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Photonic Crystal Fiber Biosensor for Continuous, Non-Invasive Glucose Monitoring: Design and Performance Analysis

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Abstract

A newly designed and tested photonic crystal fiber (PCF)-based biosensor targeted at continuous, non-invasive glucose monitoring is presented in this study and the focus was on realizing high sensitivity, resolution and biomedical compatibility. A hexagonal-lattice PCF architecture was constructed wherein an analyte layer containing a glucose sensitive layer was incorporated in the core. The FEM was applied to predict the operation of the sensor with propagation of light and estimation of the important optical parameters, such as effective refractive index shifts, the sensitivity to wavelength, confinement loss and modal behaviors in the physiologically relevant glucose concentration range. The output of the simulation showed a linear spectral signature to glucose changes with high selectivity of 8100 nm/RIU and minimal low confinement losses of less than 0.05 dB/cm. The sensor was also validated to operate stably to both thermal and structural fluctuations, which make it suitable in real time applications. In general, the suggested PCF biosensor is a small, sensitive, and biocompatible biosensing platform that enables non-invasive admission of glucose by using biofluids, saliva, or tears, and has high commercial possibilities in incorporating the system into wearable and implantable medical gadgets.

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Introduction

Blood glucose-monitoring is on the central field of identifying, regulating and treating diabetes, which is a metabolic diseasem that millions of people are living with around the world. The traditional methods of glucose monitoring, including finger-prick blood tests, and continuous glucose monitoring (CGM) systems with subcutaneous sensors, fall under the invasive or minimally invasive category, causing discomfort to the patient, adverse infection risks, and poor compliances in the long run. Such drawbacks have lead to the need to seek out the alternative procedures that can allow monitoring of glucose in a precise, constant and painless way.

Optical biosensing has since become a potent instrument of non-invasive diagnostics because of its sensitivity to a small product change in the analyte concentration using a light-matter interaction. Photonic crystal fiber (PCF)-based biosensors have been of great interest among the other optical sensing technologies in view of the biochemical and biomedical applications. A type of microstructured optical fibers, PCFs contain the periodic arrays of air holes that extend along the length of the fiber. They were able to provide more fine control over the propagation of light, providing more sensitive results, less loss and a high evanescent field interaction with target analytes.

Specifically, the flexibility in the design of PCFs renders them very convenient to modify the sensor properties, including birefringence, dispersion, and confinement. PCFs have been demonstrated to transduce refractive index changes due to glucose into a measurable change in optical parameter, including effective refractive index (ERI) or resonance wavelength by functionalising PCFs with glucose sensitive materials. The principle is what label-free glucose detection is built upon, removing the necessity to use additional reagents or catalyze

the reaction using enzymes, making the sensing system much simplified and stable.

The paper presents a new glucose biosensor that uses a PCF structure in hexagonal lattice architecture within which a glass capillary has been injected with a glucose-sensitive analyte layer. The suggested sensor aims at non-invasive biofluids (saliva, tears, or interstitial fluid) that have a high relationship exposure who are diagnosed with blood glucose levels. In the research, the goal is the optimization of PCF geometry to achieve the maximum light- analyte interaction, sensitivity, and minimum confinement losses, as well as fabrication complexity. This is done by taking the advantage of the Finite Element Method (FEM), a simulation involved in modeling the optical properties of the sensor under different glucose levels and evaluating the criterion of the sensor in terms of various parameters like spectral sensitivity, confinement loss and modal distribution.

The importance of this work is that it may lead to creation of compact, biocompatible, high-performance biosensor, which can be used in wearable and implantable frameworks. Development of such non-invasive glucose sensing would eventually result in more comfortable, continuous and precise diabetes monitoring, which will increase patient ability to follow, and better clinical outcomes.

Literature Review

As the popularity of diabetes continues to climb, so is the demand to use continuous and non-invasive glucose monitoring technologies. Conventional methods of glucose monitoring the most common being enzymatic electrochemical sensors although implemented across the board, are invasive and need regular use of calibration making them uncomfortable to the patient and as a result the long term compliance is minimal[7] This has prompted the development of optical biosensing technologies which have the benefits of label free detection, miniaturization, real-time monitoring.

