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Investigating Chiral Light-Matter
Interactions in Photonic Materials

By

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Chiral Cavities and Crystals: when light and matter interact!

Preface

In my senior year of college, as I was beginning to apply to graduate schools, an advisor stressed to me that to do a PhD is to become the world's expert in *one specific thing*. Over the course of your graduate studies, they said, you will dive deeper into your subject, narrowing down your area of research until you identify a very specific question, something that has never been done before. As you work towards answering that question, you will not only contribute something novel to the broader scientific community, but you will also become the foremost expert in that one very specific area of study.

To embark on the process of becoming not just *an* expert, but *the* expert in something was, naturally, quite intimidating. What grounded me throughout this process was placing an emphasis on the process itself. In becoming an expert in something, I learned *how* one becomes an expert in something. As I advanced my understanding of the basic concepts and content of my field, I also developed the meta-skill of how to teach myself something I want to know. I learned *how to learn*.

As our society becomes increasingly dependent upon science and technology, and as research becomes more and more interdisciplinary (a very good thing!), I feel it is especially important to make one's research relevant and accessible to as many people as possible. Of course, everyone learns differently, and just because I know how to teach *myself* something doesn't necessarily mean I know how to teach it to someone else. I have often struggled to communicate exactly what it is that I *do* as a scientist, and I usually can't go into much detail before running into issues of vocabulary and fundamentals. I understand, of course, that I've spent much more time with these concepts than almost anyone else I might meet – I am, after all, supposed to be the world's expert here! Still, I recognize the importance of communicating my work in a meaningful and impactful way – how is anyone supposed to make use of scientific research if they can't understand it?

I am a scientist today because of the people who took the time to help me understand, and I have always felt motivated to pay that kindness forward. Throughout my time in graduate school, I've taken part in a variety of science education and public engagement efforts through Science is Fun, the Wisconsin Initiative for Science Literacy, and the Delta Program in Research, Teaching, and

Learning at UW-Madison. These experiences allowed me to share my love of science with people of all ages and backgrounds. In the process, I learned how to communicate science effectively in a variety of contexts and across disciplines.

This chapter of my thesis is perhaps the ultimate culmination of my PhD, as it marries my scientific research with my passion for science communication. I have written this chapter to provide a background of the fundamentals which underpin the specific questions my research set out to answer, and to explain in simple terms for a general audience the work that I've done and what it has the potential to be useful for. This chapter is intended for people who don't necessarily have a strong background in science to learn about my field of research in an engaging and accessible way. I hope the experience of reading this chapter will prove as useful to my readers as the experience of writing it was for me.

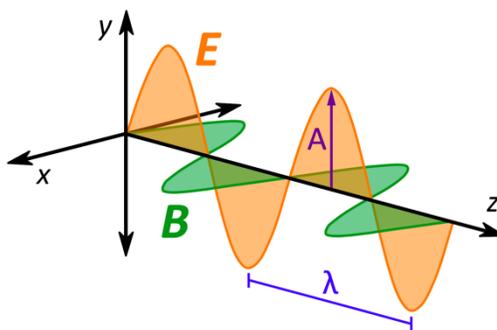
What is light?

Light is a form of energy that has been harnessed by humans since time immemorial, and over the centuries, scientists have devised numerous ways of explaining and understanding what light is and how it behaves in our world.

Light is electromagnetic radiation. Light exhibits behavior characteristic of both classical waves and quantum particles called **photons** – though we will first focus on the wave model here. Light is comprised of an electric field (**E**) and a magnetic field (**B**) that travel as waves perpendicular to one another in the same direction. The direction in which light travels is called its **axis of propagation** and is shown here as the z-axis.

The **amplitude** (**A**) describes the height of the crests of the wave, and is related to the brightness or intensity of the light. The **wavelength** (λ) of light describes how close together or far apart the crests of a wave are. Any property that is organized according to wavelength is called a **spectrum**.

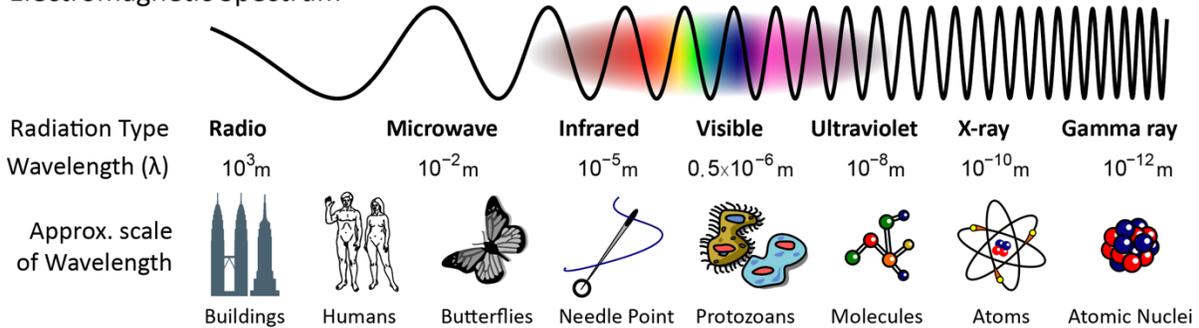
Electromagnetic Wave



The **electromagnetic spectrum** organizes the different types of electromagnetic radiation by their wavelengths. Longer wavelengths correspond to lower energy, and shorter wavelengths correspond

to higher energy. The light we can see with our eyes belongs to the visible part of the electromagnetic spectrum, with wavelengths ranging from about 400 to 700 nanometers ($1\text{nm} = 10^{-9}\text{ m}$). You might hear scientists refer to shorter wavelengths as “bluer” and longer wavelengths as “redder” because shorter visible wavelengths appear blue to our eyes, and longer visible wavelengths appear red.

Electromagnetic Spectrum



How does light interact with matter?

Interactions between light and matter are central not only to this thesis, but to numerous technological applications such as LEDs, solar cells, X-rays, lasers, and more. However, light-matter interactions are also a simple, everyday phenomenon. The rods and cones in our eyes absorb the light reflected off objects and emitted by screens, our skin cells warm up as they absorb sunlight, and so on. Light may interact with matter in a number of ways:

Transmission: light passes through a substance, e.g., light passes through windows un-distorted, allowing us to see objects outside as if there were nothing between us and them.

Reflection: light bounces off a surface, e.g., mirrors, glare off the road or the surface of a car.

Scattering: light is refracted, or bent, by a medium, e.g., items submerged in water look distorted because light travels differently in water than in air.

Absorption: light is absorbed by a material, e.g., sunglasses protect our eyes by absorbing harmful rays, stained glass transmits only certain colors (wavelengths) of light and absorbs all the others.

Emission: an already-energized material relaxes, releasing some of its energy in the form of light, e.g., glow-in-the-dark paint, bioluminescent organisms.

