State-of-the-Art Light to Digital Converter Circuits Applicable in Non-Invasive Health Monitoring Devices to Combat COVID-19 and Other Respiratory Illnesses: A Review

Umar Mohammad, M. Asfandyar Awan, Amine Bermak, Fellow, IEEE, and Fang Tang, Senior Member, IEEE

Abstract—In the past few years, a tremendous advancement in the outcome of biomedical circuits and systems has been reported. Unfortunately, at the time of the sudden outbreak of COVID-19, the electronic engineering researchers felt dearth on their side to combat the pandemic, as no such immediate cutting-edge solutions were ready to recognize the virus with some standard and smart electronic devices. Likely, in this paper, a detailed comparative and comprehensive study on circuit architectures of the biomedical devices is presented. Mostly, this study relates the industry standard circuit schemes applicable in non-invasive health monitoring to combat respiratory illnesses. The trending circuit architectural schemes casted-off to tapeout non-invasive health-care devices available in the past literature are meticulously broadly discussed in this study. Further, the comprehensive comparison of the state of art of the device performance in terms of supply voltage, chip area, sensitivity, dynamic range, etc. is also shown in this paper. The inclusive design processes of the health monitoring devices from Lab to Industry is thoroughly discussed for the readers. The authors think, that this critical review summarising all the trending and most cited health-care devices in a single paper will alternately help the industrialists to adapt and modify the circuit architectures of the health monitoring devices more precisely straightforwardly. Finally, the demand for health monitoring devices particularly responsible to detect respiratory illnesses, measuring blood pressure and heart-rate is growing widely in the market after the the incident of COVID-19 and other respiratory diseases.

Index Terms—Bio-medical circuit design, light to frequency converter circuits, pulse generator TIA, noise optimized TIA, noise cancellation circuits.

I. INTRODUCTION

With the fastest growing advancements in nanotechnology, the adaptation utility of electronic devices has become the basic prerequisites of the common man. The introduction of the VLSI artifacts to the life sciences research has sought the designers to think critically to meet the incoming needs, obligations, and necessity of the inventions [1]. Advancements in analog to digital conversion are gradually boosting the latest trends of the integrated circuit design. Over the past years, design engineers are much more concerned about low power, low voltage, low noise and energy-efficient devices. Further, a focus on the time-span from lab to industry is greatly a big concern for all the stakeholders in the circuit design industry. During the sudden outbreak of COVID-19, there was a dearth of precise and accurate biomedical devices in the global market to detect the virus digitally [2]. Only a fewer devices like pulse oximeter, infrared thermometer etc were available to ascertain the transmission of the corona-virus. Besides, a multipurpose single chip with the working combination of pulse-oximeter, heart rate, cuffless blood pressure monitoring, and non-invasive blood glucose monitoring would have been a good weapon to fight the spread and transmission of COVID-19. Likely, this study involves the congregate, study, analysis and evaluation of the most trending circuit techniques available in the past literature, cited for low power, noise reduced, and energy-efficient non-invasive health monitoring chips to combat respiratory illnesses. In the previous literature, a handful of circuit schemes pondering and cited...
for bio-medical devices are available. Several circuit schemes cited most frequently have used the light to frequency conversion technique to implement the final prototypes, whereas fewer designs are available with the traditional schemes of analog to digital signal conversion. Almost, in all the previous designs, a PD is used as a supplementary for the input current, which is then fed to the signal conditioning block (mainly consisting of TIA/ADC, low-pass filter, flip-flop, etc) for the conversion to a digital pulse. Research studies cited mostly for the keywords biomedical devices/Health monitoring include Implantable pacemakers [4], cuffless blood-pressure monitoring [5], pulse oximeter devices and heart-rate sensors [10], blood oxygen concentration detection [12]–[14], blood glucose monitoring [17], X-ray computed tomography [22], physiological fluids [33], medical diagnostics [3], [34]. Apart from these trending applications, there are hundreds of circuit architectures citing LDC design and biomedical applications [6]–[9], [23]–[32]. Apart from these, a few studies are reported using silicon nano-wire [18] and single photon avalanche diode (SPAD) [37] as sensing elements. The work cited in this section demonstrates fully the implementation of the non-invasive prototypes or the associated LDC-integrated circuits applicable in health care applications.

