Compositional-driven multiferroic and magnetoelectric properties of NdFeO$_3$-PbTiO$_3$ solid solutions

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ABSTRACT

Synthesis of polycrystalline (Pb$_{1-x}$Nd$_x$(Ti$_1$Fe$_x$)O$_3$) for $x = 0.21$–0.30 solid solutions using solid-state reaction method has been reported. The structural, dielectric, ferroelectric, magnetic, and magnetoelectric properties of the resulting solid solutions have been investigated in detail. The XRD data show that the phase transition occurs at $0.27 \leq x \leq 0.28$ at room temperature. The dielectric studies show that the transition temperature continuously decreases with increasing “x”. So it is clearly evident from XRD and dielectric data that the tetragonal to cubic phase transition occurs at $x = 0.27$ to $x = 0.28$ at room temperature. The remnant polarization ($P_r$) decreases from 19.78 $\mu$C/cm$^2$ to 11.13 $\mu$C/cm$^2$ gradually up to $x = 0.25$ whereas other samples exhibit lossy behavior. The remnant magnetization ($M_r$) continuously increases from 0.068 emu/g to 0.467 emu/g with composition. All samples exhibit a positive magnetoelectric effect which is the strongest in $x = 0.22$ sample.

1. Introduction

The switching of polarization with the magnetic field and magnetization with the electric field in multiferroics makes them important candidates for various technological applications such as spintronic devices, information storage devices, actuators, etc. [1–13]. The presence of transition metal cations having partially filled d-shell accounts for the magnetic behavior of these materials (d$^n$ configuration) and the presence of transition metal cations containing empty d-orbital imparts them simultaneous ferroelectric behavior (d$^0$ configuration) [14–16]. These are contradictory requirements and that is why very few materials exhibit multiferroicity. Due to the technological importance of these types of materials, the search for new materials exhibiting both magnetic and electric orders in a single phase is always on. The potential materials for exploring these contrasting requirements are mixed perovskite materials synthesized by substituting d$^n$ ions in the good ferroelectric material.

Lead titanate (PT) is well-known ferroelectric material having a highly distorted perovskite structure (c/a = 1.064). The ferroelectric transition temperature of PbTiO$_3$ is ~760 K making it the most important parent compound for the synthesis of mixed perovskite materials [17,18]. It has been reported that magnetic character can be introduced in purely ferroelectric materials by substitution of the magnetic ion at B-site [19]. However, the substitution of transition metals (Fe) at the Ti site is also known to enhance the leakage current which generally deteriorates the ferroelectric properties of even strongly ferroelectric materials [20]. The issue of the leakage current can be resolved by carrying out simultaneous lanthanide substitution at A-site [21,22]. Multiferroicity can hence be introduced with PT by combing it with Neodymium ferrite (NdFeO$_3$) (an orthoferrite) where Fe$^{3+}$ will impart magnetic character to the material and Nd$^{3+}$ will keep leakage current in check. Neodymium ferrite has an orthorhombic crystal structure with antiferromagnetic ordering, $T_N$ 760 K [23,24]. We recently reported the multiferroic properties of (NdFeO$_{3.7}$PbTiO$_{3.3}$) binary solid solutions [25]. Peng et al. reported the structural, ferroelectric, and magnetic properties of (1-x) PbTiO$_3$-xNdFeO$_3$ solid solutions. They reported that solid solutions undergo a structural phase transition from tetragonal to pseudocubic from $x = 0.3$–0.5. A simultaneous decrease in the remnant polarization ($P_r$) from 2.74 to 0.78 $\mu$C/cm$^2$ as x increases from 0.2 to 0.3 is also reported by them [18]. However, a sudden decrease of $P_r$ from 2.74 to 0.78 $\mu$C/cm$^2$ as x varies from 0.2 to 0.3 has to be related to either a structural transition or a decrease in grain size but they are reporting the structural transformation between $x = 0.3$–0.5. This makes it critical to investigate the (1-
x)PbTiO$_3$-xNdFeO$_3$ system for x varying between 0.21 and 0.30.

In the present work, we report the synthesis of (Pb$_{1-x}$Nd$_x$)(Ti$_{1-x}$Fe$_x$)O$_3$ (for $x = 0.21$–0.30) solid solutions using a conventional solid-state reaction route. The structural, ferroelectric, dielectric, magnetic, and magnetoelectric properties of resulting solid solutions have been discussed in detail.

