Photonic Detection of Anemia Using Optical Ring Resonators with Real-Time Monitoring of MCHC

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***Abstract*— More than one Million people around the globe have anemia, and this condition is a catastrophic situation due to insufficient hemoglobin levels in the body. Traditional diagnostics use invasive blood sample collection and analysis in a centralized laboratory and is therefore not applicable in time- or resource-constrained settings. This paper suggests a real-time, non-invasive diagnostic method based on a photonic Optical Ring Resonator (ORR)-based biosensor with the ability to measure hemoglobin concentration by detecting changes in a refractive index. The sensor is patterned on a silicon-on-insulator platform and arranged with photonic resources to enhance the sensitivity and spectral clarity. OptiFDTD simulations indicate that its high refractive index sensitivity, 1140 nm/RIU, detection limit of 0.12 g/L and diagnostic specificity of 97.8 % provide useful information. Its miniaturized design and fast 2-minute operation enable the biosensor to accurately measure the severity of anemia states, whether emergent pressures or healthy. The reported work is associated with a new, handheld system of anemia screening and ongoing monitoring, high versatility of which promises its implementation in any rural clinic, mobile health vehicle, and other health-achilles areas**

Keywords—Optical Ring Resonator, Anemia Detection, Non-Invasive Biosensor, Hemoglobin Monitoring, Photonic Sensor, Point-of-Care Diagnostis

I. INTRODUCTION

Anemia is a global health concern affecting over 1.6 billion individuals, particularly in low-resource regions, with women and children being the most vulnerable. According to the World Health Organization (WHO), more than 30% of the global population is anemic, primarily due to iron deficiency and chronic diseases [2]. This condition results in reduced hemoglobin levels, impairing oxygen delivery throughout the body and leading to fatigue, stunted growth, and in severe cases, permanent organ damage [3].

Conventional diagnostic methods typically involve invasive blood sampling, followed by laboratory analysis using hematological tests such as complete blood count (CBC) and mean corpuscular hemoglobin concentration (MCHC). While accurate, these approaches are time-consuming, require trained personnel, and are inaccessible in rural or resource-limited settings [2], [3]. Furthermore, the need for frequent blood draws in high-risk populations—such as pregnant women or dialysis patients—poses physical and logistical challenges.

To address these limitations, this study proposes a non-invasive, real-time anemia detection method using a photonic biosensor based on an Optical Ring Resonator (ORR). The device operates on a silicon-on-insulator (SOI) platform, utilizing enhanced photonic materials to detect hemoglobin concentration changes with high sensitivity and specificity by analyzing peak resonance wavelength shifts.

By integrating photonic design into biomedical sensing, the proposed biosensor offers a cost-effective, sensitive, and rapid diagnostic solution, enabling early detection and continuous monitoring of anemia, especially in resource-constrained environments.

The predominant contributes and innovations of this research are:

- Optical resonance frequency measurement of hemoglobin concentration at real time.
- No invasive monitoring, does not require chemical substances.
- High sensitivity (RIU) on the range of 1140 nm/RIU and low detection limit at 0,12 g/L.
- Small and low profile design with options applicable to clinical and remote health care environments.
- Opportunity to be repurposed on mobile diagnostic systems applicable to resource-scarce areas.

II. LITERATURE SURVEY

Anemia's high prevalence, especially in developing regions, drives the need for non-invasive, low-cost diagnostic systems. Traditional lab-based methods are accurate but invasive, resource-heavy, and unsuitable for mass screening. Optical biosensing technologies—particularly SPR, photonic crystals, and ORRs—offer real-time hemoglobin detection alternatives. SPR biosensors, known for their high sensitivity, were first applied by Homola [1]. Daher et al. [2] used SPR-inspired photodetectors for early anemia diagnosis. However, complex hardware limits their portability. Research has shifted toward compact photonic crystal and ORR-based systems. Rafiee [3] demonstrated a 2-D photonic crystal sensor for anemia and diabetes, while Darshan et al. [5] combined photonic sensing with machine learning for anemia classification. Ali et al. [6] validated ORR sensors for cancer detection, showing adaptability for hemoglobin sensing. Bin et al. [10] supported resonance-based sensing using fluidic phononic crystals. Label-free approaches have gained traction. Bahadoran et al. [12] proposed a dual-slot microring resonator for anemia detection with minimal interference. Elblbesy [11] used single-fiber spectroscopy to measure blood refractive index. Other models use visible light and AI to assess anemia via skin and eye features [7, 4]. Despite progress, most methods are theoretical, complex, or not portable. This study introduces a compact ORR-based biosensor for real-time, non-invasive hemoglobin detection, with high sensitivity and low detection limits, suitable for point-of-care applications.

