

Dielectric Spectroscopy of Liquid Crystals

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Abstract

In this experiment, we make dielectric spectroscopy measurements on the 8422[2F3] and the TSiKN65 liquid crystal compounds and observe the response of their dielectric coefficient in the isotropic, smectic-A, and smectic-C phases. In the smectic-C and isotropic phases, we found resonance peaks describing an increase in the crystal's susceptibility to align with an alternating electric field. We fit our data to the Debye dispersion model and extract the relaxation strength of the crystal at different temperature. The critical exponent γ for the crystals susceptibility is determined by fitting the power law model to the reciprocal of the relaxation strengths. We determined γ to be *blank* for the TSiKN65 compound and *blank* for the 8422[2F3] compound.

1 Introduction

The most familiar states of matter are the solid, liquid, gas, and plasma phases. For many centuries, these were the only known states; however, in 1888 an Austrian botanical physiologist, Friedrich Reinitzer, discovered a second melting point between the solid and liquid phase in a cholesterol compound. This intermediate, unique phase would later be known as the liquid crystalline phase. It has become an important concept in understanding of biological systems and development of electro-optical sciences. Such substances “flow” much like a liquid and maintain positional order like the crystalline phase. Today, the physics of these materials are used to study cellular membranes within the human body, create fast-response digital displays, and gauge temperature changes with high accuracy.

They exist due to the shape and polarization of the molecules. Liquid crystals (LC's) are typically long rod-shaped molecules, fairly rigid along their long axes, and possess a strong dipole polarization. These two characteristics cause the crystals to inherit unique positional and orientational order not seen in liquids; yet they still flow much like a liquid, without the rigid structure seen in solids. Also, there are sub-phases within the LC phase that demonstrate different positional, orientational, and bond-orientational order. Three phases that are commonly mentioned within these crystals are the nematic, smectic A (SmA), and smectic C (SmC) phases.

1.1 Phases within the Liquid Crystal Phase

In the nematic phase, the crystals do not possess any position order, only long-range directional order. Due to their rod-like shape, the long axis of all the crystals tend to align with one another, but their position may flow in any direction. Thus, their center of masses are randomly located throughout a sample. In Figure 1, the picture on the left illustrates a typical nematic phase. There is a common direction, along the director n , that the crystals point. Notice, the molecules do not necessarily all point in the same direction. In fact, they may align in many different directions; however, the average of all the directors point in one direction. This director is a fundamental characteristic of all liquid crystals.

The smectic phases are characterized by both orientational order and *positional order*. The position of each crystal is not distributed randomly; rather, they align into layers. Again, take a look at Figure

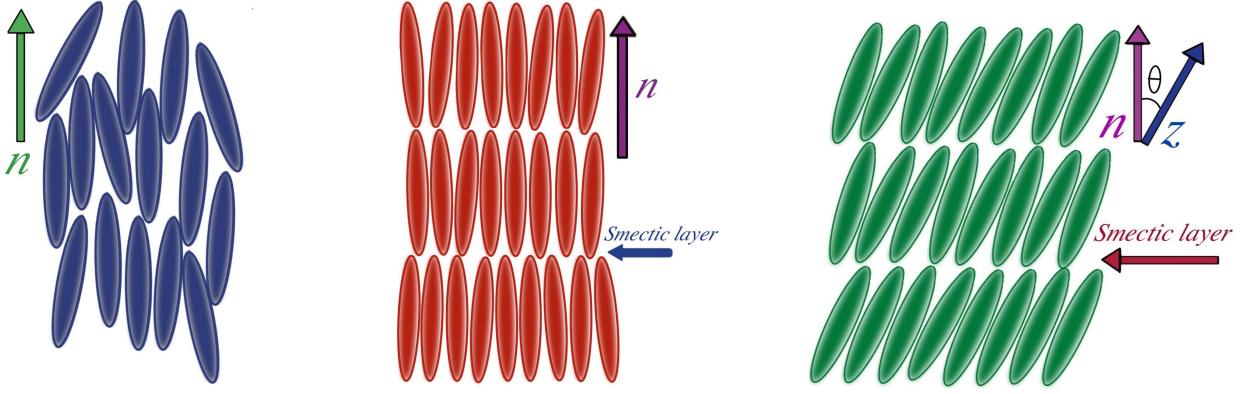


Figure 1: The illustration on the left is an example of the nematic phase of liquid crystals. All the molecules' long axes align in a common direction, while the positions of the molecules are free to move around.

1. The picture in the center illustrates the smectic A phase. In this phase, all the molecules axes align with a common director z like the nematic phase, and their center of masses align with one another. As a result, the sample forms distinct layers stacked on top of one another, much like a bookshelf, and the director is pointed perpendicular to these shelves.

The smectic C phase possesses similar characteristics to the smectic A phase. The molecules form layers on top of one another, and the molecules align along a similar director. However, this director is not perpendicular to the layers. Instead, a new director n with a small tilt angle θ is induced on all the molecules. This is shown on the right in Figure 1.

1.2 Tilt Cone, Polarization, and LC Cells

When the molecules are in the SmC phase and experience such a tilt, they are able to revolve along a cone formed along the z director (see Figure 2). This characteristic induces a polarization on a sample of LC's, a property known as ferroelectricity. In the following experiment, we explore this polarization and how susceptible these crystals are to changes in electric fields. The direction of such a polarization \mathbf{P} for liquid crystals is $\hat{z} \times \hat{n}$. Figure 2 shows the direction of \mathbf{P} is into the page. As the molecules spins around the tilt cone, the polarization direction moves around the top of the cone like hands of a clock. If an external electric field is applied across the short axis of the liquid crystal, the molecule will revolve until the polarization direction aligns with the field. For our experiments, we exploit this property by observing these materials between two conducting glass slides.

