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VCSEL Based, Wearable, Continuously Monitoring Pulse Oximeter

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***Abstract*— We present the development of a novel pulse oximeter based on low power, low cost, Vertical Cavity Surface Emitting Laser (VCSEL) technology. This new design will help address a need to perform regular measurements of pulse oximetry for patients with chronic obstructive pulmonary disease. VCSELs with wavelengths suitable for pulse oximetry were developed and packaged in a PLCC package for a low cost solution that is easy to integrate into a pulse oximeter design. The VCSELs were integrated into a prototype pulse oximeter that is unobtrusive and suitable for long term wearable use. The prototype achieved good performance compared the Nonin Onyx II pulse oximeter at less than one fifth the weight in a design that can be worn behind the ear like a hearing aid.**

I. Introduction

Chronic Obstructive Pulmonary Disease (COPD) is a progressive lung disease that makes breathing difficult. COPD usually worsens over time and eventually may make it difficult for people to carry out regular simple daily activities, such as walking or taking care of oneself. COPD is a leading cause of death and disability worldwide. It is largely preventable but is expensive to treat [1]. In the United States, COPD is the fourth leading cause of death. There is a general agreement that patients with COPD, who are developing chronic respiratory failure, benefit from long-term oxygen therapy (LTOT). LTOT is the only treatment that has been shown to improve survival in COPD patients with severe hypoxemia. In addition to a reduction in mortality, LTOT may also have the following benefits: a reduction in hypoxemia-induced elevations in hemoglobin,[2,3] decreased pulmonary artery pressure and vascular resistance, increased stroke volume index,[2-5] improved exercise tolerance, [6,7] increased functional status, and subjective improvement in quality of life [8,9]. Although LTOT is a well-established treatment to improve survival and quality of life in patients with COPD, LTOT imposes a substantial economic burden to the health care system[10]. Currently, clinical criteria for the initiation or modification of LTOT is based on a single measurement of resting oxygen levels (either partial pressure of oxygen in arterial blood PaO_2 <55mmHg or a hemoglobin oxygen saturation SpO_2<88%) in a clinic or hospital setting. Several studies have demonstrated that a significant percentage of patients are not receiving the optimum dosage of oxygen [10-13]. Despite the risks of an improper oxygen prescription, multiple studies have demonstrated that high percentages of patients are spending a significant amount of time inadequately oxygenated and some are receiving oxygen that they do not need [11,14,16-18]. In particular, oxygen needs change during sleep or exercise, but these needs cannot be accurately predicted with a single daytime measurement [11,12,14,15]. As a result studies have shown that fewer than one-third of patients would be correctly oxygenated using the current dosage guidelines [11,15]. In addition, the new technology of oxygen conserving devices, which allow patients to spend much more time away from a stationary system, require pulse oximetry to individually titrate their dose to ensure adequate oxygenation [17]. Recent data has shown that an oxygen prescription based on continuous oximetry monitoring would result in the SpO_2 being within the targeted range a higher percentage of the time [18]. Despite the significant advantages of *ambulatory oximetry monitoring; ambulatory oximetry monitoring is not the standard of care today.* An ideal system would be unobtrusive permitting the provider to evaluate oximetry during the activities of daily living and sleep.

II. Prototype Design

This paper demonstrates two major advances in power consumption to current pulse oximeter technology to achieve the goal of an unobtrusive, long-term wearable device. First the conventional LED's were replaced with Vertical Cavity Surface Emitting Laser(VCSEL) technology and second the raw sensor data was transmitted wirelessly to reduce the computational load of the sensor hardware. These techniques significantly lower the battery size requirements. To demonstrate these advances, a new wireless pulse oximeter was developed and evaluated.

