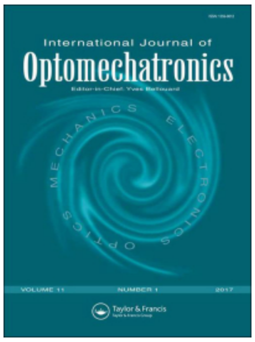

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REVIEW ARTICLE

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Bio-inspired tunable optics and photonics: bridging the gap between nature and technology

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ABSTRACT

In the realm of optical technologies, the integration of nature's designs and modern engineering has paved the way for groundbreaking innovations. Bio-inspired tunable optics and photonics, drawing from the intricate mechanisms found in biological systems, offer a new frontier in adaptive and efficient light management. Here, this review presents a comprehensive examination of the principles, advancements, and applications of natural light-manipulation and adaptation mechanisms, highlighting their translation into artificial tunable optics and photonic structures. Emphasizing the remarkable potential of bio-inspired systems, particularly those emulating the tunable optical functionalities of biological eyes and skins, it explores the current state of bio-inspired tunable optics and photonic devices. Our review categorizes these tunable bio-inspired systems into two foundational mechanisms: light-manipulation and light-adaptation, illustrating their wide-ranging implications from consumer electronics to next-generation technologies. This review also highlights the challenges and prospects of bio-inspired tunable optics and photonics. It emphasizes their role in promoting tunable optical properties for multifunctional devices, providing revolutionary opportunities across various sectors, including the military and everyday life, thus surpassing current cutting-edge optical technologies.

KEYWORDS

Bio-inspiration; tunable optics; adaptive optics; vision systems

1. Introduction

The great leap in optics and photonics technologies has been significantly propelled by advancements in fabrication and material sciences. This substantial progress introduces novel metamaterials, new classes of optical devices/systems, and eco-friendly technical solutions. For example, groundbreaking metamaterials, engineered with specialized patterns or structures, manipulate electromagnetic waves in unprecedented ways, facilitating intriguing technologies, including cloaking devices and superlenses for sub-wavelength imaging.[1–5] Furthermore, the introduction of innovative materials, like quantum dots, two-dimensional materials, and perovskites, has

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advanced traditional optoelectronics, notably in display and energy conversion technologies owing to their exceptional spectral width and electron-photon conversion efficiency.[6–14] Beyond such traditional applications, substantial efforts in inventing novel optics and photonics technologies have brought fruitions for environmental sustainability. These technologies contribute to mitigating global climate change through applications including renewable energy generation, zero-energy radiative cooling/heating, and seawater desalination.[15–22] They harness the vast thermodynamic resources from the Sun and outer space in the form of electromagnetic waves ranging from ultraviolet to far-infrared wavelengths.[22–31]

As mentioned earlier, the advancement of optics/photonics technology has led to significant progress in various applications, such as sophisticated imaging systems,[32–41] environmental solutions,[42–44] and military technologies.[45] Imaging systems can achieve higher resolution and wider field of view, while thermal infrared applications can emit desired wavelengths in intentionally selected bands. Although they show remarkable performances, these non-tunable systems have inherent drawbacks. First, these technologies are mainly optimized for specific environments, necessitating redesign and re-fabrication when the surrounding environment or application fields change.[46,47] Second, these systems necessitate multiple optical components to offer multifunctionality, which is not suitable for wearable and unmanned systems.[48–50] Third, imaging systems face challenges in capturing images under unideal conditions such as dynamic changes in dim lighting or uneven illumination. Even high-performance imaging devices are confused by the artifacts, which have primarily been addressed through image processing techniques that require additional resources.[51,52] By introducing metaoptics, there are several attempts to deal with these challenges in novel ways.[53,54] While these approaches offer promising potential, their complexity in design and fabrication introduces significant time and cost constraints, along with challenges in large-scale implementation. To address these limitations, a trend is emerging towards integrating systems with active media (*e.g.,* phase-change materials; PCMs)[55–66] and adopting tunability strategies (*e.g.,* strain-isolation design, ultrasoft materials, multi-junction, etc.).[67–70] These active systems, in contrast to their passive counterparts, facilitate adjusting their performance to suit varying operational conditions in a streamlined way and small size, driving the field into a new era of tunable optics and photonics systems.

Inspiration from natural systems, the efficient modulation functions and simple structures in biological organs (e.g., eyes and skins), significantly benefit the field of tunable optics and photonics. These features have spurred the development of bio-inspired tunable optics/photonics devices, focusing on responsiveness and softness. In the human realm, the visual system exemplifies a complex light-adaptation mechanism. This system's logarithmic adaptation across varying levels of brightness demonstrates the potential for developing similarly adaptive photonic devices.[71] In the animal kingdom, for instance, the eyes of geckos offer a fascinating case study. Their ability to adjust pupil size in response to light intensity illustrates the principles of dynamic light-adaptation that can inspire tunable optical systems. These pupils can dramatically vary from wide openings in low light to pinhole slits of $\sim$0.1 mm in bright conditions, enabling effective vision across different lighting scenarios.[72] Similarly, biological camouflage, achieved through modifications in micro/nanostructures or pigment sizes,[73] allows animals to blend into their environments or mimic other species, showcasing another form of adaptation in color and morphology.

Natural tunable optics and photonics systems can be classified with two key mechanisms: (1) light-manipulation and 2) light-adaptation. Light-manipulation includes active processes that directly control the light path by refraction or selectively reflect and scatter the targeted wavelengths. The representative examples of light-manipulation are shape-tunable lenses for focus adjustment and color-changeable skins to blend with surroundings (Figures 1(*a*) and (*b*)). On the other hand, the light-adaptation process entails light reactions to modulate light intensity or enhance image contrast. Typical examples of light-adaptation are the adjustment of pupil size in response

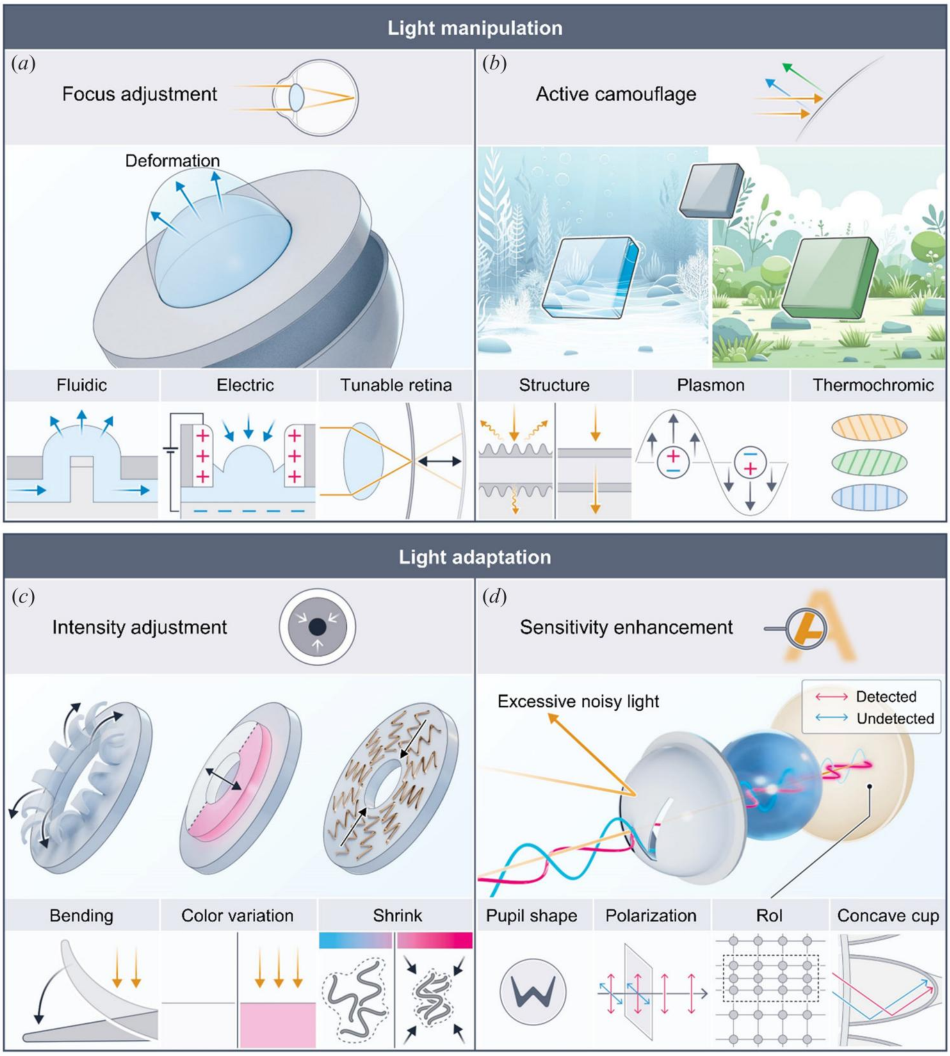

Figure 1. Overview of tunable optics for biological/bio-inspired systems. Light-manipulation in tunable optics: (a) focus adjustment and (b) active camouflage. Light-adaptation in tunable optics: (c) light intensity adjustment and (d) sensitivity enhancement.

to varying light intensities, and enhancement of visual sensitivity under extreme conditions such as low-light or noisy environments to aid in object detection (Figures 1(*c*) and (*d*)). These features found in nature have captured the interest of researchers for the implementation of bio-inspired tunable optics systems since integrating natural active mechanisms into artificial systems enhances efficiency in light-manipulation using minimal resources, leading to low-power consumption and cost-effective solutions not typically achievable through conventional engineering. Examples of bio-inspired artificial tunable applications include focus adjustment through tunable lenses, actuated by fluidic and electrical energy, and tunable retinas (Figure 1(*a*)), active camouflage achieved via adjustable structural configurations, plasmonics, and thermochromics (Figure 1(*b*)), light intensity modulation through artificial iris adjustments by bending the structure, color variation and shrinkages (Figure 1(*c*)), and sensitivity enhancement employing strategies like pupil shape adaptation, polarization alignment, region of interest (ROI) targeting, and concave cup designs (Figure 1(*d*)). Detailed descriptions of the operational mechanisms are provided in Section 3.

