Optical and Quantum Electronics (2024) 56:1303
https://doi.org/10.1007/s11082-024-06798-6

Celebrating biomimicry: bioinspired layers in optical biosensors

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Received: 6 December 2023 / Accepted: 5 March 2024

Abstract
Optical sensors have seamlessly integrated the progress of materials science, giving rise to a novel class of devices. These cutting-edge sensors incorporate bioinspired sensing layers, coatings, and mechanisms, tailor-made for various specialized applications in fields like medicine, industry, and technology. This advancement paves the way for groundbreaking improvements in biosensor technology, offering enhanced capabilities for detecting and analyzing various substances in diverse settings. In this brief report the recent and future challenges in biosensors applying bioinspired sensing layers, as well as advances in science and technology to meet them, are presented.

Keywords Optics · Fiber-optic sensors · Bioinspired layers · Biosensors · Biommicry

1 Introduction

Fiber optic sensors (Elsherif et al. 2022) can be divided in terms of modulator type or due to the size of the measuring arm. Moreover, sensors are divided into point sensors, pseudo-scattered sensors and diffused ones, the last group has the biggest modulating area. In the point sensors, the measured value is determined at one point, while the pseudo-scattered are defined as multi-point sensors. In the case of distributed sensors, the measuring head is the entire length of the optical fiber, within which many adjacent sensors can be implemented. The latest approach in general can give greater sensitivity but it is also making the sensor more fragile (Fan and Bao 2021; Szczerska 2022; Li et al. 2021).

Fiber optic sensors can be categorized into two types: intrinsic sensors and extrinsic sensors (Tosi et al. 2022). In the external processing sensors, the optical fiber is used only to transmit the light signal, the modulation of which takes place outside the waveguide. In the industry, sensors of this kind are currently more frequently employed than those featuring internal processing, where the modulation of the light signal occurs within the optical fiber forming the measurement head. The internal modulation allows e.g., constant monitoring of sensor efficiency. Another classification criterion is the parameter of the light wave, which changes under the influence of a physical quantity. In this respect, a distinction is

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Extended author information available on the last page of the article made between sensors with intensity, wavelength, polarization or phase modulation of the light wave (Habel and Krebber 2011; Monsberger and Lienhart 2021; Kumari et al. 2019).

Biomedical manufacturing (Munir et al. 2020) of sensors based on telecommunication optical fibers offers remarkable advantages, particularly in terms of relative simplicity of the construction, effectiveness, and high production capacity. This manufacturing process allows for the creation of a large number of sensors within a short period. Notably, the production of these sensors generates minimal waste in the form of chemical reagents, thanks to the micro size of the sensor based on the microstructures. Contrary to the currently used immunoenzymatic techniques (Jääskeläinen et al. 2020), capillary electrophoresis or mass spectrometry, which use significant amounts of organic chemical solvents, expensive elements such as chromatographic columns, or sets of polyester plates for determination using the ELISA method or highly toxic polyacrylamides in PAGE technology, our solution requires the use of only phosphate buffer saline, which is completely safe and environmentally friendly.

Optoelectronic sensors are willingly combined with the achievements of materials science, thus obtaining devices dedicated to specific applications with the necessary parameters achieved by the use of various nanomaterials.

Nanomaterials-based optoelectronic sensing systems have wide-ranging applications in biomedicine, environmental monitoring, and biotechnology. They play a crucial role in medical diagnostics, identifying disease biomarkers and pathogens in biological samples, contributing to early disease detection and personalized medicine. Environmental monitoring benefits from their ability to detect pollutants or contaminants in air and water with high sensitivity, aiding in environmental conservation efforts. In biotechnology, nanosensors with sensing layers facilitate precise analysis of biomolecular interactions, advancing drug development and protein research.

The synergy between optics' sensitivity and bioinspired nanolayers properties in optoelectronic sensing systems based on nanomaterials ushers in a new era of biomolecule detection. These advancements have the potential to transform various industries, bringing about improved healthcare, environmental sustainability, and breakthroughs in biotechnological research. As technology continues to evolve, bioinspired nanolayers-based sensing systems will undoubtedly play a pivotal role in shaping the future of biomolecular analysis and applications. In this letter the recent and future challenges in biosensors applying bioinspired sensing layers, as well as advances in science and technology to meet them, are presented.