A. VCSEL Design

Pulse oximeters utilize a spectral-photometric method that exploits two fundamental physiological characteristics to estimate the arterial blood oxygenation saturation. The first effect is a different, wavelength-dependent transmittance of oxygenated and deoxygenated hemoglobin; the second is the pulsatile nature of the arterial blood flow. Most commercial pulse oximeter designs use time-multiplexed red and infrared (IR) Light Emitting Diodes (LEDs) and a photodetector that detects the light attenuated by the perfused tissue. VCSELs have the performance characteristics of lasers, but since they are vertically emitting they can be packaged like LEDs. Fig. 1 compares VCSEL performance to that of edge-emitting lasers and LEDs. The output beam is symmetrical with a narrow divergence and the power consumption is 10× less than an LED for equivalent output power and 3-10× lower

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than an edge emitting laser at low output powers. The spectral width is <1 nm, and can be as low as a 40 MHz linewidth. In addition, the wavelength shifts with temperature at a rate approximately 4× slower than edge-emitters or LEDS, which is valuable for spectroscopic applications. Project partner Vixar has developed VCSELs at wavelengths of interest for pulse and regional oximetry, i.e. at 680nm, 790nm and 850nm.

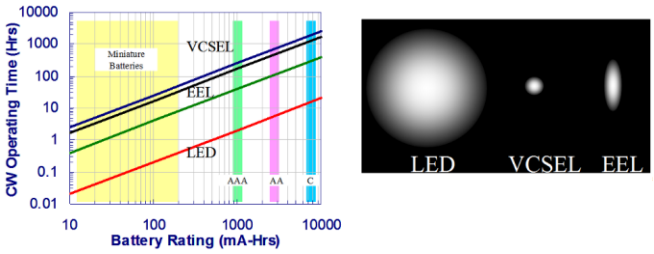

Figure 1. Comparison of VCSEL, LED, and Edge Emitting Lasers in terms of power consumption(left) and output beam profile(right).

As an example of the performance Vixar has achieved, Fig. 2 illustrates the output power versus current for 680nm and 850nm VCSELs, demonstrating that 1mW of power can be achieved at currents of approximately 3mA, an order of magnitude less than required for LEDs or edge-emitters.

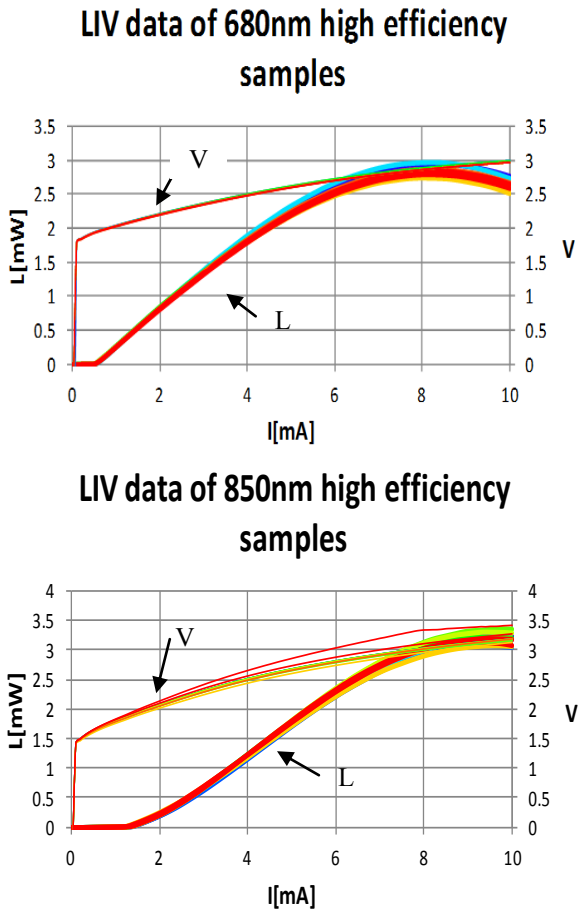

Figure 2. Light intensity versus voltage and current for the developed 680nm and 850nm VCSELs.

