Introduction to Small Signal Displacement Measurements using Precision Testers

Joe Evans

Radiant Technologies, Inc.

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Summary

The dielectric and piezoelectric properties of ferroelectric materials are directly linked. The "butterfly" displacement loop correlates with the hysteresis loop. The small signal displacement measurement correlates with the small signal capacitance measurement.

Radiant has added the small signal displacement measurement to its Vision Library!

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- Capacitance and Piezoelectricity
- Large Signal vs Small Signal Measurement
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Capacitance and Piezoelectricity

> If you charge a capacitor, it will change its size, some more than others!

- Ferroelectric materials have internal electric dipoles below their Curie temperature.
- Paraelectric materials will generate an internal dipole during the application of an external electric field.
- In both cases, the internal electric dipole consists of distortions in the crystal lattice of the material.

ϖ The dipoles must be cancelled by charge that flows onto the plates of the capacitor with the application of the electric field: capacitance!

ϖ The external electric field applies a force to the internal electric dipoles and hence a force to the crystal lattice of the material, changing the size of material: piezoelectricity!

Capacitance! <==> Piezoelectricity!

Capacitance and Piezoelectricity

- The dielectric response of a material originates from three components:
  - The vacuum dielectric constant
  - The displacement of electron orbits, forming a dipole from each atom in the material
  - The displacement of atomic nuclei from their neutral positions in the lattice, again forming an electric dipole.
- The electric field generated by an electric dipole, called its dipole moment, is defined by the amount of charge displaced per unit volume times the distance they are separated.

$$P = Q(A) \times d$$

  - P has units of polarization: $\mu C/cm^2$ in this document.
- So, to generate a capacitance greater than the vacuum dielectric constant, dipoles must be created and/or stretched, changing the size of the capacitor!

Capacitance! <==> Piezoelectricity!

Capacitance and Piezoelectricity

In summary, when you charge any capacitor that is not a vacuum capacitor with any voltage of any size, it changes its size!

Polarization and displacement should be measured simultaneously!

Capacitance and Piezoelectricity

Questions that can be answered with a Radiant tester:

- How much does the capacitor move?
- How is the movement related to the charge generated on the capacitor or the voltage applied to the capacitor?

Capacitance and Piezoelectricity

What cannot be answered with a Radiant tester:

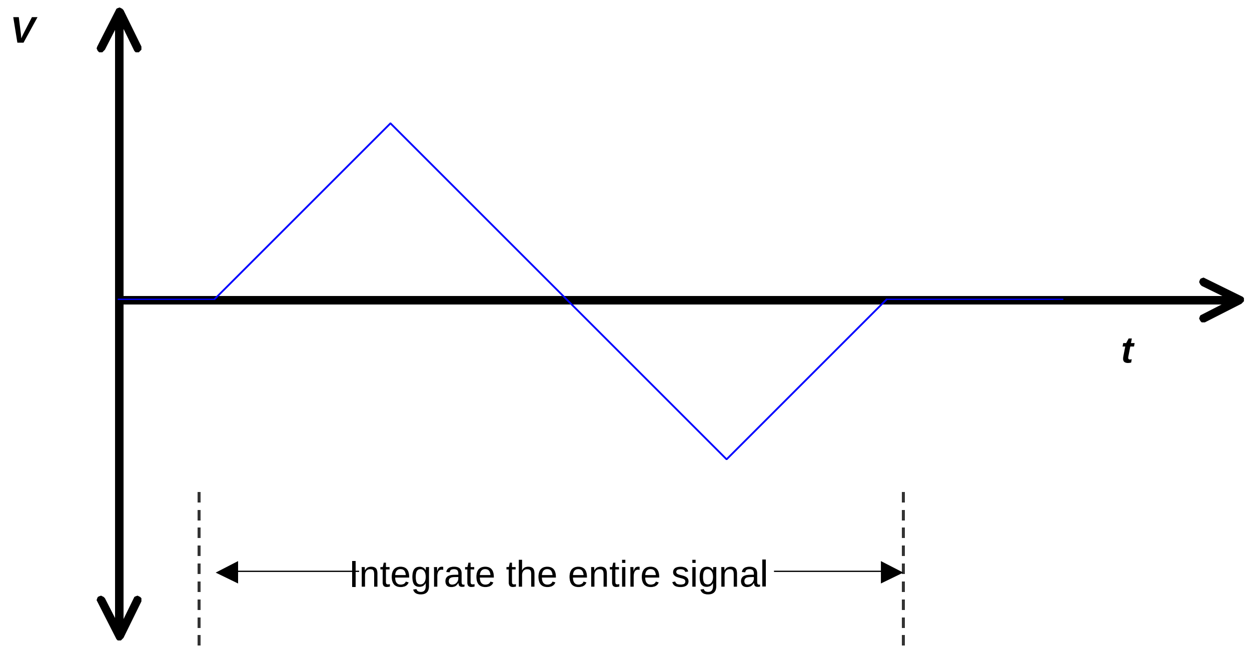
¬ How fast does does the capacitor move?

- Distortions inside the capacitor cannot move faster than the speed of sound in the material but the electric field of the polarization change associated with the displacement moves at the speed of light. Therefore, the polarization of the capacitor plates is at each instant indicative of the displacive state of the sample.
- Radiant testers are designed to operate very slow, effectively eliminating all electrical impedance effects in the measurement.
- A properly executed displacement measurement with a Radiant tester will allow the sample to reach steady state for each voltage change in the measurement signal!

Small Signal vs Large Signal

- The ferroelectric hysteresis measurement is defined at Radiant as a “large signal” measurement of the polarization properties of the sample.
- “Large signal” means that the test waveform has a large enough amplitude to switch dipoles in the ferroelectric material.
- As well, the “large signal” measurement captures and integrates all changes the sample experiences during the test waveform, showing its entire trajectory.
- The measurement result contains contributions from all components of the sample, including the remanent polarization and parasitics.

