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Theoretical Research and Scheme Design of Static Polychrome Display Based on Monodisperse Microspheres

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Abstract. Structural colors are produced by precisely designed nanostructures rather than pigments, featuring outstanding energy efficiency, extraordinary vitality and environmental sustainability. This investigation employed monodisperse microspheres for the fabrication of static multi-color displays, leveraging their consistent dimensions and self-assembly capabilities to generate periodic photonic lattices. These structures make controllable Bragg diffraction of dynamically adjustable structural colors possible. Key innovations include: a color control mechanism achieved by precisely modulating the particle diameter (controlling lattice parameters) and comparing the refractive index between the microspheres and the embedding matrix. The pixel visualization strategy, predicated on discrete color regions, is realized through the selective deposition of photonic crystal arrays. This study establishes a theoretical framework via optical diffraction modeling and validates practical methodologies through scalable convective assembly techniques. These advancements provide a powerful platform for the next generation of flexible wearable displays, offering high resolution, mechanical durability and customizable color performance for applications in consumer electronics and biomedical interfaces.

Keywords: Monodisperse microsphere, Static polychrome displays, Self-assembly, molecular engineering

1. Introduction

Monodisperse microsphere-based structural color display technology utilizes photonic crystal periodicity to generate color, a mechanism distinct from traditional pigment-based color generation via molecular absorption [1]. This technology utilizes the interaction between light and nanostructures such as interference and diffraction to achieve ultra-high color purity, non-fading, low energy consumption and environmental friendliness, making it a sustainable alternative to traditional displays like liquid crystals (LCDS). Precise control over the reflected light's wavelength is achieved through the manipulation of parameters like lattice constant and fill factor, enabling broad color gamut coverage and the generation of highly saturated colors. It is suitable for static display, ultra-high resolution imaging and reflective screens. Its advantages include dynamic colour effects that change with the viewing Angle, non-volatility (images do not require a continuous power supply), and an ultra-thin design that can be adapted to foldable screens or wearable devices [1].

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The self-assembly of microspheres to form ordered structures (such as face-centered cubic FCC) requires external force intervention to overcome entropy-induced disorder. The compatibility, mechanical strength and environmental stability of flexible substrates still need to be improved to meet the requirements of portable and outdoor scenarios. Vertical deposition methods and template-assisted technologies have recently achieved RGB monolayer photonic crystal films with micron-level resolution, which can be used for static labels and anti-counterfeiting designs [2, 3]. However, problems such as low dynamic refresh rate, high difficulty in mass production without defects, and difficulty integrating electronic drive systems have not yet been solved.

This research endeavors to engineer a static multi-color display technology spanning the visible spectrum. This will be achieved through the manipulation of microsphere dimensions and refractive index, integrated with theoretical modeling and structural simulation. The objective is to establish a structural color control mechanism based on particle design and self-assembly, providing a theoretical and technical basis for low-power flexible displays and promoting the commercial application of this environmentally friendly and power-free technology.

2. Theoretical background

2.1. Optical properties of monodisperse microspheres

Due to their high dimensional consistency, monodisperse microspheres can form highly ordered periodic arrangement structures during the self-assembly process, thereby demonstrating unique optical properties, the most typical of which is the structural color effect. In a specific lattice configuration (e.g., face-centered cubic, hexagonal close-packed), microspheres induce Bragg diffraction of incident light, reflecting specific wavelengths of visible light and thus exhibiting distinct colors [4]. This color is not caused by the absorption of pigments but by the interference and diffraction of light. Therefore, it has extremely high color purity, good stability and does not fade. By adjusting the particle size of the microspheres, the material's refractive index, and its arrangement, the reflection wavelength can be precisely controlled, achieving full-color regulation from purple to red [4]. In summary, structural colors have advantages such as a wide color gamut, low absorption, and high reflectivity, which can significantly enhance display systems' energy efficiency and visibility.

