Diamond Optics Part 3: The Effects of Polarization States on Light Behavior

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To further understand light behavior in a round brilliant cut (RBC) diamond, and how cut proportions might affect this behavior, it is necessary to continue our discussion of diamond optics. Along with reflection, refraction, and dispersion, the *polarization state* of each ray of light affects that ray's behavior in a polished diamond. This article builds on the optical concepts and definitions outlined in "Diamond Optics Part 1" and "Diamond Optics Part 2". You might want to review those two articles before reading this one.

Executive Summary:

- In calculating the effect of diamond proportions on appearance aspects (e.g., brightness or fire), the polarization of light must be considered for accurate results.
- The rest of this article explains how polarization affects the movement of light through a polished RBC diamond.

Technical Summary:

- Every light ray has a polarization state that results from the vibrational direction of its electric field.
- Light rays become increasingly polarized at every surface interaction (except when light strikes completely perpendicular to the surface).
- Light rays that are vibrating parallel to a surface have a higher reflectivity, and therefore, more of their energy will be reflected. Light rays that vibrate perpendicular to a surface have a lower reflectivity, and consequently transmit more of their energy.
- When light strikes a surface at Brewster's angle (the angle at which the reflected beam and refracted beam are perpendicular), the light rays that reflect will be completely polarized in a parallel direction, while those that transmit will be completely polarized in a perpendicular direction.
- Different polarization states lead to different reflection and refraction rates (up to a 60% difference in some cases).
- For all of these reasons, ignoring polarization states when calculating ray paths through differently proportioned diamonds can lead to inaccurate results.

In the two previous articles on diamond optics, we examined how various factors affect the behavior of light when it strikes a diamond surface. Some of these factors are the laws of reflection and refraction, critical angle, refractive index, and dispersion. Because polarization affects *every light ray* that travels through a diamond, it is necessary to keep track of a ray's polarization state at all times. Although polarization is not directly affected by cut proportions, it is an essential consideration in diamond modeling and light path calculations.

LIGHT AND POLARIZATION STATES

In addition to a wavelength, a direction of travel, and an intensity (or amplitude), each ray of light also

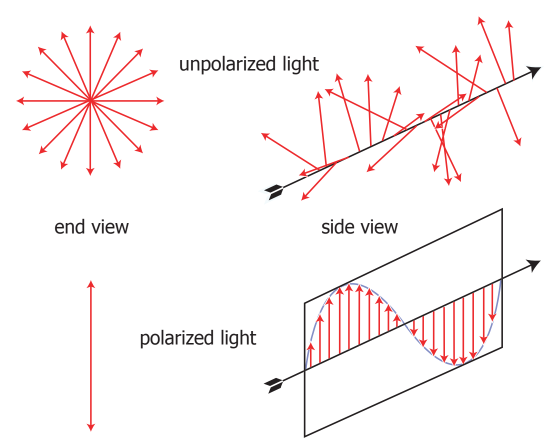

Figure 1. End and side views of unpolarized (top) and polarized (bottom) light.

has an associated electrical field[1]. The vibrational direction of this electric field dictates the ray's *polarization state*, which determines (along with the other parameters mentioned above) how much of that ray's energy will reflect back from a transparent surface, or be transmitted through that surface.

Ordinary light is usually unpolarized, which means that the electric fields of the light waves vibrate in all directions perpendicular to their directions of travel (figure 1, top).

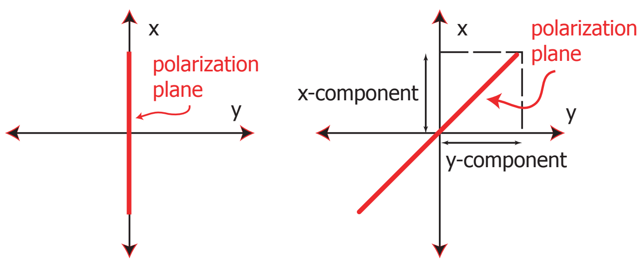

Figure 2. All polarization planes (electrical fields) may be mathematically considered to consist of an X and Y component.

This does not necessarily mean that the electric fields are vibrating in all directions *at the same time*; rather, they are *randomly changing their vibrational direction* as the light travels. In contrast, linearly polarized light (hereafter, referred to as polarized light[2] is composed of light rays for which direction of vibration is constrained to a single plane (figure 1, bottom). This plane may be oriented vertically (as in the bottom right of figure 1), horizontally, or at any angle in between.

If a light ray is linearly polarized in a direction other than completely vertical or horizontal — for example, a ray that is polarized at an angle of 45° to the x-axis and y-axis — then we can consider that ray to consist, mathematically, of two perpendicular components: an x-component and a y-component (figure 2, right). These two polarization components can be used to determine how much of the light ray's energy will be reflected or transmitted at each surface interaction.

