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Biomimetic photonic structures for optical sensing

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HIGHLIGHTS

- A selection of optical sensors, which have been developed using biomimetic photonic structures is reviewed.
- We discuss how biomimetic-based design strategies have led to the successful fabrication of different sensors.
- Types of sensors: Infrared, chemical, mechanical.
- Sensors for aerospace applications and robotics.

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ABSTRACT

This perspective reviews a selection of optical sensors, which have been developed using biomimetic photonic structures. In particular, we discuss how biomimetic-based design strategies have led to the successful fabrication of infrared, chemical, and mechanical sensors, as well as sensors for aerospace applications and robotics.

1. Introduction

In a broad sense, biomimetic and bio-inspired technologies arise from a flow of ideas from the biological sciences into such disciplines as engineering, chemistry, materials science, physics, and mathematics. Recent advances in understanding the working principles of biological functional materials and systems, achieved by a growing interdisciplinary community of scientists and engineers [1], have spurred an increase in efforts aimed at emulating nature's most impressive design strategies in man-made technology. Being just one of many approaches in technology development, "learning from nature how to build devices with a specific functionality" has the distinct advantage of capitalizing on thoroughly scrutinized, performance-optimized outcomes of millions of years of evolution and natural selection in living systems [2]. This approach is receiving increasing attention given its potential to enable major technological advances that allow artificial devices to approach the sophistication and efficiency of biological systems.

Nature has long inspired the work of inventors and artists; in the last two decades engineers and scientists have embraced the opportunities arising from mimicking natural materials and translating biological design concepts into man-made products. The structural complexity and hierarchical architecture, which frequently enable multiple desirable functions in biological materials is particularly intriguing and still challenging to emulate. Nevertheless, several examples of successful translation of biological material concepts into industrial products exist [2,3].

In this perspective, we will focus on the development of biomimetic and bio-inspired photonic devices for optical sensing, a growing field that has greatly benefitted from deeper insights into nature's light manipulation strategies. Living organisms employ a wide diversity of nano- to macroscale material structures with very specific optical response characteristics to fulfill multiple functional requirements simultaneously [4]. Frequently, these biological materials satisfy needs related to camouflage, aposematic predator deterrence, territorial assertions, and courtship. For these and other purposes, insects in particular have evolved a diverse range of photonic micro- and nanostructures to create conspicuous coloration, which have systematically been studied by scientists for centuries with increased efforts in recent decades [5–9]. Building on the profound understanding of biological light manipulation concepts resulting from such studies, a variety of

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biomimetic optical devices have been devised for various applications [10–15], including solar energy harvesting [16,17] and the fabrication of nanobioreplicated visual decoys for pest control [18].

One aspect of particular interest to scientists emulating nature's light manipulation strategies is the diversity of highly specialized biological optical sensors, which allow organisms to extract information from the environment [19–24]. These systems are a result of evolution over millennia. Biological sensors are generally small, of exceptional sensitivity, and highly energy efficient [20]. In addition, they are often built in a redundant way. The parallel sampling and processing of sensory information improves the signal-to-noise ratio and also reduces the likelihood of errors caused by the malfunctioning or the loss of single sensory elements. Emulating the strategies of biological organisms to sense light levels, assess colors, create images, and otherwise convert light into other stimuli could be beneficial in a wide variety of human devices.

In this context, this perspective reviews a small selection of examples of the current activities in the field of biomimetic optical sensors. This selection is highly representative for the benefits that can result from emulating biological light manipulation concepts in man-made devices.

2. Infrared sensors

Many biological species utilize miniaturized infrared (IR) sensing systems with outstanding performance. Emulating favorable characteristics of these biological systems may help in developing infrared sensing materials and systems for military, medical, space, and industrial applications. Snakes, vampire bats, and some species of fire beetles have IR detecting organs with a similar structural design as those of engineered bolometers [25]. More specifically, the families of boas (*Boidae*), pythons (*Pythonidae*), as well as the subfamily *Crotalinae* of the family of *Viperidae*, possess infrared absorbers to convert IR light into heat, combined with a thermal-sensitive system that directly detects IR radiation-induced temperature changes in the IR sensing organs. Vampire bats are the only animals known to have bolometer-like IR sensing organs to capture the IR signatures of their endothermic preys [26]. The larvae of fire beetles live on freshly burnt woods to avoid the defense reaction of living trees; fire beetles thus need to find these woods to allow their offspring to hatch and grow safely [27–29]. This unique survival strategy is facilitated by their sensitive IR receptors, which have received great attention from the biomimetic IR sensing community. While, as we will see in the next paragraph, some species of fire beetles have photomechanic IR sensing organs, other species such as *Acanthocnemus* and *Merimna*, have bolometer-like IR sensing organs, i.e., organs composed of an IR absorbing area and an associated thermal sensor (Fig. 1).

