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Abstract

This thesis is about the multicolored gradients seen when using certain dichroic color filters with artificial light. As of now, this phenomenon lacks a unambiguous descriptor, and “Goniochromatic Gradient” is proposed. With help of optical physics, the science of color vision and information about dichroic products, principles for the relationship between goniochromatic gradients and dichroic filters are formulated for anyone interested in exploring this visual phenomenon.

Figure 1. Ann Veronica Janssens, Red and Turquoise, 2005 (Gilmore 2005)
Acknowledgements

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Introduction

To fall into colour is to run out of words.
— David Batchelor
This thesis focuses on the color gradient that appears when a dichroic color filter is used with artificial light, a phenomenon which is rarely taken up in product descriptions for dichroic color filters. The optical process called *dichroism* is investigated in depth. In particular, its color shifting property, or *goniochromatism*, is studied to formulate principles for goniochromatic gradients with dichroic color filters.

A *dichroic* material is one which has a different reflection color than transmission color. *Goniochromatism* is the phenomenon whereby a material displays a different color as a function of the viewing geometry. The goal is to deepen the knowledge of the goniochromatic properties of dichroic material, especially when used with artificial light. The paper is written with a reader in mind who has a basic understanding of optical physics and desires a deeper understanding of this effect, either for personal interest or for professional use in the context of art, architecture and lighting design.

Dichroic filters are used in a range of fields from anti-reflection coatings on spectacles to heat-reflecting mirrors in dentistry (Johnston 1997; Rancourt 1996). Their physical properties also enables the visual phenomena here referred to as goniochromatic gradients. This effect can be seen when using a dichroic color filter with an artificial light source. A gradual fade between multiple colors appears in the fringe of the light beam. It is this phenomenon, which I call goniochromatic (dichroic) gradients, that is the main subject of this paper.

Goniochromatic gradients have been explored in the “Dichroic Projections” series by artist Ann Veronica Janssens. At her 2017 White Cube Bermondsey exhibition, the piece “Reggae Color” (Figure 2 on page 2) was shown. In the piece, a single construction luminaire equipped with a red dichroic filter is projecting a gradient on the gallery wall (White Cube 2018). The artist has mounted the filter in a slight angle to further emphasize the effect (Bal 2013, 260). Janssens’ artwork series is the starting point of this research and can be seen as the visual framing of the thesis. Her work is interesting because it showcases a feature of dichroic color filters which is otherwise often disguised. Here, the color changing properties of the filters are instead brought forward and appreciated in their own right.

The thesis explores the following questions. What is dichroism and what makes a material dichroic? How can goniochromatism be related to dichroism? What optical principles influences the colors of the gradient seen with dichroic color filters?

To answer and discuss these questions, a literature review was made around multiple aspects of dichroism. Principles for the relationship between dichroism and goniochromatism were formulated with insights from the physics of thin-film optics and theory of human color vision. Following that, a selection of dichroic products were analyzed based on the theoretical insights. In this way, theoretical principles are eventually related to practical examples to provide answers to the questions formulated above.
Method

Research by design

Initially, the plan for this thesis involved carrying out a lighting design commission and writing about the process, following a method called research by design based on Rocco (2008). Research by design forms part of practice-based research (PbR), and it can be carried out with the aim of finding shared criteria that can drive the design process to prove or disprove a hypothesis.

In this particular case, the goal of the design commission (a finished project) and the goal of research (this thesis) diverged at a point so that shared criteria became difficult to find. However, since one of the uses of research by design is to offer practice as a generator of relevant questions to be explored within traditional forms of research (Rocco 2008), this is the way that the method came to be used here, too.

Figure 2. Ann Veronica Janssens, Reggae colour, 2004-2017 (White Cube 2018). Photo by George Darrell.
During the concept phase of the lighting design project, the tension between natural and artificial light was investigated. A visual similarity between the natural gradient of twilight and the gradient seen when using certain dichroic color filters was observed (see Figure 2) — the latter being the effect studied in the artwork series “Dichroic Projections” by Ann Veronica Janssens. It turned out that the visual similarity was not anchored in a physical similarity. The gradient seen in the sky at twilight stems from Rayleigh scattering (Lilienfeld 2004; Smith 2005), whereas the gradient created with dichroic color filters is caused by thin-film interference (Johnston 1997).

Figure 3. A comparison of a natural twilight gradient (left) and three artificial dichroic goniochromatic gradients — red, cyan and pink. The optical mechanisms are different but the perceptual result is similar.

To find out which filter would be the most suitable to use as a counterpart to the twilight gradient, experiments were made where a selection of filters of different colors were evaluated. The first thing that could be established was that color-shifting gradients did not appear with pigment (absorption) filters. Second, it was seen that the set of colors in the gradient were different depending on the main color of the dichroic filter. Notably, the hue shift was much larger in some dichroic filters than others. At the time, the relationship between the main color and the colors appearing in the gradient were unclear.

