Diamond Optics Part 2: Light Dispersion, Color Wavelengths and Fire

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To further understand the effects that cut proportions have on the appearance of a round brilliant cut (RBC) diamond, we must continue our review of diamond optics. In this article we expand our exploration of light movement to include the optically dispersive nature of diamonds, the different wavelengths (colors) contained in white light, and the various causes of the visual appearance aspect of "fire".

This article builds on the concepts and definitions outlined in "Diamond Optics Part 1". (You may wish to review that article before reading this one.) Part 3 of "Diamond Optics" will cover the effect of polarization on light movement through a polished diamond.

Executive Summary:

- Fire is not the same as dispersion. Fire is the appearance of colored flashes (chromatic flares).
- Light rays of different colors, coming in at the same point and direction, can take different paths through a polished diamond.
- Fire is influenced by a diamond's proportions in four ways:
  - The angle that light enters a diamond
  - The angle that light exits a diamond
  - The number of facet interactions (bounces) the light has inside the diamond
  - The number of times that light rays spread across facet junctions
- Different illumination conditions and surroundings (the viewing "panorama") can enhance or diminish the appearance of fire.

What are those bright flashes of different colors that seem to shoot out from diamonds? Where do they come from, especially when there are no colored lights in the surrounding room? Fire is a well-recognized and appreciated appearance aspect in diamonds, and is a primary reason why people desire and treasure them.

As a first step, it is important to distinguish between the words *dispersion* and *fire* as they are used to describe polished diamonds. These two terms refer to different — but related — attributes. *Dispersion* is the scientific term for the breaking up of white light into its spectral colors. It is an inherent property of transparent materials and is often a single value — based on a material's refractive index (RI) — for all examples of the same material[1] and composition (e.g., all polished diamonds have the same dispersion regardless of their shape or proportions). *Fire,* on the other hand, is an appearance aspect of polished diamonds and other gemstones. Fire is the suite of colored flashes (which we refer to here as chromatic flares) that one sees when viewing a diamond. Fire varies from diamond to diamond, as well as under different lighting conditions and viewing environments.

These chromatic flares have several causes. Most of these causes are found in the interdependent relationship between the optical properties of diamond as a material, the effects of a polished diamond's cut (e.g., facet angles, the quality of a diamond's polish, etc.), and the illumination and environment (or "panorama") in which the diamond is viewed.

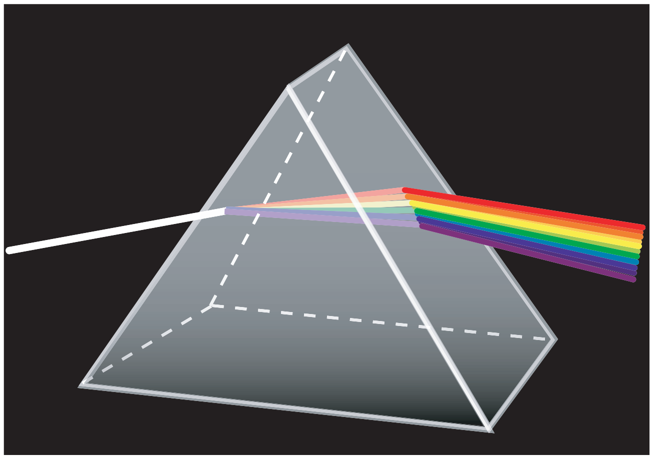

Figure 1. Dispersion of white light in a prism

Let's examine the optical property of dispersion before we explore fire. Again, dispersion is the breaking up of white light into spectral colors. Most people have seen the rainbow of colors that results from putting a prism in front of a beam of light (figure 1). Prisms allow us to see that a beam of white light is actually composed of many different-colored beams of light. To be more precise, white light is composed of different light rays, each with its own wavelength. Each different wavelength is perceived as a different color.