As mentioned earlier, there are multiple designs available, claiming the different circuit device parameters of dominance, such as; high dynamic range, energy efficiency, noise reduction, low power. Overall, the presented designs in the literature have focussed on a particular circuit parameter or a particular application to demonstrate the health monitoring device. Broadly, we can say, a big challenge is still there, to design and tapeout a suitable device, that is splendid in terms of all the aspects of the circuit parameters. Further, a multifunction and embedded device capable of measuring several respiratory illnesses is still questionable. Consequently, in this paper, the authors will try to gather the appropriate designs and suggest also the alternative design changes for the hybrid design for an embedded chip. A simplified block diagram of the non-invasive health monitoring device is provided in Fig.1

II. WORKING NOMENCLATURE OF NON-INVASIVE HEALTH MONITORING DEVICES

The basic and main working nomenclature of the light to digital converter circuits (LDC) is the transformation of the photo-current into a voltage signal. For a successful LDC prototype to function as non-invasive health monitoring medical device, the designers ultimately need a sublime-circuit or a signal generator with the output signal frequency of the proper desired frequency (100kHz or above in case of pulse-oximeter). For fewer health monitoring devices like pulse-oximeter, blood sensing devices, etc. Near infrared sensing (NIRS) is the technique widely used for the signal acquisition of biomedical systems. It typically works on the principle by light detection of a current signal proportional to the amount of the reflection photons being sensed by the PD/SPAD/silicon-nanowire. This current is then converted to a voltage signal of a particular frequency by a transimpedance amplifier (TIA) or analog to digital converter (ADC) or light to digital converter (LDC) for further signal processing. The voltage signals obtained by this method are sometimes termed as photoplethysmogram (PPG) and are very beneficial in the heart-rate and blood pressure measurements [38]. For the case of pulse oximeters, the fundamental and eminent principle behind the functionality of pulse oximeters is that, the hemoglobin changes color from dark red to bright red, when oxygenated and consequently, the reduction in the absorption of red light takes effect. Hence, if we focus red LED light at 660 nm through one side of a patient’s finger and monitor the transmitted light on the other side of the patient’s finger with a light-sensor, the initial results of the oxygen saturation can be obtained. The Spo2 sensing can be mathematically more verified by investigating the changes in light reflections on the patient’s finger by Beer Lambert’s law [9], [10]. This law describes the
attenuation of monochromatic light traveling through a medium containing an absorbing substance and projects it to be an exponential function of the product of three quantities; one is the distance through the medium, second is the concentration of the substance and the third one is its intrinsic molecular absorption (extinction) coefficient. It can be shown that the oximeter’s desired output is given by

$$S_{pO_2} = \frac{0.81 - 0.18 R}{0.63 - 0.11 R} \times 100\% \quad (1)$$

In conclusion, after getting the proper desired digital signal, we need a joint combination of reference circuits like low dropout (LDO) circuit, photodiodes (PD), light emitting diodes (Red and Infrared), a microcontroller for data acquisition, and an LCD to furnish a working prototype for the final display. The block diagram of the final basic prototype is shown in Fig 1.

III. SUMMARISED LITERATURE STUDY

Different techniques are available from the literature pertaining to the design of light to digital converter circuits. As already discussed above, these techniques focus on the conversion of photocurrent into a voltage signal of certain frequencies conversely applicable for health monitoring devices. The traditional way to convert the photocurrent (analog) signal is using analog to digital converter (ADC). In [12]–[14], the authors have used TIA, as the main reference circuit to convert the photocurrent into the voltage signal. In [9], the authors have used logarithmic-TIA as the photoreceptor elements for the frequency conversion. In [10], the authors have combined the ideas of [9], [11] to design LDC, by adopting laddered inverter quantizer/amplifier/filter (LIQAF) and digital to resistance converter (DRC) circuit architectures. In this section, we shall discuss the most cited and trending architectures adopted for LDC applicable in non-invasive health monitoring reported with real-time prototypes.

