Towards a Wearable Non-invasive Blood Glucose Monitoring Device

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Abstract. Every day, about 150 Million people worldwide face the problem of diabetic metabolic control. Both the hypo- and hyper- glycaemic conditions of patients have fatal consequences and warrant blood glucose monitoring at regular interval. Existing blood glucose monitors can be widely classified into three classes viz., invasive, minimally invasive, and noninvasive. Invasive monitoring requires small volume of blood and are inappropriate for continuous monitoring of blood glucose. Minimally invasive monitors analyze tissue fluid or extract few micro litre of blood only. Also the skin injury is minimal. On the other hand, noninvasive devices are painless and void of any skin injury. We use an indigenously developed polarization sensitive Optical Coherence Tomography to measure the blood glucose levels. Current trends and recent results with the device are discussed.

1. Introduction

Diabetes mellitus is a medical condition in which the body does not adequately produce the quantity or quality of insulin needed to maintain normal circulating glucose level in the blood. Insulin is a hormone that enables glucose (sugar) to enter the body’s cells to be converted into energy. Two types of diabetes are common. Type I is also known as Insulin Dependent Diabetes Mellitus (IDDM or T1DM) and is found to be 5-10% of the generalized cases of diabetic patients. Type II or Non-Insulin Dependent Diabetes Mellitus (NIDDM or T2DM) occurs in the rest of the diabetic population. In case of IDDM, the disease occurs in childhood and requires healthy eating, regular exercise and insulin doses to maintain a reasonably healthy life. On the other hand, NIDDM occurs usually at the human age around 40 years and require an externally supplied insulin dosage in addition to regular exercise and controlled diet.

T2DM is a non-autoimmune, complex, heterogeneous and polygenic metabolic disease condition in which the body fails to produce enough insulin, characterized by abnormal glucose homeostasis [1]. Its pathogenesis appears to involve complex interactions between genetic and environmental factors. T2DM occurs when impaired insulin effectiveness (insulin resistance) is accompanied by the failure to produce sufficient beta-cell insulin [2].

The recent survey given by World Health Organization is shocking. India tops the list with the number of T2DM patients as much as 31.7 Million. By the year 2030, the estimated number of affected by T2DM in India will be 79.4 Million. Actual interpolation of data put the value much larger than this. This data is alarming [3]. A data of global scenario of T2DM is shown in Figure 1. The diabetes mellitus is associated with the symptoms such as Polyuria (frequent urination), Polydipsia
(increased thirst), Polyphagia (increased hunger). These symptoms are rapid in T1DM and slow with T2DM. The Prolonged DM may also cause vision problems.

On the other hand, the control and treatment of T2DM requires regular monitoring, sometimes very frequently. The diagnosis methods are invasive. The pain associated with the diagnostic methods of blood glucose make the patients traumatic. Also the existing diagnostic tools are bulky, time consuming, requires blood and is available only at clinics. The authors group are aiming at a device, which could overcome these problems and is fabricating a device which is non-invasive and wearable or handheld. The design, fabrication and characterization of the device are discussed in the following Sections.

2. Non-Invasive Diagnosis Methods

Non-invasive glucose monitoring techniques can be grouped as subcutaneous, dermal, epidermal and combined dermal and epidermal glucose measurements. Matrices other than blood under investigation include interstitial fluid, ocular fluids and sweat. Test sites being explored include finger tips, cuticle, finger web, forearm and ear lobe. Subcutaneous measurements include microdialysis, wick extraction, and implanted electrochemical or competitive fluorescence sensors. Microdialysis is also an investigational dermal and epidermal glucose measurement technique. Epidermal measurements can be obtained via infrared spectroscopy as well. Combined dermal and epidermal fluid glucose measurements include extraction fluid techniques (iontophoresis, skin suction and suction effusion techniques) and optical techniques. A summary of possible methods for the non-invasive measurement of blood glucose is given in Figure 2.

The range of measurement techniques usually based upon optical properties of the sample is wide that includes some of the sophisticated methods like near infrared spectroscopy [5], infrared spectroscopy [6], Raman spectroscopy [7], photoacoustic spectroscopy [8], scatter and polarization change measurements, etc. Non-invasive optical measurement of glucose is performed by focusing a beam of light onto the body. The light is modified by the tissue after transmission through the target area. An optical signature or fingerprint of the tissue content is produced by the diffuse light that escapes the tissue has penetrates. The absorbance of light by the skin is due to its chemical components (i.e., water, hemoglobin, melanin, fat and glucose). The transmission of light at each wavelength is a function of thickness, color and structure of the skin, bone, blood and other material through which the light passes [9-11].

