Conventional synthesis of perovskite structured LaTixFe1-xO3: A comprehensive evaluation on phase formation, opto-magnetic, and dielectrical properties

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Research Article

**Keywords:** LaFeO3 perovskites, Conventional solid-state reaction, Rietveld refinement, Optical bandgap, photoluminescence, dielectric and magnetic behaviour

**DOI:** https://doi.org/10.21203/rs.3.rs-44211/v1

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Abstract

In the current study, we report a comprehensive evaluation of the microstructures, optical, dielectric and magnetic traits of Ti-substituted perovskite structured lanthanum ferrite with chemical compositions LaTi$_x$Fe$_{1-x}$O$_3$ (x = 0, 0.05, 0.15, 0.25). X-ray diffraction with Rietveld refinement and Raman analysis confirmed that both pure and Ti-substituted LaFeO$_3$ maintained single-phase orthorhombic phase with Pbnm symmetry. Fourier transform infrared spectroscopy (FTIR) studies revealed the information about the positions of the ions and their bonds within the lattice structure of the LaFeO$_3$. The spherical shaped morphology of all products was confirmed by SEM. The quantitative chemical composition and their distribution were confirmed by EDAX and mapping. The UV-Vis spectroscopic studies showed an excitonic absorption edge at 590 nm is ascribed to the electronic transition from O$_{2p}$→Fe$_{3d}$. Optical band gap (E$_g$) values were assessed by applying Tauc schemes, showed that E$_g$ values are in a narrow range (1.85–2.02 eV). The dielectric properties such as, dielectric constant ($\varepsilon'$), dielectric loss (tan $\delta$) was examined by varying with temperature and frequency. The magnetic results revealed weak ferromagnetic nature trait at 300 K. The variation in Ms (saturation magnetization), Hc (coercivity) and Mr (remanence) values were observed with increasing Ti substitution level.

1. Introduction

Lanthanum based perovskite oxides are the important class of material widely studied for their fascinating physical properties and variety of applications in vast field [1]. Lanthanum orthoferrite-LaFeO$_3$ has been utilized in a wide range of applications such as magnetic memory devices, sensors, hard disk drives, transducers, electrolytes and electrodes in solid oxide fuel cells [2–5]. The ABO$_3$-type of LaFeO$_3$ compound exhibit an orthorhombic perovskite structure at room temperature and an antiferromagnetic behaviour with a high Neel temperature ($T_N$) [6–8]. However, LaFeO$_3$ compound is proficient to accommodate large variety of dopant ions, which may occupy A or B site and modify their physio-chemical properties. Further, physical nature of the dopants has greater influences on physical properties, and it can be tuned easily [9–11]. In addition, substitution or doped at different sites of LaFeO$_3$ leads to decrease in their crystallite size and increases the surface area thus results in enhanced photocatalytic activity and magnetization [12, 13].

Recently, Ti substituted LaFeO$_3$ by different synthesis method was reported by various research groups, the visible light photocatalytic properties of LaFeO$_3$ by adding TiO$_2$ synthesized by hydrothermal method demonstrated by dhinesh kumar et al[14]. The exchange bias effect in Ti doped SrFeO$_3$ nanocrystalline compounds, reveals the ferromagnetic and antiferromagnetic interactions based on super exchange and ferromagnetic double exchange interactions [15]. The electrical properties and enhanced multi-functional properties of the oxide materials was achieved by adding dopants [5]. The magnetization of LaFeO$_3$ compounds increased with decreasing particle size and the shift in Curie temperature ($T_C$) was observed [4]. It has been reported that both the doping and synthesis technique might decrease the crystallite size thus results improved magnetization.
To improve the electrical properties of LaFeO$_3$ compounds different kinds of substitutions La$_{0.5}$Al$_{0.5}$FeO$_3$ [16], La$_{1-x}$Zn$_x$FeO$_3$ [17], La$_{1/3}$Sr$_{2/3}$FeO$_{3-d}$ [18], LaZn$_x$Fe$_{1-x}$O$_3$ [19, 20], La$_{1-x}$Ca$_x$FeO$_{3-d}$ [21], La$_{0.8}$Sr$_{0.2}$Fe$_{1-x}$Cu$_x$O$_{3-d}$ [22] on A and/or B site was done and investigated intensively. These materials shown stimulating and interesting properties such as extraordinary electrical conductivity, good thermal stability, high dielectric constant, piezoelectricity or ferroelectricity and low dielectric loss. Thus, the substitution of di-valent or tri-valent ions in lanthanum or iron sub-lattices has been precisely examined [21,23,24]. Accordingly, physical properties could be improved or modified specifically by the selection of appropriate doping at La$^{3+}$ or Fe$^{3+}$ site. In recently, a significant amount of dedication was remunerated to the perovskite-type ABO$_3$ transition-metal oxides (TMOs) in photocatalytic field due to its trivial band gap (2.0–2.5 eV) and high chemical stability. In order to enhance the physical properties of the LaFeO$_3$ compounds various ways have been used to synthesis such as co-precipitation technique [25], polymer pyrolysis method [5], hydrothermal method [26], polymerizable complex route [27], and microwave assisted method [28]. Identifying the suitable dopants and optimized synthesis procedure could make LaFeO$_3$ is potential multifunctional material.