A. Alhawari et al. [10], Heart-Rate Sensor, JSSC-2014

The simplified LDC architecture presented by alhawari et al. is shown in Fig. 2. In this study, the authors have reported light to digital converter design intended for heart rate monitoring. The striking feature of this work is that, this design has a low power dissipation of about 4μW and operates on the low voltage supply 0.5 V. This study has proposed a joint design scheme from the previously published architectures. First, one with the high dynamic range using the logarithmic technique of subthreshold NMOS device [9], and second one is the switched capacitor based closed-loop feedback design [11]. The authors have very sharply and technically presented the hybrid architecture with high dynamic range, high sensitivity, low power, and low voltage proven with complete mathematical analysis and circuit simulations. Also, the uniqueness of this study is the introduction of logarithmic-DRC utilizing δσ modulator dither switches in the resistor network to achieve the maximum resolution control of resistance. Moreover, a non-uniform quantizer is realized by using a laddered inverter quantizer/amplifier/filter-LIQAF, to enhance the working of low-noise front end amplifier and filter. Extensively speaking, LIQAF helps the design to achieve a low noise analog-to-digital interface with power and low voltage design complexity. Finally, the verification and simulation of the design are reported using 0.18mM CMOS technology with photodetector sensitivity-\(I_{bias}\) of 4nA and photodetector range-\(I_{bias}\) of 58db.

B. Tavakoli et al. [9], Pulse-Oximeter, TBCAS-2010

This study presents an energy-efficient pulse oximeter design with the power dissipation of 4.8 mW. Fig. 3 shows the architecture adopted by the authors for this work. In this study, low power-reduction results are claimed by using energy-efficient logarithmic transimpedance amplifiers with inherent contrast sensitivity, distributed amplification, unilaterisation, and automatic loop gain control. The realization of light to digital conversion without an ADC is presented in this study. The presented design employs a photodiode driven by oscillator/LED and switching control units. The
output of the photodiode is fed to the current steering switches involving the direct contact of oscillator switching control too. The oscillator circuit is made responsible for generating and synchronizing the required LED drive and current switching pulses. Two front-end transimpedance amplifiers in the form of photo-receptors are the blocks of prime importance in this study. These TIA’s help in converting the light-transformed current to the digital signal. Output from the photoreceptor is fed directly to the low-pass filters, to attenuate switching frequency components and extract blood pulsation signals. These low pass filters possess butterworth circuit topologies and traditionally cope with the transfer function, $\frac{V_{out}}{V_{in}}$. Finally, the signals from the low pass filters are fed to the ratio-computation block to detect the amplitude of the RED and IR blood pulsation signals and then computing their ratio by making the use of the translinear current divider to find $\frac{R}{S_p}O_2$ Sensing. Mathematically, the output current ratio is calculated as:

$$I_{ratio} = I_{div} = I_{ref} \frac{I_{out}}{I_{in}} = I_{ref} \frac{R_{in}}{R_{out}}$$  \hspace{1cm} (2)

$$I_{ratio} = I_{ref} \frac{i_{ac,R}}{i_{dc,R}} = I_{ref} \frac{I_{ac,1R}}{I_{dc,1R}}$$  \hspace{1cm} (3)

C. Tang et al. [12], Pulse Oximeter, TBCAS-2016

In literature, three standard articles projecting the different design techniques for pulse/blood oxygen sensing are proposed by Tang et al. [12]–[14]. This section discusses the typical aspects of the design methodologies adopted in these articles.

The design in [12] reflects a monolithic and fast-tracking light to frequency converter circuit with adaptive scaling technique. In this particular study, the authors claim, that the amplifier power consumption is adaptively scaled by the generated light-intensity positively-correlated control voltage. Thus, the chip total power consumption at low light intensity is decreased to a large extent. Moreover, the proposed adaptive power scaling is reported to be achieved using a continuous analog domain path, which does not introduce extra switching noise. To balance the contradiction between the power consumption and the tracking speed, the authors have proposed an adaptive bias current scaling technique. This can be broadly understood from the concept of a light-intensity-positively-correlated(LIPC) control voltage generated responsible to tune the resistance of an NMOS transistor in the bias circuit dynamically. As a result, the bias current feeding into the amplifier is expected to get scaled down, incase the ambient light intensity becomes small. In order to ensure the proper adjustment of the NMOS transistor in the bias circuit of the proposed design, the amplifier power consumption is adaptively scaled by the light intensity positively co-related control voltage. Alternatively, the bias current feeding in the

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**Fig. 4.** (A) Architectural block diagram of the design used in [13]. (B) Schematic of the adaptive bias current generator for amplifier A2, dynamically controlled by $V_C$.  