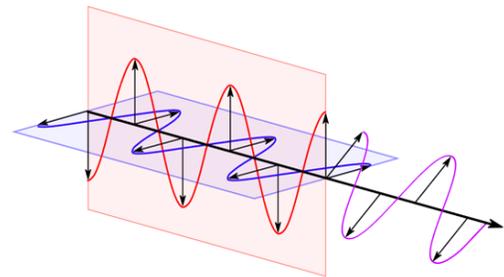
What is polarization, and what does it have to do with light-matter interactions?

Polarization describes the orientation of oscillations in a wave. In the case of light waves, polarization indicates the orientation of the *electric field's* oscillations, but for simplicity, we will just talk about polarization in terms of “light waves” and know that we mean the electric field specifically.

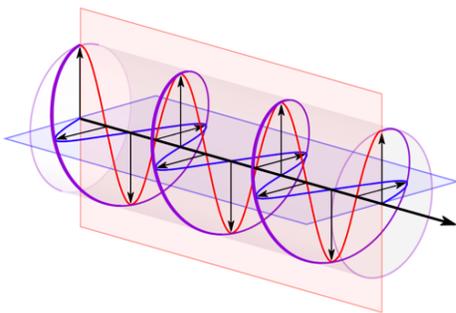
Not all light is polarized. Sunlight, for example, is unpolarized, with the orientation of its oscillations varying in time and space. The concept of polarization is most commonly encountered in the form of polarized sunglasses: these lenses reduce glare by filtering out the horizontal polarizations produced by sunlight reflecting off horizontal surfaces (i.e., the road).

When light oscillates only in one plane, it is called **linearly polarized light** (LPL). If two perpendicular LPL waves (shown here in red and blue) oscillate in phase with one another – this means their crests and valleys are lined up – the resulting wave (shown in purple) is also linearly polarized, but at an angle between the initial waves' angles of oscillation. LPL can be produced by passing unpolarized light through a linear polarizer, a kind of optical filter which transmits only light of a single polarization and blocks others by absorption or reflection.

Linearly Polarized Light



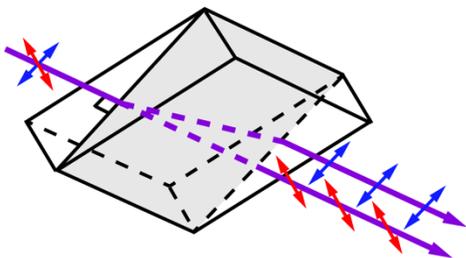
Circularly Polarized Light



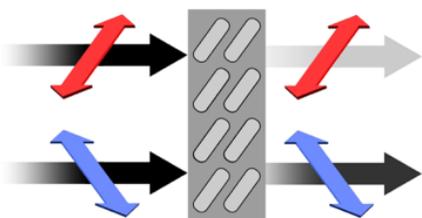
Circularly polarized light (CPL) is created when two perpendicular waves (shown here in red and blue) have the same amplitude but are shifted out of phase by exactly one quarter wavelength ($\pm\lambda/4$), meaning the crests of one wave line up with the valleys of the other wave and vice versa. The resulting wave (shown in purple) rotates around the axis of light propagation once per wavelength, forming a circle. Depending on the direction of rotation, CPL may either be **right circularly polarized** (RCP) as depicted here, or **left circularly polarized** (LCP).

CPL is produced by first generating LPL using a linear polarizer, then using an optical filter called a quarter wave plate to create a phase shift of $\pm \lambda/4$ in *just one* of the two perpendicular wave components that make up the LPL. Importantly, the amplitude of the two component waves must be equal to produce CPL. Otherwise, the same phase shift would produce **elliptically polarized light** (EPL), which also rotates once per wavelength but forms an ellipse, or oval.

Linear Birefringence



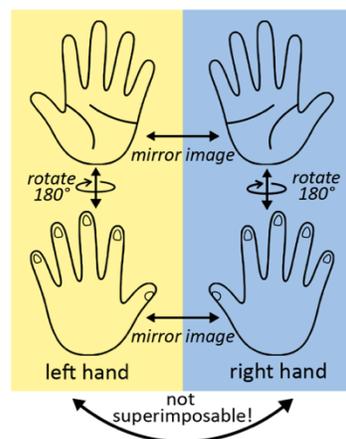
Linear Dichroism



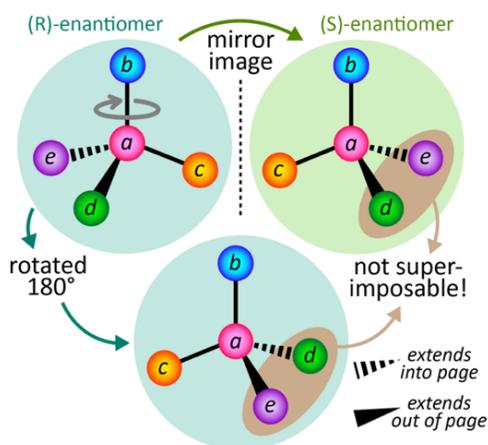
Interactions between light and matter sometimes differ depending upon the polarization of the light. **Birefringence** is a phenomenon in which a material *refracts* or bends light differently depending upon its polarization. **Dichroism** is a phenomenon in which a material *absorbs* light differently depending upon its polarization. Birefringent and dichroic interactions usually depend on the **polarization axis** of the light and the **orientation axes** along which the atoms or molecules in the sample are oriented. Only certain substances exhibit these behaviors, as they also depend upon the material's makeup and structure.

What is chirality, and what does it have to do with light-matter interactions?

An object which is distinguishable from its mirror image is **chiral**. An object which is not chiral may be called **achiral**. Our hands are an example of a chiral system – the word chiral actually comes from the Greek word for hand, $\chi\epsilon\iota\rho$. The left and right hands have the same components and connections between them, four fingers and a thumb connected to a palm. But the left and right hands are arranged differently in space; they are not **superimposable** on their mirror images.

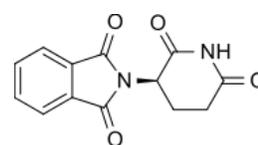


Because our hands are oriented differently in three dimensions, they cannot always perform the same functions in the same way. Some tools may necessitate a different design for use by one hand or the other, e.g., left-handed scissors, can-openers, guitars, etc.

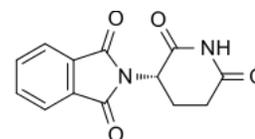


In chemistry, if a molecule is distinguishable from its mirror image, it is chiral. Although the two molecular structures shown here have the same components and the same connections between them – atoms *b*, *c*, *d*, and *e* are all connected to atom *a* by a single bond – they do not have the same arrangement in 3D space. The two different mirror-image forms of a chiral molecule are called **enantiomers**.

