Polarization of Light and Polarizers

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ABSTRACT

Light is a form of electromagnetic radiation, and has the property of *direction of polarization*. This article discusses the concept of polarization and some of its implications. Both plane (linear) and circular polarization are covered. The operation of polarizers—optical components that manipulate the polarization of light—is described, and some applications discussed. Finally, a brief introduction is given to the use of polarizers in photography.

Electromagnetic radiation

Light is a form of electromagnetic radiation, just as are radio waves. In the case of light, the frequency is very much higher than that of even the highest-frequency radio waves used today. Nevertheless, the same principles of physics apply to both.

An electromagnetic wave involves both an *electric field* and a *magnetic field*. Both are AC fields: their instantaneous values vary cyclically just like the instantaneous voltage of an AC electrical signal. Both fields have the same frequency, and are synchronized in time ("in phase").

If the wave contains only a single frequency (or wavelength), the time variation of the field is "sinusoidal"; that is, a plot of the field intensity versus time is the same shape as a plot of the trigonometric *sine* function of an angle versus the angle. (In fact, to make some of the math work out more handily, in electrical engineering work we often actually describe the variation in terms of the trigonometric *cosine* function, which is the same shape but has a different "starting point".) Figure 1 shows this pattern.

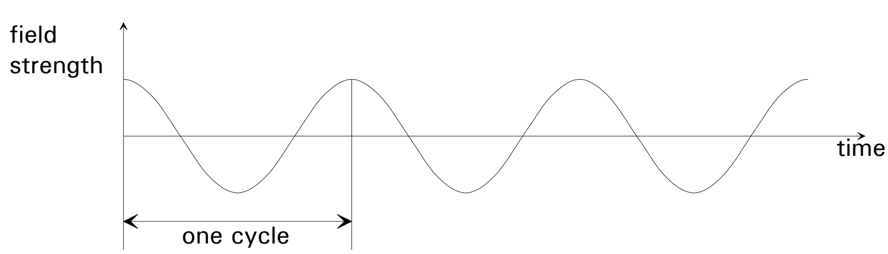

Figure 1

The strengths of the electric and magnetic fields are actually *vector* quantities; that is, they have both a direction and a magnitude, or amount. A common example of a vector in everyday life is "65 miles northeast".

The electric and magnetic fields in an electromagnetic wave are at right angles to each other and both are at right angles to the direction in which the wave propagates through space. For example, in a wave propagating to the north, the direction of the electric field might be up-and-down, in which case the direction of the magnetic field would be east-and-west.

The magnetic field creates the electric field, and the electric field creates the magnetic field! There is, however, no perpetual motion paradox here; the collective power carried by the two fields is supplied by the transmitter (the emitter, in the case of a light wave).

Figure 2 shows a “snapshot” of a propagating electromagnetic wave at a particular instant in time.