In this review, we initially delve into the principles and types of natural light-manipulation and light-adaptive strategies in Section 2. By studying efficient natural systems, we can extract valuable inspirations and principles that can be utilized to develop advanced tunable optic technologies. Then, we explore the innovative approaches proposed in previous research for the realization of tunable optics in Section 3. From various optical principles or promising materials to their demonstrations, inclusive examination is conducted. Finally, we discuss the challenges to be addressed of existing tunable optics and present future perspectives and potential applications in Section 4. This review aims to bridge the gap between biological inspiration and technological innovation, showcasing the immense potential of bio-inspired tunable optics and photonics for a wide range of applications.

2. Mechanisms and structures for tunable optics and photonics in biological systems

2.1. Active light-manipulation in biological systems

Animals employ active light-manipulation elements, including lenses, skin cells, and guanine crystals, to control optical properties through refraction, scattering, or wavelength-selective reflection. These mechanisms allow for focus adjustment and active camouflage by altering the shape or density of these materials. In this section, we present different mechanisms of light-manipulation methods in biological systems.

Focus adjustment is a key function in animal vision, facilitating clear images of objects at different distances. Two primary mechanisms of focus adjustment are used in animal vision: (1) altering lens shape and (2) adjusting lens position (Figure 2(*a*)). Most terrestrial animals, like humans, cats, and dogs, adjust focus through lens shape variation. When transitioning from distant to near vision, their lenses become more curved and thicker, thereby increasing focusing power. This dynamic adjustment accommodates vision across different distances (Figure 2(*a*), top). The vision systems of aquatic animals exhibit a different focusing mechanism. For distant vision, their lens positions farther from the retina. In contrast, for near vision, the lens is moved closer to the retina. This lens movement relative to the retina ensures clear vision across a range of distances (Figure 2(*a*), bottom).

Figure 2(*b*) demonstrates lens shape variations in mammals and birds. Mammals, like humans, adjust the focus by reshaping their lenses by contracting/releasing the ciliary muscles[74] (Figure 2(*b*), i). To focus on nearby objects, the ciliary muscles contract, causing relaxation of the zonular fibers and making the lens rounder. Conversely, when focusing on distant objects, these muscles relax, leading to tensioning of the zonular fibers and flattening of the lens. Similarly, most birds adjust their lens curvature for focus adjustment. However, some avian species, including diving birds, exhibit pronounced changes in the front surface curvature of the lens during accommodation (Figure 2(*b*), ii). In this state, the lens bulges forward through the pupil, increasing the focusing power.[75] This adaptation compensates for the refractive loss of the cornea underwater, aiding in the pursuit of aquatic prey. Figure 2(*c*) depicts the lens position alteration in fish, amphibians, and cephalopods for accommodation. As these species possess a fixed shape of a spherical lens, their focusing mechanism is a lens movement. Teleost fish, for example, have their lens positioned far from the retina in a relaxed state[76] (Figure 2(*c*), i). During the accommodation, the retractor lentis muscle pulls the lens closer to the retina for distant vision. Amphibians use a different muscle, called protractor lentis muscles, to move the lens away from the retina for near vision[76] (Figure 2(*c*), ii). Cephalopods, similar accommodation mechanism to teleost fishes,

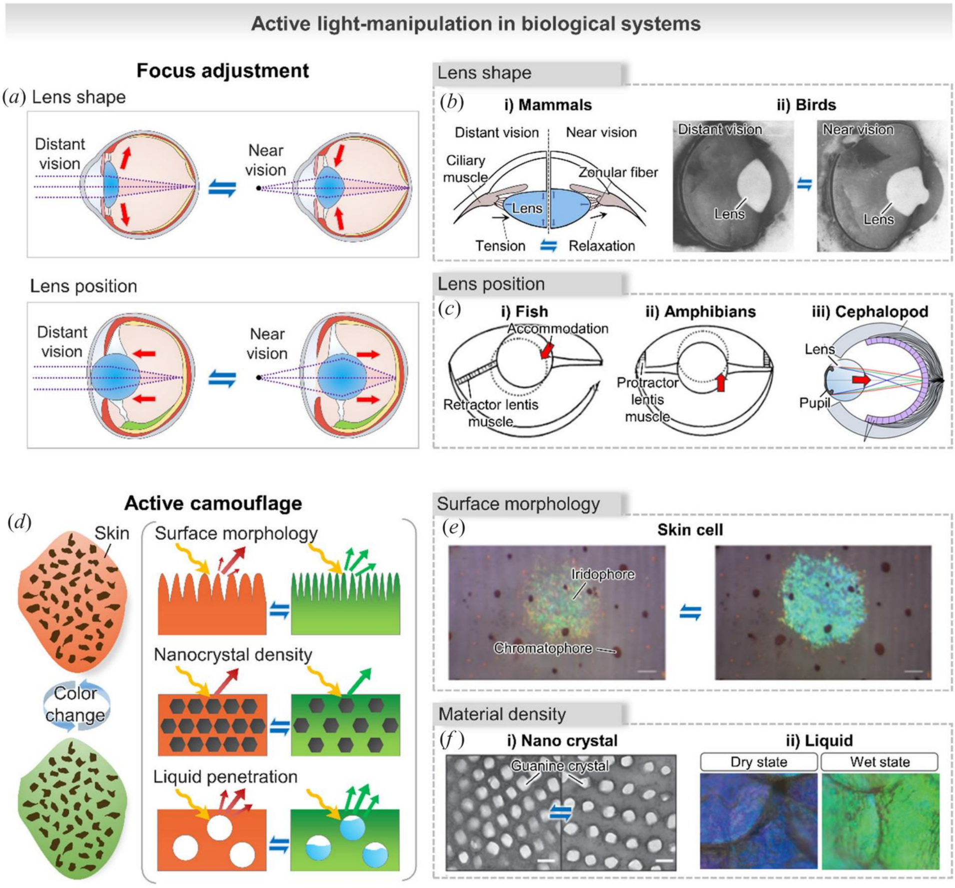

Figure 2. Active light-manipulation in biological systems. (a) Schematic of the focus adjustment in biological systems by modulating lens shape and lens position. (b) Lens shape variations in (i) Mammals[74] and (ii) Birds.[75] (c) Focus adjustment through lens movement in i) Fish,[76] ii) Amphibians,[76] and (iii) Cephalopods.[78] d) Illustration of active camouflage mechanisms, including adjustments in surface morphology, nanocrystal density, and liquid penetration. (e) Photographs of active camouflage through surface morphology alteration in iridophores.[79] (f) Images of material density tuning in (i) nano crystal[80] and (ii) liquids.[81]

adjust for distant focus by moving the lens toward the retina with ciliary muscle contractions[77,78] (Figure 2(*c*), iii).

Biological camouflage is an adaptation in color and morphology, enabling animals to blend into their surroundings, mimic other species, or communicate by tuning their skin colors and patterns. This can be achieved by modifying the micro/nanostructures or changing pigment sizes.[73] Active camouflage through structural color variations involves various mechanisms, such as alterations in surface morphology, nanocrystal density adjustments, and liquid penetration into structural pores (Figure 2(*d*)). Variation in the surface roughness differs the light path by scattering or refraction. Tuning the nanocrystal density also causes the color shift owing to changes in photonic resonance. Liquid penetration to the pore of the structure changes the effective refractive index, which is determined by the volume ratio of liquid and background material. These mechanisms influence a resonant wavelength of light-matter interaction, resulting in structural color variations.

The color variation by tuning the surface morphology is exemplified in squids (Figure 2(*e*)). Squid skin contains chromatophores and iridophores, with the latter functioning as nanostructured Bragg reflectors.[79] Stretching the skin varies the structural dimension of Bragg reflectors, shifting the wavelength of reflection and scattering, which results in a color change. Figure 2(*f*) depicts the tuning of material density in nanocrystals and liquids. The chameleon's skin features a lattice of guanine nanocrystals (Figure 2(*f*), i).[80] Modifying the spacing between these crystals shifts the resonant wavelength leading to structural color variations for active camouflage. Additionally, the skin of Hoplia coerulea beetles consists of a periodic arrangement of thin pure cuticle layers and mixed air-cuticle porous layers[81] (Figure 2(*f*), ii). Their color changes due to fluid penetration within the photonic structure, inducing changes in refractive index contrast between cuticles and pores.

2.2. Active light-adaptation in biological systems

The earlier explored light-manipulation (i.e., focus adjustment and active camouflage) strategies represent active tuning against objects, including enemies. To enhance image recognition under varying environments (e.g., light intensity), animals adjust their vision systems in response to dynamic lighting conditions. This adaptation primarily involves two approaches: light intensity adjustments and contrast sensitivity enhancement. These active light-adaptation methods are crucial for visual tasks, such as prey detection, in animal vision.

