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Detection of electromagnetic radiation in ferroelectric ceramics for non-contact sensing applications

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ABSTRACT

This paper presents some preliminary investigation of electromagnetic radiation (EMR) emissions from (1-x)($Bi_{0.5}Na_{0.5}TiO_3$)–x($BaTiO_3$) (x = 0.04, 0.05, 0.06, 0.07 & 0.08) lead-free piezoelectric ceramics. Compositions near the morphotropic phase boundary 0.94($Bi_{0.5}Na_{0.5}TiO_3$)–0.06($BaTiO_3$) (BNT-6BT) are studied. The electromagnetic radiations were detected with the help of non–contacting loop antenna placed around the sample. EMR voltage detection was done simultaneously when the piezoelectric material was subjected to alternating electric field. Digital storage oscilloscope was used to measure the EMR voltage. At highest applied alternating electric field of 5.8 kV/cm EMR Signal of 17.6 V was detected for 0.95($Bi_{0.5}Na_{0.5}TiO_3$)–0.05($BaTiO_3$) (BNT-5BT). Higher frequency of the electric field leads to the higher acceleration of the dipoles of the piezoelectric material and thus leads to the higher amplitude of EMR. The EMR Voltage is observed to be proportional to the polarization and this can lead to the development of new technique of measuring extent of polarization. Also the EMR phenomenon can be used to develop sensors for non-contact excessive deformation measurement.

1. Introduction

Piezoelectric materials have a wide range of applications such as energy harvesting [1–3], vibration and noise control [4,5], ultrasonic cleaners [6], biomedical applications [7–9]. Most of the piezoelectric materials being used in practical applications except for quartz are ferroelectric materials which give a ferroelectric hysteresis loop and have remnant polarization. Lead-based materials have been popular for their excellent properties [10–12]. However lead being a toxic element the lead-based piezoelectric materials are now restricted because of the environmental issues. Therefore the research towards the development of the lead-free piezoelectric materials is demanded worldwide as they offer easy fabrication with control free atmosphere and pollution free sintering.

There have been numerous studies in this direction which suggest some possible lead-free materials with good piezoelectric properties. Some authors have reported high piezoelectric properties for potassium sodium niobate (K,Na)NbO_3 (KNN) based lead-free piezoelectric ceramics [13,14]. One of the lead-free piezoelectric materials is bismuth sodium titanate BNT is a strong ferroelectric which possess high mechanical strength and high Curie temperature [15,16]. Improved piezoelectric response of barium titanate (BT) based ferroelectric ceramics has been reported by some authors [10,17–20]. Pure BNT ceramics are limited by some other shortcomings such as low relative permittivity, narrow sintering temperature range and high conductivity at room temperature. Properties of BNT ceramics can be improved by preparing solid solution with various perovskites such as strontium titanate (ST), barium titanate (BT), Bismuth potassium titanate (BKT), Barium Zirconate (BZ) etc. [18,21]. One of the ceramic $Bi_{0.5}Na_{0.5}TiO_3$–$BaTiO_3$–$K_{0.5}Na_{0.5}NbO_3$ (BNT–BT–KNN) produces strain of about 0.45% at room temperature due to antiferroelectric–ferroelectric transition as reported by some authors [22]. Lead-free BNKT ceramics have been studied by various authors for their Piezoelectric properties [23,24]. Additionally lead-free ceramics bismuth sodium titanate-barium titanate (1-x) ($Bi_{0.5}Na_{0.5}TiO_3$)–x ($BaTiO_3$) known as BNT-BT exhibits large polarization, high temperature dielectric constant and high piezoelectric behavior [25,26]. One of the BNT-BT ceramic 0.94($Bi_{0.5}Na_{0.5}TiO_3$)-0.06($BaTiO_3$) possesses good piezoelectric property as reported by some authors [27,28]. A number of reports are available on the morphotropic phase boundary (MPB) in (1-x)($Bi_{0.5}Na_{0.5}TiO_3$)–x($BaTiO_3$) (x = 0.06) with maximum piezoelectric and dielectric

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constants [26,29–31]. In case of BNT-BT, MPB is a transformation line where rhombohedral and tetragonal phases coexists giving rise to enhance piezoelectric properties [31]. So, MPB composition i.e. BNT-6BT and compositions in its vicinity are studied.

Ferroelectric materials have the unique tendency of getting polarized up on application of the applied electric field. The properties/efficiency of a ferroelectric material is decided based on the extent to which it can be polarized. For this the ferroelectric hysteresis loop is generally studied by applying the alternating electric field. Ferroelectric materials get polarized under the externally applied electric field. The polarization occurs due to the alignment of the dipoles existing within the ferroelectric materials along the direction of applied field. When acted up on by the alternating electric field the dipoles within the ferroelectric material will oscillate and thereby it is expected that the material will emit electromagnetic radiation (EMR). This EMR could be used for developing non-contact sensors which can be used for structural health monitoring. Embedding the piezoelectric materials in the structures will lead a way towards the development of smart structures which will allow continuous and efficient monitoring [32,33]. Besides, lead-free piezoelectric ceramics have been found to be a suitable alternate in developing environmental friendly smart systems [33]. Based on the above reported properties of lead-free BNT-BT ceramics and considering the increasing interest in the recent years towards the development of eco-friendly smart structures, it is important to investigate the EMR emission from such materials. Therefore, the present study is a step forward for developing eco-friendly sensors by obtaining EMR signals from the piezoelectric materials with simplest possible instrumentations rather than obtaining the current signals.