Melanophila acuminata beetles have infrared sensing organs, which rely on a photomechanic detection mechanism that is also frequently used in engineered photomechanic IR sensors. More specifically, these beetles possess about one-hundred infrared sensing organs (*sensilla*), which are capable of detecting fires from a long distance [30]. Fig. 1 (left) portrays a schematic of a single IR *sensillium*. The receptor cells are based on a pressure chamber made of a hard chitin structure, which is filled with a liquid [31,32]. Incident IR radiation causes an expansion of this liquid and the corresponding pressure rise leads to a deformation of the tip, which induces a response of the mechanoreceptive neuron. Although the detection mechanism has already been established, the actual sensitivity to IR radiation has not yet been determined. Calculations suggest that the beetle can detect IR radiation below 4×10^{-5} $\mathrm{W\,m^{-2}}$, thus outperforming commercial, high-sensitivity pyroelectric detectors [33].

A biomimetic micro-sensor design that emulates the functionality of IR receptors of *Melanophila acuminata* beetles has recently been developed [34–36]. In this design, incident IR radiation heats a liquid, thereby inducing a mechanical deformation of the membrane that is detected by a capacitor. Temperature changes can thus be determined by monitoring changes in capacitance. This photo-mechano-electric device, which is conceptually similar to the beetle's receptor, operates at room temperature without any active cooling, contrary to other infrared photon detectors.

3. Real-time measurement of aircraft wing deflection

Designing longer, thinner, and lighter wings is one of the current strategies for reducing the overall weight of aircrafts. It is expected that this approach would lead to better fuel economics and lower carbon emissions by at least 50% compared to current aircraft technology [37]. However, this approach would result in increased wing flexibility, which can adversely affect aircraft performance with regard to aerodynamic efficiency and safety. Accurate determination of the wing position and shape during flight can help active control methods designed to mitigate potential problems due to increased wing flexibility.

Recently, a biomimetic optical sensor based on the physiological aspects of the eye (and vision-related neural layers) of the common housefly *Musca domestica* has been developed to track wing deflection in real-time [38,39]. Compound eyes exhibit a unique optical scheme for imaging, for instance allowing for wide field-of-view detection [40]. As artificial compound eyes have enormous potential for many different applications, several biomimetic efforts have been devoted to duplicate their functionalities [4], including the bioreplication of the eyes' micro- and nanoscale textured surfaces [41]. For the envisioned application in wing deflection assessment, a biomimetic engineering approach was used to extract the relevant image processing features of the fly's eye without aiming to reproduce all the functionality and appearance of the biological vision system.

Flies use a combination of quasi-Gaussian overlapping photoreceptor responses combined with neural superposition to achieve hyperacuity, i.e., the ability to detect image features to a much higher degree than just the photoreceptor density would imply. Fig. 2 (left) depicts the overlapping Gaussian visual field of three photoreceptors, similar to that exhibited by the fly's vision system, which allows for very precise and accurate measurements of position. This is the basis for the fabrication of the biomimetic sensor platform, which consists of the sensor head and a printed circuit board (PCB). The sensor head has seven light channels connected to seven separate photodiodes located on the sensor PCB. Each photodetector has its own channel on the PCB for current-to-voltage conversion followed by signal conditioning and filtering, taking place in parallel for each channel. A particular emphasis was given to emulating the fly eyes' high sensitivity in low-light and low-contrast environments, its sensitivity to motion, and its compactness.

To test the biomimetic sensor, a target was moved in a horizontal direction in front of the sensor, to simulate the deflection of an aircraft wing. Combined with a hardware-implemented differencing algorithm the sensor showed good target tracking providing a real-time solution to monitoring the deflection of a given aircraft wing. The advantages of this biomimetic sensor over conventional sensor solutions are its low weight and small form factor, fast computation, and low power requirements.

