A 48μW Analog Front End Circuit Design for an Ultrasonic Receiver 0.18μm CMOS

Haridas Kuruveettil, M. Kumarasamy Raja, and Minkyu Je

***Abstract*—Ultrasonic transducer based sensor systems are widely used in wearable biomedical applications for indoor location sensing, tracking and other zonal compliance purposes. A system used for zonal compliance typically made up with a zonal transceiver device and a battery powered wearable device with the associated control logic at each interface. Being battery powered, the design of analog interface circuit to the wearable device is significant to overall performance of the system. In this paper, we present a fully integrated Analog Front End (AFE) interface circuit for the ultrasonic receiver designed and fabricated in 0.18µm CMOS. Measurement results shows that the single chip receiver operating at a centre frequency of 40 KHz reduce the power consumption to less than half over the discrete version.**

***Index Terms*—Biomedical, infrared, ultrasonic, wearable device.**

I. Introduction

Ultrasonic transducers are widely used in Wireless Sensor Networks (WSN) for biomedical and industrial applications for remote powering and perform wireless communication to implanted sensors, range finding and object detection and tracking etc. [1-3]. In large facilities like factories and hospitals, it may be essential to track the people, equipment, controlled zones and other resources for safety and compliance with regulatory requirements [4]. A restricted zone in a factory can be a hazardous area with special equipments or chemicals which require careful handling by a trained person wearing appropriate personal protection equipments. Each compliance zone can have its own protocols to adhere to, for example a clean room enforces a person to wear bouffant caps, bunny suits and shoe covers and also there may be a procedure for cleaning a personnel, parts and components prior to their introduction into clean room to prevent contamination. Hospitals also have such compliance zones where in which strict adherences to the zonal associated protocols need to be enforced. Surrounding area near a patient's bed can be a clean zone and may require the use of hand hygiene agent to prevent contamination and hospital acquired infections. In order to enforce the compliance to the zonal requirements, a zone may be established by a signal transmission within that region and the zone is identified with a zonal designator. Fig.1 illustrates a typical compliance zone and the sensor systems deployed to enforce compliance. A person or object entering the zone needs to be equipped with a wearable device to receive the information transmitted from the zonal transmitters or from the interactive stations like washers (as shown in Fig.1) equipped with transmitters. Upon receiving the signal transmitted from the compliance zone designator, the wearable device identifies the predefined procedures to qualify the required protocol compliance. Whether wearer of the device complies with the protocol or not is monitored by the wearable device itself with its built in intelligence and updated to the system instantly or at a later time. Each compliance zone is associated with a transmitter and the zonal boundary is shown in Fig.1 in dotted lines. An ultrasonic transmission system is well suited to establish a compliance zone over the conventional Infrared(IR) and Radio Frequency(RF) transmission systems predominantly due to their signal propagation characteristics and also due to the ultra low power requirements of such systems. Ultrasonic signals are less line of sight than the infrared and more line of sight than the RF signals and therefore it is easier to have tight control over the spatial coverage of the signal transmission. This helps to define the zonal boundaries more accurately with no overlap between zones and this is quiet advantageous in a hospital environment where in large number of beds are deployed in a ward. Over and above the favorable signal propagation characteristics, these systems also avoid interference from other medical systems like magnetic resonance imaging, pacemaker etc., typically present in a hospital environment.

Fundamental building blocks of such a zonal compliance system is comprised of an ultrasonic transducer based zonal transmitter and an ultrasonic transducer based wearable device and their associated digital and analog interface circuits as shown in Fig. 1. Analog interface circuits to the transducers consist of driving circuit at the zonal transmitter and a receiver circuit at the wearable device. Wearable device being battery operated, it is critical for the interface circuits to consume low power for prolonged battery operation and also it is desirable to be smaller in size and weight. Thus, a tighter integration of the interface circuits ensures compactness and prolonged battery life.

