Synthesis and characterization of CuFe$_2$O$_4$/CeO$_2$ nanocomposites

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A B S T R A C T

CuFe$_2$O$_4$/xCeO$_2$ (x = 0, 1, 5, 10 and 20 wt%) nanocomposites have been prepared by urea–nitrate combustion method. The particle size of the as-prepared CuFe$_2$O$_4$/5 wt% CeO$_2$ nanocomposite is 5–10 nm which has been revealed from TEM and HRTEM images. The as-synthesized materials have been sintered at four different temperatures (600, 800, 1000 and 1100 °C) for 5 h. The XRD analysis of the samples reveals that the prepared materials possess tetragonal structure and have the composite behaviour. The 1100 °C sintered samples have further been characterized by FT-IR, UV–vis, SEM, ac electrical conductivity, dielectric constant, loss tangent, and Mössbauer spectra. The SEM images clearly show that CeO$_2$ grows on the surface of the CuFe$_2$O$_4$. The electrical properties enumerate the ferrimagnetic behaviour of the synthesized materials. The Mössbauer spectra confirm both the inverse spinel structure of the prepared materials and the Fe$^{3+}$ state of iron ions.

1. Introduction

Synthesis and characterization of nanocomposites have gained prominent interest in recent years due to their tailor-made properties. The term nanocomposite encompasses a variety of distinctively different materials mixed at the nanometric scale with specific applications. Some of the reported types of nanocomposites are magnetic–metal (Fe$_3$O$_4$–Au) [1], magnetic–metallic oxide (Zn, Ni Ferrite–NiO) [2], magnetic–polymer (CoFe$_2$O$_4$–Polypyrrole) [3], magnetic–semiconductors (Fe$_3$O$_4$–PbS) [4], magnetic–alloy (Ni$_{0.5}$Zn$_{0.5}$Fe$_2$O$_4$–FeNi$_3$) [5], magnetic–zeolite [6], etc. Synthesis and characterization of CuFe$_2$O$_4$/CeO$_2$ nanocomposites have been prepared by urea–nitrate combustion method. The particle size of the as-prepared CuFe$_2$O$_4$/5 wt% CeO$_2$ nanocomposite is 5–10 nm which has been revealed from TEM and HRTEM images. The as-synthesized materials have been sintered at four different temperatures (600, 800, 1000 and 1100 °C) for 5 h. The XRD analysis of the samples reveals that the prepared materials possess tetragonal structure and have the composite behaviour. The 1100 °C sintered samples have further been characterized by FT-IR, UV–vis, SEM, ac electrical conductivity, dielectric constant, loss tangent, and Mössbauer spectra. The SEM images clearly show that CeO$_2$ grows on the surface of the CuFe$_2$O$_4$. The electrical properties enumerate the ferrimagnetic behaviour of the synthesized materials. The Mössbauer spectra confirm both the inverse spinel structure of the prepared materials and the Fe$^{3+}$ state of iron ions.

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Hence, considering the importance of the surface modified nanocomposites, a detailed preliminary study has been carried out on nanocrystalline CuFe$_2$O$_4$ with CeO$_2$ at four different concentrations of 1, 5, 10, 20 wt% prepared by simple combustion method. The structural (XRD, FT-IR, UV–vis spectra), morphological (SEM, TEM, HRTEM, SAED), electrical (ac electrical conductivity, dielectric constant, loss tangent) and magnetic (Mössbauer spectra) properties of the material have also been investigated and reported herein.