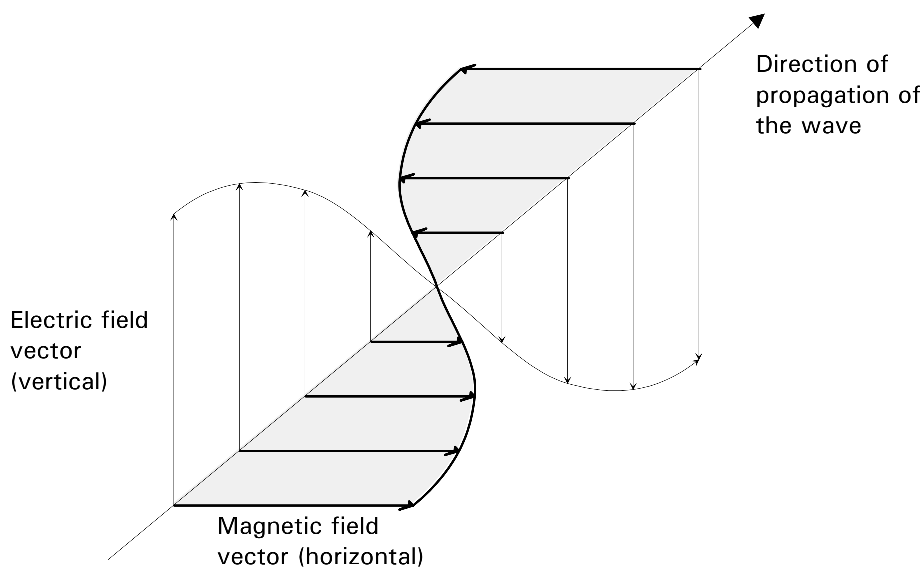

Figure 2

The wave is propagating to the “upper right” of the figure. We see the vectors describing the electric and magnetic fields at 9 different spots along the course of the wave (spanning a full “wavelength”). In this case, the electric field vector is vertical, and the magnetic field vector is horizontal. (We have shaded part of the horizontal plane to help visualize the three-dimensional arrangement.)

The curves bounding the vectors are just shown to remind us of the “sinusoidal” nature of the variation in space, as well as in time.

From here on, we will not show or speak of the magnetic field. It is, however, always present, and its required relationship to the electric wave is enforced by the laws of physics.

Direction of polarization

The direction of the electric field in a wave is said to be the *direction of polarization* (or just the *polarization*) of the wave. For radio waves, this is often the physical orientation of the transmitting antenna. For example, in a mobile radio system, a vertical transmitting antenna is used, resulting in a vertically-polarized wave. In turn, a vertical receiving antenna is best able to pick up energy from a vertically-polarized wave, thus the vertical receiving antennas on the vehicles.

The wave illustrated in figure 2 is vertically-polarized.

Waves of this basic type are said to be *plane-polarized* or *linearly-polarized* (LP).

The circularly-polarized wave

Another type of wave is the *circularly-polarized* (CP) wave. In such a wave, the instantaneous value of the electric field, rather than cyclically changing magnitude and reversing in direction as the wave moves through space, actually rotates continuously as the wave propagates through space. (The same is true of the magnetic field.) Figure 3 illustrates this behavior.

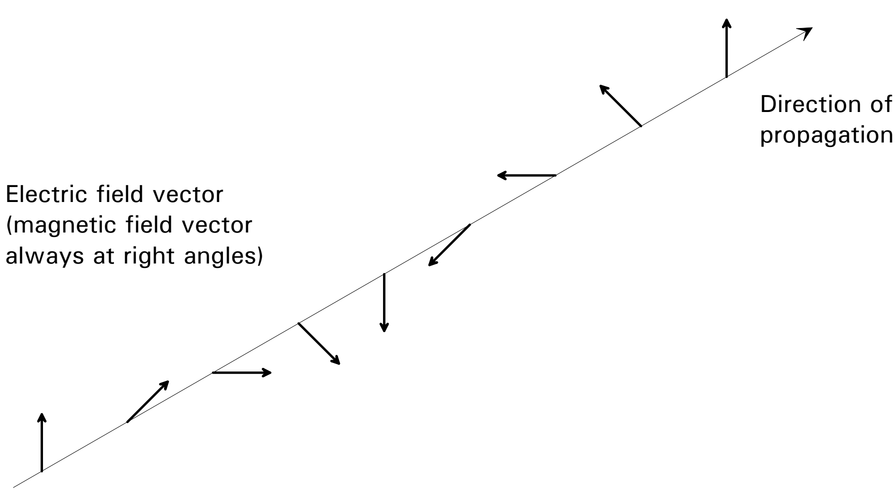

Figure 3. Circularly-polarized wave

A CP wave is equivalent to the combination of two LP waves, with their directions of polarization at right angles, 1/4 cycle out of time synchronization. We will use this concept later when we talk about forming a CP wave. (The concept is explained in Appendix A.)

In a homely analogy, the electric field of an LP wave can be thought of as like the physical wave sent down a stretched rope by shaking the near end of the rope up and down, or from left to right (depending on the direction of polarization). If instead we were to move the near end of the rope in a circle, a "spiral" wave would travel along the rope, equivalent to the electric field of a CP wave.

The polarizer

The polarizer is a filter that only allows a wave having a particular direction of polarization to pass through. (These are most commonly found in connection with light waves, although they can be constructed for lower-frequency waves, such as radio waves.)