Hence, primary focus of the present work is to investigate the effect of substituting Ti on the structural, optical, dielectric and magnetic properties of LaTi$_x$Fe$_{1-x}$O$_3$ (x = 0, 0.05, 0.15, 0.25) ceramic powders synthesized by conventional solid-state reaction method. One of the advantages of this method is lower manufacturing cost and simplicity. The conventional synthesized samples are characterized by powder X-ray diffractometer (XRD) with Rietveld refinement, Fourier transform infrared (FTIR) and Raman spectroscopy for evaluation of phase formation. The morphology, elemental composition and their distribution of the prepared samples were studied by scanning electron microscopy (SEM) with energy dispersive analysis (EDX). The UV–Vis and Photo luminescence (PL) spectroscopic techniques were analysed about the optical properties of synthesized samples. The electrical properties of the synthesized samples with respect to temperature were investigated. The magnetic properties of Ti-doped LaFeO$_3$ samples were analysed using a Vibrated sample magnetometer (VSM) at room temperature. Interestingly, it was found that Ti substituted LaFeO$_3$ considerably enhances the magnetization of LaFeO$_3$ in x = 0.05 and x = 0.25.

2. Experimental

2.1 Materials and synthesis

Lanthanum (III) oxide (La$_2$O$_3$), Iron oxide (Fe$_2$O$_3$), Titanium oxide (TiO$_2$) precursors were used as a starting material (Sigma-Aldrich with 99.9% purity).

The title compounds LaTi$_x$Fe$_{1-x}$O$_3$, (x = 0, 0.05, 0.15, 0.25) are prepared using conventional solid-state reaction method. The selected starting materials were weighed in the preferred stoichiometric proportion and well grounded (~ 1 hour) using agate mortar to produce a uniform fine powder. Then calcined at 900 °C for 12 hours, after the powders were well grounded, kept in an alumina crucible and sintered at
1000 °C for 6 hours with intermediate grinding. The prepared ferrite samples were permitted to cool down to room temperature at the rate of 5 °C/minute to attain homogeneity. Finally, the prepared ferrite powders were sintered at 1100 °C for 6 hour and grounded well then subjected to various physical property measurements. The synthesized ferrite powders were pelletized using hydraulic press and used for dielectric measurements.

2.2 Characterizations

The structural formation and phase evaluation of the prepared powders were analyzed using Bruker D2 Phaser X-ray diffractometer with Cu Kα (1.5418 Å) radiation. The XRD patterns were recorded in the 2θ range from 20 to 70°. Phase identifications were screened against the International Center for Diffraction Data (ICDD) PDF-4 database. The structural constraints, bond angle and bond length were obtained from the FULLPROF Rietveld refinement of the recorded XRD profiles. FTIR spectra were recorded from 500 to 1750 cm⁻¹ using Bruker Alpha FTIR Spectrophotometer. Raman spectra were recorded at room temperature over the range of 100–1000 cm⁻¹ using HR-800 UV Spectrophotometer in Horiba Jobin-Yvon, with an excitation wavelength of 488 nm using He-Ne laser. The surface morphology, elemental mapping and quantitative analyses of the prepared samples were studied using JEOL ZEM Scanning Electron Microscopy (SEM) equipped with energy dispersive spectrometer (EDX). The UV-Vis absorption spectra were carried out using Perkin-Elmer spectrophotometer (200–800 nm). The PL emission spectra was recorded using 'Horiba Jobin-Yvon Fluoromax 4 spectro fluorometer. Magnetic measurements were done by Lakeshore (MODEL-7407) vibrating sample magnetometer (VSM) at room temperature. The frequency and temperature dependent dielectric measurements were carried out by Wayne Kerr-LCR 4275 in the frequency range of 10 Hz to 1 MHz.

