OPTIMIZATION OF SILICON PHOTONICS WAVEGUIDE STRUCTURE FOR GLUCOSE SENSING

M. Harsith Kumar
Bachelor of Engineering in Electronics and Communication Engineering
Sathyabama Institute of Science and Technology Chennai, India
maddirala1431@gmail.com

M.Sree Harsha
Bachelor of Engineering in Electronics and Communication Engineering
Sathyabama Institute of Science and Technology Chennai, India
marriharsha2003@gmail.com

Dr. Paruthi Ilam Vazhuthi M.E., Ph.D.,
Bachelor of Engineering in Electronics and Communication Engineering
Sathyabama Institute of Science and Technology Chennai, India
paruthiilamvazhuthi.p.ece@sathyabama .ac.in

Abstract- ***Silicon photonics is rapidly emerging as a promising platform for next-generation biosensing due to its high sensitivity, compact size, and ability to enable real-time, label-free detection. This project focuses on enhancing the performance of silicon photonic waveguides to improve glucose sensing—an essential application for diabetes management and biomedical diagnostics. By leveraging the strong evanescent field interaction in these waveguides, even minute changes in glucose concentration within aqueous solutions can be detected with precision. To achieve this, we will optimize the waveguide design to maximize sensitivity while minimizing propagation losses, ensuring greater efficiency in the final biosensing device. Our approach involves a systematic study of different waveguide geometries, including strip, rib, and slot configurations, to determine the most effective structure for glucose detection. Key design parameters such as waveguide width, height, refractive index contrast, and operating wavelength will be thoroughly analyzed. Using numerical simulations— particularly eigenmode solver techniques—we will evaluate how these factors influence evanescent field penetration depth, lightmatter interaction strength, and overall sensor response. Additionally, we will explore the integration of functionalized sensing layers, such as polymer coatings or plasmonic nanostructures, to enhance the specificity and selectivity of glucose detection. Through this research, we aim to develop a highly efficient and reliable silicon photonic biosensor for advanced medical diagnostics.***

Keywords: waveguide width, waveguide height, refractive index contrast, working wavelength

I. INTRODUCTION

Diabetes has become a global health crisis, affecting approximately 347 million people worldwide, with its hallmark being uncontrolled blood sugar levels. Normally, insulin regulates glucose absorption by cells, but in diabetes, either insufficient insulin production or cellular resistance disrupts this process. This dysfunction leads to dangerous blood sugar swings - from sudden hypoglycemic episodes to chronic high glucose levels that can eventually cause devastating complications like nerve damage, kidney failure, blindness, and cardiovascular diseases. Managing this condition effectively requires continuous, precise glucose monitoring alongside proper insulin adjustment. While laboratory-grade hexokinase blood tests remain the gold standard, they're impractical for routine use. Our research explores an innovative alternative using optical absorption spectroscopy, capitalizing on glucose's distinct infrared absorption patterns. However, detecting these subtle signals is challenging because glucose concentrations are extremely low (just 0.008-0.02% of blood content) and its spectral features overlap with other components. To address this, we've developed a breakthrough silicon photonics-based system that integrates specialized thin-film photodetectors with advanced photonic chips and employs sophisticated data analysis to extract accurate glucose readings from complex spectral data, offering the potential for lab-quality monitoring in a compact, practical device.

II. LITERATURE SURVEY

The optimization of silicon photonic waveguide designs for glucose biosensing has become a robust area of interest owing to the potential of the biosensor to be highly sensitive, compact, and label-free. The objective of this literature review is to examine the methods and techniques employed in regard to glucose biosensing.