2. Experimental

The CuFe$_2$O$_4$/x wt% CeO$_2$ (x = 0, 1, 5, 10, 20) nanocomposites were prepared using urea–nitrate combustion method [27]. The stoichiometric quantities of starting materials, viz., Cu(NO$_3$)$_2$·6H$_2$O, Fe(NO$_3$)$_3$·9H$_2$O, Ce(NO$_3$)$_3$·6H$_2$O, and CO(NH$_2$)$_2$ were dissolved in 100 ml distilled water. The actual quantities of the reactants for the preparation of each nanocomposite (for 100 g) and the yields are given in Table 1. The mixed nitrate–urea solution was heated at 110 °C, with continuous stirring. After the evaporation of excess of water, a highly viscous gel, known as precursor, has been obtained. Subsequently, the gel was ignited at 300 °C to evolve the undesirable gaseous products, which has resulted in the formation of desired product in the form of foamy powder. The presented (Table 1) yields are not exactly correct. Due to the combustion reaction, lot of products are coming out the reaction vessel. So we cannot calculate the exact value. Subsequently, the powder was sintered at different temperatures (600, 800, 1000 and 1100 °C) for 5 h to obtain ultrafine powders of CuFe$_2$O$_4$/CeO$_2$ nanocomposites.

The compound formation, phase purity and crystallinity of the ferrite materials were identified by powder X-ray diffraction (XRD) technique using a X-ray diffractometer (PANalytical (Make), XP’er PRO (Model), Cu Kα radiation; λ$_{Kα}$=1.5405 Å). The FT-IR spectra of the samples were recorded with the KBr discs in the range of 400–1000 cm$^{-1}$ using a PerkinElmer spectrophotometer (PerkinElmer, UK, Paragon-500 model). Diffuse reflectance spectroscopy measurements were carried out on a Cary Varian 1E spectrophotometer in the range of 200–800 nm. The particle size was analyzed using TEM (JEOL-JEM 100SX microscope) operating at an accelerating voltage of 200 kV. The morphological features have been analyzed through SEM (JEOL JSM-3000 model). The ac conductivity measurements were made at room temperature using impedance analyzer HIOKI 3532 in the frequency range of 42 Hz to 5 MHz. The room-temperature Mössbauer measurements were made in transmission geometry using a conventional spectrometer in a constant acceleration mode. A $\alpha$-Co/Rh γ-ray source was used. The velocity scale was calibrated relative to $^{57}$Fe in Rh. A proportional counter was used to detect the transmitted γ-rays. Mössbauer spectral analysis software RECOIL [28] was used for the quantitative evaluation of the spectra. The degree of inversion (x) was calculated from the Mössbauer subspectral areas ($I_{A}/I_{A}+I_{B}$)$(1/2-\beta)$ assuming that the ratio of the recoilless fractions is $f_{x}/f_{0}=1$. Here, the degree of inversion is defined as a fraction of the tetrahedral (A) sites occupied by iron cations; i.e., the structural formula of copper ferrite may be written as (Cu$_{x}$Fe$_{3-x}$)$_{1-x}$Fe$_{x}$O$_{4}$, where round and square brackets denote sites of tetrahedral (A) and octahedral (B) coordination, respectively.

