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2D and 3D Photonic Crystal Biosensors for Viral Detection: From Mechanisms to Biomedical and Environmental Applications

[1]Muhammad Yasir Khan Painda, [2]Suaad Syed

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Muhammad Yasir Khan Painda
Beijing Institute of Technology
paindayasir@gmail.com
Suaad Syed
Beijing Institute of Technology
syedxadi@outlook.com

ABSTRACT

Among prominent light manipulating structures and label-free detection biosensors, phonic crystal (PhC) biosensors, especially 2D and 3D constructs, provide a powerful platform to detect virus. This paper covers principles, fabrication methods and performance metrics of 2D and 3D PhC biosensors with a focus on how they can be sensitive, selective, and practical for use in real-time and at the point-of-care. Comparative analysis discusses advantages and challenges of the both designs, and their roles in biomedial diagnostics and environmental sensors application. PhCs open doors to next generation rapid diagnostics that could be integrated into lab-on-chip systems and microfluidics despite the current fabrication and commercialization challenges.

INTRODUCTION

In today's world where recent global crises have highlighted the need for the rapid and sensitive detection of virus, it is essential to control infectious disease outbreaks (Tsalsabila et al., 2024). Although PCR is an effective diagnostic method, it is time consuming, and not easily practical in a resource limited setting (Kheirollahpour et al., 2025). On the other hand, photonic biosensors have higher sensitivity, require more minimal sample requirements, and are easily miniaturized for point of care virus diagnosis. Among these, biosensors based on photonic crystal (PhC) have received a lot of attention due to their label-free detection, and PhC's capability for control of light-matter interactions (Bubba et al., 2020). This article reviews the principles, mechanisms and application of 2D and 3D PhC biosensors for virus detection in the biomedical and environmental domains (Zhao et al., 2010). The 2D PhCs are dielectric materials in two dimensions, organized into a planar lattice, having photonic bandgaps (PBGs)—frequency ranges for which light propagation is forbidden. It also introduces resonant modes sensitive to changes in local refractive index. The index is changed by virus binding on biofunctionalized surfaces, i.e., with DNA/RNA, aptamers or antibodies, resulting in detectable shifts in wavelength or light transmission (Kalyani et al., 2022). Typically fabrication techniques such as electron beam lithography and reactive ion etching (RIE) using materials such as silicon, GaAs, or polymers are used (Mohammed et al., 2022).

Performance of 2D PhC biosensors for the detection of pathogens (SARS-CoV-2, influenza, Zika, chikungunya) and environmental monitoring of Vibrio cholerae and E. coli have been shown (Asuvaran et al., 2022). Being very compact and promising on-chip integration, they are particularly well adapted to portable diagnostics, and 3D PhCs embarking the refractive index periodicity into three dimensions, leading to complete photonic bandgaps and improved light control. In comparison to 2D analogs (Shen et al., 2021), these structures can provide higher sensitivity and more elaborate optical behavior. The same shift in resonant modes due to binding events can be used for detection of viruses in 3D PhCs. However, fabrication of these structures by self-assembly or advanced lithography is more complex, and this provides a limiting step. Therefore, developing scalable and cost effective methods is key to unleash their full potential in applications of high throughput biomedical and environmental sensor (Chiappini et al., 2020).