4. Applications in robotics

The new millennium has seen a rapidly growing interest in the development of autonomous robots for applications in industry, health services, medicine, and entertainment. Mobile robots are used to sense information about their surroundings, process the captured data, and in response initiate and effectuate movements to complete specific tasks autonomously. However, implementation of real-time detection and response systems in autonomous robots is challenging, even with the computational power of modern hardware. By contrast, a vast abundancy of biological organisms has mastered the use of sensory-motor

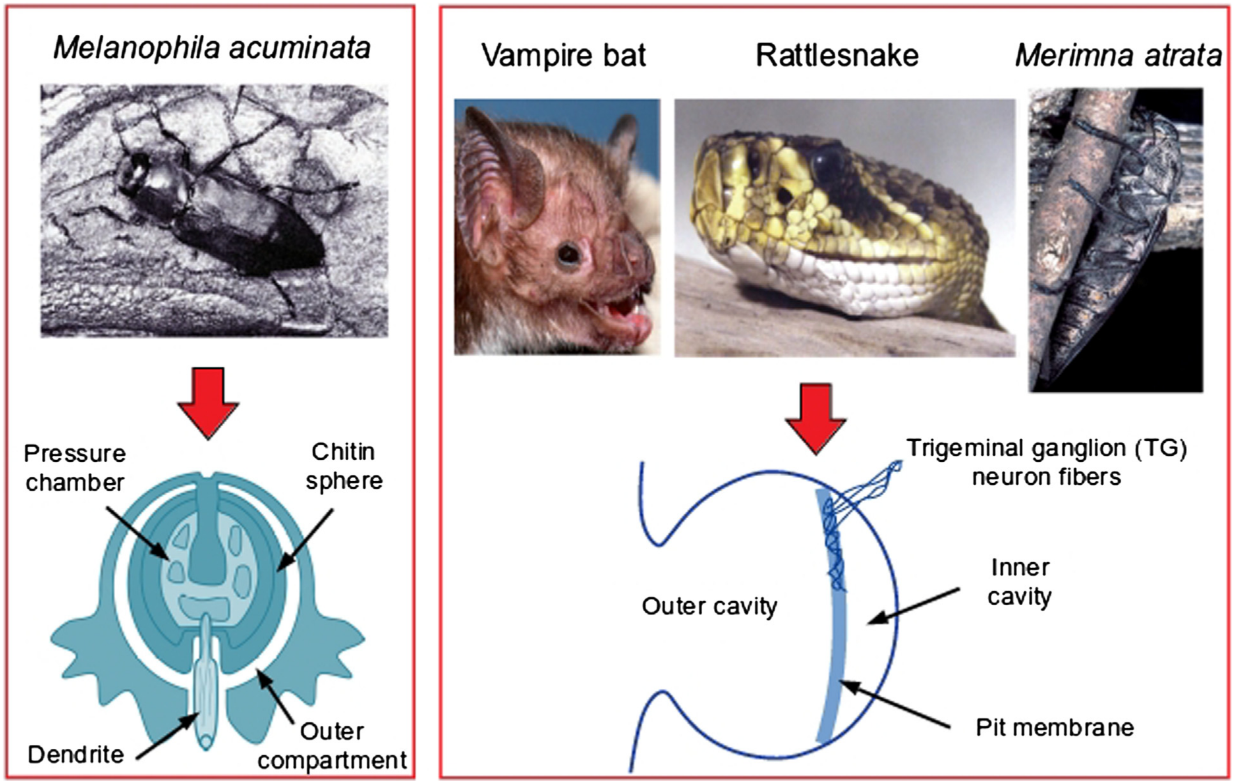

Fig. 1. Two different natural IR sensing organs. Biological systems with (left) photomechanic IR sensing organs and (right) bolometer-like IR sensing organs [25]. Courtesy of Prof. Tao Deng.

control and autonomy to perform their daily activities. For instance, many lightweight and low-powered flying insects track prey or conspecifics within cluttered natural environments, illustrating an efficient biological solution to the target-tracking problem [42]. Dragonflies pursue prey and mates deftly selecting their target amidst swarms. This insect-inspired approach has recently been translated into a robust and efficient target-tracking algorithm inspired directly by insect neurophysiology [43]. Moreover, bio-inspired, multifocal compound eyes have recently been developed, with application in various optical imaging systems, such as three-dimensional imaging and real-time detection of targets [44].