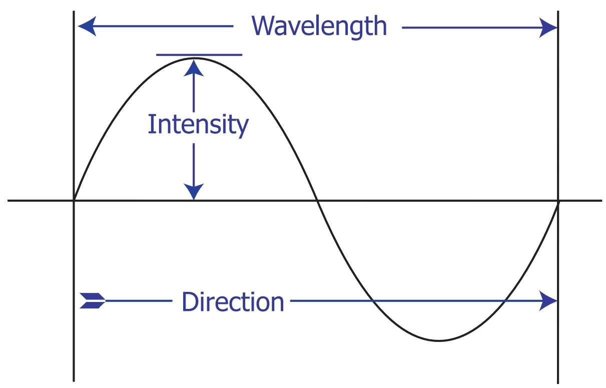

Figure 2. Wavelength properties.

Each ray of light has its own wavelength, direction of travel, and intensity (or amplitude; see figure 2). The *wavelength* is the distance covered by a single cycle of the wave. The full range of wavelengths for light and related radiation is called the electromagnetic spectrum[2]. The wavelengths vary from shorter than the diameter of an atom to about the distance from the Earth to the Moon. The visible spectrum — the range of wavelengths that contains all of the colors that we can see — is only a small part of this electromagnetic spectrum, the region from approximately 400 to 700 nanometers. (A nanometer is a thousand millionth of a meter, and is abbreviated as nm.) Our eyes see the different wavelengths as different spectral colors. Violet has the shortest wavelength (averaging 410 nm) and red has the longest (averaging 665 nm; figure 3).

In "Diamond Optics Part 1," we stated that diamond has a refractive index of 2.417. RI is measured for materials at the Fraunhofer[3] D-line (due to light

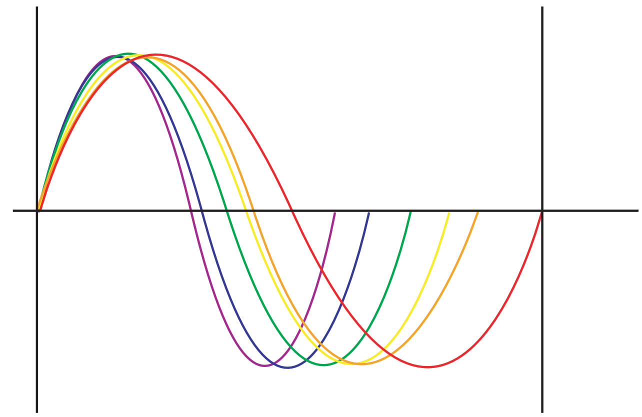

Figure 3. Relative wavelengths of various colors of light

emission from sodium) in the yellow region of the visible spectrum at 589.3 nm. We also stated that diamond has different RI values for different wavelengths of light. The difference in RI's between the G-line (431 nm) in the violet region and the B-line (687 nm) in the red defines diamond's dispersion (figure 4). This dispersion is 0.044, which is one of the highest values for any natural, transparent gemstone. Again, all diamonds have the same dispersion.

The refractive index indicates how much a beam of light will bend, based on the direction in which it is traveling, when it passes between two materials of

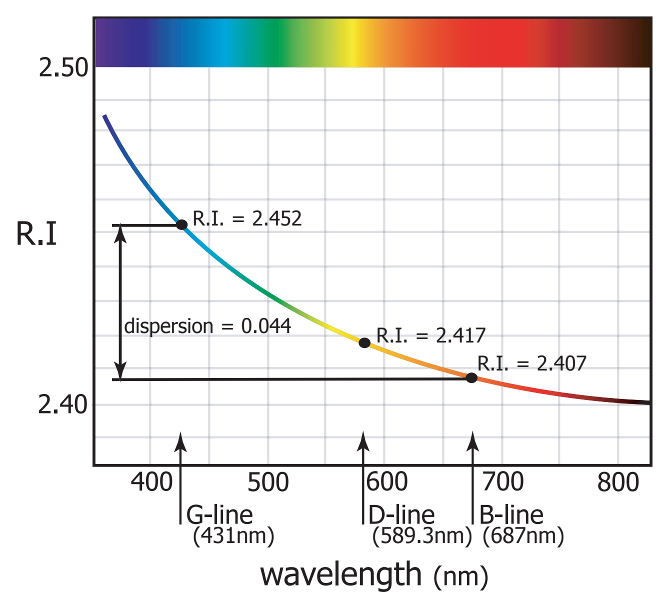

Figure 4. Dispersion curve for diamond, along with Fraunhofer lines used for determining the dispersion value