GENERAL EFFECTS OF POLARIZATION

One way to see the effects of polarized light is with polarized sunglasses, or with a polarizing filter on a camera. These special lenses only allow light with one plane of vibration to pass through (this is sometimes referred to as the "privileged direction" of the lens or filter). Light becomes increasingly polarized as it bounces off reflective surfaces (e.g., glass or water). Because reflected light is polarized parallel to the plane of the surface, sunglasses and polarizing filters that are polarized perpendicular to the surface can absorb these light beams, preventing them from reaching our eyes. This is how they reduce glare (figure 3).

As an example, imagine looking at a shallow fishpond. On a sunny afternoon, without the aid of polarized lenses, you primarily would see glare off the surface of the water. With polarized sunglasses, however, you would be able to see through the surface of the water to the fish swimming below because the glare had been eliminated.

POLARIZATION IN A DIAMOND

A light ray's polarization state can strongly affect the amount of light that is transmitted at each facet surface interaction. Early ray-tracing programs often neglected the effects of polarization by providing only two options for each light ray interaction with a diamond surface[3]: The ray either reflects 100% or transmits (escapes) 100% every time it strikes the diamond's surface. (In such a model, 100% of the light ray's energy is carried along as the ray bounces around inside the colorless, flawless diamond, and all of that energy escapes when the ray first strikes an inner surface within the critical angle.) In reality, a light ray's path is

Figure 3. In the left photo, taken without a polarizing filter, notice the light and glare reflecting off the waves in the ocean. Compare this to the right image which was taken with a polarizing filter. Much of the glare that is reflecting off of the water is blocked by the filter. The filter can accomplish this because the reflected light is polarized.

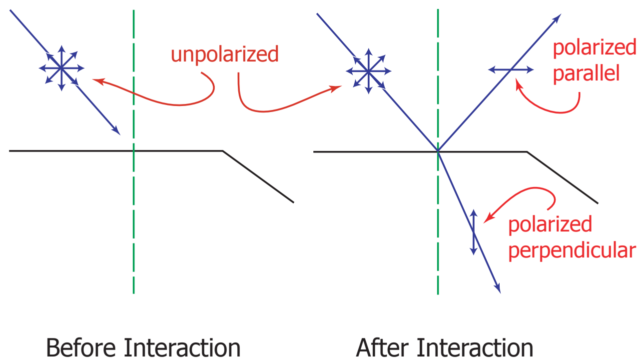

Figure 4. Unpolarized light becomes increasingly polarized as it reflects and transmits.

much more complicated than this. Every facet interaction (except when the light ray strikes exactly perpendicular to the surface) changes the polarization state of the light ray, thereby changing the amount of energy that will reflect or transmit in the next interaction. *This starts from the very first interaction, when the light ray first enters the diamond*.

Let's start by examining this initial interaction. In most cases, the light that strikes a polished diamond's outer surface will be unpolarized. That is, it is partially polarized parallel to the surface and partially polarized perpendicular to the surface (figure 4, left). The portions of the light rays that are vibrating parallel to the diamond's surface have a higher reflectivity, so more of their energy is reflected, rather than transmitted, into the diamond. These

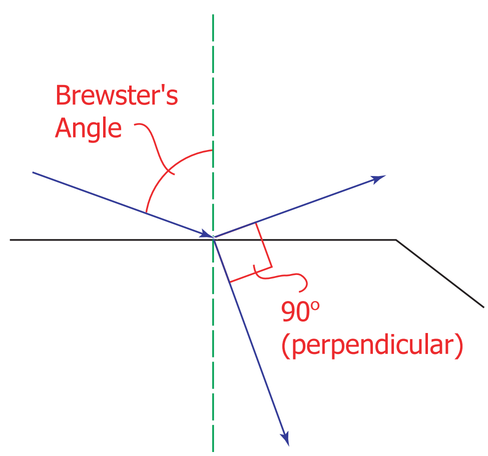

Figure 5. When light strikes a surface at Brewster's angle, the reflected and refracted rays will be perpendicular to each other.

portions will be seen as glare. However, the portions of those light rays that vibrate perpendicular to the surface have lower reflectivity, therefore more of their energy is transmitted into the diamond (figure 4, right). Since this is the only light energy that enters the diamond, these rays determine the diamond's appearance aspects.

For any refractive index value, there is one specific angle of light incidence at which all of the light that is reflected from the diamond surface will be linearly polarized in a direction *parallel* to that surface. Also at that angle, all of the light energy that is transmitted into the diamond will be linearly polarized in a direction *perpendicular* to that surface[4]. This is called *Brewster's angle*, and is the angle at which the reflected and transmitted (refracted) rays are at 90° to each other (figure 5). For incident light that strikes the outer surface of a diamond, Brewster's angle (measured from the normal) is about 67.5°[5]. Angles close to Brewster's angle produce light rays that are almost completely linearly polarized.

Light rays are affected by their polarization states while inside the diamond as well. However, because the light is now traveling from diamond to air when it transmits (escapes), there are more aspects of light behavior that need to be considered. The first is that all light rays that strike the inner surface at an angle greater than the critical angle (24.5°), regardless of their polarization state, will be totally reflected back into the diamond. *Polarization only affects those light rays that strike within the diamond's critical angle, since these are the only light rays that have any chance of transmitting out of the diamond*.

