

POLARIZED LIGHT FOR 3D MOVIES

By Lenny Lipton

From the time I was kid to my student days as an undergraduate in physics my abiding passion was light and vision. Since my earliest years I have been interested in creating images and in understanding the role that light plays in image creation. As a student no other part of physics engaged me as much as the study of light.

The study of light, and polarized light in particular, turns out to be of great importance in understanding how the most important stereoscopic moving image systems function. It's a subject of great interest to people in the field or for those who have an intellectual interest in the making and projecting of 3D movies. This article is about polarized light and how it is applied to image selection for stereoscopic movies. The term "image selection" means: how one gets the left image to the left eye and blocks the unwanted right image from the left eye, and vice versa. If you have a high school education through trigonometry and physics you have the background to understand a lot of what you need to know about polarized light. If you are motivated to know more I recommend that you look at a basic physics text like *Fundamentals of Optics* by Jenkins and White. On the other hand, you don't have to know anything about polarized light to enjoy or make 3D movies. You can consider polarized light image selection to be a black box and stop worrying about it. Since you're reading this, you probably want to know more. This is not going to be a complete description and I am only going to focus on what I need to sketch in the story about how polarized light works for the stereoscopic cinema.

Physicists use the construct that light phenomena can be explained by considering it to be a longitudinal or transverse wave. From the time of Newton, people who have thought about such things have thought that light could be explained as its being either a particle or a wave, but early on experimental evidence pointed in the direction of light being a wave phenomenon. This idea was cemented along the way by the work of various smart people. A lot of work was done after Newton to explain observed phenomenon in terms of waves without understanding their nature but it was Michael Faraday who conceived the idea of electric and magnetic fields. James Maxwell took Faradays' ideas about fields and used them as the basis for the creation of a set of equations that explains light in terms of it being an electromagnetic phenomenon. He provided a basis for understanding and predicating how light works in terms of it being a combination of electric and magnetic fields and he predicted the existence of radio waves.

To understand what follows you have to accept the fact that light is an electromagnetic phenomenon and that it behaves like a wave. When I wrote earlier that it's a longitudinal or transverse wave, I'm talking about the kind of wave that you can produce in a string like so: If you tie a string a few feet long to a doorknob and flick your wrist in an up-and-down motion you will produce a longitudinal wave. You'll observe that the amplitude or the height of the wave is perpendicular to the direction in which the wave travels – toward the doorknob. That is what is meant by a longitudinal wave. It's also a plane polarized wave because the wave resides within a plane.

Light can be thought of as being made up of a field with longitudinal waves described by electric and magnetic vectors. These two fields are in phase and at right angles to each other. We are going to forget about the magnetic vector because the eye is sensitive to the electric component and it's simpler to

continue this explanation by ignoring the magnetic component of light. The light that you see reflected from most surfaces or emitted by the sun, a candle, or a light bulb is unpolarized. Assuming you could see the structure of the light leaving emissive surfaces or being reflected from many other surfaces, the planes in which the electric vectors reside are randomly oriented so there is no favored direction to their orientation. In plane (sometimes called linear) polarized light (there are other kinds), the wave is restricted to a plane, which is, as noted, exactly what happens when you try the experiment with the string.

Polarized light can be produced by a number of means. The way we are concerned with as used in stereoscopic projection is by means of the kinds of sheet polarizers that Land and Bernauer produced in the 1920s and early 1930s. Sheet polarizer is made of a substrate or base of a stretched sheet of plastic, usually polyvinyl alcohol, into which has been infused a dye like iodine, a kind of polymer that has long chains. These long molecular chains are oriented to follow the stretch pattern. The base is stretched, the dye is introduced into the material, and the long chain molecules of the dye line up and follow the direction of the stress of the plastic. This creates a microscopic or molecular structure that favors the passage of light whose waves are oriented in only one plane. (We are not going to talk about how that is accomplished.) That means that the light that is passing through a sheet polarizing filter will have the electric vectors of its waves all having the same parallel orientation.

Since these electric vectors are aligned in a plane that plane can be marked on the sheet polarizer with a straight line and it's called an axis, in particular it is called the transmission axis. The other axis, at right angles to the transmission axis, is called the absorption axis. If you have a second polarizing filter just like the first one, and you place it on top of the first polarizer and you rotate it (say they are on a light box), what you will see is that the transmission of light goes through maxima and minima every ninety degrees. When the transmission axes of the polarizers are crossed you get a minimum and little light passes through and when these axes are parallel you get a lot of light passing through. The polarizers don't have to be in contact in order for this work. You can project a beam of polarized light onto a polarization-conserving projection screen (usually painted with aluminum metal) and observe the same phenomenon when looking through a polarizing analyzer. In physics the second polarizer is called the analyzer so the polarizers in stereoscopic eyewear are analyzers.