C. Pulse Oximeter Design

The amount of red and infrared VCSEL light received by the sensor depends on tissue and blood absorption. There are two parts of light absorption: the stable or DC component due to tissue, venous blood, and arterial blood and also the time-varying absorption or AC component caused by pulsatile arterial blood flow. Sensing of the illumination transmitted through the tissue and blood is accomplished using a reverse biased photodiode, which produces a current that is linearly proportional to the received light level. Photodiode current is converted to a voltage using a transimpedance amplifier and then sampled by a 12-bit ADC (analog to digital converter) connected to the microcontroller. The sampled voltage includes both DC and AC signals related to the DC and AC absorption components. Within each 1/50th of a second period, two samples are taken with the ADC; one from the red VCSEL illumination and one from the infrared VCSEL illumination. The ratio of the AC signal amplitudes measured for the red and infrared lights are used in the PC software application to calculate SpO_2. The DC signals are used within the pulse oximeter to trim the VCSEL intensity in order to keep the photodiode signal within the operating range of the ADC. The driver interface also includes an ambient offset removal circuitry that reduces the effect of ambient light. All of the VCSEL drive and light sensing circuitry is powered down during the time period when neither VCSEL is illuminated to achieve the ultra-low power operation.

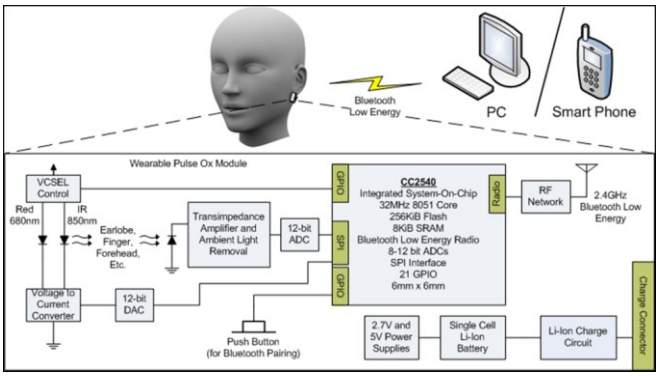

Figure 3. Block diagram of the prototype wireless pulse oximeter. The design include VCSEL optical power regulation, data capture, and wireless transmission of raw data for processing on a smartphone or PC.

The pulse oximeter module block diagram is shown in Fig. 3. To reduce module size and power consumption, both the processing and RF telemetry is performed by a Texas Instrument's CC2540 Bluetooth Low Energy system on a chip. It incorporates a 32MHz 8051 8-bit CPU and a number of useful features including a built in Bluetooth Low Energy radio, general purpose I/Os used to select VCSELs, detect button presses, and enable analog circuits during light sampling, a SPI bus used to control the sampling ADC and the light intensity DAC, a 12-bit ADC used to measure the battery voltage, a 16-bit timer with multiple trigger points for timing the VCSEL illumination duty cycle and power management modes used to idle the CPU when not busy (~1uA current consumed.) The pulse oximeter circuitry also includes VCSEL output power control circuits, a push button

for enabling the Bluetooth discovery mode, a 2.7V regulator for the analog and processor circuits, a 5V regulator for the VCSEL driver, a 60mAh lithium ion polymer battery with a battery recharging IC, and a board mounted antenna with impedance matching network. Raw readings are buffered in internal CPU memory and sent to the host through the radio link. The module embedded firmware uses the Bluetooth Low Energy RF protocol while connecting to the host every 200ms to send pulse oximeter samples. Final calculations of the raw data are performed on the host, greatly simplifying the processing done within the wearable module resulting in reduced module power consumption.

We developed a prototype earpiece to evaluate the performance and power savings of using VCSELs in place of LEDs. The prototype shown in Fig. 4 includes a VCSEL component with two VCSELs (680nm red and 850nm infrared) from Vixar. The two VCSEL dies are placed next to each other to minimize any differences in optical path to the photodetector. The photodetector is placed on the opposite side of the earpiece. The positioning of the VCSELs was set to maximize the light transfer between the VCSEL and the photodiode when the earpiece is opened and placed on the ear. The earpiece connects to the pulse oximeter assembly through a shielded cable. The plastic enclosure for the prototype pulse oximeter shown in Fig. 4 was designed using ProEngineering CAD tools and prototyped with a Stratasys 3-D prototype printer. This enclosure conforms to the circuit board maintaining the miniature size and incorporates a clip to hang the assembly from the ear similar to a Bluetooth head set. The electronic assembly has dimensions 40.5mm by 19.1mm with a 2.1mm thickness. Combined with the battery, the overall electronics volume is 2.7cm^3.