**Fig. 5.** Architectural block diagram of the design used in [12].
amplifier is tuned precisely by the declining scale of the light ambient intensity. In short, the adaptive current scaling of the proposed design is achieved in the analog domain causing the current adaptation in the continuous flow, without interrupting the extra switching noise. The design presented is shown with PVT simulations as well as the working prototype with accuracy at the paramount scale. Secondly, the verification of the design is claimed to have done on the gold standard measurements of the blood $O_2$ concentration and pulse rate measurements using FLUKE’S Index-2 oximeter simulator. This design demands a voltage supply of 3.3V with a total current consumption of 1.9 mA scaled down to 0.7 mA. The dynamic range of the design is linear 126dB with sensitivity recorded as 55 Hz/μW/cm². The functional schematic block and the amplifier used for adaptive scaling are given in Fig.4.

**D. Tang et al. [13], Blood-SpO2 Sensing, TBCAS-2018**

Another remarkable chip targeted for blood oxygen concentration detection is reported by Tang et al. [13]. The proposed architecture of the LFC chip is shown in Fig.5. The chip highlights the high dynamic range with dark current suppression up to 125 °C. To minimize the bias-dependent current leakage current under a low light radiance, the Nwell/Psubstrate related to the PD is regulated to zero voltage drop. The replica amplifier is implemented to monitor the offset voltage of the regulator against the process-voltage-temperature-variation. The study reports the chip-tape out of the design including a 7×7 photodiode(PD) array, bandgap reference circuit, photocurrent mirror, photodiode(PD) regulator, replica amplifier circuit, power-on-reset module, and other digital control circuits.

**E. Tang et al [14], Blood-SpO2 Sensing, TBCAS-2020**

Recently, an outstanding study claiming the minimum measurable perfusion index using the proposed blood $S_pO_2$ sensor could be as low as 0.06 percent with 2-percentage-point error of $S_pO_2$ indexing of 0.1 perfusion index [14]. In this study, tang et.al have utilised the noise reduced light to frequency converter design to enhance the performance of $S_pO_2$ Sensing system for low perfusion index of 0.1%. The PI-perfusion index is the ratio between the AC and DC blood $S_pO_2$ signals, which reflects the vascular pulse intensity parameter [24]. The proposed design pitches on the noise reduction in two ways. Initial one is the implementation of the low-noise photocurrent buffer with a gain boosting transconductance circuit structure. Secondly, a DSP unit of pulse frequency duty cycle modulation is proposed to minimise the quantisation noise by limiting the maximum output frequency. The final chip is reported to have implemented using 0.35μM CMOS technology with the nominal voltage supply of 3.2 V and total current consumption of 1.8 mA. The chip architecture adopted in this study is shown in Fig.6.

**F. Rhee et al. [18], LDC, JSSC-2020**

The study presented in [18] is quite unique and distinctive. It uses a silicon nano-wire instead of single photon avalanche diode(SPAD)/photodiode to implement the LDC. The circuit scheme presented facilitates dark-leakage current cancellation by arranging silicon nano-wires in a unique way incumbent to the design configuration. The LDC architecture in this work poses a read-out integrated circuit(ROIC) with a resistive feedback TIA to provide the constant error signals. The study uses switched capacitor incremental delta-sigma analog to digital converter, which doubles the output of the TIA and feeds a digital back end to get the decimated output. The final chip is fabricated on a 0.18μM CMOS process. The LDC has a dynamic range of 106.7 with operating temperatures and voltages ranging from $-40^\circ$ to $85^\circ$ C and 1.8-3.3 V respectively. The potential results of this study have suggested the design for physiological monitoring, proximity, and medical imaging as prospective applications.