At this point, a certain set of colors were chosen for the design project. At the same time, the thesis took a more theoretical turn. A literature review was initiated, together with a survey of projects using dichroic materials within lighting design, architecture and art. It was first much later that the term goniochromatism\footnote{The definition of goniochromatism used is the optical phenomenon whereby the color of a material changes noticeably as the viewing geometry changes. More on this in the theory chapter.} was found, which would eventually turn out to be a suitable word for the phenomenon that is the subject of this thesis.
Literature review

The first two fields that were studied in the literature review were the ancient history of dichroic materials and the science of modern thin-film optics. This is simply because dichroic materials have seemingly been studied in most depth within optical physics, chemistry, archaeology and mineralogy.

A need to contextualize the material within architecture and art was also needed. This was made possible with what might be the only in-depth scholarly work about the theory and practice of dichroic optics within architecture, Laura Johnston's dissertation at the University of Sunderland — *The innovative application of the coated glass surface in architecture* (1997).

Since it is now more than 20 years since her dissertation was published, much has changed in relation to dichroic materials². So while the work of Johnston informs much of this thesis, my goal is to extend it, especially focusing on the goniochromatic quality (angle-color dependency) of certain dichroic materials.

Project review

In Johnston (1997), a number of projects done on an architectural scale using dichroic material are presented. To see what had changed since the time the dissertation was written, a review of projects in architecture, design and art was done. The method for collecting projects was through non-structured online querying. The primary search keyword used was the word “dichroic”. Other words such as “lens”, “filter”, “film” etc. were added as well as “architecture” and “art”. Note that the searching for relevant projects was made relatively difficult since the desired gradient effect (which I call goniochromatic gradients) is not defined with any unambiguous term. The project review phase, although interesting, did not add anything to the questions that were finally decided upon investigating. The result of this work is an additional appendix with a reference bibliography containing a large selection of architecture and art projects using dichroism in various ways. The idea behind this is that the appendix might guide readers and lighting designers in their future exploration of dichroism and goniochromatism.

² Polymeric dichroic film was for example not available at the time of her writing. The scale of coated glass was limited by the size of the coating chambers used to apply chemicals to the glass surface. The larger the coated area, the worse the coating quality became (Johnston 1997). Now, film can be applied between large glass slabs with practically invisible seams. As such, the potential scale of dichroic surfaces has increased drastically.
Analysis of dichroic products

Another study carried out in this thesis was a survey of dichroic products. A selection of the products were analyzed and function as devices for understanding the relationship between dichroism and goniochromatism.

Initially, only products displaying what I now define as goniochromatic characteristics were searched for. Since this effect is rarely described in detail by any manufacturer, it was not easy to judge which products would display the sought for gradients. During the research phase of the lighting design project, luminaire samples were ordered equipped with red and blue dichroic filters. There was no mention of the effect in the data sheet of the luminaires, and the customer service did not know about any such effect. It nonetheless came to light that the luminaires ordered displayed the same gradients as those in Janssens’ projections. Later, the theoretical literature review offered an explanation for this.

Moving on, a selection of dichroic products were analyzed based on the theoretical principles. A collection of standard dichroic color filters (red, green, blue, yellow, cyan, orange and magenta) from two suppliers were used as references. The first supplier, Lumena Lights, supplied photos on their webpage where the goniochromatic characteristic of the filters is shown. I found no other supplier that provided equivalent visual documentation for their filters. The second supplier, Thor Labs, also provided detailed data concerning their filters online. The transmission in percent for every wavelength is specified in 1 nanometer steps for angles of incidence in five degree steps from 0 to 45 degrees. Both suppliers were chosen since they contributed information that couldn’t be found elsewhere for dichroic color filters. The point here is not to make a comparison between the two product lines. They rather form a valid source for understanding the relationship between the physics of thin-film interference dichroic filters and goniochromatic gradients.

The product survey also includes a presentation of the 3M “Radiant Light Film” product family and its successor. This product is chosen since it might be the first widely available product that explicitly advertises its goniochromatic properties (albeit with the word radiant).
Theory

Dichroism

The word dichroic has a Greek origin and means two-colored. A dichroic material has a different reflection color than transmission color. While there are many uses of this technical property in many fields ranging from ‘fine optics’ in technical instruments to anti-reflective coatings on spectacles (Johnston 1997), this thesis is specifically focused on the visual property that can be called goniochromatism which is found in certain dichroic materials.