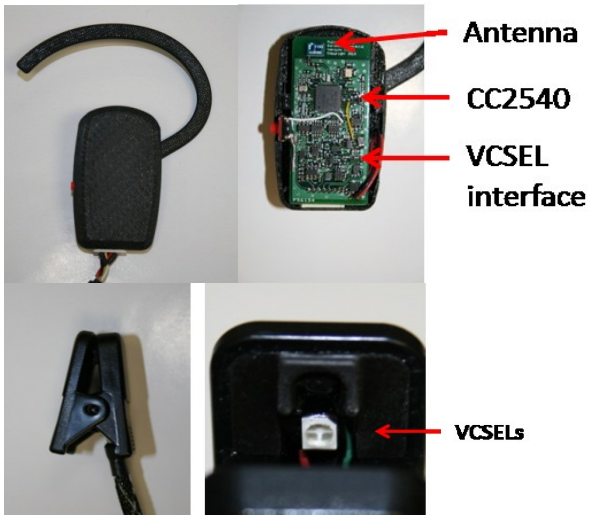

Figure 4. Prototype ear worn VCSEL based pulse oximeter. Top pictures show the electronics in the custom developed case. The bottom pictures show the modified ear clip with VCSELs replacing LEDs.

A Windows PC-based wireless data capture interface was developed to collect raw data from the pulse oximeter and process it into SpO2 and heart rate. We used this interface to evaluate and test the wearable pulse oximeter. The interface used a Bluetooth Low Energy USB dongle attached to a PC running the data analysis software. The processing could alternatively be performed on a Bluetooth Low Energy enabled smartphone.

Computation of SpO_2 and heart rate from raw data starts with additional filtering to remove noise and averaging to smooth the red and infrared signals. The data is then run through an edge detector to identify the beginning and end of each heart beat. This detector has an adjustable threshold to maintain detection across variable signal amplitudes. The heart rate displayed to the user is an average of multiple beats. SpO_2 is calculated from the ratio of red to infrared rms level (1) across multiple beats using (2) based on the absorption coefficients of oxygenated (HbO_2) and deoxygenated (Hb) hemoglobin measured in homogeneous blood at the red and infrared wavelengths.

$$R = \frac{(I_{RD}/I_{IR})_{ac}}{(I_{RD}/I_{IR})_{dc}} \quad (1)$$

$$SpO_2 = \frac{\epsilon_{Hb}(\lambda_{RD}) - \epsilon_{Hb}(\lambda_{IR})R}{\epsilon_{Hb}(\lambda_{RD}) - \epsilon_{HbO_2}(\lambda_{RD}) + [\epsilon_{HbO_2}(\lambda_{IR}) - \epsilon_{Hb}(\lambda_{IR})]R} \quad (2)$$

III. Results

The developed prototype is 2.7 cm^3 volume and weighs 10g. This is over 5 times lighter than the finger worn Nonin Onyx II pulse oximeter. The battery life is 40 hours for 1SpO_2/sec sampling and 240 hours sampling at a 1/8 Hz rate.