Figure 4 illustrates the working of a polarizer.

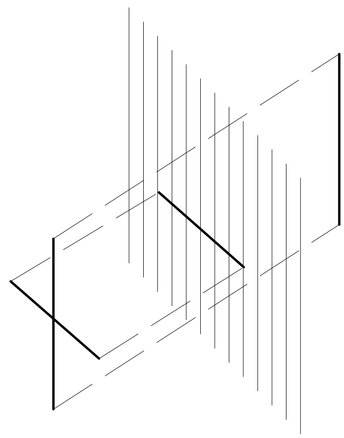

Figure 4. Polarizer.

Here, the polarizer is fancifully represented as a comb-like structure of vertical parallel tines, the metaphor being that only "vibrations" parallel to the tines could pass through. On the left, we show the directions of polarization of two light beams, one vertically polarized and one horizontally. The vertically-polarized beam passes though the polarizer, but the horizontally-polarized one does not.

Random polarization

The light emitted by most light sources, including lamps and the sun, is *randomly polarized*. This means that it consists of a large number of different electromagnetic waves, traveling together, with their directions of polarization oriented randomly in different directions.

Suppose we wanted to have a plane-polarized light beam. We can pass a randomly-polarized beam of light through a polarizer. As we saw previously, such a device (if ideal) will only allow the passage of those light waves whose direction of polarization matches the orientation of the polarizer.

It might seem that this would only let through the tiniest fraction of the whole beam—those few components whose directions of polarization exactly match the axis of the polarizer. But we really do much better than that in terms of the "output" of the polarizer. Here's why.

Any light wave with a certain direction of polarization can be considered equivalent to the sum of two waves with their directions of polarization at right angles, where we can choose that pair of directions arbitrarily. Figure 5 illustrates the concept.

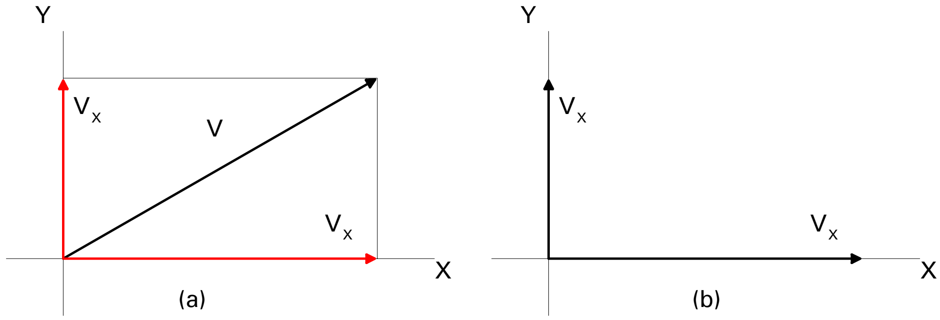

Figure 5. Decomposition (resolution) of a vector

On the left we see a vector, V. We (arbitrarily) establish a set of axes, *X* and *Y*. That vector can be decomposed into two vectors, one lying along the *X* axis and one lying along the *Y* axis. In effect, we could replace the vector V by the two vectors V_X and V_Y. This is called *resolving the wave into two components*. In section (a) of the figure, we see how this can be reckoned by geometric construction. In section (b), we set the two components out separately.

Thus, if we have linearly-polarized light wave with its direction of polarization 30° to the horizontal, we can choose to think of that wave as the sum of a wave with horizontal polarization (with its "amplitude" 0.866 that of the original wave) and a wave with vertical polarization (with its amplitude 0.5 that of the original wave).

Suppose we submit such a wave to a polarizer with its axis of polarization horizontal. The horizontal component of the wave passes through unaffected, while the vertical component is completely blocked. We thus end up with a horizontally-polarized light wave (with amplitude 0.866 that of the original wave).

Now, let us send a beam of "ordinary" (randomly polarized) light through our polarizer. For each of its many constituent waves, the process we described above takes place, with the horizontal component passing through the polarizer and the vertical component blocked. Of course, the relative amplitude of the horizontal component compared to the amplitude of the constituent wave of which it is a component varies with the direction of polarization of the particular constituent wave.