2 Recent and future challenges

The demand for rapid diagnostics in various settings, including homes, airports, schools, and workplaces, necessitates efficient and large-scale screening methods. An excellent illustration of this pressing requirement emerged during the worldwide SARS-CoV-2 / COVID-19 outbreak, where the timely identification of the virus played a pivotal role in managing its dissemination. Presently, COVID-19 diagnosis relies on techniques such as RT-qPCR (Reverse Transcription Quantitative Polymerase Chain Reaction (Dutta et al. 2022)) or immunochromatography. It is vital to highlight that effective and widespread screening tests can be instrumental in managing ongoing and potential future pandemics. By conducting mass screening tests to detect the virus in humans and monitoring the pathways of disease transmission, health authorities can identify and isolate infected individuals promptly, reducing the risk of further spread. Fast and accessible diagnostics not only aid in containing pandemics but also play a pivotal role in making informed public health decisions and implementing appropriate preventive measures. The availability of rapid screening tests in various locations allows for timely identification of cases, enabling immediate isolation and treatment, thus safeguarding both individuals and communities from the detrimental effects of infectious diseases. To sum up, it is essential to emphasize the significance of rapid and widespread screening methods, as they represent a critical frontline defense against infectious diseases and play a vital role in facilitating proactive measures to effectively manage and mitigate outbreaks. As technology continues to advance, the development and widespread implementation of rapid diagnostic methods will remain a top priority in ensuring global health security (Wagenhäuser et al. 2021).

The use of a biosensor seems to be an ideal solution that allows performing screening tests and refer only to people whose test showed a positive result for further confirmation with a genetic test (RT-qPCR, ELISA) (Yan et al. 2020). Minimizing contact, no need to send samples to the laboratory, and preliminary analysis at home are the obvious advantages of such a system. The possibility of multiple uses of the biosensor and the lack of the need to isolate the virus RNA should significantly reduce the examination time, which is the bottleneck in the diagnosis. Currently, the RT-qPCR technique for identification takes from 3 to 6 h depending on the available test. In our case, we aim to complete the test in $<$ 30 min (shorter than the currently available serological tests). Certainly, the technological hurdle involves the successful integration of progress in molecular biology with advancements in information and communication technology (ICT). The technological challenge is therefore to combine technology and use knowledge in the field of molecular biology and ICT (Yan et al. 2020; Özçürümez et al. 2020). By synergizing these two fields, we can overcome significant barriers and achieve breakthroughs in various areas, particularly in healthcare and biotechnology. The intersection of these fields creates fresh opportunities for inventive solutions to intricate issues:

(i) Diagnostics and Personalized Medicine—Integrating molecular biology techniques with ICT enables the development of rapid and accurate diagnostic tools, leading to early disease detection and personalized treatment plans. For instance, leveraging genetic information through DNA sequencing, coupled with sophisticated data analysis algorithms, allows for precise disease profiling and tailored therapies.

(ii) High-Throughput Screening and Drug Discovery—Combining molecular biology knowledge with advanced computational methods in ICT facilitates high-throughput screening of potential drug candidates. This approach expedites the drug discovery process and enhances the identification of novel therapeutic targets for various diseases.

(iii) Precision Agriculture—By utilizing molecular biology techniques to understand plant genetics and coupling it with sensor technologies and data analytics, precision agriculture practices can be optimized. This integration empowers farmers to make data-driven decisions for crop management, leading to increased yields and resource efficiency.

(iv) Bioinformatics, the application of ICT in the field of molecular biology, plays a crucial role in managing and analyzing vast biological data sets, such as genomic sequences, proteomics, and metabolomics. It helps extract meaningful insights and patterns from this wealth of information, accelerating scientific discoveries and medical advancements.

(v) Telemedicine and Remote Monitoring—Integrating molecular biology knowledge with ICT facilitates the development of remote monitoring devices and telemedicine platforms. These technologies allow healthcare professionals to monitor patients' health remotely, analyze molecular biomarkers, and provide timely interventions.

(vi) Synthetic Biology and Gene Editing—The combination of molecular biology and ICT provides a powerful toolkit for synthetic biology and gene editing applications. This synergy allows scientists to design and engineer genetic materials with precision, opening up possibilities for biotechnological advancements and gene therapies.