Tremor, sometimes called physiological *nystagmus*, is an aperiodic, wave-like motion of the eyes with a frequency of around 90 Hz [45]. Tremor eye movements inspired the development of an optical sensor termed Vibrating Optical Device for the Kontrol of Autonomous robots (VODKA) [46]. Basically, the bio-inspired sensor relies on the repetitive micro-translation of two photoreceptors set behind a small lens and on the subsequent signal processing designed to locate a target from the two photoreceptor signals. The experimental results showed that the VODKA sensor, depicted in Fig. 3, is able to locate a contrasting edge with an outstandingly high resolution 900-fold greater than its static resolution, regardless of the scanning law imposed on the retina. The remarkable hyper-acuity factor demonstrated by this two-pixel-retina has its origin both in the micro-vibration of the retina behind the lens and the employed signal processing strategy. Accordingly, hyper-acuity is realized at a very low cost, which constitutes a promising approach

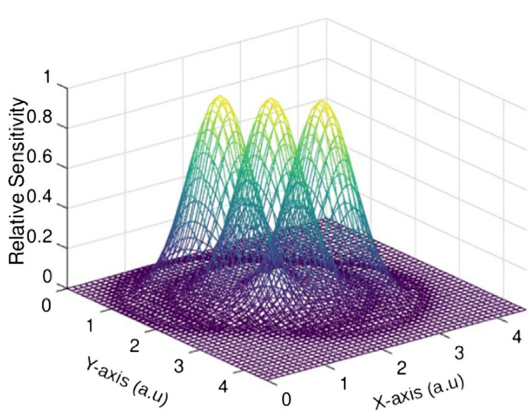

Fig. 2. (left) Overlapping sensitivity curves of the biomimetic sensor similar to that exhibited by the fly's vision system. (right) View of the sensor head [38,39]. Images courtesy of Prof. Cameron H.G. Wright.

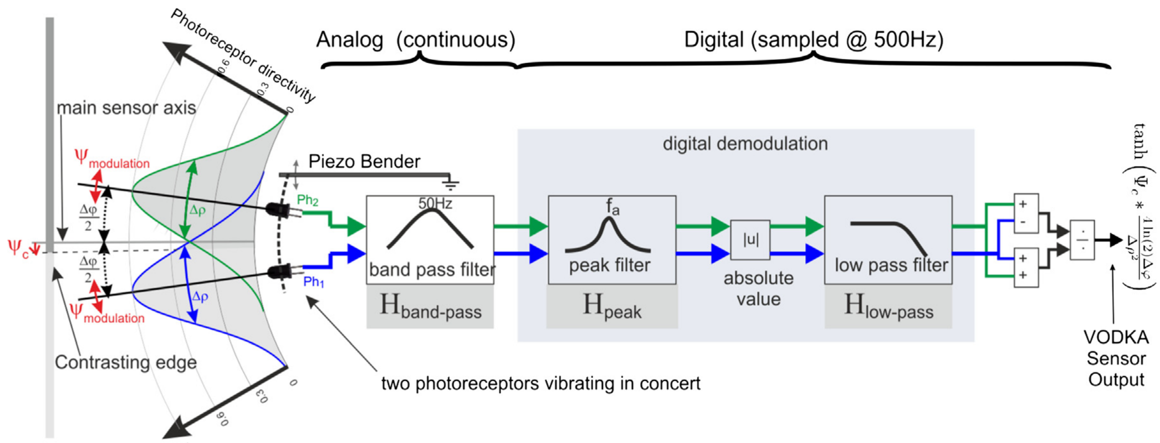

Fig. 3. Schematic representation of the VODKA sensor. To the left the Gaussian angular sensitivity of each of the two photoreceptors placed in front of a contrasting edge is shown. Mechanical vibration applied to the photoreceptors cause their optical axes to rotate jointly. A bandpass filter acting as a pseudo-derivative filter extracts the signals generated in each photoreceptor by the relatively high frequency vibration. An optional peak filter removes all frequencies not associated with the vibration. A demodulator extracts the envelope of the signal. The relative difference between the two signals yields the VODKA sensor output [46]. Image courtesy of Dr. Lubin Kerhuel.

for the accurate visual sensory-motor control of robotic platforms.