2. Experimental

The (Pb$_{1-x}$Nd$_x$)(Ti$_{1-x}$Fe$_x$)O$_3$ where ($x = 0.21$–0.30) solid solutions were synthesized using conventional solid-state reaction route. The raw materials Nd$_2$O$_3$, PbO, TiO$_2$, and Fe$_2$O$_3$ (99.9% pure) from Sigma-Aldrich were weighed in stoichiometric proportions and mixed using mortar and pestle for 1 hour. These mixed powders were transferred to a bottle containing propanol as a medium and zirconia balls and ball-milled successively for 12 hours in a simple ball and planetary ball mill, respectively. The mixed powders were calcined at 1100°C for 12 hours for the phase formation. The calcined powders were then mixed with polyvinyl alcohol (2 wt %) as a binder. The binder-mixed powder was then pressed in the form of pellets of 10 mm diameter and thickness ~1 mm. The pellets were then sintered at 1200°C temperature for 2 hours in a closed crucible furnace in the presence of a lead environment to reduce the concentration of lead due to its volatility at a high temperature. The XRD data over the sintered samples were collected from 10° to 120° at a step size of 0.02° and at a scan speed of 2θ/min using Shimadzu (Maxima) diffractometer equipped with Cu Ka ($\lambda = 1.54 \, \text{Å}$). The surface morphology was investigated using FE-SEM (Supra 55) from Carl Zeiss at the same magnification of 10 KX using InLens detector and accelerating voltage of 10 kV. The ferroelectric properties were measured by using an automatic PE loop tracer from Marine India. The dielectric studies were done using an impedance analyzer (E4990A) from KEYSIGHT TECHNOLOGIES. The room temperature magnetic measurements were done using vibrating sample magnetometer (VSM) EZ9 from MicroSense. The magnetoelectric study was confirmed by performing polarization vs. electric field measurement in the absence and presence of a magnetic field using an automatic PE loop tracer.

3. Result and discussion

Figure 1 shows the room temperature X-ray diffractograms of (Pb$_{1-x}$Nd$_x$)(Ti$_{1-x}$Fe$_x$)O$_3$ (for $x = 0.21$–0.30) samples for 2θ varying from 45°–60°. The sharp and high-intensity diffraction peaks show the crystalline nature of all the samples. It is clear from the figure that the reflections at 2θ ~46.4° and 52.3° are doublets (peak separation decreases with increasing x) for $x \leq 0.25$ and appears to be singlet for $x \geq 0.28$. For $x = 0.26$ and 0.27, these two peaks merge resulting in asymmetric broadening of these peaks toward the lower 2θ region. Nearly similar behavior is displayed by the reflection at 2θ ~ 57.6°. The clear doublet separation (for $x \leq 0.25$), asymmetric broadening (for $x = 0.26$ and 0.27), and singlet peaks (for $x \geq 0.28$) imply a gradual transition of crystal structure from lower symmetry toward higher symmetry. Thus we expect that for $x \leq 0.27$, the crystal structure is similar to PbTiO$_3$ (tetragonal with space group P4mm) while for $x \geq 0.28$, the crystal structure is simple cubic (space group Pm3m).

In order to retrieve further structural information about these solid solutions, the Rietveld refinement of the experimental data was carried out using

Figure 1. Room temperature X-ray diffractograms of (Pb$_{1-x}$Nd$_x$)(Ti$_{1-x}$Fe$_x$)O$_3$ (for $x = 0.21$–0.30) samples.
FULLPROF suite software. The Rietveld refinement was carried out using the P4mm space group for $x \leq 0.27$ and the Pm3m space group for $x \geq 0.28$ compositions. The initial parameters for P4mm were taken to be those reported by Kumar et al. [25] and for Pm3m were taken to be those reported by Peng et al. [18]. A Thompson Cox Hastings function with axial divergence symmetry was used to model peak profiles. The background was fitted using a sixth-order polynomial. The scale factor, zero displacements, lattice parameters, the atomic position of Ti, Fe, and O (O1 and OII) atoms were taken as refinement parameters. Figure 2 (a–g) and (h–j) shows the observed, calculated, and difference data obtained from Rietveld refinement of XRD data of (Pb$_{1-x}$Nd$_x$)(Ti$_{1-x}$Fe$_x$)O$_3$ for $x = 0.21$–0.27 (tetragonal with space group P4mm) and $x = 0.28$–0.30 (cubic with space group Pm3m) samples, respectively. The refined data (Red circles are shown in Figure 2 (a–g) and (h–j)) match quite well with experimental data. The nice agreement between the observed and Rietveld refined data shows that the initial model has been properly refined. The systematic variation of “a” and “c” parameters, c/a ratio, and cell volume (obtained from Rietveld refinement) as a function of composition (x) are shown in Figure 3. It is clear that the lattice parameter “a” continuously increases whereas “c” continuously decreases with increasing “x” which results in a decrease in c/a ratio. The c/a ratio keeps on decreasing till $x = 0.28$, at which it becomes 1. This implies a tetragonal to pseudocubic transformation (for $x \geq 0.28$) in the present case. It is also to be noted that Peng et al. reported the tetragonal to cubic phase transition for $x = 0.3$–0.5 in (1-x)PbTiO$_3$xNdFeO$_3$ solid solutions [18]. The refined lattice parameters, c/a ratio, R-factors, $B_{iso}$, polarization (calculated from atomic position), the atomic position of various atoms, cell volume have been summarized in Table 1.

