Diamond Optics Part 1: Reflection, Refraction and Critical Angle

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Polished diamonds rely on light for their beauty. Light brings together the inherent properties of diamond, the optical effects created by faceting, and the observer's ability to appreciate the gemstone. To understand the effects that cut proportions have on the appearance of round brilliant cut diamonds, it is important to begin with a general review of light and optics. This is the first of three articles in this diamond cut series that will briefly explore these topics as they relate to a polished diamond's appearance. This article will cover general principles of light interacting with a diamond, including reflection (light bouncing back from a surface), refraction (light transmitting through a surface), and critical angle (which relates to the inherent optical properties of the material)[1]. Later articles will cover other topics on optics, such as dispersion in diamonds and the effects of polarization.

Executive Summary:

- The angle at which light reflects from a surface is equal to the angle at which it strikes the surface. Both angles are measured from the normal (which is an imaginary line perpendicular to the surface at the point where the light strikes).
- When a light beam passes from a material of lesser optical density (e.g., air) to a material of greater optical density (e.g., diamond), that light will slow in speed. It will also bend in direction, unless the beam strikes perpendicular to the surface; this bending is called refraction.
- A beam of light will bend toward the normal when entering a diamond and away from the normal when leaving a diamond.
- The incident light beam, normal, and reflected (or refracted) light beam comprise a single plane. This is the plane of incidence.
- The critical angle (based on a material's refractive index) partially determines when a light beam striking the inner surface of a diamond will reflect back into, or transmit out of, a diamond.
- The higher the refractive index of a material, the smaller the critical angle will be.

REFLECTION AND REFRACTION

When light strikes the outside surface of a clean, well-polished diamond, or any other transparent material, some of that incident light is *reflected* (bounced) back from the surface. The remaining incident light is *refracted*, which means that it is transmitted (or enters) through the surface and into the diamond. This also means that some of the incident light's *energy* is reflected, while the rest of the light's *energy* is transmitted into the diamond. How much of that light's energy is reflected or refracted depends on several factors: the angle at which the light strikes the surface; the optical properties of the material (in this case, diamond); the wavelength, or color, of the particular ray of light that is striking the surface; and the polarization state (direction of vibration) of that ray.

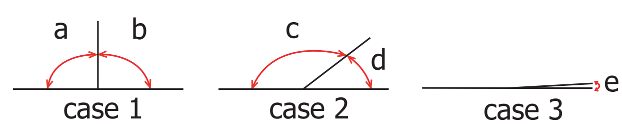

Figure 1. Different types of angles

Let us begin by considering the effect of the angle at which light strikes a diamond's surface. For simplicity, we can consider two types of angles. The first is the perpendicular or right angle, when the ray of light is at 90° to the plane of the diamond's surface (figure 1; case 1, angles a and b). An oblique angle, in contrast, is any angle that is not perpendicular (case 2, angles c and d). How does this angle of incidence affect the behavior of light? Maximum transmission of energy occurs when light strikes perpendicular to the surface of a diamond. Maximum reflection occurs when the light strikes nearly parallel to the surface (case 3, angle e).

The angle at which light strikes a surface is called the *angle of incidence*. The angle at which the light bounces off, if it does, is called the *angle of reflection*. Both angles are measured from the normal, an imaginary line perpendicular to the surface at the point where the light strikes. Therefore, a perpendicular ray (90° to the surface plane) has a 0° angle of incidence (from the normal). The angle of incidence always equals the angle of reflection (figure 2).

This relationship, the *law of reflection*, can be written as a simple mathematical equation: **θi = θrl** (where θi stands for the angle of incidence and θrl stands for the angle of reflection). This equation describes the relationship of light rays whenever light reflects from a surface, *whether the rays are coming from outside or inside the diamond*. The two lines that represent the incident light beam and the normal to that surface define a specific plane, called the *plane of incidence* (figure 3).

The amount of reflection depends on the optical properties of the material. With its high refractive index, diamond is one of the most reflective of all gems. For example, 17% of all the light that strikes perpendicular (angle = 0°) to a well-polished diamond's outer surface is reflected back, whereas only 4% would be reflected from well-polished glass. This leads to one of diamond's many appealing characteristics: clean, well-polished diamond-facet surfaces display a very high luster when compared to other gem materials.

These properties and relationships provide the basic concepts for light reflection. When light is transmitted, however, there are other factors that should be considered. The first is the speed at which light travels. In the vacuum of space, light travels at nearly 300,000 kilometers per second (186,282 miles per second). Within other substances, such as diamond, light travels much slower. The more optically "dense" a material is, the slower light will travel through it. Therefore, whenever light passes from a substance of lesser optical density (e.g., air) to a substance of greater optical density (e.g., diamond), it slows down. In addition, the decrease in velocity is usually different for different wavelengths

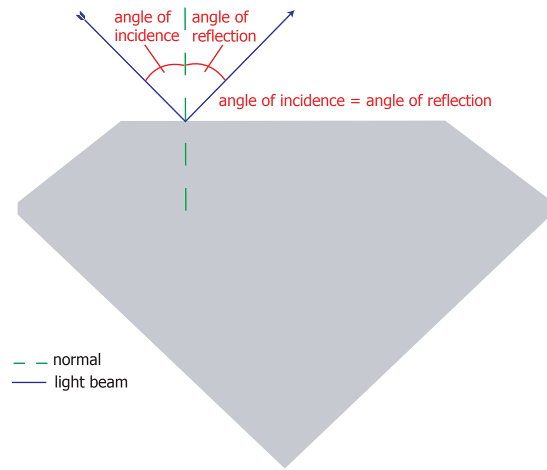

Figure 2. The angle of incidence equals the angle of reflection.