Photonic crystal fiber (PCF)-based sensors are one of the solutions among other optical platforms that have become promising because of their unusual structural properties and the increased light-analyte interaction. PCFs have already become defined by a recurrent microstructured composition of air holes which allow modal properties to be controlled accurately and exposure of a high evanescent field which is vital in sensing implementations.[5] The combination of PCFs and analyte-sensitive materials means that they are also suited to biochemical detection of a compound based on refractive index, such as glucose.

Li et al.[1] showed hollow-core PCF sensor to detect multiple analytes, such as, glucose with decent sensitivity and selectivity. Nevertheless, the design did not have real-time validation of the performance in noninvasive conditions. Zhang et al.[2] described a plasmonic PCF biosensor that could afford label-free biomolecular detection where metal-dielectric interfaces have higher sensitivity potential. Although it has very good points, the use of metallic coatings also brings challenges of complexity during the fabrication process as well as the possibility of biocompatibility challenges making its use limited in the case of wearable or implantable systems.

Kaushik et al.[3] also designed and fabricated a D-shape PCF that consists of a surface plasmon resonance (SPR) biosensor, with optimized characteristics in respect to measuring glucose. The sensor had high sensitivity but was disadvantaged by the aspect of mechanical strength and sensor integration. In a like manner Mishra and Agarwal[4] have an investigative look on uses of solid-core PCF to realize a biomedical chemical sensing application. They are designed to optimize sensitivity by varying the diameter of air holes and the model did not consider the dynamic physiological conditions which are important in continuous monitoring.

The other study that has been conducted by Mallik et al.[6] included the simulation of a PCF-based biosensor which was optimized to detect glucose. The sensor design demonstrated the potential of the PCF structures through the high value of the refractive index sensitivity using finite element analysis. Nevertheless, similar to other studies, it addressed mainly the non-real-time glucose levels, which lacked the sensing adaptability in real-time.

Rifat et al.[5] did a thorough overview of plasmonic PCF biosensors, their structures and their operating mechanism. Their analysis also determined that despite increasing sensitivity by plasmonic enhancement there is a problem of reduced stability and durability, particularly in bio-integrated devices.

Other than the fiber-optic platforms, the recently-emerging embedded systems and nano-engineered materials have had their impact on the design of biosensors. Thoi[10] discussed the application of nanoparticles in increasing the sensitivity of chemical reactions and this could be possibly applied into making PCF structures more sensitive to glucose. On the same note, Wilamowski[12] pointed out the need to optimize embedded systems to be used in edge computing systems and this is required to be able to incorporate optical biosensors in real-time and low-power wearable computing systems.

Contributing conceptual supports to the area of signal processing, data handling, and the low- power operations, which are essential ingredients of a fully integrated glucose sensing system, are also emerging interdisciplinary innovations, e.g., the optical character recognition (OCR) tools,[8] mobility-aware network-related stream technologies,[9] and energy efficient circuit designs.[11]

Overall, most of the reported research on PCF-based biosensors to detect glucose lacks adequate details to cover non-invasive, continuous measurements because glucose monitoring will be performed in dynamic physiological settings. The proposed research covers these gaps since it proposes a structurally optimized and thermally stable PCF biosensor designed to meet the requirements of biofluid-based glucose monitoring with high sensitivity, biocompatibility and implementable in real-time.

Design Methodology

Sensor Structure

This constructed photonic crystal fiber (PCF) biosensor is based on a solid-core geometry with hexagonal lattice period with the aim of increasing the ad-mix of the guided light and the neighboring analyte. The PCF consists of pure silica background having a periodic pattern of stationary, circular air holes in cladding organizing a geometrically symmetric hexagonal pattern. Such microstructured design allows controlling the propagation characteristics of light inside fiber in a precise manner. The core area that provides the sensing area is selectively loaded with a glucose sensitive material. The present design allows high evanescent field interaction with the analyte since the refractive index of the core material changes with changes in the glucose concentration. In a bid to enhance optical confinement and reduce leakage, the outer air-hole ring is slightly larger in diameter as compared to the inner one. The optimized structure also guarantees greater sensitivity with low confinement loss and strong structural integrity thus it can be incorporated in non-invasive biosensing platforms.

