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Research Article

Butterfly Wing-Inspired Structural Color Design for UV-Blocking Architectural Windows

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Abstract

Conventional UV-blocking windows often rely on chemical coatings that degrade over time and distort transmitted light. Inspired by the structural-color mechanism in African butterfly wings, this paper proposes a bio-inspired window design that uses alternating nanoscale glass and air layers to reflect UV light selectively through thin-film interference rather than chemical absorption. Applying Bragg's law and the quarter-wave condition, we calculate the layer thicknesses required to reflect a target UV wavelength of 320 nm while allowing the full visible spectrum to pass through undistorted. We further show that, as the sun's angle changes throughout the day, the reflected wavelength remains within the UV range, preserving the window's transparency and color neutrality at all times. Because the UV-blocking effect arises from physical structure rather than chemistry, the proposed design offers a durable, maintenance-free alternative to existing coatings, with potential applications in architecture, automotive glass, and museum displays.
Keywords: Structural Color, Bio-Inspired Design, UV-Blocking Window, Thin-Film Interference, Bragg's Law, Butterfly Wing.

Introduction

Excessive ultraviolet (UV) light entering a building can harm human skin (Gordon and Brieva, 2012; Furukawa *et al.,* 2021) and damage indoor furnishings (Yousif and Haddad, 2013; Andrady *et al.,* 2023). Modern buildings often use large glass windows to admit natural light and provide open views, but doing so increases indoor UV exposure and raises cooling loads on air-conditioning systems. Present-day UV-blocking windows typically rely on chemical coatings to address this problem (Nagashima and Kuramashi, 1994); however, these chemical layers fade over time and can alter the color of the transmitted light, reducing indoor visual comfort (Haghshenas *et al.,* 2017). In search of a more durable solution, this study draws inspiration from the wing structures of African butterflies such as *Charaxes bohemani* (Figure 1). Unlike everyday objects that obtain their color from chemical dyes, the wing colors of these butterflies do not arise from pigments. Instead, their vivid colors result from "structural color," in which the microscopic physical geometry of the wing reflects light rather than a pigment absorbing it (Vukusic and Sambles, 2003; Kinoshita *et al.,* 2008). The thin, alternating layers of transparent chitin and air in the wing act as a natural optical filter, a structure shaped to reflect specific wavelengths through physical geometry alone.

This research aims to apply such a microscopic structure to architectural glass, the most common medium through which light enters buildings. Standard glass provides clear views but readily transmits UV radiation. We hypothesize that adding bio-inspired microstructures to glass surfaces can filter out harmful UV light selectively while keeping the glass fully transparent.

The principal goal of this paper is to translate these natural design rules into mathematical formulas in order to develop a new bio-inspired UV-blocking window. The design functions as a natural filter, transmitting visible light while reflecting harmful UV rays. By preventing UV from entering a room, the window also reduces cooling energy demand. In combining biology, physics, and design, this study contributes toward a more sustainable window for future architecture.

Figure 1. The color of *Charaxes bohemani* derives from its wing structure.

Related Works

Window Designs for UV Protection

In modern architecture, UV protection relies primarily on two commercial technologies: laminated glass and chemical coatings or films. Laminated glass, which inserts a polyvinyl butyral (PVB) resin layer between two glass sheets, absorbs more than 99% of incident UV radiation (Meinen *et al.,* 2022) but is heavy and considerably more expensive to manufacture (Galić *et al.,* 2022). Alternatively, low-emissivity glass and window films use thin layers of silver, metal oxides, or chemical absorbers to block UV (Yunos *et al.,* 2023). These chemical approaches, however, have fundamental limitations. Prolonged exposure to sunlight causes chemical degradation, shortening their protective lifespan (Queant *et al.,* 2018). They also tend to lower visible-light transmittance or tint the glass, usually blue or yellow, compromising visual transparency (Zhang *et al.,* 2026). A structural approach that blocks UV rays permanently through physical geometry rather than chemistry, while keeping the window clear, therefore addresses a clear need.

