Assessing silicon photonic biosensors for home healthcare

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An experimental and theoretical comparison of silicon photonic resonators identifies which are most promising for implementing lab-on-chip diagnostic devices.

Silicon nanophotonics has the transformative potential to produce highly integrated, low-cost medical biosensors for point-of-care (POC) clinics and home healthcare diagnostic applications. The recent literature has seen significant advances, reporting silicon photonic biosensors capable of delivering results with clinically relevant sensitivities. Additionally, the repertoire of molecules that bind to specific biomarkers, which signifies the presence of certain pathogens or disease states, is rapidly expanding. Detecting and quantifying the circulating biomarkers is a route to diagnosis, and such analyses can operate in increasingly complex samples such as saliva and human serum, a major component of blood.

By leveraging existing CMOS fabrication processes and their economies of scale, silicon photonic sensors offer significant advantages over traditional biosensing platforms, such as thousands of sensors assembled on a single millimeter-scale chip. In the near future, these biosensors could displace traditional clinical assays that rely on multistep liquid handling, trained operators, and benchtop instrumentation. However, the field must overcome numerous challenges to realize a fully integrated silicon photonic biosensing platform. These include determining the optimal sensor characteristics, fluidic and analyte control, and on-chip lasers and detectors. Our work reviews important sensor performance metrics in aqueous environments similar to saliva, serum, or blood, that are essential for medical diagnostic applications.

Evanescent field sensors, such as surface plasmon resonance (SPR) or planar waveguide-based sensors (including silicon photonics resonators), represent some of the most popular optical techniques for sensitive and label-free detection of biological analytes (see Figure 1). Compared to other sensing methods, these optical sensors have the advantages of high sensitivity, no physical contact between sensor and target analyte, immunity to electromagnetic interference, and the possibility of sensing multiple biomarkers simultaneously. Waveguides with dimensions smaller than the free-space wavelength of light have a strong evanescent field that extends a few hundred nanometers beyond the waveguide’s surface into the surrounding media. By including surface chemistries that bind to the analyte of interest, it is possible to functionalize the waveguide for specific capture of biological molecules, pathogens, or cells. Any interaction with molecules or particles in close proximity to the waveguide’s surface will change its effective refractive index for the guided mode, which leads to a detectable shift in the resonance peaks of the device.

While numerous silicon photonic resonators have been demonstrated for sensing purposes, it remains unclear which structures provide the highest sensitivity and best limits of...
detection. For example, disc resonators and slot-waveguide-based ring resonators have been shown to provide improved sensitivity (see Figure 2).\(^1\) The limit of detection involves both the refractive index sensitivity and the width of the resonance peak. (The refractive index sensitivity is the magnitude of the resonance peak shift in response to a change in refractive index, which is dependent on the proportion of the field traveling in the sensing medium. The peak width is dependent on the field losses in the resonator.) As a result, the limit of detection is influenced both by the proportion of the field traveling in the fluid and the losses incurred during travel. For instance, disc resonators yield lower losses and thus sharper peaks, while slot-waveguide resonators yield higher sensitivities by confining more of the field in the fluid.

In our work, we compared various resonators in terms of sensor metrics for label-free biosensing in a microfluidic environment. We integrated resonator arrays with polydimethylsiloxane microfluidics for real-time detection of biomolecules in experiments such as an antigen-antibody binding reaction using Human Factor IX proteins (see Figure 1). As part of the

**Figure 2.** Scanning electron micrograph of a slot waveguide racetrack resonator. The inset shows a scanning electron microscope image of a focused ion beam cross-section of the through-port coupler. The slots in these waveguides are well-defined, all the way through the 220nm of silicon.

CMC Microsystems and University of British Columbia Silicon Nanophotonics Fabrication course,\(^3\) several student projects focused on conducting microfluidic experiments with different resonator configurations. We fabricated and experimentally characterized numerous resonators on the same wafer. Evanescent-field sensors operate on the principle of detecting a shift in refractive index around the device, which is typically associated with capture of the biological analyte. However, we identified important differences between implementations that relate to the amount of overlap between the optical field and analyte, as well as the relative contributions of the various loss mechanisms.

Specifically, we found that sensors operating in aqueous media are fundamentally limited by the optical absorption of water. In the cases where the water absorption is dominant, all sensor geometries (such as ring resonators based on strip or slot waveguides, disks, Bragg grating cavities, or 1D photonic

**Figure 3.** Summary of model results on limits of detection for 1550nm silicon photonic biosensors for the various configurations studied in this work (data points). In this figure, higher quality factor (Q-factor) and higher sensitivity led to an improved detection limit. The theoretical maximum based on the water absorption limit is the line in which the single data point represents light traveling exclusively in water. The diagonal line represents the theoretical detection limit shared by all sensor geometries. This is because raising one parameter means lowering the other: at higher Q-factors, the light interacts less with water, resulting in lower sensitivities. The limit in water alone depends only on the index of refraction of the analyte, while the diagonal limit depends only on the optical loss of the analyte. TM: Transverse magnetic. TE: Transverse electric. RIU: Refractive index unit.

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crystals) will theoretically offer the same performance in terms of the limit of detection (see Figure 3). Likewise, light polarizations falling into the transverse electric (TE) or transverse magnetic (TM) categories work equally well. The differences between sensor configurations become important when other loss mechanisms are present, such as waveguide scattering loss, waveguide material absorption, or resonator radiation loss. In these cases, it is important to minimize the ratio of other losses relative to the analyte’s optical absorption losses. In particular, increasing the analyte’s absorption by resorting to TM modes and moving the optical field away from the rough waveguide sidewall improves this ratio and allows the sensor to approach the fundamental limits of detection. The structures that are most amenable to reaching the theoretical detection limit are, in decreasing order, TM waveguides, disks, and TE waveguides. Slot waveguides and 1D photonic crystals are the furthest away from reaching fundamental limits due to much higher scattering losses.

Silicon photonic resonator biosensors have matured to the point where benchtop systems are commercially available and capable of facilitating cutting-edge biomedical research. Of the sensors surveyed in this work, we found that many silicon photonics sensors are already near the fundamental limit of detection. Future sensor development should focus on tailored designs specific to particular biosensing needs, including improved sensitivity, noise immunity, very large array operation, and simplified read-out schemes. Only when we have a fully-integrated, easy-to-use diagnostic device capable of analyzing complex biological samples like blood, saliva, and urine, will we impact home health care and expand the capabilities of low-resource health settings. Achieving these goals is necessary for the transition of silicon-nanophotonic sensors from the laboratory to clinical, point-of-care, or low-resource settings.

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References