

Measuring Magnetoelectric and Magnetopiezoelectric Effects

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Abstract

The authors are characterizing a new test procedure for measuring magnetoelectric properties. The procedure captures the charge generated by a magnetoelectric device when stimulated with a magnetic field. The test is an exact analog to the traditional electrical hysteresis test with the exception that the test instrument cycles a magnetic field across the sample instead of an electric field. The authors found that by mathematically fitting the measured charge curve, predictive equations for the α and the α_{ME} coefficients of the sample may be derived.

I. INTRODUCTION

The ratio of charge to voltage generated by a magnetoelectric capacitor when exposed to a magnetic field is defined as

$$\alpha_{ME} = \delta E / \delta H \quad (1)$$

If a virtual ground charge measurement circuit is connected across the device, the device remains in a constant shorted condition so the magnetoelectric response generates charge instead of voltage. The magnetoelectric coefficient α may be defined either as

$$\alpha = P/H \quad \text{or} \quad \alpha = \delta P / \delta H \quad (2)$$

Ferroelectric hysteresis testers use virtual ground as the input to their measurement circuits so they must determine the magnetoelectric coefficient according to (2). The relationship between α and α_{ME} is defined by the dielectric constant which itself converts electric field to polarization or vice versa.

$$\alpha_{ME} = \alpha / \epsilon_0 \epsilon_r \quad (3)$$

In (3), the α coefficient is in units of polarization per oersted while α_{ME} is in units of electric field per oersted. Dividing polarization by dielectric constant ϵ yields electric field so (3) is consistent in units. Dr. Chee-sung Park, then at the Center for Energy Harvesting Materials and Systems at Virginia Polytechnic University, demonstrated the unity of the charge-based measurement of α with the voltage-based measurement of α_{ME} in 2011.[1] The authors of this experiment explored the charge-based measurement in detail along with possible error sources in a paper recently submitted to Veritas.com.[2] The goal of this experiment was to measure the α coefficient for a sample capacitor for magnetoelectric properties and then derive equations from that result to predict α_{ME} over the tested magnetic field amplitude. Future work will attempt to identify error sources arising in the voltage-based measurement circuits and determine the procedures necessary to ensure close correlation of α and α_{ME} coefficients over a wide range of test conditions and environments.

II. EXPERIMENT

A. Sample Preparation

The sample used for this experiment was fabricated at Virginia Tech by Su Chul Yang of the Center for Energy Harvesting Materials and Systems (CEHMS). The sample consisted of lithium and antimony-doped KNaNbO composited with NiZnFe. The sample was cut into the form of a disk with an area of 0.918 cm² and a thickness of 1.02 mm.

B. Test Configuration

The sample was connected to the virtual ground charge-measurement input of a Radiant Precision Multiferroic tester. The stimulus output of the tester drove a Radiant current source capable of sourcing up to 1.8 amps into a Lakeshore MH-6 six-inch diameter Helmholtz coil. The magnetic field was driven to ± 45 Oersted over a one-second period. No bias field was applied to the sample so the sample saw only the 1 Hz ± 45 Oe

triangle wave during stimulation. To capture the amplitude of the magnetic field during the test, a current sensor was placed in series with the Helmholtz coil. The output of the current sensor was measured by a voltage-sensing input to the Precision Multiferroic tester synchronously with the charge measurement channel of the tester. The accuracy of the current sensor was calibrated against a NIST-traceable ammeter to determine that the sensor always remained within 1% of the true current in the Helmholtz coil. The test configuration is in Figure 1.

III. TEST RESULTS

The sample generated 3.54 picocoulombs over the ± 45 Oersted stimulation range with a parabolic response. The only parasitic charge in the measurement not associated with magnetoelectric generation by the sample arose in the tester, a value that was easily characterized. This is one of the advantages of the charge-based measurement using a virtual ground circuit: parasitic contribution from the test fixture itself is virtually non-existent. The parasitic charge generated by the tester was characterized by disconnecting the sample from the tester to conduct the same test procedure. The tester produced a linear parasitic charge with a peak of -48 femtocoulombs, a value 70 times smaller than the sample response. Parasitic charge did not distort the measurement results. Figure 2 shows the sample response after subtracting the tester parasitic charge.

