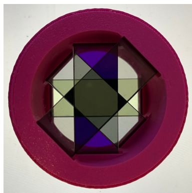


The Quantum Kaleidoscope: Seeing the Quantum Nature of Light

By Paul Cadden-Zimansky, Updated 11/06/24

Introduction

The year 2025 marks 100 years since the development of quantum mechanics. This anniversary has prompted the United Nations to proclaim 2025 The International Year of Quantum Science and Technology, encouraging people around the world to initiate activities at all levels aimed increasing public awareness of the importance of quantum science and applications.

Quantum science underlies our modern understanding of the physics of light and matter. It explains the rules of chemical bonding and chemical reactions. It has enabled technology ranging from cell phones, solar panels, and lasers, to LED lighting, MRI machines, and GPS tracking. However, the basic concepts of quantum science are often viewed as off-limits topics for secondary school students due to the perceived abstractness or complexity of the subject and the expense of specialized equipment.

This activity is an answer to the question "what is a simple activity that allows secondary school students a hands-on introduction to fundamental concepts of quantum science?"

The activity is based on simple crossed-polarizer effects that may be familiar to science teachers and are often used to teach about light wave polarization. While the effects can be explained using the electromagnetic wave description of light, here they are explained entirely using the photon ("light quanta") description of light that introduces some fundamental quantum concepts.

Concepts Taught

light polarization, photons ("light quanta"), quantum states, quantum bits ("qubits"), quantum measurement, probability. Related Next Generation Science Standards: *PS3.A: Definitions of Energy, PS3.B: Conservation of Energy and Energy Transfer, PS4.B: Electromagnetic Radiation and PS4.C: Information Technologies and Instrumentation*.

Key Objectives

Understanding the quantum nature of light, that light and photons can be polarized, that measurements of photon polarization can change the polarization, and that measurement outcomes can be probabilistic.

Activity Time

The full activity outlined here takes around 45 minutes, allowing time for students to explore and hypothesize, but the time can be shortened by allowing less time for exploration and can be condensed to a demonstration that is as short as 5 minutes.

The Quantum Kaleidoscope

Education Level

The main activity is designed for students in grades 6-8 with minimal science background, but can also be equally effective with older students and adults.

Materials

The activities are most easily done using the layers of a Quantum Kaleidoscope, which each have a single, rectangular linear polarizer that can be snapped together and oriented with each other at fixed angles of 0°, 45°, and 90°. It can alternately be done by acquiring sheets of polarizing film. A single sheet can be cut into small rectangles (e.g. 2" x 1") for each student to use. It is recommended to have the long edge of the rectangle cut along the polarization axis for reference.

One kaleidoscope layer or polarizer rectangle per student is sufficient if the students can then form groups of two and three to use them in combination; alternately students can each have multiple layers.

Ambient polarized light from screens (tv's, computers, tablets, phones, overhead projectors) are not needed, but are recommended if possible as they can produce the most dramatic effects. Having a screen or screens with white light set up that all students in the classroom can see them is thus useful.

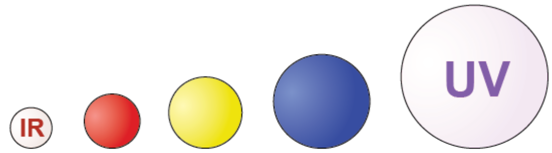
Background

The **photon** (or "light quantum") description of light posits that when light and matter interact the energy from light is transmitted to matter (absorbed) in discrete amounts of energy – "quanta" of energy. The size of these quanta depends on the frequency f or wavelength λ of the light with the size increasing with frequency (or decreasing with wavelength). Red light quanta are smaller quanta than yellow light, yellow light quanta are smaller than blue light quanta. The energy transmitted by visible, white light to matter will be a mix of different-sized quanta corresponding to the different colors comprising the light. Beyond what's visible, infrared (IR) light quanta are smaller than visible ones; ultraviolet (UV) light quanta are larger than visible ones. Sunburns are primarily caused by the damage at the cellular level from the large UV photons in sunlight; x-ray quanta, which are even larger than UV quanta are more penetrating than visible or UV light, but also more damaging to the matter that absorbs them.

When looking at a single wavelength of light, brighter, more intense light corresponds to more photons hitting the eye each second. Individual photon energies are very small – the body of a person standing in sunlight will be hit by around one billion trillion (10^{21}) photons each second.