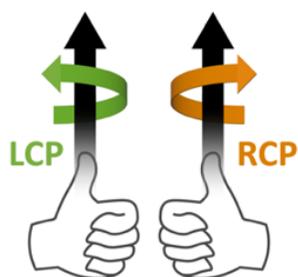
Just as our hands cannot perform the same functions in the same way as one another, enantiomers do not always have the same properties and behaviors in chemistry. Often only one enantiomer is effective for a given application, while the other may be ineffective or even harmful, as in the case of thalidomide. This drug was prescribed to combat morning sickness in the mid-twentieth century, and while the (R) enantiomer was effective, the (S) enantiomer caused birth defects. This example is just one of many in which enantiomers exhibit different behaviors, and it illustrates why it is often desirable to synthesize or isolate one enantiomer for a given application.



(R)-thalidomide



(S)-thalidomide

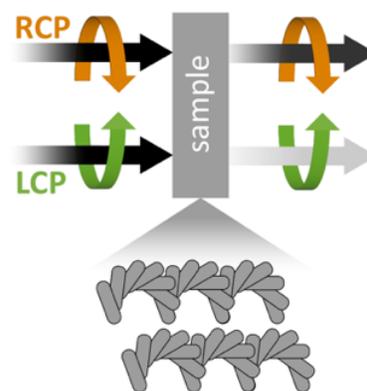


Enantiomers may also exhibit different interactions with polarized light. In fact, CPL is another example of a chiral system! RCP and LCP are enantiomers of one another, and this is why they are sometimes referred to as “right-handed” and “left-handed” CPL. Here, the **handedness** of CPL is illustrated using hands, with the thumb indicating the direction of light propagation, and the fingers curling in the direction of the field’s rotation.

CPL is essentially chiral light, and it may interact with chiral (and achiral) matter in a number of unique ways. The term **chiroptics** is often used to refer to such phenomena more generally. Chiroptical phenomena have proved useful for various applications across the sciences.

One of the most significant chiroptical phenomena is **circular dichroism** (CD), a specific form of dichroism in which a sample exhibits a **differential absorption** of LCP and RCP. One might intuit that a right-handed molecule would absorb right-handed light more readily than left-handed light, and indeed, that is what differential absorption is. This is the basis of CD spectroscopy, which allows scientists to investigate the chirality of a sample through its interactions with CPL.

Circular Dichroism



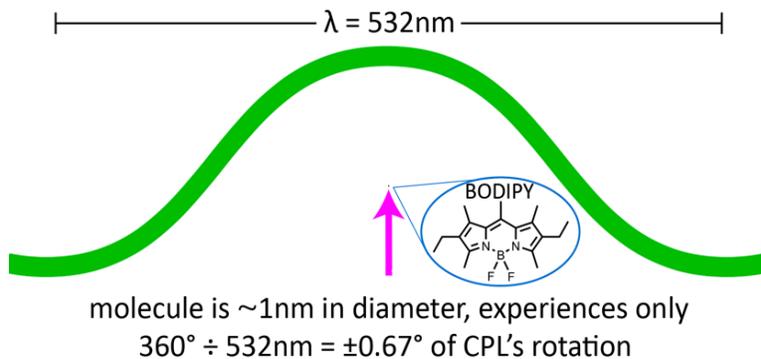
CD responses are frequently reported in terms of the dissymmetry factor, or **g-factor**, a measure of the difference in the sample's absorption of LCP and RCP divided by the total absorption. One way to calculate the g-factor is to measure the intensities of LCP and RCP transmitted through a sample (T_{LCP} and T_{RCP}) and plug them into the equation given at the right.

$$g = 2 \times \frac{T_{RCP} - T_{LCP}}{T_{RCP} + T_{LCP}}$$

There are other ways of reporting CD signals, but a positive value always means that more LCP was absorbed, which means there are likely more left-handed molecules than right-handed ones in the sample. A negative value, on the other hand, means more RCP was absorbed, which means there are likely more right-handed molecules than left-handed ones in the sample.

If the sample has many, many more of one enantiomer than the other, the **magnitude** of the CD signal will be much larger (very positive or very negative) than if the sample has only slightly more of one enantiomer than the other.

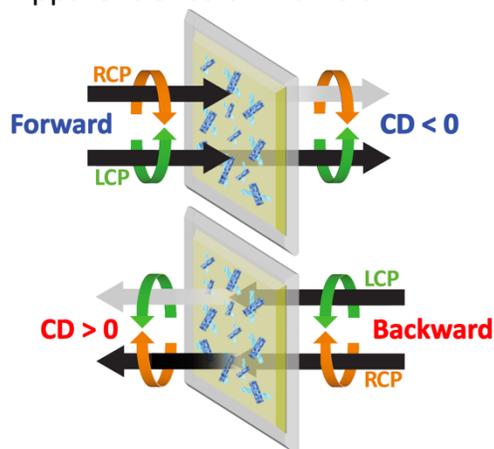
CD signals are usually quite small due to the size mismatch between the wavelength of light and the absorbing molecule. As CPL rotates only once per wavelength, the difference between LCP and RCP is very small at the scale of the molecule. Still, CD spectroscopy can be a useful tool for investigating the chirality of larger molecules, such as proteins, or crystalline samples.



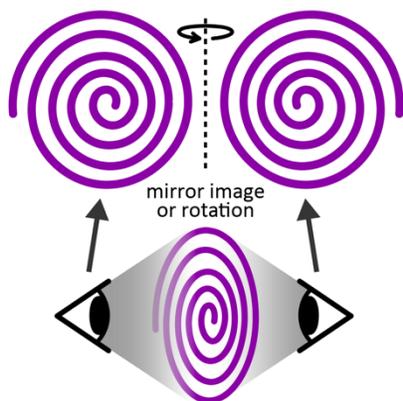
What is Apparent Circular Dichroism?

Some materials exhibit **apparent circular dichroism** (ACD), a chiroptical phenomenon in which the sample's CD response is opposite for **counterpropagating** light (traveling in opposite directions). Put simply, an ACD-active sample will absorb more RCP than LCP when the light is applied in one direction, and it will absorb more LCP than RCP when the light is applied in the opposite direction.

Apparent Circular Dichroism



2D Chirality

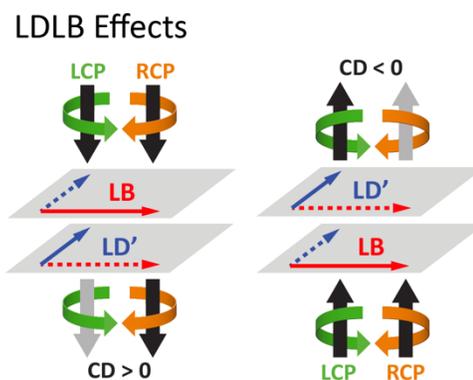


ACD-active samples are sometimes called **2D chiral**, which means, as the name suggests, they are chiral only in *two* dimensions. 2D chiral objects appear to have one handedness when observed from one direction, and the other handedness when observed from the opposite direction. This is why the CD signal from a 2D chiral sample is opposite for light traveling in opposite directions.