A. VCSEL reliability

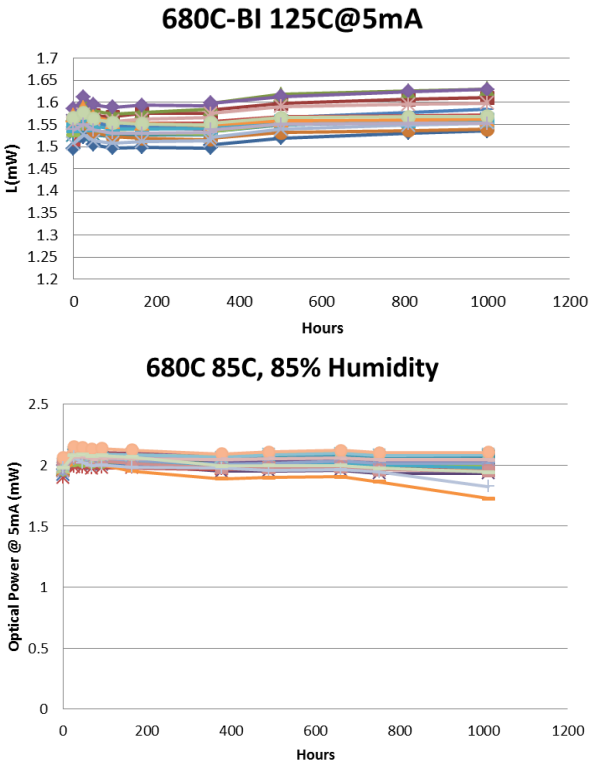

Figure 5. (Top) Accelerated lifetesting of red VCSELs. 1000 hours at 125C, 5mA is equivalent to around 300K hours at 40C, which is approximately body temperature. (Bottom) Testing under conditions of

85°C and 85% humidity in a non-hermetic package. This acceleration condition is equivalent to 100K hours at normal temperature and humidity.

Vixar evaluated the long term packaged VCSEL performance including encapsulant. The test assessed the VCSEL power output for a fixed current at multiple time steps up to 1000 hours under accelerated life conditions (125C temperature and 85% relative humidity).

The result of this test showed that the VCSEL packaged in the PLCC-4 package with the encapsulant operated without loss of function in the high temperature, humid environment for 1000 hours (see Fig. 5).

B. Performance Testing

The prototype wearable pulse oximeter was tested concurrently with a Nonin Onyx II finger pulse oximeter while resting and also after running for 10 minutes. Fig. 6 shows the measurement results. The heart rate measured by the prototype matched the commercial pulse oximeter within 2.5% across the entire test. The SpO_2 calculation was consistently lower for the VCSEL based design but followed the same trend as the Nonin device. We expect some deviation in SpO_2 with the initial algorithm because it's based upon homogenous blood measurements. We will improve the accuracy in a future design using a desaturation study to calibrate the measured red/infrared ratio to SpO_2 measurements recorded with a gold standard co-oximeter across a range of SpO_2 values.

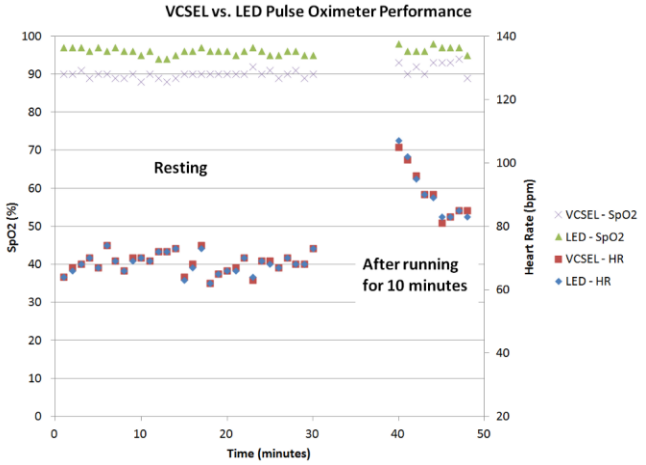

Figure 6. Prototype wireless pulse oximeter performance compared to a Nonin finger based pulse oximeter.

IV. Conclusion

This project has demonstrated the feasibility of a VCSEL based pulse oximeter with improved power consumption for smaller and lighter designs with better battery life. Future work will be to calibrate the equations to the wavelengths being utilized and further develop the software and enclosure.

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