Thin-Film Interference and Bragg's Law

To understand how structural color works, we turn to the physics of thin-film interference (Kinoshita and Yoshioka, 2005) and Bragg's law (Parker and Townley, 2007). Unlike chemical pigments, which produce color by absorbing light energy, structural color relies entirely on nanoscale physical geometry (Kinoshita *et al.,* 2002). The bright blue color of a butterfly wing, for instance, arises from thin, alternating layers of chitin and air spaced roughly 200–300 nm apart (Vukusic and Sambles, 2003). When light strikes these layers, the reflected waves interfere: they may cancel one another or strongly reinforce a specific color. This reinforcement is described by Bragg's law, $n\lambda = 2d \sin \theta$, which specifies the exact physical conditions required to reflect a given wavelength (Vukusic and Sambles, 2003).

We apply this same physics to the design of our window. By mimicking the butterfly wing, we construct a structure with alternating layers of glass and air. To reflect a target UV wavelength λ, we calculate the required thickness of each layer using the quarter-wave condition (Born and Wolf, 2013). The glass-layer thickness is set to $t_1 = \lambda/(4n_1)$, where $n_1 = 1.5$ is the refractive index of glass, and the air-layer thickness to $t_2 = \lambda/(4n_2)$, where the refractive index of air is taken as $n_2 = 1$. Stacking layers with these precise thicknesses produces a strong interference effect, so that the window acts as a mirror for harmful UV rays while transmitting visible light.

Bio-Inspired Designs

Bio-inspired design applies proven solutions from nature to human problems (Vincent *et al.,* 2006; Kennedy *et al.,* 2015). Anti-glare screens, for example, replicate the textured structure of a moth's eye to absorb light (Clapham and Hutley, 1973), and self-cleaning windows imitate the microscopic bumps on lotus leaves so that water rolls off and carries away dirt (Nishimoto and Bhushan, 2013). More closely related to our approach, several displays and fabrics, such as Qualcomm's Mirasol and Teijin's Morphotex, reproduce the Morpho butterfly to display vivid blue color without chemical dyes (Das *et al.,* 2017; Prabhu and Prasad, 2019). Such prior work has generally focused on controlling visible light to create colors for the human eye. In contrast, the present study targets invisible, harmful UV light in order to make indoor spaces safer, an emphasis that offers a fresh and practical direction for bio-inspired design.

System Design

System Overview: Bio-Inspired UV-Blocking Window

The core concept of the proposed system is a smart window film that mimics the microscopic structure of butterfly wings. The design uses no chemical pigments or dyes; instead, it relies entirely on a precise physical structure to control light wavelengths. Figure 2 shows the overall architecture in both 2D and 3D views. As illustrated, the system consists of a multilayer structure in which glass and air layers are stacked alternately, like a sandwich. Its core function is to transmit visible light fully, so that the window remains clear and transparent, while selectively reflecting harmful UV light to prevent damage to human skin and indoor furnishings.

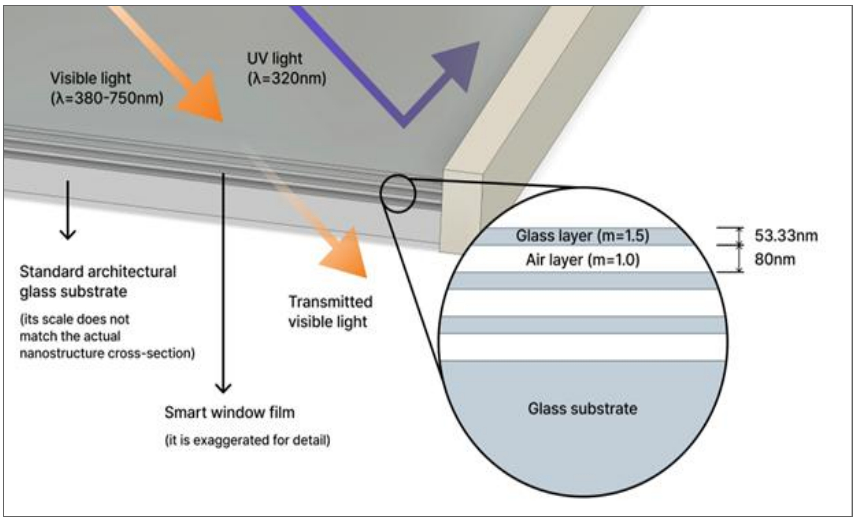

Figure 2. Schematic of the glass–air structure that transmits visible light while reflecting UV light.