The Quantum Kaleidoscope

A simple visualization of the different sized quanta of light is the different-sized discs shown here. While physical quanta are not small discs, this is a useful starting visualization for understanding their basic properties.

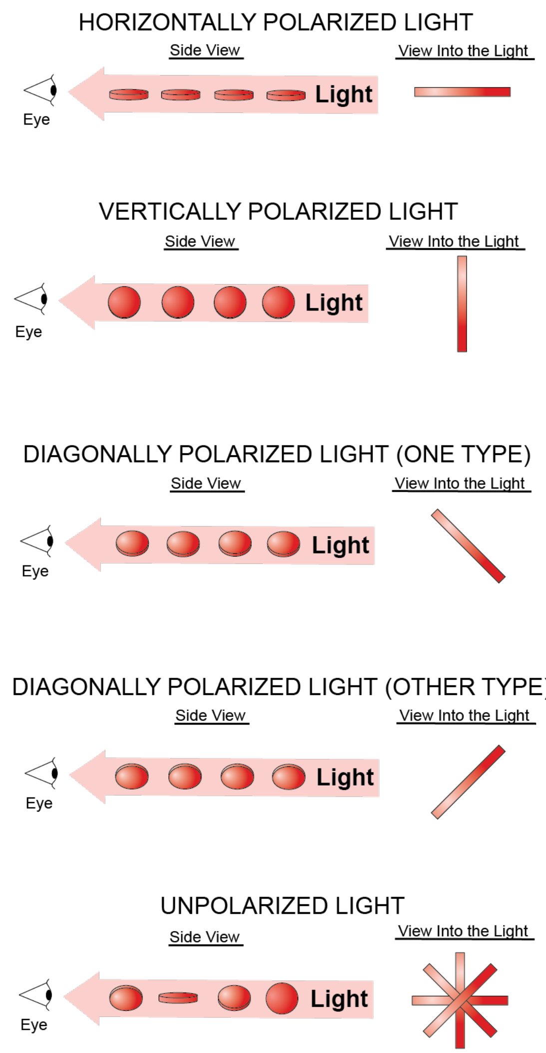


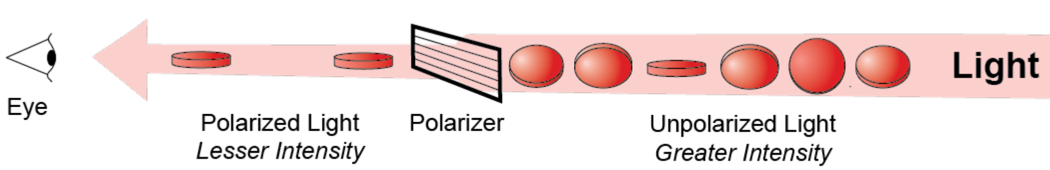
Different colors of light have different light quanta energies.

In addition to carrying energy, each photon also has a **polarization**. While there are many types of polarization, this activity focuses entirely on linearly polarized photons. Using our disc model of a photon with the photons traveling with a side edge leading, the polarization of the photon corresponds to the orientation of this edge with respect to the observer. The polarization types to be investigated are horizontal, vertical, diagonal, and unpolarized – the last of which is an equal mixture of all possible polarizations. For those familiar with the electromagnetic wave description of polarization, the orientation of the photon polarization corresponds to the plane in which the electric field of the wave oscillates.

The **quantum state** of the photon's polarization is the orientation of the photon. Since there are infinitely many orientations a photon could have, corresponding to all possible angles it could be oriented in, each photon is in one of infinitely many possible quantum states.