different optical densities (such as between diamond and air). Because rays of different wavelengths (colors) are associated with different RI values, they will refract or bend by different amounts. For almost all materials (including diamond), violet light (for which diamond has the highest RI) will bend the most, while red light (for which diamond has the lowest RI) bends the least. This difference in the degree to which wavelengths within a beam of light bend creates the spectrum (rainbow) of light that we see. This is illustrated by the light exiting the prism in figure 1.

So, dispersion leads to the separation of white light into colors that take separate paths, caused by differing amounts of refraction taking place in a material. Also, just as white light can be broken up into its separate spectral colors, separate spectral colors can re-combine. When all of the spectral colors overlap in a balanced fashion, our eyes will see white light. However, if some spectral colors are missing or are weak in intensity, we will see a resultant color that is the combination of those colors that are present and strong (for example, we would see orange light if only orange wavelengths were present, but we might also see this if orange wavelengths were absent and only red and yellow wavelengths were present).

Dispersed rays spread out more widely as the length of the light path increases. A beam of spreading white light begins as a tight bundle of white light, then becomes a bundle of mostly-white light with some colors around the fringes (figure 5), and then fans out into the spectrum we are familiar with (figure 5, right)[4]. Therefore, the longer the light path, the more chance there is of seeing different spectral colors. Remember that these images are just for a single beam of light. In most cases there are billions of beams of light simultaneously interacting with the diamond in this way.

FIRE AND FACETS

If all diamonds have the same dispersion value, why do some diamonds display more fire? How are fire and dispersion related? This is where the proportions of an individual polished diamond come into play. Four factors cause the separation of light rays as they exit a diamond (which leads to the appearance of greater fire). These factors are: (1) the angle at which the light exits the diamond, (2) the angle at which the light enters the diamond, (3) the number of facet interactions (bounces) that the light has while inside the diamond, and (4) the number of times that the light rays spread out across junctions between two adjacent facets. To help the reader better understand each of these factors, we will first explore how a single beam of white light behaves in a diamond.

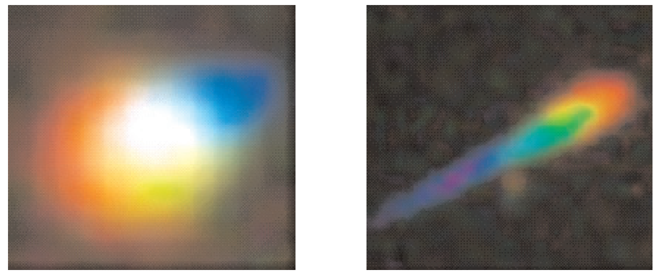

Figure 5. Tight (left) and spread (right) chromatic flares

Because the effects of *exit angle* are the best known, we will review them first. In 1919, Marcel Tolkowsky wrote *Diamond Design: A Study of the Reflection and Refraction of Light in a Diamond* (E. & F.N. Spon, London). Although it wasn't the first work to calculate light paths within a polished diamond, it would become the most famous. Much of twentieth century diamond cutting philosophy for RBC diamonds was, and still is, based on Tolkowsky's findings.

