PHOTONICS INSIGHTS

Structural coloration: advancements and challenges

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Structural coloration, a phenomenon where color is created by micro- or nano-structures rather than chemical pigment, has gained traction due to its eco-friendliness, robustness to fading over time, high-resolution capabilities, and tunability[1]. As interest grows in next-generation displays like mini-light-emitting diodes (LEDs), micro-LEDs, and high-resolution near-eye displays, structural coloration emerges as a promising solution to meet their demanding specifications. Structural coloration has been developed to achieve improved resolution and larger coverage of the standard RGB (sRGB) gamut[2], which are paramount in display. Various design principles have been demonstrated to meet these demands including photonic crystals made of multilayer-thin films, localized surface plasmon resonance (LSPR) from metallic structures, and Mie resonance from dielectric structures. For example, over 10,000 pixels per inch have been demonstrated for next-generation near-eye displays[3,4].

Furthermore, tunability in structural coloration is also pivotal for various applications such as sensors and optical security[5]. For example, ultrafast humidity-sensitive colorimetric sensors have been demonstrated using metal nanoparticles and chitosan hydrogels, which can vary their resonant frequency according to humidity[6]. Furthermore, optical encryption platforms have also been implemented by combining structural-coloration-based QR patterns and polarization-multiplexed holographic images[7].

Despite potential applications, the commercialization of structural coloration faces challenges due to the fabrication cost associated with sub-wavelength structures and the time-intensive process of electron beam lithography. Recently, nanoimprint lithography (NIL), capable of replicating nanopatterns from reusable master molds with high resolution, has emerged as an alternative for low-cost and mass-production fabrication[8]. For example, Ko *et al*. have demonstrated humidity-responsive structural coloration using one-step printable polyvinyl alcohol structures[9]. High aspect ratios with various structures such as nanogratings, nanopillars, and nanoholes have been achieved with high throughput. This group has also demonstrated full coverage of the sRGB gamut with high-throughput 3D NIL techniques[10]. Nevertheless, the production rate is still insufficient for commercialization due to the limitations in the producible area of master molds and the manual NIL process.

In *Photonics Insights*, Li *et al*. have organized recent progress on structural coloration, encompassing all the issues and topics discussed earlier, thereby providing a comprehensive overview of advancements in structural coloration[11]. They begin with design strategies and working principles such as LSPR, gap plasmon, Mie resonance, and bound states in the continuum. Additionally, they summarize advanced design methods such as machine learning and optimization algorithms as alternatives to address the rising demand for large-area metasurfaces. This surge in demand has led to an increase in the number of constituent nano-building blocks, pushing traditional design approaches to their limits in terms of time and resources.

Furthermore, this group introduces tunable structural coloration categorized by phase change materials, liquid crystal, and flexible substrate deformations. Tunable structural coloration holds the potential for lower power consumption, compact volume, and high resolution[12], especially given the increasing demands of the wearable device. Additionally, they highlight both challenges and opportunities for commercialization, with the most significant obstacle being the swift and economical fabrication of complex nanostructures. Recently, high-resolution 3D nanofabrication methods such as two-photon lithography[13] and high-throughput NIL, including roll-to-plate and roll-to-roll NIL[14], hold promise for overcoming these challenges. We believe that this perspective review article on structural coloration will boost multidisciplinary research and, when combined with advanced fabrication methods[15], pave the way for the commercialization of structural coloration, thus enabling the development of next-generation novel devices.

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