In biological vision systems, light intensity regulation is primarily achieved through the modulation of pupil area and retinal structure (Figure 3(*a*)). Adjusting the pupil area, the aperture for light entry, directly modulates the intensity of the light reaching the photoreceptor. In low light conditions, the pupil expands to gather more light, while in bright environments, it contracts to reduce the intensity of incoming light. An additional method to adjust light intensity involves the movement of pigments within the retinal structure. Under bright conditions, black pigments migrate towards the surface of the retina or tapetum, leading to partially absorbing incoming light. In contrast, these pigments are withdrawn in dim conditions.[82]

Figure 3(*b*) illustrates the pupil area variation in both chambered and compound eyes. In human eyes, a type of chambered eye, the iris adjusts the pupil size to control the intensity of incoming light (Figure 3(*b*), i). The sphincter muscles of the iris constrict the pupil under bright light to reduce light entry, while the dilator muscles expand the pupil in dim conditions to allow more light.[83] In some species with compound eyes, like polyrhachis sokolova, called swimming ants, the primary pigment cells (ppc) constrict the crystalline cone into a narrow tract in adapting to bright light[84] (Figure 3(*b*), ii). This adjustment effectively reduces the light reaching the photoreceptors. Figure 3(*c*) presents the migration of the black pigments in the retinal structure in response to light conditions. Under bright light, the tapetum layer that assists in low-light vision can disrupt clear image recognition. Some species, like elasmobranchs, including sharks and skatefish, can occlude the tapetum as part of their adaptation to bright conditions (Figure 3(*c*), i). They have black pigment cells that cover the tapetum's surface during the day to reduce the light reflection in the tapetum, and then retract at night to allow more light into the photoreceptors.[85,86] Additionally, species like zebrafish and Megalops atlanticus adapt to changes in light conditions by varying the pigment density in their retina[87] (Figure 3(*c*), ii). In the absence of pupillary reflexes, they use retinomotor movements for adaptation to light intensity. In dark conditions, pigment granules concentrate at the basal part of the retinal pigment epithelium. While in bright light, the pigment shifts towards the upper part of the retinal pigment epithelium, reducing the light rays to the retina cell.

Some animals enhance contrast sensitivity by employing eye rotation and altering pupil shape (Figure 3(*d*)). For example, mantis shrimps, possessing the capability of polarization vision, enhance object detection and distinction by rotating their eyes to optimize polarization contrast. This process is similar to rotating a Polaroid filter, acting as a linear polarization analyzer, in front of a camera to find the optimal angle for minimizing polarized glare.[88] Additionally, changing the shape of the pupil is another strategy to enhance detection sensitivity. During the

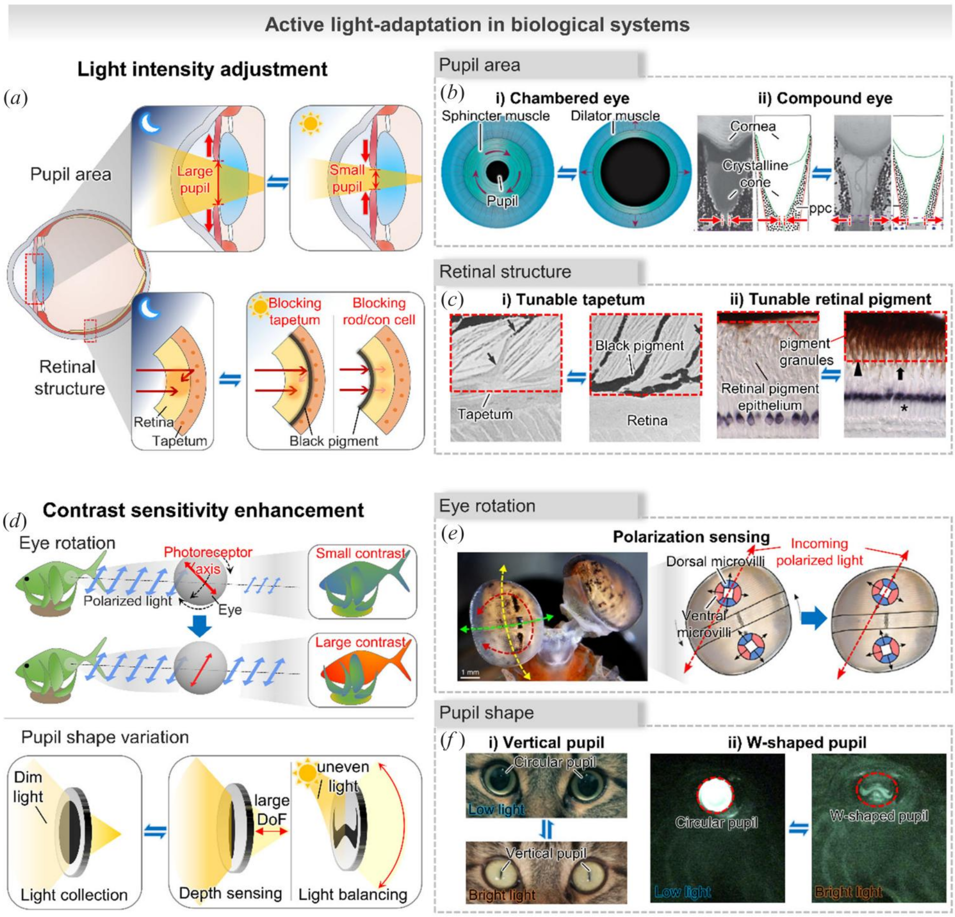

Figure 3. Active light-adaptation in biological systems. (a) Schematic of light intensity adjustment by tuning pupil area and retinal structure. (b) Images of pupil area variations in (i) chambered eyes[83] and (ii) compound eyes.[84] (c) Light intensity adjustment with (i) tunable tapetum[86] and (ii) tunable retinal pigment.[82] (d) Illustration of contrast sensitivity enhancement via eye rotation and pupil shape variations. (e) Enhancement in the polarization detection through three-dimensional eye rotation.[93] (f) Variations in pupil shape exhibiting (i) vertical pupils[92] and (ii) W-shaped pupils.[89]

day, intense sunlight can significantly reduce the dynamic range of image sensors to detect an object, lowering image contrast and making object detection more challenging. A W-shaped pupil is beneficial in these situations, as it enhances the detection contrast by balancing the vertically uneven light itself.[89–91] Meanwhile, an elliptical pupil, which is another type of special pupil shape, is advantageous for depth sensing due to its different depth of field (DoF) in the horizontal and vertical planes, providing a more nuanced perception of depth in the environment.[92] Detailed mechanisms of these enhancements are as follows.

Figure 3(*e*) depicts the working principle of Mantis shrimps for maximizing polarization sensitivity by eye rotations. Mantis shrimps possess unique polarization receptors within their photoreceptors, known as microvilli. By rotating their eyes, the orientation of the microvilli aligns parallel to the axis of polarization of incoming light, thereby maximizing the information gathered from polarized scenes.[93] Figure 3(*f*) shows the variations in pupil shape, particularly vertical and W-shaped pupils. The pupil shape of nocturnal predators, such as cats, changes from circular in low-light conditions to vertical in brighter conditions (Figure 3(*f*), i). The vertical pupil provides a smaller f-number (i.e., focal length/pupillary diameter) on the horizontal field compared to the vertical field. This feature reduces DoF in the horizontal field, generating a higher image blur of the horizontal field than the vertical field, thereby enhancing object sensing with a blurring background.[92,94] Cuttlefish eyes are notable for their unique W-shaped pupils, especially under bright light conditions (Figure 3(*f*), ii). These pupil designs, characterized by their narrower top area compared to the bottom area, efficiently reduce the light entering from the upper side. Thus, this W-shaped pupil helps balance the vertically uneven light field of its natural habitat such as sunlight.[89]

3. Bio-Inspired artificial tunable optics and photonics

3.1. Bio-Inspired tunable optics for light-manipulation systems

In the harshness of nature, wild animals have struggled to catch either prey or predators for survival. Under the scarcity of resources, they have evolved to develop compact focusing systems that ensure both rapid response and high-power efficiency with minimal ocular muscles. Biomimicry of these efficient focus adjustment systems, found in biological eyes, has provided people clues for the development of imaging system that maintains high visual acuity at both far and near distances. In this regard, focus tuning has progressed from two major perspectives: one is a deformation of lens shape, and the second is position shifting of lens and/or photodetector. Several novel approaches have been reported based on fluid, electricity, and mechanics. Common features emphasized in proposed systems are reconfigurability through reversible mechanisms and compactness achieved from simple structures, the same as that of animals.

Solid lenses, typically made of rigid materials, such as N-BK7, are not suitable for the implementation of a deformable lens due to their irreversibility. One strategy to develop the deformable lens is inflating a flexible membrane such as polydimethylsiloxane (PDMS) filled with liquid (Figure 4(*a*), i). The liquid enveloped by the flexible membrane is connected to an external fluid controller device. By controlling the flow rate that induces expansions or contraction of the flexible membrane, the focal length is precisely regulated to the objective. This intuitive approach is demonstrated in both single-chambered eyes[69] and compound eyes,[95,96] proving effective in focal tunability and wide field of view.