IV. ANALYSIS

The 4th-order polynomial fit equation for the sample response is plotted in Figure 3. It is

$$Q = -6.84 \times 10^{-3} h + 1.80 \times 10^{-3} h^2 - 8.50 \times 10^{-7} h^3 - 1.08 \times 10^{-7} h^4 \quad (4)$$

in units of picocoulombs per oersted. Equation (4) describes the charge that the sample will generate for a magnetic field between ± 45 Oe. From this equation the equivalent equation for α and for α_{ME} can be derived using the physical constants of the sample.

Defining the α as in (2), Equation (4) may be transformed into an expression of α by dividing by area of the sample to change to units of polarization and then taking the mathematical derivative of the resulting equation.

$$\alpha = -7.45 \times 10^{-3} + 3.92 \times 10^{-3} h - 2.78 \times 10^{-6} h^2 - 4.71 \times 10^{-7} h^3 \quad (5)$$

While (3) can be used to convert (5) to predict α_{ME} , the relative dielectric constant of highly non-linear materials is not usually well characterized with a high confidence factor, leading to potential error in the coefficients of the converted equation. Instead, the predictive charge relationship in (4) can be used instead to predict the voltage the sample would generate at each value of the magnetic field if the small signal capacitance of the sample is known. To that end, the authors measured the small signal capacitance of the sample under test over the same range of magnetic field values. The results are plotted in Figure 4.

To derive an algebraic expression to predict the voltage that would be generated by the sample at any value of H between ± 45 Oe, the two halves of the small signal capacitance can be fit with linear regressions and the equations for those regressions can be divided into (4). Once the voltage vs magnetic field relationship is known, α_{ME} can be constructed by dividing the voltage equation by the sample thickness, 1.02mm, to generate the necessary electric field vs oersted expression.

Fortunately, the change in the small signal capacitance of the sample over the test range of ± 45 Oe is so small that a single numeric value from Figure 4 value may be substituted in place of the full algebraic fit equation for small signal capacitance. Taking from Figure 4 the value of 346pF as representing the small signal capacitance of the sample over the entire ± 45 Oe range, the voltage prediction derived from the charge equation (4) is

$$V = -1.98 \times 10^{-5} h + 5.20 \times 10^{-6} h^2 - 2.46 \times 10^{-9} h^3 - 3.12 \times 10^{-10} h^4 \quad (6)$$

Equation (6) is then divided by the sample thickness and the mathematical derivative of the resulting equation is executed to arrive at the predictive expression for α_{ME}

$$\alpha_{ME} = -1.94 \times 10^{-4} + 1.02 \times 10^{-4} h - 7.22 \times 10^{-8} h^2 - 1.22 \times 10^{-8} h^3. \quad (7)$$

It may be possible to derive an expression for the dielectric constant of the sample by dividing (7) by (5).

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- [2] S.P. Chapman, J.T. Evans, S.T. Smith, B.C. Howard, A. Gallegos, "Measuring Magnetoelectric and Magnetopiezoelectric Effects", submitted to *Versita.com* December, 2012.
- [3] Sample synthesized by Su Chul Yang of the Center for Energy Harvesting Material and Systems. All data rights are retained by CEHMS.

FIGURE CAPTIONS

Fig. 1: Magnetoelectric capacitor test configuration.

Fig. 2: Magnetoelectric charge generated by the sample from a triangular ± 45 Oe stimulus loop.

Fig. 3: Fourth order polynomial fit to the loop in Figure 2. The fit has an R^2 of 9987.

Fig. 4: Small signal capacitance vs H-field for the sample under test.