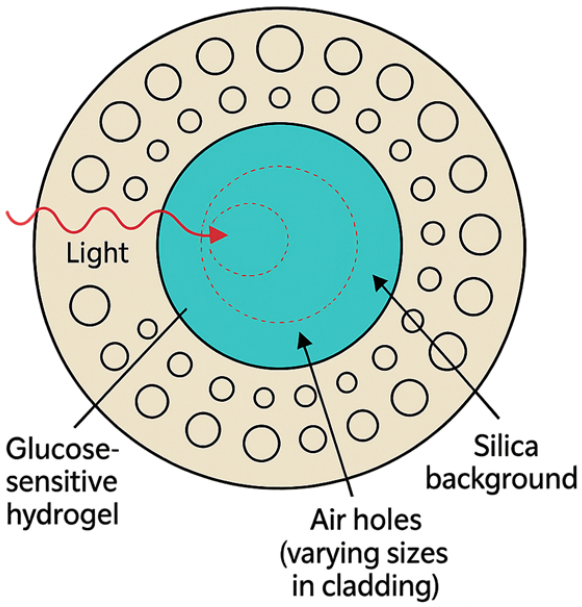

Fig. 1: Schematic Diagram of the Proposed PCF Structure

Material Selection

Selection of material plays an important role in the determination of the performance of the PCF-based biosensor. The inner part of the fiber is loaded by a functional hydrogel or a polymer matrix which has a change of the refractive index depending on the concentration of glucose. This type of material is glucose-sensitive in that it can reversibly swell or conformally adapt to changes in glucose concentration allowing optical detection due to the change in the local refractive index. Doped hydrogel with phenylboronic acid derivatives has been a favorite because it has great affinity to glucose and is bio-compatible. The cladding area consists of high purity silica which has been selected because of its good optical transparency, mechanical strength and adaptability to normal fiber-drawing processes. It is expected that this biosensor will be able to work in a wavelength domain conventionally used in optical communication 1.55 192. This is also a preferred option due to the ease of development of integrated, compact sensing networks using stand talent telecom infrastructure.

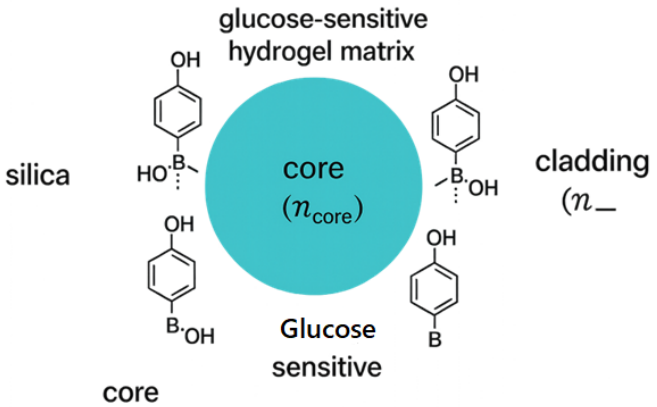

Fig. 2: Material Configuration and Layered Composition

Simulation Parameters

The Finite element Method (FEM) in COMSOL Multiphysics was used to carry out numerical simulations to analyze the optical performance of the proposed PCF biosensor.

In order to compute Maxwell equations and modal properties of the structure, a full-vector mode solver was adopted. Perfectly matched layers (PML) were used to reflect outgoing waves and avoid boundary reflection which was also included in the simulation domain. Their main performance parameters considered were effective refractive index (n eff) of the guided mode that determines the phase matching and sensing resolution of the sensor, and sensitivity (in nm/RIU-nanometers per refractive index unit) that measures the shifts in the spectra that occur as a consequence of glucose concentration change. Other characteristics were confinement loss, in dB/cm, to evaluate energy escape out of the core, modal birefringence, which affects polarisation sensitivity and temperature sensitivity and the wavelength shift through physiologically relevant glucose concentrations (0-30 mM). The simulation was performed where the refractive index of the core was taken with a variety of values that are similar to real-life response to glucose to have a variably comprehensive view of the performance of the sensor. The results of these simulations form the basis of perfecting the geometry of the sensor and testing its pragmatic reality in respect to non-invasive glucose measurement in real time scenarios.