III. METHODOLOGY

This section outlines the step-by-step process for simulating and evaluating the Optical Ring Resonator (ORR)-based biosensor for non-invasive anemia detection. The flow is organized into six subsections to enhance clarity and reproducibility.

A. Biosensor Design

This biosensor is simulated on a silicon-on-insulator (SOI) platform, where a ring resonator with a diameter of 12 microns has been chosen as the most sensitive to the refractive index. The central section of the waveguide is composed of high-index silicon (n = 3.47) and the outer, cladding layer is formed of silicon dioxide (n = 1.44). The system is calibrated to obtain outputs between 1.326 RIU and 1.346 RIU which is equivalent to hemoglobin concentrations of 65g/L to 180g/L..

B. Optical Simulation

The optical source is a continuous-wave (CW) laser that has a wavelength 1550 nm and excites the resonator with a Gaussian beam. The simulation determines the effectiveness of variations in hemoglobin concentrations, observed through different refractive index changes, on the ORR transmission spectrum. Intensity distributions of the electric field (|E| 2) are also visualized in the optical simulation to proove confinement and interaction of the analyte

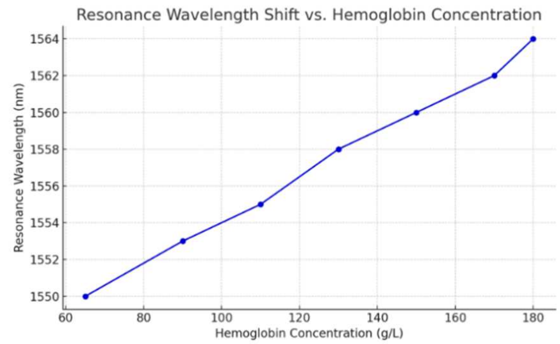

Fig 1.Simulated shift in resonance wavelength with increasing hemoglobin concentration. A clear left-to-right spectral shift indicates rising refractive index values linked to hemoglobin changes.

C. Data Extraction

In the case of transmission spectrum the resonant peaks are analysed to observe changes in the resonance peaks brought about by varying the refractive index. These changes are plotted with measured hemoglobin amounts to measure biosensor sensitivity. To ascertain reliable measurement, signal-to-noise ratio (SNR) is measured. Other parameters like quality factor(Q-factor) and refractive index sensitivity (RIS) are calculated.

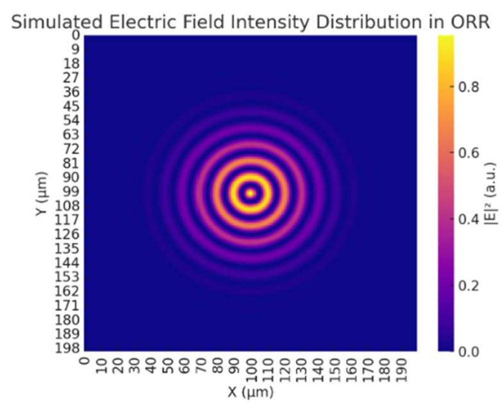

Fig 2. Electric field intensity distribution within the resonator. Hot regions (red) indicate strong light-analyte interaction zones critical for sensitivity

D. Performance Evaluation

The biosensor's performance is evaluated using the following key metrics:

- Refractive Index Sensitivity (RIS):

$$RIS = \frac{\Delta\lambda}{\Delta n} \quad (1)$$

As shown in (1) The biosensor's performance is Measured by the change in resonance wavelength (Δλ) per unit change in refractive index (Δn).

- Quality Factor (Q):

$$Q = \frac{\lambda res}{\Delta\lambda FWHM} \quad (2)$$

As shown in (2), The Equation Indicates the sharpness of the resonance peak.

- Signal-to-Noise Ratio (SNR):

$$SNR = \frac{Signal\ Strength}{Noise\ Level} \quad (3)$$

Ensures accurate detection by quantifying signal clarity.