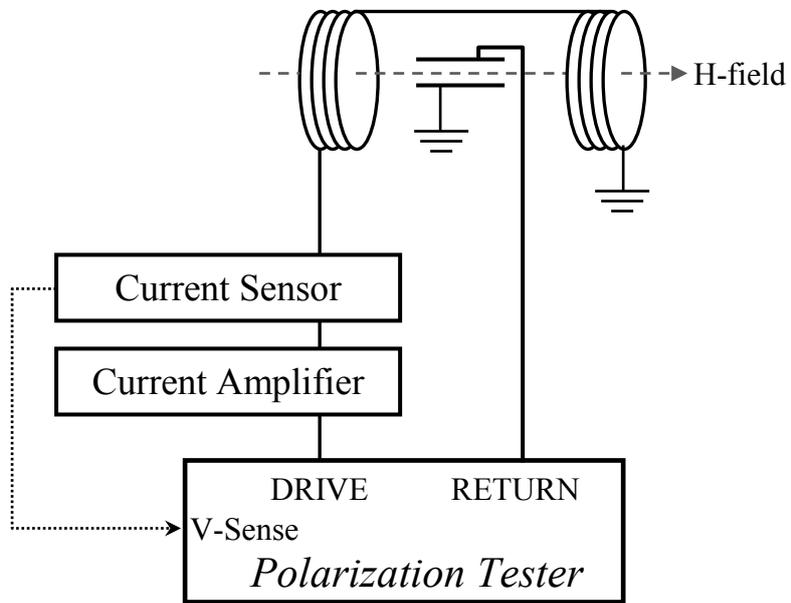


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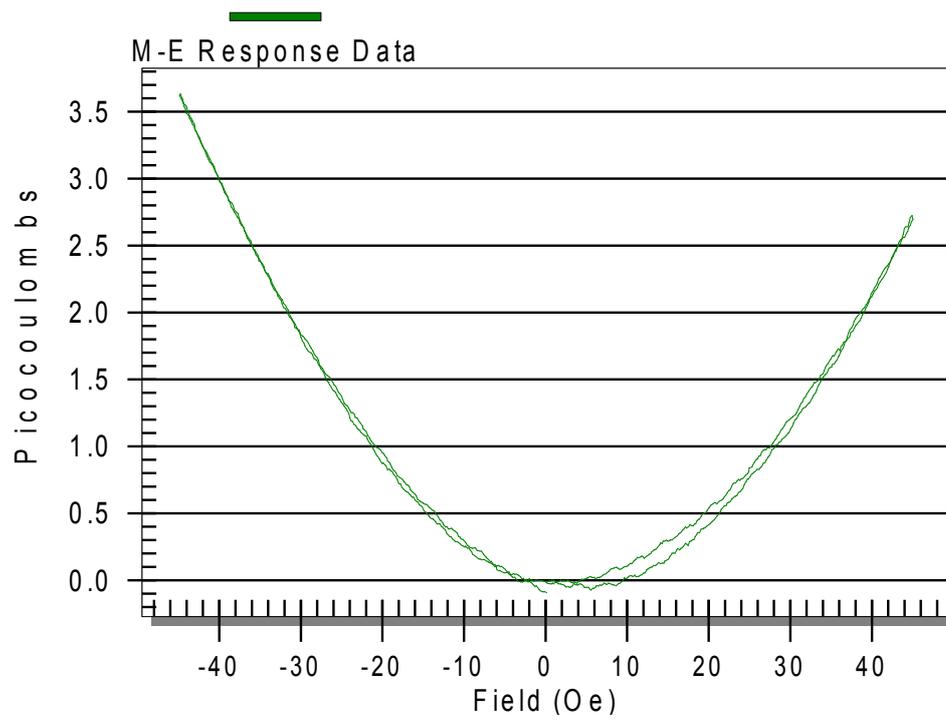


Fig. 2: Magnetoelectric charge generated by the sample from a triangular ± 45 Oe stimulus loop.