3. Results And Discussion

3.1. Powder X-ray Diffraction Analysis

Figure 1a shows the XRD patterns of Ti substituted LaFeO₃ ferrite powders. All synthesized samples reveal the peaks reliable to the standard orthorhombic structure of LaFeO₃ (JCPDS No. 037-1493) with space group Pbnm. From the diffraction pattern, the prepared powders are well crystalline in nature. In addition, all the peaks are shifted towards higher (2θ) angle, whereas the highest Ti (x = 0.15) substitution shows the shift at higher (2θ) angle with peak broadening, this may be ascribed to the lattice distortion and variation in their ionic radius as shown in Fig. 1b. From these observations, lattice constants decrease with increasing in amount of Ti substitution owing to smaller radius of the substituents compared with higher value of host lattice. The refined crystallographic parameters such as \( R_p, R_{wp}, R_{exp}, \chi^2 \) along with unit cell constraints are listed in Table 1. The average crystallite size of the synthesized sample is evaluated using Scherrer's formula [29]:
The crystallite size was calculating from high intensity peak (200) at 32.2°. The crystallite size was
decreases with increases of Ti concentration except (x = 0.15) which may suggest that the x = 0.15 is the
right degree of substitution concentration for La-Fe-O lattice as mentioned in Table 1. It is seen that
average bond distances of Fe-O are 2.00 Å, 2.00 Å, 1.88 Å and 1.99 Å for (x = 0 to 0.25) respectively. The
minimum and maximum bond distances of O-La are 2.37 Å and 3.27 Å for pristine LaFeO₃, then 2.42 Å
and 3.15 Å is for (x = 0.05), 2.41 Å and 3.08 Å (x = 0.15), 2.42 Å and 3.08 Å (x = 0.25) correspondingly. The
observed small inconsistencies among bond distances and lattice parameters at presence of Ti in
LaFeO₃ is due to strain, difference in ionic radius. Hence, the XRD analysis confirm the formation of
LaFeO₃ perovskite structure and substitution of Ti without altering the crystal structure.

3.2. FTIR analysis

The FTIR spectra of prepared Ti substituted LaFeO₃ ferrite powders displayed in Fig. 2. The spectra
illustrated the strong and broad vibrational band at 550–600 cm⁻¹, which is ascribed to the
antisymmetric stretching vibrations of Fe-O and O-Fe-O of FeO₆ octahedral and tetrahedral units of
perovskite ABO₃ [30]. Typically, IR bands from 300–1000 cm⁻¹ are allocated to the vibration of inorganic
ions in the crystal system. The existence of a band around 560 cm⁻¹ strongly suggests the Me-O in
tetrahedral sites [31], which emphasis that the La-Ti crystalline are essentially formed and the materials
prepared at higher temperature indicate better crystalline nature.

3.3. Raman spectroscopy analysis

Figure 3 shows the Raman spectra of LaTiₓFe₁₋ₓO₃ (x = 0, 0.05, 0.15, 0.25) synthesized compounds.
Gradual changes observed in the raman spectra can be associated to the alteration of local structural
disorders. Since, LaFeO₃ belongs to orthorhombic structure with Pbnm space group. The predicted raman
modes by group theory given as [32],

\[
\Gamma_{\text{opt,Pbnm}}=7A_{g}(R) + 7B_{1g}(R) + 5B_{2g}(R) + 5B_{3g}(R) + 8A_{u}(S) + 7B_{1u}(IR) + 9B_{2u}(IR) + 9B_{3u}(IR) + B_{1u}(ac) + B_{2u}(ac) + B_{3u}(ac) 
\]

Out of these, only A₉, B₁g, B₂g and B₃g are 24 Raman active modes and B₁u, B₂u and B₃u are 25 IR active
modes. Where R, IR, ac and S are Raman active, infrared active, acoustic and silent modes respectively.
Among all, 60 normal modes and 24 are Raman active modes \((7A_g + 7B_{1g} + 5B_{2g} + 5B_{3g})\) [32].