3. Results and discussion

3.1. Structural studies

The XRD patterns of as-prepared CuFe$_2$O$_4$/x wt% CeO$_2$ nanocomposites and thermally treated at different temperatures (600, 800, 1000 and 1100 °C) are shown in Fig. 1. The as-prepared (Fig. 1a) sample contains broad diffraction peaks corresponding to CuFe$_2$O$_4$ along with the presence of CuO and Fe$_2$O$_3$ phases. The observed broad peaks indicate the nanocrystalline nature of the as-synthesized materials as well as the amorphous behaviour of the materials. When the sintering temperature increases to 600 °C, large number of peaks emerged that correspond to impurity phases of precursor. In order to avoid the impurity phases, the samples were further sintered at 800 °C. As expected, the XRD pattern reveals the formation of only CuFe$_2$O$_4$ compound with the lattice planes of (202), (220), (3 1 0), (3 1 1), (2 2 2), (4 0 0), (0 0 4), etc. [14]. Samples sintered at higher temperatures of 1000 and 1100 °C exhibit very sharp and well-defined peaks confirming the increased crystallinity of the compounds. Unfortunately, no peak for CeO$_2$ is identified, which infers that the added CeO$_2$ is dissolved in the spinel structure of CuFe$_2$O$_4$ [23] or otherwise it coated on the surface of the CuFe$_2$O$_4$ particles [22]. Generally, the Bragg planes of (4 2 2) and (4 4 0) correspond to tetrahedral and octahedral sites of spinel type materials, respectively [29]. For CuFe$_2$O$_4$/1 wt% CeO$_2$ sample, the relative intensity of the XRD peak corresponding to the (4 2 2) plane, I$_{422}$, increases from 6.82 to 9.47° compared with the parent CuFe$_2$O$_4$ [28]. This indicates that the added Ce$^{4+}$ ions enter into the octahedral [B] sites causing the replacement of some of the Fe$^{3+}$ ions from [B]-sites into (A)-sites. As a consequence, the relative intensity of the XRD peak corresponding to the (4 2 2) plane $I_{422}$ increases from 6.51 to 8.14. Thus, it can be concluded that the added Ce$^{4+}$ ions enter into the B-sites of copper ferrite. The calculated lattice constant values (Table 2) enumerate that the samples possess tetragonal structure and the values slightly increase with the addition of CeO$_2$, which may be due to the difference in ionic radii of Ce$^{4+}$ and Fe$^{3+}$ ($\sigma$(Ce$^{4+}$) = 0.87 Å, $\sigma$(Fe$^{3+}$) = 0.645 Å). The primary particle size calculated using Debye–Scherrer formula (Table 2) indicates the growth of particles with increasing temperature.

The XRD patterns of CuFe$_2$O$_4$/5, 10 and 20 wt% CeO$_2$ nanocomposites sintered at different temperatures are shown in Fig. 1b, c and d. It is observed that the intensity of CeO$_2$ peaks, i.e., (1 1 1) at 28$^\circ$ and (3 1 1) at 56.7$^\circ$, in all the samples increases with increase in CeO$_2$ wt% as well as with sintering temperature. A scrutiny of the lattice parameter values of c and a makes it clear the retention of tetragonal structure all along. It is understood that the tetragonal structure of parent CuFe$_2$O$_4$ remains more or less intact. Thus, addition of CeO$_2$ does not have much influence on the original structure of CuFe$_2$O$_4$, and hence it is presumed that a composite has been resulted. The calculated primary particle size of the materials decreases with increasing concentration of CeO$_2$ (see Table 2), which is due to the formation of secondary phases that hinders the grain growth of the primary particles [30].

FT-IR spectra of 1100 °C sintered CuFe$_2$O$_4$/xCeO$_2$ (x = 0, 1, 5, 10, 20 wt%) nanocomposites are shown in Fig. 2. In ferrite the metal cations are situated in two different sub-lattices namely tetrahedral (A-sites) and octahedral (B-sites) according to the geometric configuration of the oxygen ion nearest neighbours. The band $\nu_{1}$ around 600 cm$^{-1}$ is attributed to stretching vibration of tetrahedral complexes and $\nu_{2}$ around 400 cm$^{-1}$ to that of octahedral complexes. It can be seen that the observed band at 570 cm$^{-1}$ in the spectrum of CuFe$_2$O$_4$ is attributed to the stretching vibration of tetrahedrally coordinated Fe$^{3+}$–O$^{2-}$ bonds. The similar spectral features are also observed for all composites irrespective of the amount of added CeO$_2$. At higher concentration of CeO$_2$ (≥ 10 wt%), a small band is noticed around 650 cm$^{-1}$, which is due to the Ce–O vibration [31].