Conversely, the conventional **3D chiral** samples we encountered previously have the same handedness no matter what vantage point they are observed from, and therefore their CD responses are independent of the direction of light propagation.

ACD results from **LDLB** effects, a combination of linear dichroism (LD) and linear birefringence (LB) effects oriented at an angle to each other within the same sample. To understand how this works, recall that CPL is composed of two perpendicular LPL wave components, shifted $\lambda/4$ out of phase from each other. In ACD, LB along one axis first alters the *phase* of the two components differently, then these phase-shifted components are *absorbed* differently by LD which is oriented along a different axis (this axis is indicated by the ' in LD'). These LDLB interactions differ for LCP and RCP due to their difference in phase ($\pm\lambda/4$), producing an overall differential absorption of LCP and RCP, even if the sample has no 3D chirality.

The 2D chiral component involved in ACD is the angle between the axis of LD and the axis of LB. This angle can be thought of as “positive” for light traveling in one direction and “negative” for light traveling in the other direction. Thus, the orientation of the LDLB interactions is inverted for light traveling in opposite directions, yielding a positive CD signal in one direction and a negative CD signal in the other direction.



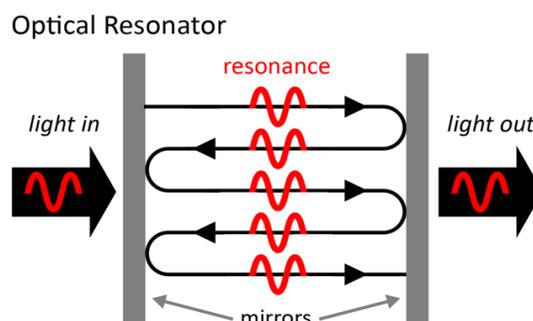
ACD is a double-scattering effect: the *first* molecule in the beam path causes the phase shift by LB, then the *next* molecule causes the differential absorption by LD. The process repeats, with the next molecule causing another phase shift, and the next a differential absorption, and so on. This effect cascades, resulting in a CD response which increases with sample thickness.

3D chiral samples, on the other hand, display a differential absorption of LCP and RCP due to single scattering events, that is, individual interactions between CPL and molecules that are 3D chiral. The magnitude of the CD signal depends somewhat on the orientation of the molecules relative to the light, but it will never change sign: no matter how you rotate it in 3D space, a right-handed molecule will always be right-handed and will always preferentially absorb RCP.

What can you *do* with Apparent Circular Dichroism?

Light-matter interactions are generally quite weak and short-lived, which complicates their use in various applications. These interactions may be strengthened by embedding the absorbing material in an **optical resonator**, which confines light via multiple reflections between two mirrors. Only certain wavelengths of light reproduce themselves upon each reflection within the resonator; these are called the cavity **resonances** and they vary depending on the distance between the two mirrors.

The total “distance” light travels over its many reflections within a resonator is called the **path length**. It is beneficial to increase the path length using highly reflective mirrors, as each round-trip within a cavity strengthens the light-matter interaction.

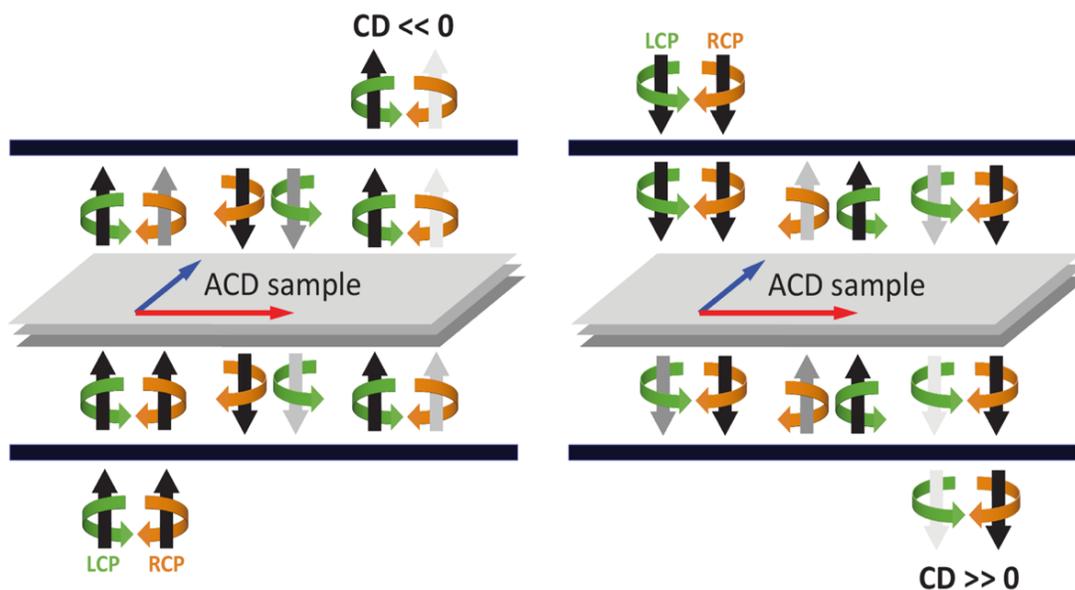


The promise of optical resonators is not just that they strengthen light-matter interactions, but that they are capable of strengthening light-matter interactions to such an extent that the light and matter actually *hybridize*, forming a particle-like state that has characteristics of both light and matter. These hybrid light-matter states are called **polaritons**. The energies of polaritons are different from the energies of light and matter, which makes them attractive for use in many different applications, such as catalysis, where the energies of the different chemical components involved play an important role in making a reaction happen.

Chiral polaritons, generated by strong *chiral* light-matter interactions, are particularly promising for quantum computing purposes, as the LCP and RCP polarization states of light could act as qubits (quantum bits) for storing and transferring information quite quickly and efficiently. There has also been recent interest in using chiral polaritons to create chiral lasers which generate CPL without linear polarizers and quarter wave plates.

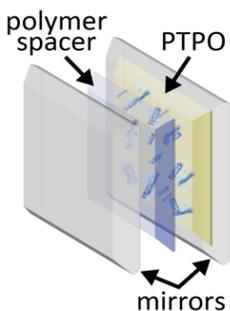
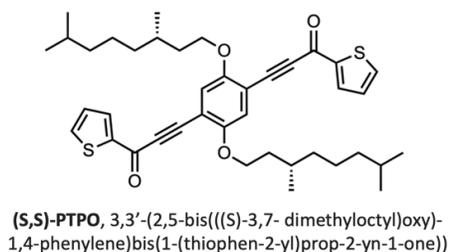
Unfortunately, chiral polaritons cannot be created with conventional optical resonators, as they cannot enhance *chiral* light-matter interactions. This is because CPL changes handedness when reflected in a mirror. Special mirrors are capable of maintaining the handedness of CPL upon each reflection, though these usually require precise nanofabrication and are not easily scaled up.