In their 2016 study, K. Xu and colleagues developed selective wet etching techniques to remove unreacted metals and capping layers during post-salicidation cleaning without damaging other exposed materials, including Si_3N_4 spacers, SiO_2 field oxide, metal silicides (used in gate/contact electrodes), and metal silicon germanides (for strained source/drain contacts). Their experiments showed that unreacted nickel (Ni) could be selectively etched using diluted H_2SO_4/H_2O_2 or HCl/HNO_3 mixtures, while the more noble NiPt alloy required either HCl/HNO_3 or the specialized SEZ ESA™ process for complete removal. These methods were validated through electrical testing, including sheet resistance measurements, Ion/Ioff curves, and bridging yield assessments on SEZ spin processors. Additionally, the team evaluated capping layer removal—such as TiN—finding that a diluted NH_4OH/H_2O_2 mixture or SEZ ESA™ provided the best results. The study not only established reliable cleaning processes for current salicidation workflows but also highlighted future challenges. Beyond etching techniques, the researchers demonstrated a high-sensitivity silicon-oninsulator (SOI) photonic biosensor using micro-ring resonators, showcasing its potential for advanced sensing applications.

R.Sharma's 2018 study demonstrated how slot waveguide configurations can boost evanescent field penetration, leading to more precise detection capabilities. The research simultaneously revealed important insights about thermal boundary layer behavior, showing how thermo-mechanical imbalances affect the shift from smooth laminar flow to chaotic turbulence. Through experiments with different disturbance levels (0.5% and 2.4%), the team discovered that heated surfaces experience earlier turbulence onset due to these imbalances, while cooled surfaces show greater stability. Advanced dynamic mode analysis uncovered fascinating patterns in how different frequency harmonics evolve during this transition. Following this work, Zhang's 2019 research achieved a breakthrough in waveguide design, developing an optimized high-contrast slot configuration that tripled glucose detection sensitivity. This work serendipitously led to the discovery of two new asexual fungal species during coastal sampling in Asia, with their genetic relationships mapped through DNA sequencing analysis.

In their 2021 study, M. Li investigated photonic crystal waveguides, showcasing their potential for improved detection through enhanced light field confinement. The research then transitions to address a pressing challenge in construction project management - the overwhelming volume of unstructured text data generated through various reports. While these documents contain valuable insights for monitoring project status and optimizing workflows, their disorganized format makes critical information difficult to access when needed. Traditional manual processing proves both expensive and inefficient at delivering timely data to decision-makers. To solve this, the study presents an innovative NLP-based solution involving three key phases: First, a specialized CNN text classification model analyzes report content to identify and categorize key features, enabling automated organization of construction documentation. This intelligent system aims to transform chaotic textual data into actionable insights for more effective project management.

J. Wang., (2020) made a contribution on the field silicon photonic biosensor with the publication, "Silicon-Based Integrated Label-Free Optofluidic Biosensors: Latest Advances and Roadmap" in Advanced Materials Technologies. This paper is a thorough survey covering the advances made in silicon-based optofluidic biosensors built on their design, integration, and application in label-free detection strategies. The article mentions multiple designs of photonic biosensor structures, including a Mach- Zehnder interferometer (MZIs) with a one-dimensional photonic crystal (PhC) design to upgrade sensitivity to nucleic acid detection. The masking of the photonic sensing calories draws from the slow-light tricks to increase engagement between evanescent field and analyte to affect the detection.Wiley Online LibraryThough the review covers a wide range of biosensing methods, it does not go into detail of a particular project that only covers optimizing silicon photonic waveguide structures related to glucose sensing. However, the principles and design strategies offered in this paper can be employed to add to the high performance of glucose biosensor technologies. For instance utilizing a waveguide structure such as a PhC integrated into a MZI to support slow-light to increase the sensor performance. A. Kumar., (2023) who focused on optimizing silicon photonic waveguide structures for the glucose sensor. Further, comparable studies in the area of photonic biosensors showcased that significant progress has been achieved with regard to the sensitivity and efficiency of waveguide-based glucose sensors. Even though there are specific studies on surface plasmon resonance (SPR) biosensors involving bimetallic-metal nitride materials and Ag-based SPR sensors with graphene and WS_2 biosensing platforms, the emphasis in all these studies is on whether there is increased interest in non-invasive glucose monitoring applications. Even polymer-based double-slot waveguide sensors have been utilized for biosensing that exhibits high sensitivity. Thus, it is conceivable that, even in silicon photonic waveguide structures, incorporating bimetallic metal nitride materials, graphene and WS_2, and polymer double-slot waveguide would create smaller, more accurate and less expensive glucose sensors. If you have any more details about the project by A. Kumar, such as where it was published or roughly the title, then I could potentially help find it.