The glucose concentration can be determined by analyzing the optical signal changes in wavelength, polarization or intensity. The sample volume measured by these methods depends on the measurement site. The correlation with blood glucose is based on the percent of fluid sample that is interstitial, intracellular or capillary blood. Not only is the optical measurement dependent on concentration changes in all body compartments measured, but also the changes in the ratio of tissue fluids (as altered by activity level, diet or hormone fluctuations) and this, in turn, affects the glucose measurement. Problems also occur due to changes in the tissue after the original calibration and the lack of transferability of calibration from one part of the body to another. Tissue changes include:
body fluid source of the blood supply for the body fluid being measured, medications that affect the ratio of tissue fluids, day-to-day changes in the vasculature, the aging process, diseases and the metabolic activity in the human body [12].

3. Design and Characterization

Of late, the advances in the area of Micro-Opto-Electro-Mechanical Systems (MOEMS) based [13], devices are utilized widely for various applications in the area of biomedical applications. We explore the possibility of using a MOEMS devices as a optical coherence tomography for non-invasive measurement of blood glucose. We use nanophotonic Silicon on Insulator (SOI) as the platform for the fabrication of the structures. SOI waveguides normally have a silicon core (refractive index $n_0=3.45$) surrounded by cladding layers of air or silica (SiO$_2$), with typical refractive indices $n_1$ between 1 and 2. An SOI wafer consists of a thin top Si layer sitting on silica layer, which is carried on a thick Si substrate. Photonic components are realized by etching the top Si layer, resulting in high

![Figure 2](image2.png)

**Figure 2.** A summary of glucose measurement techniques used. All non-invasive methods are use optical models with associated mathematical equations.

![Figure 3](image3.png)

**Figure 3.** Simultaneous measurements of blood glucose using the current device as well as with commercial grade glucometer. The PS-OCT monitors the degree of circular polarization of backscattered light, which is a non-invasive method, while the glucometer measurements are minimally invasive method.
refractive index contrast in all directions between waveguide core and cladding, allowing good confinement of optical modes and reduction of device dimensions. Using wafer scale CMOS compatible processes, low loss waveguides with core cross-sectional area of 0.1 µm$^2$ and bend radii of 5 µm can be realized [14].

Figure 3, demonstrates some of the results obtained with various human volunteer subjects. The PS-OCT device developed by the authors measures the degree of circular polarization of the back-scattered signal. Simultaneously, the glucose concentration is measured with a commercial grade glucometer. The measurements were carried out for every ten minutes. The results reported in Figure 3, establishes a linear correlation between the measurements.

Figure 4. The complete MOEMS based optical coherence tomography setup and various components integrated to complete the setup. The first row shows the MOEMS-OCT after integration. The next image shows the simulated results of bi-directional coupler. The second and third rows shows the simulated results of a straight waveguide, waveguide radiation in a circular path and a MOEMS mirror. The second row shows the radiation pattern after finite element analysis. The 3d radiation patterns are shown in third row.
4. Simulation model and results
Design and simulation of whole MOEMS OCT system done using Finite element method (FEM) based analysis. For that, we employed COMSOL Multiphysics as the frontend to simulate and report results. We optimize all parameter for active and passive waveguides through it, which is required for MOEMS-OCT. The MOEMS based TD-OCT has various components. We study and optimize each components systematically. At the end all the components are integrated to bring all of them to a single chip. The various components such as the following are analyzed independently (i) Waveguide (ii) Directional coupler (equivalent of a beam splitter), (iii) Reference arm, (iv) mirror and (v) light coupling and decoupling. Since the light coupling and decoupling is a complicated mechanism and needs more understanding, we discuss them in a separate paper. In the following sections, we discuss each component separately.

5. Conclusions
To conclude, we have designed and studied MOEMS based optical coherence tomography setup. The results show that the successful demonstration of MOEMS-OCT is possible with Silicon on Insulator type structures.

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5