (Oe)</th>
<th>Remanent magnetization $M_r$ (emu/g)</th>
<th>$M_r/M_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaFe$_2$O$_4$</td>
<td>12</td>
<td>8.989</td>
<td>2550.7</td>
<td>4.591</td>
<td>0.5038</td>
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<tr>
<td>BaFe$<em>{1.9}$Mg$</em>{0.1}$O$_4$</td>
<td>17</td>
<td>22.619</td>
<td>1890.4</td>
<td>11.431</td>
<td>1.2549</td>
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<tr>
<td>Ba$<em>{0.9}$Cs$</em>{0.1}$Fe$<em>{1.9}$Mg$</em>{0.1}$O$_4$</td>
<td>34</td>
<td>25.010</td>
<td>1711.7</td>
<td>12.795</td>
<td>1.0990</td>
</tr>
</tbody>
</table>

4 Conclusions

The reliable and facile chemical co-precipitation technique integrated with the microwave treatment was employed, thus the spinel barium nanoferrites were synthesized successfully. The oxygen annealing on the nanoferrites especially above 700 °C showed no unidentifiable phases with a single orthorhombic phase and some secondary phases, which were confirmed by the powder XRD. Also in the powder XRD analysis, there appeared a large variation in the grain size especially for the Mg, Cs co-doped BaFe$_2$O$_4$ nanoferrites that may be due to high lattice strain on the tetrahedral and octahedral spinel sites. The default presence of octahedral and tetragonal complexes in all spinel ferrites were approved by the FTIR band spectra. The SEM and EDX revealed aggregates of substantial nanoparticles with marginal nanorods Mg, Cs in appropriate proportions. The UV-Vis analysis exhibits an incredible band gap of ~6 eV compared to its relative spinel mixtures. The isothermal magnetic hysteresis studies of Ba$_{0.9}$Cs$_{0.1}$Fe$_{1.9}$Mg$_{0.1}$O$_4$ show higher saturation magnetization and coercivity values than as-synthesized and Mg doped spinel.
nanoferrites. It seems that the optical and magnetic properties of BaFe$_2$O$_4$ nanoparticles are enhanced by the doping of alkaline and alkaline earth metals. So, the suitable metal doping of BaFe$_2$O$_4$ will improve its crystallinity and their physical properties.

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References