(colors) of light — in diamond, wavelengths in the violet/blue range slow the most, while those in the red range slow the least.

If the angle of incidence is 0° (i.e., the light ray is perpendicular to the surface), the light will slow down but continue to travel in its original direction within the denser medium. However, if the angle of incidence is oblique (more than 0° but less than 90°), any transmitted light will not only slow down but also bend, or change the direction in which it is traveling. This bending of light is called *refraction*, and the angle at which the ray bends (again, measured from the normal) is called the *angle of refraction* (figure 4). As with reflection, the angle formed by the beam of incident light and the normal to that

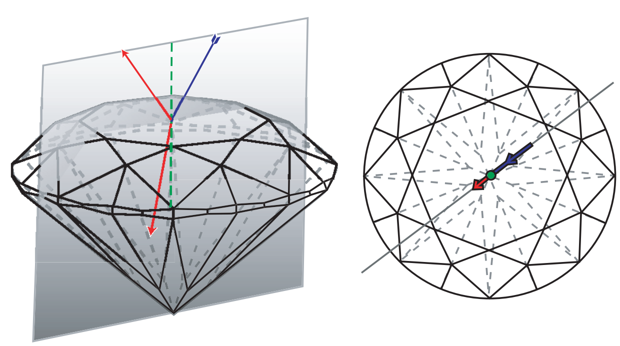

Figure 3. A reflected (or refracted) light beam is restricted to its plane of incidence

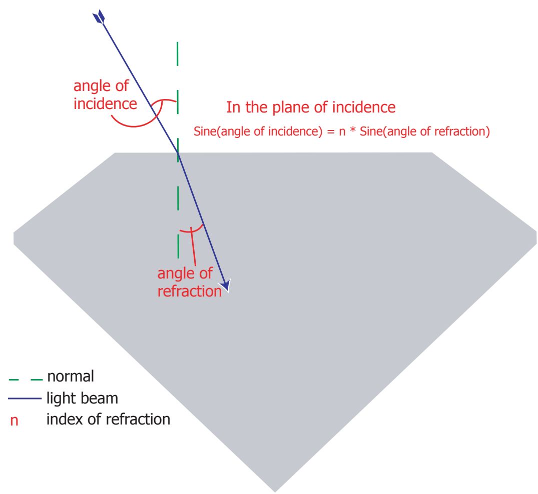

Figure 4. Angles of incidence and refraction

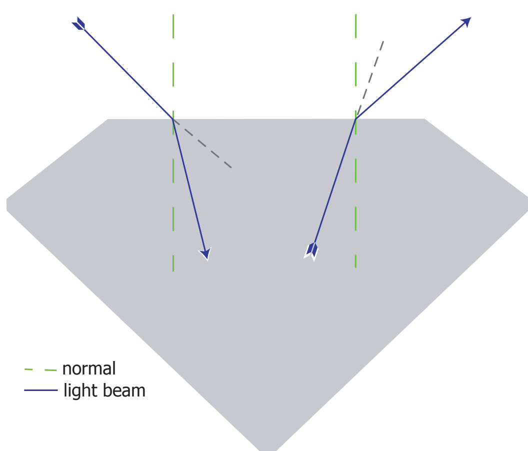

Figure 5. Refraction of light in relation to normal

surface defines the plane of incidence; the refracted ray is found in this plane.

The direction in which light will bend depends on whether that light is traveling into a medium that is of greater or lesser optical density. When light enters a diamond, which is optically denser than the air it was originally traveling through, it will bend toward the normal. Its angle of refraction will be less than its angle of incidence ($\theta r < \theta i$; figure 5). However, when light leaves a diamond it bends away from the normal. In these cases, its angle of refraction is greater than its angle of incidence ($\theta r > \theta i$; figure 5).

The degree to which light bends (the angle of refraction) is determined by the difference in optical density between the two media through which the light passes. This density is described by a quantity called the index of refraction, or *refractive index* (RI). The RI of a medium can be computed by dividing the sine[2] of the angle of incidence by the sine of the angle of refraction. Or, stated as an equation (called *Snell's Law*) where light passes between air and a medium with an RI of n: **$\text{sine } \theta i = n \text{ sine } \theta r$**

This equation allows us to see that the higher the RI of a material (or the larger the difference between the RI's of two materials), the more a ray of light traveling through an interface will bend. The RI of diamond is about 2.417. This is one of the highest refractive indexes of any natural transparent gem. (For comparison, most manufactured glasses have RI's in the range between 1.47 to 1.70.)