To test the performance of the bio-inspired sensor, the device was mounted onto a miniature aerial robot. The results showed that the system was able to track a moving target accurately by exploiting the robot's uncontrolled random vibrations as the source of its ocular microscanning movement. In all, it was found that the VODKA sensor was able to determine the angular position of a naturally lit target by extracting and processing the low-amplitude and high-frequency signals transmitted by two jointly vibrating photoreceptors.

5. Chemical sensing

Many animals utilize micro- and nano-scale structures to create conspicuous colors. Some remarkable examples include beetle exocuticles, butterfly wings, cephalopod skins, mammalian skins, and avian skins and feathers [10,47–54]. Moreover, some species have the capability of changing their coloration as a strategy for communication, camouflage, predator deterrence, thermo-regulation, and other functions [55–61].

The ability of cephalopods to rapidly change their skin coloration led to the investigation of the underlying proteins for the development of bio-inspired sensors that change color in response to the presence and concentration of target chemicals [62,63]. More recently, a bio-inspired, colorimetric sensing material composed of filamentous bacterial viruses (M13 phage), mimicking the structure of turkey skin (*Meleagris gallopavo*) has been developed [64]. In this work, tunable phage-based structures were fabricated using a self-templating assembly process. The resulting structures are composed of quasi-ordered phage-bundle nanostructures, which exhibit viewing-angle independent colors. The sensing material thus consists of arrays of differently colored phage matrices, which rapidly swell or shrink upon exposure to external chemicals. This behavior results in color changes comparable to those observed on turkeys, when they become flustered. As such, chemicals can be quantitatively identified through color pattern analysis. Moreover, the function of the phage matrices can be tailored through directed evolution for specific target molecules. Furthermore, large-area multicolor matrices that are readable by common handheld devices were produced.

A few years ago, the iridescent scales of the *Morpho sulkowskyi* butterfly were shown to exhibit variations in their optical properties when exposed to different vapors [65]. More specifically, the reflectance spectra of the scales can give information about the nature and concentration of the vapor phase around the scale nanostructures. This allows identifying different closely related chemical vapor constituents, when they are analyzed individually. Subsequent research revealed a chemical polarity gradient as the mechanism responsible for the biological structure's ability to act as an optical transducer with highly selective vapor response [66]. Employing the insights gained about the natural system, photonic vapor sensors were demonstrated that emulate structural and chemical key features of the biological counterpart [67]. Individual units of this novel bio-inspired design are capable of multivariable vapor sensing and thus have the potential to outperform conventional vapor sensor arrays. This sensing paradigm can also be applied for non-condensable gases, as has recently been shown by detecting hydrogen, carbon monoxide, and carbon dioxide [68].

The bio-inspired nanostructures, comprising periodic ridges and lamella, were fabricated on silicon wafers as periodic silicon oxide ridges normal to the wafer surface using a combination of conventional photolithography and chemical etching (Fig. 4). These ridges supported periodic layers of silicon nitride lamella parallel to the wafer surface and separated by air gaps. As depicted in Fig. 4(B), the structures showed a strong reflectance in well-defined spectral ranges (colors). Fig. 4(C) and (D) show images of the resulting structures, their main structural differences being the number and the thickness of individual *lamellae*.

The experimental results showed that the bio-inspired photonic gas sensors provided specific, distinguishable responses to individual gases. In conclusion, the fabricated sensors were able to distinguish individual closely related vapors in mixtures and in the presence of water vapor interference, which is difficult to achieve with the natural *Morpho* nanostructures and other conventional sensors.

An alternative approach for the development of biomimetic chemical sensors involves the use of spider silk. Spiders are known to be able to spin up to seven different types of silk [69], all of which have a precise function in the web. For instance, viscid silk is used by the spider to catch preys, while dragline silk serves as material for the framework of the web. The latter is reputed for its high tensile strength and extreme toughness [70]. This fact is exploited to make strong and extendible textile fibers. Silk wires have also been used as light guides, for instance in a demonstration of light guiding along dragline silk fiber with transmission losses of the order of a few dB/cm [71–73]. The potential of using such dragline silk as an optical fiber for detecting chemical agents has been explored recently [74,75]. Given that the elemental building blocks of dragline silk are proteins, the presence of chemical agents around the silk can induce changes in the properties of