**G. Lin et al. [38], PPG Sensor Sensor, JSEN-2021**

In this work, the authors have designed and demonstrated practically, a heart rate sensor and a blood pressure measuring device. The authors of this work have claimed the design as low power sensor chip portable system for the data acquisition of photoplethysmograph signals. The design is drafted precisely with the context of optical receiver end, transmitter end and the digital part. The design claims to have comparable
higher accuracy in terms of area, power consumption and various other chip efficiency parameters, than other work cited and reported in the state of art of the paper [18]. The design is implemented in 350nm CMOS technology. The final chip and the accusation setup of this design is shown in Fig.8 (III) and Fig.8 (IV).

**H. Pribadi et al. [39], PPG Sensor, MCTCEF-2021**

This study presents a new model of light to digital converter circuit, claiming to be used for photoplethysmography (PPG) continuous monitoring. This circuit scheme employs a transimpedance amplifier (TIA), a delta-sigma modulator (DSM), and a decimation filter as shown in Fig.8 (II). The study claims to have achieved 10 Hz bandwidth of the design system, which is the highest reported among all the allied designs cited in their work [39]. The design is implemented in 0.18 micrometer TSMC technology with the supply voltage of 1.8 volt.

**I. Stanchieri et al. [41], PPG Sensor, BioCAS-2021**

In this work, a new light to frequency converter circuit is presented. The circuit scheme is typically different from the other work cited in this paper. The design in this work consists of an inverter based oscillator circuit responsible for the final output voltage signal. The design presented may be considered, where the complexity issues are of great concern.
The authors in this work are claiming the design being suitable for analog front-end cum low-voltage design, low-power wearable medical devices that make use of optical electrodes (optrodes) for telemedical diagnostic and therapeutic screening. The design was implemented at the transistor level in TSMC 180 nm standard CMOS technology.

IV. COMPARATIVE RESULTS AND STUDY ANALYSIS

The authors in the past have suggested and proved multiple circuit architectures citing biomedical/healthcare devices. Every single architecture is presented in a different way to cope with the domestic as well as the industry standard healthcare application. The trending circuit architectures among all these have been described thoroughly in this paper. Table-I summarises the state-of-art of the various LDC architectures available. To the author’s prior knowledge, this is the first combined/summarised review of the implemented LDC architectures for healthcare applications. Apart from the circuit architectures briefed in this work, few outstanding allied articulates of work in the biomedical engineering fields are present in the literature. Hundreds of articles cited on the name of LDC and bio-medical devices are available, however, the authors have tried their best to present the architectures of most trending bio-care devices with furnished prototypes. This work is expected to help the designers to gather and study the information relating the devices responsible for non-invasive health monitoring. The authors feel, that this design will boost the enthusiasm of the designers to think and work for an embedded-chip, that provides diverse platforms for measurement of heart rate pulses, blood glucose monitoring, Blood oximeters etc.

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TABLE I
STATE-OF-THE-ART COMPARISON OF THE PROPOSED LDC ARCHITECTURES

| CMOS Technology(μm) | Sensitivity | Supply voltage(V) | Supply current(μA) | Sensor type | Illuminance range lx | Dynamic range(dB) | Power consumption mW | Operating temperature °C | Sensor Area/Total Area mm² | Application | Temperature Dependent Dark Cancellation |
|---------------------|-------------|-------------------|-------------------|-------------|---------------------|------------------|----------------------|--------------------------|---------------------------|-------------|---------------------------------------|
| 0.18                | 2.2 kV/mW/cm² | 2.5-5             | 0.5               | SPAD & PD   | 0.3-6,300           | 85               | 2.3-SPAD, 2.75-PD   | -40-125                  | 0.9                       | Pulse Oximeter/SPO2 Sensing | No          | Yes                                   |
| 0.35                | --          | 2.4-5.5V          | 1.6-1.8           | PD          | 0.0015-300          | NR               | --                   | -25-85                   | 0.9                       | Pulse Oximeter/SPO2 Sensing | NO          | NO                                    |
| 0.35                | --          | 2.4-5.5V          | 0.7@25kHz and 1.9@50kHz | PD          | 30-300              | 100              | --                   | -25-80                   | 1.05 x 0.7                | Light monitoring            | No          | No                                    |
| 0.35                | 3.3         | 3.0               | 4nA               | PD          | 15.5-2650           | 86               | 0.486/0.014          | -40°C-85                  | 1.998 x 1.616             | Physiological monitoring   | No          | No                                    |
| 0.18                | 3.0         | Analog Digital 1.8 | 59.5μA/3.5μA      | PD          | 0.3-1.4M            | 100              | 0.55                 | Upto to 70°C             | 0.0027/1.12               | Heart Rate Sensor           | No          | No                                    |
| 0.18                | --          | 0.5V              | 240μA             | Silicon Wire| 58                  | 40               | 2.2 x 2.2            | --                      | 0.5                       | Biomedical Application      | --          | --                                    |