When a single refractive index is given for a medium, it is usually given for a specific wavelength of light in the yellow region of the visible spectrum (at 589.3 nanometers) called the sodium D line. For other wavelengths of light, diamond has slightly different RI values, which means that rays of other wavelengths refract more or less than for yellow light at 589.3 nm. (These RI differences cause dispersion, which will be a topic of future discussion.)

CRITICAL ANGLE

Refractive index also affects the amount of light that is reflected and refracted at each surface (or interface) between two materials — here, diamond and air. We already know that diamond is one of the most reflective gem materials (exemplified by its high luster). This strong reflective quality also affects light as it reaches the air/diamond interface from inside the diamond. To understand this, we need to review a concept called the critical angle.

First, imagine a beam of light striking the outside surface of the table facet of a diamond. If the light strikes perpendicular to the table (figure 6, case 1) the transmitted beam continues traveling in the same direction. In this case, the directions of both the incident beam and the transmitted beam lie along the normal. However, if the incident beam enters at increasingly larger angles to the normal, the refracted

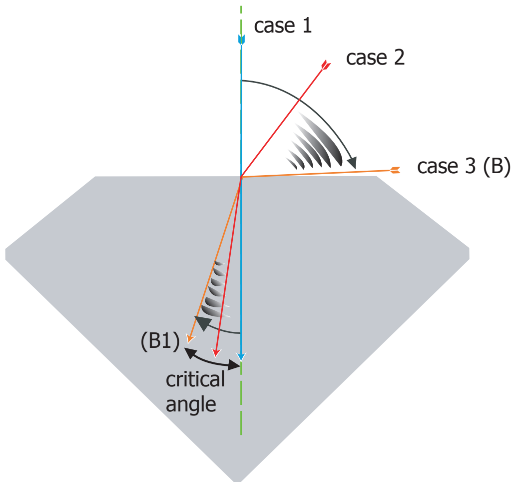

Figure 6. The critical angle is formed by the maximum angle at which light will refract when entering a diamond at a given point.

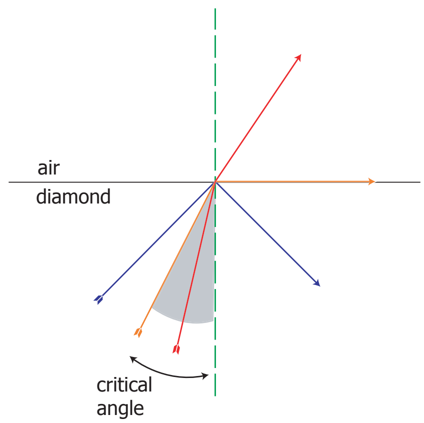

Figure 7. The critical angle defines which light beams are reflected or refracted.

ray of each beam tilts away from the normal, *but at a shallower angle* (case 2). When the incident beam is just short of parallel to the table (case 3), the angle of refraction is the largest angle possible for transmitted light. This angle is called the *critical angle*.

Light moves along the same path whether it travels forward or backward. (Figure 6 shows a light ray path B — B1. Light traveling from B1 to B would trace the same path as light traveling from B to B1.) Thus, the critical angle not only describes the maximum angle at which light may be bent when entering a diamond, but also describes the angle within which light must strike the inner surface of the diamond in order to be refracted out of it. If light strikes the inner surface of a diamond outside the critical angle, all of that light's energy will be reflected back into the diamond. As before, the angle of reflection will equal the angle of incidence. If, on the other hand, the light strikes the surface within the critical angle, much of that light's energy will be transmitted and escape from the diamond (figure 7). The remaining energy will be reflected back into the diamond to continue moving around, until it is eventually transmitted or dissipated. The angle at which the light strikes the surface, as well as the polarization state of that light (covered in a future article), determines how much of the light's energy will be reflected or transmitted if it strikes within the critical angle.

The higher a medium's refractive index is, the more it bends light and the smaller its critical angle will be. Because diamond has a high refractive index, it has a small critical angle (24.5°). This is one reason why diamonds have the potential to be so brilliant. Most gems have larger critical angles, which allow more possibilities for light to leak out when that light strikes the inner surface of the pavilion. The fact that diamonds reflect much of their internal light allows diamond cutters to more easily create facet angles that direct most of that light through the crown of the polished diamond and toward the viewer.

The particular effects of diamond optics need to be considered at *each interface* where a light beam strikes. Each meeting of light and surface has its own effect on a light beam's energy. When we begin to consider the effects of dispersion and polarization on diamond appearance, the need for a comprehensive approach will become increasingly clear.

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. ■

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[Some parts of this article have been adapted from Assignment 6 of the *GIA DIAMOND GRADING* course material (1995).]

[1]Optical properties, such as refractive index and optic character, arise from the particular chemical composition and atomic structure of a transparent material.

[2]Sine is a mathematical function that, for an angle less than 90°, is the ratio of the length of the leg opposite the angle (when it is considered part of a right triangle) to the length of the longest leg of the right triangle. For our purposes, the sine increases from 0 to 1 as an angle increases from 0° to 90°.