The scanning electron microscopy (SEM) micrographs of (Pb$_{1-x}$Nd$_x$)(Ti$_{1-x}$Fe$_x$)O$_3$ for $x = 0.21$–0.25, and $x = 0.26$–0.30 samples are shown in Figure 4 (a–e) and (f–j), respectively. The images clearly reveal that the microstructure consists of very small, homogenous, randomly oriented, well-interlinked, and non-uniform (in shape and size) grains. The experimental density was measured to be

![Figure 2](image-url)
whereas the theoretical density is \(~7.90 \text{ g/cm}^3\). The close match between experimentally measured and theoretical expected density value shows that all the samples have been proper sintered. The size of the grains has been calculated using Image J software. The approximate
Figure 3. The systematic variation of “a” and “c” parameters, c/a ratio and cell volume of (Pb$_{1-x}$Nd$_x$)(Ti$_{1-x}$Fe$_x$)O$_3$ (for $x = 0.21$–$0.30$) samples.
Table 1. The refined lattice parameters, R-factors, atomic positions of various atoms, c/a ratio, volume, $B_{iso}$, and polarization (calculated from atomic position) of (Pb$_{1-x}$Nd$_x$)(Ti$_x$Fe$_{1-x}$)O$_3$ for $x = 0.21$–0.30 solid solutions.