Table 1 shows the UV–vis spectra of CuFe$_2$O$_4$ sample and of CuFe$_2$O$_4$/xCeO$_2$ (x = 0, 1, 5, 10, 20 wt%) nanocomposites sintered at
The optical band gap ($E_g$) values are calculated from the spectra using the following relation: $(\alpha E)^2 = \text{const} (E - E_g)$, where $\alpha$ is the absorption coefficient, $E$ is the photon energy; $E_g$ values can be derived by extrapolating the linear portion of the $(\alpha E)^2$ vs. $E_g$ plot. The $\alpha$ and $E$ can be converted from the absorbance, $A$, using the relationship $\alpha = (A \times \ln 10)/d$ and $E = 1240/\lambda_p$, respectively, where $d$ is the thickness of the material and $\lambda_p$ is the wavelength [32]. The optical band gap values obtained are 2.63, 2.68, 2.54, 2.53, and 2.46 eV for CuFe$_2$O$_4$/xCeO$_2$ ($x = 0, 1, 5, 10$, and $20$ wt%), respectively, which shows that the materials have semiconducting behaviour.

3.2. Morphological studies

Fig. 4 shows the SEM images of CuFe$_2$O$_4$/xCeO$_2$ ($x = 1, 5$, and $20$ wt%) nanocomposites sintered at 1100°C. Smooth and well-defined grains with grain boundaries are observed in

Fig. 1. XRD patterns of CuFe$_2$O$_4$/1 wt% CeO$_2$ (a), CuFe$_2$O$_4$/5 wt% CeO$_2$ (b), CuFe$_2$O$_4$/10 wt% CeO$_2$ (c), CuFe$_2$O$_4$/20 wt% CeO$_2$ (d) nanocomposites; (▲) CuFe$_2$O$_4$, (●) CuO, (■) Fe$_2$O$_3$, (▼) CeO$_2$. 
Table 2
XRD parameters (lattice constants $a$ and $c$, and grain size $D$) of the CuFe$_2$O$_4$/xCeO$_2$ nanocomposites

<table>
<thead>
<tr>
<th>Sample</th>
<th>Parameters</th>
<th>Sintered at °C</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Green</td>
</tr>
<tr>
<td>CuFe$_2$O$_4$/1 wt% CeO$_2$</td>
<td>$a$(Å)</td>
<td>8.3546</td>
</tr>
<tr>
<td></td>
<td>$c$(Å)</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>$D$(nm)</td>
<td>12 ± 3.4</td>
</tr>
<tr>
<td>CuFe$_2$O$_4$/5 wt% CeO$_2$</td>
<td>$a$(Å)</td>
<td>8.3726</td>
</tr>
<tr>
<td></td>
<td>$c$(Å)</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>$D$(nm)</td>
<td>8 ± 4.9</td>
</tr>
<tr>
<td>CuFe$_2$O$_4$/10 wt% CeO$_2$</td>
<td>$a$(Å)</td>
<td>8.3986</td>
</tr>
<tr>
<td></td>
<td>$c$(Å)</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>$D$(nm)</td>
<td>5 ± 2.2</td>
</tr>
<tr>
<td>CuFe$_2$O$_4$/20 wt% CeO$_2$</td>
<td>$a$(Å)</td>
<td>8.3657</td>
</tr>
<tr>
<td></td>
<td>$c$(Å)</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>$D$(nm)</td>
<td>5 ± 1.5</td>
</tr>
</tbody>
</table>

CuFe$_2$O$_4$/1 wt% CeO$_2$ nanocomposites. When the concentration of CeO$_2$ increases above 5 wt%, CeO$_2$ grows up on the CuFe$_2$O$_4$ particles and modifies its surface, which is obvious from the SEM image. As well as the grain size of the materials decreases with the increasing concentration of CeO$_2$ due to the hindering of grain growth [33]. This is the most important favorable property for delivering better electrochemical performance of the electrode materials [21–26].