In this paper, we report the design and development of a power efficient and compact analog interface circuit in 0.18μm CMOS for the ultrasonic receiver used in the wearable device. Section II illustrates the ultrasonic zonal compliance system and Section III describe the receiver design in detail. Section IV describes the measurement results followed by conclusion in Section V.

II. Ultrasonic Zonal Compliance System

Schematic diagram of an Ultrasonic telemetry system is

Manuscript received June 6, 2012; revised August 27, 2012.

This work was supported by the Agency for Science and Technology and Research (A-STAR) Singapore under the Grant A*CIMIT 001.

The authors are with the Institute of Microelectronics (A-STAR), 11, Science park road, Science park II, CO 117685 Singapore (email:kuruh@ime.a-star.edu.sg).

shown in Fig.1. In the transmit side, the driver circuit provides a high voltage (typically 10V-50Vpp, $20mA_{rms}$) electrical signal to drive the ultrasonic transducer. The ultrasonic output generated by pulse excitation produces an On-Off keying (OOK) modulated sound pressure signal which is directly transmitted into the channel.

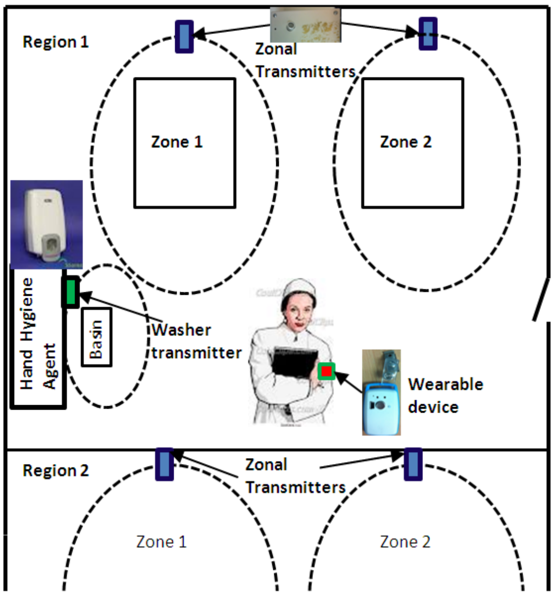

Fig. 1. Zonal compliance system

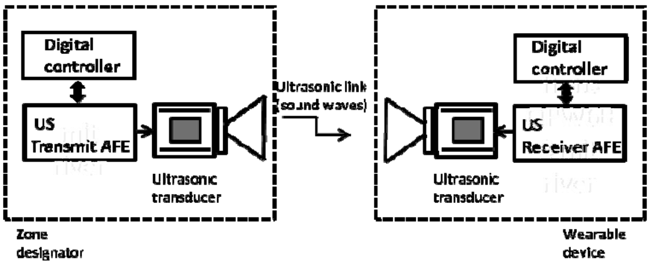

Fig. 2. Block diagram of an ultrasonic telemetry system.

At the receiver the transducer converts the sound pressure variations into equivalent electrical signal. A low noise front end amplifier and subsequent gain stages together boosts the weak signal acquired by the transducer. A threshold detection circuit followed by the gain stages helps to recover a clean signal from the noisy received signal. We can determine the received signal at the transducer by a simple calculation. The first step is to determine the Sound Pressure Level (SPL) at the receiver for a distance from the transmitter, giving a specific SPL in decibels (dB) at 30cm distance from the transducer surface. As in any transmission medium, the SPL at a distance away from the transmitter reduces due to the signal path losses. The losses are mainly due to two major mechanisms called the scattering and the absorption in air[8]. So the received sound pressure level at a distance will be obtained by subtracting the path losses from the transmit SPL. The next step is to convert the resultant SPL to Pascal (Pa) or microbar (μbar) and then the receiver sensitivity must also be converted from a dB scale to mV/Pa or mV/ μbar to obtain the final receiver output voltage. In this design we set 112dB transmitting SPL (0dB at 0.0002 μbar, 10Vrms, and 30cm as the near field region) and -80 dB as receiver sensitivity; the received signal voltage can be calculated as below.