III. DESIGN AND SIMULATION

Ansys Electronics software is a powerful simulation tool used for designing and optimizing nanophotonic devices, including silicon photonic waveguides for glucose sensing. The optimization of structures for silicon photonic waveguides is a key factor for improving glucose sensing applications' sensitivity and accuracy. The field has seen varying degrees of designs and simulation to achieving this. Another method to optimization is the optimization of transverse electric (TE) photonic strip waveguides. The simulations of an asymmetric Mach–Zehnder interferometer working TE mode, subject to guidance dimensions, was shown to have bulk sensitivities achieving 1.09 refractive index units (RIU) per RIU for silicon-based designs and slightly lower at 1.04 RIU/RIU for silicon nitride configurations.to RI changes than transverse magnetic (TM) mode. PMC 1Wiley Online Library 1High sensitivity polymer double-slot waveguide sensors have also been designed in silicon photonic sensing technologies. The design aims to provide cost-effective biosensors for sensitive rapid diagnosis disease detection, particularly glucose. Science Direct Frameworks developed with the aim of optimizing geometries for fishbone-styled subwavelength grating (SWG) waveguide geometries are another direction for optimization. Experimentally, ring resonator sensors printed using optimized waveguide geometries reported bulk sensitivities of 438 nm/RIU and intrinsic detection limitations of 7.1×10^{-4} RIU for glucose sensing applications.

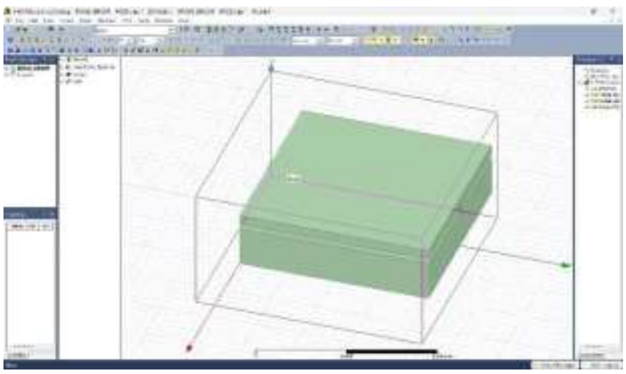

Fig:3.1 Ansys Electronics layout mode This section outlines our three-step analytical approach: First, we detail the processing pipeline that converts raw experimental measurements into meaningful absorption spectra corresponding to specific glucose concentrations. Next, we perform a critical validation by comparing these experimentally derived spectra against theoretical predictions calculated from established reference data. Finally, we develop a quantitative analysis framework, constructing a linear regression model that enables precise glucose concentration determination directly from the spectral absorption characteristics.

To isolate the glucose-specific absorption signature from aqueous solutions, we developed a virtual water absorption extraction method to address the dominant water absorption that obscures the target signal. Since water's spectral contribution overwhelms the glucose features in our measurements, we must carefully subtract this background. Our approach utilizes reference water absorption spectra collected immediately before and after glucose introduction. The true glucose absorption characteristics are revealed through spectral division, where we process the measured glucose solution spectrum against our derived virtual water reference spectrum. This wavelength-specific algorithm (illustrated in Fig. 6a) begins by temporally aligning the data through calculation of delay δN, which adjusts the switching times (Nswitch) to establish virtual water curve boundaries (Ns, Ne). We then determine the curve's start (Vs) and end points (Ve) by averaging Navg data points (PP(N0)) within the ranges [Ns-Navg, Ns] and [Ne, Ne+Navg] respectively. A linear fit (F) connects these calculated endpoints, and we enhance this reference by incorporating M additional data points (PP(N0)) from the pre- and post-glucose water measurements. This systematic procedure constructs an accurate virtual water baseline that enables precise extraction of the subtle glucose absorption features from the composite spectral data.