Recall the bookshelf analogy from before. In our liquid crystal samples, the glass slides are the sides of the book shelf. The layers are the shelves, and the crystals are the books standing upright. If the crystal is in the SmA phase, the \hat{z} (perpendicular to the layers or shelves) and \hat{n} directors (parallel to the orientation of the books) are parallel to each other. The direction of polarization, by definition, is the cross product of these two directors; therefore, there is no polarization in the SmA phase (See Figure 3). When the crystal melts into the SmC phase (the books lean on the shelf), the tilt induces a polarization also shown in Figure 3.

Our samples are built using two glass slides coated with indium-tin oxide for conducting electric charge at their surface. We add a separate coating of nylon material and run a brush over the surface of

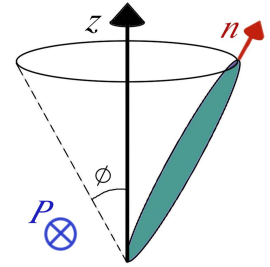


Figure 2: Crystals in the SmC phase experience a tilt, with angle θ , and are free to revolve around a cone.

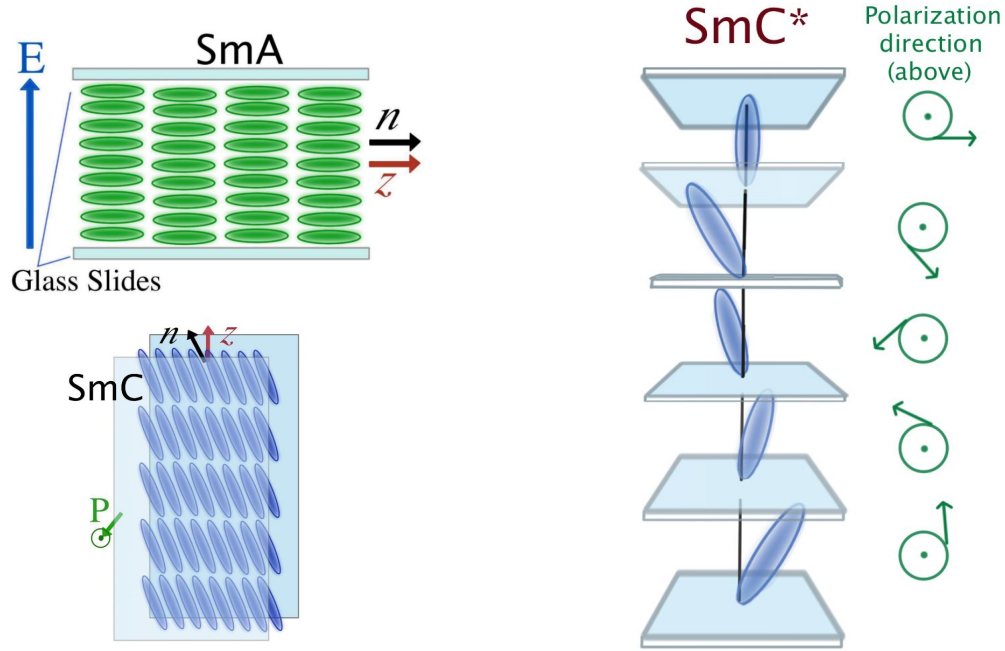


Figure 3: The capacitor consists of two plates separated by a distance, d . When a dielectric material is between the two plates (such as liquid crystals), the properties of the capacitor changes.

the slide. This “scratches” microscopic grooves onto the glass that causes the liquid crystal material to align between the slides. Micro-spacers are dropped onto the slide to create micrometer spacing between the two plates. After the liquid crystal material is applied, we use an Ocean Optics spectrometer to measure the thickness of the cells. Two wire leads are connected to the surface of the cells using conducting epoxy. These connections allow us to apply electric fields across the slides and polarize the material. Figure 8 illustrates a liquid crystal slide used in this experiment.

1.3 Ferroelectricity, Antiferroelectricity, and Chirality

The principle of **ferroelectricity** (briefly described earlier) is important in determining the difference between SmA and SmC phases in LC’s. It is analogous with ferromagnetism, which is the permanent magnetization present in materials like iron (“ferro” means iron). Ferroelectricity describes the phenomena when the bulk of a material has a permanent electric polarization without an external electric field, and all the molecules point in the same direction. This property can be reversed in the presence of an external field. The SmA phase of liquid crystals do not exhibit ferroelectric behavior. In SmC phase, the tilt of the molecules induces a polarization in each of the layers of the sample. If the layers all point in the same direction, the sample is ferroelectric. It is also possible for each layer to polarize in opposite directions, and the bulk to show zero net polarization (a phenomena known as **antiferroelectricity**). If layers’ directors do not align or show any antiferroelectric symmetry, the system is neither ferroelectric or antiferroelectric. All of the samples used in this experiment are ferroelectric.

Ferroelectricity brings the concept of symmetry to question. In several branches of science, the term **chirality** describes a property of asymmetry. In liquid crystals, chirality can be used to describe individual molecules or a full system of LC’s. If a bulk is not identical to its mirror image [4], the system is considered chiral. If molecules is not symmetric about its short or long axis, the molecules itself is considered chiral. Achiral systems show these kinds of symmetry. For example, a unique achiral

phase is the helical structure shown in Figure 3. This type of SmC phase has no net polarization in the sample (antiferroelectric). When the layers are formed and an angle is induced in the SmC phase, each layer has a different polarization direction with an angle ϕ in the azimuthal plane. Each layer’s polarization angle is slightly shifted from the surrounding layers, forming a helix-twisted structure in the bulk sample. This phase is described as an achiral antiferroelectric SmC liquid crystal. Phases that demonstrate chiral structure are labeled with an asterisk (i.e. SmC*).