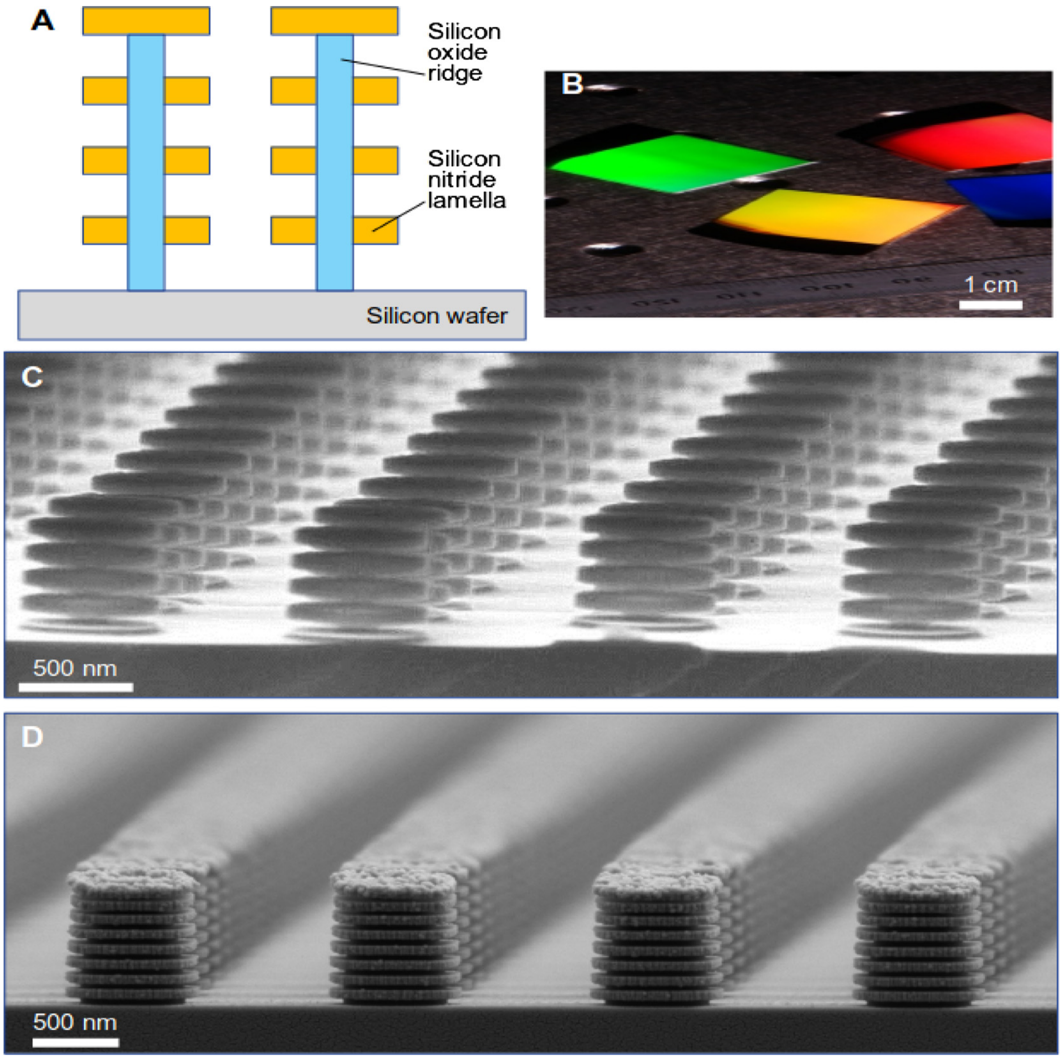

Fig. 4. (A) Schematic representation of bio-inspired nanostructures fabricated using conventional photolithography and chemical etching, and applied for gas sensing. (B) Reflectance of white light of four different nanostructures. (C),(D) Scanning electron microscopy images of the fabricated nanostructures [68]. Images courtesy of Dr. Radislav A. Potyrailo.

the fiber material in its entire volume. This leads to a measurable change of the properties of light propagating inside silk fibers. In particular, dragline silk directly collected from the major ampullate gland of a female *Nephilia edulis* spider was used in the above-mentioned work. Linearly polarized light was launched into the silk fiber and the state of polarization of the output light was analyzed. The experimental results showed that the presence of non-polar molecules did not impact the silk fiber's birefringence. Additionally, when exposed to pure carbon dioxide gas, the polarization of the output light barely changed. However, when the fiber was put in contact with hydrogen bond-active chemical agents, such as water and ammonia vapors, the polarization state drastically changed. These results have the potential to bring a major breakthrough in the field of optical fiber sensing.