Small Signal vs Large Signal



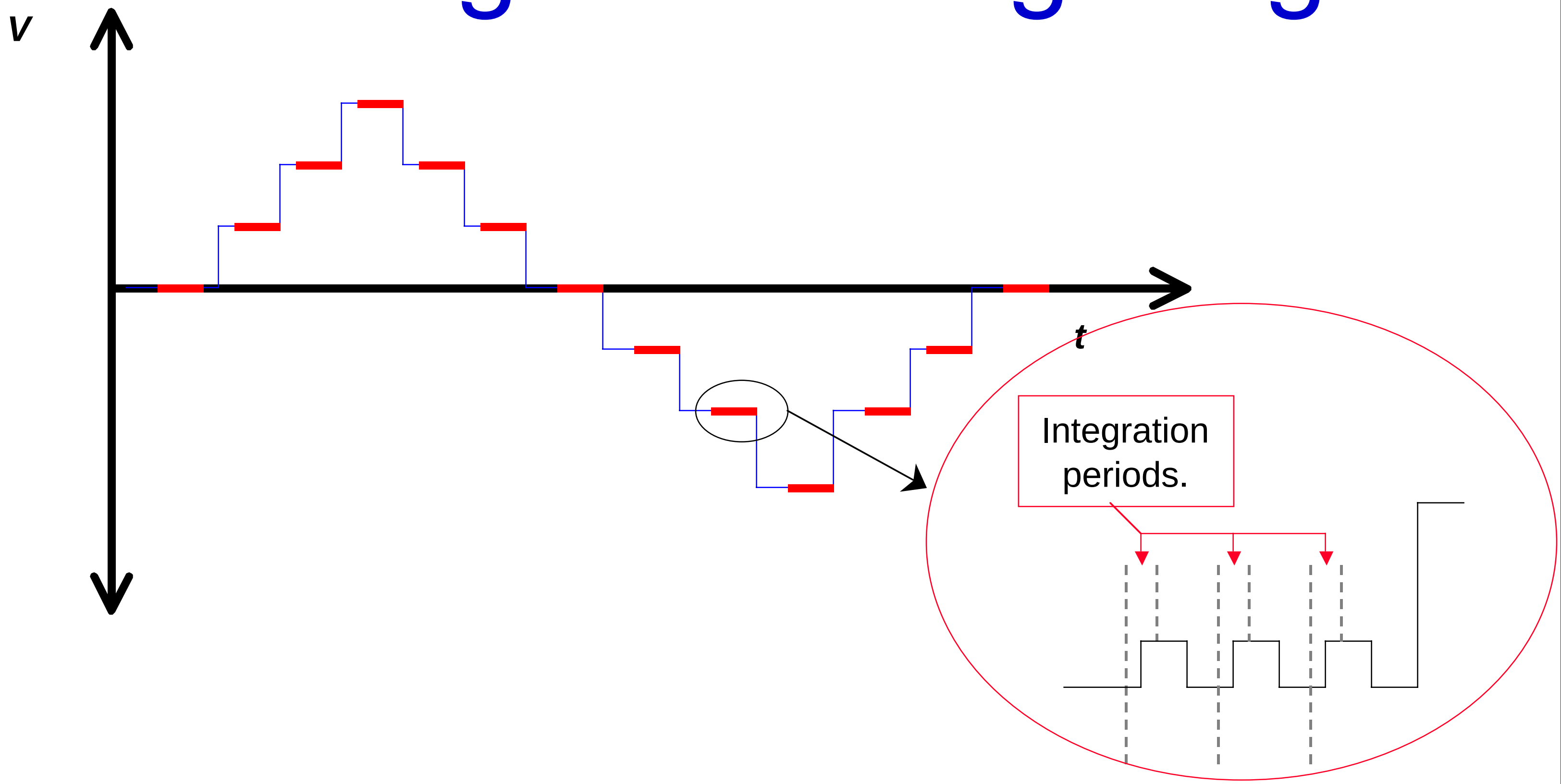
- A “large signal” measurement captures every electron that moves into or out of the capacitor during the stimulus waveform.

Small Signal vs Large Signal

- The "small signal" measurement is defined as one where the test amplitude is small compared to that required to switch remanent polarization in a ferroelectric capacitor.
- Since the response of a non-linear sample changes with the absolute value of the voltage applied and the remanent polarization state, the "small signal" measurement must also have a steady state voltage component as well as a remanent polarization pre-set procedure to put the sample in the appropriate state.
- Therefore, the "small signal" measurement captures and integrates only those changes the sample experiences during a small amplitude stimulation of the sample at a specified voltage and polarization state.

By definition, the "small signal" measurement contains no contribution from switching dipoles!

Small Signal vs Large Signal



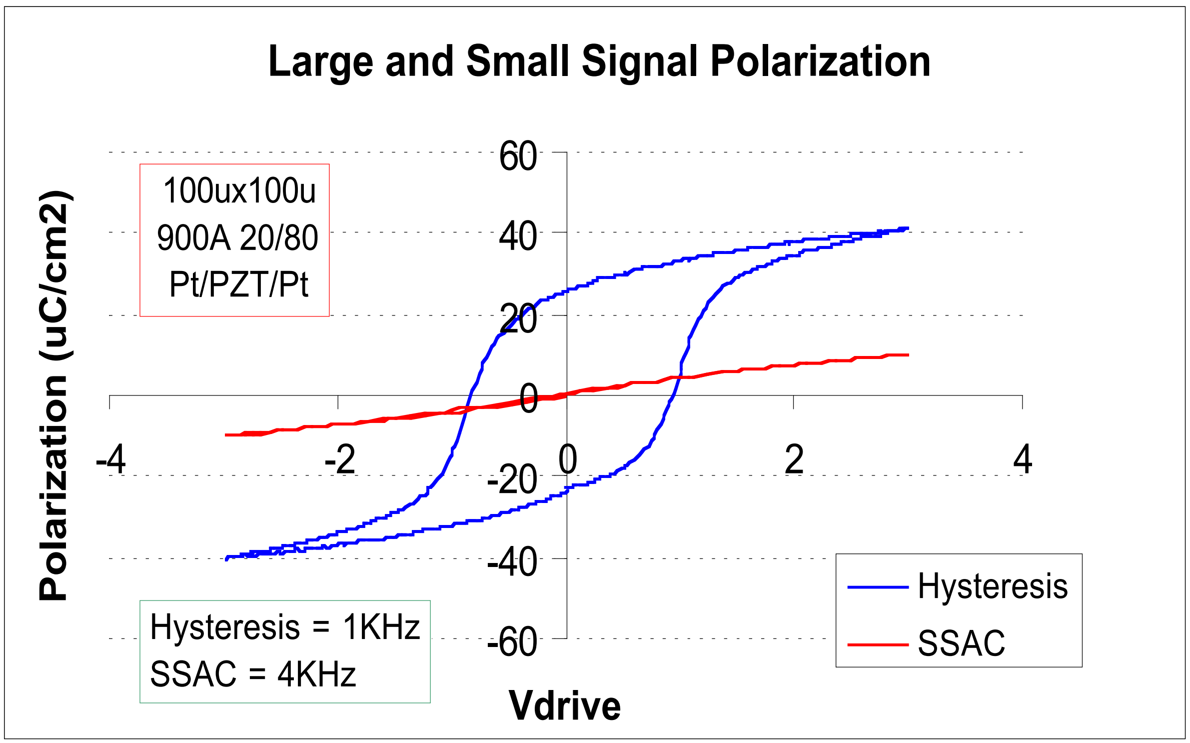
- In “small signal” measurements, many small measurements are taken that capture only the small changes associated with small stimuli.
- In a “small signal” measurement, the sequence of DC bias values is the same as the voltage profile used for hysteresis so the two can be compared directly.