Meanwhile, photonic crystals composed of monodisperse microspheres also exhibit other optical behaviors. Given the strong dependence of Bragg diffraction on the incident angle, these structurally colored materials typically display angle-dependent iridescence. This is an advantage in anti-counterfeiting and decorative applications, but in display applications, its angular sensitivity needs to be reduced through material design [5]. Certain microsphere architectures can also demonstrate Mie scattering resonance, thereby amplifying reflected intensity at discrete wavelengths. In addition, the photon bandgap structure formed in the three-dimensional ordered arrangement can suppress the propagation of light in certain bands, achieve light control and filtering functions, and is suitable for sensors and optical devices, etc. Overall, monodisperse microspheres possess highly programmable optical response capabilities and, due to their low energy consumption, environmental friendliness, and material processability, provide a broad space for the research and development of new structural color display and photonic functional materials.

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2.2. Photonic crystals and structural color formation mechanisms

Bragg diffraction is a fundamental physical process responsible for the generation of structural colors in monodisperse microspheres, particularly within photonic crystals assembled via the self-assembly of monodisperse microspheres [6].

Monodisperse microspheres form three-dimensional lattice structures with long-range order through highly uniform particle size and regular arrangement, such as face-centered cubic (FCC) or hexagonal close packing (HCP). The diameter of the microspheres determines the lattice face spacing, thereby precisely controlling the main wavelength of reflection and achieving a specific structural color. This color generation is entirely based on the physical interference of light. It does not rely on chemical dyes, thus having the advantages of extremely high stability and being less prone to fading. The display's design, which is based on this theory, exhibits stringent viewing angle constraints. The pattern is only fully discernible at a specific angle [5]. To address this issue, by introducing disordered or quasi-ordered structures, the long-range order of the material can be broken, thereby avoiding the formation of a fixed relationship between the specific lattice direction and the incident Angle. Achieving this objective involves employing microspheres characterized by a broad size distribution (approximating monodispersity but not perfectly uniform). Furthermore, controlling their self-assembly during desiccation facilitates the formation of hierarchical structures, including short-range ordered and long-range disordered morphologies, such as spherical clusters [5, 7].

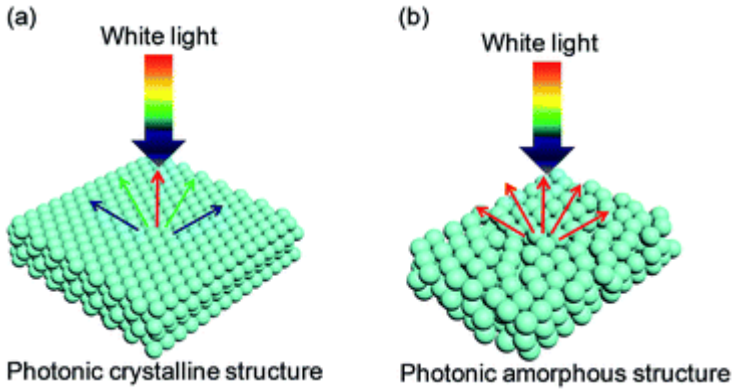


Figure 1. Reflection of long-range order and short-range order [7]

By adjusting the particle size of the microspheres, precise control of the wavelength of the reflected light can be achieved, thereby covering the entire chromatographic range from blue-violet to red. Through the ordered or regional self-assembly of microspheres with varying particle sizes on a single substrate, it is possible to achieve multi-color spatial regulation, resulting in the formation of complex colored patterns. In addition, the high uniformity of monodisperse microspheres ensures the regularity of the structure and the narrow linewidth of the reflection peaks, significantly improving both the color purity and brightness. Integrating sophisticated self-assembly techniques with patterning methodologies, monodisperse microsphere-based photonic crystal displays exhibit enhanced characteristics, including reduced energy demands, robust color fidelity, and environmental compatibility, thus signifying a pivotal advancement within the domain of structural color displays [2, 3].