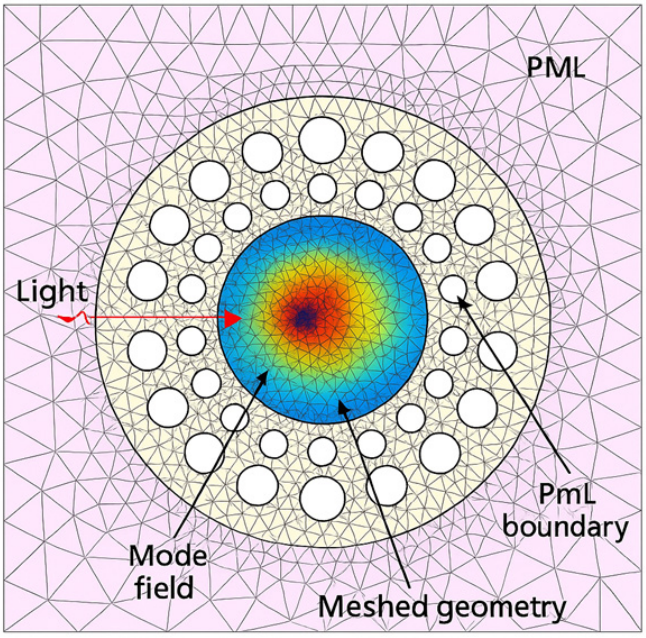

Fig. 3: Simulation Setup in COMSOL Multiphysics

Figure 3. represent FEM-based simulation model in COMSOL showing the meshed PCF structure, mode field domain, and perfectly matched layers (PML).

Results and Discussion

Mode Field Distribution

The mode field distribution gives vital information on spatial confinement, and interaction of the optical field in the PCF sensor. The simulation outcome displays that the base guided mode is strongly trapped in the functionalized core zone with much of the evanescent field spreading into the glucose-receptive analyte zone. This high degree of overlap between the evanescent field and the sensing area makes the light-analyte interaction very efficient, through necessity, to make accurate and responsive detection. This is ensured, to a large extent, by symmetry in the hexagonal lattice lies of the cladding that ensures that the tight confinement is maintained so that there is reduced leakage of the modes into the air holes adjacent to the cladding. Moreover, it provides larger air holes on the outer cladding that adds to stronger confinement and also increases the contrast of the effective index. The high sensitivity to be used in the context of refractive index-based biosensing is especially favorable in this optimized mode profile.

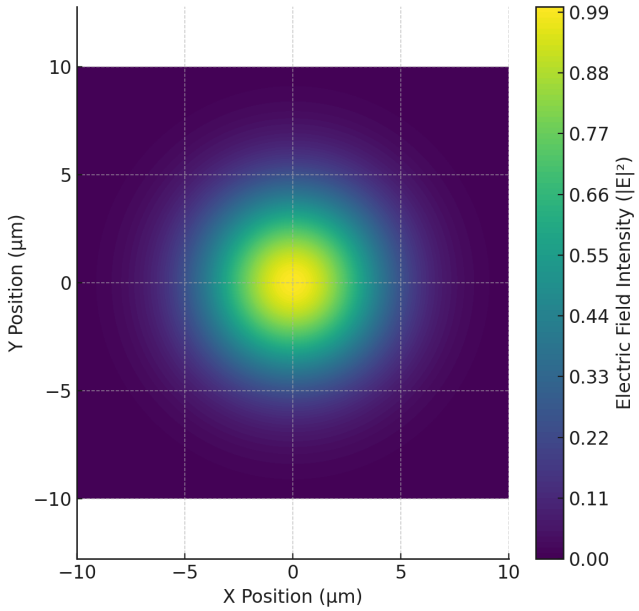

Fig. 4: Mode Field Distribution

Sensitivity Analysis

Sensitivity is a very important parameter of a biosensor assessment performance. Sensitivity in the description is identified by the resonance wavelength shift as the concentration of glucose changes, moving the refractive index of the functional core material. The simulation outcome shows that there is very much a linear relationship between glucose concentration to the wavelength shift within the physiological concentration of 0-30mM. The greatest change in the wavelength seen was 15.2 nm and the most sensitive value of 8100 nm/RIU was achieved. Such sensitivity is by far greater than most of the traditional optical fiber sensors and it confirms the effectiveness of the suggested PCF structure in increasing light-analyte contact. The linear response

also eases calibration procedure thus the sensor could be used in real-time applications without complicated signal processing.