Small Signal vs Large Signal

- Radiant testers execute both standard "large signal" hysteresis and "small signal" capacitance measurements.
  - "large signal" hysteresis results are normally given in units of polarization ($\mu C/cm^2$) but can be converted to capacitance using the CV or Normalized CV plotting functions of the Hysteresis Task or the Hysteresis Filter.
  - "small signal" measurements are normally given in units of capacitance (nF or $\mu F/cm^2$) but can be converted to equivalent polarization using the appropriate plotting function of the Advanced CV measurement task.

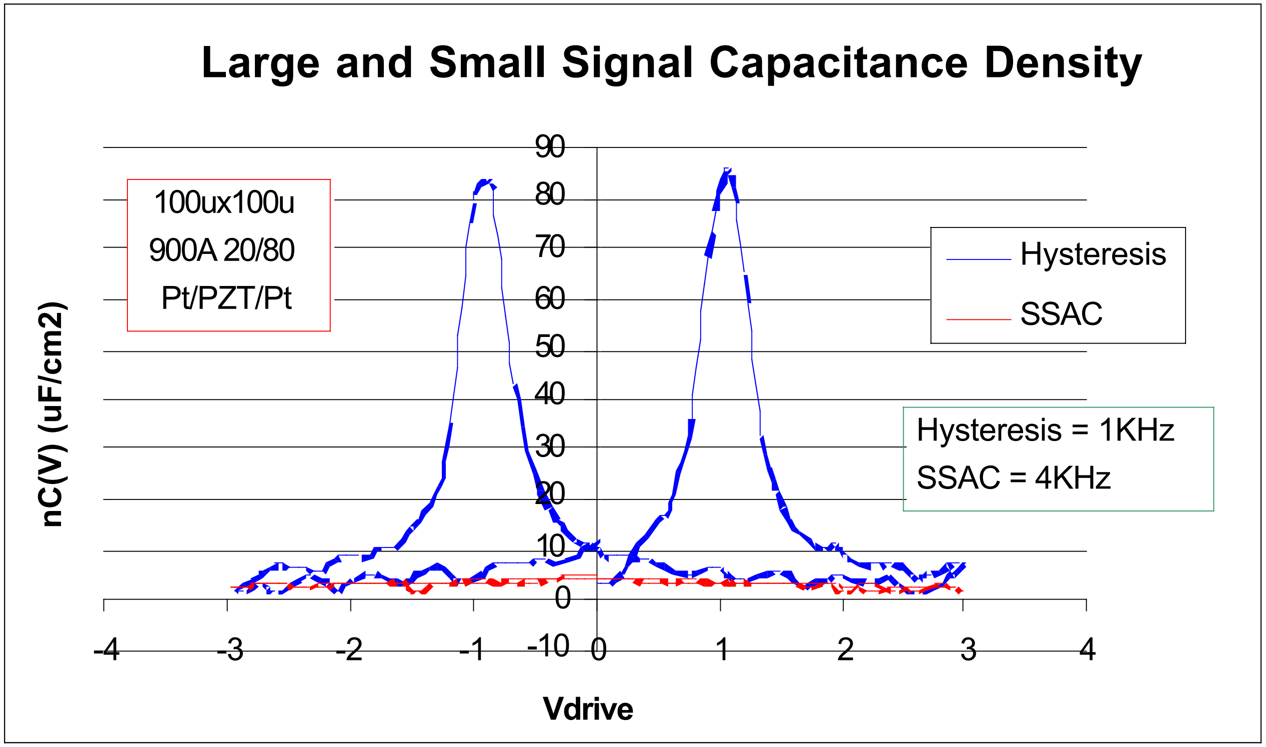
Small Signal vs Large Signal

- Comparison of the Hysteresis and Polarization of the Small Signal Capacitance is shown below:



Small Signal vs Large Signal

- Comparison of the Large and and Small Signal Capacitance is shown below:

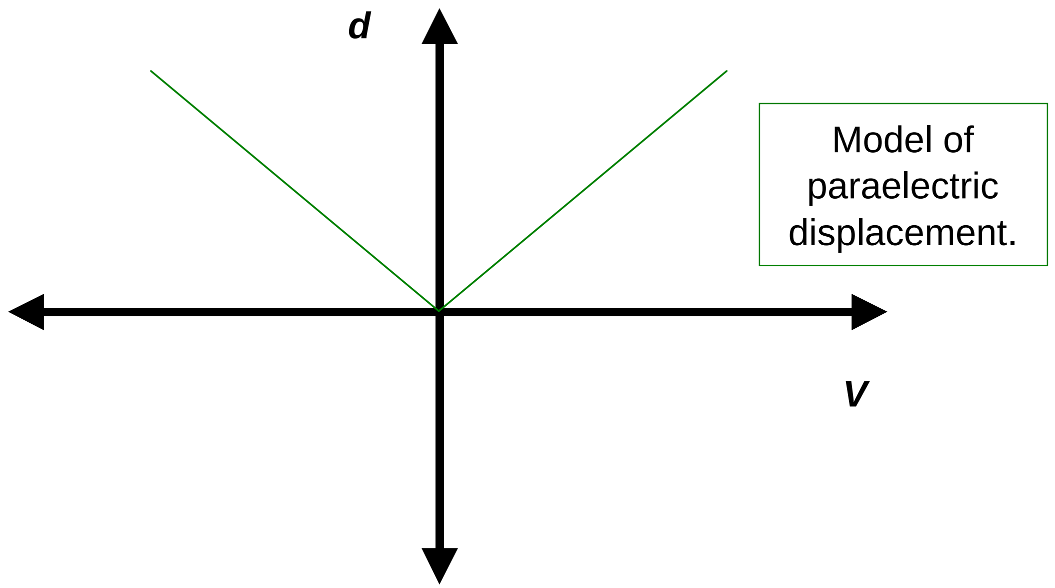


Small Signal vs Large Signal

In summary, Radiant Precision testers can measure both the large and small signal responses of a capacitor and give the results in either units of polarization or capacitance!

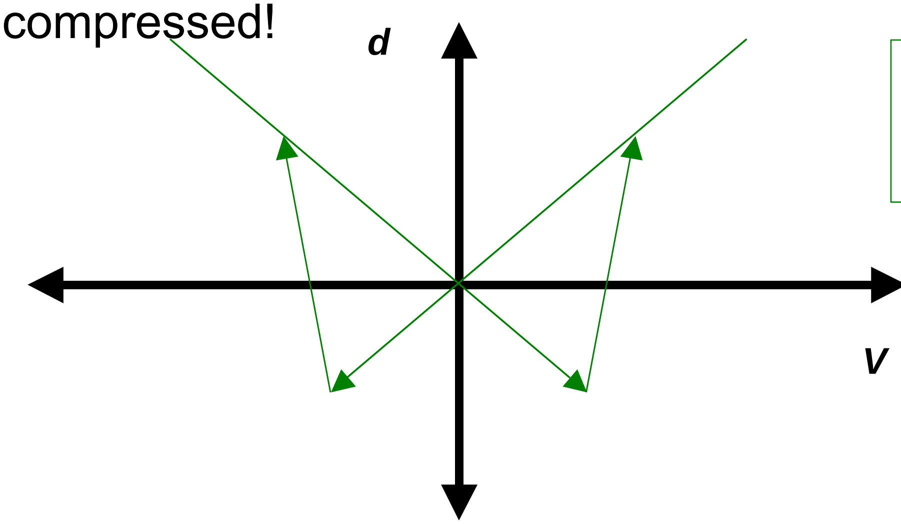
Hysteresis vs Displacement

- When an electric field is applied to a paraelectric lattice, it stretches the lattice.



Hysteresis vs Displacement

- When an electric field is applied to a ferroelectric lattice, the result is more complex.
  - When the field is in the opposite direction of the dipoles, as in a capacitor where the remanent polarization is already flipped towards the applied field, the dipoles stretch just as in a paraelectric material.
  - When the field is in the same direction as the dipoles, as in a capacitor before the remanent polarization begins switching, the dipoles are compressed!



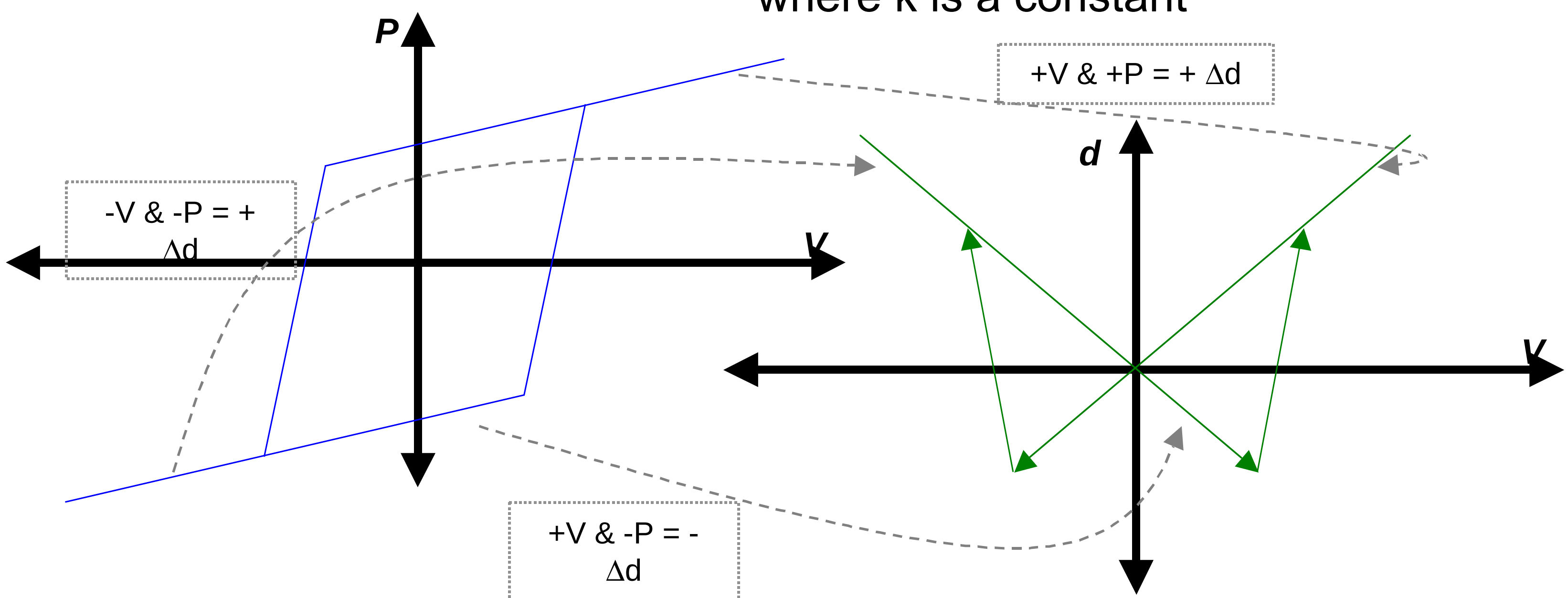
Model of ferroelectric displacement.