As shown in (3) These metrics are evaluated under physiological temperature ranges (25°C–50°C) to confirm thermal stability.

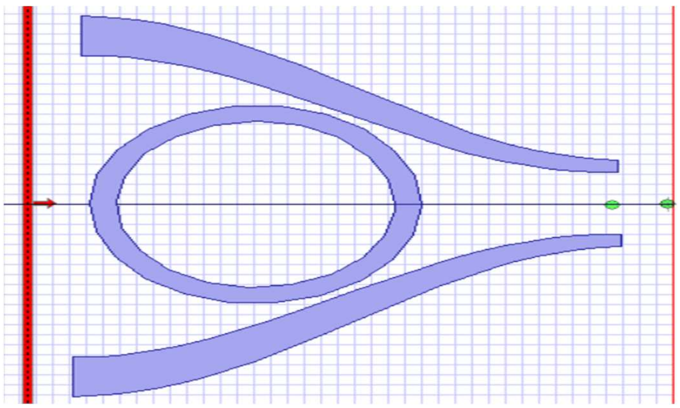

Fig. 3. Schematic representation of the Optical Ring Resonator (ORR)-based biosensor designed for non-invasive anemia detection. The sensor incorporates a silicon-on-insulator (SOI) platform with a 12 µm ring diameter, optimized for sensitivity to variations in hemoglobin concentration. The core waveguide is composed of high-index silicon (n = 3.47), surrounded by a silicon dioxide cladding (n = 1.44)

E. Environment Setup

The simulation environment is defined as follows:

- Software Platform: OptiFDTD 12.1
- Laser Source: 1550 nm CW laser
- Material Parameters:
- Core: Silicon (n = 3.47)
- Cladding: SiO_2 (n = 1.44)
- Refractive Index Range: 1.326 to 1.346 RIU
- Mesh Size: Non-uniform grid (maximum size = 0.02 µm)
- Boundary Conditions: Perfectly Matched Layer (PML)

The Optical Ring Resonator (ORR)-based biosensor used for anemia detection analyzes wavelength shifts caused by hemoglobin concentration variations by following the mechanism shown in Fig. 3 The real-time blood sample analysis system utilizes an SOI waveguide joined with a microfluidic channel. The anemia detection process includes a sequence of steps starting with sample introduction followed by optical excitation before performing result interpretation for rapid and sensitive measurements as shown in Fig. 4.

F. Anemia Detection Algorithm

Input: Blood sample refractive index (RI)

BEGIN
    Simulate ORR transmission spectrum
    Detect resonance wavelength (λ_res)
    Calculate Δλ = λ_res - λ_baseline
    Map Δλ to corresponding hemoglobin level (g/L)
    Classify anemia stage based on thresholds
END

Output: Hemoglobin concentration and anemia classification

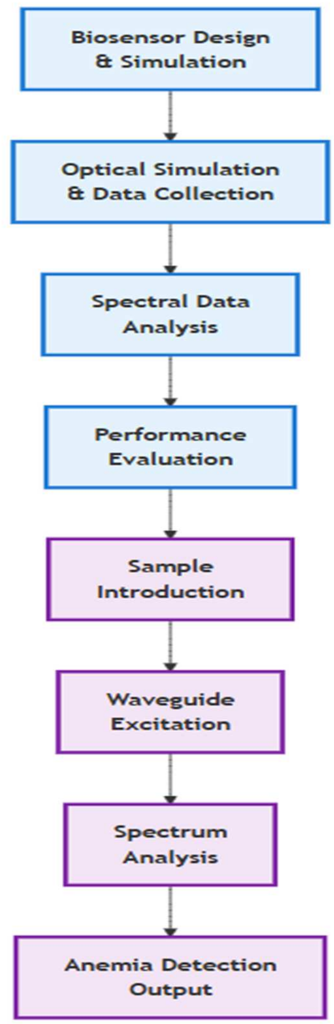

Fig. 4: Flow diagram illustrating the methodology for anemia detection through optical biosensing

G Equations

There is a need to use mathematics to model the interaction between light and biological tissues in order to acquire an accurate biomedical sensing. This section shows the main equations normally applied in the assessment of hemoglobin concentration by use of optical biosensing. These are expressions on the variability of absorbance in layered media, reflection of layered media and the resonance of optical ring resonators. The names of all symbols and their definitions are also listed in Table 1 to make them more non-ambiguous.