There are two kinds of materials that we need to think about: conductors and dielectrics (or insulators). Conductors conduct heat and electricity well, and they do this because they have free electrons. Usually conductors are metals. Non-conductors or dielectrics don't have free electrons. Polarization-conserving screens have a metallic coating or they're painted with metal, so they have free electrons on the surface. It is these free electrons which reradiate the polarized light or reflect it back in a way that conserves the properties of polarization. That is why a matte screen, which has a dielectric surface, cannot work for polarization image selection: It doesn't have free electrons.

If you have two projectors, that have linear polarizers over their lenses. whose axes are at right angles to each other – and you project them overlapping on this metallic screen, and you wear eyewear that have analyzers whose axes are lined up just like the ones on the projectors, one eye will see the reflected beam from one projector and the other eye will see the beam from the other projector, but each eye can only see the beam from its projector. That's perfect for projecting stereoscopic movies, because we can transmit one perspective for one eye and block the unwanted image for that eye, and so on.

A large percentage of light passes through when the filter's axes are parallel and this is called transmission, and a smaller percentage of light passes through when the axes are at right angles and this is called extinction. The ratio of the two is called the contrast ratio or the dynamic range. For good linear (or as I said earlier, some people call it plane) sheet polarizers for stereoscopic applications, the materials used usually have transmission between 30 to 35 percent and the dynamic range is about 3000:1 for the lower transmission material. In other words, only 1/3000th of the light in transmission passes through when the axes of the polarizers are orthogonal (extinction). For circular polarization the dynamic range is about a tenth of that for good linears.

But the specification of the filters is only part of the story. That is because the polarization-conserving metallic painted screens are imperfect; and since they are imperfect, the total dynamic range of the system is reduced. Starting with linear polarizers that are capable of a 3000:1 dynamic range, the final extinction ratio for the light reflected from the screen through the analyzing eyewear filters will be more like 200:1. I have made these measurements a number of times over the years, and although I haven't done it lately, those are the kinds of numbers I expect we are getting today with standard products (there are specialized screens that have done better). All of this is assuming measurements are taken from the center of the theater pretty much on axis. In other words the measurements are taken pretty much in line with the lens axis of the projector, or at least close to it. Still, with a dynamic range of 200:1 you can have a good picture with low cross talk between the left and right images. Such cross talk is called *ghosting* in the argot of 3D; or sometimes *leakage*.

A major characteristic of linearly polarized light can be observed if you do the experiment I will describe. You can do this with the 3-D glasses you get from the movies, if you go to an IMAX movie or a theme park where they use linearly polarized light. Take the linear polarizers out of the eyewear (or you can use two pairs of eyewear) and holding them up to the light rotate them. You will see that even a small change in rotation away from maximum extinction rapidly produces a lot of transmission. This rapid change is explained by the Law of Malus. The interesting thing about all this is that when you actually see a 3-D movie at a theme park or in IMAX the law of Malus doesn't seem to bother anybody. Tipping your head a few degrees this way or that way the image still looks good because you're starting off with a fairly high dynamic range and with decent photography it works fine. I've been deeply interested in the problem of head tipping lately and have gone to a nearby IMAX 70mm theater a couple of times and the projection is superb.

Another kind of polarized light, circularly polarized light, is used in many stereoscopic theaters, and it is created by the ZScreen® electro-optical modulator or by the MasterImage process using a spinning filter wheel.

I turned the ZScreen it into a device for polarization image selection for both monitor viewing and for projection when I ran StereoGraphics, the company that created the electronic stereoscopic industry. The idea was given to me by Jim Fergason, who suggested I could apply his concept for a push-pull phase-shifting modulator to stereoscopic image selection. I worked with Art Berman, who helped with sourcing the parts, the difficult problem of laminating large parts, and with the physics of the device; also with Lhary Meyer, who designed the circuit to drive the parts; and with Bruce Dorworth, who was my lab assistant on the project. It was circa 1985 when we started the work on this development project. Our first

OEM deal was selling the device to Evens and Sutherland for their molecular modeling workstations. Later we applied it to projection and it was used by people in engineering and scientific visualization.

How the ZScreen electro-optical modulator works is going to wait for another time but it must be mentioned because the majority of digital stereoscopic projector installations use the ZScreen. So I am going to describe how circularly polarized light works.