1.4 Universality Classes

In this experiment, we seek to determine whether our liquid crystals fall into a particular universality class. Universality classes are groups of mathematical expressions that attempt to model the behavior of physical systems. Each expression contains the same set of “critical exponents”: α the heat capacity exponent, β the magnetic order parameter exponent, γ the susceptibility exponent, and ν the correlation length. A physical material is considered part of a class when the it’s properties align with the critical exponents of the model. This process of classification allows scientists to study complex, foreign materials more efficiently. If this material acts fits the universality class of a known substance or computer simulated system, a scientist can perform similar experiments on both.

Class Name	α	β	γ	ν	Dimension count
XY Model	-0.0146(8)	0.3485(2)	1.3177(5)	0.67155(27)	3
2d Ising Model	0	1/8	7/4	1	2
3d Ising Model	0.1096(5)	0.32653(10)	1.2373(2)	0.63012(16)	3
Mean Field (Landau) Model	0	1/2	1	1/2	2, 3

Table 1: Universality classes and their critical exponents used to describe the behavior physical substances [1].

A few common universality classes are listed in Table 1. In earlier experiments, the Landau theory seemed to successfully fit the classical behavior of liquid crystals; however, later experiments shows that around the SmC-SmA phase transition, the crystals behave similar to three-dimensional XY critical exponents [13]. In this experiment, we determine the susceptibility exponent γ for our samples and compare them to the above models. In the SmC-SmA transition, we expect to see a critical exponent similar to the XY model.

2 Dielectric Spectroscopy

We use the technique of dielectric spectroscopy to obtain this susceptibility exponent. Dielectric spectroscopy is an important tool in studying the molecular dynamics and relaxation characteristics in ferroelectric LC’s. This measurement uses an alternating current and impedance analyzer to measure the crystals’ polarization response in an electric field. This measurement is repeated over multiple temperatures to obtain a spectrum of the susceptibility, and the data is compared with the universality models.

2.1 Review of a Capacitor

Before diving into the complex details of dielectric spectroscopy, we begin with a review of the physics of capacitors. Liquid crystal slides behave as a capacitor with dielectric material between the two plates. Recall, that the capacitor consists of two parallel conducting plates with a separation, d , between them. Each plate holds equal and opposite charge, creating an electric field between them.

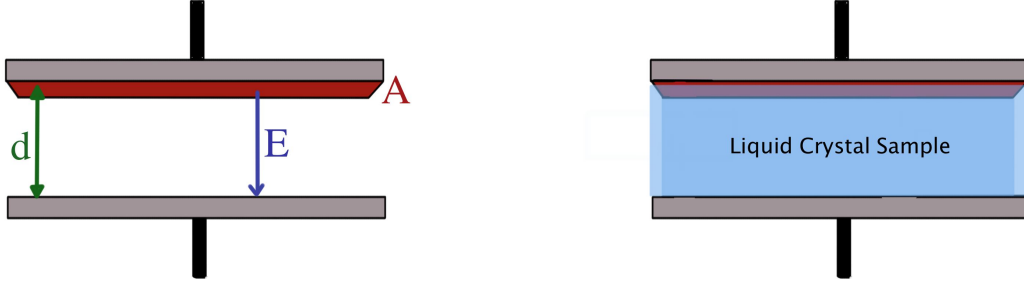


Figure 4: The capacitor consists of two plates separated by a distance, d . When a dielectric material is between the two plates (such as liquid crystals), the properties of the capacitor changes.

The ratio of the charge on each plate over the potential between them is known as the capacitance:

$$C = \frac{Q}{V}. \quad (1)$$

Assuming that the area, A , of the plates is much larger than the distance, d , between plates, the potential between the two plates is defined as the line integral of the electric field in the capacitor.

$$V = \oint_0^d E dz = \int_0^d \frac{\rho}{\epsilon_0} dz = \frac{\rho d}{\epsilon_0} = \frac{Qd}{\epsilon_0 A} \quad (2)$$

where ρ is the free charge collected at the surface of the capacitor and ϵ_0 is the permittivity of free space. Therefore, the total charge on the surface of the capacitor is

$$\frac{Q}{A} = \epsilon_0 E. \quad (3)$$

This new expression for the potential can be substituted into the equation for capacitance. Thus, the capacitance is directly related to the permittivity within the capacitor (in this case, this region is a vacuum), and indirectly related to the electric field:

$$C_0 = \frac{\epsilon_0 A}{d} = \frac{Q}{Ed} \quad (4)$$

In this experiment, an alternating power source is used to observe the response of the capacitor when a potential is applied across the plates. As the potential difference between the glass slides switches direction, there is time delay before the current changes direction due to the charging at the capacitor's surface. Thus, there is lag between the applied voltage and current phase angles (shown in Figure 5) Recall that the current is defined as motion of charge over time (dQ/dt) and the potential is Q/C for a capacitor. Thus, we see that the current is simply the time derivative of the potential across the plates. The ratio of the potential and current is known as the impedance of the capacitor, or the opposition to current flowing across the plates when voltage is applied.

$$\begin{aligned} \frac{v_c}{i_c} &= \frac{V \sin(\omega t)}{\omega V C \cos(\omega t)} = \frac{\sin(\omega t)}{\omega C \sin(\omega t + \frac{\pi}{2})} \\ Z_{\text{capacitor}} &= \frac{1}{\omega C} e^{-j\frac{\pi}{2}} = \frac{1}{j\omega C} \end{aligned} \quad (5)$$

The impedance tells us a lot about the capacitor. It is dependent upon the frequency of the applied oscillating field; therefore, we will observe how it changes when the sample is scanned over a range