Design Objectives for UV Protection

To design an effective UV-blocking window, we established specific performance targets and constraints. The primary goal is complete reflection of the most harmful UV wavelength, set here at 320 nm. This target corresponds to solar noon, when sunlight is strongest and strikes the window surface at normal incidence (90°). The system must also satisfy a strict constraint: it must block UV light completely while transmitting all visible light (380–750 nm) without reflection. This constraint ensures that the window appears identical to standard transparent glass and maintains a comfortable visual environment without altering the color of the indoor light.

Component Details: Nanoscale Layer Design

The proposed window film consists of repeating nanoscale layers designed to produce precise optical interference. The first layer is a high-refractive-index glass layer. Taking the refractive index of glass as $n_1 = 1.5$, the quarter-wave condition $t_1 = \lambda/(4n_1)$ gives the required thickness. For the target wavelength of 320 nm, this yields a glass-layer thickness of approximately 53.33 nm. The second layer is an air layer, which serves as the low-refractive-index medium. Taking the refractive index of air as $n_2 = 1.0$, the condition $t_2 = \lambda/(4n_2)$ gives an air-layer thickness of exactly 80 nm. Together, one 53.33 nm glass layer and one 80 nm air layer form a single period, which repeats to create a multilayer stack that reflects the target UV light.

Optimization for Varying Sun Angles

In real-world applications, the angle of the sun changes continuously throughout the day. According to Bragg's law, as the angle of incidence decreases from 90° to 45° or 30°, the reflected wavelength shifts toward shorter values. We used a color chart (Figure 3) to examine how the reflected color changes with the sun's angle over the course of a day. The chart shows that if the target wavelength is set near the visible range (for example, 400 nm), the window will display unwanted colors, such as blue or green, as the sun descends and the angle changes.

To keep the window fully clear, we therefore set the target wavelength much lower, at 320 nm for normal incidence (90°) at noon. Under this choice, when the sun's angle drops to 45° later in the day, the reflected light shifts to approximately 226 nm. Because both 320 nm and 226 nm lie in the invisible UV range, they fall entirely outside the visible band in Figure 3. This mapping confirms that the design blocks UV light throughout the day without any color change, keeping the indoor view clear.

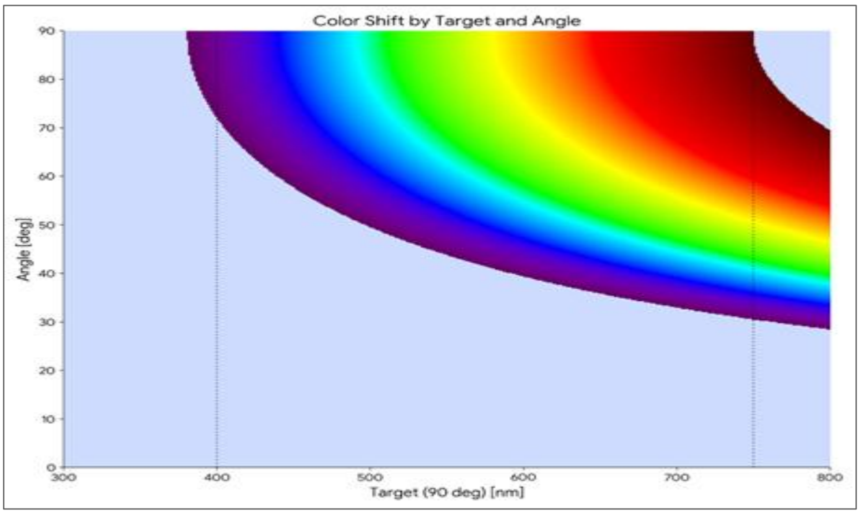

Figure 3. Reflected wavelength as a function of target wavelength and solar incidence angle, showing the UV-only region used to keep the window color-neutral.

Design Implications

Sustainability and Human Health

Building on the physical structure described above, the proposed window does more than block UV rays; it offers durable environmental benefits and supports human health. As noted in the introduction, conventional window films rely on chemical coatings that fade and degrade under sunlight. Because the proposed window uses a permanent physical structure rather than chemicals, it does not lose its UV-blocking capacity and does not require periodic replacement of the film. This durability lowers maintenance costs and reduces plastic waste, making the design an environmentally favorable solution. In addition, standard UV-blocking windows often introduce a color tint that alters the natural sunlight entering a room. Such altered light can cause eye fatigue and disrupt daily biological rhythms. Because the proposed structural window transmits all visible light without color change, it preserves natural indoor lighting and supports a healthy, comfortable visual environment.