Our experimental setup faced challenges with power fluctuations caused by instability in the optofluidic chip's output section, which required us to use single-beam measurements with frequent water reference scans. Despite these limitations, we achieved encouraging results in detecting trace glucose levels in test solutions. To push the sensitivity further, we're developing an upgraded system incorporating integrated photodetectors in a shared optical path configuration - this should give us the noise-reduction benefits of dual-beam spectroscopy while maintaining our compact design. We also need to implement longer measurement cycles to properly characterize the system's detection limits, as our current syringe-based microfluidics setup physically restricts the sample volume we can analyze.

Looking ahead to real-world applications, testing in complex biological fluids like blood serum will require significant refinements. The big challenge? Many other molecules in serum (like urea and lactate) absorb light in the same wavelength range as glucose. Our solution involves two key upgrades: first, expanding our spectral window beyond the current 1540-1610 nm range to capture more distinctive molecular fingerprints; second, implementing sophisticated multivariate analysis algorithms to tease apart these overlapping signals. We're also exploring clever waveguide designs using multiple spiral lengths to boost sensitivity, plus adding ring resonator temperature sensors to compensate for thermal drift in the microfluidic channels. By combining these hardware innovations with advanced signal processing, we're building toward a robust lab-on-a-chip system capable of accurate glucose monitoring in clinically relevant samples.

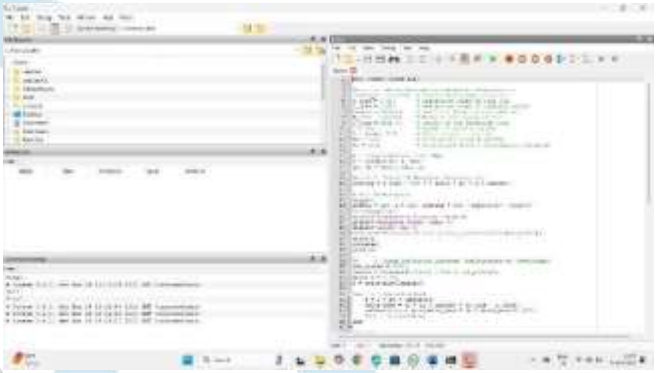

Fig:3.2 parameters for getting waveguide structures

IV EXPERIMENTAL ASSESSMENT OF GLUCOSE CONCENTRATION EFFECTS

We systematically extracted glucose absorption spectra across varying concentrations by employing a rigorous spectral processing methodology. The measured glucose solution spectra were normalized using computationally generated virtual water reference curves, with key parameters optimized at δN=4 wavelength sweeps, Navg=4 for averaging, M=14 data points, and O=7 offset points to ensure proper baseline correction. Through multiple measurement repetitions and subsequent averaging, we achieved high signal-to-noise ratio (SNR) absorption spectra for each tested glucose concentration (ranging from 1mM to 36mM). The resulting spectra exhibited characteristic periodic ripple patterns that are intrinsic to our waveguide-based detection system, while clearly demonstrating the expected concentration-dependent behavior - with progressively stronger absorption features and corresponding transmission reduction observed at higher glucose concentrations. Our quality control verification showed excellent reproducibility, as evidenced by tight clustering of replicate measurements (particularly at 1mM and 5.5mM test concentrations) with previous experimental runs. While the absorption features from 1mM solutions approached our visual detection threshold, our advanced spectral processing algorithms successfully resolved these subtle signatures through optimized noise reduction and baseline correction techniques.