To extract more information from raman spectra lorentzian fit was used and the parameters are listed in Table 2. On deconvolution, the peak location of each component, that is the regular frequency \((\text{cm}^{-1})\) of each Raman active modes are shown in Fig. 4. With the LaFeO\(_3\) system have peaks around 146 cm\(^{-1}\), 171 cm\(^{-1}\), 284 cm\(^{-1}\), 425 cm\(^{-1}\), 630 cm\(^{-1}\) and 785 cm\(^{-1}\) the appearance of an additional \(A_g\) and \(B_g\) modes. Similarly, \(A_g\) and \(B_g\) modes at 150 cm\(^{-1}\), 436 cm\(^{-1}\) are completely available in all compounds. As shown in Fig. 4, the peak at 150 cm\(^{-1}\) shifted to 153 cm\(^{-1}\), the peaks 141 cm\(^{-1}\), 165 cm\(^{-1}\), 171 cm\(^{-1}\) are merged 150 cm\(^{-1}\) and the peak at 624 cm\(^{-1}\) shifted to 778 cm\(^{-1}\) as the substituting concentration was increased to 0.25. As displayed Fig. 4, the increasing intensity of the peak at 624 cm\(^{-1}\) also reveals that the motions of LaFeO\(_3\) were affected by Ti substituting, the small variation in position of strong band and induced newer Raman active bands 687 cm\(^{-1}\) and 778 cm\(^{-1}\) confirm the incorporation of Ti in the LaFeO\(_3\) lattice.

### 3.4. Morphology and compositional analysis

Figure 5(a-d) demonstrate the SEM images of synthesized ferrite powders. Well recognized micro structural features and morphology was achieved. The SEM images exhibited that the microstructures comprised of submicron level particle. The pristine LaFeO\(_3\) sample seemed to be small agglomerated spherical particles. In all Ti substituted LaFeO\(_3\) compounds clearly exhibit the spherical-shaped particles and it can be understood from Fig. 5(a-d). The modification in morphological behaviour of prepared ferrites could be owing to consequence of substituting Ti concentration. Energy dispersive X-ray analysis (EDX) was assisted to examine the purity and chemical composition of prepared Ti substituted LaFeO\(_3\) ferrite powders, the shape of calcined synthesized samples is exposed in Fig. 5(a-d). In this investigation, lanthanum (La), iron (Fe), oxygen (O) and titanium (Ti) were present in the prepared samples and elemental distributions were clearly shown in Fig. 6(a-d).

### 3.5. Optical properties

Figure 7 presents the UV-Visible spectra of prepared La-Ti ferrite powders in the wavelength range of 200–800 nm, recorded at room temperature. The strong absorption edge at 590 nm is ascribed to the electronic transition from the valence state to the conduction state, \(O_{2p} \rightarrow Fe_{3d}\). In Fig. 8 indicates the absorbance spectra allows to calculate the optical bandgap of the compound established on the absorption edge perceived at 590 nm and it was found to be 2.10 eV using Tauc equation [33].

\[
\alpha h\nu = A(h\nu-E_g)^n
\]

\(\alpha\) is absorption coefficient, \(E_g\) is the direct bandgap, \(h\nu\) is the photon energy and \(A\) is a constant. The extrapolation of the linear parts of curve toward absorption equal to zero gives \(E_g\) for direct transitions. The evaluated optical bandgaps are observed in the range of 1.85–2.02 eV. The results are in reliable with
the earlier reported value of 2.10 eV. These small bandgap values of the prepared compounds are interesting for photocatalytic applications [25].