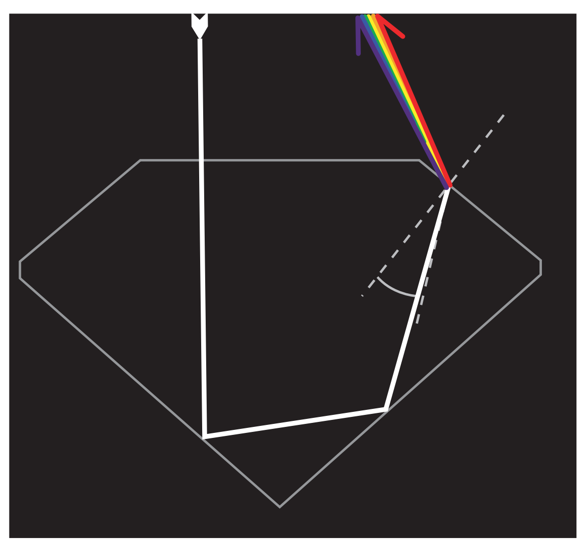

Figure 6. In Tolkowsky's model, dispersion is only calculated when the white light beam exits the crown facets.

Although Tolkowsky knew that different wavelengths have different refractive indexes (and discussed it early in his text), he only computed their dispersive effect *when the beam of light exited the diamond* (figure 6). Tolkowsky stated that the sharper the angle on exiting (i.e., the larger the angle of refraction when measured from the normal), the more "dispersion" the light displayed. Seen from the inside of the diamond, this means that for a wider spread of light rays, the light should strike the inner surface as close to the critical angle as possible (while still remaining inside of that angle so that the rays are not reflected back into the diamond). Therefore, sharp exit angles lead to fire in a diamond. However, this is only one of several factors (as noted above). Tolkowsky did not calculate (or at least did not publish anything about) the dispersion of light *while inside the diamond,* and he never included other causes of fire in his model of diamond cutting and facet angles.

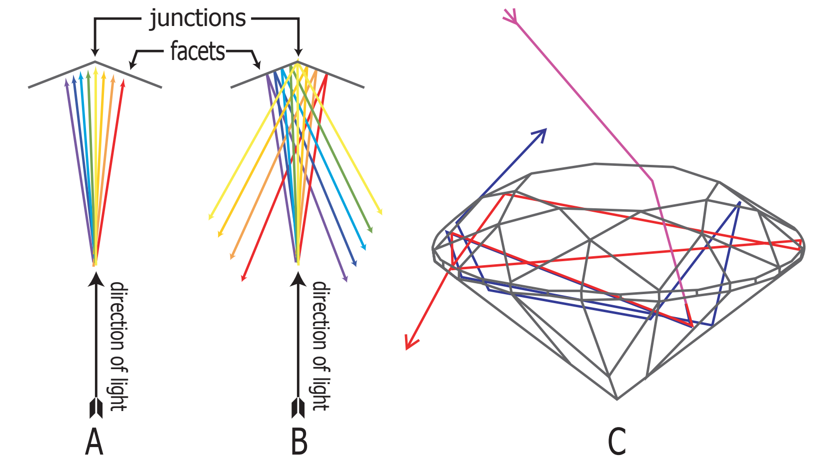

Figure 8. A) Dispersing light spreads across facet junction. B) Light beam then "splits apart" and travels in two different directions. C) A beam of light (that for this example contains red and blue wavelengths and appears purple) strikes a facet junction on its second bounce within a diamond. Although the beam already begins to disperse after first entering the diamond, the act of striking the facet junction causes the red and blue wavelengths to take off on wildly divergent paths.

The second factor that affects the amount of fire a particular polished diamond can display is *entry angle*. Again, the sharper the angle through which the light enters the diamond, the more the light beam will be dispersed (figure 7). Light begins to disperse *as soon as it enters the diamond*. This initial dispersion becomes increasingly important as the light experiences the next two types of interactions.

A third important factor is the number of *facet interactions* the beam of light has while inside the polished diamond. Basically, the more times the beam of light bounces (reflects) inside the diamond, the longer the light beam's path will be before it exits the diamond. Longer light paths lead to more widely spread light beams.