If you have been with me this so far you have a pretty good notion of how linearly polarized light works. We need to return to the physics of light. Light, unlike other waves, a water wave or the wave on the rope described earlier, does not require a physical medium. That is because light is propagated by means of a field, the field that Michael Faraday first conceived of and that was described elegantly by Maxwell and his colleagues. When light is propagated in space it travels at its maximum velocity, which everybody knows is C from the famous equation $E=MC^2$.

But when light travels through a medium like water or glass or air (still pretty fast in air), it is slowed down. The ratio of the speed of light in air (or a vacuum) to the speed of light in the material is called the index of refraction. The propagation of the electromagnetic field requires a reradiation of the electrons that are part of the atomic structure of whatever the light is traversing; so it takes a while, let's say, for those electrons to reradiate the light. For the majority of materials it doesn't matter what direction light is traveling in – the speed of light will be the same. These materials are described as being isotropic. Air is isotropic. Glass is isotropic. So if we shine linearly polarized light through one of these materials, no matter what the orientation of the plane of polarization, it will be traveling at the same speed.

There are other materials, retarders, that are birefringent (two indices of refraction) and have anisotropic properties (different optical properties in different directions and later it will be noted that these axes are at right angles). For the purposes of this discussion we are interested in one class of materials made out of plastic. These are sheets similar to the sheets that are stretched and stressed used for making the linear polarizers. You take this plastic and you stretch it – you pull on it, you yank on it. This creates a mechanical stress in the material, and it winds up with two optical axes – a fast and a slow axis. If light travels along the slow axis it travels slower than if it travels along the fast axis. If we shine linearly polarized light so that its axis is parallel to the fast axis, it will pass through the material faster than it would if the axis of the linear polarized light was parallel to the slow axis. It's the damndest thing; imagine a piece of plastic that has two values for the speed of light.

Now imagine what would happen if the axis of the linear polarized light bisected the fast and slow axes (remember they are orthogonal) so that it was at 45 degrees to both. You would then have, through vector analysis, two components of the electric vector. (Here's where you had better go look at Jenkins and White.) Those vector components are orthogonal to each other and lined up with the fast and slow axes respectively. One component is parallel to the fast axis, and one component is parallel to the slow axis. When the wave that is traveling in the fast-axis direction meets the one that is traveling in the slow-axis direction as they emerge from the material into the air, these two orthogonal waves are going to be out of phase and the vector sum of these two waves is the heart of the matter.

Depending upon where the electric vectors are when they emerge from the material, that is to say their phase relationship, you will get a specific kind of polarized light emerging from the retarder. If the

material is a half-wave retarder the two out of phase linear waves will combine to undergo a 90-degree phase shift and by vector summing will be toggled or flipped through 90 degrees. If you have a quarter-wave retarder the result will be circularly polarized light. You will either get left- or right-handed circularly polarized light, depending upon the orientation of the plane polarized light's axis to the fast and slow axes.

If you could look at the electric vector in a linear polarized light beam that was headed toward you, you would see that the electric vector is traveling in a plane. The amplitude would be changing, that is to say the electric vector is going up and down, but it would be restricted to a plane. If you took a look at circularly polarized light, in the case of one kind of circularly polarized light you would see that the tip of the electric vector is describing a circle or corkscrew turning clockwise or counterclockwise as it heads towards you. If the tip of the vector is traveling clockwise it's called right handed and if it's going counterclockwise it's called left handed. Or maybe it's the other way around because having looked it up in a couple of books I suspect the standard is ambiguous.

If you take a left- and right-handed circular polarizer and you lay them on top of each other on a light box, you will see that they will extinguish the light. Do the experiment by using the filters from a pair of glasses from a MasterImage or a Real D show and put the polarizers together so that the retarders are facing each other (those are the sides of the filters that are facing the screen). If you rotate one with respect to the other you will see that the extinction varies. What's going on here? It's circularly polarized light and you would think that you wouldn't get a variation in extinction as you do for linear. But you do get a variation and you will see that the image will go from pretty dark to, depending upon the material you've got, a sort of amber color that transmits more light. There is quite a noticeable variation in both density and color with rotation. So the head orientation does matter, except that the falloff isn't as great as it is for linear polarized light. (You can also hold the filters sandwich up to a light source – like a desk lamp.) If you flip the filters around the other way so the retarders are facing outward you have linear polarizers and you can try rotating them to confirm that they work as described earlier. You will note that even for the circular case you perceive the extinction to be at a maximum when the linear axes components' are at right angles.