### 3.6. Photoluminescence Studies

Figure 9 shows the emission and excitation spectra for a prepared perovskite ferrite samples. Excitation spectra corresponding to 356 nm and it transition $^1S_0 \rightarrow ^3P_1$ is shown in Fig. 9 (inset). Broad emission peak centered at 388 nm reveals the characteristic of La$^{3+}$-O$^{2-}$ charge transfer process, along with sharp peaks due to intra f transitions of La$^{3+}$ ion, including $^3P_2 \rightarrow ^1S_0$ (388 to 441 nm), $^3P_1 \rightarrow ^1S_0$ (450 & 476 nm) respectively. The sharp peak at 388 nm is attributed to $^3P_2 \rightarrow ^1S_0$ transition. The intensity of the peak 388 nm is stronger than the others, which are related to the emission wavelengths of near UV chips. The charge transfers band (CTB) excitation sharp peak reflects the electronic excitation of O$^{2-}$→La$^{3+}$ and O$^{2-}$→Fe$^{3+}$, whose intensity was the highest among all the excitation sharp peaks. Furthermore, the f-f transitions show that energy is efficiently transferred to the La-Fe-O host lattice. The related wavelength of the excitation peaks of La ions 4f levels is the same as that found in the literature [34–36]. The detailed Ti substituted LaFeO$_3$ electronic transitions with the index are listed in Table 3. In relation to the energy level diagram of the optical transitions within Ti, Fe ions schematically represented by Fig. 10, such emission bands correspond to the transitions of La, Ti and Fe ions, which are mainly contributed by the intra band transition of 4f configurations in rare earth elements. Strong La$^{3+}$ emission has been observed from the samples on exciting at the charge transfer peak maximum. Then the emission spectra results suggest that the potential candidates for making light emitting materials and photocatalytic applications [35].

### 3.7. Dielectric Measurement

Figure 13 and 14 shows the temperature dependence dielectric constant and tangent loss for all the prepared LaTi$_{1-x}$Fe$_x$O$_3$ ($x = 0, 0.05, 0.15, 0.25$) ferrite compounds. The frequency range could be perceived that the dielectric constant is intensely dependence on the sintering temperature. For each sample, the dielectric constant increases rapidly at the frequency region between 10 Hz to 100 KHz and the become constants at higher frequency region. From Figs. 12 and 14, the increasing of Ti concentration, the dielectric loss decreases which depends on the frequency as well as temperature. Generally, the four types of electrical polarization processes (electronic, ionic, dipolar, and interfacial polarization or space charge polarization) give the dielectric properties [38–40]. At lower frequency region, all types of polarization process can follow the modification of external field, giving enhancement to a high dielectric constant [41]. The frequency increases, space charge polarization process gradually intervals behind the change of external field, and dielectric constant going to be down. Further increasing the frequency, space charge polarization process cannot make any response to the external field, for this reason, the dielectric constant becomes constant at higher frequency region. In the pristine LaFeO$_3$ compounds for the origin of giant dielectric properties revealed by Idrees et.al, [40]. The dielectric constant of the prepared materials can be expressed as following equation,
\[ \varepsilon' = \frac{C_p d}{\varepsilon_0 A} \]

(3)

D-is the thickness of disc sample, \( C_p \)-is the capacitance, \( \varepsilon_0 \) is the permittivity, A is the cross-sectional area of disc sample [42]. The frequency dependence of \( \varepsilon' \) and \( \tan \delta \) of the prepared materials between \( 10^2 \) and \( 10^6 \) Hz measured in different temperatures and plotted in Figs. 11 and 12. These prepared ferrites demonstrated giant dielectric constant of (values) at 100 Hz matching with the grain size increases. Dielectric relaxation in these materials is ascribed to the electron hopping between \( \text{Fe}^{3+} \) and \( \text{Fe}^{4+} \), which is associated to that of pristine LaFeO_{3} ferrite as reported earlier [40]. This electron hopping mechanism is accountable for the polarization, foremost to the giant dielectric constant in LaFeO_{3} systems. Generally, high \( \varepsilon' \) values have been described by Khetre et.al and Mantas [41, 43]. High dielectric constant values in low frequencies it may be owing to the existence of space charge polarization [41].