When a material is illuminated with the whole visible spectrum (“white light”) and only part of the spectrum is seen (“color”), it can be either due to absorption of electromagnetic radiation in the material (pigmentary color) or due to reflection, scattering, transmission or deflection of part of the spectrum away from the eye of the viewer (structural color). The color appears in the latter case due to physical spatial inhomogeneity, and does not lose energy. In absorption, on the other hand, light loses energy to the material (Kinoshita 2008, 1f). Traditional color filters are normally absorption-based filters. Dichroic color can be the consequence of various combinations of processes belonging to structural color. The dichroic color filters used with artificial lighting today work by reflecting part of the spectrum through thin-film interference. This is explained in depth later on.

History of fabricated dichroics

While dichroism is present in nature, for example in vertebrate photoreceptors (Snyder and Laughlin 1975), the scope of this thesis is limited to fabricated material. One of the first known instances of fabricated dichroic material is a Roman glass vessel, the Lycurgus cup, made in the fifth century CE (Freestone et al. 2007). This ancient vessel is an example of technical achievement in Roman glassmaking, not only due to its elaborate glass sculpting but also because of the dichroic color of the glass, which is unique and has not been duplicated (Tilley and Wiley 2011, 193).
Figure 4. The Lycurgus cup in transmitted light (Tilley and Wiley 2011) Photo attributed in reference to the Trustees of the British Museum

Figure 5. The Lycurgus cup in reflected light (Tilley and Wiley 2011) Photo attributed in reference to the Trustees of the British Museum
The Lycurgus cup changes color from a deep wine-red in transmitted light to a pea green in reflected light (Brill 1965; Barber and Freestone 1990). It has been shown that the origin of this color is a combination of light absorption by gold particles and light scattering\(^3\) by silver particles. This effect is only possible if the particles are finely dispersed in the glass solution in colloidal form\(^4\) and the sizes are within a fine range (50-100 nm). In the Lycurgus cup, it is the gold nanoparticles that are responsible for the red transmission color and the silver that is responsible for the green reflection color (Barber and Freestone 1990).

The color of modern dichroic glass or plastic film does not arise from absorption and scattering but from \textit{thin-film interference}.

**Thin-film interference**

The early history of the science of thin-film optics starts with Newton's \textit{Opticks} from 1704 and his technique now known as Newton's rings (Macleod 2018, 2). It is the phenomenon that can be seen in an oil patch on a wet surface (seen in Figure 6). Newton struggled with the explanation of the phenomenon, and it was first in 1801 that Thomas Young laid out the theory that two rays of light can add up to produce darkness (Macleod 2018, 2).

The ability to control this optical process did not start until the 1930s. There were many factors that led to the increased pace of technical development that enabled precise control. Photographic objectives, telescopes and binoculars all benefitted from the discovery of anti-reflective metallic film in 1932 by Rouard (Macleod 2018, 4). This was followed by a number of technical innovations that enabled a sophisticated manufacturing of thin-film optical filters.

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3 Scattering is the optical phenomenon that arises in the atmosphere that gives the sky its blue color. While dichroism here comes partly from scattering, it is not present in modern dichroic glass and film.

4 A colloid is a “substance consisting of particles substantially larger than atoms or ordinary molecules but too small to be visible to the unaided eye” (Britannica Online Encyclopedia 2018a).
The use of the technology in architecture first became necessary with the dramatic increase in energy costs in the 1970s. While glass is regarded as a desirable primary facade material in architecture, it is much less energy efficient than solid insulated walls. The problem of high energy usage due to greenhouse-like environments in summer and heat-loss during winter needed to be solved. The consequences of both problems were reduced with the possibility of changing the properties of transmission and reflection with deposition of chemicals on the surface of large panels of glass (Johnston 1997, 36f). A notable example of a facade composed of various types of coated glass is the Harpa in Reykjavik (see Figure 7). Nowadays, optical coating technology is ubiquitous as uses has been found for thin-film filters “in almost every branch of science and technology” (Macleod 2018, 5).
The previously mentioned oil patch on the wet surface is due to the optical process called thin-film interference. Light is reflected to the eye from both the top and the bottom of the oil surface. The difference in light path length from the bottom and top parts of the oil spill causes different colors to either become reinforced or cancelled out. The reason behind the varying colors of the oil film is consequently due to a variation in the thickness of the film. (Johnston 1997, 41). When light is reflected and refracted in a thin material layer, the light is altered so that certain wavelengths are either in phase or out of phase. When they are in phase, as shown in Figure 8, they reinforce each other and the corresponding colors are then seen with a higher intensity. This would be called constructive interference (Figure 8) and the opposite destructive interference (Figure 9).

The colors seen in dichroic filters are also the result of constructive and destructive interference. Unlike the colors in the oil patch, the colors of dichroic interference filters can be designed by the calculation and manufacturing methods developed since the 1930s.
Figure 8. Wave pattern creating constructive interference, after Tilley and Wiley (2011)

Figure 9. Wave pattern creating destructive interference, after Tilley and Wiley (2011)
With an increasing angle of incidence, the path length in the filter increases. This causes light of different wavelengths to be more or less affected. With a certain filter design, a short path could cause a red color to be transmitted and the longer path would let through a blue color. The opposite goes for reflection. The principle is illustrated in Figure 10.

