Exploring the Spectrum: Fano Resonant Optical Coatings for High Purity and Full Gamut Structural Colors

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*Abstract*— This review paper provides an exhaustive exploration of Fano Resonant Optical Coatings (FROCs) in the context of structural coloring. Structural coloring, utilizes optical interference and nanophotonic resonances. This offers photostability, resistance to chemical degradation and environmental benefits. FROCs employs a unique photonic Fano Resonance and thus represents a significant advancement in this domain. They offer unparalleled color purity (up to 99%), extensive color gamut coverage (61% of the CIE color space) and controlled iridescence. This all while ensuring scalability and eco-friendliness. This paper delves into the fundamentals of structural coloring, the specifics of FROCs, their advancements, and a comparative analysis with traditional methods.

# INTRODUCTION

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n the expansive domain of color production, structural coloring emerges as a new crucial technology. It is very different from conventional pigment-based methods. This approach, rooted in optical interference and nanophotonic resonances, leverages the physical structure of surfaces to generate colors. Its importance lies not only in its photostability and resistance to chemical degradation but also in its environmental friendliness, creating possibly a new era in sustainable color production. Structural colors have found their way into a lot of applications. This can be ranging from advanced display technologies, decorative arts, to utility based roles in data storage and anti-counterfeiting measures.

Among the various strategies for structural coloring, Fano Resonant Optical Coatings (FROCs) represent a groundbreaking development. FROCs capitalize on the photonic Fano Resonance. This is phenomenon that offers a unique set of optical properties unattainable by traditional optical coatings like metallic films or anti-reflective coatings. The ability of FROCs to provide full color access, high color purity, and controlled iridescence, while ensuring scalability in manufacturing, positions them as a good choice for wide-area structural coloring applications. The recent improvement of these coatings with an additional oxide film layer, increases both color purity and gamut coverage. This underscores their potential in revolutionizing color production technologies.

This review explores Fano Resonant Optical Coatings in the context of structural colors. First, the paper delves into the fundamentals of structural coloring, explaining the underlying principles and natural occurrences of this phenomenon. It then progresses to discuss Fano Resonant Optical Coatings (FROCs), providing an in-depth look at their unique characteristics and the physics behind their operation. The recent technological breakthroughs in FROCs for structural coloring are highlighted. A comparative analysis follows telling what the advantages and limitations are. The paper concludes with a summary of the findings, future prospects, and potential applications of FROCs.

# Fundamentals of Structural Coloring

Structural colors is a phenomenon where color is produced not through chemical pigments but through the physical interaction of light with micro- and nanostructures. This type of coloring relies on optical interference and nanophotonic resonances. The colors we see are the result of specific wavelengths of light being reflected, transmitted or absorbed by these structured surfaces. A key point in this process is the interaction of light with structures that are often on the same scale as the wavelength of visible light.

In nature, structural colors are very common. for example the iridescent shades seen on a peacock's feathers or a butterfly's wings are due to microscopic structures that scatter light in specific patterns. [1] The principles of structural coloring have been used to create a lot of different applications. These include color filters in display technologies, decorative effects, and even functional uses in data storage and anti-counterfeiting measures. Structural colors can also be dynamic and change with the angle of observation or light source. This is the property known as iridescence.

The main difference between structural and pigment-based colors lies in their methods of color generation. Pigment-based colors come from the selective absorption and reflection of certain wavelengths of light by chemical substances. The color we see is the result of specific wavelengths being reflected back to our eyes, while others are absorbed by the pigments. This method of color production is common in paints, inks, and dyes.

In contrast, structural colors are produced by physical structures that manipulate light at the nanoscale. Unlike pigment-based colors, structural colors are not prone to fading over time as they do not rely on chemical stability. They are photostable and there for not affected to chemical degradation making them environmentally friendly. Structural colors can also produce a wider range of shades, including vibrant and iridescent colors that are difficult to achieve with pigments. [2] [3]

Another difference lies in the environmental impact. Many Pigment-based colors often involve potentially harmful chemicals and can lead to environmental pollution during production and disposal. Structural colors, on the other hand, offer a more sustainable alternative, minimizing the use of toxic substances. [4]

# Fano Resonant Optical Coatings (FROCs)

Fano Resonance in optical coatings is a principle in the functioning of Fano Resonant Optical Coatings (FROCs). it’s a physical phenomenon where asymmetric line shapes in the spectral response are produced due to the interference between a discrete resonance and a continuum of states. In the context of FROCs this is achieved through the coupling of two types of nanocavities: a broadband nanocavity representing the continuum and a narrowband Fabry-Perot (FP) nanocavity representing a discrete state. The interaction between the two creates the unique and asymmetric Fano resonance line-shape which is key to the properties of these coatings.

The structural design of FROCs is centered around the strategic coupling of these two nanocavities. For reflective FROCs, a reflective and blurry material is used as the substrate, leading to a highly reflective resonant peak at the narrowband nanocavity’s resonance. This design enables the coatings to selectively reflect specific wavelengths of light, a property needed for their structural coloring capabilities.