Chiral asymmetry within an optical resonator could instead be achieved by embedding it with a 2D chiral material. Because LDLB interactions are opposite for counterpropagating light, *the asymmetry between LCP and RCP intensity compounds with each round trip* through the ACD-active material in the resonator.



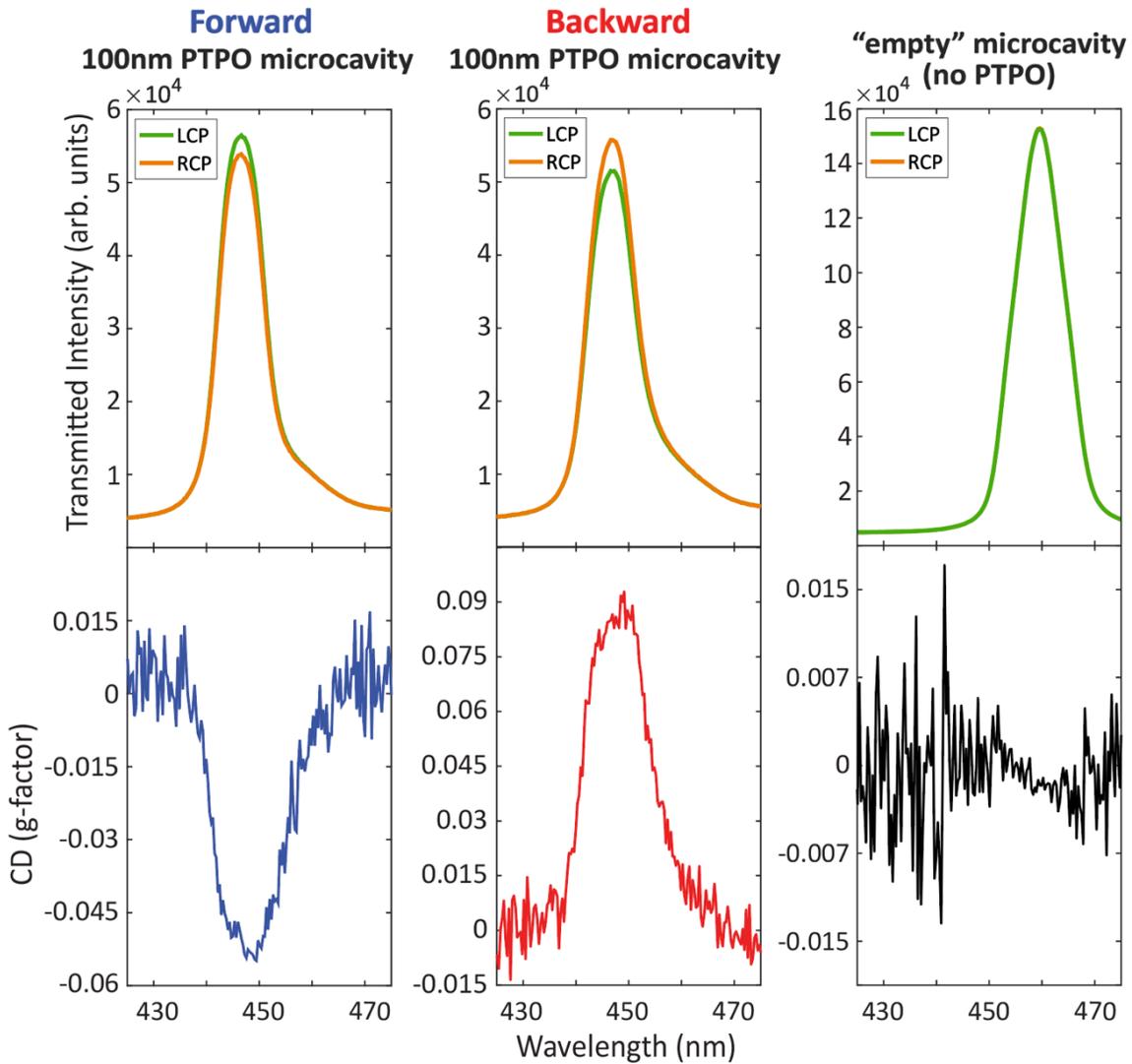
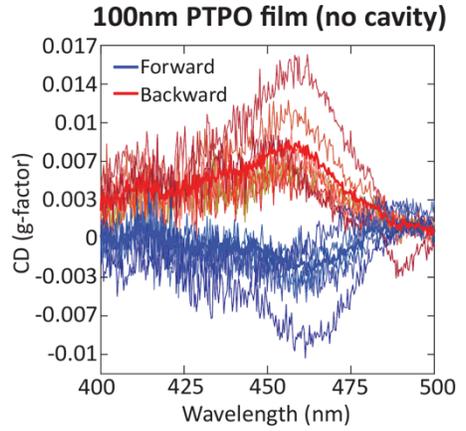
What *did* you do with Apparent Circular Dichroism?

We created a **2D chiral microcavity** by embedding an optical resonator with an ACD-active material called PTPO, an organic polymer which forms ordered crystals that exhibit different CD responses. Although this compound is 3D chiral on its own, its crystalline domains possess axes of LD and LB at the appropriate orientation to produce the ACD effect: the CD signal changes sign when the sample is flipped.



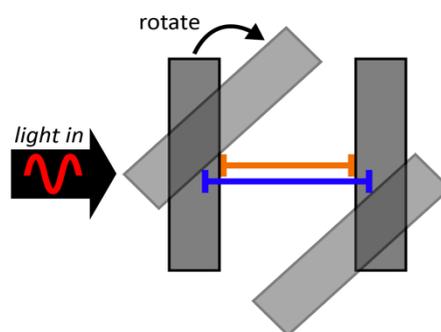
We fabricated our 2D chiral microcavities by sandwiching two mirrors together: one coated with a thin film of PTPO (provided by our collaborators), and the other coated with an achiral polymer spacer. The thicknesses of the PTPO and spacer layers were designed to produce a cavity resonance near the wavelength at which PTPO is expected to show ACD behavior, around 450nm.

We then illuminated the cavities with LCP and RCP, measured the transmitted intensities of each using a detector, and plotted the CD response as a function of wavelength. We also measured the CD responses of PTPO films not embedded in optical resonators. As expected, their CD responses, though the signals are relatively small, are of similar magnitude but opposite sign for counterpropagating light, which we determined by flipping the sample to measure the CD signal in “Forward” and “Backward” transmission configurations.