The angle of influence has a significant impact on the transmission and reflection spectra on all interference-based optical films. When tilted away from the normal direction, the transmission spectrum moves to shorter wavelengths (in the blue direction) (Baumeister 2004, 1–11; Rancourt 1996, 68f). The color-angle dependency of interference filters is the reason gradients appear when using interference-based dichroic color filters. This characteristic will henceforth be called goniochromatism.

The spectrum of absorption filters, on the other hand, is much less affected by the angle of influence compared to that of interference filters. Absorption filters also act opposite to interference filters: as the angle increases, the filter edge moves toward longer wavelengths (Baumeister 2004, 1–22). Accordingly, it is not surprising that absorption-based color filters show no goniochromatic gradient. Note that in some coating designs, a combination of absorption and interference is used to achieve desired optical characteristics (Energy Products Distribution 2013).
Goniochromatism

The optical phenomenon whereby the color of a material changes noticeably as the viewing geometry — the geometric relation between viewer, object and light source — changes was first proposed to be termed “goniochromatism” by Hemmendinger and Johnston (1970). It originates in the greek words "gonia" and “chroma”, meaning angle and color. Tilley (2013) defines goniochromism\(^6\) as a synonym to iridescence, irisation, labradorescence, opalescence, pearlescence, polychromatism, and schiller. Many of these terms are used for minerals and gemstones like opal and mother of pearl to describe that various colors appear or disappear depending on the viewing geometry. Iridescence is typically used to describe colors from peacock feathers or soap film, but is also used to describe the reflected colors from data storage disks and security labels. In glass craft, dichroic glass is in fact used to create iridescent effects. Goniochromatism is used here to define a systematic use of the angle-color dependency in contrast to the typically random or unstructured visual appearance of an iridescent material.

Figure 12. The iridescent colors of CD’s or DVD’s. The photo of oil on a wet surface above also displays iridescent colors. Photo by Flickr user mangle_b. CC BY-SA 2.0

\(^6\) I stick with the original proposition of goniochromatism by Hemmendinger and Johnston (1970).
When using dichroic filters with artificial lighting, the optics involved in the beam angles is important for the goniochromatic gradient. The more the light beam deviates from the normal direction of the dichroic color filter, the more of the potential goniochromatic gradient will be seen. However, the beam is in fact often adjusted to remove the goniochromatic effect with barn doors. As mentioned in the introduction, it is assumed that the cause might be a lack of knowledge about the effect.

Figure 13. Barn doors on the luminaire disguise the pink part of the goniochromatic gradient for this dichroic cyan color filter close to Karlbergs slott in Stockholm, Sweden.

7 A normal is the direction which is perpendicular to a surface. In this case, the surface is the dichroic filter.
8 Barn doors are small panels mounted on a luminaire housing. They are used to shrink the light beam of a luminaire, a commonly used technique in stage lighting design.
The colors of goniochromatic gradients

In this chapter, the required background for understanding the relationship between the design of dichroic color filters and the colors in the goniochromatic gradient is presented. Since goniochromatism is intimately connected to color, and color can be defined as a subjective response to the appearance of spectral qualities of light, we begin with discussing the basics of human color perception. (Macleod 2018; Tilley and Wiley 2011).

Perception of spectral and non-spectral colors

The light that is detectable by the human eye is just a small part of the larger electromagnetic spectrum, as seen in Figure 14. In the human eye, the receptors that detect color are called cones. In a normal eye, there are three different types of cones that have different spectral responses. We describe the colors sensed by these as red, green and blue (Macleod 2018, 457). As seen in Figure 15, there is an overlap between the spectral responses, in particular between the cones responding to red and green. This causes the eye to be more sensitive to certain colors than others. As seen in Figure 16, the maximum sensitivity of an average human eye is close to 555 nm.

**Figure 14.** The visible spectrum is only a small part of the electromagnetic spectrum. After Tilley and Wiley (2011)
**Figure 15.** The spectral sensitivity of the three different types of cones in a normal human eye. Figure after Tilley and Wiley (2011).