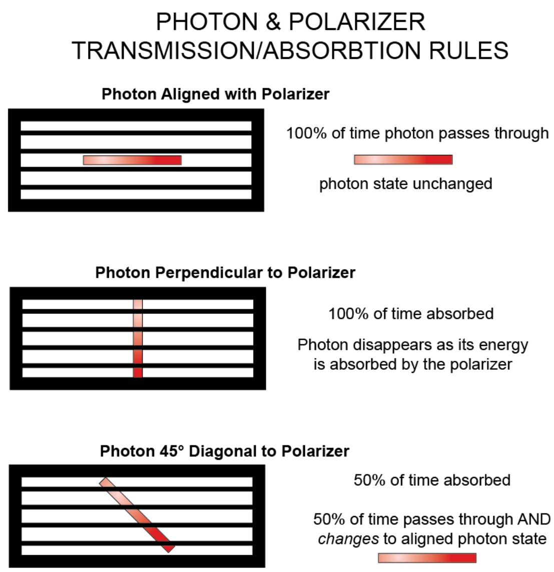
Most light sources emit unpolarized light where each photon has a random polarization, but we can turn unpolarized light into polarized light by passing it through a linear polarizer. A linear polarizer is a material that only allows photons of a particular orientation to pass through it. As shown below, only some of the randomly oriented photons in unpolarized light make it through the polarizer. Fewer photons means that less energy passes through and the intensity of the light is reduced. The energy from the photons that don't make it through is absorbed by the polarizer (some are also reflected off it in other directions). One can change the type of linearly polarized light that makes it through the polarizer by rotating the polarizer into different orientations.





The Quantum Kaleidoscope

Note that human eyes cannot see the polarization of the light, we only detect its color and intensity. However, there are other animals, including many species of birds, fish, and insects, whose eyes are known to be able to detect whether light is polarized.



It would be natural to expect that only photons whose polarization matches the orientation of the polarizer will make it through the polarizer, but this is not the case. Each photon has some **probability** of making through the polarizer, with this probability determined by the relative orientation of the photon and the polarizer. For simplicity this activity focuses on only the three cases shown at right, which the Quantum Kaleidoscope is designed to highlight.

If a photon is aligned with the polarizer, it makes it through 100% of the time and its polarization state is unchanged. If a photon is perpendicular to the polarizer, it makes it through 0% of the time. But if a photon is at any other orientation, then one of two things happens: the photon is absorbed by the polarizer or the photon passes through the polarizer *and its polarization state changes to be the one that is aligned with the polarizer*. For each photon at a diagonal to the polarizer (a relative orientation of 45°) these two outcomes happen with a 50/50 probability.

The different probabilities of photons with different polarizations making it through a polarizer also results in 50% of the photons in unpolarized or randomly polarized light making it through a polarizer rotated in any orientation. All photons that do make it through will have their polarization state aligned with the polarizer. Thus passing unpolarized light through a polarizer creates polarized light, with the orientation of the polarizer determining what type of polarization.

Trying to send a photon through a polarizer is an example of a **quantum measurement** – the polarizer is making a measurement of the quantum state of the photon polarization. It is a hallmark of quantum measurements that they have probabilistic outcomes and can change the state of what is being measured. This is also the simplest type of measurement as it has only one of two outcomes, either the photon is absorbed or it passes through. A quantum measurement of an object which gives one of two outcomes is said to give one **bit** of information. A quantum state, in this case the polarization of the photon, that can give only one bit of information on measurement is known as a **quantum bit** or **qubit**.

Understanding the observed phenomena requires being aware of the current polarization state of the photons in the light, the particular orientation of the polarizer these photons hit, the above probabilities for transmission through a polarizer for each type of photon, and the resulting photon polarization state of those photons that do pass through.

The Quantum Kaleidoscope

Set-Up

Besides handing out the kaleidoscope layers or polarizing rectangles, the activity needs no set-up. If one or more screens (e.g. tv, computers, tablets, phones, overhead projector) are available, have them turned on and set to emit white light. Experimenting with looking at these screens through a polarizer as it is rotated before the activity starts will help prepare the instructor for what students will observe.

Activity

This activity outline is based on a pedagogical sequence of

1. Student observation, experiment, and exploration
2. Student hypothesis generation and model building
3. Introduction of a theoretical model by the instructor
4. Moving to more complicated phenomenon and repeating this sequence

This sequence gives students the chance to explore the quantum kaleidoscope effects empirically and come up with their own explanations for what they observe *before* they are given a standard theoretical explanation. This structure can help give the students more experience with hypothesis generation, testing, and revision. An alternate method, which shortens the activity time, is to first give the students the standard theoretical model presented in the background and have them test this model with their observations. Each round of this sequence adds one kaleidoscope layer.