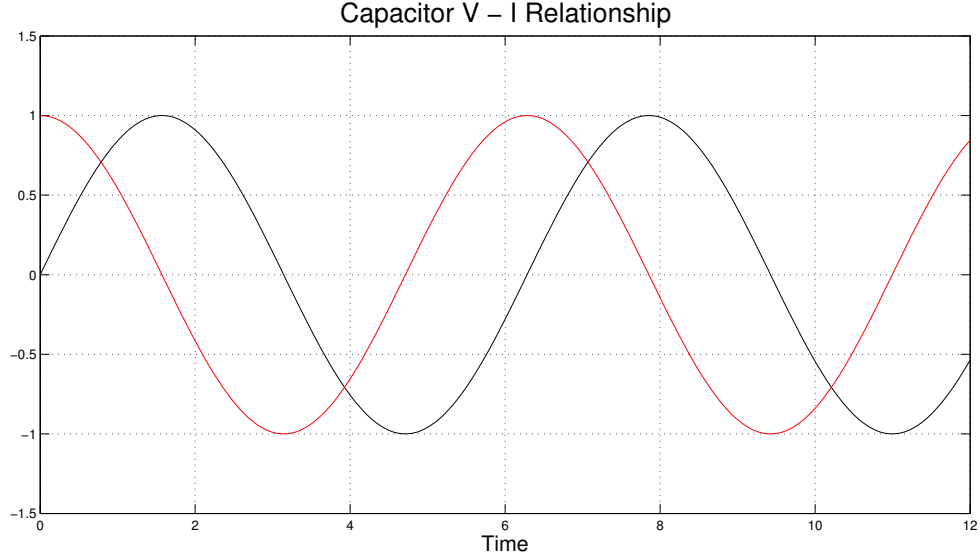


Figure 5: This shows the phase angle lag between the current and the applied potential. (The potential is the black wave while the current is the red wave.)

of frequencies. Notice that the impedance of the capacitor is imaginary. Our samples, however, are not empty capacitors. They are comprised of two glass microscope slides with liquid crystals between them. Thus, before we begin to describe the experiment, we must review the physics of a capacitor with dielectric material between the two plates.

2.2 Capacitor with Dielectric Material

A dielectric material is an electric insulator that can be polarized in the presence of an electric field. Liquid crystals are a type of dielectric material. Electric charges do not flow through the material as they do a conductor, rather they slightly shift in location by polarization of the molecules inside. In this case, positive charges shift in the direction of the external electric field, and negative charges away from the field. If the molecules of a material are weakly bounded, they will flip their axis of symmetry parallel to align with the direction of the field, a phenomenon known as polarization. An increase in polarization inside a capacitor will increase its surface charge. The polarization density, \mathbf{P} , within a capacitor is an expression for the vector field describing the number of dipole moments between the two plates.

$$\mathbf{P} = \epsilon_0 \chi \mathbf{E} \quad (6)$$

where χ is the electric susceptibility of the dielectric material, or how easily the dipoles align with electric field. The susceptibility factor describes how sensitive the dielectric is to its environment. Temperature, density, and pressure can effect the material's response to the external electric field. Thus, this factor is the interest of dielectric spectroscopy. Equation 6 is linear under small alternating electric fields, and is related the dielectric's permittivity:

$$\epsilon_r = \chi + 1 \quad (7)$$

The total charge on the surface of capacitor's plates is altered by this polarization density caused by the dielectric is

$$\frac{Q}{A} = \epsilon_0 \mathbf{E} - \mathbf{P}. \quad (8)$$

Plugging in the expression for the polarization density and solving for the electric field, we can see how the electric field is effected by the dielectric (through the susceptibility constant).

$$\mathbf{E} = \frac{Q}{A\epsilon_0(1 + \chi)} = \frac{Q}{A\epsilon_0\epsilon_r} \quad (9)$$

The new capacitance of the slides is

$$C = \frac{Q}{dE} = \frac{Q}{\frac{Q}{A\epsilon_0\epsilon_r}d} = \frac{A\epsilon_0\epsilon_r}{d}. \quad (10)$$

Notice, there is a new factor ϵ_r . Thus, by measuring the capacitance of our samples, we can study the polarization susceptibility of liquid crystals. We will exploit this fact through using alternating electric fields at different frequencies and observing the sample's response. After scanning across a wide range of frequencies, we expect to see a particular frequency at which the capacitance falls off (and conductance peaks).

2.3 The Theory Behind the Experiment

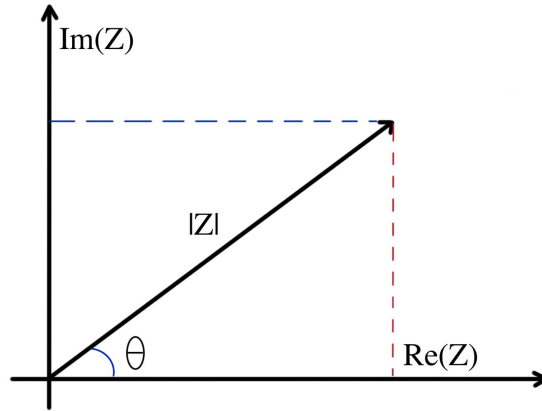


Figure 6: Imaginary Vs. Real plane for the capacitor's impedance. $|Z| = \sqrt{R^2 + X^2}$