**Figure 16.** The photopic spectral luminous efficiency function. Describes the sensitivity of the eye depending on wavelength. The maximum sensitivity is close to 555 nm. If this wavelength were isolated, it would be perceived as a greenish yellow color. Figure after Tilley and Wiley (2011).
There is no way to directly measure the subjective color response. Instead, certain quantitative standards are used to convert a large number of measurements into representative objective measurements of subjective color responses. Based on these measurements, functions are set up to form a chromaticity diagram (Figure 17). In such a diagram, the part of the electromagnetic spectrum that is visible to human eyes is drawn as a curved line. The colors on this line are called spectral colors, as they can be represented with a single wavelength. The colors along the bottom line (the “purple line”), as well as points within the area of the diagram are non-spectral since they cannot be represented by a single wavelength. If a purple located in the middle of the purple line is desired, equally perceptible amounts of blue and red light have to be mixed (Macleod 2018, 458). The word perceptible is used since the eye has an uneven color response across the spectrum. Due to the uneven color response of the human eye, it is much more sensitive to yellow-green light than blue or violet light. Hence, to create a filter with a color in the middle of the purple line, the required physical quantity of blue/violet light is much larger than that of red light.

This mixing of color is a significant part of understanding the set of colors that appear in the goniocromatic gradient. Another part is understanding the various bandforms that give optical filters their spectral character.

![Figure 17. The CIE 1931 chromaticity diagram after Tilley and Wiley (2011)](image)

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9 It should be noted that the standardization process of averaging a large number of human spectral responses is bound to simplify the incredibly complex process of human color perception.
Optical color filters

Optical color filters change the spectral composition of the transmitted light. Dichroic color filters reflect the light that is not transmitted. The parts of the spectrum that is transmitted is represented with bandforms which are curves that represent to what extent wavelengths are transmitted and rejected through a filter. These principal forms are used across many fields, for instance in sound synthesis and other forms of electronic signal processing. In this section a few basic filter bandforms are presented.

Basic filter bandforms

Filters that abruptly change between transmitting to rejecting wavelengths are called edge filters. Edge filters can be either longwave pass or shortwave pass (Macleod 2018, 213). Band-pass filters are filters that transmit wavelengths within a range and rejects the wavelengths outside of it. Notch filters are filters that rejects wavelengths in a certain range and transmits wavelengths below and above this range. Bandpass and notch filters are combinations of a longwave pass filter and a shortwave pass filter (Macleod 2018, 243).

As seen in Figure 18, combinations of the mentioned bandforms can be designed, such as shortwave-band pass, band-longwave pass, longwave-band-shortwave pass filters.

Figure 18. Optical filter bandforms

To create a violet color filter, only a shortwave pass filter is needed that let short wavelengths through and reject longer wavelengths. To make a purple color filter on the other hand, red and blue wavelengths need to be mixed. This requires a more complicated filter configuration of at least a shortwave pass filter combined with a longwave pass filter. An example of a dichroic filter with such a filter design is shown in the product review section.

10 Bandform template (https://en.wikipedia.org/wiki/File:Bandform_template.eps, CC BY-SA 3.0). The dimension was changed from frequency to wavelength (as advised by Macleod (2018, 213) and the figure texts were changed accordingly.
Figure 19. The dichroic filters offered by Lumena Lights. Images are ordered from short frequencies (violet/purple) to long frequencies (red) (Lumena Lights Ltd 2018)
Analysis of dichroic products

In this section three dichroic product lines are analyzed in relation to the theoretical processes previously described. In particular, the validity of the principle that transmission spectra of interference-based optical filters move toward shorter wavelengths when tilted is tested. The filters examined include dichroic color filters from Lumena Lights and Thor Labs. “Radiant Light Film” and its successor “Dichroic Glass Finishes” from 3M is further brought up as an example of a product which is explicitly goniochromatic. Although the spectrum of the light source has a large influence on the resulting colors, an abstract neutral illuminant is assumed here for the sake of clarity.

Dichroic color filters

In the product survey of dichroic color filters, only the supplier Lumena Lights provided images where the goniochromatic gradient of the filter is seen (Figure 19 on page 19). As the light source used in the images has a wide beam, the range of incidence angles is larger and a potential gradient is made visible. The gradients were extracted from the images, the result of which is shown in Figure 20.
In parallel to the images from Lumena, spectral transmission data of various angles of incidence from Thor Labs dichroic color filters was acquired and plotted in the graphs below (Figure 21–Figure 26). Note that the maximum angle in the graph is 45°. Used with a wide angle floodlight, the maximum angle is even larger. The spectral transmission data from the Thor Labs filters, the visual impression of the Lumena dichroic color filters and selected pieces from the “Dichroic Projections”-series by Janssens are grouped by color. All of this is tested against the theoretical principles. The captions explain the reasoning and the results of these tests are presented after the diagrams.

Figure 21. Spectrum dependency on angle of incidence for the Thor Labs dichroic red filter (Thor Labs 2018). A longwave pass filter is seen that, when shifted toward shorter wavelengths, should add yellow and then green to the gradient. A similar effect is seen in the image of the red filter from Lumena.
Figure 22. Spectrum dependency on angle of incidence for the Thor Labs dichroic yellow filter (Thor Labs 2018). A longwave pass filter is seen that, when shifted toward shorter wavelengths should mix in green and then blue wavelengths. The result of this should in fact be a reddish white, while the image of the yellow filter from Lumena shows a bluish white.