Transmitting SPL =112dB

SPL losses at a distance 5meters from the transmitter,

Scattering loss: $\frac{d_{ref}}{d_{total}} = 20\log(0.3m/5m) = 24.44dB$

Absorption loss: $1.25(dB/meter) * d_{total} = 1.25dB * 5 = 6.25dB$

Received SPL: $112dB - 24.44dB - 6.25dB = 81.31dB$

Received SPL to μbar: $11627 * 0.0002\ \mu bar = 2.326\mu bar$

Receiver sensitivity: $-80dB\ to\ mV/\mu bar = 100\mu * 1V/\mu bar$

Received signal at 5m:

$$(100\mu V/\mu bar) * 2.326\mu bar = 232.6\mu V \tag{1}$$

Fig. 2. shows the calculated, received signal strength for transmitting SPLs of 115dB, 110dB, and 105dB at a distance of 1-10meters from the transmitter. Based on the minimum received signal and assuming OOK data detection scheme, the required noise performance and the bandwidth for the pre amplifier can be calculated as below.

Assume a received signal voltage for t_{otal} >5m: S =200 μV

Minimum SNR required for OOK = 18dB (7.9)

Noise voltage at the input $= \frac{S}{SNR} = \frac{200\mu V}{7.9} = 25.3\mu V$

Assuming a receiver bandwidth of 120 KHz, the noise spectral density $= \frac{25.3\mu V}{120KHz} = 73nv/\sqrt{Hz}$

Therefore the required noise performance of the pre amp and the overall system gain specifications can be derived from the above calculation as shown in Table1.

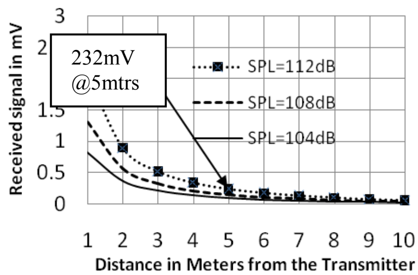

Fig. 3. Received signal at a distance from the transmitter.

TABLE I: Specification for the Receiver Front End

Parameter	Specification
B.W(Low pass)	120KHz
Input referred noise	<73nv/rt(Hz)
Gain(for voltage swing>2Vpp)	~66dB
Operating frequency	40KHz +/-3KHz
DC Voltage & Current	3V+/-10% , <25μA

III. US Receiver Circuit Design

A. US Receiver System Design

Schematic diagram of the Ultrasonic signal receiver is shown in Fig.3. The receiver circuit consists of three sub blocks, a low noise pre amplifier, second gain stage followed by a Schmitt trigger to obtain a digital compatible output signal . An Operational transconductance (OTA) amplifier is used as the front end circuit and it is designed to achieve low-noise and low power operation by minimizing the currents in the differential as well as the folded cascade output stage [6].The pass band of the amplifier is shaped by the pseudo resistor [7] element M1, M2 with the capacitor C_f which determines the low frequency high pass cut off. The bias current to the OTA determines the high frequency low pass cut off. C_f and C_{in} form the feedback network and the ratio C_i/C_f sets the desired (35dB) gain.

To provide a DC path to the input node of the OTA, a high value resistor R is used to clearly define the input node voltage. The R value is typically chosen to be greater than 10's of MΩs such that the DC current through it is much smaller than the signal current through the feedback capacitor. The condition is expressed as below

$$R >> \frac{1}{2\pi f_{sig} C_f} \tag{2}$$

where in f_{sig} is the input signal frequency and C_f is the signal feedback capacitor. From (2) the R value need to be more than 20 MΩ for f_{sig}= 40 KHz and C_f = 200fF.