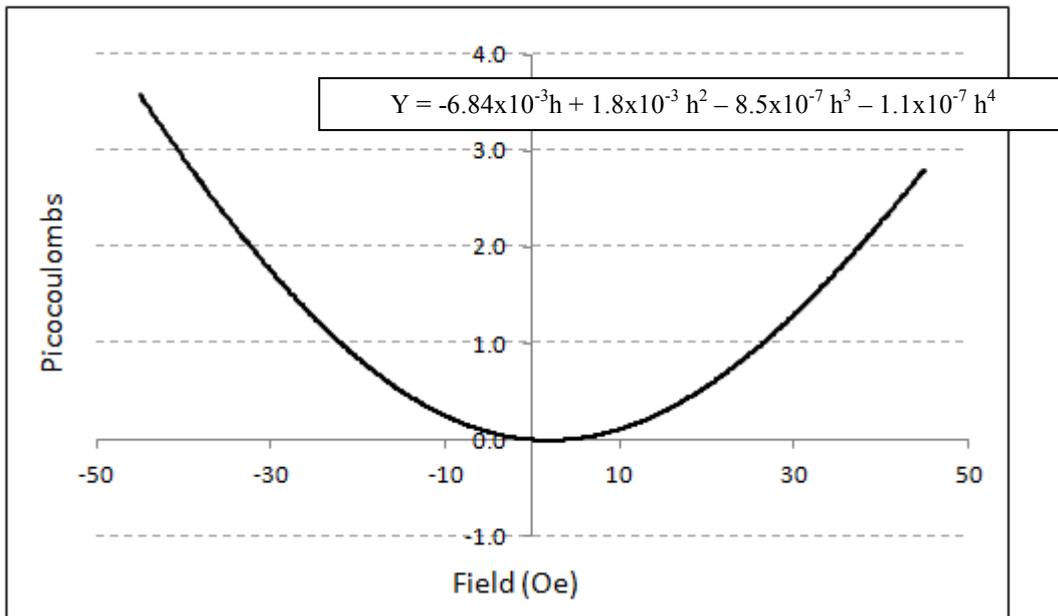


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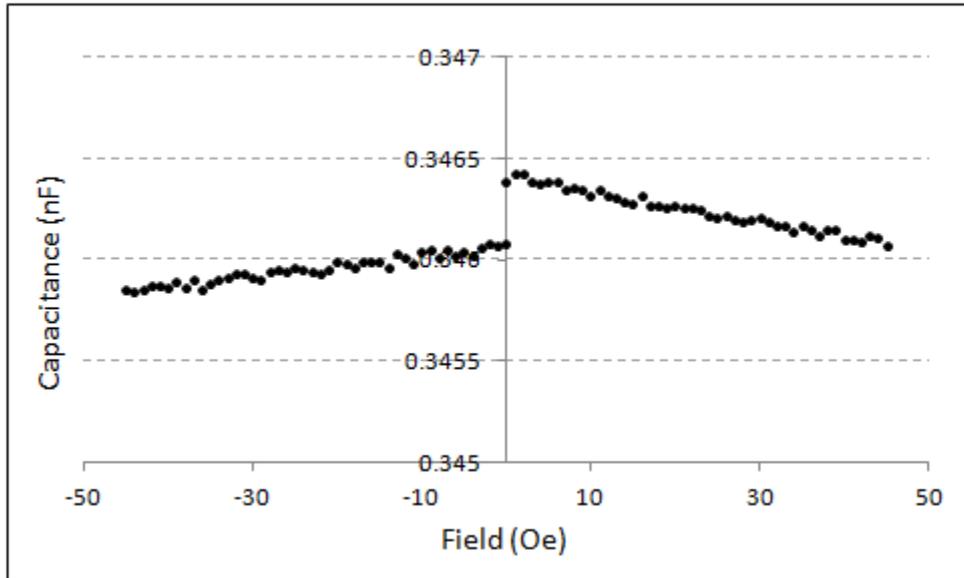


Fig. 4: Small signal capacitance vs H-field for the sample under test.