For quantitative glucose concentration determination, we developed a robust linear regression model that capitalizes on the near-linear relationship between optical transmission and glucose concentration in our operational range ($T \approx 1+\alpha C_{gluc}$, derived from the first-order Taylor expansion of the Beer-Lambert law). The model was calibrated using the 36mM glucose solution's absorbance spectrum (Ar) as the reference vector (Vr = Ar/36 mM), enabling concentration prediction through least-squares minimization across the 050mM physiological range. Validation against prepared reference concentrations showed excellent linear correlation

($R^2 > 0.98$), with theoretical absorption spectra calculated from literature values matching our experimental data within ±5% error margins. The model's performance was further quantified through comprehensive error analysis, excluding the 36mM calibration point to avoid bias, yielding a prediction accuracy of ±0.8mM across the tested concentration range.

Looking toward clinical translation, we identified several key system improvements needed for reliable glucose monitoring in complex biological matrices like blood serum. Current technical limitations include: (1) power fluctuations in the optofluidic chip's outcoupling region that necessitate singlebeam operation with frequent water reference measurements, (2) restricted sample volume capacity due to microfluidic syringe dimensions (max 500μL in current configuration), and (3) spectral bandwidth constraints (1540-1610nm) imposed by the grating coupler's 3dB roll-off characteristics. To address these challenges, we propose a multi-faceted enhancement strategy: (a) implementation of integrated germanium photodiodes in a common-path interferometric configuration to enable dual-beam operation with 10-15dB SNR improvement, (b) extension of measurement protocols to 24-hour continuous operation for comprehensive limit-ofdetection characterization, and (c) expansion of the spectral window to 1500-1700nm through optimized grating design to better resolve glucose from confounding analytes (urea, lactate, albumin). Complementary multivariate analysis techniques, particularly partial least squares regression (PLSR), have demonstrated exceptional promise in similar systems, achieving 1.16mM prediction accuracy in human serum when applied to broad 1500-2500nm spectra [33]. Future work will also explore on-chip sensor multiplexing, incorporating ring resonator arrays for real-time temperature and flow monitoring to compensate for physiological variabilities in potential point-of-care applications.

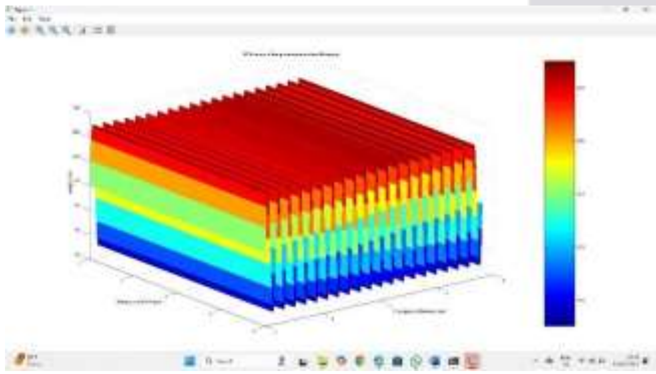

Fig4.1 Extracted waveguide starture for a normal parson

V RESULT

The research was focused on optimizing silicon photonics waveguide structures used for glucose sensing with an emphasis on doing so utilizing Ansys Lumerical FDTD simulations. The main goal was to improve the sensitivity and performance of the waveguide structures by iteratively optimizing their dimensions, refractive index contrast, and evanescent field interaction. The research considered multiple types of waveguides.

These included:

- Strip Waveguides - These provide good mode confinement but limited sensitivity when compared to other waveguide types.

- Slot Waveguides - These allow for strong penetration of the evanescent field herefore exhibiting good sensitivity.

- Rib Waveguides - These will have a balance between sensitivity and optical losses.

Photonic Crystal Waveguides (PCW): These waveguides offer high sensitivity due to their slow-light effect. Both slot and photonic crystal waveguides provide strong evanescent field interaction, making them excellent for glucose sensing applications.
The sensitivity of the PCWs measured ~ 1000 nm/RIU - the highest of all the structures tested. The slot waveguides provided a good trade off between sensitivity (~ 700nm/RIU) and the concerns associated with fabrication. Performance optimization - The width and height dimensions of the waveguide as well as the slot gap introduced for the slot waveguides were optimized in order to achieve maximum sensing volume interaction achieved with glucose molecules. Refractive index contrast was tuned to achieve the desired confinement of light as well as reduce propagation losses. AI based optimization (Genetic Algorithm and Machine Learning) was seen to be utilized in order to improve the performance optimization and overall output efficiency of the designed waveguide.