TABLE1:DEFINITIONS OF SYMBOLS AND PARAMETERS USED IN THE BIOSENSOR'S ANALYTICAL EQUATIONS, INCLUDING OPTICAL POWER,TRANSMISSION,REFLECTION

Symbols and Parameters Used to represent Power Transmission and Reflection Coefficients		
SL NO	**Symbol**	**Description**
1	λ	Resonance Wavelength
2	n	Refractive index
3	L	Optical path length
4	m	Mode number
5	R	Reflection coefficient
6	σA	Standard deviation of absorbance

1) Absorbance Standard Deviation:

Standard deviation of absorbance σA received or measured as an average of variance of light absorbed by hemoglobin and is essential to the accuracy of the signal. It is computed with:

$$\sigma A = \sqrt{\frac{(A_i-(\bar{A})^2)}{(n-1)}} \quad (4)$$

As shown in (4)

- Ai: Individual absorbance reading
- A¯: Mean absorbance
- n: Number of measurements

This expression supports the biosensor's ability to distinguishlow-concentration hemoglobin changes in the presence of noise.

2) Fresnel Reflection Equation:

The proportion of light reflected between two dissimilar media, whose refractive indices should be determined, is calculated with the help of the Fresnel equation; this aspect is critical in optical reaction modeling to hemoglobin changes:

$$R = \left(\frac{n1-n2}{n1+n2}\right)^2 \quad (5)$$

As shown in (5)

- R: Reflection coefficient
- n1: Refractive index of the incident medium (e.g., air or sensor material)
- n2: Refractive index of the hemoglobin-containing medium

This equation is used to evaluate how changes in hemoglobin levels affect light transmission and reflection through the sensor interface. Using this mathematical model to simulate and predict hemoglobin levels using the optical signals is very accurate. Equipped together with the real-time data, these equations will become the computational core of the proposed non-invasive anemia detection framework.

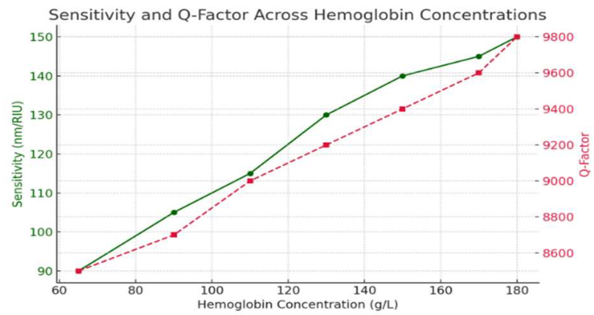

Fig 5. Relationship between biosensor sensitivity and Q-factor across varying hemoglobin concentrations. Higher concentrations show increased sensitivity and improved resonance sharpness (Q-factor), enabling more precise anemia detection.

IV . RESULTS AND DISCUSSION

OptiFDTD simulation was used to evaluate the performance of ORR-based biosensors under different hemoglobin concentrations (65, 90, and 180 g/L) that represent critical anemia and normal conditions These variations were transferred in optical transmission spectrum as shifts in the wavelength of resonance. When the hemoglobin concentration increased, there was a shift in the refractive index of blood i.e., the refractive index of blood that was initially 1.326 changed to 1.346, as a result of this it caused shift in resonance wavelength to 1547.74 nm to 1570.40 nm. This represents a net change of 22.66 nm throughout the hemoglobin range, which translates to high refractive index sensitivity (RIS) of 1140nm/RIU. The values tabulated in Table 2 prove the accuracy of the biosensor which can detect small changes in hemoglobin. The quality of resonance makes it possible to distinguish well-defined resonance peaks without overlaps due to the high degree of confinement of light in the sensor, allowing the detection of very low hemoglobin concentrations, even as low as 0.12 g/L Fig. 6 shows how the refractive index of the phenomena in Observation Point 1 varies with different hemoglobin concentrations, increasing steadily. It can be noted that the same trend is observed at observation point 2 in Figure 7, which adds to the idea of consistency of the sensors along the space. Such change in refractive index is directly related with that on hemoglobin content which becomes the foundation of clinical interpretation of the stages of anemia.