Sensors applying bioinspired layers, with their enhanced sensitivity and selectivity in detecting biomolecules like antibodies, offer a potential solution for efficiently prioritizing individuals for vaccination to achieve herd immunity. Indeed, measuring a patient's blood count may also contribute to more effective vaccination planning. According to the literature data, there is no need to vaccinate people with very high IgG / IgM antibody titers (Yang et al. 2021; Watson et al. 2020). With this information, healthcare authorities can prioritize those individuals for vaccination, focusing efforts on the segments of the population that may have reduced immunity against the disease. By strategically vaccinating those with lower antibody titers, the overall population's immunity level can be bolstered more rapidly. The integration of sensors with tailored sensing layers in vaccine distribution strategies can optimize resource allocation and vaccination campaigns, allowing for a targeted and efficient approach to achieve herd immunity. This not only protects vulnerable individuals but also helps to curb the spread of the disease in the community. To recap, optical sensors with bioinspired sensing layers have the potential to assume a crucial role in the fight against infectious diseases. They can assist in identifying and prioritizing individuals for vaccination, thus contributing to the overarching objective of attaining herd immunity and protecting public health.

3 Advances in science and technology to meet changes

In recent years, fiber optic sensors based on the use of light interference (low-coherence interferometry) have attracted considerable interest in biosensing applications. Such sensors offer sensitivity and measurement resolution comparable to the values achieved in classical interferometry, but can be translated to biological samples. In addition, they increase the dynamic range of the measurement with the possibility of using popular light sources (LEDs, deuterium, tungsten or xenon lamp) with a small coherence path, in some cases the multimode laser diodes can also be used.

Many scientific groups focused on development of such solutions, among which optical sensing devices can be found (Lukose et al. 2021). Several approaches were reported to date. Point-of-care antibody tests can be performed with a fiber-optic immunosensor utilizing Long Period Gratings (LPG) with a matrix allowing for bio-receptors immobilization (Wu et al. 2021). The increase of antibody concentration corresponds with the increase in refractive index on the LPG surface, inducing the wavelength shifts of LPGs. The Phase-Shifted Long-Period Fiber Gratings were also used for a label-free detection of SARS-CoV-2 (Lee et al. 2021). Exposition to different protein concentrations results in the variation of the wavelength separation in the signal. The solution offers reusability and storage stability. The immunoglobulin detection using biofunctionalization and spike protein with interferometric optical detection was described (Murillo et al. 2021). Within in vitro laboratory conditions the results were in agreement with the reference ELISA method. The idea of a U-shaped probe made from plastic optical fiber was introduced (Hadi and Khurshid 2022). The prototype's operational principle relies on intensity modulation. Another group describes a biolayer interferometry for a rapid detection of antigen-specific antibody levels (Dzimianski et al. 2020). A single-use biosensor offers automated 'dip-and-read' measurement giving a result in less than 20 min.

A low-coherence, miniature antibody sensor with a Fabry–Perot interferometer was also developed (Szczerska et al. 2023a, 2022). The principle of operation of the sensor is based on the measurement of radiation absorption in the range of ~ 1300 nm by the adhering IgG present in the solution. To enable the sensor to specifically identify SASR-CoV-2-specific antibodies, the S1 domain of the SARS-CoV-2 Spike protein was affixed or immobilized onto the fiber head. This biocoating of the optical fiber head allows an interaction to be established between the antibody and the S1 domain. Those kind of interactions and immobilization allow washing away the interfering background of e.g., serum, blood or another biological matrix, due to strong interaction antibody/antigen.

Fiber-optic biosensors can also be applied for the detection of CRP (C-reactive protein) and the determination of its level to detect inflammation (Szczerska et al. 2023b). For this purpose, the measurement head has to be modified accordingly. During the preparation stage, the optical fiber with a microsphere was immersed in a series of liquids to biofunctionalize its surface for CRP detection. Successive immersions in Avidin and Antibody solutions resulted in the formation of layers on the surface of the microsphere. The proposed method of biofunctionalization for SARS-CoV-2 and CRP detection are presented in the Fig. 1.