3.8. Magnetic property analysis

The M-H loop of the prepared LaTi_{x}Fe_{1-x}O_{3} (x = 0, 0.05, 0.15, 0.25) ferrite powders are shown in Fig. 15. The substitution of non-magnetic Ti ions has a different site occupancy which decreases of the exchange interaction between B sites. Hence, by increasing the Ti concentration, it is possible to vary the magnetic properties of the prepared ferrite materials. Usually, LaFeO_{3} have been confirmed a canted antiferromagnetic (AFM) nature with a Neel temperature at 740 K. Commonly, La^{3+} is nonmagnetic but subsequently all the electrons were paired. The main source of the magnetic properties is presented by magnetic moments of Fe. Hence, the ferromagnetic behavior of pure LaFeO_{3} is due to the spin canted magnetic moments of Fe, which are arises from disordered surface spins [44]. Further, this performance is owing to the uncompensated spin which makes ferromagnetic shell surrounding the antiferromagnetic core, consequential in a net magnetization. For the prepared samples, Ti^{4+} ions have 3d^{0} valence electrons that cannot contribute to ferromagnetic ordering. At higher contents of Ti, there could be decrease in the particle size and coercivity (Hc), which may increase the number of uncompensated spins, thus results in an improved magnetization. Some researchers have described the transposed relation of coercivity, and crystallite size based on domain theory [45]. In the present investigation, similar results were observed. Stoner-Wolfforth model clearly demonstrated that role of single domains and multidomains on their coercivity value as the particle size decreases, their Hc values also decreases [45–48]. From Table 4, the coercivity is higher for pristine LaFeO_{3} compound. As Ti substituted in La-Fe-O lattice, the coercivity values decreases. Conversely at \( x = 0.15 \), coercivity value increases, this may be due to the effect of Ti on crystallite size and shape, further increase in Ti concentration, there is a decrease in their values. All the prepared samples exhibit weak ferromagnetic behavior and pure sample shows high magnetization associated with 0.05 to 0.25 Ti concentration. The magnetic parameters Ms, Mr, squareness ratio, Hc and anisotropy constant values are listed in Table 4. The existence of secondary phases and high concentrations of nonmagnetic ions (Ti^{4+}) can hide the domain wall motion [25]. The
coercivity (Hc), saturation magnetization (Ms) values are decreases and increasing the nonmagnetic cations.

The observed change in magnetic properties, may be due to a high antiferromagnetic spin alignment of Fe$^{3+}$-O$^{2-}$-Fe$^{3+}$ and Fe$^{4+}$-O$^{2-}$-Fe$^{4+}$ super exchange interaction [25]. The substitution of Ti$^{4+}$ ions may create a greater number of Fe$^{3+}$ ions to ensure the charge impartiality which may enhance the double exchange (DE) interactions that results in higher magnetization (x = 0.25) [26]. The magnetization value is maximum at substitution of Ti (x = 0.25). Hence, the prepared materials may find useful for magnetic memory storage device applications.

4. Conclusion

The influences of Ti ion on structural, optical, magnetic and dielectric properties of LaFeO$_3$ with different concentrations was investigated. The LaFeO$_3$ ferrite powders were prepared by conventional solid-state reaction method. The refined structural parameters were revealing the structural information. The Me-O vibrations and local structural disorder were examined by Fourier transform infrared and Raman spectroscopy. SEM analysis was exhibits poly crystalline nature of prepared compounds. The optical and PL spectra clearly shows the effect of Ti on host lattice. The magnetic measurements were demonstrated the weak ferromagnetic behaviour of the prepared samples. We found that the coercivity is found to be maximum for pristine LaFeO$_3$. Then it, accordingly, decreases on substituting Ti content, except for x = 0.15. this probably understood in terms of variation in their crystallite size. Hence, from the above results, we have concluded that the prepared compounds are may useful for spintronics, magnetic memory devices applications.