Expanding Applications Across Industries

Because the proposed window is fully transparent and color-neutral, it can address practical problems in industries beyond conventional architecture. To block UV light, many vehicles use dark window tints; however, dark windows reduce the driver's visibility at night, which is hazardous. Applying the proposed film to windshields would give drivers a clear view for safe night driving while protecting passengers' skin and the vehicle interior from sun damage during the day. Similarly, clothing and furniture stores often apply chemical UV-blocking films to storefront windows to protect their products, but these films typically add a blue or yellow tint that makes it difficult for passers-by to see the true colors of the items. A fully clear window resolves this issue, preventing sun damage while displaying accurate colors. Finally, historical artifacts and paintings are easily damaged by even small amounts of UV light, so museums often keep rooms dark or use tinted display cases, which prevents visitors from fully appreciating the colors of the works. Using the proposed glass for display cases or museum skylights would allow bright or natural light into the space, letting visitors enjoy the artwork in its true colors without risk of UV damage.

Discussion

Novelty of the Proposed Structural Approach

The proposed approach differs from prior work in ways that underscore its value. Most existing windows use chemical coatings to block UV light, but these coatings degrade over time and often alter the color of the glass (Queant *et al.,* 2018; Zhang *et al.,* 2026). Earlier bio-inspired designs, meanwhile, have focused largely on visible light to produce vivid colors for human viewing (Zhao *et al.,* 2012). By contrast, the present design targets invisible, harmful UV light and uses a permanent physical structure of thin glass and air layers rather than chemicals. As a result, the window does not fade and remains clear. In moving away from chemical dyes and toward the control of invisible light, this study offers a durable strategy for protecting people and saving energy.

Effects of Parameter Variation on Window Properties

The present analysis calculates layer thicknesses for standard glass (n = 1.5) and air (n = 1.0). Using other materials with different refractive indices, such as clear plastics or thin coatings, would change the required thickness of each layer. This flexibility is useful, as it allows manufacturers to select materials that are cheaper or easier to process; lighter materials, for example, could simplify installation on tall buildings. The number of stacked layers is also an important factor: adding more layers strengthens UV reflection and brings the blocking rate closer to 100%. However, additional layers complicate manufacturing, lengthen production time, raise cost, and increase film thickness. For commercial use, further testing is therefore needed to identify the best balance between low production cost and high blocking performance.

Aesthetic Applications Through Target-Wavelength Adjustment

The primary design targets a low wavelength, 320 nm at normal incidence, to keep the window clear at all times. Deliberately raising this target closer to the visible range, to 400 nm or higher, would change the window's purpose entirely. As Figure 3 shows, the reflected wavelength shifts toward shorter values as the sun's angle decreases through the day. With a higher target wavelength at noon, the reflected light would sweep through the visible spectrum, from red and yellow to green and blue, as the sun moves across the sky. Such a window would change color dynamically over the day without electricity or chemical dyes; a building could, for example, glow soft blue in the morning and warm orange in the late afternoon. This aesthetic application could appeal to modern buildings, cafes, or landmark structures seeking a distinctive visual experience.

Limitations

Although the proposed window shows strong potential, several practical challenges remain. First, fabricating precise nanoscale layers over large architectural windows is currently difficult and expensive; while straightforward in small laboratory samples, achieving uniform layers across large panes is costly. Second, maintaining the 80 nm air gap between glass layers is difficult, as the glass layers may press together and close the gap; tiny support pillars could hold the gap open but might slightly alter light transmission. Third, viewing the window at very oblique angles may produce unwanted color shifts. Future work should focus on strengthening the air gaps and developing lower-cost methods for producing these windows at large scale.

Conclusion

This paper proposed a smart window inspired by the wings of African butterflies. Rather than chemical coatings that fade under sunlight, the design uses thin physical layers of glass and air to block harmful UV light. Applying Bragg's law, we calculated the layer thicknesses required to reflect 320 nm UV radiation while transmitting all visible light, keeping the window clear throughout the day without unwanted color change. The bio-inspired design offers a durable, environmentally favorable solution that reduces cooling energy demand and supports human health. Because it is fully transparent, it can be applied in vehicles, retail stores, and museums to protect people and valuable objects from sun damage. Although manufacturing challenges must still be solved to produce these windows at large sizes, this structural approach represents a meaningful step forward, illustrating how strategies drawn from nature can help create better and more sustainable windows.

Declarations

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