Finally, it is worth pointing out that silk fibroin has also been used as a very versatile material system for the fabrication of free-standing three-dimensional photonic crystals and other functional optical devices [76–82].

6. Mechanical sensing

The need for quantifying forces, stresses, and pressures acting on an object and assessing the related mechanical strains with spatial and temporal resolution has led to a wealth of research aimed at transducing mechanical stimuli into an optical response. The use of color variations as an indicator of changes in an object's mechanical state are particularly interesting in situations where the application of sophisticated mechanical sensing equipment is prohibitive or unnecessarily difficult and costly. In this regard, several studies have drawn inspiration from biological mechanochromic materials to design synthetic systems that encode mechanical stimuli into clearly perceivable color variations. In particular, the guanine-based photonic crystals present in the skin of chameleons, which enable the organism's ability to change its coloration [83], have inspired the design of mechanochromic photonic films formed from non-close-packed colloidal arrays. The fabrication of these synthetic mechanochromic sensors is based on embedding face-centered-cubic arrays of silica nano-particles into an elastomer, as portrayed in Fig. 5(A). A non-close packed particle configuration is achieved by tailoring the inter-particle repulsion due to solvation layers on the particle surface. In this configuration, any deformations of the elastomer matrix leads to changes in the particle spacing, resulting in a variation of the material's structural color. Anticipated applications for this material range from real-time visualization of skin deformations to the conversion of acoustic waves into visual color vibrations [84,85]. These materials can also be expected to be useful in sensing strains and pressure, recognition of fingerprints, encryption of information, and flexible displays [86–88].