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3. Materials and methods

3.1. Material selection of monodisperse microsphere

Polystyrene (PS), as a monodisperse microsphere material, has multiple advantages in the design of polychrome displays. The particle size is both controllable and uniform, which is advantageous for the fabrication of ordered photonic structures, thus enabling high-fidelity structural color display with high purity and saturation [8]. Meanwhile, PS is easy to synthesize spherical particles with regular morphology and smooth surface, and it is convenient to form ordered arrangement through self-assembly. Its optical performance can be flexibly controlled by adjusting the particle size to achieve precise presentation of various colors. In addition, the synthesis process of polystyrene is mature, and the cost is relatively low. The material exhibits excellent chemical stability and material compatibility, rendering it amenable to large-scale synthesis and integrated applications. These characteristics establish its suitability as a prime candidate for structural color display fabrication [9].

3.2. Preparation of monodisperse microspheres

Microspheres will be synthesized by emulsion polymerization. This process is widely used in the preparation of monodisperse polystyrene microspheres due to its simple operation, strong controllability, and suitability for large-scale preparation [10]. The basic process of emulsion polymerization includes the following steps: Firstly, styrene monomer is dispersed in deionized water containing an appropriate amount of surfactant (such as sodium dodecyl sulfate, SDS), and a stable water-in-oil emulsion is formed through high-speed stirring [10]. Following this, the system undergoes heating to a specified temperature range (commonly 70-80℃) under an inert atmosphere (e.g., nitrogen). Water-soluble initiators, such as potassium persulfate (KPS), are then introduced to catalyze the free radical polymerization process [9]. The decomposition of the initiator generates free radicals, which trigger the polymerization of monomers within the micelles in the emulsion, forming tiny polymerization nuclei. Subsequently, the monomers continuously diffuse into the micelles and grow, eventually forming uniform polystyrene microspheres. Following polymerization, the reaction solution underwent centrifugation and washing to eliminate unreacted monomers, surfactants, and byproducts, thereby yielding a purified polystyrene microsphere dispersion. The final product will have its particle size and distribution detected by dynamic light scattering (DLS), and its surface morphology and particle size consistency will be observed by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Its monodispersity and structural integrity will be comprehensively evaluated to provide high-quality basic particles for the subsequent construction of structural color materials.

The particle size of polystyrene (PS) microspheres can be precisely controlled by regulating multiple parameters in the emulsion polymerization reaction. By modulating parameters including styrene monomer concentration, emulsifier dosage (e.g., sodium dodecyl sulfate), initiator concentration (e.g., potassium persulfate), reaction temperature, and agitation rate, the nucleation rate and particle growth kinetics can be effectively controlled [11]. For instance, increasing the concentration of emulsifiers or initiators usually leads to the formation of more and smaller particles, while reducing their concentration is conducive to the generation of microspheres with larger particle sizes. Furthermore, the incorporation of crosslinking agents or organic solvents allows for the fine-tuning of particle morphology and dimensions. Through the comprehensive regulation of these parameters, the particle size of PS microspheres can be controlled within tens to hundreds

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of nanometers or even larger, meeting the requirements for particle size consistency and tunability in multi-color structure color display and other applications [11].

3.3. Color control strategy

Polystyrene microspheres can form photonic crystal structures when arranged in order, and the structural color is derived from the Bragg diffraction of light of specific wavelengths. The particle size of the microspheres directly affects the lattice spacing, thereby determining the wavelength of the reflected light and the final color presented. When considering approximately vertical incidence ($\sin\theta \approx 1$), this relationship can be expressed by the simplified Bragg formula as:

$$\lambda \approx 2n_{eff}d \tag{1}$$

Where neff is the effective refractive index of the entire optical structure. PS microspheres are more likely to form a face-centered cubic crystal structure during self-assembly because they have lower free energy. For the most common lattice plane {111} in the face-centered cubic (FCC) structure, the relationship between the crystal plane spacing and the microsphere diameter D is $d_{111} \approx 0.47D$. Substituting this into the formula gives $\lambda \approx 0.94D \cdot neff$.