Regarding materials FROCs typically involve layers of metallic films and dielectrics. In the study, the FROCs comprised alternating layers of silver (Ag), titanium dioxide (TiO2), and germanium (Ge). The Ge layer is important for converting the FP nanocavities into FROCs, enhancing their color properties. Also, the inclusion of a silicon dioxide (SiO2) capping layer has been shown to further increase the color purity and gamut coverage of FROCs. This addresses the challenge of achieving high-purity colors across the spectrum.

The coatings are not only capable of providing full color access, high color purity, and high brightness but also allow controlled iridescence making them suitable for a wide range of applications. These include things like display technologies, colorful solar panels, cryptography, décor/art, data storage, and anti-counterfeiting measures. [5] [6]

# Advancements in FROCs for Structural Coloring

Fano Resonant Optical Coatings (FROCs) mark a crucial advancement in structural coloring, namely in terms of color purity and gamut coverage. The application of FROCs has led to an impressive improvement in color purity, reaching up to 99%. This level of purity is higher than most other thin-film structural color platforms. The reason behind this high purity is the selective reflection mechanism of FROCs, which contrasts with the selective absorption mechanism seen in Fabry-Perot (FP) cavities. Unlike FP cavities that produce a restricted palette of Cyan-Magenta-Yellow (CMY) colors, FROCs can produce a wide range of colors, including RGB shades which are crucial for high purity color reflection.

Additionally, FROCs have significantly expanded the color gamut coverage. With the incorporation of a silicon dioxide (SiO2) capping layer FROCs have achieved a color gamut coverage of 61% of the CIE color space. This coverage is notably higher than the color space accessed by FP cavities and other existing thin-film structural coloring platforms. The ability to control the wavelength of selective reflection simply by changing the dielectric thickness has been important in this increase of gamut coverage.

Iridescence is a challenge when uniform color appearance is desired. FROCs have introduced a way to control this iridescence. By adjusting the refractive index of the dielectric cavity material FROCs can modulate the angle dependence of the observed colors. As an example, with high refractive index materials FROCs exhibit low iridescence. Meaning it will maintain consistent color reflectance over a wide angular range. With lower refractive index materials the iridescence increases, offering tunable control over this property. Such control makes FROCs suitable for applications requiring either angle-independent or angle-dependent coloring.

In terms of brightness FROCs have also shown promising results. The peak reflectance from FROCs is calculated to be greater than 0,9. This indicates a high brightness level. This is an important metric in structural colors as it represents the intensity of the reflected light compared to the incident light at the peak resonance wavelength. Even in experimental conditions FROCs have exhibited measured reflectance ranging from 0,63 to 0,85, demonstrating their effectiveness in achieving bright colors. [5]

# Comparative Analysis

Fano Resonant Optical Coatings (FROCs) differ significantly from other structural coloring methods, such as multilayer films, thin film nanocavities, plasmonic nanostructures, dielectric nanostructures, and photonic crystals. These traditional methods generate colors through mechanisms like selective absorption (as seen in FP nanocavities) or reflection. However, FROCs utilize the Fano Resonance effect providing a unique approach to structural coloring. [5]

1. Color Purity and Gamut: FROCs offer a color purity of up to 99% and cover 61% of the CIE color space. This is a considerable improvement over many existing schemes. While traditional methods like FP nanocavities might show limited color palettes and purity, FROCs provide a wider range of vivid colors with high purity.
2. Brightness: The reflective nature of FROCs, surely when designed with a reflective and blurry substrate, leads to a high brightness level. This is a marked advantage over some structural coloring methods that might exhibit lower brightness due to absorption or diffusion of light.
3. Iridescence Control: FROCs allow for controlled iridescence, a feature which is not easily achievable with other methods. The ability to control the angle dependence of observed colors adds to their versatility in applications like anti-counterfeiting.

**Advantages of FROCs:**

1. High Color Purity and Wide Gamut: FROCs ability to achieve high color purity and a wide color gamut is unparalleled. This makes them suitable for applications requiring accurate color representation, such as displays and decor.
2. Controlled Iridescence: The ability to control the iridescence in FROCs adds to their functionality, making them suitable for dynamic applications like anti-counterfeiting measures.
3. Scalable Manufacturing: FROCs can be manufactured on a large scale, making them feasible for widespread commercial and industrial applications.
4. Environmental Friendliness: Being photostable and immune to chemical degradation, FROCs offer an environmentally friendly option in the realm of color technology.

**Limitations of FROCs:**

1. Complex Fabrication Process: The fabrication of FROCs might require precise control over the materials deposition and structure, which could be more complex than some traditional methods.
2. Cost: The initial cost for setting up the manufacturing process for FROCs could be higher than that for simpler structural coloring methods.
3. Color Range Limitation: Despite their wide color gamut, achieving certain colors, especially high purity greens and reds, may still be challenging and require additional materials like a SiO2 capping layer.

[7]

# Conclusion

In conclusion the review paper looked into the innovative world of Fano Resonant Optical Coatings (FROCs) and their role in structural coloring. FROCs are very different from other types of coloration methods. They offer a new and better color purity, extensive gamut coverage, and higher brightness. They also change color technology, merging environmental sustainability with advanced optical capabilities. Although there are still certain challenges in fabrication and cost, FROCs potential in many kinds of applications from display technologies to anti-counterfeiting measures cannot be denied. This paper shows the promise of FROCs in shaping future color production technologies, paving the way for more sustainable, vibrant, and versatile coloring solutions in the near future.

# VII. References

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