In a different way, lenses can be tuned electrically by utilizing electrowetting materials or controlling a constant volume of liquid (Figure 4(*a*), ii). Electrowetting materials such as polyvinyl chloride[97] have dependent adhesion energy on the applied voltage and variation of the energy changes the contact angle to the surface. For example, in the absence of voltage, the liquid has a round shape like water due to surface tension, but becomes flattened when voltage is applied (Figure 4(*a*), ii, left). This mechanism is implemented to arbitrarily form a desired surface used as a lens either on a surface in contact with air and a single liquid[97,98] or an interface between two liquids.[87,99–102] On the other hand, volume control is relocating a fixed volume of liquid to the desired location (Figure 4(*a*), ii, right). Typically, a flexible membrane such as PDMS is used as to surface of the lens and integrated into a housing filled with liquid. The key distinction from the early introduced fluidic method is that it has a predetermined volume instead of the external supply of liquid. When deformation occurs within the internal space of the housing due to external force, inner fluid is pushed away. Subsequently, the liquid moves exclusively in the direction of the flexible membrane, leading to convex deformation of the membrane due to increased internal pressure. The change in radius of curvature enables an effective tuning in focus. Lenses utilizing this mechanism have been extensively studied in various ways such as compression,[103] zipping,[104] shape memory alloy spring,[105] and pressure control,[106] demonstrating the precise adjustment of focus.

Nevertheless, there are still lots of imaging systems incorporating solid lenses owing to their prominent durability. Although liquid lenses are predominantly used in focus tunable lenses due to the mentioned reversibility and deformability, they have unstable performance in extreme

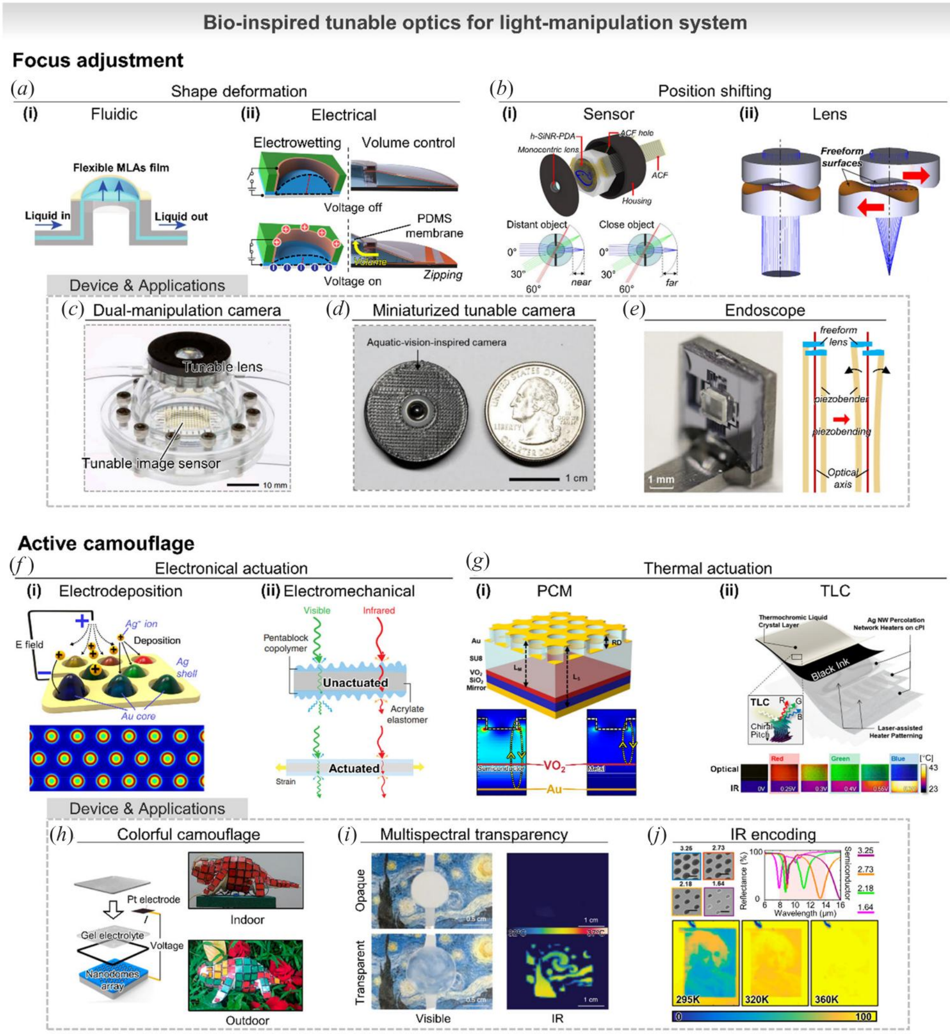

Figure 4. Mechanisms and applications of bio-inspired light-manipulation system. (a) Deformation of lens shape from (i) fluidic flow control[96] or (ii) electrical vias with electrowetting material[97] or volume control.[104] (b) Shifting position of (i) retina to focal spot[107] or (ii) freeform lens horizontally.[108] (c) Demonstration of a single device integrating both tunable lens and tunable sensor.[69] (d) Miniaturized tunable camera capable of small-size integration.[107] (e) Endoscope suitable for use in extremely restricted spaces.[108] (f) Electronical actuation for tunable camouflage. (i) Reversible electrodeposition of Ag shell covering Au core for plasmonic tuning.[112] Inset shows strong resonance at the bottom edge of the structure. (ii) Wrinkled surface actuated both mechanically/electrically to adjust transmittance at Visible/IR range.[113] (g) Thermal actuation for tunable camouflage (i) Tunable plasmonic system coupled by cavity.[115] Inset shows changing length of the cavity with the phase of VO_2. (ii) Thermochromic liquid crystal (TLC) exhibiting tunable coloration in response to heat generated by patterned Ag nanowire.[116] Inset shows temperature dependency of coloration. (h) Demonstrated chameleon mockup with plasmonic camouflage cell.[112] (i) Transparency of actuated wrinkled surface for both visible and IR range.[113] (j) IR encoded picture only visible at low temperatures depending on hole size at single pixel.[115]

environments such as high temperature or pressure, even acidity. Also, the use of liquids entails additional risks, such as leakage due to external impact, thereby raising the difficulty of packaging. Solid lenses can use their outstanding advantages, including inherent stability and rigidity coming from materials, in such harsh conditions. The key challenge lies in how to change focus using solid lenses that are non-deformable. A few researchers have introduced other strategies that involve the movement of the lens or sensor with mechanical actuation. As earlier mentioned in Figure 2(*c*), aquatic animals adjust focus by moving their lens. Since the focusing or not is determined by the relative position between the lens and retina, a similar effect is achieved by moving either of them. Therefore, by moving the position of the sensor, the focus of the imaging system is adjusted efficiently (Figure 4(*b*), i).[107] In the use of a solid lens where the shape of the lens remains constant, no external connection is needed for the deformation of the lens. Given the presence of an external connection to the sensor for readout, the moving position of the sensor is advantageous for integration because the circuit for shifting can be integrated with the readout connection. In another manner, in contrast to the previous where optical elements shift along the optical axis for adjusting focus, a substituting approach is introduced. This fresh method of moving lenses in the perpendicular direction to the optical axis is capable of smaller physical size (Figure 4(*b*), ii).[108] Based on the Alvarez principle,[109–111] the movement of a pair of custom-made freeform lenses in opposite directions is useful for precise focus adjustment. Additionally, with the development of improved processes and design techniques, there is room for better tuning performance and correction of aberration.

Several fields require these methodologies for focus tuning easily integrated into small and sophisticated devices. A representative example of integrating a tunable lens, utilizing fluid flow control, and a tunable sensor is shown in Figure 4(*c*). During focus adjustment using a tunable lens, aberration occurs due to Petzval field curvature. To mitigate this aberration, changes in the lens are tracked in real-time with a tunable sensor resulting in improvement in image quality. Figure 4(*d*) demonstrates a device integrated within 3D-printed housing. Despite its noble performance in focus adaptation, the size of the device is measured at less than 2 cm. The miniaturized camera highlights the potential for seamless integration of these devices into various portable electronics such as mobile and wearable devices. Another example, a tunable lens integrated into an endoscope is shown in Figure 4(*e*). In endoscope design, bulky elements and biodegradable materials are not desirable due to the restriction of space arising from entering narrow passages and harsh external environments. As a solution for this constraint, the lateral driving of solid lenses through piezoelectric benders is suggested. As shown in the right of Figure 4(*e*), actuating through piezoelectric benders is usable for the tiny system. The piezoelectric bender can induce substantial displacement at the tip through applying voltage, without a bulky and complex driving mechanism. This technique is a suitable precedent for tuning focus working in constrained and narrow environments. One of the promising commercialized systems, near-eye display (NED), should require several tunable lens systems for providing depth information. Considering that this device is worn on the head, weight and size are paramount factors as well as focusing performance. The necessity for focus tunable devices is universal for the realm of wearable or portable devices, including NED. In this context, the previously examined state-of-the-art technologies for focus tuning present valuable solutions. With the aid of more advanced manufacturing processes, the development of smaller and more precise focus tunable devices serves as a solid cornerstone for the Internet of Things (IoT) where sensors spread everywhere.

Active camouflage has developed to allow animals to avoid being captured, as an antithesis of focus adjustment allowing animals to better capture other organisms. This survival strategy aims to frustrate the detection capabilities of an adversary by either getting out of their detection spectra or blending in with the environment. Camouflage used by relatively small organisms (*e.g.*, chameleons, cephalopods, and insects) has proven its effectiveness over time. Humans have adopted the enchanting tactic since primitive times even though they cannot naturally use it. Nowadays, principles for camouflage are used not only to match the environment, but also to tune the color of devices as desired in the visible spectrum. After our operating frequency band has been expanded, it is used as a stealth strategy to counter surveillance and reconnaissance by sophisticated detectors in the infrared (IR) spectrum. To implement this fascinating technology, a wide range of advanced principles and materials is used from surface morphology to surface plasmon, PCM, and TLC as follows.