The effective refractive index (neff) is the weighted average of the refractive indices of the microsphere material (such as polystyrene, with a refractive index of approximately 1.59) and the surrounding medium (such as air or water), usually ranging from 1.4 to 1.5. Polystyrene monodisperse microspheres are stacked in a face-centered cube form to form a photonic crystal, and its effective refractive index is 1.46. Therefore, by controlling the microspheres' particle size, the reflected light's wavelength can be adjusted to achieve visible light structural colors ranging from blue to red. For example, when the particle size of the microspheres is approximately 300 nm, they can reflect blue-violet light (approximately 410nm). When the particle size increases to approximately 500 nm, it can reflect red light (approximately 686nm). An increase in the particle diameter of polystyrene microspheres results in a bathochromic shift of the corresponding reflection peak wavelength, with a resultant shift in color towards the red spectrum. The smaller the particle size, the shorter the reflection wavelength and the bluer the color. By precisely regulating the diameter and arrangement structure of the microspheres, high-purity and multi-color adjustable structural color display can be achieved [12].

3.4. Display construction method

In the process of constructing multi-color structured color displays formed by self-assembly of polystyrene monodisperse microspheres, the evaporation-induced self-assembly (EISA) method is usually adopted, combined with template-assisted technology to enhance orderliness and regional controllability. In the specific operation, polystyrene microsphere dispersions of different particle sizes are dropped or sprayed onto a flat substrate surface that has undergone hydrophilic modification. Meanwhile, micro-nano template structures (such as photolithography patterns or physical channels) are introduced in advance on the substrate to define the accumulation area and arrangement direction of the microspheres. Under controlled humidity and temperature conditions, the solvent (such as water or a mixture of ethanol and water) evaporates slowly. The capillary flow generated by the retreat of the liquid surface drives the microspheres to accumulate and accumulate under the guidance of the template boundary and surface tension, gradually forming a one or more layers of photonic crystal structure dominated by face-centered cubic (FCC) {111} crystal planes

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and arranged in a hexagonal pattern. By applying microsphere solutions of different particle sizes in other regions, spatial control of the reflected wavelength can be achieved, thereby constructing sub-pixel areas such as red, green, and blue, and forming high-resolution and multi-color structural color display patterns [13].

Achieving ordered microsphere self-assembly requires precise control over multiple parameters to counteract entropy-driven disorder. Solution concentration and particle size distribution must be optimized to allow sufficient migration and arrangement time during evaporation. Substrate hydrophilicity enhances solution spreading, improving microsphere distribution uniformity. Template assistance is crucial, as physical boundaries constrain microsphere movement and regulate capillary forces, increasing packing density, interlayer alignment, and reducing defects. Techniques like oblique evaporation, interfacial confinement, controlled drying, or low-temperature annealing can induce a transition from disorder to order at the two-dimensional interface. This enables the creation of large-area, uniform, and robust photonic crystal films, providing an excellent foundation for structural color display applications.

Following microsphere self-assembly into structural color patterns, polydimethylsiloxane (PDMS) encapsulation is commonly employed for photonic crystal layer protection and integration. A 10:1 PDMS prepolymer/curing agent mixture is applied via spin or drop coating, with a thickness of tens to hundreds of micrometers, ensuring physical protection without compromising structural color. To maintain microsphere order, slow thermal curing at 60°C or room-temperature cross-linking is performed. The resulting PDMS film offers optical transparency and flexibility, effectively shielding against dust, moisture, and external forces, while also facilitating pattern transfer to flexible substrates, thus enabling processability, packability, and integrability of structural color displays [14].

4. Conclusion

This study proposes a structural color display technology using monodisperse polystyrene microspheres, achieving adjustable colors by controlling particle size and self-assembly. Template-directed, evaporation-driven self-assembly yields ordered face-centered cubic superstructures, mitigating disorder and enabling spatial RGB color patterning for static display applications. PDMS packaging enhances durability without compromising optical performance and promotes compatibility with flexible electronic devices. Applications include environmental protection, power-free displays, anti-counterfeiting labels and sensors. The scalability of this technology enables higher-resolution and wider color gamut displays through improved size and component control. The incorporation of stimulus-responsive materials, such as thermal or photochromic polymers, enables the creation of dynamic color systems. Its ultra-thin and energy-saving features make it suitable for flexible/wearable devices (electronic paper, smartwatches) in outdoor or low-power environments. Future research may focus on dynamic regulation, self-repair, biocompatibility and electronic integration to expand the practical application of this green technology.

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