Figure 23. Spectrum dependency on angle of incidence for the Thor Labs dichroic green filter (Thor Labs 2018). A band-longwave pass filter is seen that, except for green wavelengths, also transmits infrared wavelengths. When shifted toward shorter wavelengths, the infrared component becomes visible and blends in a red component to the gradient. This is similar to the effect seen in the image of the green filter from Lumena, where the gradient goes from green to teal, blue and purple.
Figure 24. Spectrum dependency on angle of incidence for the Thor Labs dichroic magenta filter (Thor Labs 2018). A band-longwave pass filter is seen that lets through red and blue wavelengths. When shifted towards shorter wavelengths, the filter should let through less blue and violet and more red, orange, yellow and even green. This is similar to the effect seen in the image of the purple filter from Lumena, which goes from purple to pink, pale yellow and green.

Figure 25. Spectrum dependency on angle of incidence for the Thor Labs dichroic cyan filter (Thor Labs 2018). A band-longwave pass filter is seen that, except for blue and green wavelengths, also transmits infrared wavelengths. When shifted towards shorter wavelengths, the filter should shift the green part towards blue and the infrared component should become visible and blend in a red component to the gradient. The gradient in the image of the light blue filter from Lumena goes from light blue/cyan to blue and purple, and can be regarded as something in between this filter and the Thor Labs blue dichroic filter.
**Figure 26.** Spectrum dependency on angle of incidence for the Thor Labs dichroic blue filter (Thor Labs 2018). A band-longwave pass filter is seen that, except for blue wavelengths, also transmits infrared wavelengths. When shifted towards shorter wavelengths, the filter should let through less blue and the infrared component should become visible and blend in a red component to the gradient.

**Figure 27.** Ann Veronica Janssens, Hot Pink Turquoise, 2006 (Institut d’art contemporain 2017)
Judging by the above presented analysis, a number of statements can be made which are helpful in formulating principles for understanding the colors in the goniochromatic gradient of dichroic color filters.

- The red and yellow filters from Thor Labs are designed with only longwave pass filters. All other filters have more complex transmission spectra resulting from the filter design which generate more vivid goniochromatic gradients. This implies that if goniochromatic gradients are sought for, filters with only longwave pass filters should be avoided. This principle has exceptions, for instance regarding red filters.

- The purple-pink-yellow-green gradient in the “hot pink” luminaire in Janssen’s Hot Pink Turquoise (the left luminaire in Figure 27) is expected from a magenta, purple or pink dichroic color filter if designed like the Thor Labs filter.

- The cyan-blue-purple gradient projected from the turquoise luminaire in the same piece as above is expected from a cyan dichroic color filter if designed like the Thor Labs filter. A similar effect but with less cyan/green would be acquired for blue dichroic color filters if the longwave-pass edge filter is tuned to a long enough wavelength or if longer wavelengths are reflected.

- The green-teal-blue-purple gradient in Janssens’ piece “Green Aura” (Figure 30) can be expected with a green dichroic filter if designed like the Thor Labs filter, but is theoretically not guaranteed if the longwave-pass edge filter is tuned to a long enough wavelength or if longer wavelengths are reflected.

- The whitish color in the edge of yellow filters arises due to the increasing inclusion of the spectrum.

- The above might be true also for the red Thor Labs filter, but it shows no unambiguous sign of becoming green in the graph. We do not know what happens at larger angles than 45 degrees. Both the red filter from Lumena and the red filter in Janssen’s “Reggae Color” (Figure 2) do fade towards a saturated green in the outer edge, even though this would mean that a lot of the red wavelengths would need to be suppressed. This should not be possible without a shortwave pass filter. This unpredictable behavior will be further discussed in the next chapter.
Dichroic film

Dichroic filters are now available not only as a coating on glass, but also as a multi-layer polymeric polyester film. First introduced by 3M under the name Radiant Light Film, it is one of the earlier products — if not the earliest — widely available product that explicitly advertises a goniochromatic effect\(^\text{11}\). The introduction date may be June 2006, as this is the date present in the data sheets (3M 2006a, 2006b). The product family has now been discontinued in favor of the newer product “Dichroic Glass Finish” (3M 2018). It is available in two colors. The “Chill” color transmits blue, magenta and yellow and reflects gold and blue and the “Blaze” color transmits cyan, blue and magenta and reflects red and gold.