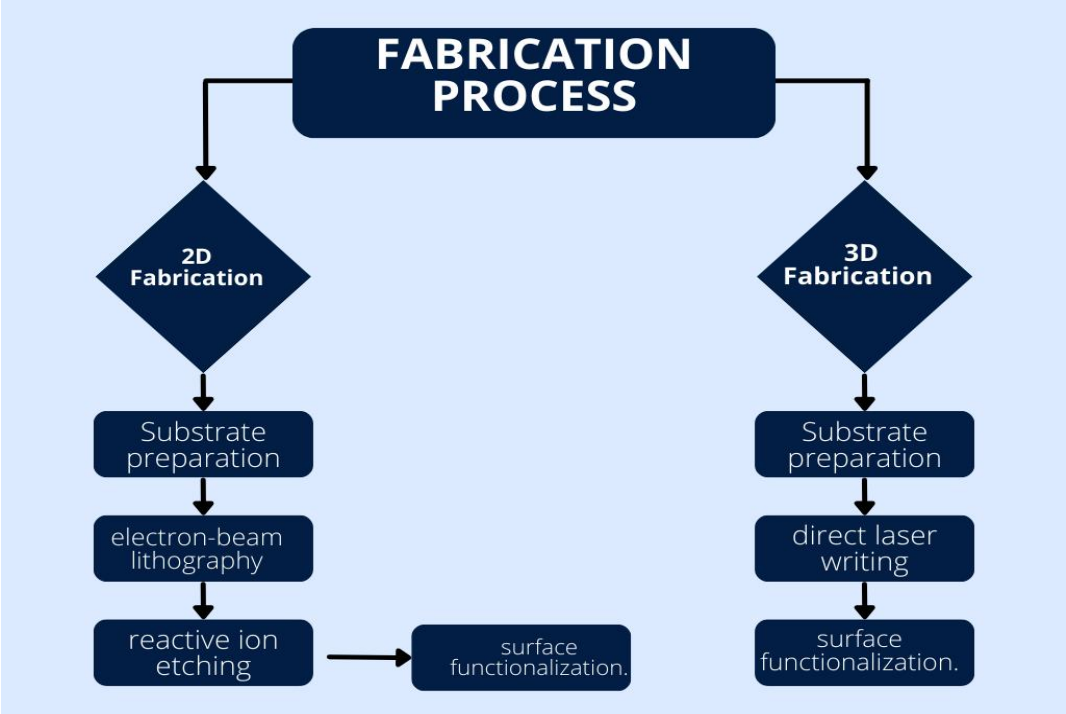

FIGURE 1: A FLOWCHART ILLUSTRATING THE STEP-BY-STEP FABRICATION PROCESS FOR 2D AND 3D PHOTONIC CRYSTAL BIOSENSORS, HIGHLIGHTING KEY TECHNIQUES LIKE ELECTRON-BEAM LITHOGRAPHY, REACTIVE ION ETCHING, AND SELF-ASSEMBLY

DIFFERENCES BETWEEN 2D AND 3D PHOTONIC CRYSTALS

While Photonic Crystals differ in their dimensionality of periodicity; 1D Photonic Crystals (a.k.a Bragg reflectors or stacks) are periodicity in only one dimension which is normally created by turning layers of different dielectric constants (Zhang et al., 2021). Trapping of electrons as single waves in every direction in space leads to the creation of areas where electrons cannot move. 2D Photonic Crystals present periodicity in two spatial directions and reflect a specific range of wavelengths. Nanostructures such as arrays of holes or rods are often fabricated using top down methods such as photolithography and etching. 3D Photonic Crystals comprise of repeating material element arrangement in the three basic spatial dimensions (Xia et al., 2004); Although they may not have a full photonic bandgap for all propagation directions, they may however have directional stopgap. 3D photonic bandgaps (where light of certain frequencies can be banned from propagating in any direction within the crystal) are realized in such a way that complete absorption of that light is possible. Currently, however, their fabrication is much more involved than 1D or 2D PhCs (Gesemann et al., 2010). An PBG is a range of frequencies or wavelengths for which light propagation is prohibited or strongly suppressed within the photonic crystal. Bragg diffraction, which is produced by periodic modulation of the refractive index (Russell et al., 1992), is the mechanism upon which the PBG formation is based on. If light waves having Bragg condition can propagate through the PhC, they have strong reflections at the material interfaces to the materials with different refractive indices. For certain frequencies however the reflected wave interfere destructively forming the band gap. Due to the PBG, there is unprecedented control over light propagation (Qiao et al., 2018). Localizing optical modes within the bandgap can be achieved by introducing defects (e.g., remove or alter a structural element) in the periodic structure. These defect modes

are able to confine and direct light at the resonant frequency within the defect region. This property is of critical importance for the development of advanced biosensors, where changes of the refractive index because of analyte presence can cause drastic spectral shifts of defect mode frequencies, the reflection or transmission spectrum. Furthermore, other applications of such substrates are possible—optical filters, waveguides, lasers (Naresh et al., 2021).