One Kaleidoscope Layer (15 minutes)

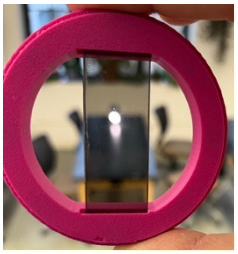
Give each student one Quantum Kaleidoscope layer. Ask them to look through the rectangle and observe what they see when they look at different objects and lights. Encourage them to rotate the rectangle around as they look through it to see if anything changes. Prompt them to compare what they see with their neighbors and try to explain their observations.

Tip: Encourage students not to touch the rectangles with their fingers to avoid getting them dirty.

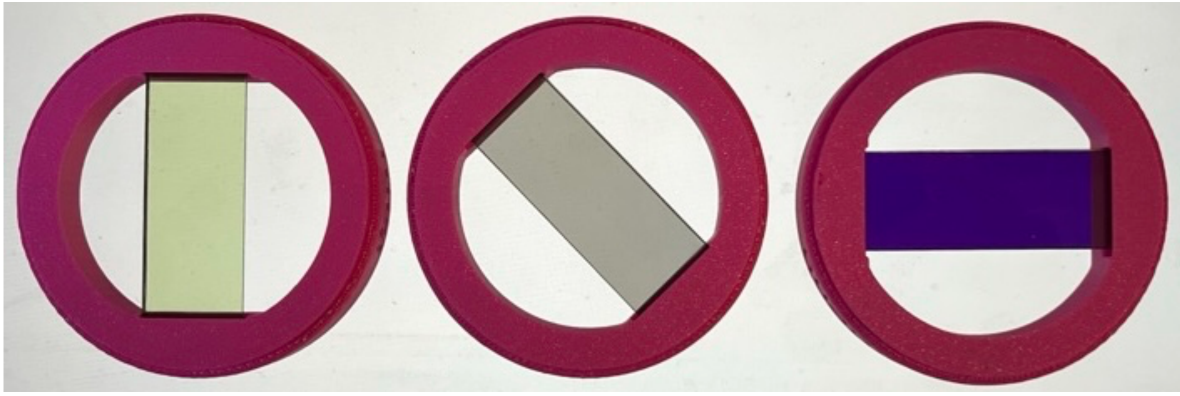
After ~5 minutes of observations and discussion ask them to volunteer what they observe and what are some possible explanations for these observations. Three relevant observations that may be made are

1. The light/image is dimmer when looking through the rectangle and looks the same regardless of orientation. This is the result of only ½ of the unpolarized photons in unpolarized light making it through the polarizer and becoming polarized.

2. The amount of reflective glare from surfaces changes when the rectangle is rotated. The glare reduction occurs because light reflected off surfaces becomes preferentially polarized in directions that align with the surface (in analogy with the disk-photon model one can think of how flat stones can more easily "skip" off a water surface when oriented the right way).



3. The amount, and perhaps color, of light from screens changes when the rectangle is rotated. This effect is because most screens emit polarized light; some emit photons that are all polarized the same way, while others emit the red, green, and blue photons with different polarizations



Single layer looking at a screen where the red photons + blue photons = purple light emitted are polarized horizontally and green photons are polarized vertically.

Observation 1 will be obvious, while only some or no students might spot 2 or 3 – if they don't these observations can be prompted. Students may note that the rectangles are like sunglass material, which is correct, particularly as sunglasses are also typically polarized filters. The screen light changes are the most dramatic ones and clearly indicate that light and the polarizer rectangles must have some orientation to them.

Students may come up with varying hypotheses that explains the observations. If energy is a topic the students are familiar with, a discussion can be introduced about what is happening to the energy of light as it passes through the rectangles. An instructor can either introduce the photon (a.k.a. "light quantum") model at this point to help them or wait to do this until after they've had a chance to use a second Kaleidoscope layer. It is possible that students may also note that combining two layers leads to new effects at this point, which can lead naturally into two-layer observations. The most dramatic, but also most complicated, effect is how the colors of some screens or projectors change when the Kaleidoscope layer is rotated. This will not be observed for all screens, but is due to the fact that many screens and projectors have different polarization orientations for the three different colors they use to produce images.