![3M DF Chill](image)

**Figure 28.** The typical (normal angle) spectral response of the polymeric film product 3M Dichroic Glass Finish DF-Chill (Energy Products Distribution 2013)

11 Interference-based thin films are in general polarization sensitive. Due to polarization splitting, the angle-shifting is different depending on the polarization angle of the light. If the layers are made birefringent, this effect can be reduced and the color made more vivid. It is likely that the explicitly goniochromatic product from 3M has this property, and unlikely that the dichroic color filters previously discussed have it (E-mail correspondence with Angus Macleod 2018).
Figure 29. The typical (normal angle) spectral response of the polymeric film product 3M Dichroic Glass Finish DF-Blaze (Energy Products Distribution 2013)

The normal angle spectrum is given in the data sheets (figures %x and %x), and they clearly show that the products are made with band-longwave pass filters that enable the goniochromatic color gradient. According to the data sheet, the band pass short edge should come from an absorption filter at 400 nm. Due to the nature of absorption filters, the angle shift is low on this edge (Energy Products Distribution 2013).

The typology of a band-longwave pass filter in these products is shared with many of the dichroic color filters. In fact, all filters studied except for the red and the yellow filters had a band-longwave pass bandshape.
Discussion

With the help of the analysis methods that were presented in the previous chapter, it becomes possible to predict goniochromatic effects with only a limited amount of available information about the products. The implications of this are discussed in this chapter.

Goniochromatism in dichroic color filters

Many of the dichroic color filters (especially blue and green) would have shown a smaller goniochromatic hue shift if there were no pass edge close to the red visible threshold. If designed like this, the green filter would have become blue and the blue would have become a (weak) violet. Instead, in letting the gradient move towards magenta/purple they showed a significant goniochromatic hue shift similar to the 3M film, even though it was not advertised by neither Lumena nor Thor Labs.

Why is the goniochromatic property of dichroic color filters not described by the manufacturers and suppliers? This can have several reasons. First of all, the customers might not be seeking out any goniochromatic effect when buying these products. The red component in the blue and green filters could even be seen as a negative side effect, as a lack of “color purity”. Pushing the longwave edge of these filters towards longer wavelengths could be coupled with a significant increase in costs. Consequently, it would be unwise to specify that a large hue shift is present, as this would imply a cheap manufacturing method. Figure 13 on page 14 shows an example where the goniochromatic effect has even been disguised with barn doors. Of course, the principal demand for dichroic color filters can be assumed to be related to what it is most known for: they are much more durable than their absorptive counterparts, which fade over time due to the absorption of heat (Coatings by Sandberg 2018). This might imply that suppliers are unaware that this effect could be desired by certain customers. There is, in any case, a lack of unambiguous vocabulary to describe the effect.

Iridescence or goniochromatism

Iridescence is defined as the “interference of light either at the surface or in the interior of a material that produces a series of colors as the angle of incidence changes” (Britannica Online Encyclopedia 2018b). It seems that this definition could also fit the gradient phenomenon discussed in the thesis. However, as previously mentioned, there seems to be a general agreement on that iridescence is the unstructured and random display of colors on a surface. Compared to this, the gradients in the “Dichroic Projections” series are methodical and systematic, which calls for a distinct term.
Radiant dichroic color

When the dichroic film was introduced by 3M, they chose the word “radiant” to describe the goniochromatic effect. Using this word has the disadvantage that the term is already defined within physics. Radiant energy is defined in Britannica Online Encyclopedia (2018c) as “energy that is transferred by electromagnetic radiation”. A radiant color film could imply that the coating is luminous in itself. Yet, the colors observed are obviously dependent on a light source. One can speculate if this was the reason that 3M renamed the products. Still, while this word is not used anymore by 3M, it is used by other suppliers to describe the same property\textsuperscript{12} (PyraSied 2018).

Conclusion

Initially, it was assumed that goniochromatism was inherent in dichroism. With the Lycurgus cup as an example of a dichroic material which does not display any goniochromatism, this was disproven. Thin-film interference dichroic filters on the other hand, display more or less goniochromatism depending on the spectral design of the filter. In the following paragraphs, a number of optical principles are formulated which influence the colors in dichroic goniochromatic gradients. Again, the hope is that such principles might be of assistance to those looking to explore goniochromatic gradients.

Goniochromatic principles for dichroic color filters

With increasing angle of incidence through the filter, the hue shifts counter-clockwise in the chromaticity diagram. This is due to the fact that thin-film interference filters move to shorter wavelengths when increasing the angle of incidence. The colors in the purple line will be included in the gradient if red or infrared wavelengths are not rejected.

If infrared wavelengths close to the visible range are not rejected, green and blue dichroic filters will move towards purple and even yellow with an increasing angle. Green filters can regardless be expected to (at least) move towards a blue color.

Purple dichroic filters can be expected to have large hue shifts toward yellow and green.