In this experiment, we use a HP 4192A LF Impedance Analyzer to measure the dielectric properties of our liquid crystal samples. This machine applies an AC voltage across the sample and measures the magnitude of it's impedance. Recall from earlier, the applied voltage lags the current through the capacitor by some angle. This device measures this phase angle (as well as the magnitude), allowing us to determine the real and imaginary parts of the total impedance. Figure 6 shows the imaginary versus real plane. The real part is known as the resistance of the circuit, R , while the imaginary part is known as the reactance, X . Equation 5 describes the impedance of a capacitor as imaginary; therefore, an ideal liquid crystal sample would only displace the imaginary part. However, there is a small bit of resistance in the samples due to the electrode connections across the slides. Using the data output from the impedance analyzer, the magnitude and phase angle, we can determine the values for the reactance and resistance:

$$R = |Z| \cos \theta \quad \text{and} \quad X = |Z| \sin \theta \quad (11)$$

These two expressions lead us to the complex impedance:

$$Z = R + iX. \quad (12)$$

If we take the reciprocal of this value, we get the admittance, Y , which can lead us straight to the capacitance of the sample. The complex admittance is

$$Y = G + i\omega C \quad (13)$$

where G is the conductance and C is the capacitance of the circuit (The expression ωC is known as the susceptance B). In this experiment, we measure the impedance and use it to calculate the values for G and C . These expressions are simply:

$$G = \frac{R}{R^2 + X^2} \quad \text{and} \quad C = \frac{-X}{\omega(R^2 + X^2)} \quad (14)$$

From these, we can derive the complex dielectric constant, ϵ_r , which also has real and imaginary parts ($\epsilon_r = \epsilon' + i\epsilon''$). These expressions are

$$\epsilon' = \frac{C}{C_0} \quad \text{and} \quad \epsilon'' = \frac{G}{\omega C_0}. \quad (15)$$

This dielectric variable is the interest of this experiment. We will study the behavior of value at different frequencies and temperatures.

The Debye relaxation model describes a dielectric's relaxation response to a population of ideal dipoles exposed to an alternating external field. When the liquid crystal is in the Goldstone mode, it behaves similar to bulk of ideal dipoles. Thus, we will use this model to monitor and probe our data for such modes. It will be used to fit out experimental data and determine the susceptibility of the crystals to align with the field. The general model is:

$$\epsilon_r = \epsilon_\infty + \frac{\Delta\epsilon}{1 + [i(f/f_r)]^\beta} + g(f) \quad (16)$$

where ϵ_∞ is the permittivity at the high frequency limit, $\Delta\epsilon$ is the relaxation strength, f_r is the relaxation frequency, and $g(f)$ is the lower-frequency contribution [11]. This model contains complex values and can be plotted for both the real and the imaginary part against the frequency (known as a Debye plot). Figure 7 plots the model with generic values.

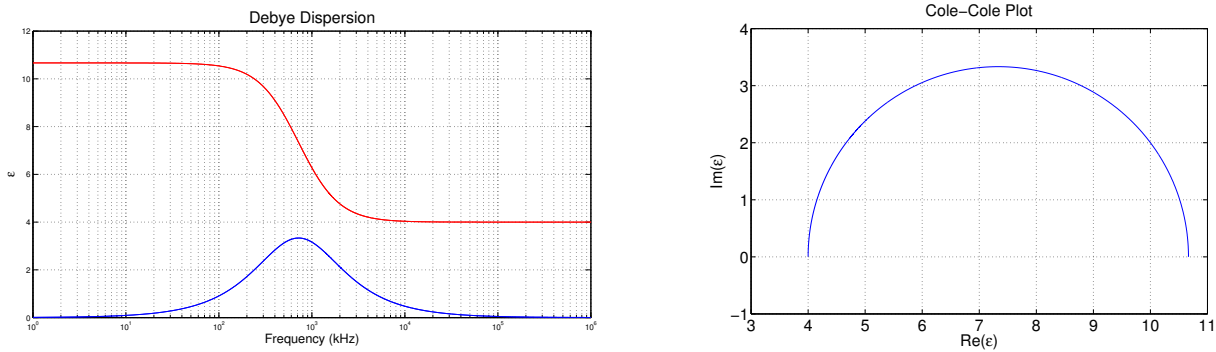


Figure 7: The left plot shows an example of a Debye dispersion. The real part (ϵ') of the model is plotted as the red line, while the imaginary part (ϵ'') is plotted as the blue line. The right plot shows a typical Cole-Cole plot of Debye dispersion.

It is important to remember our goal in this experiment. We are seeking to measure the electrical susceptibility χ_e of our liquid crystal samples. From this figure, we can see that the imaginary part of the dielectric variable shows a distinct “peak” known as the Goldstone mode. Recall that this plot is related to the conductance G (or ease of current flow through the sample) of the liquid crystal cell.

Thus, this peak describes a rise in conductance and shows that the crystals are more *susceptible* to align with the alternating electric field at this frequency. Ultimately, this is a plot of the samples susceptibility factor.

Using the Debye dispersion model, we measure the height of this Goldstone mode peak, $\Delta\epsilon$, and determine the dielectric constant at that temperature. The reciprocal of this value is plotted against the temperature for each measurement, and the susceptibility critical exponent, γ , is determined used a fit with the power law model [13]:

$$(\Delta\epsilon)^{-1} = A|t|^\gamma. \quad (17)$$

2.4 What is Going on with the Liquid Crystal?

Now that we know how to make the measurements, we take a moment to explain what exactly we are measuring. More specific, what is happening inside the liquid crystal cell? As described earlier, when a material is in the SmC phase, it tilts an angle θ away from the perpendicular director z . While the average direction of all the molecules have the same director n , this director has the freedom to move anywhere on the tilt cone. Especially in an alternating electric field, the molecules will revolve back and forth to align with the field. In this experiment, we observe the response of the crystals to such a field by measuring the dielectric coefficient shown in Figure 7. The imaginary piece ϵ'' of this coefficient is the susceptibility of the crystals to revolve at the frequency of the alternating field. Any peaks visible on this graph describe the phenomenon when the crystals revolution rate is closest to matching the frequency of the field. This is known as the **resonance frequency** of the crystal.