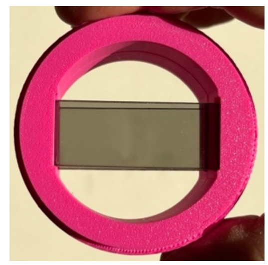
The Quantum Kaleidoscope

Two Kaleidoscope Layers (15 minutes)

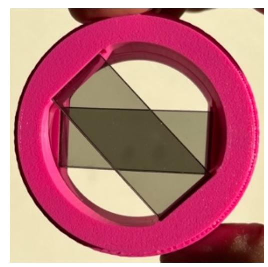
Either hand out a second layer to each student or ask them to combine their layers with a partner. Prompt them to experiment looking through the layers and rotating them relative to each other, comparing what they see with their neighbors, and trying to explain their observations.

After ~5 minutes of observations and discussion ask them to volunteer what they observe and what their explanations for these observations are. Three relevant observations that may be made when looking through the kaleidoscope at anything in regular unpolarized light are:

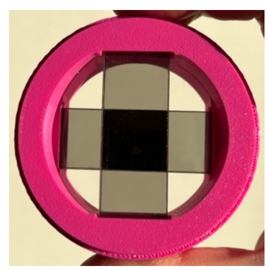
1. When the two layers are aligned the amount of light transmitted through is approximately the same as when there is only one layer. Here the ½ of unpolarized photons that make it through the first polarizer now all have their polarization state aligned with the second polarizer, meaning 100% of them will pass through it and the intensity of the light is not reduced further



2. When the two layers are at 45° less light is transmitted through the overlapping region. Here the ½ of unpolarized photons that make it through the first polarizer are diagonally polarized relative to the second polarizer, meaning only ½ of these make it through the second one. In total, only $\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$ of the photons make it through the two polarizers and ¾ are absorbed.

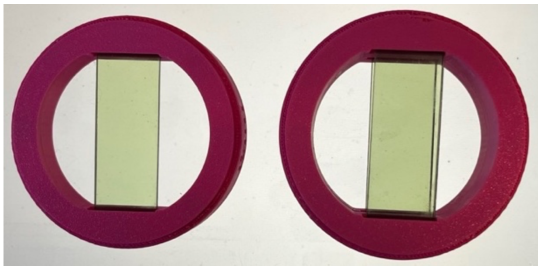


3. When the two layers are at 90°, effectively no light is transmitted through the overlapping region. Here the ½ of unpolarized photons that make it through the first polarizer are polarized at 90° relative to the second polarizer and so none of them make it through the second one.

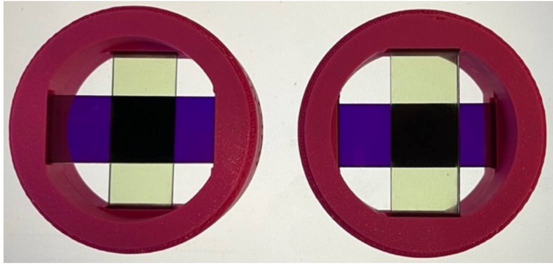


The Quantum Kaleidoscope

When looking at screens with polarized light additional effects may be observed.

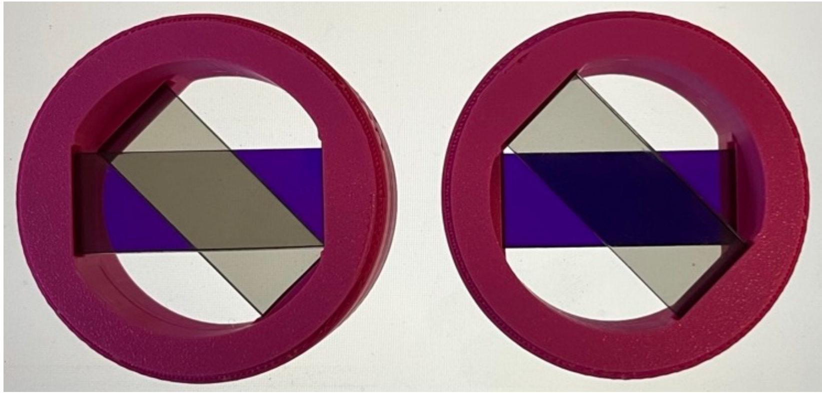


Light from a screen through single (left) and double (right) layers of aligned polarizers.



Light from a screen through polarizers at 90° layered in two possible orders – the appearance is similar no matter the order.