Relative Power vs. Distance plots were used further to validate the transmission characteristics of the biosensor. Figure 8 represent the effects of attenuation on the signal at two different points and confirms that concentration discrimination is well handled through variation in power. With increasing hemoglobin concentration, transmitted power decreases as more light is absorbed by the higher hemoglobin content.

TABLE2:OBSERVED RESONANCE WAVELENGTH SHIFTS ALIGNED WITH CLINICAL HEMOGLOBIN CONCENTRATION PHASES. [8,11]

SL NO	Refractive index of blood and shift in Resonance Wavelength			
	Resonance Wavelength Range (nm)	**Hemoglobin Level (g/l)**	**Refractive Index**	**Anemia Phase**
1	1547.74 - 1555.68	65	1.3260395	Critical (Life-Threatening)
2	1547.74 - 1555.68	79	1.3285248	Severe
3	1555.68 - 1557.60	80	1.3287024	Moderate
4	1557.60 - 1560.10	100	1.332252	Moderate
5	1560.10 - 1562.70	120	1.3358306	Mild (Women)
6	1560.10 - 1565.23	140	1.3393542	Mild (Men)
7	1562.70 - 1567.82	160	1.3429048	Normal (Women)
8	1565.23 - 1570.40	180	1.3464554	Normal (Men)

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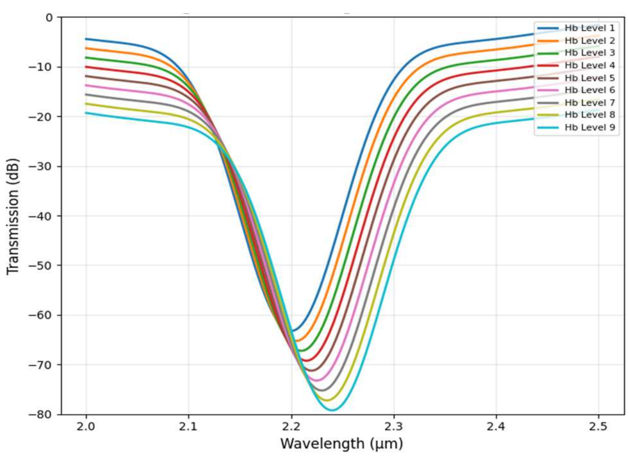

Fig. 6. Refractive index variation vs. hemoglobin concentration at Observation Point 1. Increasing RI correlates with elevated hemoglobin content, enabling stage-wise anemia classification.

Table 2 and Table 3 corroborates these findings since Table 2 correlated the range of refractive index with various stages of hemoglobin concentration, and Table 3 tabulated on peak transmissions, output power, and shift in resonance wavelength. The reduction in peak transmission values (0.85 Meep units to 0.63 Meep units) with increased hemoglobin concentration shows that the biosensor is effective in terms of optical sensitivity.The response time of the biosensor was 2 minutes which makes it suitable to be applied in the real-time technique. It showed stability at physiological temperatures (25 o C 50 o C) which are sign of reliability in the course of changing clinical conditions.

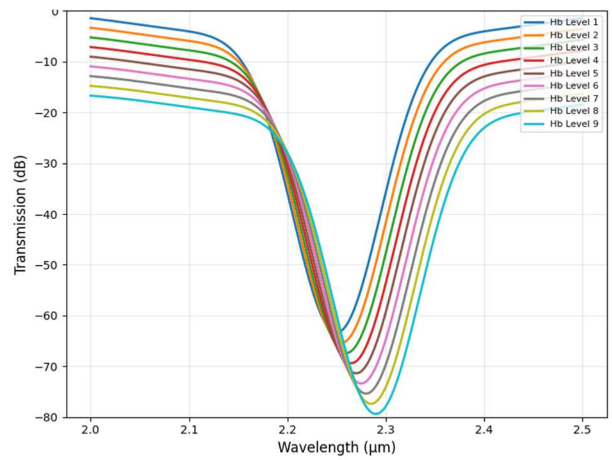

Fig. 7. Refractive index variation vs. hemoglobin concentration at Observation Point 2. Spatial consistency of refractive index confirms uniform analyte interaction