All those horizontally-polarized components, passing through the polarizer, collectively form the output wave, which of course which will be wholly horizontally polarized. The total power of the emerging beam will be half that of the arriving beam since, averaged over all the constituent waves, the average fraction of the constituent wave's power that ends up in the horizontal component is one half.

Circular polarizer

How could we create a circularly-polarized light beam?

Consider an optical component called a *quarter-wave plate*. This is a thin plate of a special transparent material with a very curious property. Imagine that we orient it with its "axis" at 45° to the horizontal. A plane-polarized wave with horizontal polarization will pass through it with a certain transit time. A plane-polarized wave with vertical polarization passes through it with a transit time which is greater than that by 1/4 the period of the frequency of the light[1].

Now, let us pass a beam of randomly-polarized light through a conventional polarizer with its direction of polarization at 45° to the horizontal. As we saw before, a plane polarized wave with its direction of polarization at 45° emerges.

We saw before that we can think of that wave of as equivalent to the combination of two component waves, one with its direction of polarization horizontal and one with its direction of polarization vertical. If we send this wave through the quarter-wave plate, these two components pass through it with different transit times and emerge 1/4 cycle apart in their "phase", or time relationship. This combination is in fact a circularly-polarized wave. Exactly how this happens is described in Appendix A.

The combination of a conventional polarizer and a quarter-wave plate, mounted together for this purpose, is called a *circular polarizer*.

Note that a circularly-polarized beam of light does not have any unique direction of polarization. For example, regardless of the orientation of the polarizer, the output beam is the same.

What good is a circular polarizer?

There are many uses for a circular polarizer. Think of a circularly polarized beam of light with a "right-hand twist" as being like a bolt with a right-hand thread. If we were to try and thread it through a nut with a left-hand thread, it wouldn't go.

Thus, if we were to direct a beam of light with "right-hand" circular polarization to a "left-hand" circular polarizer, it will not pass back through it.

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[1] This can also be looked at as the one wave being a distance of 1/4 the wavelength of the light behind the other wave, thus the name of the device.

Suppose we are troubled with the reflection of ambient light from the glass cover window of a self-luminous digital readout on a gasoline pump. If we place a circular polarizer in front of the window, the ambient light passing through it will be given, let's say, a right-hand circular polarization.

When circularly-polarized light is reflected from a smooth surface (called *specular reflection*), the returning beam has the opposite "hand" of polarization. Thus the polarized light reflected from the display window will not pass back "upstream" through the circular polarizer, and thus will not interfere with the user's view of the display.[2] The light emitted by the display, however, is randomly-polarized, and passes only once through the circular polarizer, with only a loss of half its power.

There is another important use, in photography, which will be discussed in the next section.

Polarizers in photography

When natural light strikes a smooth semi-reflective surface (such as the surface of a glass window, or the surface of a body of water) at an angle, the reflected light has a component that is linearly polarized[3]. Thus, part of the "glare" we encounter from the sun's reflection from such surfaces is linearly polarized light.

If we put a polarizer in front of the camera lens, and rotate it until its axis of polarization is at right angles to the direction of polarization of the polarized component of the reflection, that component will be blocked. Thus the relative brightness of the light from the reflective surface is reduced compared to the brightness of the light from normal "diffuse" surfaces (which remains randomly-polarized), reducing the effect of the glare in the photographic image. In fact, light arriving from the sky is also partly polarized, and so a polarizer can be effective in reducing the brightness of the sky compared to that of the typical subject "on the ground", often desirable for "dramatic" artistic effects.

The details of practice in using polarizers for this purpose are beyond the scope of this article.

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[2] The first attempt at radio transmission via satellite involved a passive reflective satellite (an aluminized Mylar balloon). Circularly polarized radio transmission was used. The designers specified right-hand antennas at both sending and receiving ends. The radio system designers weren't physicists, and didn't realize that the "hand" of polarization of the wave would be reversed upon reflection from the satellite. When the satellite first came over the horizon, the system didn't work at all.