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Tables
Table 1
Structural constraints, bond angle and bond length of LaTi$_x$Fe$_{1-x}$O$_3$ ($x = 0, 0.05, 0.15, 0.25$) as tabulated from the Rietveld analysis.

| Structural parameters | $x = 0$  | $x = 0.05$ | $x = 0.15$ | $x = 0.25$ |
|-----------------------|----------|------------|------------|------------|
| $a$ (Å)               | 5.5595   | 5.5520     | 5.5477     | 5.5438     |
| $b$ (Å)               | 5.5694   | 5.5630     | 5.5543     | 5.5552     |
| $c$ (Å)               | 7.8603   | 7.8430     | 7.8556     | 7.8505     |
| Volume                | 243.70   | 243.39     | 242.06     | 241.77     |
| $W_{Rp}$ (%)          | 14.4     | 15.6       | 14.8       | 14.8       |
| $W_{p}$ (%)           | 9.88     | 10.6       | 11.1       | 10.2       |
| $\chi^2$              | 1.91     | 3.32       | 6.11       | 3.39       |
| $R_{exp}$             | 7.15     | 5.80       | 4.50       | 5.56       |
| $\alpha$              | 90       | 90         | 90         | 90         |
| $\beta$               | 90       | 90         | 90         | 90         |
| $\gamma$              | 90       | 90         | 90         | 90         |
| Crystallite size (nm) | 98       | 79         | 59         | 72         |
| Fe – O bond length (Å)| 2.00     | 2.00       | 1.88       | 1.99       |
| Minimum Fe – O bond length (Å) | 2.37 | 2.42 | 2.41 | 2.42 |
| Maximum Fe – O bond length (Å) | 3.27 | 3.15 | 3.08 | 3.08 |
Table 2  
Symmetry assignments of LaTi$_x$Fe$_{1-x}$O$_3$ (x = 0, 0.05, 0.15, 0.25) ceramic compounds.

|                  | LaFeO$_3$ | LaTi$_{0.05}$Fe$_{0.95}$O$_3$ | LaTi$_{0.15}$Fe$_{0.85}$O$_3$ | LaTi$_{0.25}$Fe$_{0.75}$O$_3$ |
|------------------|----------|-------------------------------|-------------------------------|-------------------------------|
| 146 (A$_g$)      |          |                               | 141 (A$_g$)                   |                               |
| 150 (A$_g$)      |          | 153 (A$_g$)                   |                               | 153 (A$_g$)                   |
| 165 (B$_g$)      |          |                               |                               |                               |
| 171 (A$_g$)      |          | 171 (B$_g$)                   |                               |                               |
| 284 (A$_g$)      |          | 293 (A$_g$)                   | 284 (A$_g$)                   | 274 (B$_g$)                   |
| 425 (B$_g$)      |          | 432 (B$_g$)                   | 449 (B$_g$)                   | 436 (B$_g$)                   |
| 501 (A$_g$)      |          |                               |                               |                               |
| 630 (A$_g$)      |          | 624 (A$_g$)                   | 673 (A$_g$)                   | 687 (A$_g$)                   |
| 785 (B$_g$)      | 791 (B$_g$) | 771 (B$_g$)                   | 778 (B$_g$)                   |                               |

Table 3  
Details of emission spectra of LaTi$_x$Fe$_{1-x}$O$_3$ (x = 0, 0.05, 0.15, 0.25) ceramic compounds.

| Wavelength (nm) | Energy (eV) | Wavenumber (cm$^{-1}$) | Transition     |
|-----------------|-------------|------------------------|----------------|
| 388             | 3.19        | 25773                  | $^3P_2\rightarrow^1S_0$ |
| 408             | 3.03        | 24509                  | $^3P_2\rightarrow^1S_0$ |
| 415             | 2.98        | 24096                  | $^3P_2\rightarrow^1S_0$ |
| 428             | 2.89        | 23364                  | $^3P_2\rightarrow^1S_0$ |
| 433             | 2.86        | 23094                  | $^3P_2\rightarrow^1S_0$ |
| 441             | 2.81        | 22675                  | $^3P_2\rightarrow^1S_0$ |
| 450             | 2.75        | 22222                  | $^3P_1\rightarrow^1S_0$ |
| 476             | 2.60        | 21008                  | $^3P_1\rightarrow^1S_0$ |
Table 4
Magnetic parameters of La\textsubscript{Ti\textsubscript{x}}\textsubscript{Fe\textsubscript{1-x}}O\textsubscript{3} (x = 0, 0.05, 0.15, 0.25) ceramic compounds