| Sample | Cell Parameters (Å$^3$) | Position Coordinates | $B_{iso}$ | R-factors | Polarization (μC/cm$^2$) |
|--------|-------------------------|----------------------|------------|-----------|--------------------------|
| $x = 0.21$ | a = b = 3.924 Pb/Nd(1a) | 0 0 0 | 0.529 | $R_p = 4.91$ | 2.63 |
| | c = 3.980 Ti/Fe(1b) | 0.5 0.5 | 0.5837 | 0.112 | $R_{wp} = 6.28$ |
| | c/a = 1.014 O1(1b) | 0.5 0.5 | 0.1625 | 0.709 | $R_{wp} = 4.75$ |
| | $V = 61.30$ Å$^3$ | O2(2c) | 0.5 0.5 | 0.5116 | 0.708 | $χ^2 = 1.75$ |
| $x = 0.22$ | a = b = 3.921 Pb/Nd(1a) | 0 0 0 | 0.523 | $R_p = 4.57$ | 2.68 |
| | c = 3.973 Ti/Fe(1b) | 0.5 0.5 | 0.5852 | 0.125 | $R_{wp} = 5.83$ |
| | c/a = 1.013 O1(1b) | 0.5 0.5 | 0.1670 | 0.676 | $R_{wp} = 4.47$ |
| | $V = 61.09$ Å$^3$ | O2(2c) | 0.5 0.5 | 0.5089 | 0.711 | $χ^2 = 1.70$ |
| $x = 0.23$ | a = b = 3.922 Pb/Nd(1a) | 0 0 0 | 0.982 | $R_p = 5.04$ | 2.62 |
| | c = 3.964 Ti/Fe(1b) | 0.5 0.5 | 0.5828 | 0.273 | $R_{wp} = 6.41$ | 2.61 |
| | c/a = 1.010 O1(1b) | 0.5 0.5 | 0.1607 | 1.664 | $R_{wp} = 4.99$ |
| | $V = 60.86$ Å$^3$ | O2(2c) | 0.5 0.5 | 0.5142 | 0.533 | $χ^2 = 1.39$ |
| $x = 0.25$ | a = b = 3.922 Pb/Nd(1a) | 0 0 0 | 0.583 | $R_p = 4.87$ | 2.61 |
| | c = 3.956 Ti/Fe(1b) | 0.5 0.5 | 0.5822 | 0.087 | $R_{wp} = 6.17$ |
| | c/a = 1.008 O1(1b) | 0.5 0.5 | 0.1595 | 0.664 | $R_{wp} = 5.38$ |
| | $V = 60.85$ Å$^3$ | O2(2c) | 0.5 0.5 | 0.5142 | 0.533 | $χ^2 = 1.38$ |
| $x = 0.26$ | a = b = 3.926 Pb/Nd(1a) | 0 0 0 | 0.622 | $R_p = 4.36$ | 2.58 |
| | c = 3.937 Ti/Fe(1b) | 0.5 0.5 | 0.5818 | 0.098 | $R_{wp} = 5.51$ |
| | c/a = 1.002 O1(1b) | 0.5 0.5 | 0.1563 | 0.534 | $R_{wp} = 4.68$ |
| | $V = 60.71$ Å$^3$ | O2(2c) | 0.5 0.5 | 0.5135 | 0.454 | $χ^2 = 1.38$ |
| $x = 0.27$ | a = b = 3.925 Pb/Nd(1a) | 0 0 0 | 0.623 | $R_p = 4.19$ | 2.56 |
| | c = 3.934 Ti/Fe(1b) | 0.5 0.5 | 0.5819 | 0.097 | $R_{wp} = 5.34$ |
| | c/a = 1.002 O1(1b) | 0.5 0.5 | 0.1537 | 0.369 | $R_{wp} = 4.44$ |
| | $V = 60.63$ Å$^3$ | O2(2c) | 0.5 0.5 | 0.5149 | 0.382 | $χ^2 = 1.45$ |
| $x = 0.28$ | a = b = c = 3.927 Pb/Nd(1a) | 0 0 0 | 1.914 | $R_p = 5.75$ | Cubic |
| | c/a = 1.00 Ti/Fe(1b) | 0.5 0.5 | 0.134 | 1.760 | $R_{wp} = 7.60$ |
| | $V = 60.49$ Å$^3$ | O3(3c) | 0.5 0.5 | 0.384 | 4.34 | $χ^2 = 1.83$ |
| $x = 0.29$ | a = b = c = 3.925 Pb/Nd(1a) | 0 0 0 | 1.01 | $R_p = 4.81$ | Cubic |
| | c/a = 1.00 Ti/Fe(1b) | 0.5 0.5 | 0.125 | 1.25 | $R_{wp} = 6.29$ |
| | $V = 60.49$ Å$^3$ | O3(3x) | 0.5 0.5 | 3.64 | 4.53 | $χ^2 = 1.92$ |
| $x = 0.30$ | a = b = c = 3.925 Pb/Nd(1a) | 0 0 0 | 1.785 | $R_p = 5.75$ | Cubic |
| | c/a = 1.00 Ti/Fe(1b) | 0.5 0.5 | 1.147 | 7.76 | $R_{wp} = 7.76$ |
| | $V = 60.49$ Å$^3$ | O3(3x) | 0.5 0.5 | 4.02 | 4.63 | $χ^2 = 1.85$ |

The value of the grain size for samples $x = 0.21$–0.30 are 1.5, 1.9, 2.5, 1.5, 1.9, 1.8, 2.8, 1.5, 2.8, and 2.6 μm, respectively. The size and the densities of the grains (both experimental and theoretical) and the compactness of the grains show that samples are well sintered.