Directly changing the shape of the surface is a common way for living organisms to camouflage. However, it is difficult to modulate the morphology in a reversible way using conventional materials because structures made of rigid materials are not deformable due to their stiffness. Due to this limitation, camouflage is implemented by setting target spectra and designing only for fixed wavelengths. Wang *et al.* addressed this issue by utilizing electrodeposition for tunable camouflage (Figure 4(*f*), i).[112] The proposed device is a new type of camouflage system that employs reversible oxidation-reduction reactions of metal through a 2-electrode system. The Ag shells encapsulating Au cores become either thicker or thinner in response to electrodeposition voltage. This change in nanoscale structure induces the desired coloration by shifting the extinction spectra of plasmonic resonance. Another approach for achieving reversible surface deformation is to create a stretchable multilayer structure consisting of dielectric elastomer and conducting membrane (Figure 4(*f*), ii).[113,114] The sandwich structure is fabricated to have a wrinkled surface morphology when it is not actuated. In this state, the diffuse transmittance in the visible region increases due to the rough surface, while the absorption in the IR region also increases due to the thick middle layer. As a result, the structure is opaque in the wide multispectral region. On the contrary, in the actuated state when strain is applied, the surface and thickness become smooth and thin, making it transparent in the multispectral region. Actuation can be driven by mechanical pulling or electromechanical pressure generated by a capacitor-like structure, expected to be compatible with a variety of applications.

The performance of the proposed system can be reduced by external impacts damaging the structure or moisture. Therefore, for practical use in non-ideal environments, the discussed methods require additional protection to shield. However, the protection layer brings about degradation in purity and transparency. To address this drawback, novel structures tuned by heating are introduced for camouflage without surface change. First, an approach using promising materials of PCMs such as VO_2, which have already demonstrated their performance in many areas (Figure 4(*g*), i).[115] The change in optical constants of VO_2 with temperature allows VO_2 to exhibit properties from dielectric to metallic. Depending on the state of VO_2, the lower reflective mirror layer of the system changes as either VO_2 or Au in the cavity-coupled plasmonic system. This alters the effective thickness of the cavity and fundamental resonance modes are shifted, modulating the absorption wavelengths. Second, a thermochromic liquid crystal (TLC) with Ag nanowire heaters was proposed (Figure 4(*g*), ii).[116] Ag nanowire has many benefits for the heating-based camouflage panel due to high thermal conductivity, flexibility, and ease of patterning. By using a pre-patterned multilayer of Ag nanowire heaters, the custom pattern of camouflage can be created by heating only desired. In addition, the reflective spectrum in the visible matches a narrow temperature range, which results in low power consumption and fast response. This system shows effective and customizable camouflage for practical applications.

Camouflage strategies in multispectral regions are used for hiding appearance or information for various purposes. Real-time camouflage using the aforementioned electrodeposition is demonstrated in Figure 4(*h*).[112] The individual cell is fabricated by packaging an Au nanodome array, an electrolyte containing Ag^+ ions, and two electrodes. Cells were attached to a chameleon mockup and demonstrated camouflage capabilities in outdoor conditions. The interesting point is that the camouflage in the visible region can be self-operating by combining with sensors recognizing the surrounding environment. This approach can be utilized for military purposes, such as unmanned reconnaissance aircraft. The adjustment of transparency in multispectra utilizing reconfigurable wrinkled structure is also a promising application (Figure 4(*i*)).[113] The target area is switched between opaque and highly transparent to any desired level. The simultaneous transmittance control in wide spectra and soft texture serve as necessary characteristics for windows with thermal management and soft robotics. A new approach has also been proposed, the concept of transferring information from the visible region to the IR region (Figure 4(*j*)).[115] At first, pixel values of the original image are mapped to diameter sizes of unit holes where reflectance dips are formed at specific wavelengths. Based on the mapping, an image is designed to have a proper diameter at a single pixel region. In the semiconductor state, pixels reflect different spectra depending on the size of holes engraved in itself, showing the original image. As temperature increases, a phase transition occurs from the semiconductor to the metallic state. Then, the image disappears due to a rise in reflectance regardless of the hole size. This approach demonstrates the potential for anti-counterfeiting and tagging in the IR region. In conclusion, the active camouflage technologies that have been discussed so far are not limited to camouflage to avoid detection, but also the principles of coloration in a comprehensive manner. It is anticipated that coloration based on these diverse principles will versatilely facilitate applications across a broad spectrum, ranging from camouflage to information security and displays.

3.2. Bio-inspired tunable optics and photonics systems for light-adaptations

In dynamic environments, our eyes are easily disturbed by rapidly changing light levels. For instance, excessively abundant light in the daytime impairs cognitive ability. To maintain vision acuity, it is necessary to regulate the amount of light in response to lighting conditions. Unfortunately, a complete adaptation of the transition between day and night vision takes tens of minutes because it involves changing perceptual systems such as sensory cells. As a more quick and immediate solution, the structural modification of the iris for controlling the area of the pupil occurs as known as the pupillary light reflex. To imitate this effective strategy, several studies have been reported with extrinsic or intrinsic control systems with photo-responsive materials.

Receiving a signal from an external circuit to adjust the blocking area of an artificial iris is a common practice. Liquid crystal elastomer (LCE), one of the great prospects in soft electronics as a reversible actuator, also significantly contributes to this field. LCEs tend to shrink when heated along with their initial orientation determined by force during the curing stage. Taking this property, an artificial iris with a radially oriented LCE structure is introduced with embedded platinum heaters (Figure 5(*a*), i).[117] The Pt heater is stretchable due to its winding structure, making it perfectly compatible with the radial actuation of the LCE iris. In a dark environment, the Pt heater generates heat to contract the LCE iris in the radial direction, increasing the pupil size. On the contrary in a bright environment, it is cooled to expand the LCE iris for reducing the pupil size. There is also a system that utilizes polymer dispersed liquid crystal (PDLC) to regulate light transmittance (Figure 5(*a*), ii).[118] By applying a voltage to the indium tin oxide (ITO) electrodes connected to the PDLC, the phase of PDLC changes and straightforward adjustment of transmittance is achieved. The proposed iris consists of eight ring-shaped PDLC films arranged in a concentric figure. They are sequentially actuated according to the intensity of the surrounding light. Initially, in a dim condition, all PDLC films are activated by applying a voltage, making them transparent overall. As the environment becomes brighter, the voltage is reduced starting from the outmost films, whereupon light is blocked by disordered liquid crystals. These externally controlled devices can be automatically activated to modulate the amount of light when they are paired with a sensing system that monitors external light intensity.

However, even if the automatic system is configured, the existence of the control circuit is still cumbersome and consumes additional power. For more promising and futuristic applications like as robotics or wearable devices, further streamlined and integrated methodologies are necessary. In this regard, approaches that are fully independent of control circuits have been investigated by utilizing photo-responsive materials: (1) photochromic and (2) photothermal. Photochromic materials undergo molecular switching and change their coloration when illuminated by light of specific spectra.[119] An auto-attenuative iris is developed exploiting this property (Figure 5(*b*), i).[120] Photochromic material is processed to the shape of an annular disk and transferred onto the PDMS substrate. Activated by ultraviolet (UV) illumination, the color of the iris changes from colorless to redly opaque with increased absorption in the visible region. The visible