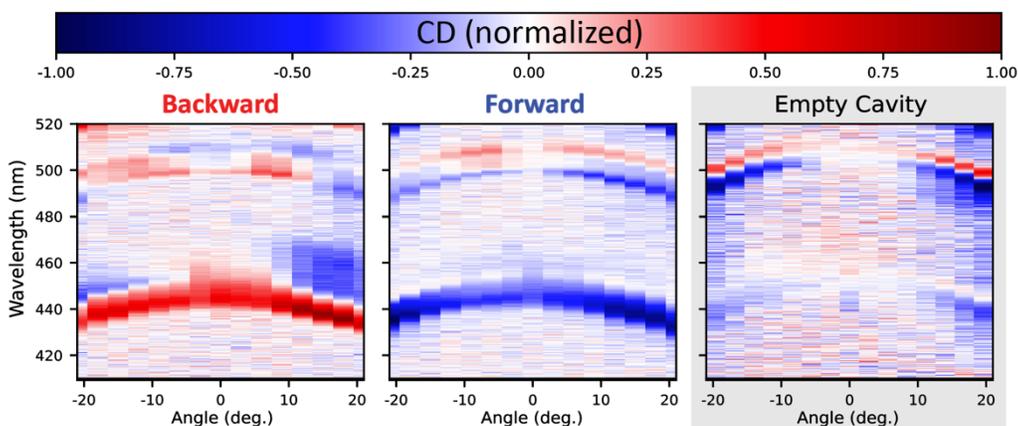


When embedded in microcavities, the PTPO thin films retained their ACD behavior, exhibiting **opposite CD signals upon sample-flipping**. The CD signals from the PTPO microcavities were up to **ten times stronger** than those displayed by the PTPO films alone. Control cavities without PTPO films (only polymer spacers) did not show any CD signal at all, indicating that the cavity does not have its own ACD behavior and only enhances that of PTPO.

These data were taken by illuminating the cavities at normal (perpendicular) incidence. We also rotated the cavities to record CD at oblique incidence (at an angle). This increased the magnitude of the CD signals somewhat, as the rotation increased the path length, leading to a stronger light-matter interaction. Rotation also shifted the cavity resonances to slightly lower wavelengths.

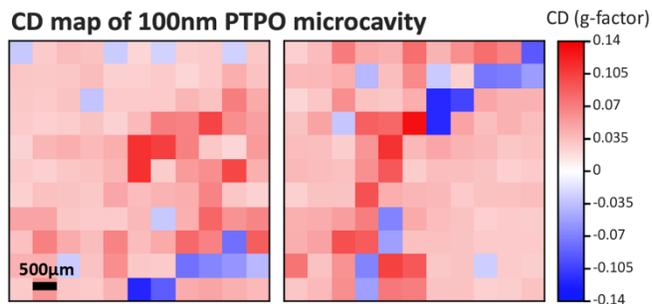


Additional cavity resonances around 500nm – wavelengths that PTPO does not absorb very well – displayed some ACD behavior only when illuminated at an angle. Empty cavities also exhibited appreciable CD from both the ~450nm and ~500nm resonances when rotated. Here, the CD is reported as “normalized,” meaning all the CD values are divided by the maximum CD value. This is just a simplification which makes it easier to compare datasets with different values.



There are some geometry-related reasons for this behavior, but for our purposes this finding mainly serves to provide some guidelines for any future applications of these 2D chiral cavities. Watch out, they may display odd signals when illuminated at an angle!

Finally, we measured the CD signal (at normal incidence) at many different spatial locations on the cavities to generate “CD maps” of the resonators. The CD values varied widely depending on which spot of the microcavity was illuminated, and even changed sign.



This was expected, as the PTPO films are made up of many different crystalline domains which orient themselves randomly during the fabrication process. Recall that the CD response of 2D chiral materials depends on their orientation relative to the direction of light propagation. One PTPO crystal may have formed with its axes of LD and LB at a “positive” angle for light traveling in one direction, yielding a positive CD response. Meanwhile, an adjacent crystal may have formed with its axes of LD and LB oriented oppositely, at a “negative” angle, for light traveling in the same direction, yielding a negative CD response.

Through this research, we were able to achieve enhanced chiral light-matter interactions with a simple, easy-to-make optical resonator by harnessing the power of ACD – no polarization-maintaining mirrors required!

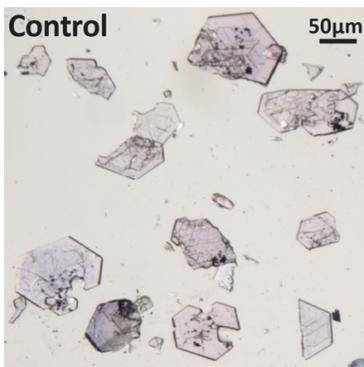
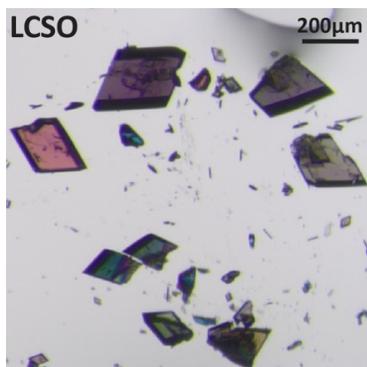
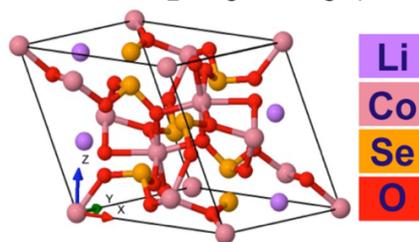
What *else* did you do with Apparent Circular Dichroism?

The phenomenon of ACD has, until now, only been observed in *organic* samples like PTPO (organic just means carbon-containing). However, the symmetry required to produce the ACD effect – that is, specific orientations of the axes of LD and LB in a sample – is present in some inorganic crystalline materials as well. Crystal structure symmetry plays a more important role here than it did for our studies of PTPO. We didn’t know the exact orientation or symmetry of the PTPO films’ crystalline domains, but we knew from the molecular structure that the compound should have the appropriate LDLB interactions so as to show ACD. To find an *inorganic* ACD-active sample, we needed to consider what constitutes 2D chirality and 3D chirality in terms of crystal structure and symmetry.

Non-centrosymmetric crystal structures are so named because they possess no center of inversion. A **center of inversion** is any point across which a reflection of every atom in the structure will recreate the exact same structure. Although this is a bit of a simplification, you can think about non-

centrosymmetry as equivalent to 3D chirality: the unit cells of these crystals (their most basic structural unit) do not possess a center of inversion. Therefore, non-centrosymmetric structures exhibit chiroptical phenomena such as circular dichroism in much the same way that 3D chiral molecules do. **Centrosymmetric** crystal structures, on the other hand, are so named because they *do* possess a center of inversion. These structures are by definition *not* 3D chiral, but they *may be 2D chiral*, depending on their other symmetry characteristics.

We identified an inorganic compound that forms centrosymmetric crystals which possesses the 2D chirality necessary for LDLB. This compound, which we shall call **LCSO**, forms small purple crystals shaped like parallelograms with sides 10-200 microns in length ($1\mu\text{m} = 10^{-6}\text{ m}$) and ranging from 5-40 μm in thickness. These crystals are on average about 100 times thicker than the PTPO thin films, but still transmit enough light to make a CD measurement.