Another difference is that light striking the inner surfaces of a polished diamond has a different value for Brewster's angle. This is because the refracted light will be bending *away* from the normal rather than toward it (as it does when it enters the diamond). This reversal in direction changes the angle of the incident light ray that will produce a reflective beam and refractive beam that are at right angles to each other (figure 6). Brewster's angle on the inside of a diamond is about 22.5° at 589.3 nm. At this angle of incidence, light that is reflected back into the diamond will be completely polarized in a vibrational direction parallel to the surface, while light that transmits (escapes) will be completely polarized in a vibrational direction perpendicular to the surface.

As before, the fraction of the energy that reflects (or transmits) will be determined by the relative amounts of the perpendicular and parallel components of the light ray's electric field. Therefore, at almost every facet interaction within the diamond (every interaction within the critical angle), the amount of the light ray's energy that will be reflected and/or transmitted is likely to change. There may be as much as a 60% difference in the amount of light that is reflected based on its polarization directions (figure 7). As noted above, this difference (caused by polarization) in the amount of energy that may be reflected or escape is not considered in calculations of light behavior that do not take polarization into account.

Furthermore, the effect of polarization may lead to additional separation of wavelengths (colors), creating another cause of fire: some wavelengths may have polarization states that allow them to escape the diamond, while adjacent wavelengths with different polarization states are reflected.

In summary, in this three-part diamond optics series we have seen: (1) that diamond (as a transparent solid) reflects and refracts light; (2) that RI and therefore light paths through a diamond are different for each wavelength (color); and (3) that the polarization state of a light ray affects light behavior, and continually changes as the light interacts with the surfaces of the diamond. All of these factors must be taken into consideration when calculating light paths in a polished RBC diamond.

We hope that you enjoyed this article, and invite any feedback or comments that you may have. You may contact us by e-mail at DiamondCut@gia.edu. ■

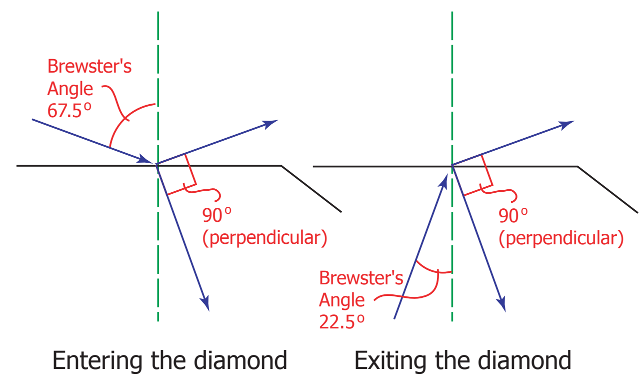

Figure 6. Brewster's angle has a different value, depending on whether the light ray is entering or exiting a diamond

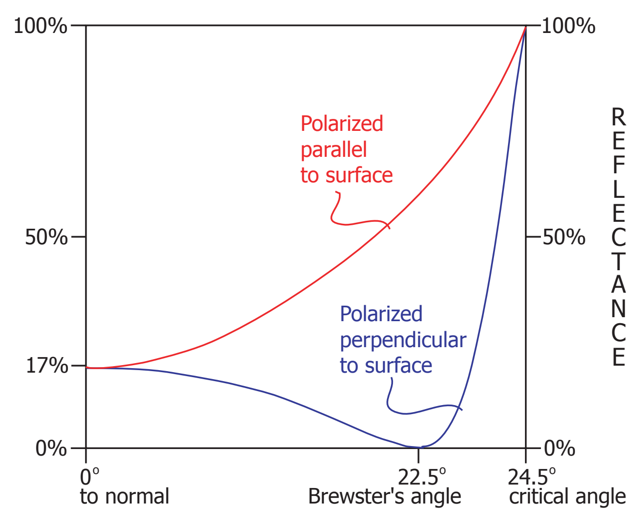

Figure 7. There may be as much as a 60% difference in energy reflection inside the diamond caused by the polarization states of light rays.

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[1]Each ray of light also has an associated magnetic field.

[2]In these articles, unless otherwise stated, we will use the term "polarized light" to refer strictly to linearly polarized light (although there are several other polarization states, such as circular polarization).

[3]Calculations that take polarization into account are more difficult to program and analyze than those that do not. Computing the effects of polarization states at each facet interaction in a diamond necessitates keeping track of an additional variable during millions of individual mathematical calculations.

[4]This does not necessarily mean that the light will still be 100% linearly polarized in a perpendicular direction to the next diamond surface that it strikes inside the diamond. Depending on the facet angle, much of the light might still be vibrating in a perpendicular direction to the new surface, but some of that light's energy may be polarized in other directions as well.

[5]This value is for Brewster's angle at 589.3 nm. Values taken from different Brewster's angle refractometers may vary, depending on which wavelength they are calibrated to measure.