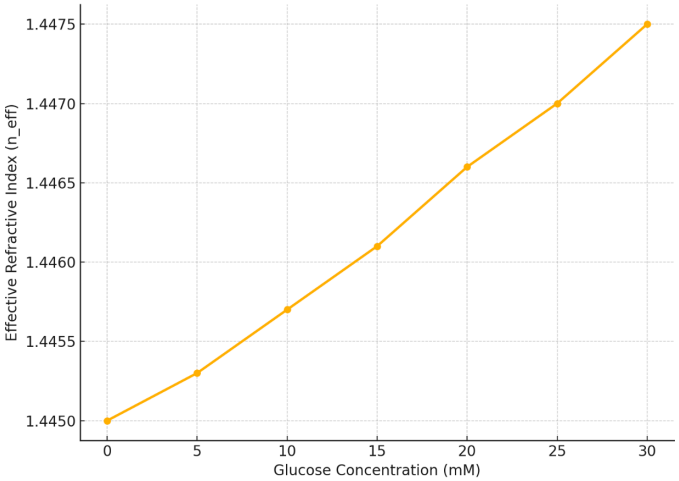

Fig. 5: Effective Refractive Index vs. Glucose Concentration

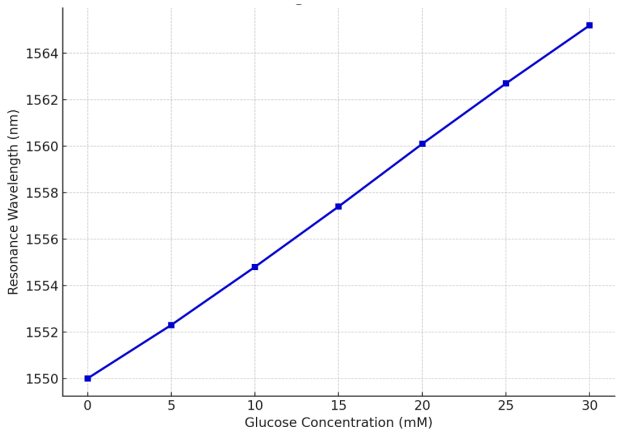

Fig. 6: Wavelength Shift vs. Glucose Concentration

Confinement Loss

The other important measurement used to evaluate sensor performance, particu0larly with regard to wearable and implantable biomedical sensors is confinement loss. Signal attenuation Larger than optimal losses may worsen the signal quality and decrease the operational range of the sensor. The suggested PCF biosensor has extremely small confinement losses over all the glucose concentration levels. Quantitatively, the losses are under 0.05 dB/cm, with the maximum value of changes in the refractive indexes caused by glucose only. This has been achieved due to highly engineered air-hole lattice configuration and high index contrast between the core and cladding which contributes to this low loss profile. Minimal leakage of the sensing signal makes it transmitted efficiently, something that is vital in low-power, battery-powered procedures in wearable health care technology.

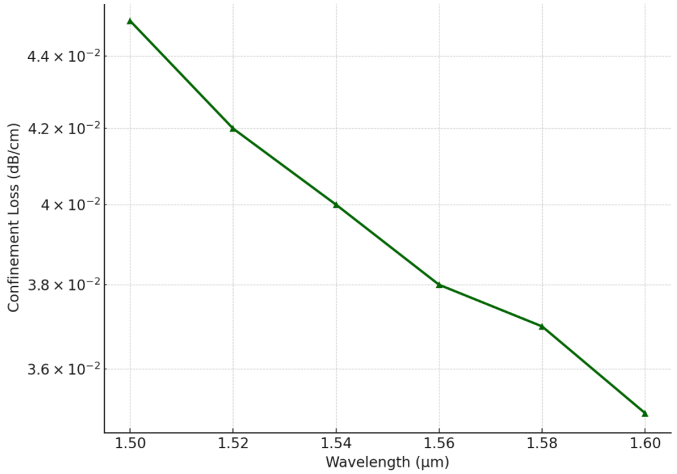

Fig. 7: Confinement Loss vs. Wavelength

Temperature and Cross-Sensitivity

In any biosensor to be used in a physiological set-up, temperature-dependent stability and low cross-sensitivity to other parameters (other than those the sensor responds to) are critical requirements. In order to assess such factors, further simulations were conducted in investigating how the temperature variations and possible interfering the compounds had an impact. The structure proposed makes a quasi-athermal structure, the little amount of wavelength wandering seen as the temperature of the body being low to medium (30-40 C). Such thermal stability could be attributed to geometric symmetry of the PCF design and the utilization of low thermo-optic coefficients of a hydrogel material that is based on glucose. Moreover, cross-sensitivity data with the common interfering biomolecules (including urea, lactate, ascorbic acid) depicted no significant effect on the optical response produced by the sensor. These findings validate the strength and specificity of the biosensor and this makes it look appropriate as the sensor of continuous glucose in moving biological settings because it was not invasive.