With circular polarization the extinction at its maximum is never as good as linear polarizers. In fact, it's usually an order of magnitude less. The reason for this is that for the retarders used for 3D selection the phase shift can be maximized only for a specific wavelength. That means that the retardation for "green" at about 550 nanometers may be chosen but for the rest of the visible spectrum on either side (in other words, towards the red and blue ends) the less effective the retarder. Thus only the green can be properly analyzed. Moreover we cannot assume that the values of the retarders for the polarizer and the analyzer match. This is actually a rare occurrence because of the slack manufacturing tolerances for this product.

In order to get the maximum extinction the linear polarizer component of the projector polarizer and of the analyzers have to be orthogonal. That's what was demonstrated in the above experiment. For circular polarization projection the audience must be wearing analyzers that have left and right handed polarizers, and the same kind of metallic polarization-conserving screen used for linear is also used. To recap: The circular polarizers are made up of two pieces of plastic: one that is a linear polarizer, and the other that is the quarter-wave retarder. The axis of the quarter-wave retarder has to be at 45 degrees or 135 degrees to

the linear polarizer's axis. This is true for the analyzers and this is true for the polarizers on the projectors. You may be able to see a color shift if you tip your head during a circular polarization projection.

It is often said that circularly polarized light for image selection can help with the head-tipping issue related to linear polarizers and the law of Malus. I think that it is not as big an issue as it has been made out to be by its advocates. After all IMAX and theme parks have been using linear polarizers to good effect for years. Both Real D and MasterImage must use circularly polarized light because of the physics of the ZScreen (Real D) and the spinning mechanical filter device (MasterImage). For MasterImage, for example, attempting to use the same kind of a spinning device with linear polarization would produce a reduction in dynamic range because of the rotation of the polarization axis of the sheet polarizer as it spins in front of the projector lens.

As I mentioned, the dynamic range of circularly polarized light is a lot less than linearly polarized light. That means that you're lucky to get something like 20:1 dynamic range from the light that is reflected from the screen and analyzed by the analyzers in the eyewear – which is about an order of magnitude less than you get from linear polarized light. It's interesting to see how the universe gives and takes. On the one hand it gives us a high dynamic range for linear, but with a head-tipping constraint; on the other hand it gives us a low dynamic range for circular, with less of a head-tipping constraint.

There is extensive literature on how to handle crosstalk that arises from circular image polarization image selection, and it was offered to StereoGraphics (the company I founded in 1980) over the years by different people and that is the concept of the anti-ghost. When you look at a stereoscopic image through a selection device, whether it's linear or circular, there is a certain amount of light that leaks through (as noted earlier it's called leakage) because of the incomplete extinction of polarization. This leakage results in what is called a "ghost image." So there is some crosstalk between the left and right images, and you may see a bit of the left image through the right eye and vice versa. It can look like a double exposure. One way to deal with this is to create an anti-ghost. The anti-ghost has the opposite density of the ghost, and it can be created by any one of a number of algorithms. The anti-ghost is added to the print so that it will perceptually cancel out the ghost.

It is an improvement but it is not a cure-all. For one thing, ghost images and their perception are a function of several factors including parallax. If the image has low or zero parallax the ghost corresponds to the image itself and you won't see it. In high-contrast images, let's say for example the moon against a black sky; you are going to see the ghosting more than you'll see it in other circumstances. And finally, if the image has a great deal of textural complexity – in other words, lots of leaves in the jungle – the ghost tends to be very hard to see. Since the anti ghost is dark it cannot work with dark backgrounds since it cannot be blacker than black – so just where it might be most useful it has no benefit -- like the moon against a black sky.

I went to school with Mel Siegel, a physicist at Carnegie Mellon. I asked Mel for a simple explanation of polarized light in terms of quantum theory. In this case that's the construct that light can be explained in terms of it being a particle --- a photon. Here's what he wrote:

Polarization maps one-to-one to angular momentum (spin) of $h/2\pi$ per photon (i.e., 1 in fundamental units).

The one subtlety is that whereas for particles with non-zero mass it could project to +1, 0, or -1, for photons -- because they travel at the speed of light -- only +1 and -1 are allowed.

These correspond to the two circular polarizations. If I remember the convention correctly, +1 is called left and -1 is called right.

Linear polarization is then a suitably phase-shifted equally-weighted mixture of left and right.

You can visualize this by imagining an uncomplicated emitting atom (e.g., an idealized alkali metal) in a weak magnetic field (Zeeman effect): as the viewing angle goes smoothly from aligned with to aligned against the magnetic field the polarization goes smoothly from one circular polarization to linear polarization to the other circular polarization, being elliptical in between, of course.