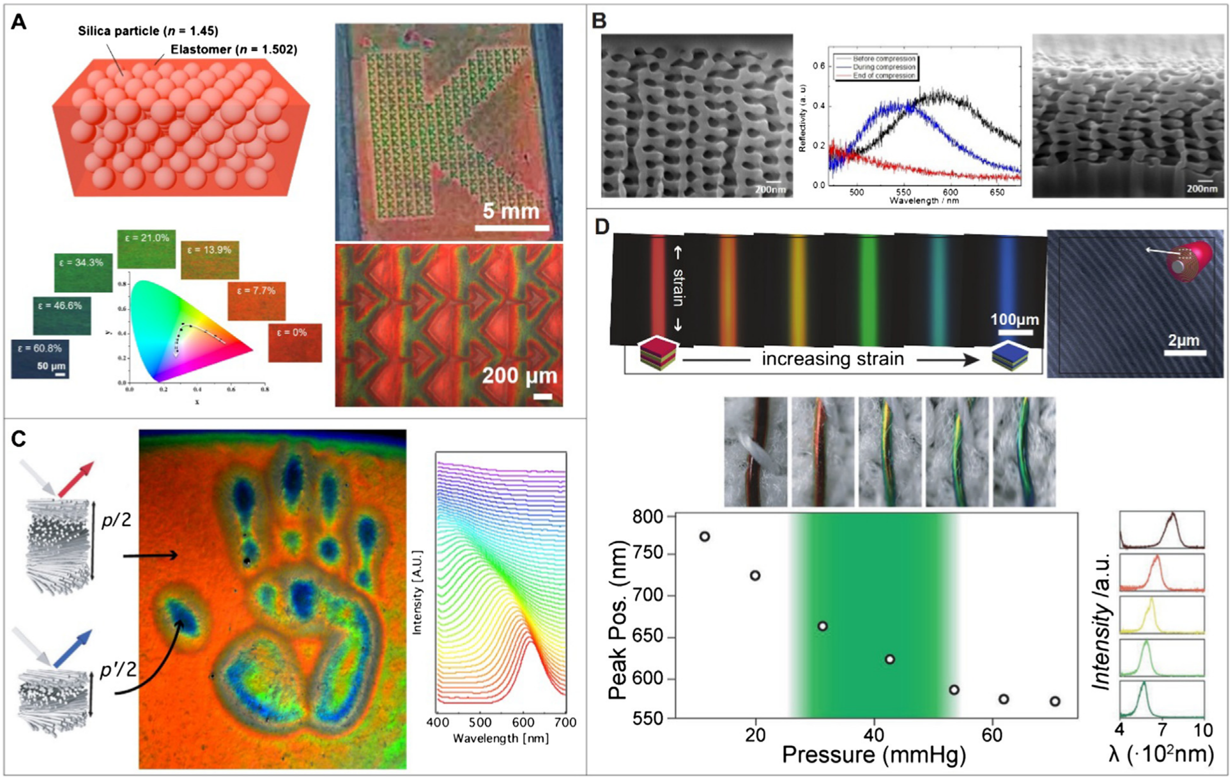

Fig. 5. (A) Chameleon-inspired mechanochromic 3D photonic crystal films that respond to a deformation with a change in color [83]. Images courtesy of Prof. Shin-Hyun Kim. (B) Reflection spectra and scanning electron microscope images of bicontinuous cubic nanostructures found in insect scales before and after compression [89]. Images courtesy of Dr. Xia Wu. (C) Cellulose-based photonic crystal films as compressive strain sensors [13]. Images courtesy of Dr. Silvia Vignolini. (D) Color-tunable multilayer photonic fibers that indicate pressure changes in bandages via a predictable color variation [91].

Another study explores the interplay between mechanical structure and optical properties in bi-continuous cubic nanostructures in three-dimensional photonic crystal architectures found in the scales of many insects [89], as depicted in Fig. 5(B). This study provides the fundamental knowledge and offers design guidelines for mechanochromic sensors fabricated from elastic constituents.

Furthermore, helicoidal photonic cellulose architectures found in tropical fruits have inspired the creation of biomaterial-based optical strain sensors from hydroxypropyl cellulose, which exhibits a cholesteric liquid-crystalline phase that reflects circularly polarized light with spectral selectivity [13], Fig. 5(C). The sensors appear to reliably detect compressive strains of up to 100% with a resolution of 2%. These scalable, biocompatible, and inexpensive strain sensors could be useful in a variety of biomedical and biomechanical applications.

Color-tunable elastomeric photonic fibers are another type of mechanochromic material inspired by tropical fruits. The fibers consist of a multilayer architecture formed from two elastomers with different optical density wrapped around an elastomeric absorbing core [90]. They can sustain axial strains of over 100% reversibly and respond to a deformation with a predictable change in color. These mechanochromic fibers, shown in Fig. 5(D), have been incorporated as colorimetric pressure indicators into compression bandages, thus providing quantitative feedback about the pressure underneath them [91]. Knowledge of the pressure applied by a bandage is critical in compression therapy to optimize the treatment of a variety of ailments.

The present efforts in creating biomimetic mechanochromic sensors complement non-biomimetic sensor design initiatives that target the transduction of a mechanical stimulus via an optical readout mechanism, which have led to the development of a variety of promising material systems [92–95]. While knowledge of biological mechanochromic materials is *per-se* not required in these efforts, it might allow for faster identification of useful concepts, material combinations, geometries, and sensor integration strategies with great potential to reduce the time from conception to realization of a working prototype.

7. Conclusions and perspectives

In this perspective, we have showcased a few exemplary uses of biomimicry applied in the development of optical sensors. These include infrared, mechanical, and chemical sensors, as well as sensors used in robotics and aerospace applications.

These examples show how the mimicking and emulating of nature's light manipulation strategies can offer novel and exciting ways to address technological challenges in a creative fashion. The growing field of biological optics and bio-inspired photonics is highly interdisciplinary, building on the expertise of biologists, chemists, material scientists, physicists, mathematicians, and engineers alike. Biological systems have plenty of inspiration to offer for the design of functional materials and devices in optics and beyond. However, it is still a formidable challenge to translate the control of nano- and microscale morphology and composition observed in many biological optical materials into man-made systems. We also know very little about the formation of functional optical materials in nature and are struggling to parallel the ability of many organisms to reconfigure and tune their material structures and resulting optical appearance and other functions on the fly.

The examples of biomimetic and bio-inspired optical devices discussed in this review provide evidence for the benefits and utility that arises from research aimed at understanding biological optical systems and their formation principles and translating this knowledge into synthetic analogues. While biological strategies rarely provide the full solution needed for developing a specific technology, natural systems with optical properties and other functions of interest to humans can indicate very useful starting points for the design and optimization of multifunctional materials and devices. We expect biomimetic and bio-inspired approaches in technology development to blossom in the coming years, with an increasing number of emerging applications in fields beyond optical sensing.

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