Feature	2D Photonic Crystal Biosensors	3D Photonic Crystal Biosensors
Dimensionality	2D periodicity	3D periodicity
Fabrication Methods	Electron-beam lithography, RIE	Self-assembly, Direct Laser Writing
Sensitivity	Moderate	High
Complexity	Lower	Higher
Applications	Pathogen detection, POC testing	High-throughput screening, Multiplexing
Advantages	Simpler fabrication, Integration with microfluidics	Enhanced sensitivity, Complete photonic bandgap
Challenges	Limited light confinement	Complex fabrication, Higher cost

TABLE 1: A table summarizing the key differences between 2D and 3D photonic crystal biosensors, including fabrication methods, sensitivity, complexity, and applications.

PRINCIPLES OF PHOTONIC CRYSTAL-BASED BIOSENSING

Photonic crystal (PhC) bio sensing takes advantage of periodic nanostructure's capability of handling the light in response to biological analyte, like the viruses. Based on the altered light propagation, namely a shift in resonant frequency or a change in transmission or reflection of PhC due to interaction with analyte causing a change in the local refractive index (Inan et al., 2017). PhCs are made of alternating materials with different refractive indices that construct photonic band gaps (PBGs) in which some frequencies cannot penetrate (Berger et al., 1999). Light confined in specific modes can be greatly enhanced due to sensitivity when structural defects, such as nanocavities or waveguides, are included. Thus, detection is based on such binding, which changes the local refractive index and thus shifts these resonant modes (Munday et al., 2002). Different modalities for improving light–matter interaction are offered by various PhC structures, 1D, slabs, waveguides, microcavities; among those, nanocavities are able to trap the viruses by superstrong optical fields (Butt et al., 2021). A major advantage of PhC biosensors is that it is also label free. Instead, they do not use fluorescent tags, but measure directly the change of optical properties (e.g. wavelength, intensity) resulting from virus binding. It simplifies the workflows, decreases the interference and allows real time monitoring (Shamah et al., 2011; Ramachandran et al., 2005). In order to achieve selectivity, PhC surfaces are functionalized with biorecognition elements such as antibodies, aptamers, or strand of DNA/RNA probes that specifically bind a target virus. Techniques such as adsorption, covalent bonding, or electrostatic interaction serve to immobilize these elements (Inan, et al., 2017). From this, precise identification is via detection of the resulting refractive index shift upon virus binding. There is a critical need to select an appropriate recognition element for proper specificity and performance (Soler et al., 2020). Here in Figure 2, general working principle of a photonic crystal-based biosensor is illustrated.