Our collaborators synthesized LCSO crystals and deposited them on glass coverslips. They also provided a control sample of $\text{Li}_6\text{Co}(\text{SeO}_3)_4$ crystals which belong to a centrosymmetric crystal class and are not expected to show CD or ACD.

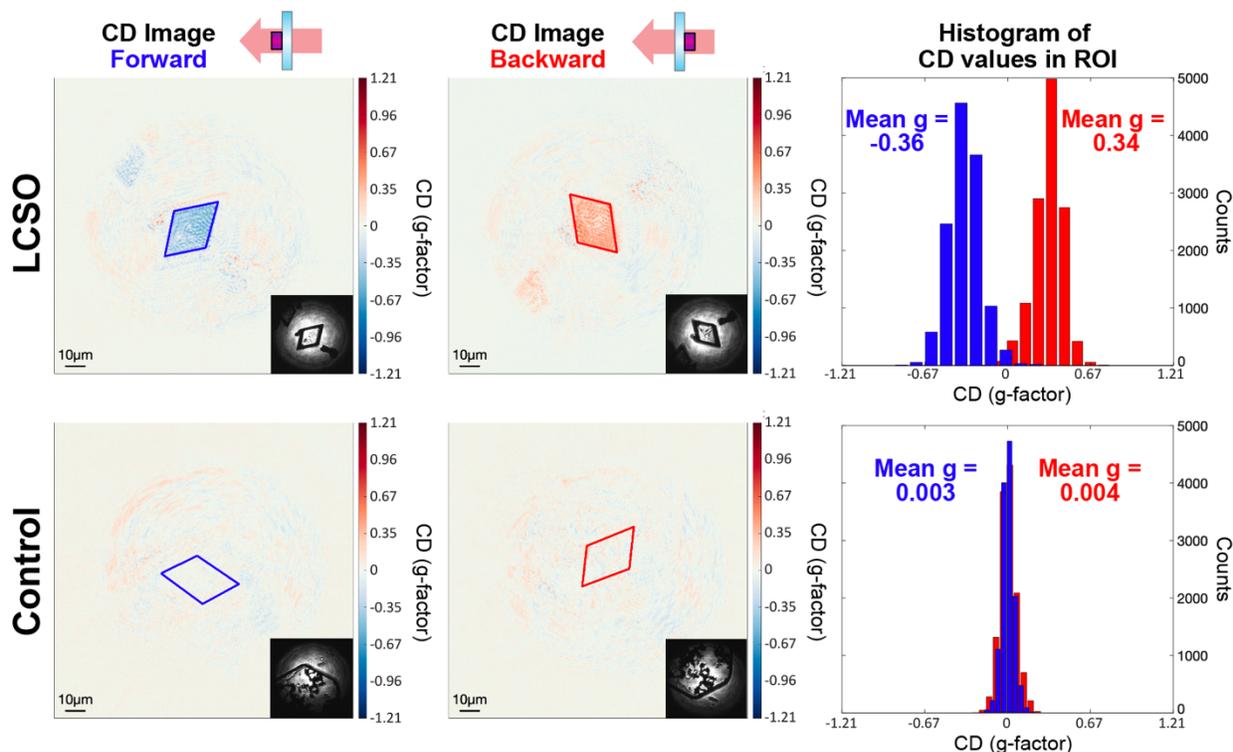
I performed circular dichroism measurements in a similar manner as I did for the 2D chiral cavities. This time, however, I used only one wavelength: 635nm, in the red part of the visible spectrum where the crystals absorb and are theoretically expected to exhibit ACD behavior. Another key difference was the use of a camera instead of a wavelength-dependent detector (as we were only measuring CD at one wavelength), which provided spatial resolution and made it easier to find the small crystals.

I illuminated each crystal with LCP and RCP and recorded the transmitted intensities in the form of LCP and RCP transmission images, then produced a CD image by essentially plugging the LCP and RCP transmission images into the g-factor equation provided earlier.

$$\text{CD (g-factor)} = 2 * \frac{\text{RCP} - \text{LCP}}{\text{RCP} + \text{LCP}}$$

I analyzed the CD images of the crystals by **region of interest (ROI)**, selecting for the pixels only in the area of the crystal, to generate an average CD value and a histogram of all the CD values inside the ROI. This procedure was performed for all crystals in forward and backward configurations to assess ACD behavior.

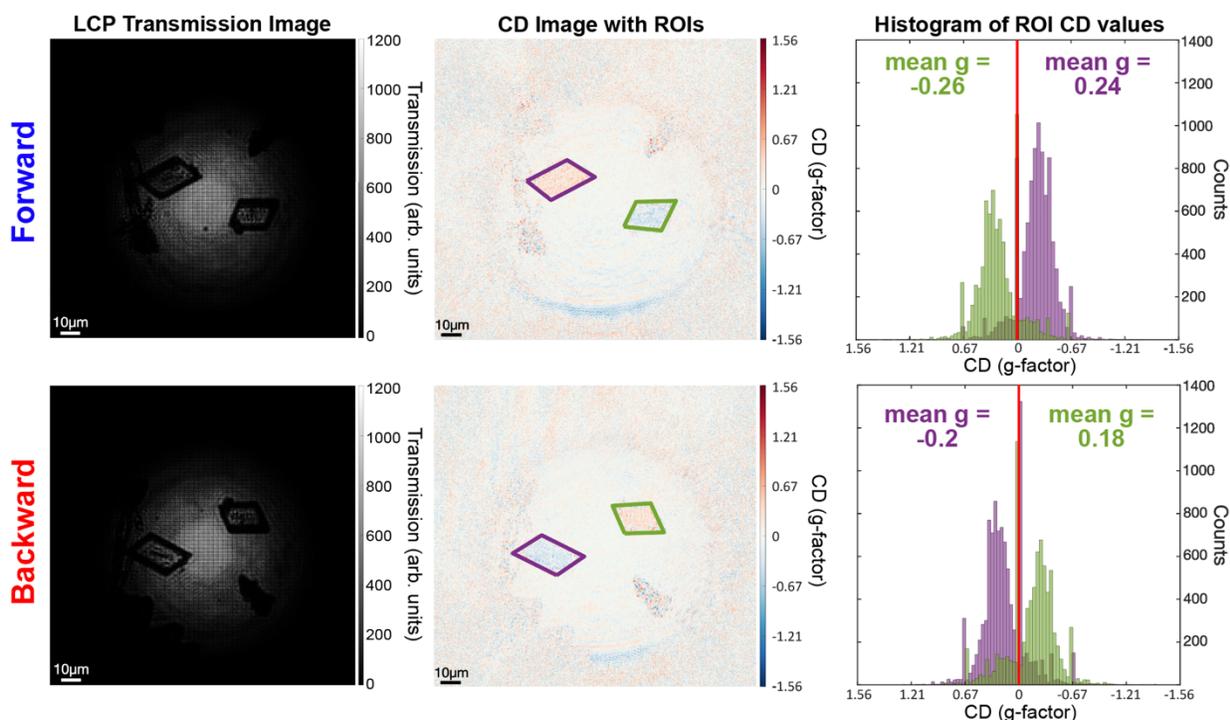
As expected, *all the LCSO crystals measured exhibited ACD*, and none of the control crystals displayed any chiroptical response at all. This was the first demonstration of ACD by an inorganic material!