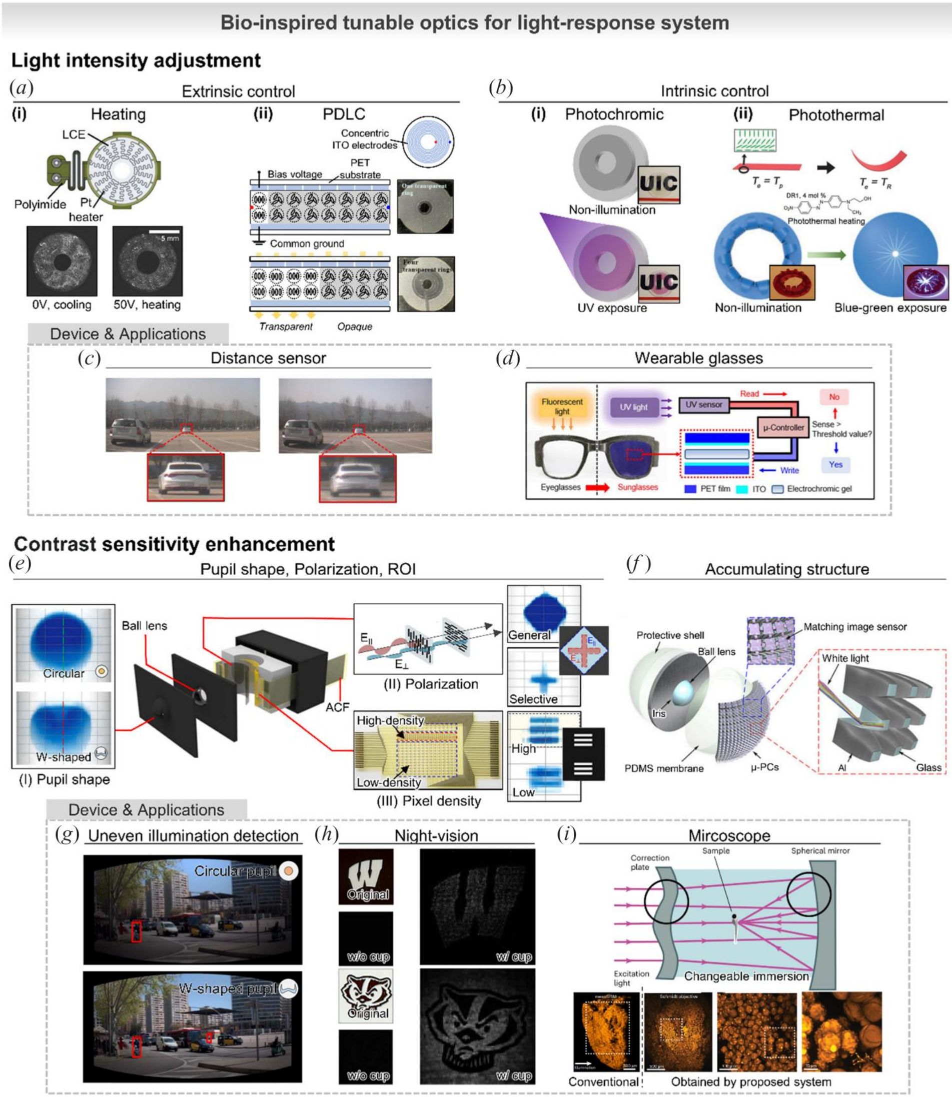

Figure 5. Mechanisms and applications of bio-inspired light-adaptive system. (a) Artificial iris with extrinsic control system. (i) LCE with external heater[117] or (ii) PDLC with external bias voltage source.[118] (b) Intrinsic response to light of polymer used to self-controlled artificial iris. (i) photochromic[120] or (ii) liquid crystal elastomer (LCE) doped with photothermal.[121] (c) Real-time distance sensor in automobile using artificial iris.[124] (d) Multi-functional wearable glasses.[125] Combined with external UV sensor, extrinsic self-controlling system is demonstrated. (e) (i) W-shaped pupil balancing light under uneven (i.e., upper dominant) illumination, (ii) selective polarization sensing to opt redundant information out and (iii) High resolution at region of interest (ROI).[90] (f) Light-concentrating structure of the inhabiting at dim circumstance.[129] (g) Blackbox camera showcased in daytime illumination with W-shaped pupil.[90] (h) Night-vision system utilizing light-accumulating cup. Inset shows sensitivity improvement with the structure.[129] (i) Microscope inspired by eye of scallop and Schmidt telescope. Inset is pictures of pollen pellet imaged in air.[130]

transmittance of the pupillary region is maintained at a high level, while the transmittance of the peripheral region is adjusted by the state of the artificial iris, leading to an adjustment of the overall transmittance. In another approach, based on previously examined LCE, a self-regulated iris is also proposed doped with photothermal material (Figure 5(*b*), ii).[121] LCE film, polymerized at a higher temperature than room temperature, shows the flattened figure in polymerized temperature regardless of the orientated direction. As the ambient temperature is cooled to room temperature, it bends due to inside stress coming from the initial molecular orientation. The temperature-induced deformation of LCE can be converted to light-induced deformation by doping Disperse Red 1 (DR1), one of the photothermal materials. DR1 undergoes repetitive *trans-cis-trans* cycling under the illumination of blue-green light, emitting substantial heat to actuate LCE film. The proposed iris consists of 12 petal-shaped LCE films doped with DR1. In a dim environment, the films bend providing sufficient pupillary area to accept light. When illuminated, the films flatten to reduce the amount of light. Other approaches to self-regulated artificial irises have been reported using polydopamine (PDA) as an alternative to DR 1. Their responsiveness to the near-IR rather than blue visible provides a valuable option for tailored applications.[122,123] These intrinsically controlled structures have disadvantages of lower stability and less precise controllability. Nonetheless, owing to fully automatic merit and unconstrained integration, they are still attractive for fully wireless and battery-free purposes.

Light adjusting techniques are versatile in many fields showing their potential, not only including acuity enhancement in image sensors but also distance sensing and wearable devices. In automobiles including self-driving cars, it is necessary to collect the distance information to nearby structures. Tunable irises can be used to easily obtain precise distance information from depth information (Figure 5(*c*)).[124] This technique, called depth from defocus (DFD), utilizes the blur difference between two images captured by two cameras in the same scene but with different aperture sizes. Smart glasses, the most promising wearable device, incorporating the function of anti-ultraviolet is another application of intensity adjustment (Figure 5(*d*)).[125] In the daytime, intense UV light has harmful effects on both ocular tissues and the immune system. To cope with these undesirable effects, an automatic UV blocking system is integrated into the smart glasses. Cell structure containing electrochromic gel is used as spectacles of the smart glasses, activated by external UV sensor for automatic operation. It can reversibly switch between glasses and sunglasses modes depending on the UV intensity of the outside environment. The fully self-regulated techniques introduced earlier, or combined with energy harvesting and sensing, are expected to be applied in broader fields such as unmanned and self-powered drones.

Under natural illumination, the amount and direction of sunlight is constantly changing. During the day, the redundant light disrupts our vision through visual artifacts such as glare. Moreover, the intensity of direct light from above is greater than that of reflected light from the front, as the position of the sun is above. On the other hand, at night, the scarcity of light hinders to distinguish objects. The organisms in nature have adapted to their living habitat, hence they are less affected by these adverse conditions. Several studies have devised innovative ways to bring the benefits of their vision systems into our devices. This part shows a comprehensive overview of effective techniques to identify objects in challenging environments, for robustness against dynamic conditions.

Uneven illumination, where the intensities coming from different directions are sloped, always occurs outdoors as long as the light source (*i.e.,* sun or moon) exists in the above. In this environment, the top of the pupil is exposed to more light than the bottom. As a result, the contrast of the vision is degraded as the darker areas of the image are not as distinguishable. Inspired by the eye of cuttlefish, a W-shaped pupil can balance this imbalance (Figure 5(*e*), i).[90] In the case of ordinary circular pupils, the profile of uneven distribution with a high intensity at the top is presented. Meanwhile, in the case of the W-shaped pupil, the intensity of the upper part is reduced due to light blocking by the pupil. As a result, a more uniform distribution of light intensity is achieved across the entire region, which is self-equalizing against ununiform incident light. Polarization sensing is another powerful means to improve contrast (Figure 5(*e*), ii).[90] By selectively accepting light in a specific polarization state among redundant light, only the concerned information is obtained without any confusion. This can be achieved by integrating polarizer film into imaging systems (*e.g.*, carbon nanotube polarization film,[90] anisotropic nanowire,[126] and one-dimensional metal grating[127]). Increasing the number of photoreceptors in the region of interest (RoI) is known as the fovea of predators, which helps to improve the contrast of important parts (Figure 5(*e*), iii).[90] Due to the limited resources and resolution limit, it is efficient to acquire as much information as possible regarding the RoI where the gaze is directed. Selective placement of photodiode density during the manufacturing process is one to carry through this strategy.[90] Digital micromirror device (DMD) is another viable solution for implementing RoI.[128]

Imaging in low-light environments is challenging due to the lack of enough light to form a clear image. Inspired by the eye of elephantnose fish, sensitivity enhancing structure is suggested to address this notorious situation (Figure 5(*f*)).[129] Micro-cup structure is fabricated by micromachining with femtosecond laser onto a glass substrate and subsequent aluminum deposition as a reflective layer. The cup structure behind the retina can collect light and enable additional detection under dim conditions, ensuring better image quality.

These techniques, which are designed to aim at specific situations, show outstanding performance in practical applications. In automobile driving, uneven illumination with dominant upper illumination is a major obstacle. W-shaped pupils can deal with this situation as applied to front cameras and windshields (Figure 5(*g*)).[90] When using W-shaped pupils, the contrast of peripheral vision is significantly improved, and the auto-recognition system detects a person who were undetected with the circular pupil. Light-concentrating cup structure shows notable performance at night vision (Figure 5(*h*)).[129] Without the proposed structure, the camera cannot collect enough light to present the original image. However, in the opposite case, the proposed structure allows for the acquisition of images of sufficient quality for identification in the same dark environment. Another novel approach is a microscope that carries out advanced microscopic imaging by increasing numerical aperture (NA) through the replacement of an immersion medium.[130] Inspired by the Schmidt telescope and the eye of a scallop, the system utilizes a correction plate and spherical mirror (Figure 5(*i*)). This system can change NA (0.69–1.08) and field of view (1.1–1.7 mm). These characteristics are determined by the choice of immersion medium such as air, water, and immersion oils. Contrast and sensitivity are very important factors in the field of imaging, and novel methods to improve them are priceless for high-quality imaging. The ability to obtain higher-quality images in more extreme and undesirable environments will be a foundation for the advancement of many fields.

In this section, we investigated novel approaches for achieving tunability in optics. While the underlying principles of these state-of-the-art methodologies are worthy, their quantitative tunability emerges as another key factor in their potential application. Table 1 shows a comprehensive overview of the performance and properties of the introduced demonstration. Quantitative information is provided in each proposed tunability (*i.e.,* focal length, operating wavelength, and iris area) and the response time. Because items in the contrast sensitivity enhancement part aim for adaptation in specific conditions, they are separated and presented in Table 2 for qualitative analysis. Incorporating diverse perspectives will expedite the development and adoption of more viable and practical tunable optics.