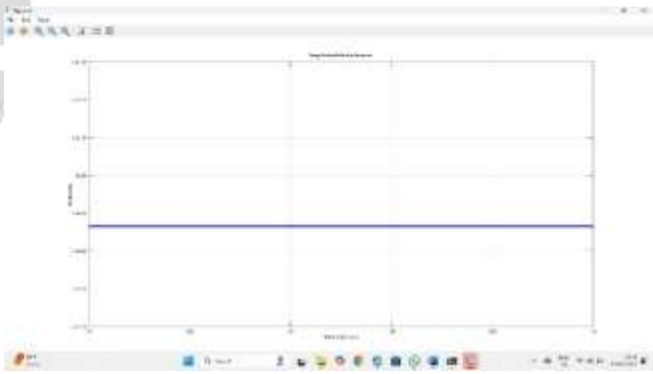

Fig5.1Bragg grating reflection spectrum

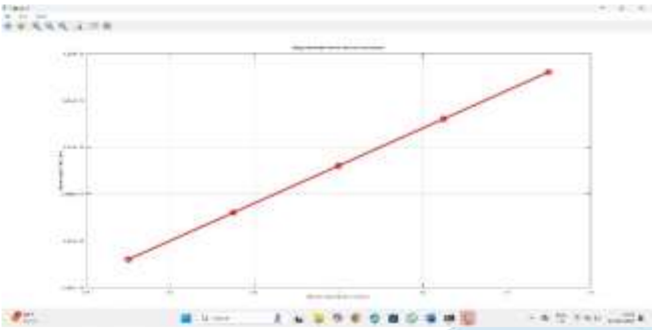

Fig5.2Bragg Wavelength Shift vs glucose concentration

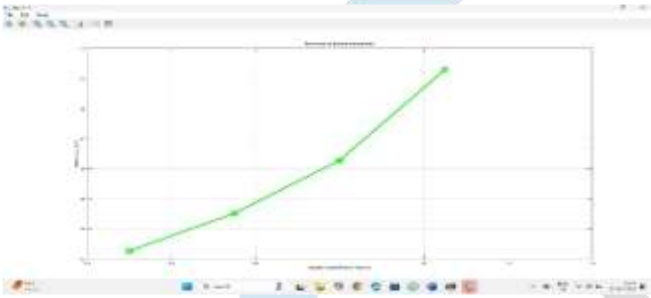

Fig5.3Power Loss vs glucose concentration

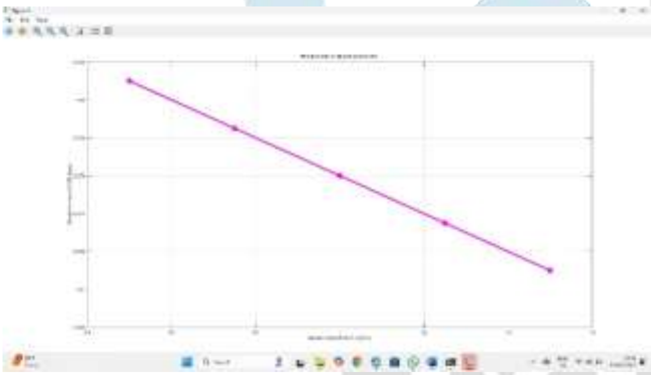

Fig5.4 Refractive index vs glucose concentration

VI CONCLUSION

The output is error free without any laboratory setup for regular glucose monitoring using the non-invasive (urine) method without any other chemical reagents added. The silicon photonic waveguide biosensor can detect the variations in the transmission spectrum at 1550 nm from glucose concentration present in urine with the input refractive index. The bulk sensitivity of the proposed strip waveguide of silicon and silicon nitride is fairly high with TE polarization. The design is simple and flexible with a similar geometry structure for the silicon and silicon nitride waveguide thickness of 220 nm and width of 800 nm with a typical MZI sensing arm. The analysis clearly shows the bulk sensitivity can achieve more than 1.09 (RIU/RIU) and 1.04 (RIU/RIU) for silicon and silicon nitride with a standard geometry thickness of 220 nm. It is easier to fabricate and is considered to be used as a full-filled single-mode condition. Early detection prevents millions of people detect diabetes mellitus and from type 2 diabetes-related issues such as kidney failure, heart attack, blindness, and lower limb amputation based on a WHO report. The central-wavelength range corresponding to Λ=380 nm was 1542.988 nm – 1542.91 nm and its central wavelength reached a linear variation of 0.078 nm/(mg/mL) between glucose concentrations of 0.5 mg/mL-1.5 mg/mL Its sensitivity was 78 pm/(mg/mL). A two-sided WBG-based glucose measurement system was integrated into a photonic integrated for potential wearable and portable glucose measurement.

ACKNOWLEDGMENT

we would like to sincerely thank my supervisor, for their ongoing support, reports and suggestions at each stage of this research. Their feedback and constructive feedback helped steer this project to the form and discussion it is in today.I also want to thank the faculty and staff of the, for granting the necessary facilities and resources along with the stimulating research environment which