The crystallinity, particle size and morphology of the as-prepared CuFe$_2$O$_4$/5 wt% CeO$_2$ nanocomposites were studied using TEM, HRTEM and SAED methods. The TEM image (Fig. 5a) shows that the particle size of the as-synthesized nanocomposite are in the range of 5–10 nm and the particles are found to be polydispersed materials. The HRTEM image (Fig. 5b) confirms the presence of CeO$_2$ phase and the ferrite material. The CuFe$_2$O$_4$ spinel (2 2 0) planes with a $d$ value of 2.92 Å and layered CeO$_2$ (1 1 1) planes with a $d$ value of 3.33 Å are observed, which confirm the composite nature of the as-prepared particles. SAED pattern (Fig. 5a(inset)) of CuFe$_2$O$_4$/CeO$_2$ nanocomposites depicts well-defined rings for CuFe$_2$O$_4$. The presence of bright spots for CeO$_2$ may be attributed to the composite and polycrystalline nature of the prepared materials.

3.3. Electrical properties

The frequency-dependent ac conductivity of the samples CuFe$_2$O$_4$/xCeO$_2$ ($x = 0, 1, 5, 10$ and $20$ wt%) measured at room temperature is shown in Fig. 6. It is well known that three different effects are involved in the ac conductivity, i.e., electrode effect, dc plateau, and defect processes [34]. It can be seen that two different regions are observed in the conductivity plot within the measured range.
frequency window. One is low frequency plateau region and the other is high frequency dispersion region. At high frequency, all the curves are merged together indicating the formation of disordered solids. The plateau region shows the frequency-independent behaviour corresponding to the dc conductivity. The frequency dependent behaviour is observed at higher frequency which corresponds to ac conductivity and obeys the Joncher's Power law [35];
\[
\sigma_a = \sigma_{dc}(1 + (f/f_p)^n),
\]
where \( n \) is the frequency exponent in the range of \( 0 < n < 1 \), \( \sigma_{dc} \) is the dc conductivity, \( f \) and \( f_p \) are applied frequency and relaxation frequency, respectively. According to the literature, an \( n \) value smaller than unity indicates the conduction through hopping mechanism and above one is due to localized hopping [36]. Below the relaxation frequency, the conductivity is constant and frequency independent. Above \( f_p \) the conduction mechanism is believed to be sub-diffusive and the conductivity is ac conductivity.
that depends on frequency. In this region, the transport is dominated by the contribution of hopping of infinite clusters. According to electron hopping model suggested by Heikes and Johnston [37], the conduction mechanism is the hopping of Fe$^{2+}$ and Fe$^{3+}$ ions as well as Cu$^{2+}$ and Cu$^{4+}$ in the adjacent octahedral sites in the spinel lattice. Fig. 6 also explains the effect of CeO$_2$ addition on the frequency dependent ac conductivity of CuFe$_2$O$_4$. It can be observed that at low frequencies no significant improvement of the electrical conductivity of CuFe$_2$O$_4$ could be observed while at higher frequencies the conductivity increases with the increasing addition of CeO$_2$ up to 10 wt%. This may be explained by the fact that when an ion with variable valency enters the structure, charged vacancies are produced in order to maintain the local charge neutrality. Since Cu$^{2+}$ ions are substituted by Ce$^{4+}$ ions, negative ion vacancies or oxygen vacancies are created which result in high conductivity [38]. At higher concentration of CeO$_2$ (>10 wt%), the conductivity values decrease due to the formation of large number of secondary phases, which hinders the electron hopping between the adjacent sites [33]. In general, the tetravalent ions act as the electrostatic trapping centres when they are substituted in the spinel matrix and thereby reduces the conductivity. Similar observations have also been reported for Ti$^{4+}$ substituted MgFe$_2$O$_4$ and Ce$^{4+}$ substituted NiAl$_2$O$_4$ [29,39].