Polarization versus electric field (P-E) hysteresis loops of (Pb$_{1-x}$Nd$_x$)(Ti$_x$Fe$_{1-x}$)O$_3$ (for $x = 0.21$–0.27) samples were measured at room temperature and are shown in Figure 5. It is clear from the figure that the samples exhibit proper hysteresis behavior up to $x = 0.25$ and the loops become lossy for $x > 0.25$. The lossy behavior of $x = 0.26$ and 0.27 samples can be due to decreased lattice distortion and enhanced leakage current. The remnant polarization ($P_r$) decreases from 19.78μC/cm$^2$ to 11.13μC/cm$^2$ as “x” varies from 0.21 to 0.25. This decrease in remnant polarization ($P_r$) can be correlated to a simultaneous decrease in c/a ratio from 1.014 ($x = 0.21$) to 1.008 ($x = 0.25$) as discussed in structural studies. The ferroelectric hysteresis loops for $x = 0.26$ to $x = 0.27$ are lossy in nature due to enhanced leakage current effects. The values of remnant polarization ($P_r$) and spontaneous polarization ($P_s$) of all samples are summarized in Table 2.
the phase transition from tetragonal to cubic at $x = 0.28$ which is directly supported by XRD data. The temperature-dependent loss tangent ($\tan \delta$) for $x = 0.21$ to $x = 0.28$ samples has been shown in Figure 7. The enlarged view from $x = 0.21$ to 0.24 samples has also been shown in the inset of 7 (a–d). The graphs clearly depict that the loss tangent ($\tan \delta$) is continuously increasing with "$x$" which is inconsistent with the ferroelectric hysteresis loops as shown in Figure 5. The P-E loops exhibit non-lossy nature for $x \leq 0.25$ samples whereas for $x = 0.26$ and 0.27 samples the loops show lossy nature. However, samples $x = 0.26$ and 0.27 exhibit tetragonal phase but due to the presence of large value of loss tangent the hysteresis loops are lossy in nature.

Figure 8 shows the room temperature magnetization hysteresis loops for ($Pb_{1-x}Nd_x)(Ti_{1-x}Fe_x)O_3$ (for $x = 0.21$–0.30) samples. It is clear from the figure that all the samples exhibit hysteresis loops, implying the presence of magnetic order. The presence of the
magnetic behavior in these samples may be attributed to the substitution of the magnetic ion (Fe$^{3+}$ having five unpaired electrons in d-shell) at B-site. The value of remnant magnetization ($M_r$) has been observed to continuously increase from ~0.065 emu/g to 0.469 emu/g as $x$ increases from 0.21 to 0.30 as given in Table 3. This enhancement in the remnant magnetization is due to an increase in the concentration of Fe$^{3+}$ with increasing $x$. The value of remnant magnetization in our sample is 0.469 emu/g (for $x = 0.30$) is much better than the value of reported by Peng et al. (0.249 emu/g for $x = 0.30$) [18]. This may be due to the using of optimized processing parameters such as sintering temperature and sintering time while sample preparation process [25].

The measurement of the magnetoelectric (ME) response represents a measure of the strength of magneto-electric coupling. The magneto-electric response is defined as [25].

$$\text{Magnetoelectric response (ME)} = \frac{P_r(H) - P_r(0)}{P_r(0)} \times 100\%$$

where $P_r (H)$ and $P_r (0)$ represent the electric polarization in the presence and absence of magnetic field (H), respectively. It is to be noted that
The magneto-electric studies were performed for 0.21 ≤ x ≤ 0.25 as these samples exhibit ferroelectric behavior. The magnetoelectric response of these samples was studied by carrying out the polarization (P) versus electric field (E) measurements in the absence and presence of the external magnetic field (2 Tesla). The polarization versus electric field plots, in the presence and absence of the magnetic field, are shown in Figure 9. The plots clearly reveal that the polarization measured in the presence of the magnetic field is larger than the polarization measured in the absence of a magnetic field for all samples. This implies the presence of positive magnetoelectric coupling in our samples. The magneto-electric response for 0.21 ≤ x ≤ 0.25 samples is summarized in Table 4. The best ME effect has been observed for x = 0.22 sample. The sample x = 0.22 exhibits a large value of both remnant magnetization and remnant polarization. Since the ME effect is the product of magnetic susceptibility and electric susceptibility, the sample x = 0.22 exhibits the maximum value of ME effect. The origin of magnetoelectric coupling in multiferroic materials may be attributed to the simultaneous presence of electric and magnetic domains. When the external magnetic field is applied to multiferroic materials, the material will get strained. Due to coupling between magnetic and ferroelectric domains, the strain will induce stress thereby generating an electric field on the

**Figure 5.** Polarization vs. Electric field plots of Pb_{1-x}Nd_x(Ti_{1-x}Fe_x)O_3 (for x = 0.21–0.27) samples.

**Table 2.** The remanent polarization (P_r) and spontaneous polarization (P_s) of (Pb_{1-x}Nd_x)(Ti_{1-x}Fe_x)O_3 for x = 0.21–0.25 solid solutions.

| Composition | P_r (µC/cm²) | P_s (µC/cm²) |
|-------------|--------------|--------------|
| x = 0.21    | 19.78        | 20.74        |
| x = 0.22    | 17.17        | 17.95        |
| x = 0.23    | 15.69        | 15.71        |
| x = 0.24    | 11.97        | 12.88        |
| x = 0.25    | 11.13        | 11.60        |
Figure 6. The plots of the temperature dependence of permittivity ($\varepsilon'$) at different frequencies of $\text{(Pb}_{1-x}\text{Nd}_{x}\text{)}\text{(Ti}_{1-x}\text{Fe}_x\text{)}\text{O}_3}$ (for $x = 0.21–0.28$).