The most surprising effect, as show below, is that when the polarizers are oriented at 45° changing the *order* in which the polarizers are layered changes light that is transmitted through the overlapping region. One can see this effect either by rotating the layers with respect to each other to change their order, by unsnapping them and putting them back together while keeping their rotations the same, or by taking the whole kaleidoscope and flipping it to look through the same two layers in from the other direction.



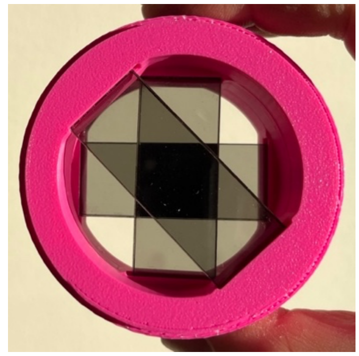
Light from a screen through polarizers at 45° layered in two possible orders – the appearance is different for different orders. More light is transmitted through the overlapping region when light passes through the diagonal polarizer first. In the left configuration, ½ of the vertically polarized photons from the screen make it through the diagonal polarizer and become diagonally polarized photons. ½ of these then make it through the horizontal polarizer. In the right configuration the vertically polarized photons from the screen are entirely absorbed by the first horizontal polarizer.

Again students may not notice all of these effects and can be prompted to observe them. Most of these effects are evidence that after passing through a polarizing rectangle the polarization state of the light has changed. If it hasn't already been introduced, after allowing students to suggest hypotheses and models, the photon model of light and photon polarization concept can be presented to explain these effects. In addition to using diagrams of photon polarization included in the background information, using a flat object (e.g. a plate or a book) with a side that can be oriented in different directions can help to make the picture of a photon's polarization more intuitive. Once the students have reviewed how this theoretical model explains the observations with two layers, a third layer can be added to the Kaleidoscope.

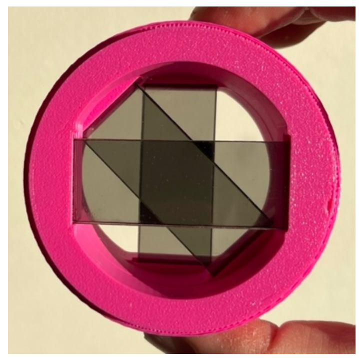
The Quantum Kaleidoscope

Three Kaleidoscope Layers (10 minutes)

Again, either hand out a third layer to each student or ask them to combine their layers with another partner. Prompt them to experiment with looking through the three layers, focusing on orientations where one is horizontal, one vertical, and one diagonal. Students should concentrate on the light through the center portion of the kaleidoscope. Looking through these kaleidoscope configurations at anything in regular unpolarized light, the students should observe two different patterns depending on whether the diagonal polarizer is in the middle or not.



1. If the diagonal polarizer is first or last in the sequence, the light through the center is blocked by the two successive polarizers that are 90° to each other.



2. If the diagonal polarizer is between the vertical and horizontal polarizer, *more* light makes it through the center section. ½ of the initial unpolarized photons make it through the first polarizer and are then vertically polarized photons. ½ of these vertical photons make it through the diagonal polarizer and then become diagonally polarized photons. Finally, ½ of these diagonally polarized photons make it through the horizontal polarizer and become horizontally polarized photons. The number of photons making it through all three layers is $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$ of the initial number, but this is *more* photons than make it through two polarizers at 90°.

Underlying this effect are two facts, which seem paradoxical,

A) Each single polarizing layer will either reduce the number of photons that pass through it or leave this number unchanged, and

B) Adding a polarizing layer to a stack of polarizers can actually increase the light transmitted through the stack.

Understanding that these two facts can both be true should be emphasized and understood. It is the fact that a quantum measurement can change the quantum state of an object, in this case the photon polarization, that makes it possible for both these facts to be true.

The Quantum Kaleidoscope

Four Kaleidoscope Layers (5 minutes)

Adding in a fourth layer to the stack to complete the Quantum Kaleidoscope produces more complicated patterns for students to observe; all can be understood using the established rules of photon polarization states and polarizer measurements. The primary reason for a fourth layer is the aesthetics of the patterns created, as shown in the gallery below. For some students, the aesthetics of the device can be the draw towards understanding the physics. An alternate way to approach the activity is to *start* by looking at the various patterns seen in the full 4-layer device patterns and then de-construct the Quantum Kaleidoscope into individual layers in order to understand how the patterns are formed.