| Sample       | Ms (emu/g) | Mr (emu/g) | Mr/Ms | Hc (Oe) | Anisotropy constant (K) |
|--------------|------------|------------|-------|---------|-------------------------|
| LaFeO\textsubscript{3} | 0.108      | 0.01       | 0.093 | 1409    | 158.52                  |
| LaTi\textsubscript{0.05}Fe\textsubscript{0.95}O\textsubscript{3} | 2.971      | 0.232      | 0.078 | 749     | 2074.02                 |
| LaTi\textsubscript{0.15}Fe\textsubscript{0.85}O\textsubscript{3} | 0.129      | 0.0212     | 0.165 | 1231    | 49.148                  |
| LaTi\textsubscript{0.25}Fe\textsubscript{0.75}O\textsubscript{3} | 3.101      | 0.332      | 0.107 | 805     | 12.230                  |

Figures

Figure 1

A. Rietveld refinement patterns of synthesized LaTixFe1-xO3 (x=0, 0.05, 0.15, 0.25) ceramic samples. B. XRD patterns enlarged view of (200) high intensity peak of synthesized LaTixFe1-xO3 (x=0, 0.05, 0.15, 0.25) ceramic compounds
Figure 2

FTIR spectrum of synthesized LaTixFe1-xO3 (x=0, 0.05, 0.15, 0.25) ceramic samples.
Figure 3

Raman spectra obtained from LaTi_xFe_{1-x}O_3 (x=0, 0.05, 0.15, 0.25) ceramic compounds.
Figure 4

Fitting curves of the Raman signal for the LaTixFe1-xO3 (x=0, 0.05, 0.15, 0.25) ceramic compounds with Lorentzian line shapes. The Black lines with shapes are experimental data, the strong curves with green shade with shapes are the fitting of Lorentzian shapes and the solid curves with red shade with shapes are the total intensities of the Lorentzian lines.

Figure 5

A. SEM images of synthesized LaTixFe1-xO3 (x=0, 0.05, 0.15, 0.25) (a-d) ferrite samples. B. Energy Dispersive X-ray (EDX) pattern of synthesized LaTixFe1-xO3 (x=0, 0.05, 0.15, 0.25) (a-d) ferrite samples.
Figure 6

Elemental mapping: column (1) the area of mapping, (2) iron distribution, (3) lanthanum distribution, (4) oxygen distribution, and (5) titanium distribution of the synthesized LaTixFe1-xO3, row wise (a) x=0, row (b) x=0.05, row (c) x=0.15, row (d) x=0.25, row of ferrite samples.
Figure 7

UV-Vis absorbance spectra of synthesized LaTi\textsubscript{x}Fe\textsubscript{1-x}O\textsubscript{3} (x=0, 0.05, 0.15, 0.25) ferrite samples.
Figure 8

Tauc plots of $(\alpha h v)^2$ versus photon energy ($h v$) of synthesized LaTi$_{x}$Fe$_{1-x}$O$_3$ ($x=0, 0.05, 0.15, 0.25$) ferrite samples.
Figure 9

The photoluminescence excitation (inset) and emission spectra of LaTixFe1-xO3 (x=0, 0.05, 0.15, 0.25) ceramic compounds.
Figure 10

Schematic Energy level diagram of the optical transitions within LaTixFe1-xO3 (x=0, 0.05, 0.15, 0.25) derived from using the Rare Earth Handbook [37].
Figure 11

Frequency dependence of dielectric constant of the synthesized (a-d) LaTi$_x$Fe$_{1-x}$O$_3$ (x=0, 0.05, 0.15, 0.25) samples.
Figure 12

Frequency dependence of dielectric loss of the synthesized (a-d) LaTixFe1-xO3 (x=0, 0.05, 0.15, 0.25) samples.
Figure 13

Temperature dependence of dielectric constant of the synthesized (a-d) LaTixFe1-xO3 (x=0, 0.05, 0.15, 0.25) samples.
Figure 14

Temperature dependence of dielectric loss of the synthesized (a-d) LaTixFe1-xO3 (x=0, 0.05, 0.15, 0.25) samples.
Figure 15

Hysteresis loops of synthesized LaTixFe1-xO3 (x=0, 0.05, 0.15, 0.25) ceramic compounds at room temperature.