Hysteresis vs Displacement

- In either case, the displacement may be modeled with a simple equation relating displacement to the polarization and the voltage:

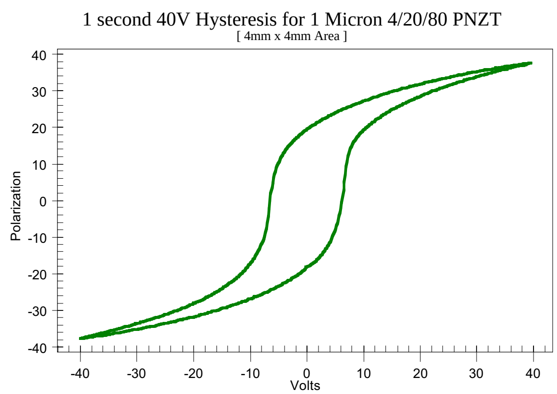
  - Displacement = k x P x E

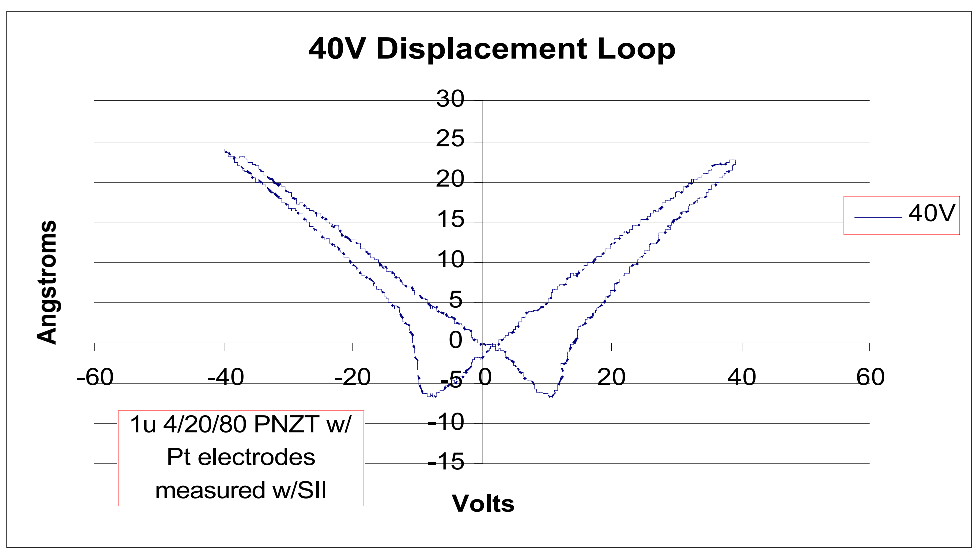
    where k is a constant



Hysteresis vs Displacement

- Below is an example of the hysteresis and displacement of a 1µ thick 4/20/80 PNZT capacitor.





Small Signal Displacement

- The small signal displacement measurement is conducted in the same manner as the small signal capacitance measurement except that SENSOR is used to capture displacement simultaneously with a small signal capacitance stimulation.
- In this case, the change in E is constant and the displacement equation becomes:

$$\text{Small Signal Displacement} = k \times dE \times P$$

where both k and dE are constant

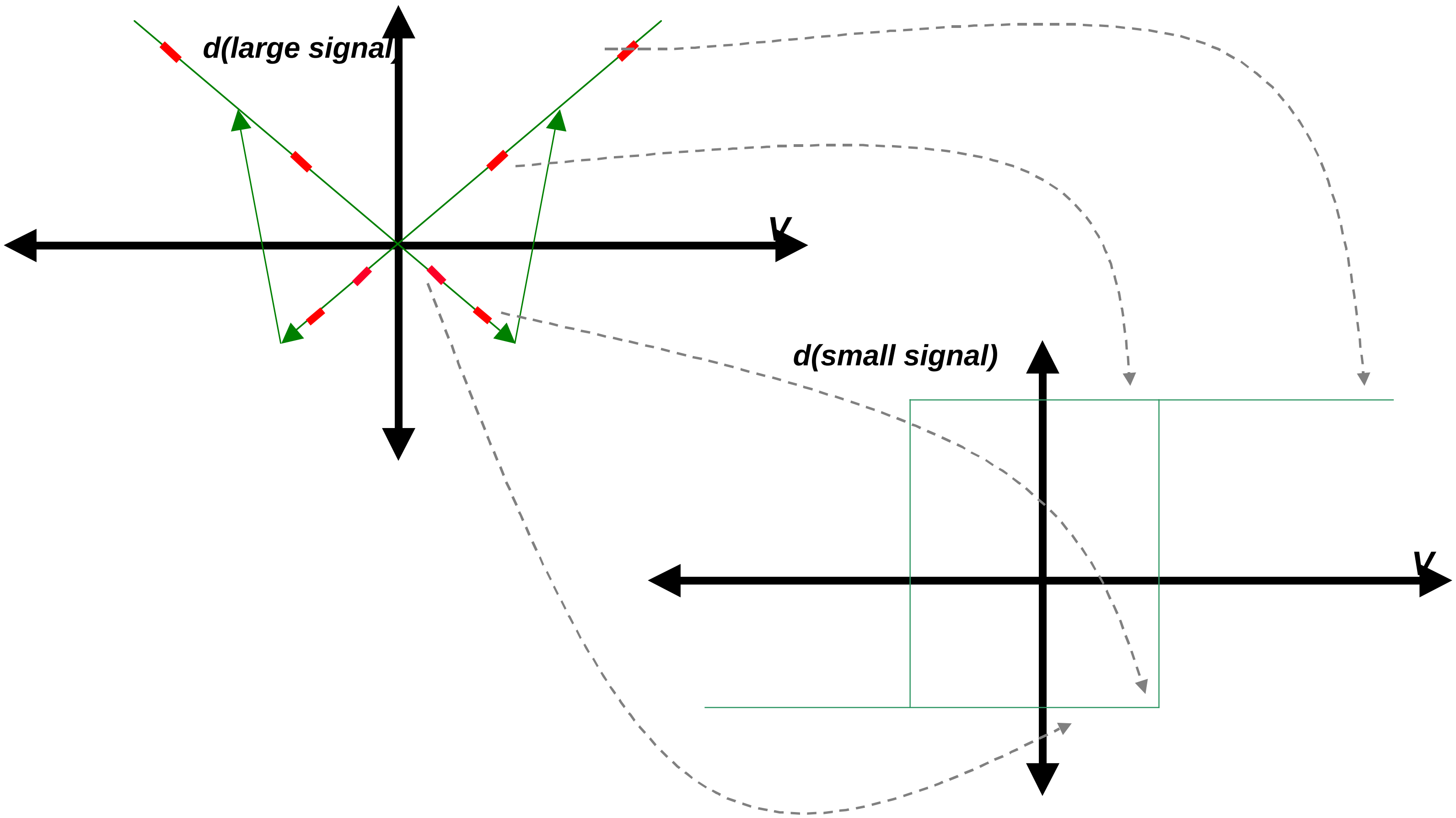
- The equation reduces to:

$$\text{Small Signal Displacement} = \alpha \times P$$

where $\alpha = k \times dE$

The small signal displacement loop should look like a hysteresis!

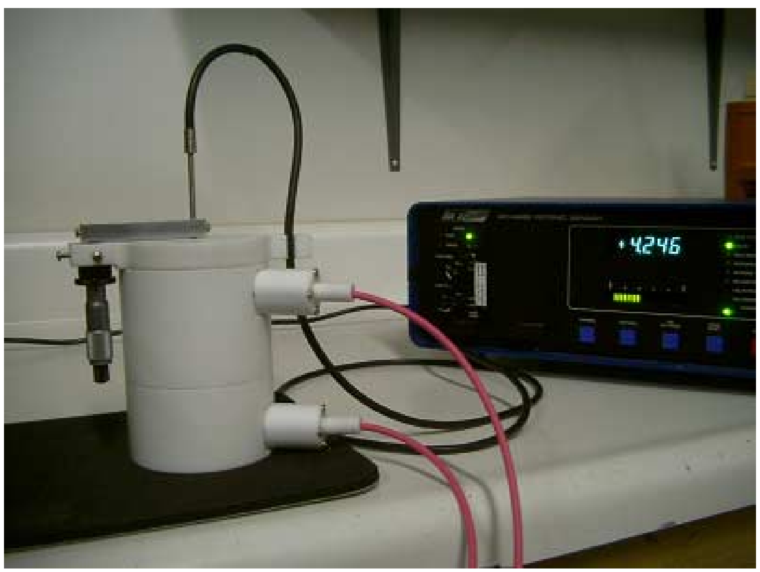
Small Signal Displacement



Example Measurement

- I conducted a measurement of a sample at Radiant Technologies:
  - 2/65/35 PNZT ceramic
  - Area = 3.8cm^2

- I mounted the sample in a Radiant High Voltage Displacement Fixture and used an MTI2000 with a 2032 sensor probe mounted on the HVDF.



The measurements were made using a Radiant Technologies Precision Workstation operating under the Vision Data Management Software

Example Measurement

- I executed both the Hysteresis measurement and the Small Signal Capacitance measurement and captured both polarization and displacement.

- Four measurements are plotted in the next pages:

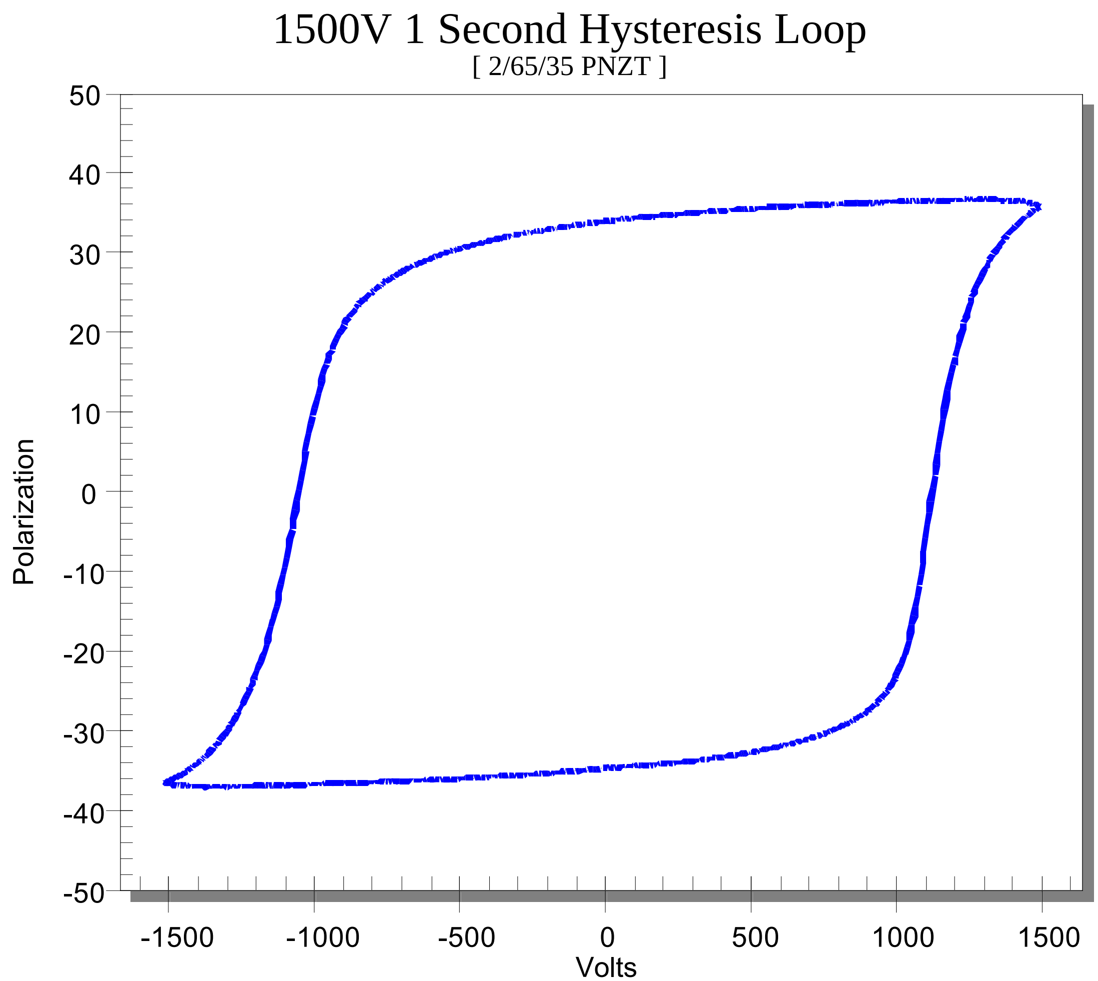
  – Polarization hysteresis

  – Displacement Butterfly Loop

  – Small Signal Capacitance

  – Small Signal Displacement

Hysteresis



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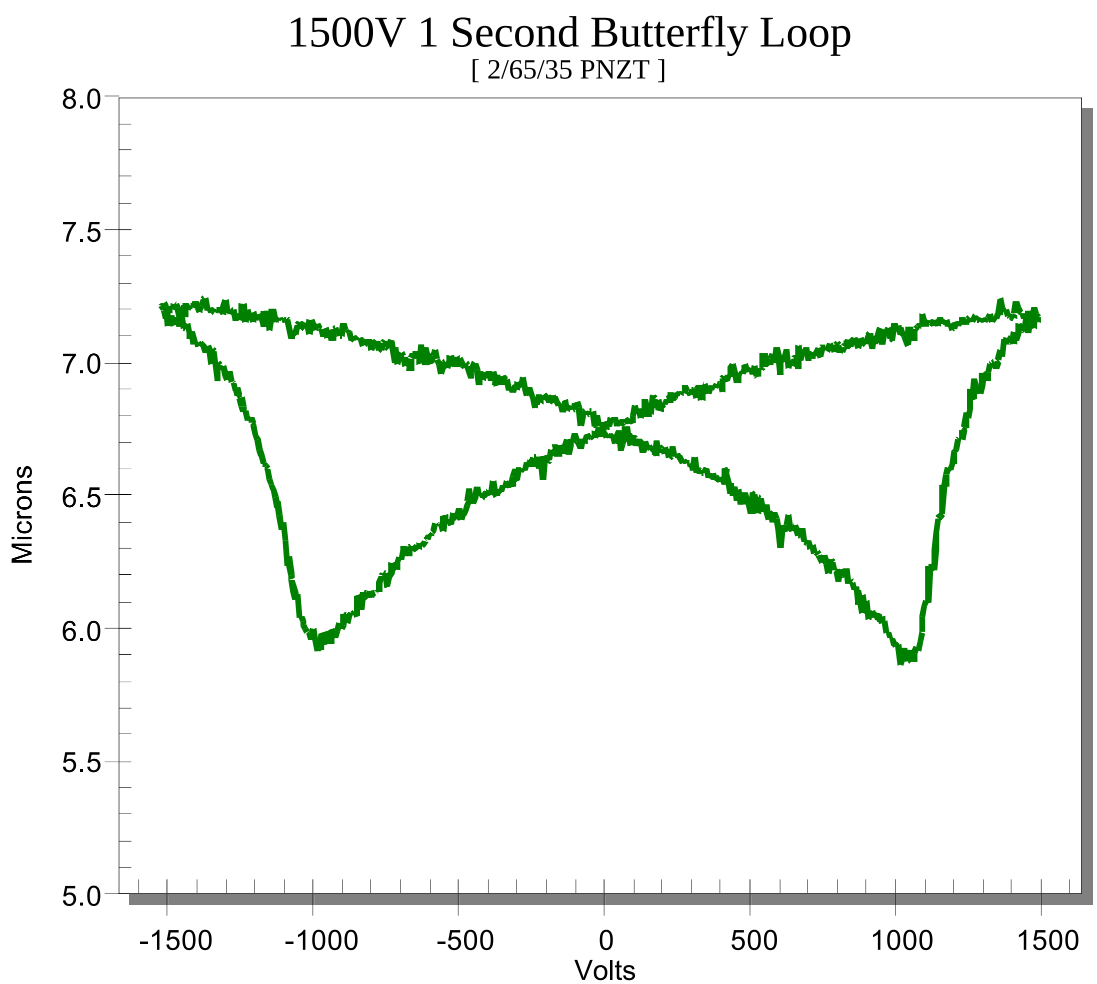
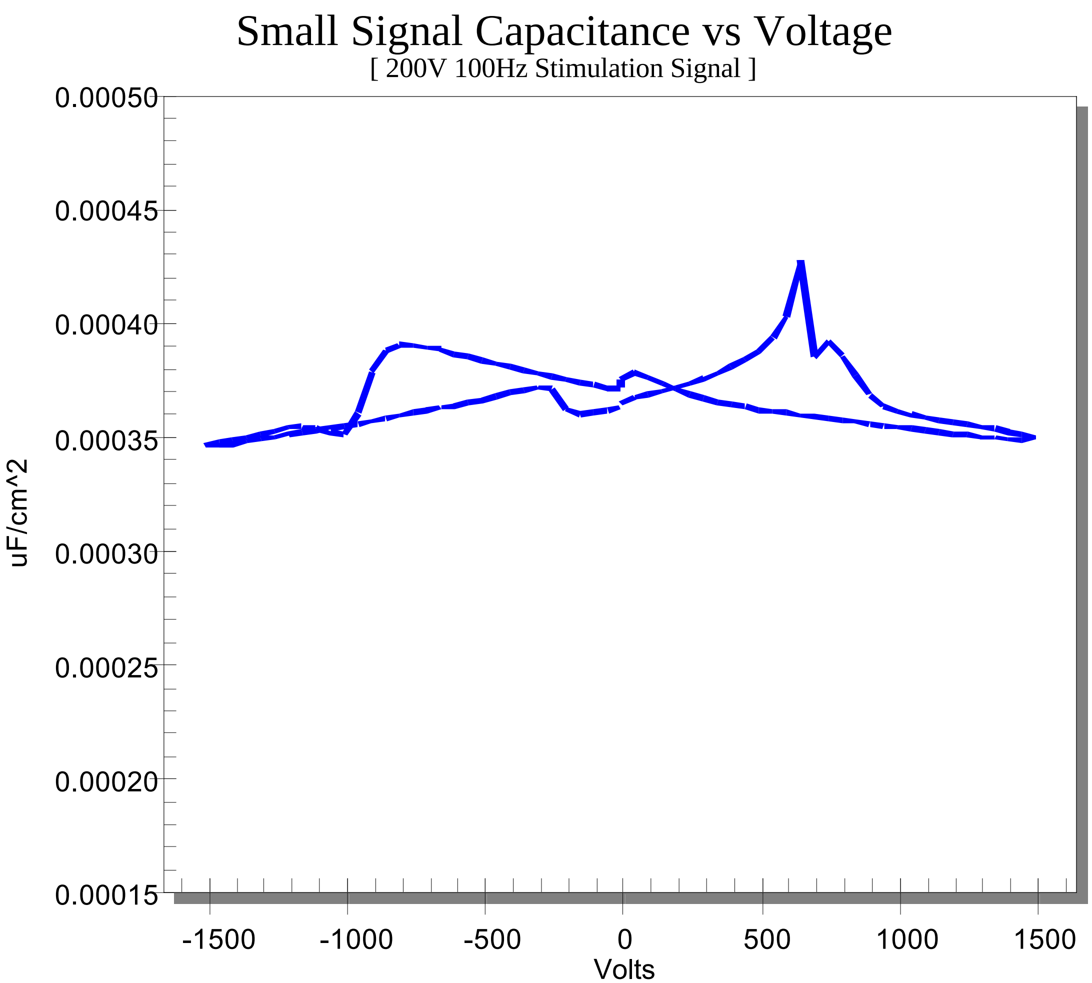
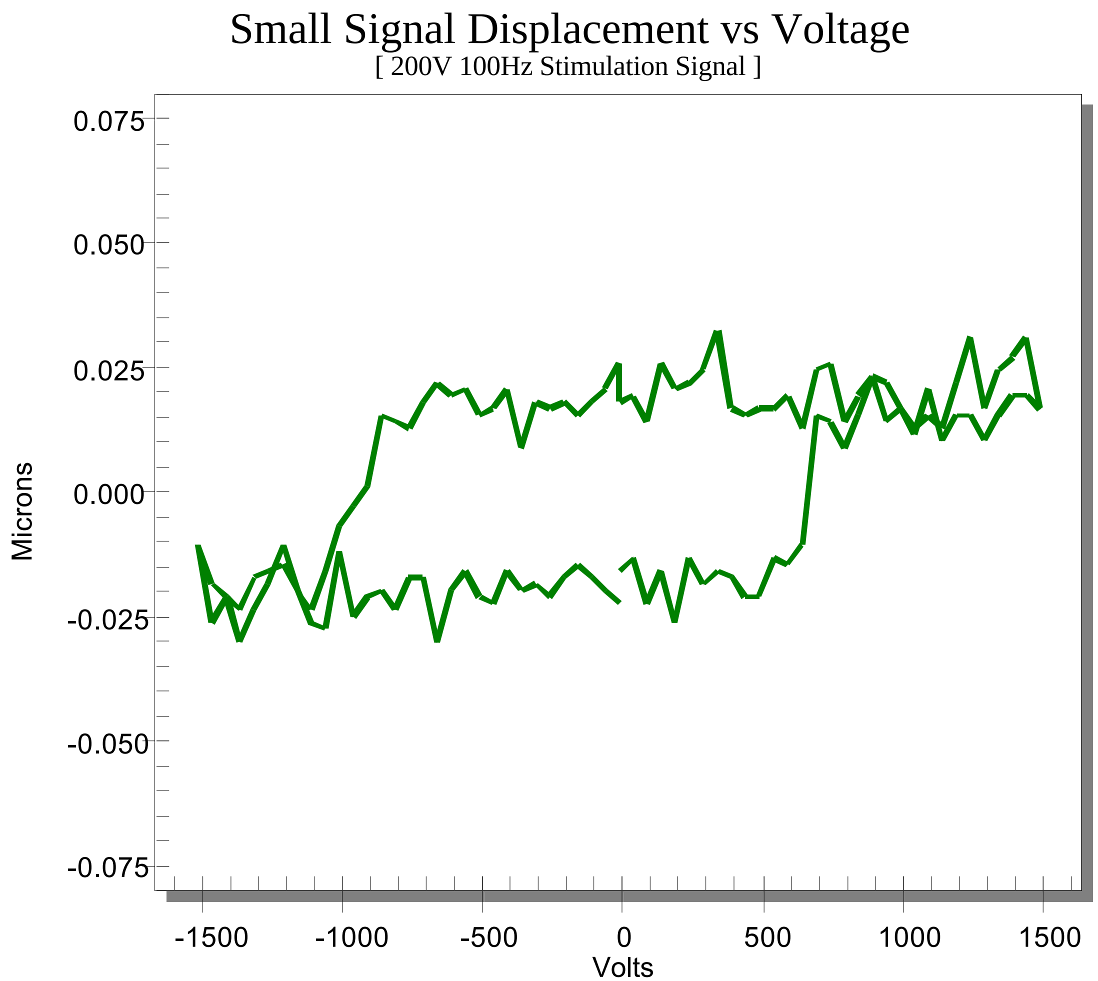
Large Signal Displacement



Small Signal Capacitance



Small Signal Displacement



Conclusion

- The dielectric and piezoelectric properties of ferroelectric materials are directly linked.
- The "butterfly" displacement loop correlates with the hysteresis loop.
- The small signal displacement measurement correlates with the small signal capacitance measurement.

All four measurements can be captured and compared using Radiant Technologies Precision testers.