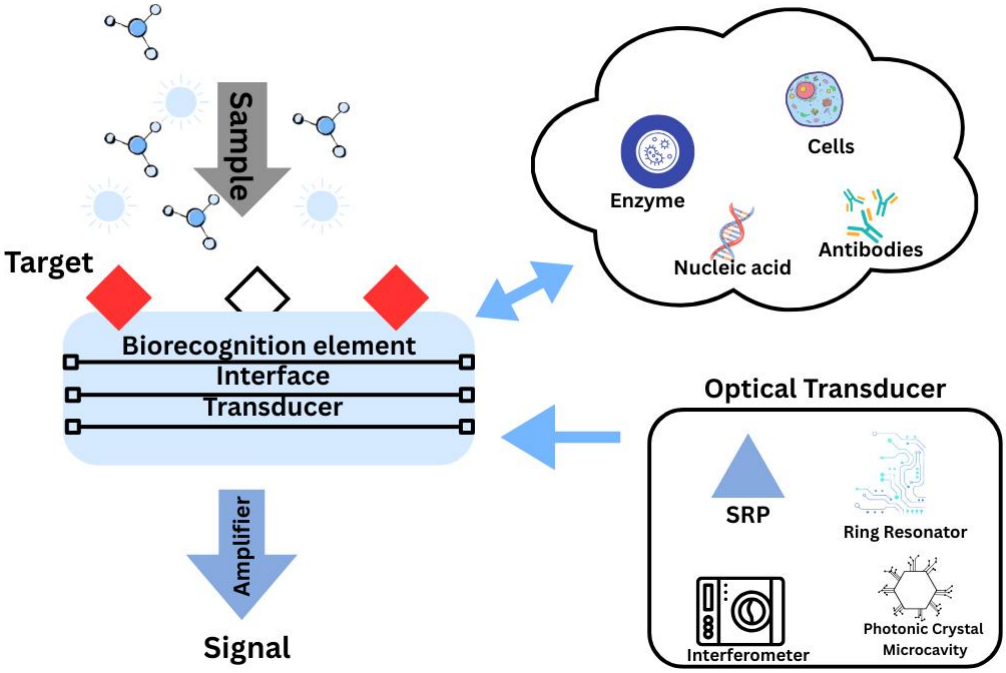

FIGURE 2: *The system involves a biorecognition element (such as enzymes, nucleic acids, cells, or antibodies) immobilized on the interface, which interacts specifically with target analytes from a sample. This interaction is detected by an optical transducer (e.g., SPR, ring resonator, interferometer), converting the biochemical binding into a measurable optical signal, amplified for output. The structure emphasizes modular layering from target recognition to signal amplification.*

2D PHOTONIC CRYSTAL BIOSENSORS FOR VIRAL DETECTION

Photonic crystal biosensors formed from two-dimensional (2D) photonic crystals are promising as highly sensitive detect sensors for viruses. Periodic nanostructures fabricated in two spatial dimensions are used by these biosensors to manipulate light, and then create photonic band gaps (Sharma et al., 2021). The local refractive index on the sensor surface changes by the presence of a virus or a viral component, and this will give a wavelength shifted optical transmission or reflection spectrum, e.g. a shift in resonant frequency.

Pettronaics, Recently developed fabrication techniques for 2D photonic crystal structure include electron beam lithography and reactive ion etching (RIE). Because this process permits the generation of precise periodic structures like array of air holes or rods across a slab of materials (Chen et al., 2019). Gallium arsenide (GaAs), silicon and polymer composites are among the materials used in 2D photonic crystal biosensors. And some have 2D materials like graphene in them, which gives extra sensitivity. Also, 2D slab photonic crystal sensors integrated to waveguides by using 2D optofluidic setups have been studied (Raga et al., 2023).

Sensitivity of a photonic crystal biosensor is usually defined as the shift of the resonance wavelength per unit change of the refractive index (nm/RIU). Lower detection limits are achieved due to high quality factors (Q-factors) of the resonant modes (Tavousi et al., 2018). A GaAs 2D photonic crystal biosensor in waterborne bacteria detection demonstrated a high Q-factor of 9227.9 and sensitivity of 226.97 nm/RIU with a detection limit of 4.405×10^{-4} RIU (Ould Bahammou et al., An ultra-high quality factor and an excellent sensitivity for the

application of detecting malaria are also realized in another 2D photonic crystal design with a double hole cavity. The surface of the photonic crystal is usually functionalized with biorecognition elements such as antibodies, aptamers or DNA/RNA probes specific to the target virus to get selectivity for viral detection (Gowdhami et al., 2024). The change in the refractive index on virus binding is the basis for this labelfree detection method. With some photonic biosensors, detection limits are in the range of picogram per milliliter (pg mL^{-1}) and are highly sensitive to the design and to the target analyte (Arshavsky-Graham et al., 2018).

CASE STUDIES: APPLICATIONS IN SARS-COV-2, INFLUENZA, ZIKA

While some studies focus mainly on 1D photonic crystals and other optical methods for the detection of SARS-CoV-2, they nonetheless bring out the general potential of photonic biosensors in virus detection. For example, optical ring resonators are specially noted for their high sensitivity and specificity in detecting such different biological analytes, and can be fabricated with 2D photonic crystal principles (Bukasov et al., 2021). A study also refers to the use of a light guide in a three-dimensional photonic crystal for user friendly point of care detection of influenza A (H1N1) virus. It is not 2D strictly, but shows how photonic crystals can be applied for influenza detection. A second method was developed that utilized a microcavity in-line MZI optical fibre sensor functionalized with anti N SARS-CoV-2 protein antibodies to make rapid, label free detection possible. For planar fluorescence excitation and detection of Zika virus NS1 protein or a particular segment of the Zika genome, there is an optofluidic setup that uses 2D slab photonic crystal sensors that intersected with ARROW waveguides (Manzanares-Meza et al., 2020). Finally, this illustrates the application of 2D photonic crystal–based platforms for Zika virus detection but only in a fluorescencebased assay. For rapid, sensitive, and selective viral detection in biomedical and environmental applications, advancements in fabrication techniques and material science are expected to be continued to improve the performance of 2D photonic crystal biosensors (Petersen et al., 2020).

