Experimental set up of a magnetoelectric measuring system operating at different temperatures

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Abstract. The magnetoelectric effect is the phenomenon whereby through a magnetic stimulation can be produced an electrical response or vice versa. We implement a magnetoelectric voltage measuring device through the dynamic method for a different range of temperatures. The system was split into an electric set and an instrumentation and control set. Design and element selection criteria that the experimenter must take into account are presented, with special emphasis in the design of the sample holder, which is the fundamental component that differentiates the system operating at high temperature and the one operating at room temperature. The experimental equipment consists of an electromagnet with DC magnetic flux density (B) in a range of (0.0 to 1.6) KOe, a Helmholtz coil which operates with a sinusoidal B between (0.0 and 0.016) KOe and a PT100 temperature sensor. A tubular heating resistance, a Checkman temperature control and an SSR 40A were used for controlling the temperature. As an application of the system, the transverse and longitudinal magnetoelectric coefficient was measured for a thin film of $BiFeO_3$ at room temperature and 307K. It was observed that the behaviour of the longitudinal and transverse magnetoelectric coefficient matches the reported value and decreased with increasing temperature.

1. Introduction

The magnetoelectric effect is the phenomenon whereby a magnetic field (H) produces an electrical polarization, or an electric field (E) produces a magnetization. This effect has drawn attention from the scientific community because of their potential applications in the new generation of magnetic field detectors, sensors, transducers and improvements in magnetic storage [1]. The experimental methods for measuring the magnetoelectric coefficient (α_{ME}) are the static, quasi-static, dynamic and pulsed dynamic methods [2]. For the dynamic method, the sample is subjected to the action of a superimposed AC field in a variable DC magnetic field, which generates at the ends of the material a voltage response (ME signal) which permits to obtain, based on Equation 1, the α_{ME} value indirectly [3]. This method has had a great reception since it reduces the problems of charge accumulation at the edge of the sample. The magnetoelectric coefficient expression is given by:

$$\alpha_{ME} = \frac{V}{h_0 d} \tag{1}$$

Where h_0 is the amplitude of the applied AC magnetic field, d is the sample thickness and V is the voltage measured at the ends of the test specimen [2].

For the design and implementation of a α_{ME} coefficient measurement system through the dynamic method, two effects can be take into account, depending on the material to be studied. Single phase materials have a weak response and require low temperatures measurements while composites can be measured at room temperature (RT) and high temperature.

The aim of this work is to perform a comparative analysis of a magnetoelectric system implemented by the dynamic method, which operates at different temperatures. The voltage signal generated across the ends of a sample with magnetoelectric response, particularly using a $BiFeO_3$ thin film, is studied.

2. Materials and methods

2.1. Design criteria for the DC magnetic field generator
- Depending on the maximum density of the magnetic flux generated by a DC electromagnet, set the current range in which to operate the DC source that feeds it.
- Define the range of the DC magnetic flux density (B_{DC}) with which the sample is stimulated.
- Set the size of the AC coil, which will define the separation between the electromagnet's cores.

2.2. Design Criteria for the AC magnetic field generator
- Set the maximum value of the AC magnetic flow density (B_{AC}), which depends on the maximum current to be generated and the geometrical characteristics of the AC Helmholtz coil.
- Define the operation range of the AC source that depends on the desired maximum B_{AC}, set the type of wave to be generated, ensuring high stability and accuracy, also establish the operating frequency range.
- Set the size of the thin film to be studied, which will determine the radius of the AC coil.

2.3. Design criteria for the instrumentation and control
This set should treat the signal from the DC source and condition the ME signal and the Hall signal, the design criteria are:
- For the control of the DC power source, it must be guaranteed: linearity, stability and flexibility in managing the sampling time.
- Ensure synchronicity between the B_{DC} growth and the displayed voltage signal generated by the sample.
- Depending on the instrumental characteristics of the Hall sensor, determine the maximum value of B_{DC} in order to measure the DC field.

2.4. Magnetoelectric measuring system operating at room and high temperature
For implementing a measurement system operating at different temperatures, using the dynamic method, the system was divided into two functional units, an electrical assembly and instrumentation and control set. The first functional unit contains the generators B_{DC} and B_{AC}; while the second regulates the electrical signals from the electric set, the EM signal and the Hall signal. The curve is displayed via a user interface developed in LabVIEW.

2.4.1. Sample holder design criteria at low and high temperature
- Depending on the size of the sample, define the size of the sample holder and the AC coil.
- Set the temperature range to which the sample will be studied, that defines the thermocouple and resistance heating type that allows varying the temperature.
- To control the temperature, it should be ensured stability and flexibility.