2. Experimental procedure

2.1. Materials and characterization

In this paper varying compositions of (1-x)($Bi_{0.5}Na_{0.5}TiO_3$)–x($BaTiO_3$) ($0.04 \leq x \leq 0.08$) viz. 0.96($Bi_{0.5}Na_{0.5}TiO_3$)–0.04($BaTiO_3$), 0.95($Bi_{0.5}Na_{0.5}TiO_3$)–0.05($BaTiO_3$), 0.94($Bi_{0.5}Na_{0.5}TiO_3$)–0.06($BaTiO_3$), 0.93($Bi_{0.5}Na_{0.5}TiO_3$)–0.07($BaTiO_3$) and 0.92($Bi_{0.5}Na_{0.5}TiO_3$)–0.08($BaTiO_3$) designated as BNT-4BT, BNT-5BT, BNT-6BT, BNT-7BT and BNT-8BT respectively have been used to study the electromagnetic radiation phenomenon. BNT-BT ceramics were prepared by using conventional solid route mixture method. The raw materials used to prepare ceramics were $Bi(OH)_3$ (99.975%), Na_2CO_3 (99.5%), $BaCO_3$ (99.9%) and TiO_2 (99.9%). These raw materials were weighed according to their stoichiometric ratio as per their respective compositions and mixed using mortar-pestle in acetone to obtain physical homogeneity. The mixture was then calcined at 900 °C for 3 h. The calcined powder was then ground and X-ray diffraction was done to characterize the single phase of the calcined powder. The powders were then pressed into green disk with a diameter of 12 mm. For maintaining the uniform thickness of the green disks, 4.5 gm powder of each of the composition was pressed under the pressure of 260 MPa in a die of diameter 12 mm. This resulted in a uniform thickness of 8 mm of the green pellets. The green pellets were then sintered at 1100 °C in covered alumina crucibles for 3 h. Before sintering the surfaces of the green pellets were smeared with their corresponding powder to prevent the evaporation of Bi^{3+} and Na^{+} ions. The current study is aimed at suggesting the materials giving better radiation performance, which could be incorporated in some structural material. The incorporation of these materials into the structural materials will be easiest when mixed in powder form. Considering this the unpoled samples of the (1-x)BNT-xBT have been chosen for the study. Unpoled samples were coated with silver paste on both the opposite flat faces which act as electrodes. The electrodes were connected to the Sawyer–Tower loop tracer to apply alternating electric field to the sample. The Sawyer Tower loop tracer has a capacity of 5 kV. Thus for a 1 cm thick specimen the highest applied voltage will be 5 kV/cm. However the electric field required for causing the domain switching to the saturation is generally of the order of 50 kV/cm for the (1- x)BNT-xBT ceramics. Thus to check whether the (1-*x*)BNT-*x*BT samples prepared actually get polarized up to saturation or not thin samples of thickness 0.81 mm were separately prepared for all the compositions being studied.

2.2. Instrumentation

The electrodes of the unpoled samples were connected to the Sawyer–Tower loop tracer having capacity of 5 kV to apply the alternating electric field. Sawyer–tower loop tracer had a facility to plot polarization with electric field (P-E) loop which characterizes ferroelectricity of the sample.

As design of antenna affects the measured EMR signal so, antenna selection should be made carefully such that maximum EMR signals can be detected. The electrically small loop antennas are poor radiators so are generally used in receiving mode, where antenna efficiency is not as important as signal-to-noise ratio [34]. O. Borla et al. has used a circular loop antenna calibrated according to the metrological requirements for detecting EMR emission from rock specimens [35]. V. Jagasivamani and Iyer have employed a cylindrical antenna for measuring the electromagnetic radiation from metallic samples loaded in tension and EMR with a frequency range of 200 Hz to about 10 kHz was detected [36]. A. Misra has used the semi cylindrical antenna for capturing the EMR signals from metallic fracture [37,38]. We have also adopted a similar type of circular loop antenna made of copper. For making the loop antenna a rectangular strip of 8 mm width and 100 mm length was cut from copper sheet of thickness 0.1 mm. It was folded into a circular loop antenna having a diameter of 30 mm and was placed around the sample. The height of the loop antenna was maintained to be such that it was covering the majority of sample surface for maximum EMR detection. The loop antenna was connected to the 1 MΩ impedance probe of the Rohde & Schwarz (Hameg) HMO 2524, 250 MHz/2.5 GSa/4 MB Digital Storage Oscilloscope (DSO) which was used to record the EMR signals. The reference end of the oscilloscope probe was made electrically grounded. Before conducting the experiment the same experimental set up was tested for the environmental noise and noise level was observed to be negligible. The whole experimental set up (including sample, loop antenna, oscilloscope probe and electric cables) was placed at an isolated place in the laboratory so that it remains unaffected by any external environmental factor. Thus chances of triboelectric effect i.e flexing, twisting, transient impacts on cables and rapid changes of capacitance between the conductors are negligible in this case. Schematic diagram of Experimental set up is shown in Fig. 1. X ray diffraction was done using a using Cu-Kα radiation (Rigaku Smart lab, Rigaku Tokyo, Japan). The pattern was collected in the angular range (2θ) of $20^\circ - 90^\circ$ with step size of 0.02°.

3. Results and discussions

The X–ray diffraction pattern of five (1- x)BNT-xBT samples which are used in the present study is shown in Fig. 2. XRD pattern conforms the single phase perovskite structure of the ceramics under study. Archimedes method was used to measure density of the sintered samples and the relative densities of the sintered samples were found to be in the range of 93%–97%.

Takenaka et al. have shown that there is a coexistence of two phases viz. rhombohedral-tetragonal for the MPB composition in