If the crystal is in the SmA phase, we expect the sample to have no polarization, because the z and n director are parallel. The illustration in Figure 3 shows the alignment of the crystals with our glass slides. The crystals do not flip or align with any external electric field applied across the slides without polarization. Therefore, when observing the dielectric response of the crystal in this phase, we expect to see no resonance peak in the measurements.

If the crystal is in the SmC phase, the crystals have a polarization from the tilt cone. As a field is applied across the slides, the polarization director aligns with this field and the molecules revolve accordingly. Therefore, these type of crystals typically have high dielectric permittivity in the SmC phase due to a collective relaxation response of every crystal in the system. This phenomena is known as the Goldstone mode (GM) [4]. As a result, we expect to see a resonance peak appear in the dielectric coefficient when sweeping over a range of frequencies. We repeat these measurements at many different temperatures to create a surface plot of the dielectric spectrum. On this surface, we look for a clear phase transition at the transition temperature for each sample we test.

3 Results

We run the experiment on a TSiKN65 sample cell of thickness $10\mu\text{m}$ using the HP 4192A LF impedance analyzer. The machine applies an 0.1V potential through the electrodes of the cell, oscillating at a frequency sweep range of 50Hz to 10MHz . The data is recorded using a NI Labview program and

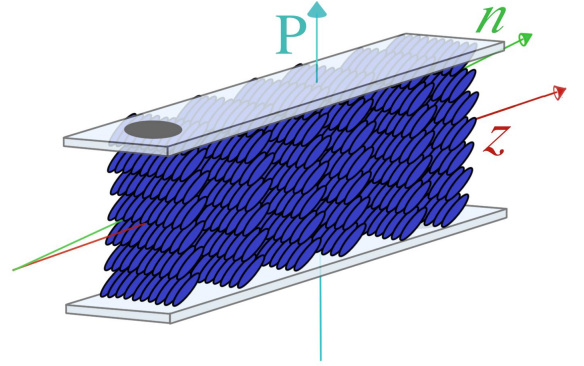


Figure 8: Illustration of a typical SmC liquid crystal sample between two conducting slides. Due to the direction of the tilt (along the horizontal plane of the cell), the polarization points vertically through the sample.

analyzed using Matlab. This measurement is repeated at different temperatures ranging from 20 - 60°C and steps of 1°C. The data retrieved from the impedance analyzer is the magnitude of the impedance across the sample, the angle projected into the imaginary vs. real plane, and the frequency of each data point. Using the geometric conversion described in the section above, the data of the crystals' behavior is described in three plots for each temperature: the imaginary part of the dielectric constant, the real part of the constant, and the Cole-Cole plot. The plots for each temperature are shown in Appendix I.

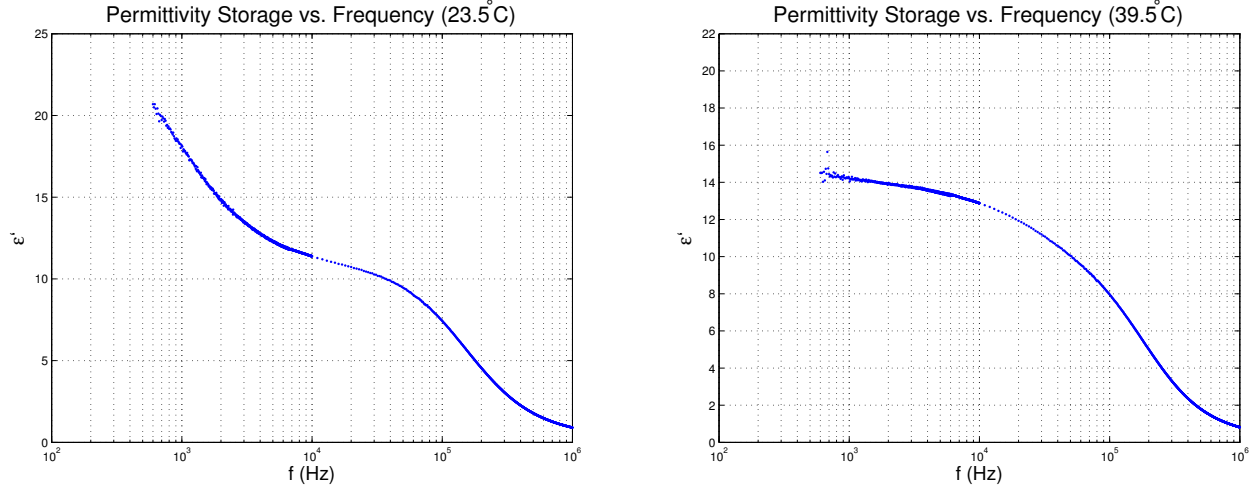


Figure 9: The left plot shows an example of a Debye dispersion. The real part (ϵ') of the model is plotted as the red line, while the imaginary part (ϵ'') is plotted as the blue line. The right plot shows a typical Cole-Cole plot of Debye dispersion.

The results for two temperatures, 23.5°C and 39.5°C, are shown in Figures 9, 10, and 11, comparing the characteristic behavior for the dielectric spectra in the SmC and SmA phases. In both phases, there is a dielectric resonance peak in the 10^5 Hz range known as the dipolar relaxation. The dipole polarization orientation is disturbed by thermal noise and there is a relaxation period where the molecules realign their polarization vectors with the external field. For our experiment, our interest lies in the second peak visible in the lower frequency range. (Unfortunately, at frequencies lower than 300 Hz, the data from the impedance analyzer's data becomes too noisy to interpret.) Figure 10 shows two distinctly different behaviors in the SmC and SmA phase. In the SmC, there is a relatively large peak seen in the $10^2 - 10^3$ Hz range, but in the SmA phase, this peak completely disappears. This is Goldstone mode described earlier. Due to the tilt in the molecules, there is an increase in this unique polarization relaxation in the SmC phase that occurs in this frequency band. The Cole-Cole plots in Figure 11 aid in illustrating the significant difference between the two phases. The full spectrum over all temperatures for the TSiNK65 sample is shown in Figure 12.