3. Results and discussion

3.1. Magnetoelectric measuring system operating at room temperature

The result of applying the design criteria previously mentioned was studied by setting a device that measures the transverse and longitudinal magnetoelectric coupling in a material. Since the spacing between the cores of the electromagnet is limited by the size of the AC coil (that was previously designed and built); the system operates with a B_{AC} between (0.0 and 0.016) KOe and a B_{DC} in the range of (0.0 to 1.6) KOe. Magnetoelectric coefficient curves as function of the B_{DC} are presented on a user interface developed in LabVIEW. The coefficient was obtained indirectly from the voltage response of the material, which is amplified and limited in band, to improve the signal-to-noise ratio. Figures 1 and 2 exhibit the experimental setup and the sample holder employed, respectively.
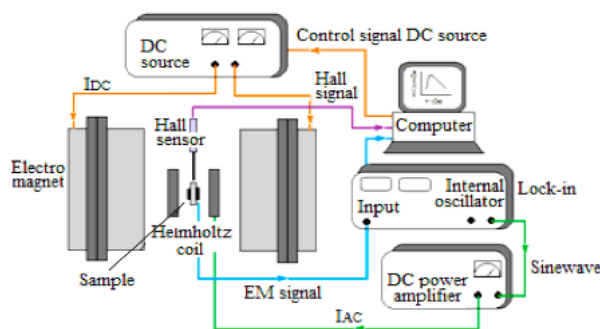

Figure 1. Experimental setup of a ME measurement system operating at room and high temperature.

3.2. Magnetoelectric measuring system operating at high temperature

This system differs from the one that operates at room temperature in the sample holder and the temperature control system. This control was implemented so the user can operate at the desired temperature. Figure 3 presents the design of the sample holder, which has three sections. The innermost containing the sample and the sensor that monitors the material temperature during the α_{ME} measurement and the outer section which has the heat resistance that controls the temperature of the sample. If the ME system operates at low temperatures, the middle section of the sample holder contains the cooling fluid that allows to diminish the temperature.
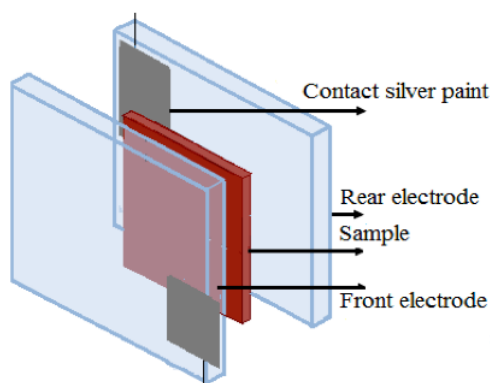

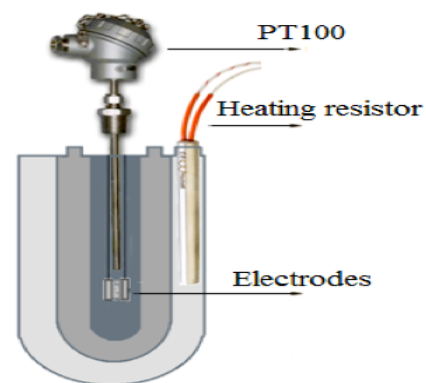**Figure 2.** Sample holder used when the system is operating at RT. Adapted from [4].

Figure 3. Sample holder implemented when the system is operating at lower and higher temperatures than RT.

For the temperature control a tubular heating resistance, a Checkman temperature control, an SSR 40A and a PT100 for measuring temperature, were used. The designed control is limited by the type of

temperature sensor that is connected. In the case of PT100, the working range is from 83K to 874K, which gives flexibility to the equipment to perform magnetoelectric characterizations both at low and high temperature.

3.3. Test run

Figure 4 shows the magnetoelectric response of a thin film of BiFeO$_3$ at 300K (RT) and 307K for a frequency of 200Hz. By comparing the response of the material (except the behaviour of the transverse test at RT), it can be noticed a rapid increase of α_{ME} for DC fields below 0.25KOe and a subsequent saturation can be attributed to the alignment of the electric dipoles induced in the direction of the applied field. At room temperature, saturation values of α_{ME} are 37.5V/cmOe and 109V/cmOe, respectively, in transverse and longitudinal configuration. This behaviour and values are consistent with those reported [5,6]. On the other hand, the response coefficient for both configurations decreases with increasing temperature. We have not come across similar data from the published literature; however, it is possible to infer that there is temperature dependence with the magnetoelectric response in BiFeO$_3$ according to [6].
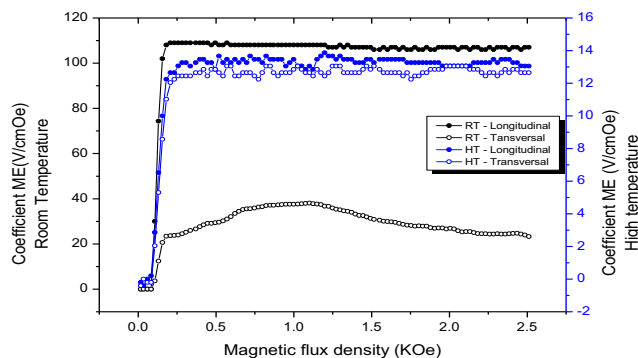

Figure 4. Magnetoelectric coefficient variation depending on the DC magnetic flux density at room temperature and 307K in a sample of BiFeO$_3$ for a frequency of 200Hz.

4. Conclusions

According to the design criteria that were considered, we have implemented a system to measure the magnetoelectric coefficient (α_{ME}) using the dynamic method which operates at different range of temperatures. In order to test the equipment, the behaviour of the longitudinal and transversal magnetolectric coefficient in a thin film of BiFeO$_3$ was observed at high and room temperature. It was noticed that the α_{ME} significantly decreased with the increase of temperature, showing a possible loss of the magnetoelectric characteristic in the specimen.

References

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