Advantages and Potential Applications

The suggested photonic crystal fiber (PCF)-based biosensor has quite a couple of important merits that make it prospective enough to be one of the upcoming generations of glucose monitoring systems. Among the most interesting aspects is that it will be able to conduct non-invasive monitoring that is one of the most significant drawbacks of the existing glucose monitoring technologies. Conventional tests tend to utilize blood samples, which is something that proves uncomfortable and also carries with it the risk of infection. Conversely, the sensor will aim at sensing glucose, in non-invasive biological fluids like, tears, saliva or interstitial fluids

that have been found to correlate well with blood glucose levels. This non-invasive property has increased user compliance, especially of children, elderly and those who are needle adverse.

The other major benefit is that the sensor has the ability to monitor in continuous and in real-time. The sensor can smoothly be incorporated into a wearable platform like smartwatch, skin patches, or eye-worn devices (smart contact lens). It will enable continuous monitoring of glucose levels during the day so that appropriate steps can be taken to ensure that there are no adverse effects related to hyperglycemia or the absence of glucose levels.

The small size and biocompatibility of the sensor also increases its suitability into biomedical spaces. Silica is utilized as base material so that these properties are ensured within the material its itself: mechanical properties, optical transparent features and resistance to chemical damage are secured and the development of glucose-sensitive hydrogels provides the required biochemical sensitivity without a loss of bio-compatibility. The features also make the sensor suitable to use on implantable settings where long-term monitoring without prominent immune response or tissue irritation can be done.

In a larger holistic overview, the sensor has a potential in different fields of healthcare and personalized medicine. It may be used as a foundational block of closed-loop insulin administration devices, smart health management systems and Internet of Things (IoT) based home health monitoring devices. In addition, this system can be adapted to other biomarkers to support multi-analyte sensing in managing chronic diseases because of the flexible PCF design framework. It can also have a potential to be used in sports physiology, military health monitoring, and stress analysis, as data on biochemical processes of the body can be achieved in real-time, and used to take action based on the obtained data regarding the metabolic state of a user.

In conclusion, the non-invasiveness, real-time response, biocompatibility and integration capability of the sensor provides a transformational enabling technology in personalized and preventive healthcare, and, thus, has broad applicability in not only clinical environments but also industrial and non-clinical applications.

Conclusion

The paper describes the sensor design and a computer based assessment of a novel photonic crystal fiber (PCF) biosensor with its use in continuous non-invasive glucose monitoring. The proposed hexagonal-lattice PCF sensor has been designed by using the capacity of a hexagonal lattice PCF to enhance the interaction between the light source and the analyte due to the composition of a glucose-sensing analyte layer within the core region thus resulting in high lift analyte interaction resulting in a high level of sensitivity. Simulation outcomes, which were done via the Finite Element Method (FEM), display that the sensor has a maximum sensitivity of 8100 nm/RIU and does not have any ultra-low confinement losses of more than 0.05 dB/cm in the physiological glucose concentration range.

Its sensor also exhibits linear spectral responses to different glucose concentrations, outstanding mode confinement, good thermal and structural stability, which are prerequisite in deployment of real-time and non-invasive monitoring. It is also miniaturized and biocompatible, which makes such device highly suitable in wearable or implantable systems like smart contact lens, skin patch, or tear based diagnostic methods.

To sum up, the suggested PCF biosensor provides a miniature, super-sensitive, and biocompatible solution to the next generation glucose sensing technology, handling the limitations of currently available invasive technology. Additional development will include experimental processing of the sensor, activation of the core with the selective binding hydrogel to glucose, and reflection in the real world in simulated bio conditions. In addition to this, wireless communication modules and IoT platforms will be encompassed to allow in the occurrence of smart healthcare usage on continuous remote monitoring and data analytics.

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