[3] The light passing through the surface is also partially polarized, in the other direction.

Why a circular polarizer?

Some single-lens reflex (SLR) cameras use a partially reflective ("half-silvered") reflex mirror so that, prior to shooting, the image generated by the lens can be sent simultaneously to two different subsystems—perhaps one "branch" to the viewfinder and exposure metering system and the other "branch" to the automatic focusing system.

Just as we described before with respect to reflections from water or glass windows, the light for each branch of the image leaving the partially-reflective mirror will in general have a component that is polarized. If the light arriving at the mirror is already polarized (as a result of using a regular—"linear"—polarizer in front of the lens for glare reduction), and its direction of polarization isn't the "right" one, part of the image light will be prevented from being reflected to the exposure metering system, disrupting the calibration of that system and resulting in improper exposure.

The solution is to use a circular polarizer. Its first stage (recall that it is just a linear polarizer) still blocks the light component having a certain direction of polarization (just as with an ordinary linear polarizer), giving us the glare reduction we seek. The light emerging from that stage is of course linearly polarized (in the opposite direction to that of the light being blocked). The second stage—the quarter-wave plate—takes this linearly polarized light and turns it into circularly-polarized light.

Circularly-polarized light does not have a unique "direction of polarization". Accordingly, it will be consistently reflected by the semireflective mirror regardless of the orientation of the polarizer. Thus the operation of the exposure metering system is not disrupted.

For this reason, the use of circular polarizers, rather than linear polarizers, is often recommended for cameras of this type.

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Appendix A

Generation of a Circularly-Polarized Wave

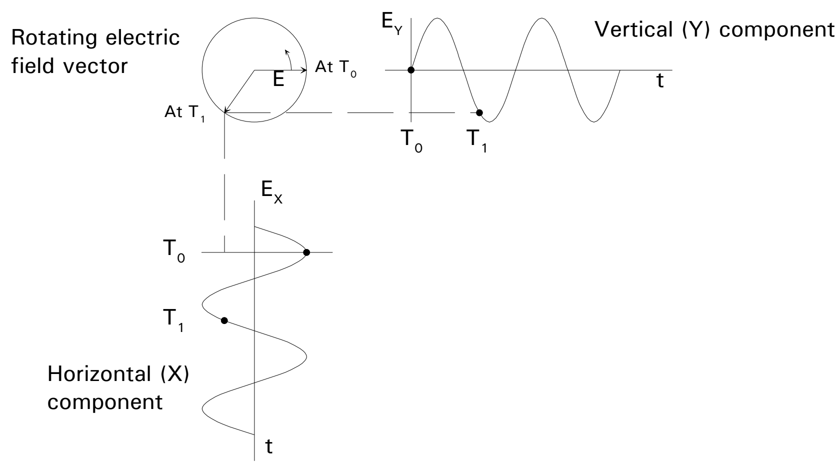

Figure 6. Decomposition (or composition) of the electric field vector of a circularly-polarized wave

Suppose we already have a circularly-polarized wave. Its electric vector has a constant magnitude and rotates at a uniform rate.

In the upper left-hand portion of the figure, we see such a rotating vector.

As we learned before, any vector can be decomposed, or "resolved", into two other vectors having arbitrarily chosen axes at right angles. We will do that with vector E, resulting in a horizontal (X)l component, E_X, and a vertical (Y) component, E_Y. We plot the magnitudes of these two components versus time. We see that both plots are sine waves, but their time references differ by 1/4 cycle.

The dots call attention to the values of the two component vectors at T_0 (the reference instant) and at an arbitrary later time (T_1).

If we can **decompose** the rotating electric field vector of a circularly-polarized wave into two vectors, then we could **compose** the rotating electric field vector by combining those two vectors. In this case, each vector has a fixed axis (the two being at right angles), the field varies sinusoidally, and the time phases of the two sinusoidal variations are 1/4 cycle apart. But those are exactly the descriptions of the electric fields of the two linearly-polarized waves that emerge from the quarter-wave plate of a circular polarizer. Thus, the combination of the two components emerging from the circular polarizer is in fact a circularly-polarized wave.

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