Figure 7. The plots of the temperature dependence of loss tangent (Tan $\delta$) at different frequencies of $\text{(Pb}_{1-x}\text{Nd}_{x}\text{)}\text{(Ti}_{1-x}\text{Fe}_x\text{)}\text{O}_3}$ (for $x = 0.21–0.28$).
ferroelectric domains. As a consequence, the ferroelectric properties of the material get modified [26–29].

4. Conclusions

Single-phase (Pb$_{1-x}$Nd$_x$)(Ti$_{1-x}$Fe$_x$)O$_3$ (for $x = 0.21–0.30$) solid solutions have been synthesized using solid-state reaction route. X-ray diffraction data confirm that the samples are phase pure and exhibit tetragonal structure (with P4mm space group) for $x \leq 0.27$ and pseudocubic structure (with Pm3m space group) for $x \geq 0.28$. The scanning electron microscopy (SEM) micrographs reveal that the microstructure consists of very small, homogenous, randomly oriented, well-interlinked, and non-uniform grains. The gradual decrease in ferroelectric transition temperature (from ~432K for $x = 0.21$ to ~305K for $x = 0.27$ sample) with composition correlates nicely with decreasing c/a ratio as calculated from diffraction data. The gradual decrease in remnant polarization from 19.78 µC/cm$^2$ to 11.13 µC/cm$^2$ as “$x$” varies from 0.21 to 0.25 has been explained in terms of decreasing c/a ratio and enhanced leakage current value due to Fe$^{3+}$ incorporation. The enhancement in remnant magnetization value from ~0.065 emu/g to 0.469 emu/g has been observed as “$x$” increases from 0.21 to 0.30. This type of behavior has been explained in terms of increasing Fe$^{3+}$ ion concentration. All the samples have been found to exhibit a positive magnetoelectric effect which is the strongest in $x = 0.22$ sample.

Table 3. The remanent magnetization ($M_r$) of (Pb$_{1-x}$Nd$_x$)(Ti$_{1-x}$Fe$_x$)O$_3$ for $x = 0.21–0.30$ solid solutions.

| Sample Name | $M_r$ (emu/g) |
|-------------|---------------|
| $x = 0.21$  | 0.068         |
| $x = 0.22$  | 0.089         |
| $x = 0.23$  | 0.129         |
| $x = 0.24$  | 0.130         |
| $x = 0.25$  | 0.216         |
| $x = 0.26$  | 0.231         |
| $x = 0.27$  | 0.318         |
| $x = 0.28$  | 0.397         |
| $x = 0.29$  | 0.464         |
| $x = 0.30$  | 0.467         |

Figure 8. Magnetization (M) vs. Magnetic field (H) plots at room temperature of (Pb$_{1-x}$Nd$_x$)(Ti$_{1-x}$Fe$_x$)O$_3$ (for $x = 0.21–0.30$) samples.
Figure 9. The Polarization vs. Electric field plots in the absence and presence of magnetic field (in Tesla) for \((\text{Pb}_{1-x}\text{Nd}_{x})(\text{Ti}_{1-x}\text{Fe}_x)\text{O}_3\) (for \(x = 0.21-0.25\)).
Table 4. The $P_r$ (0), $P_t$ (H), and ME response $(P_r(H)-P_t(0))/P_t(0) \times 100$ of $(Pb_{1-x}Nd_x)(Ti_{1-x}Fe_x)O_3$ for $x = 0.21$–0.25 solid solutions.

| Composition | $P_r$ (0) | $P_t$ (H) | $(P_r(H)-P_t(0))/P_t(0) \times 100$ |
|-------------|-----------|-----------|----------------------------------|
| $x = 0.21$  | 19.78     | 20.32     | 2.7%                             |
| $x = 0.22$  | 17.17     | 19.39     | 12.9%                            |
| $x = 0.23$  | 15.69     | 15.96     | 1.7%                             |
| $x = 0.24$  | 11.97     | 12.44     | 3.9%                             |
| $x = 0.25$  | 11.13     | 11.44     | 2.7%                             |

Magnetoelectric effect has been explained in terms of the magnetic field induced strain in the material.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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