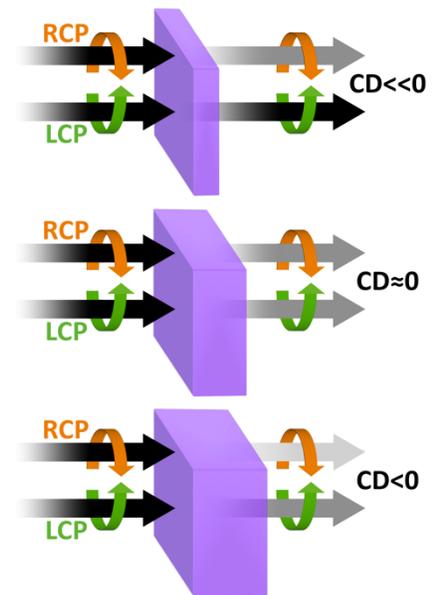
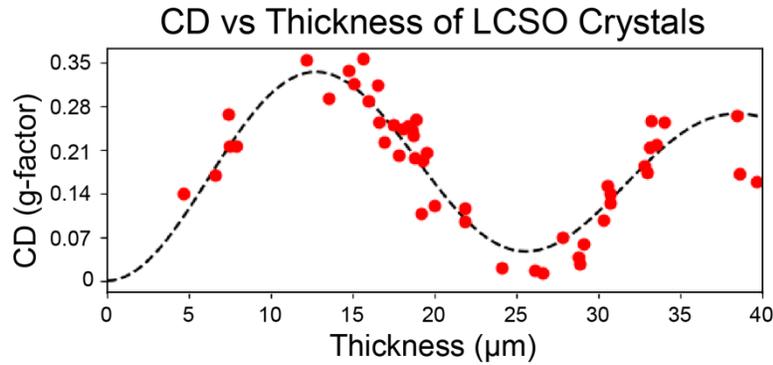
Next, I measured the thicknesses of the LCSO and control crystals using an instrument called an optical profilometer, which makes very precise height determinations based on how light reflects off a sample. The thicknesses of the two samples were comparable (the LCSO and control crystals shown above are 12µm and 15µm thick respectively), so that was not the reason for their very different CD

behavior. The transmitted intensities of light were also similar for the LCSO and control samples, so the difference in chiroptical behavior is not due to their opacity (how much light they absorb). Finally, since the LCSO and control samples have very similar chemical makeups, we were able to conclude that LCSO displays ACD behavior as a result of its crystal structure alone.

I was able to locate two LCSO crystals in the same field of view which exhibited CD signals that were opposite for counterpropagating light *and* opposite from one another, indicating they were deposited on the glass coverslip at opposite orientations. This confirmed that the sign of the CD signal is not due to some curiosity of the measurement but rather depends on the inherent physical properties of the crystals and their orientation relative to the direction of light propagation.



Plotting the LCSO crystals' CD signals against their thicknesses yielded a very interesting result. In much thinner ACD-active samples, like the PTPO thin films, CD is only expected to increase with thickness. However, with much thicker ACD-active samples, like these LCSO crystals, the CD response increases with thickness up to a point, then decreases, then increases again.



There is some complex mathematics at play here, but our qualitative explanation for this has to do with the fact that the phase shifts caused by the LB interactions within the material *rotate* the angles of polarization of the two perpendicular LP components that make up CPL.

Up to a certain thickness, the LB interactions will rotate these components such that their angles of polarization are better aligned with the axis of LD for one handedness of CPL than the other, resulting in a preferential absorption of the components of that handedness and therefore a strong CD response.

If we increase the sample thickness, however, the additional LB interactions rotate the components further, so the components of the *other* handedness are now better aligned with the axis of LD, resulting in preferential absorption of *that* handedness over the additional thickness. This essentially cancels out the CD response from the initial thickness, yielding no CD response from the sample overall.

Finally, if we increase the sample thickness *even more*, the additional LB interactions rotate the CPL components *even further*, such that the components of the first handedness are once again aligned better with the axis of LD than the other handedness. This results in preferential absorption of the original handedness over the additional thickness and therefore over the entire sample thickness. This produces an appreciable CD response from this thickest sample, albeit one somewhat diminished by the effect described in the previous paragraph: as LCP was not preferentially absorbed over the entire length of crystal, the CD signal isn't as strong.

This curious result appears to be the first time that the thickness-dependence of ACD has been demonstrated experimentally. Future applications that aim to make use of the ACD behavior of these materials will need to target the crystal thickness appropriately. In fact, this finding has important implications for the next immediate step in this research. We hope to embed optical resonators with LCSO crystals to generate very strong chiral light-matter interactions, though we will need to make sure the crystals are around 12 μm thick in order to observe the greatest CD signal.

Where do you go from here?

The instances of unconventional chiral light-matter interactions described in this chapter constitute original research done in collaboration with some incredible scientists. I am grateful to have had the chance to contribute to some of the incredible innovation happening now in the field of photonics, and I am excited to see how these projects progress – I know I am leaving them in good hands.

Over the nearly six years I've spent in graduate school, I've learned a lot about optics, microscopy, and light-matter interactions of all kinds, while simultaneously developing my science communication skills. Following my graduation, I will be putting the knowledge and practices I've gained to good use as I embark upon a Scientific Research and Conservation Fellowship at the Metropolitan Museum of Art in New York City. This fellowship will allow me to gain experience in a museum laboratory setting while contributing to cutting-edge conservation research and the technical studies of cultural heritage.

Beyond the analysis and preservation of art and artifacts, I am eager to explore the interplay between science and art as an avenue for promoting science literacy as well as cultural literacy. Through the Met's existing public outreach programs, I hope to integrate science with the broader narrative of art and history, elucidating and interpreting historic pieces and practices in a way that resonates with diverse audiences and inspires them to think about science in new contexts. As I embark on my postdoctoral career, I am excited to embrace these humanistic elements that have motivated my work as a scientist and communicator in and out of the lab.

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Image Sources

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The data from PTPO films and cavities on pages 12-14 is reproduced from “Chen, Salij, and Parrish et al. A 2D chiral microcavity based on apparent circular dichroism. *Nature Communications*, **2024** 15, 3072.” I have only included those figures to which I directly contributed a majority of the data. For simplicity, CD signals reported in millidegrees were converted to the approximate g-factors.

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