4 Analysis

Using Matlab's "fit" function and the model in Equation 16, we extract the value of $\Delta\epsilon$. An example of this fit is shown in Figure ???. This value is plotted against the temperature and

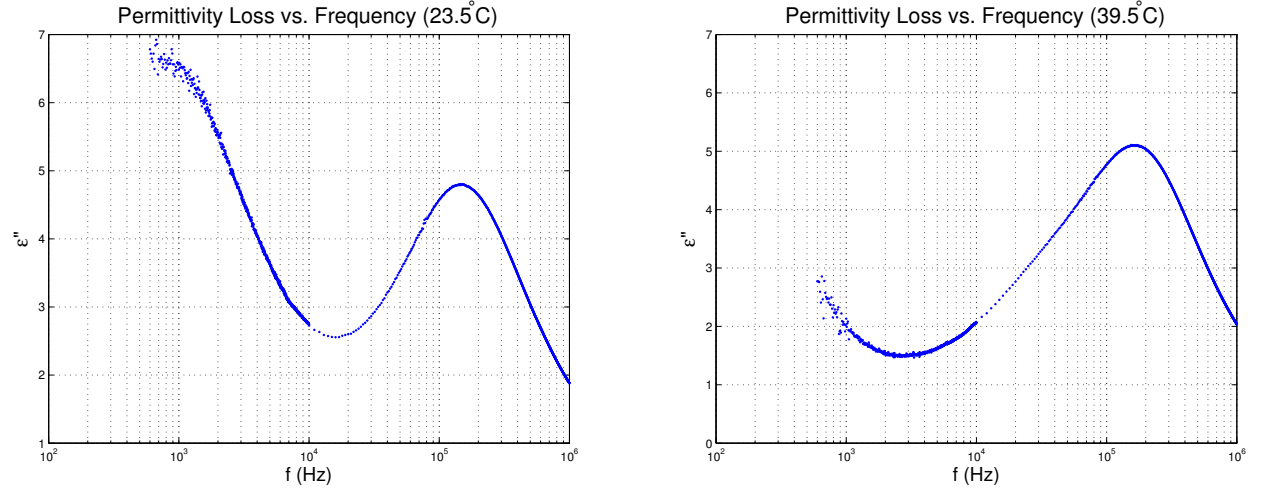


Figure 10: The left plot shows an example of a Debye dispersion. The real part (ϵ') of the model is plotted as the red line, while the imaginary part (ϵ'') is plotted as the blue line. The right plot shows a typical Cole-Cole plot of Debye dispersion.

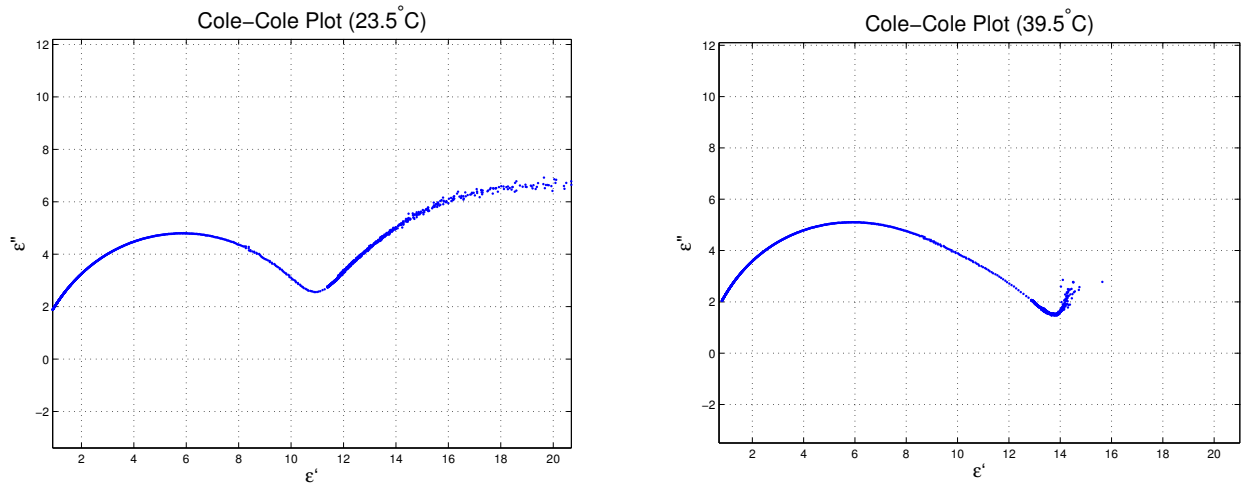


Figure 11: The left plot shows an example of a Debye dispersion. The real part (ϵ') of the model is plotted as the red line, while the imaginary part (ϵ'') is plotted as the blue line. The right plot shows a typical Cole-Cole plot of Debye dispersion.