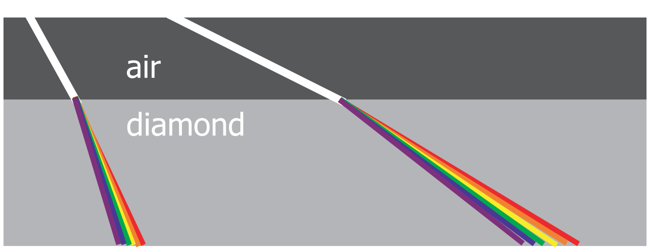

Figure 7. Dispersion increases from sharper entry angles (right).

The fourth factor that affects the amount and distribution of fire that a diamond displays is related to *facet junctions*. Any time that a beam of light fans across a facet junction (the edge where two or more facets are joined; figure 8A) the different wavelengths in that light will "split apart" and begin to travel in different directions (figure 8B). This is caused by some of the wavelengths striking one side of the junction (thereby being reflected at an angle to that facet's normal), while the other wavelengths strike the opposite side of the junction (and are reflected along a different plane of incidence formed by a different facet and its normal). Figure 8C demonstrates this phenomenon for a beam of light in three dimensions.

All four of these factors affect the amount of fire a particular polished diamond displays, and+- all of them can be affected by variations in cutting proportions. The final consideration that affects the appearance aspect of fire in a polished diamond is the surrounding environment (including illumination).

PANORAMA AND FIRE

Have you ever noticed how polished diamonds look different in office lighting, candlelight, or outside on a sunny day? This is because of differences in the viewing environment. In this case, the environment includes not only the type of lighting that is illuminating the diamond, but also the surroundings (such as walls, ceiling, floor coloring, and other objects in the immediate area) in which the diamond is viewed. All of these variables can be classified under the heading of viewing *panorama*.

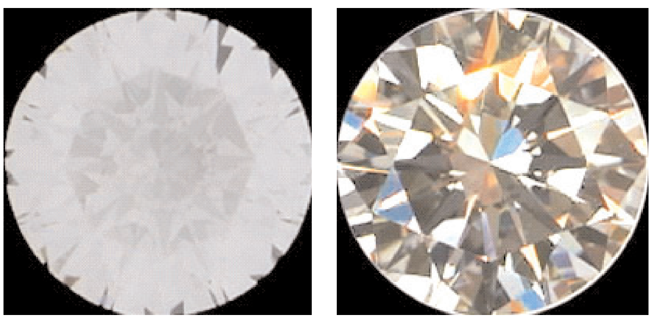

Figure 9. The same diamond in diffused lighting (left) and spot lighting (right).

An important distinction between typical office lighting and candlelight (or sunlight) is the spread of directions from which the light beams enter the diamond. Office lighting (often fluorescent lighting that bounces off white ceilings and light-colored walls) is considered a type of *diffused lighting*. In completely diffused lighting, light strikes the diamond evenly from everywhere and from all angles. Although this type of lighting may highlight the brightness of a polished diamond, the more evenly diffused it is, the more it will suppress fire. Candlelight or sunlight is the opposite of diffused lighting and is called *directional lighting* or *spot lighting*. In spot lighting, light strikes the diamond from one or more single point sources which are small and bright compared to the areas around them. The contrast between the light and dark areas in spot lighting, along with the contrast due to the edges of the diamond facets, bring out the fire in a diamond.

Edges between light and dark in the panorama also have an important effect on fire. Recall that separate rays of colored light can recombine into white light when they overlap. In diffused lighting, because the light enters evenly from all angles, there are usually enough wavelengths of all colors to add up to white (or mostly white) light coming from the diamond (ignoring the color of the diamond itself). In spot lighting, the spread of colors that becomes apparent on the edges of the light beam is not recombined into white light, because there are no other light beams right next to them. Therefore, these wavelengths (colors) remain separated and are seen by an observer as fire. For an example of this, see figure 9. On the left is a photograph of a diamond that was taken in very diffused lighting, and on the right is the same diamond photographed in spot lighting.