The authors in this work are claiming the design being suitable for analog front-end cum low-voltage design, low-power wearable medical devices that make use of optical electrodes (optrodes) for telemedical diagnostic and therapeutic screening. The design was implemented at the transistor level in TSMC 180 nm standard CMOS technology.
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Umar Mohammad received the bachelor’s and M.S. degrees from India. He is currently pursuing the Ph.D. degree with the School of Microelectronics and Communication Engineering, Chongqing University, Chongqing, China. His research interests focus on analog amplifiers and biomedical interface circuits.

M. Asfandyar Awan received the bachelor’s (Hons.) degree in electronics engineering from the COMSATS Institute of Information Technology, Abbottabad, Pakistan, in 2009, and the master’s (Hons.) degree in electrical engineering (system-on-chip) from Linkoping University, Sweden, in 2011. He is currently pursuing the Ph.D. degree with HBKU, Doha, Qatar.

Amine Bermak (Fellow, IEEE) received the master’s and Ph.D. degrees in electrical and electronic engineering (microelectronics and microsystems) from Paul Sabatier University, Toulouse, France, in 1994 and 1998, respectively. In July 2002, he joined the Electronic and Computer Engineering Department, The Hong Kong University of Science and Technology (HKUST), where he was a Full Professor and the ECE Associate Head of Research and Postgraduate Studies. He has also been serving as the Director for Computer Engineering as well as the Director for the Master Program in IC Design. He is the Founder and the Leader of the Smart Sensory Integrated Systems Research Laboratory, HKUST. He is currently with Hamad Bin Khalifa University, Qatar Foundation, Qatar. Over the last decade, he has acquired a significant academic and industrial experience. He has published over 250 articles in journals, book chapters, and conference proceedings. He has designed over 30 chips. He has graduated 13 Ph.D. and 16 M.Phil. students. He was a recipient of the 2011 University Michael G. Gale Medal for distinguished teaching (Highest University-Wide Teaching Award). He was also a two-time recipient of the Engineering School Teaching Excellence Award in HKUST in 2004 and 2009, respectively. He has received five distinguished awards, including the Best Student Paper Award at IEEE International Symposium on Circuits and Systems ISCAS 2010, the 2004 IEEE Chester Salt Award from IEEE Consumer Electronics Society, the IEEE Service Award from IEEE Computer Society, and the Best Paper Award at the 2005 International Workshop on System-On-Chip for Real-Time Applications. He has served on the Editorial Board for IEEE TRANSACTIONS ON VERY LARGE SCALE INTEGRATION (VLSI) SYSTEMS, IEEE TRANSACTIONS ON BIOMEDICAL CIRCUITS AND SYSTEMS, the Journal of Low Power Electronics and Applications, and Frontiers in Neuromorphic Engineering. He is the Guest Editor of the November 2010 Special Issue in IEEE TRANSACTIONS ON BIOMEDICAL CIRCUITS AND SYSTEMS. He is an IEEE Distinguished Lecturer.

Fang Tang (Senior Member, IEEE) received the B.S. degree from Beijing Jiaotong University, China, in 2006, and the M.Phil. and Ph.D. degrees from The Hong Kong University of Science and Technology in 2009 and 2013, respectively. He worked as a Research Associate at The Hong Kong University of Science and Technology. He is currently the Distinguished Research Fellow at Chongqing University, China; the Associate Director of the Chongqing Engineering Laboratory of High-Performance Integrated Circuits; and leads the Smart Integrated Circuits and Systems Laboratory (http://sislab.cqu.edu.cn). He has published over 40 articles in journals and conference proceedings. He has designed over ten chips. His research interest includes mixed-signal circuit design for advanced smart integrated circuit and systems.