4. Conclusions and future perspective

Recent advancements in bio-inspired tunable optics/photonics with delving into the principles and various functions of biological tunable optics were summarized in this review. First, tunable lenses inspired by the focus adjustment mechanisms of natural eyes have been reviewed. Different types of technologies are being explored, using smart materials driven by a variety of stimuli, such as hydraulic, magnetic, optical, thermal, chemical, and electrical. Compared with conventional focus tuning systems whose focal length is usually tuned by displacing one or more constant-focus lenses, using a single tunable lens does not need moving parts in optical systems, allowing miniaturization of optical systems, advantages for advanced applications, such as mobile phones, drones, optical fiber components, and endoscopes.

Next, active camouflage devices inspired by tuning of color and patterns in animal skins have been reviewed. Techniques such as electrodeposition, PCMs, morphology tuning, and TLCs

Table 1. The performance and applications of the tunable optics introduced in Section 3.

Parts (Tunability)	Working principle	Tunability	Response time	Application	Note	Ref
Focus Adjustment (Focal length)	Fluid	16 mm–55 mm	N/A	Adaptive imager	Magnification function	[96]
	Volume control (electrowetting)	3.8 mm–22.3 mm	680 ms	Tunable lens module		[97]
	Volume control (zipping)	Variable to dimension	260 ms	Tunable lens module		[104]
	Detector shifting	2.95 mm–4.72 mm	N/A	Miniaturized camera		[107]
	Alvarez lens shifting	5.5 mm–7.5 mm	110 ms	Endoscope		[108]
Active camouflage (Operating band)	Electrodeposition	Visible	<1 s	Real-time camouflage	Plasmonic display	[112]
	Electromechanical (Wrinkled surface)	Visible to IR	570 ms	Concealment	–	[113]
	PCM	IR	<1 s	IR encoding	–	[115]
	TLC	Visible to IR	<0.6 s	Customized camouflage	–	[116]
Intensity adjustment (Iris change)	Direct heating	Diameter 2.7 mm–3.8 mm	Opening 7 s Closing 3 s	Miniaturized photographic optics	–	[117]
	PDLC	Diameter 1.5 mm–8 mm	N/A	Robotic vision	–	[118]
	Photochromic	Absorption in visible 50%–65%	30 s	Ocular prosthesis	Intensity dependence	[120]
	Photothermal	Transmission power 10%–70%	5 s–30 s	Micro-robotics	Intensity dependence	[121]

Table 2. The summary and applications of the contrast sensitivity enhancement optics.

Parts	Working principle	Target Condition	Inspiration	Application	Note	Ref
Contrast sensitivity enhancement	Pupil shape (W-shape)	Uneven illumination	Cuttlefish	Light balancing	–	[90]
	Micro-cup structure	Dim condition	Elephantnose fish	Night-vision	–	[129]
	Multi-immersion	Microscopic condition	Scallop	Microscope	–	[130]

enable these devices to undergo visual changes for effective camouflage. Beyond mimicking the colorful camouflage, these technologies also provide the function of thermal camouflage, crucial for evading thermal detection. These advancements in camouflage technology have extended beyond military equipment, offering advanced adaptive camouflage solutions for personal privacy protection and information encryption.[131,132]

Thirdly, we reviewed tunable devices for light intensity adjustment, inspired by the function of an animal's pupil. To achieve this tunability, several methods have been employed such as color variation/structural bending induced by light exposure and thermal as well as electrical stimuli. Mirroring biological mechanisms, tuning the aperture area facilitates variation in both light intensity and depth of field. Exploiting these features, tunable apertures in distance sensors capture two different DoF images by altering aperture sizes. Furthermore, color-tuning glasses employ materials that adjust color upon UV exposure, providing protection against UV irradiation from sunlight. Such advancements in light-intensity adjustment devices open avenues for use in medical and autonomous vehicle applications.

Furthermore, the tunable devices for enhancing contrast sensitivity have been reviewed. Inspired by the cuttlefish and elephantnose fish, cameras that balance light intensity have been developed. These cameras employ strategies such as pupil shape variation and micr-cup structures to adjust light intensity. These strategies allow practical applications in fields such as artmobile driving, microscopes, and night-vision cameras.

Although recent advances in tunable optics for bio-inspired light-manipulation and adaptation technologies, there are some remaining challenges for advanced bio-inspired tunable optics, including auto-tuning, fast response, small aberration, high resolution, and compactness. Specifically, bio-inspired light-manipulation technologies, including focus adjustment and active camouflage, mostly face hurdles in auto-tuning to dynamic environmental conditions and moving objects owing to the absence of feedback systems. Also, thermal and optofluidic actuations for tuning cause a slow response, which is impractical for real-time applications like military camouflage. Another significant challenge is the large aberration in tunable lens optics, which degrades the image quality. The low resolution of deformable image sensors in tunable lens optics is also a critical issue. Conforming sensor arrays to curved surfaces can introduce strain, especially in the metal lines connecting pixels (e.g., serpentine and arc-shaped structures), leading to increased pixel spacing and reduced image resolution. Moreover, for advanced mobile optics, the demand for compact focus adjustment and camouflage systems is growing.

Similarly, the light-adaptation process, encompassing light intensity adjustment and contrast sensitivity enhancement, encounters challenges similar to those in the light-manipulation process. Auto-correction for sensitivity and contrast is crucial for adapting to variations in light intensity or the presence of moving objects. A fast-switching process is essential for real-time applications, and the miniaturization of these technologies is imperative for integration into advanced mobile optics. Addressing these challenges is vital for advanced applications, including adaptive camouflage, self-driving automobiles, bio-medical optics, and mobile devices. The following subsection briefly represents a potential approach, outlining recent efforts to overcome current limitations and highlighting the potential of next-generation optics with visible readouts. Apart from this, future works are required for advanced technologies, such as adaptive camouflage, self-driving automobiles, bio-medical optics, and mobile devices.

4.1. Challenges

The bio-inspired tunable optics, including tunable optical lenses, active camouflage devices, tunable apertures, and deformable image sensors, provide adaptability actuated by external controls such as electrical, thermal, electrodeposition, strain, displacements, magnetic, and hydraulic pressures.[133–141] Although efficient for tunability, most of these systems lack self-operation and require feedback systems for auto-tuning (Figure 6(*a*)). For practical applications, such as autofocus cameras and military camouflage, the capability for auto-tuning to environmental changes is vital to ensure high performance in dynamic conditions (e.g., object movement and background changing). Furthermore, since certain tuning technologies actuated by electrical and thermal stimuli require large voltage (>2kV)[142] or elevated temperature (>600 °C),[143] ensuring low power consumption becomes vital for miniaturized optical systems such as drones and mobile devices. Consequently, across a wide range of applications from consumer electronics to specialized equipment, there is a strong demand for advanced optical devices that offer auto-tuning with low power consumption.

For real-time applications, including depth-sensing cameras in automobiles and military camouflage, both fast response and wide modulation ranges are crucial (Figure 6(*b*)). Active camouflage, for example, requires a rapid color change to evade detection from others (e.g., enemies), yet some camouflage systems switch their color or IR emissivity slowly (>10s),[144] heightening the detection risks. A wide tuning range of colors is also imperative for concealment in diverse environments. Similarly, depth-sensing cameras in self-driving cars need fast depth estimation and wide sensing range to quickly avoid obstacles, such as vehicles and pedestrians. Despite these requirements, some tunable devices, including lenses, apertures, and camouflage devices, that rely on optofluidic and thermal actuations, exhibit slow response times (>1s),[121,122,145–151] impeding

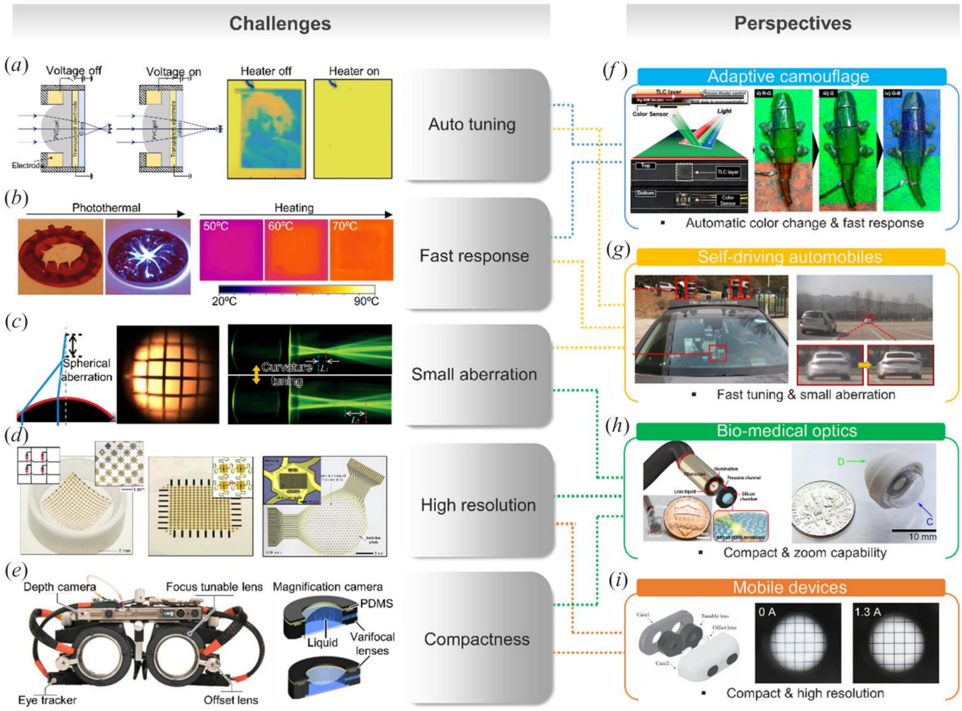

Figure 6. Current challenges and perspectives for bio-inspired tunable optics. Current challenges: (a) auto-tuning for tunable devices,[115,133] (b) fast response for tunable devices,[121,148] (c) small optical aberration of tunable optics,[155,158] (d) high resolution of tunable image sensors,[69,107,159] and (e) compact optical devices.[163,166] Perspective innovations and applications: (f) adaptive camouflage to the background,[116] (g) self-driving automobiles with tuning the f-number,[124] (h) bio-medical optics with magnification capabilities,[129,178] and (i) compact mobile devices for focus tuning.[164]

the applications in real-time scenarios. Therefore, achieving rapid response and wide modulation ranges remains a challenge in the development of these advanced optical systems.

