Pioneering Silicon Photonics for Wearable Sensors

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Abstract: The Rockley silicon photonics platform has unique advantages perfectly suited to addressing the needs of wearable health sensors. An overview of the platform is presented including its application to non-invasive continuous monitoring of body temperature.

1. Introduction

Silicon photonics has emerged as a mature, high-volume commercial technology addressing a wide range of applications. Much of the development of silicon photonics has been motivated by the drive to miniaturize complex optical systems for use in communications products such as transceivers. The ability to translate a complex optical system into a single photonic-integrated-circuit (PIC) can be readily extended to other applications using the same underlying components and platform. One such application is wearable health sensors, where existing solutions are based on integrating discrete optical components into wearables enabling continuous monitoring of health indicators such as blood oxygen saturation [1]. However, the compact footprints of wearable form factors limit the range of techniques that can be robustly integrated and applications that can be addressed. This limitation creates an opportunity for silicon photonics to be extended into wearable optical health sensors, not only to miniaturize existing systems, but also to enable entirely new functionality providing unprecedented insight into key health indicators. One example application is the development of a compact laser spectrophotometer which meets the broad wavelength range and high SNR requirements for noninvasive optical sensing.

In this work we demonstrate the suitability and unique advantages of the Rockley silicon photonics platform for addressing the needs of wearable optical health sensors. We furthermore demonstrate, as an example, its application to the determination of body temperature based on interrogating the spectroscopic signature of water.

2. Rockley Silicon Photonics Platform

2.1. Large waveguide platform

The Rockley silicon photonics platform features a toolbox of devices and components engineered and matured for use in commercial applications such as transceivers [2,3]. Sensing-based optical systems require many of the same fundamental transmit and receive building blocks, and as such this same toolbox serves as an excellent platform for engineering PIC's addressing wearable health sensors.

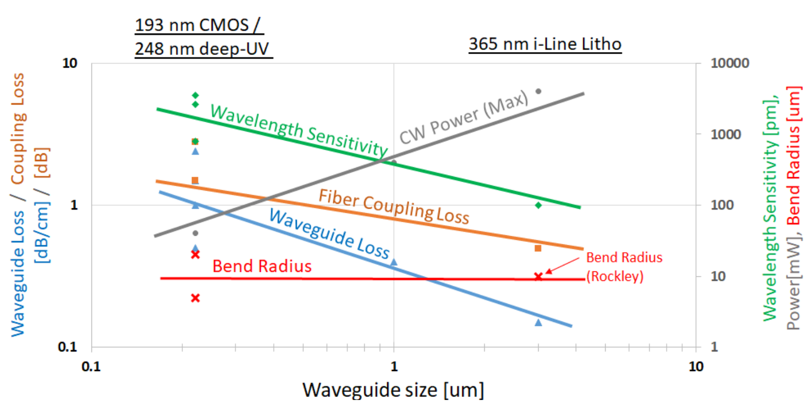

Fig. 1. Scaling of key waveguide performance characteristics with waveguide size

The foundation of the Rockley solution is the "large waveguide" silicon photonics platform [3], which exhibits micron-scale cross-sections of the underlying optical waveguide. This solution contrasts with the majority of silicon photonic platforms which are optimized for sub-micron geometries, historically motivated by the ultimate push to monolithically integrate optics and electronics using established CMOS foundry infrastructure, and reliance on p/n junction-based modulators for communications applications. However, many critical performance metrics of the optical components themselves are optimized towards larger cross-sectional areas, where waveguide loss, fiber coupling loss, optical power handling, and wavelength registration sensitivity are all improved by at least an order of magnitude, as shown in Fig. 1. At the same time, by utilizing compact bends as the foundation for waveguide routing [3], comparable PIC footprints are enabled. Together, these features of the PIC support a compact platform that has superior loss, power-handling, and wavelength registration characteristics which are critical for addressing the needs of wearable spectroscopic systems.

2.2. Opportunity for short-wave IR sensing using silicon photonics

Silicon is transparent above its band-gap (~1.1um) and is thus well suited to sensing applications relying on radiation in the short-wave IR (SWIR) band, a band which is considered a finger-print region for many biomolecules because of their strong and differentiating absorption features in the SWIR. Figure 2 shows an example of the absorption spectra of a number of key blood constituents, demonstrating the rich array of bio-markers addressable by a compact silicon-photonics-based SWIR spectrometer. Another key consideration is water absorption. Since the majority of the human body consists of water, it is important to operate in spectral windows where water absorption is low. The SWIR band has several water absorption windows and also water absorption features which allow for applications that interrogate the characteristics of water itself such as the direct measurement of hydration [4], or determining body temperature through the temperature-response of the water absorption spectrum [5] as will be summarized in section 3.2.