Case Study	Type of Biosensor	Target Virus	Key Findings
Study 1	2D GaAs-based	SARS-CoV-2	High sensitivity, suitable for POC testing
Study 2	3D self-assembled	Influenza A	Single-particle detection, high throughput
Study 3	2D optofluidic	Zika virus	Rapid detection, multiplexing capability

TABLE 2: A table summarizing key case studies on the application of 2D and 3D photonic crystal biosensors for detecting specific viruses, including the type of biosensor, target virus, and key findings.

3D PHOTONIC CRYSTAL BIOSENSORS: ENHANCED SENSITIVITY AND COMPLEXITY

In an evolution of 1D and 2D counterparts, three dimensional (3D) photonic crystal biosensors have the potential to push the sensitivity and provide more complex control over light matter interactions (Inan et al., 2017). 3D photonic crystals consisting of the periodic structuring of materials in all three spatial dimensions can lead up to the complete photonic band gap, i.e. light of particular frequencies is altogether forbidden to propagate in the structure. Such property can be utilized to fabricate highly confined optical modes and enables strong coupling with the analytes, which is theoretically projected to result in the improved sensitivity as compared to more conventional less dimensional structures (Khani et al., 2022). The creation of 3D photonic crystals is hindered by the requirement of high precision in three dimensions. Traditional lithographic techniques, while advanced for 2D structures, face limitations when

extending to complex 3D architectures. However, significant progress has been made through advanced fabrication methods. Self-assembly has emerged as a promising approach for creating periodic 3D structures (Men et al., 2017). For instance, magnetic photonic crystals capable of self-assembly have been explored for biomedical applications. Furthermore, self-assembled plasmonic-3D photonic crystals have been utilized for fluorescence enhancement in biosensing. Advances in techniques like direct laser writing (DLW) lithography and multi-photon lithography enable the fabrication of complex 3D structures with increasing resolution. While not explicitly detailed for viral detection in these sources, these methods are crucial for realizing intricate 3D photonic crystal designs (Sharma et al., 2014). The development of three-dimensional graphene architectures also presents possibilities for novel 3D photonic crystal biosensors, although the integration into functional sensing platforms is an ongoing area of research. Resonant frequency shift or transmission spectrum change induced by analyte binding is mostly used in the detection in 3D PhC biosensors (Feng et al., 2016). An analyte will disturb the photonic bandgap and any engineered defect modes by changing the local refractive index in their presence. Thanks to the 3D structures, making such changes results in larger optical responses for greater sensitivity. For instance, Microcavity based 3D PhCs can realize single particle detection with resonance shift (Liu et al., 2018).

However, 3D PhCs are still emerging for large scale use in viral high throughput screening but they well suited for large interaction volumes and multiplexing capabilities. In 2D platforms, the lab-in a photonic crystal concept can carry over to 3D cases, where multiple viral markers can be detected simultaneously and spectrally unambiguously (Zhao et al., 2010). Yet owing to their size and binding characteristics being able to differentiate pathogens, implemented in microfluidic systems, 3D PhCs stand as promising tools of rapid, automated, and high throughput viral diagnostics (Shi et al., 2021).

BIOMEDICAL APPLICATIONS

A biosensor is a compact analytical device that combines a biological sensing element coupled with a transducer. However, in recent decades, the functionalization, design and fabrication of biosensors has been able to achieve significant advancements with the introduction of new materials and fabrication techniques. Biosensors are crucial to clinical settings for their uses in diagnosing a wide range of diseases and disorders. To minimize mortality rates, early diagnosis is necessary to manage infections. Various biosensors have been developed to streamline pathogen and immune response detection, addressing the limitations of traditional methods (Lakshmanan et al., 2025). These emerging biosensing technologies aim to provide more efficient means of diagnosis. Current 2DM-based biosensors for diagnosing infected patients are classified into two main types: electrode-based devices (including electrochemical and field-effect transducers) and optical systems (mainly relying on sensing by fluorescence, surface plasmon resonance (SPR), and SERS). These devices integrate bioreceptors such as antibodies, nucleic acids, proteins, aptamers, or peptides, which interact with the analytes to produce a physical or chemical change that is then detected (Xiao et al., 2022). Optical based biosensors are in demand due to their fast detection, high sensitivity, real-time monitoring, and high-frequency quantification without time-consuming pretreatment steps. Label-free optical detection methods are of great interest for biosensing as they avoid time consuming and costly biomolecular labelling and enable the elucidation of molecular interactions in a non-invasive and dynamic approach (Zhang et al., 2022). SPR methods, in particular, hold great promise for biosensing and bioimaging due to their compatibility with physiological solutions, robust performance, and ability to provide real-time quantification of biomolecule interactions.