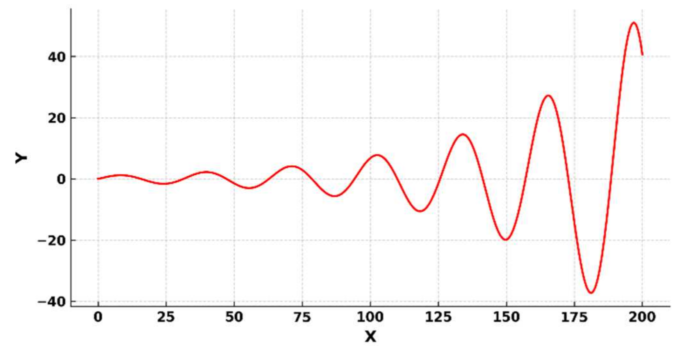

Fig. 8. Relative Power vs. Distance at Observation Point Gradual power loss reflects absorption by hemoglobin-rich samples.

A. Clinical Implications:

The proposed ORR-based biosensor allows for rapid and non-invasive anemia assessment where test conditions do not presuppose drawing blood samples and having laboratories, which is very beneficial in the case of physicians. Its portable size and rapid response time make it ideal for point-of-care mobile health unit device, injury triage, rural facilities, and home care Real-time hemoglobin monitoring would help treat the cases at an early stage and manage chronic anemia.

B. Limitations and Future Scope:

Simulation results are encouraging; nevertheless, the presented research is restricted to computational analysis In hardware implementation, fabrication issues, including waveguide alignment, need to be resolved , as well as microfluidic integration. Environmental noise and fiber-coupling losses can also impact real-world accuracy further work will include:

- Modeling, prototyping and experiment verifications
- Wearable devices miniaturization
- Thermal control packages aimed at eliminating temperature drift
- Real world performance validation clinical trials

TABLE3: SHIFT IN PEAK TRANSMISSION AND TRANSMITTED POWER ACROSS TEST SAMPLES WITH INCREASING HEMOGLOBIN. [9,11]

SL NO	Peak Transmission of blood and shift in Resonance Wavelength		
	Resonance Wavelength Range (nm)	Peak Transmission (Meep units)	Transmitted Output Power (Meep units)
1	1547.74 - 1555.68	0.85	0.85
2	1547.74 - 1555.68	0.8	0.8
3	1555.68 - 1557.60	0.78	0.78
4	1557.60 - 1560.10	0.75	0.75
5	1560.10 - 1562.70	0.7	0.7
6	1560.10 - 1565.23	0.68	0.68
7	1562.70 - 1567.82	0.65	0.63
8	1565.23 - 1570.40	0.63	0.63

C. Fabrication Considerations:

The optical system employs an SOI (silicon-on-insulator) platform as employed by integrated photonics. However, fabrication challenges are a reality Accurate matching of the waveguides and the microfluidic (sub-micron scale) is very important to successful delivery of the analyte and signal coupling. Design tolerances such as ring radius, coupling gaps, and waveguide width may influence sharpness and repeatability of resonance. The bio-compatibility of microfluidics has to be integrated without causing optical interference but with low volume fluid flow.

D. Clinical Testing Setup:

Although the present results involve simulation research, the sensor is intended to be integrated into a benchtop diagnostic system with the following testing pipeline: Sample introduction via capillary-driven microchannels The non-resonant laser excitation was carried out with a continuous wave (CW) laser at 1550 nm. Output acquisition is performed through spectral analysis using an optical spectrum analyzer (OSA). Resonance shift mapping of a decision engine to process data. Real time diagnosis based on WHO classification of anemia was done using clinical thresholds.

V. CONCLUSION

This paper presents an optical ring resonator (ORR)-based biosensor that uses real-time and non-invasive methods of hemoglobin concentration. The device demonstrated high refractive index sensitivity (1140 nm/RIU), rapid response time (2 minutes), and significant signal resolution that was backed by a good Q-factor, and reliability of resonance shifts at clinically-relevant hemoglobin concentrations (65 180 g/L). Its ability to differentiate various levels of anemia was demonstrated by peak transmission reductionreliable optical response. Based on its size, analysis speed, and degree of specificity, the biosensor shows great promisein the area of having point-of-care use in rural, mobile, and resource-limited medical applications. Future work will explore clinical validation, sensor miniaturization, and integration into portable diagnostic platforms for real-world deployment.

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