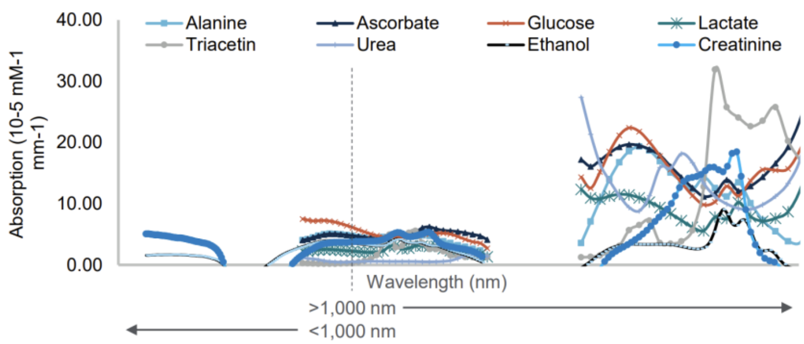

Fig. 2. Absorption spectra of key biomarkers

3. Rockley Photonics Spectrophotometer

3.1. Overview

The Rockley Photonics approach to health sensing is centered on the development of a compact spectrophotometer leveraging the unique and mature silicon photonics platform outlined in section 2. The spectrometer consists of multiple continuous-wave laser sources at different wavelengths directed to an optical output of a PIC which spectroscopically interrogates underlying tissue. The spatial relationship between the sensor emitters and detectors allows different layers or depths of the tissue to be probed as illustrated in Fig. 3. By selecting the wavelengths appropriately, depending on the absorption features of the biomarker of interest, numerous applications are enabled.

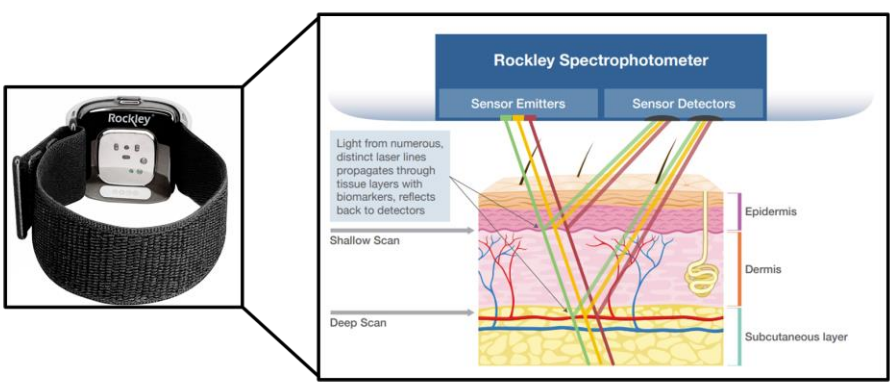

Fig. 3. Skin-probing capabilities of the Rockley Photonics spectrophotometer

3.2. Example application: body temperature

Body temperature is a vital health indicator correlated to normal cellular function and organism survival. It often serves as a clear initial indicator of illness and is thus a common measurement both at home and in clinical settings.

Continuous monitoring of body temperature can provide valuable insight into the onset of illness, as well as an early indicator of health change.

Body temperature is a measure of how well your body can make and get rid of heat in order to maintain homeostasis. Typical measurement techniques focus on areas of the body easily accessible such as the skin surface on the forehead using infrared sensors targeting the temporal artery, optical IR emission measurements from the tympanic membrane in the ear, or the mouth/armpit/rectum using either a mercury or electronic thermometer. Each of these commonly used techniques measure the body's temperature at the skin surface and is subject to its own limitations and errors.

The Rockley Photonics temperature sensor is uniquely positioned for determining body temperature in a non-invasive and continuous way since the sensor itself is capable of interrogating tissue below the surface of the skin (Fig. 3). Using multiple laser lines also targeting different penetration depths into the skin dermis, the temperature dependence of the absorption spectrum of water present in the interstitial fluid can be measured and correlated to body temperature, providing a stronger correlation to body temperature as compared to standard techniques.

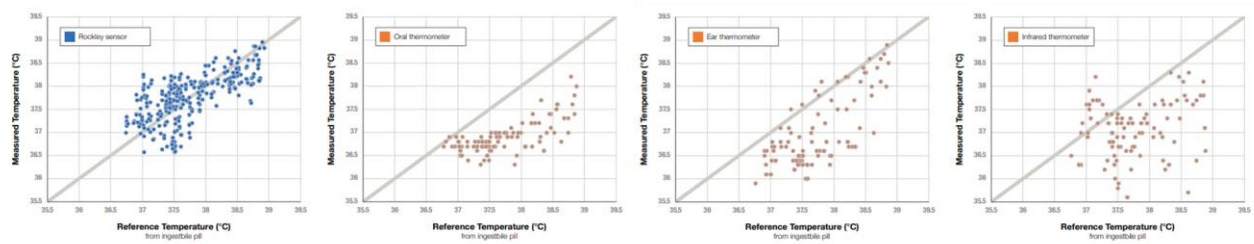

Fig. 4. Comparative results of various temperature measurement methods vs the Rockley Photonics sensor

To demonstrate the technique, preliminary IRB-approved body human temperature studies have been conducted comparing common auxiliary approaches to the Rockley photonics-based sensors focused on detecting the spectra of water over different layers of the dermis. The body temperature reference for the study was obtained through an ingestible pill monitor, which was ingested by the research subjects 12 hours prior to the study start. Figure 4 shows an example result from the study comparing the Rockley sensor to standard ear, oral, and infrared thermometers, demonstrating excellent performance as compared to the other auxiliary sensors. These results provide an encouraging proof-of-concept for the viability of the approach.

4. Conclusions

We have described the unique advantages of the Rockley silicon photonics platform and the potential of engineering PICs addressing wearable health sensors. Using this platform, in an example, non-invasive monitoring body temperature has been demonstrated and excellent performance against typical auxiliary measurement techniques was exhibited. In addition to performance, a distinct advantage of realizing an application like body temperature in a wearable form-factor is the ability to monitor in real time and continuously.

Ultimately, as the monitoring of additional biomarkers addressable by the Rockley spectrophotometer matures, data analytics and artificial intelligence will be leveraged to develop holistic assessments of an individual's health, thus helping both patients and healthcare providers make more informed decisions.

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