The frequency dependent dielectric constant ($\varepsilon'$) of CuFe$_2$O$_4$/CeO$_2$ nanocomposites measured at room temperature is shown in Fig. 7. It can be seen that $\varepsilon'$ decreases with increasing frequency and gets saturated at higher frequency. The decrease in dielectric constant with increasing frequency is due to the fact that the electronic exchange between the Fe$^{2+}$ and Fe$^{3+}$ ions cannot follow the externally applied frequency and will also obey the Debye relaxation process. On the other hand, the non-Debye behaviour is observed at high frequencies, which indicates the possible cation motion through the conduction pathways. It is seen that the values of dielectric constant decreases with increasing concentration of CeO$_2$. This variation mainly depends upon the number of space charge carriers and the resistivity of the samples, i.e., the increase in resistivity with the addition of CeO$_2$, prevents the flow of space charge carriers and therefore low value of dielectric constant is observed [40].

Fig. 8 shows the variation of loss tangent with frequency for all the samples measured at room temperature. At low frequency the loss tangent is very high because the energy required for the electronic exchange between Fe$^{2+}$ $\leftrightarrow$ Fe$^{3+}$ is large and it decreases with increasing frequency. At higher frequencies, lower energy is enough to maintain the charge and hence the loss tangent is low. The mechanism can be correlated with the Koops bi-layer formation. At lower frequency, the grain boundary effect is predominant and so the resistivity of the materials is high while at high frequency, the maximum conductivity is observed due to the larger grain effect. Fig. 8 also explains the effect of CeO$_2$ on the loss tangent values of copper ferrite. At low frequency the loss tangent values increase with increasing concentration of CeO$_2$ and at high frequency, the values are low compared to the pristine copper ferrite. The dielectric relaxation peaks are observed at 30 kHz for CuFe$_2$O$_4$ and 20 kHz for 1, 5 and 20 wt% CeO$_2$ composites. This happens when the jumping frequency of the localized charge carriers is approximately equal to the externally applied frequency. The appearance of dielectric relaxation peaks could be related to the collective contribution of both the type of charge carriers, which could be explained by Rezlescu model [41]. For CuFe$_2$O$_4$/10 wt% CeO$_2$ composite, no peak is observed in the measured frequency window.

3.4. Magnetic properties

The Mössbauer spectra of CuFe$_2$O$_4$/xCeO$_2$ (x= 0, 1, 5, 10, 20 wt%) samples measured at room temperature are shown in Fig. 9. The strategy for fitting the Mössbauer spectra was based on the fact that owing to the supertransfer mechanism in spinel ferrites [45,46], the Fe$^{3+}$[B] ion experiences local fields that reflect the distribution of magnetic ions in its neighbourhood, i.e., the Fe$^{3+}$[B] ion is very sensitive to the number of its [A] site nearest magnetic neighbours. This results in a broad distribution of the [B] site magnetic hyperfine fields ([B] site subspectrum displays a broadening). Thus, the subspectra belonging to octahedrally coordinated iron cations

![Image](80x574 to 321x772)

![Image](348x121 to 590x319)

![Image](356x437 to 458x766)
were fitted with a broad field distribution characterized by Gaussian width of the magnetic field component $\sigma \sim 1.9$ T. On the other hand, local magnetic fields experienced by Fe$^{3+}$ (A) are independent of the detailed distribution of magnetic [B]-site nearest neighbours [47–49]. Thus, the (A)-site lines were fitted with a narrow field distribution characterized by Gaussian width of about 0.4 T. The spectra of all the samples show two well-defined sextets belonging to the tetrahedral and octahedral sites of Fe$^{3+}$ ions, which confirm that the synthesized materials possess inverse spinel structure. The sextet with the lower isomer shift and hyperfine field values corresponds to the tetrahedral sites and the higher isomer shift and hyperfine field values exhibit the octahedral sites. The measured values of isomer shift (IS), quadrupole splitting (QS), magnetic hyperfine field ($B$), Lorentzian line width ($\Gamma$), relative intensity ($I$) and degree of inversion ($\lambda$) are given in Table 3.