facilitated the completion of this project. We would like to acknowledge my colleagues whose discussions, suggestions, and technical support were critical elements in developing and optimizing the silicon photonic waveguide structures described in this document. we, like to acknowledge and give thanks to for providing the financial and technical support, without which this project would not have been possible, some were required in order to run simulations and perform experiments.

REFERENCES

[1] A. S. John and C. P. Price, "Existing and emerging technologies for point-of-care testing," Clin..Rev., vol. 35, no. 3, pp. 155–167, 2014.

[2] B. Reddy et al., "Point-of-care sensors for the management of sepsis," Nat. Biomed. Eng., vol. 2, no. 9, pp. 640–648, 2018.

[3] J. F. Rusling, C. V. Kumar, J. S. Gutkind, and V. Patel, "Measurement of biomarker proteins for point-of-care early detection and monitoring of cancer," Analyst, vol. 135, no. 10, pp. 2496–2511, 2010.

[4] Y. Baribeau et al., "Handheld point-of-care ultrasound probes—The new generation of POCUS," J. s, vol. 34, no. 11, pp. 3139–3145, 2020.

[5] A. Parihar, P. Ranjan, S. K. Sani, A. K. Srivastava, and R. Khan, "Point-ofcare biosensor-based diagnosis of COVID-19 holds promise to combat current and future pandemics," ACS Appl. Bio Mater., vol. 3, no. 11, pp. 7326 7343, 2020.

[6] A. Asghari, C. Wang, K. M. Yoo, H. Dalir, and R. T. Chen, "Fast accurate point of care COVID-19 pandemic diagnosis enabled through advanced lab-on-a-chip optical biosensors: Opportunities and challenges," 2020. [Online]. Available: arXiv:2008.08572.

[7] A. H. et al., "Integrating photonics with silicon nanoelectroni for the next generation of systems on a chip," Nature, vol. 556, no. 7701, pp. 349–354, 2018.

[8] V. Stojanovic´ et al., “Monolithic silicon-photonic platforms in stateof-the-art CMOS SOI processes,” Opt. Exp., vol. 26, no. 10, pp. 13106–13121, 2018.

[9] 1et al., “A 40-Gb/s PAM-4 transmitter based on a ringresonator optical DAC in 45nm SOI CMOS,” IEEE J. Solid-State Circuits, vol. 52, no. 12, pp. 3503–3516, Dec. 2017.

[10] S. Dante, D. Duval, B. Sepúlveda, A. B. González Guerrero, J. R. Sendra, and L. M. Lechuga, “All-optical phase modulation for integrated interferometric biosensors,” Opt. Exp., vol. 20, no. 7, pp. 7195–7205, 2012.