Although diffused lighting suppresses most fire in polished diamonds, there are situations in which chromatic flares (color flashes) may still be seen. These also have to do with contrast in the panorama, but in this case the contrast is a result of objects surrounding the diamond. *These objects include the observer*. (Examples of objects that may cause contrast in a diamond's panorama are dark bookshelves against light walls, and dark clothing against light clothing or light backgrounds.) The flashes of fire from these influences in the panorama are much more subtle than those from spot lighting, since the intensity of the light is much less. Figure 10 shows a close-up photograph of a diamond.

It is possible to see a blue flash of color even though the photo was taken in diffused lighting and there was nothing blue in the diamond's panorama.

Figure 10. A chromatic flare in diffused lighting.

This flash of color was due to the observer wearing a black suit while standing against a white background — as this contrasting edge is dispersed through the diamond, a colored patch results.

A last consideration regarding dispersion and fire in polished diamonds is that flashes of color will only be observed if the viewer's eye is in the path of the colored light beam. Chromatic flares are somewhat narrow beams of light that emanate from the diamond. There are many gaps between these flares. Observers will see a bright flare if it is directed at their eye, but will see faint color or no color if their eye is between the flares (figure 11). An observer's eye can only view the flares that are in its direct line-of-sight. So, *an observer has to be in the right position to see fire*. This is why different chromatic flares can be seen when an observer tilts a diamond. Because the observer cannot be in all positions above the diamond at once, it is not solely the amount of fire (number or intensity of chromatic flares) that is important, but also the direction in which those chromatic flares escape from the diamond.

In summary, each ray of light has its own color, and each ray of light will have its own fate. Each ray will travel an individual path within a polished diamond. That individual path will determine where the light exits the diamond, and how much of that ray will recombine with other rays of different wavelengths to form white light. Any rays that escape complete recombination may be seen as fire, or chromatic flares, if the observer is in the right location. In the next article on diamond optics, we will examine how the polarization state of each light ray also affects its behavior in a polished diamond.

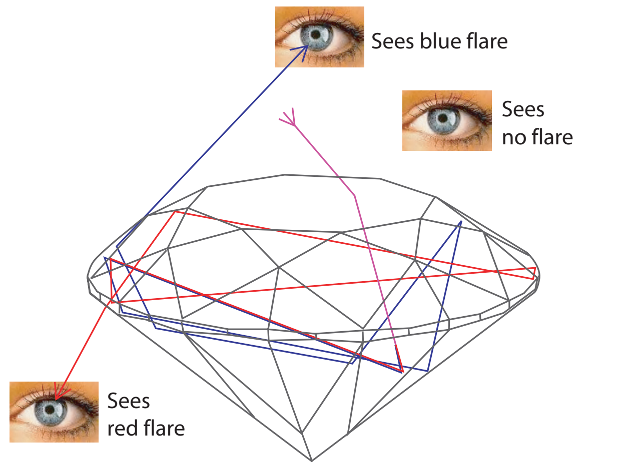

Figure 11. Different color flares will be seen, depending on the direction that the flares exit the diamond, and where the observer is located.

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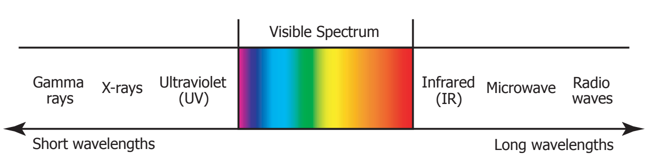
[1]This is true for all materials, like diamond, in which light travels at the same speed in any direction. These materials are considered singly refractive, or optically isotropic. Those materials in which light travels at different speeds depending on the direction of its travel are considered doubly refractive, or optically anisotropic.

[2]The electromagnetic spectrum. These wavelengths range from shorter than the diameter of an atom to about the distance from the Earth to the Moon.



[3]In 1814, while studying the spectrum of light from the sun, Joseph von Fraunhofer discovered a number of sharp, dark lines caused by the absorption of certain wavelengths by the Sunss and the Earthss atmospheres. These "Fraunhofer lines" are often used to compute optics values such as dispersion.

[4]The images of these flares illustrate how they would appear to your eyes, if magnified, when viewing a diamond.