Point-of-Care Testing (POC): Point-of-care (POC) diagnostics are urgently needed in the

healthcare system, taking place near or by patients rather than in a hospital or medical testing laboratory. The global POC testing market is experiencing dramatic growth, calling for new POC testing technologies. POC biosensors are a diagnostic platform aimed to address the issues of high cost and lack of portability associated with traditional laboratory techniques (Drain et al., 2019). They offer the promise of substantially reducing the time required for treatment, especially in infectious diseases. 2DMs are amongst the best platforms for the realization of point of care tools. Field-effect based-biosensors are a possible primary choice for POC as they have major advantages. Such POC diagnostics require the development of highly sensitive, portable, reusable or low cost disposable devices (Markandan et al., 2024). It is the aim of optical microfluidics to bring low cost point of care diagnostics, rapid and simultaneous on site diagnostic methods. The growth of the POC testing market is driven by the demand for fast diagnostics, technological innovations, and a greater interest in epidemic preparedness.

Early Detection of Viral Pathogens: Optical technologies, especially biosensors are emerging as potent diagnostic tools which can have a great impact on public health through shaping of diagnosis and therapy. Dispersed 2DMs are especially attractive for this purpose because they have a high surface area and sensitivity. Specific binding of virus particles, proteins, or host derived markers on 2DMs is possible by functionalizing them with antibodies, nucleic acids, peptides or aptamers (Yeh et al., 2014). The biosensors enable multiplexed detection consisting of the simultaneous identification and differentiation of virus strains. Detection normally consists of antibody–antigen interactions, with lateral flow assays (LFA) being carried out as immunoassays (LFIAs) or nucleic acid-based LFAs (NALFAs) for point-of-care testing. Förster resonance energy transfer (FRET) based advanced optical biosensors such as those based on graphene oxide (GO) are made use of for fluorescence quenching that reports the presence of viruses (Ding et al., 2018). Field effect transistor (FET) biosensors, which incorporates bioreceptors, are capable of converting the virus–analyte interactions into the electrical signals that can be measured. Simultaneous detection of multiple critical viruses essential for early and accurate diagnosis can be achieved with fluorescent multiplexing using color coded antibodies, for example, with enterovirus 71 and Coxsackievirus B3 (CVB3) (Panahi et al., 2023). Central to this are also photonic biosensors with their miniaturization potential, high sensitivity. Instead, they generally sense a shift in wavelength or a luminescence change upon virus binding. Detection is performed with virus specific detection by surface functionalization with biorecognition element eg, DNA/RNA probes or antibodies.

MONITORING VIRAL LOAD IN REAL-TIME

Monitoring viral load using optofluidic biosensors is highly promising for clinical and POC diagnostics. Capable of miniaturization and multiplexing, they can test on the low level viral loads (aM fM levels) within 1 hour. Understanding this progression is crucial in understanding progression of the patient's infection. Real time, label free biosensing can be achieved with the use of surface plasmon resonance (SPR) based biosensors (Fernandez Cuesta et al., 2022). This gives quantifiable data that amenable to kinetic analysis of biomolecular interactions. Thus techniques such as localized surface plasmon resonance (LSPR) have been used to detect viral components in real time. So, for instance, Au nanoparticles (AuNPs) have been employed in real time detection of the porcine reproductive and respiratory virus (PRRSV) using the optical response of conformationally altered antibodies upon antigen binding (Sharma et al., 2021).

Real time evaluation of virus detection through conductance changes and optical imaging is possible in multiplexed biosensors, for example, a silicon nanowire Au array modified FET. In turn, real time detection of viral epitopes has also been achieved in optofluidic LOC devices. Differentiative diagnosis and immune surveillance are performed with

quantification and screening of whole viruses or virus-specific biomarkers to better manage disease (Xiao et al., 2022). In general, biosensors, especially optical and 2DM platforms, have a great prospect for both preliminary detection and real time monitoring of viral pathogens in biomedical applications, including in clinical diagnostics and point of care testing. suchas speed, sensitivity, portability, and the possibility of use of multiplexing, overcoming many disadvantages of usual diagnostic methods.