In 2021, Lu et al. adopted long range organization to enhance chiroptical response of achiral Au nanorods. They achieved this by assembling the nanorods into cholesteric liquid crystal-like helices, resulting in a 4600-fold increase in the g-factor (Lu et al. 2021). The authors found that when Au nanorods were co-assembled with the helical structure of the human islet amyloid polypeptide (hIAPP), it enabled them to finely manipulate the geometry, including the gap distance between Au nanorods, the pitch length of the nanohelix, and the number of turns. This precise control led to a high asymmetry factor of 0.1. Due to the

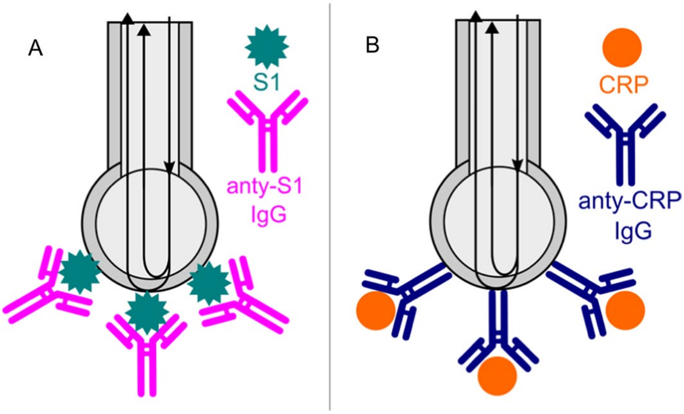

Fig. 1 A diagram illustrating various approaches to biofunctionalizing optical fiber microstructures. **A** The sensor for anty-S1 antibody detection from serum samples, **B** The sensor for CRP protein detection fr0m serum samples

high asymmetry factor and the time-dependent structural changes, the system exhibited a nontrivial optical rotatory dispersion signal that depended on the amount of amyloids present. This feature made the system suitable for screening inhibiting drugs, such as EGCG and D-NFGAIL, which bind to amyloids and inhibit their self-assembly.

The Nam research group reported the formation of 3D chiral Au nanostructures using amino acids and peptides through the enantioselective interaction of high-Miller-index surfaces in 2018 (Lee et al. 2018). These structures exhibited a high g-factor of 0.2. Subsequently, the same research group utilized these chiral Au nanostructures to develop a 2D biosensor (Kim et al. 2022). The biosensor involved the deposition of a 2D array of helicoid Au nanoparticles, enabling the quantitative determination and in situ monitoring of molecular chirality during DNA-RNA hybridization and protein folding, even at very low concentrations down to 10^{-12} M. Notably, the controlled alignment of the helicoid Au nanoparticles into a periodic hexagonal pattern on a nanopatterned polymer surface, along with the collective resonances, facilitated the detection of low concentrations.

4 Conclusion

The application of bioinspired layers, coatings, and mechanisms in biosensors presents an opportunity to create a novel category of sensors that can be effectively employed in point-of-care testing or even in home settings. For instance, optical sensor for anty-S1 antibody detection from serum samples was developed. The miniature measurement head diameter was 250 μm, requiring less than 1 μL of sample volume. The solution assures quick measurement time (less than 5 min), no need for preparation of the sample, and the limit of detection equal to1 μg/ml (Szczerska et al. 2023a). Another example shows a sensor for CRP protein detection. The described optical sensor assured detection limit of 5.65 μg/L in a CRP standardized solution of 10 μL sample volume, within less than 10 min. The optical sensors are hence promising supporting tools for medical purposes (Szczerska et al. 2023b). Furthermore, advancements in technology have enabled the collection of capillary blood samples from patients in a minimally invasive manner, which can then be analyzed using these sensors. Notably, fiber optic sensor solutions offer rapid diagnostic measurements and meet the specific conditions and requirements of the medical industry for sensor production.

Author contributions P.W. and M.S. were involved in conceptualization, project management, writing—original draft, review, and editing. M.K., and J.K., were involved in writing—the original draft, reviewing and editing. I.I., M.B., and R.V. were involved in writing—reviewing and editing.

Funding The research has been supported by the Ministry of Education and Science, Poland within the NdS/551425/2022/2022 grant, as well as the European Cooperation in Science and Technology under the grand CA21159—Understanding interaction light—biological surfaces: possibility for new electronic materials and devices (PhoBioS). Additionally, this study received supplementary support through DS programs at both the Faculty of Electronics, Telecommunications, and Informatics at Gdańsk University of Technology, and the Faculty of Telecommunications, Computer Science, and Electrical Engineering at Bydgoszcz University of Science and Technology.

Declarations

Conflict of interest The authors declare no financial or commercial conflict of interest.

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