Red, orange and yellow dichroic color filters — color filters with a longwave pass filter only — cannot be expected to show a large hue shift. The move towards shorter wavelengths in a longwave pass-only filter results in an inclusion of larger parts of the spectrum which in turn should create an increasingly whitish color. It should be theoretically possible to design a red, orange and yellow filter which would show a gradient towards green and blue. This would require a shortwave pass filter blocking the red wavelength range at normal incidence.

\textsuperscript{12} E-mail correspondence with PyraSied confirmed that the effect is the same, but that they use a different manufacturer than 3M. Yet, as mentioned, they still use the same word.
It has been observed, however, that some red dichroic filters which are unlikely to have a shortwave pass filter still show a significant hue shift toward green (while they theoretically should become more white). The reason behind this might be that the rejected wavelengths are not absorbed but reflected by dichroic filters. Accordingly, the light may bounce in unexpected ways in the system. Due to this, part of the goniochromatic gradient is depending on the reflector system in the luminaire, and cannot be predicted if the whole optical system is not known.

Goniochromatic gradients

Using goniochromatism as a definition of the phenomenon in which the color of a material changes noticeably as the viewing geometry changes (Hemmendinger and Johnston 1970) has proven to be useful to describe the usage of dichroic goniochromatic gradients as represented by Ann Veronica Janssens. Following this assertion it can be concluded that the “Dichroic Projections” series in fact studies goniochromatic gradients in dichroic color filters and not dichroism in itself.
Epilogue

“Who or what makes these endless colors, then? For all to see, dichroic filters have been placed in front of these lamps. That is all.” (Bal 2013, 260)

In the quote above, which is from “Endless Andness: The Politics of Abstraction According to Ann Veronica Janssens”, cultural theorist Mieke Bal downplays the physical process creating the endless colors in “Dichroic Projections” as mundane. What is profound, according to Bal, is rather the “creation of conditions for the possibility for people to produce worlds of meaning”.

“That is all”, she writes. But, is that really all? While certain parts of the dichroic goniochromatic gradient have indeed proved to be readily explicable, and can as such be deemed mundane, the outer edge of the goniochromatic gradient remains unpredictable. To create new goniochromatic gradients in new optical systems—and to celebrate them—is therefore something that has a potential to create meaning not only in the worlds of meaning inside of people, but also outside of them.

Figure 30. Ann Veronica Janssens, Green aura, 2016 (Nasher Sculpture Center 2016)
References


Appendix: Notable dichroic projects

- **Spectral Light Dome** by James Carpenter, Portland Centre for the Performing Arts, USA. (Johnston 1997)
- **Structural Glass Prisms** by James Carpenter, Indianapolis, USA (Marpillero 2006)
- **Refractive Tensegrity Rings** by James Carpenter, Munich Airport (Antonelli 1995, 95)
- **Dichroic Light Field** by James Carpenter, New York, USA (Carpenter | Lowings 2016)
- **Harpa Windows** by Olafur Eliasson. (Hagel 2011; SCHOTT AG 2018)
- **LightPlay** by Harries Heder, Southstar Lofts, Philadelphia (Heder 2016; Goldray Glass, n.d.)
- **Folded Light** by Carpenter|Lowings, London, UK (Carpenter | Lowings 2016, 2018; Lighting Design Awards 2017; Singhal 2017; The Society of Light and Lighting 2017)
- **Museum at Prairiefire** by Verner Johnson, Overland Park, Kansas (Verner Johnson 2014)
- **Ohio State University South Campus Chiller Plant** by Ross Barney Architects, Columbus, Ohio (Ross Barney Architects 2013; Feinknopf, n.d.)
- **Little Sun Swarms** by Olafur Eliasson, Copenhagen, Denmark (Little Sun 2017; Eliasson 2018a)
- **Spectra Blinds** by Kukka Studio, Tel Aviv, Israel (Kukka Studio 2017).
- **Prayer Mills** by Stephen Dean (Dean 2007)
- **One State Street** by SoftLAB, New York, USA (SOFTlab 2017)
- **Dichroic Projections** by Ann Veronica Janssens, 2004–2017 (White Cube 2018; Nasher Sculpture Center 2016; Bal 2013; Rubin et al. 2010)
- **Color Square Sphere** by Olafur Eliasson, 2007 (Eliasson 2007)
- **Wavelength Lamp** by Olafur Eliasson (Eliasson 2018b)
- **Rising** luminaires by Millelumen (millelumen 2018)
- **3M Dichroic Film Install** by Architecture AF at GIPHY (Architecture AF 2017)
- **Canvas Worldwide** by Architecture Plus Information, Playa Vista, CA (Architecture Plus Information 2017; Patos 2017)
Project references


Architecture AF. 2017. “3M Dichroic Film Install at GIPHY.” *Architecture AF*.


Marpillero, Sandro. 2006. *James Carpenter: Environmental Refractions*.


Verner Johnson. 2014. “Museum at Prairiefire.”