It is well known that the isomer shift of Fe$^{2+}$ and Fe$^{3+}$ ions lies within a range of 0.6–1.7 mm s$^{-1}$ and 0.1–0.5 mm s$^{-1}$, respectively. The isomer shift values given in Table 3 enumerate that the iron ions in CuFe$_2$O$_4$/xCeO$_2$ (x = 0, 1, 5, 10, 20 wt%) samples are present only in the Fe$^{3+}$ state. Due to Ce$^{4+}$ substitution interestingly, no change in the oxidation state of iron ions is observed in all the samples. There is no systematic change in the isomer shift values of all the systems, which implies that the s-electron density is not much altered with the CeO$_2$ addition. The values of quadrupole splitting of the composites are negligibly small, which is attributed to the overall symmetry of the Fe$^{3+}$ surroundings, which is maintained with the addition of CeO$_2$. Compared with all the nanocomposites, the parent CuFe$_2$O$_4$ exhibited a slightly enhanced value of QS, which indicates an altered distribution of ionic charges in the sub-lattices [50].

**Table 3**

Mössbauer parameters of the CuFe$_2$O$_4$/xCeO$_2$ (x = 0, 1, 5, 10, 20 wt%) samples measured at room temperature

<table>
<thead>
<tr>
<th>Compounds</th>
<th>Mössbauer parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IS$_{AA}$ (mm s$^{-1}$)</td>
</tr>
<tr>
<td>CuFe$_2$O$_4$</td>
<td>0.1396 (67)</td>
</tr>
<tr>
<td>CuFe$_2$O$_4$/1 wt% CeO$_2$</td>
<td>0.1462 (39)</td>
</tr>
<tr>
<td>CuFe$_2$O$_4$/5 wt% CeO$_2$</td>
<td>0.1395 (64)</td>
</tr>
<tr>
<td>CuFe$_2$O$_4$/10 wt% CeO$_2$</td>
<td>0.1414 (66)</td>
</tr>
<tr>
<td>CuFe$_2$O$_4$/20 wt% CeO$_2$</td>
<td>0.1416 (47)</td>
</tr>
</tbody>
</table>

IS: the average isomer shift; QS: the average quadrupole splitting; $B$: the average magnetic hyperfine field; $\Gamma$: Lorentzian line half-width; $I$: relative intensity; $\lambda$: the degree of inversion.
The hyperfine field values of (A)-sites are slightly increased with increasing concentration of CeO₂, but no remarkable change is observed for (B)-site hyperfine magnetic fields. The average values of the hyperfine magnetic fields experienced by iron ions in the two sub-lattices are about 47.1 and 49.2 T, respectively, for all the CuFe₂O₄/CeO₂ composites. These values are characteristic for ferric (Fe³⁺) ions in tetrahedral and octahedral sub-lattices of CuFe₂O₄ spinel [51]. The values of the degree of inversion (Table 3) clearly indicate that the addition of CeO₂ caused the migration of some of the iron ions from (B)-site to (A)-site.

4. Conclusions

This is an ever first attempt to synthesize CuFe₂O₄/CeO₂ nanocomposites by simple combustion method. XRD analysis confirms that the synthesized CuFe₂O₄/CeO₂ materials have the tetragonal structure and the composite behaviour. FT-IR spectra reveal the stretching vibration of the Fe–O and Ce–O bonds. The observed optical band gap values confirmed that the synthesized CuFe₂O₄/CeO₂ nanocomposites decreases with increasing concentration of CeO₂. The ac and dielectric constant values decrease with increasing concentration of CeO₂, but no remarkable change is observed for [B]-site hyperfine magnetic fields experienced by iron ions in the two sub-lattices are about 47.1 and 49.2 T, respectively, for all the CuFe₂O₄/CeO₂ composites. These values are characteristic for ferric (Fe³⁺) ions in tetrahedral and octahedral sub-lattices of CuFe₂O₄ spinel [51]. The values of the degree of inversion (Table 3) clearly indicate that the addition of CeO₂ caused the migration of some of the iron ions from (B)-site to (A)-site.

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