In equipment that requires precise operation, such as endoscopes and depth sensors, it is essential to provide images with low optical aberration. A single tunable lens, while beneficial for simplifying optical systems, can lead to the Petzval field curvature,[69] necessitating the use of curved image sensors. Although various curved image sensors have been developed to match the Petzval surface, addressing spherical aberration remains a challenge because most tunable lenses manipulate curvature in spherical shapes[133,136,137,146,152–154] (Figure 6(*c*)). Recent studies have introduced the tuning method for aspherical surfaces to suppress spherical aberration using gradient electrostatic force,[142,155,156] integrating with a fixed aspherical surface,[157] and employing dual arrays in optofluidic systems.[158] Despite these advancements, the practical application of focus-tunable lenses is hindered by their requirements for high driving power ($\sim$2 kV)[142] or complex fabrication techniques.[158] Therefore, further development is needed to overcome these limitations for aberration-free imaging with low-energy consumption.

The advancements in material and fabrication technologies have led to a remarkable interest in deformable image sensors. To achieve a curved surface through stretching, several structures have been introduced, including buckling, island-bridge, and kirigami structures (Figure 6(*d*)). Furthermore, the use of intrinsically stretchable materials offers flexibility without any structural restrictions. However, a challenge arises when utilizing deformable structures based on rigid pixel (e.g., silicon) arrays, especially on highly curved surfaces. Conforming these arrays to hemispherical shapes induces strain, particularly in the metal lines (*e.g.*, serpentine and arc-shaped structures) connecting the pixels, increasing the spacing between the pixels.[33,63,69,107,159–161]

Consequently, on highly curved surfaces, demanded in compact optics, the fill factor of pixel decreases, reducing the image resolution. While fabricating the image sensor on a curved surface could address this issue, most image sensors are produced on a two-dimensional plane for simplicity in manufacturing. For transforming two-dimensional (2D) into three-dimensional (3D) layouts, image sensor designs necessitate longer metal lines, which reduces a fill factor in unstretched states (<30%).[69,159] Intrinsically stretchable pixels present a potential solution to these issues, as they can conform to curved surfaces without requiring specialized device designs and geometries.[70] However, some challenges remain in terms of the performance and durability of materials and devices. The pop-up structure, employed in flexible photodetectors, does not degrade a fill factor during transformation to a curved surface. However, to achieve high curvature, this structure necessitates a larger size in its original state, posing a limitation for compact applications. Ensuring long-term functionality and reliability in such systems is a key area of ongoing research.

Integrating tunable lenses in optical systems offers a significant advantage over conventional muti-lens systems by reducing the size and complexity. This advantage has propelled the development of several prototypes, such as focus-tunable eyeglasses[162,163] and head-mounted displays[164] (Figure 6(*e*)). While these devices offer multi-functionality (e.g., focus tuning and depth sensing), integrating depth sensors, tunable lenses, and other components increases the size and weight of the devices, which presents a significant drawback for real-world applications. Furthermore, a prevalent challenge with single tunable lenses is achieving magnification modulation. While a single tunable lens can vary focal length through curvature adjustment, it typically lacks the capability to modulate magnification. To independently control focal length and magnification, a direct solution is using a combination of independently tunable lenses.[165,166] Nonetheless, for applications requiring compact and lightweight solutions, like drones, a more desirable solution would involve integrating both tunable focusing and zooming capabilities into a single lens. This integration is key to minimizing the size and weight of the system, which is important for the functionality and usability of smaller-scale applications.

4.2. Perspective applications

Overcoming current obstacles in tunable optics is key to elevating technology in numerous promising fields. This encompasses the development of adaptive camouflage, enhancement of autonomous vehicles, advancements in biomedical optics, and innovations in mobile device technology. In this section, we will briefly discuss prospective applications in tunable optics, focusing on key factors.

Inspired by biological camouflage, adaptive camouflage technologies have been developed for military applications (e.g., vehicles, soldiers, and equipment), stimulated by mechanical, chemical, electrical, magnetic, and thermal inputs[73,112,167–172] (Figure 6(*f*)). Recent research on adaptive camouflage prioritizes the rapid environmental adaptability of these systems. In this context, auto-tuning and quick responsiveness become crucial factors. While current developments in adaptive camouflage exhibit prominent functionality of color changing, most camouflage systems operate with external stimuli independent of the environmental conditions and exhibit slow response.[55,143,144,173,174] For instance, the chameleon-inspired camouflage device can achieve RGB colors using thermal stimuli at low voltages (0–0.7 V), however, their response time is slow (∼1s).[116] Additionally, utilizing a tunable conductive polymer, such as poly (3,4-ethylenedioxythiophene): polystyrenesulfonate (PEDOT:PSS), has been explored to achieve low-power consumption (<1 V).[60] Auto-tuning in camouflage necessitates a closed-loop control system with environmental feedback, such as color sensors for detecting ambient patterns.[112,116] For a rapid response, electrical actuation is commonly employed.[112,175] Integrating these two factors would improve the efficiency of these technologies, demanding advancements in the fields of information security and military camouflage.

In self-driving automobiles, DFD techniques offer a notable advantage due to their lower cost and more compact design compared to light detection and ranging (LiDAR) techniques.[176] Recent advancements have integrated tunable apertures in DFD systems, enabling more accurate depth sensing by comparing two different depth of field images (Figure 6(*g*)). For real-time applications, rapid aperture size adjustments, auto-tuning, and minimal image aberration are necessary to prevent accidents. In this context, implementing comb-drive actuators and the electro-optic effect, coupled with a closed-loop feedback system, can significantly improve switching speed.[124,177] Thus, recent studies on DFD[124] have aimed at achieving low voltage (5 V) requirements for aperture tuning from f/1.8 to f/40 with quick switching time (<6 ms). Additionally, integrating aspherical tunable lenses can further reduce optical aberrations, yielding more precise depth images. Further, the incorporation of systems that passively balance light intensity could improve image contrast and depth accuracy while preserving cost-effectiveness, compactness, and sensitivity in autonomous vehicles. Combining these functionalities in depth sensing systems would advance the technologies of self-driving cars.

Endoscopes, pivotal in medical diagnostics for inspecting body cavities, require high optical magnification and a compact design to enhance observation accessibility. Varifocal lenses satisfy these requirements as they allow compact size compared to traditional multi-lens zoom cameras. Consequently, an endoscope equipped with a single tunable lens provides a prominent focal tuning range (2-10mm) while maintaining a compact size (diameter: 4 mm) (Figure 6(*h*)).[178] While single tunable lenses provide compactness, achieving zoom capabilities in such systems typically involves moving the lens, which increases the size of optics. Utilizing a pair of tunable lenses allows for adjustment in both focal length and magnification,[179] presenting a more compact solution than traditional zoom endoscopes.[178–180] Despite this, there is a continuing demand for even more compact single-tunable lens systems that can perform both focal tuning and magnification. Methods from previous studies on single-tunable lens systems, capable of providing both variable focus and magnification, offer a strategy for achieving miniaturized optical designs. These methods independently modulate the thickness and curvature of liquid lens via electrowetting-on-dielectric actuation and electrowetting.[101,175,181] The integration of these advanced tunable lenses into endoscopic designs heralds the development of more compact zoom endoscopes, which can reduce discomfort risks and improve accessibility.

Focus-tunable lenses, reducing the complexity of conventional focusing/zooming systems, are emerging as an innovative element in smart mobile devices such as consumer electronics, robotics, and head-mounted displays. Particularly in virtual reality (VR) displays, gaining attention as the next-generation display technology, focus-tunable systems are being explored to mitigate visual discomfort from the vergence-accommodation conflict.[182] Recent studies have concentrated on miniaturizing head-mounted displays with tunable lenses, which provide focus-tuning capabilities[164,182–184] and address the bulkiness of conventional zoom optics that impede user immersion (Figure 6(*i*)). Furthermore, high resolution, essential for immersive experiences, is a key factor in VR displays, demanding a high fill factor of pixels of displays. As noted earlier, employing a single lens results in a Petzval surface; therefore, integrating deformable displays with a high fill factor could be a key strategy in minimizing aberrations and further enhancing the immersive experience.

In conclusion, the rapid developments in modern optics/photonics and manufacturing technology have significantly triggered the renaissances of bio-inspired tunable optics and photonics devices, paving the way for practical and innovative applications. Despite advancements, these devices have yet to fully capitalize on vast market opportunities owing to several challenges, including auto-tuning, fast response, minimal aberration, high resolution, and compactness. We believe that addressing the challenges and perspectives in Figure 6 will drive advancements in tunable optical properties for multifunctional devices and provide revolutionary opportunities across various sectors, industries, the military, and daily life, expanding our perspectives and limitless possibilities.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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