ENVIRONMENTAL APPLICATIONS

Particularly in 2D and 3D configurations, photonic crystal (PhC) biosensors have become state-of-the-art optical sensing instruments for virus detection with exciting potential uses in environmental monitoring (Chen et al., 2019). By using PhCs' special capacity to control light through photonic bandgaps, these biosensors allow for label-free, real-time viral detection through changes in refractive index brought on by analyte binding. 2D PhC biosensors are ideal for field-deployable viral detection systems due to their easier manufacture and seamless integration into lab-on-a-chip devices (Tsalsabila et al., 2024). Their tiny size and planar shape allow easy insertion into microfluidic systems for monitoring ambient water sources, detecting waterborne viruses such as Vibrio cholerae or E. coli, which are markers of viral contamination. 3D PhC biosensors, however more complicated in production, offer greater sensitivity and total light confinement, making them appropriate for high-throughput environmental screening (Vishalatchi et al., 2023). When trace virus loads are present, their volumetric interaction zones allow detection in larger sample volumes, which is advantageous for wastewater surveillance or air quality monitoring. Both 2D and 3D PhCs are particularly appealing in situations requiring ongoing environmental surveillance, early outbreak identification, or pollution tracking in public health contexts due to their capacity to function without labeling and provide quick optical responses (Tan et al., 2015). The conversion of these technologies into reliable, affordable instruments for environmental biosensing and pandemic preparation depends on ongoing developments in scalable manufacturing processes and surface functionalization (Maeng et al., 2016).

CHALLENGES AND LIMITATIONS

However, wide adoption for clinical and POC testing applications has proven to be difficult for biosensors due to several current limitations. Each of these issues falls generally into 3 main categories, technical barriers to measurement, sample complexity, and regulatory and/or other commercial constraints. High-performance biosensors often have high demand for complex nanofabrication techniques such as electron beam lithography, which are expensive and difficult to scale (Kabay et al., 2022). In particular, uniform and high quality structures, like magnetic photonic crystals or SPR nargin photonic crystal fibers are especially difficult to manufacture (Sin et al., 2014) due to sensitivity to solution and coating uniformity. Another challenge of miniaturization of POC devices includes heat management as well as device integration problems. However, a big hurdle still remains, which is incorporating the necessary components: spectrometers, microfluidics and sample preparation steps into compact lab-on chip systems.

It is difficult to maintain high sensitivity and specificity in complex biological samples such as blood. Although label free systems perform well, non specific binding and matrix interference can degrade the performance significantly, resulting in false positives leading to compromised reliability (Zheng et al., 2023). Optical methods like ATR-FTIR also have limitation for overlapping spectral bands; however, visual detection methods such as lateral flow assays generally have low quantitative accuracy. Strategy to minimize interference, and maximize selectivity is imperative (Sharma et al. 2021). Translating lab developed biosensors

into real world diagnostics is also heavily scrutinized by regulatory authorities in terms of commercial and regulatory barriers. Since these are novel and complex technologies, they are not ready to receive approval because there has not been enough standardized testing protocols that is used to approve basic drugs. In addition, regulatory inconsistency adds more delay across countries. Scaleability is hindered by high prices of production, especially for bio-recognition elements. Additionally, it is difficult to convince clinicians to replace their current diagnostic methods with new technologies (Saylan et al., 2019). The instrumentation remains labor-intensive and are lacking in cost efficiency to commercialize many promising biosensors.

CONCLUSION

Transformative potential for rapid sensitive and label free viral detection is offered by 2D and 3D photonic crystal biosensors in biomedical and environmental domains. While 2D PhCs benefit from simpler fabrication and established integration with microfluidics, 3D PhCs offer superior sensitivity through complete photonic bandgaps. However, widespread demise of hybrid cannibal has been hindered by complex manufacturing and cost challenges. Scalable, high performance diagnostic platforms for the path to future pandemic preparedness and healthcare innovation are made possible with continued advances in fabrication, materials science, and system integration.

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