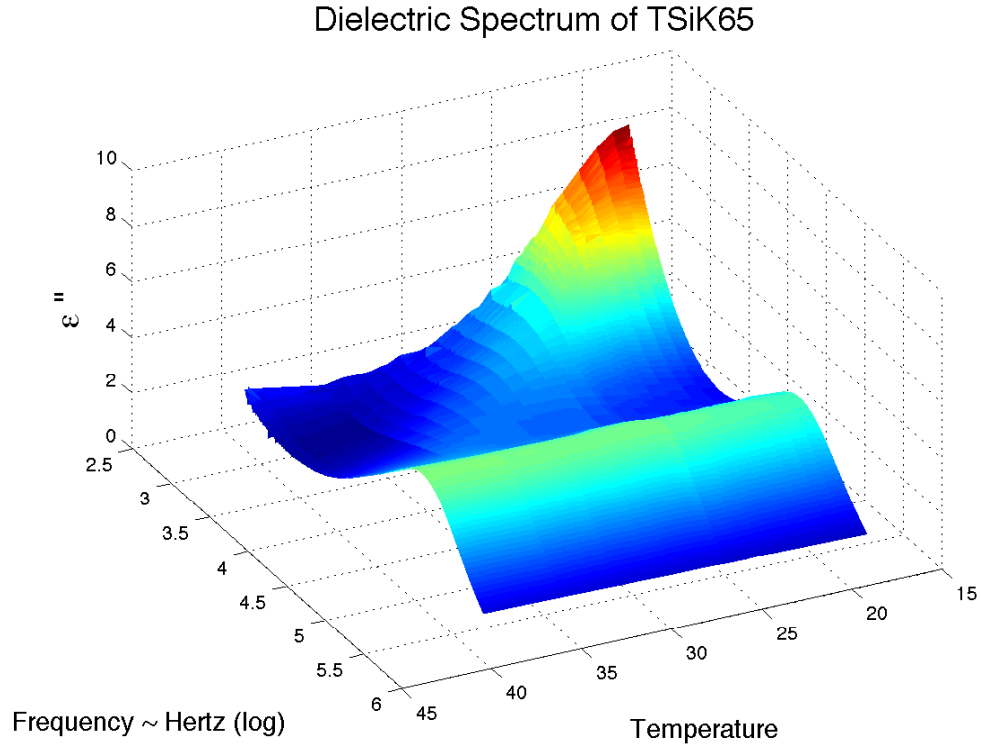


Figure 12: The full spectrum of the dielectric constant for the TSiNK65 liquid crystal sample cell.

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5 Appendix I

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1 %% Import data and Format!
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5           ;...
6           'test14'; 'test15'; 'test16'; 'test17'; 'test18'; 'test19'; 'test20'
7           ;...
8           'test21'; 'test22'; 'test23'; 'test24'; 'test25'; 'test26'; 'test27'
9           ;...
10          'test28'; 'test29'; 'test30'; 'test31'; 'test32'; 'test33'; 'test34'
11          ;...
12          'test35'; 'test36'; 'test37'; 'test38'; 'test39'; 'test40'; 'test41'
13          ;...
14          'test42'; 'test43'; 'test44'; 'test45'; 'test46'; 'test47'; 'test48'
15          ;...
16          'test49'; 'test50'];
17
18 fL = size(filename); % should be an even number (if not, check 'filename')
19 epsilon1 = zeros(1,fL/2);
20 epsilon2 = zeros(1,fL/2);
21 frequency = zeros(1,fL/2);
22 T = [40.5 39.5 36.1 35.1 34.1 33 31.9 30.9 29.9 29 28 27 25.9 25.5 25.2 25
23      24.6 24.4 24 23.5 22.9 22 21 20.1 19.2];
24
25 TL = length(T);
26 %%
27 for i = 1:2:fL;
28     % filename1 = uigetfile;
29     % filename2 = uigetfile;
30     data1 = importdata(filename(i,:));
31     data2 = importdata(filename(i+1,:));
32
33     data1(1:50,:) = [];
34     data2(1,:) = [];
35     n1 = length(data1);
36     n2 = length(data2);
37     m = n1+n2;
38
39     fullMagn = zeros(m,1);
40     fullMagn(1:n1) = data1(:,1)';
41     fullMagn(n1+1:m) = data2(:,1)';
42
43     fullAngl = zeros(m,1);
44     fullAngl(1:n1) = data1(:,5)';
45     fullAngl(n1+1:m) = data2(:,5)';
46
47 end
```

```

40     fullFreq = zeros(m,1);
41     fullFreq(1:n1) = data1(:,2)';
42     fullFreq(n1+1:m) = data2(:,2)';
43
44     % Find your epsilons!
45     A = .01^2;
46     eps0 = 8.854187e-12;
47     d = 5e-6;
48     omega = 2*pi*fullFreq;
49
50     G = cos(fullAngl)./(fullMagn);
51     C = -sin(fullAngl)./(fullMagn);
52     C0 = (A*eps0)./(d);
53     epsilon2(1:m,(i+1)/2) = G./(omega.*C0);
54     epsilon1(1:m,(i+1)/2) = C./(omega.*C0);
55     frequency(1:m,(i+1)/2) = fullFreq;
56 end
57 %%
58 Temperature = meshgrid(T,1:1:m);
59
60 %% Plot the dielectric spectrym of sample
61 figure(1)
62 surf(Temperature,log10(frequency),epsilon2, 'LineStyle', 'none');
63 title('Dielectric Spectrum of TSiK65', 'fontsize', 18)
64 xlabel('Temperature', 'fontsize', 14)
65 ylabel('Frequency\n ~ Hertz (log)', 'fontsize', 14)
66 zlabel(' \epsilon " ', 'fontsize', 18)
67
68
69 % figure(2)
70 % mesh(Temperature,epsilon1,epsilon2);
71 % title('Dielectric Spectrum of TSiK65')
72 % xlabel('Temperature')
73 % ylabel('Frequency ~ Hertz (log scale)')
74 % zlabel(' \epsilon " ')
75 % axis equal

```