In our design a MOS- Bipolar pseudo resistor [7] with a W/L value of 100µm/0.18 µm is used as the DC feedback in both the pre amp as well as in the subsequent gain stage.A reset pin is provided to set the DC voltage to zero (0V)upon power up to the circuit. Following the OTA is a low power operational amplifier (opamp) based gain stage such that the overall signal gain achieved in the chain is over 66 dB. A two stage op-amp is designed to provide a closed loop gain over 33dB and the bias currents to the amplifying stages are lowered to make optimal use of the supply current. Pseudo resistors M3, M4 configured in diode connection are used to provide the DC bias to the input stage in the same way as in OTA stage. The ratio of C_f /C_1 set the mid band gain similar to the preceding folded cascade OTA stage. A Schmitt trigger circuit useful in generating clean pulses from a noisy input signal is employed as the output stage in the US receiver chain [5]. The operation of the receiver circuit is easily understood from the block diagram given in Fig.4. Typically a received signal V_{in} will be ranging from 200µV to 10000 µV. This signal pass through the low noise amplifier and the gain stage to eventually drive a Schmitt trigger comparator circuit. Schmitt trigger circuit is designed in such a way that it produces 3V pulses at its output in response to a weak and noisy V_{in} at the receiver input.

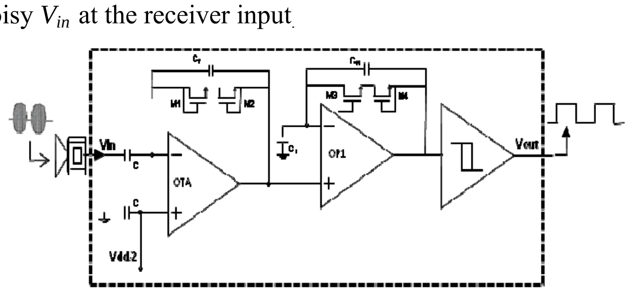

Fig. 4. Block diagram of ultrasonic Receiver circuit.

B. OTA Design

The schematic diagram of the low noise OTA is shown in Fig. 4. A standard folded cascode topology is modified and used in this design to improve the noise performance as well as to reduce the power consumption [6]. The biasing technique employed in this circuit restricts the currents in the folded branch M5-M10 to be equal to the current in the input differential pair transistors M1 and M2. Reduced current in the folded cascade branch reduces the total current and also reduces the noise contributed by this branch and hence reduces the overall input referred noise of the OTA. Current mirror formed by M11 and M12 operate in strong inversion so that there is minimal effect on the current scaling due to threshold variations. Current mirrors formed by M13 and M3, M4 which are source degenerated [6] to set the desired current flow in the M3-M4 branch. The main advantage of this OTA design is the reduction in noise contribution from the cascode branch over the standard cascode topology. The current through the differential pair branch is already set to $I_B/2$ and therefore the current trough M3 and M4 will be the sum of the current through M1 and M2 and the current through the branch M5-M10. In this design the current through the folded cascade branch is chosen as equal ($I_B/2$) to the branch current in the differential pair and therefore to facilitate the scaling, the current through M3 and M4 is set as I_B. To achieve such a current ratio between the M13 and M3, M4 we set the resistor value R3= *11R*1 and the transistor M13 is a parallel combination of two unit fingers and the transistor M3 and M4 are formed by combining 11 of such unit fingers in parallel. In order to achieve a low input referred noise for the OTA, the transconcductance *Gm* which will be near to the tranconductance *gm1* of transistor M1 need to be maximized for the given current. A transistor operating in sub threshold region achieves maximum *gm* for the given current. W/L ratios of M1 and M2 are maintained as large such that the device is driven to sub threshold. Device sizing for the design and their operating points are given in Table II.

TABLE II: DEVICE DIMENSIONS AND CURRENTS

OTA			Opamp			Schmitt Trigger	
Devices	W/L (µm)	$I_{D(\mu A)}$	Devices	W/L (µm)	$I_{D(\mu A)}$	Devices	W/L (µm)
M1,M2	34.87/0.84	2.36	M1,M2	89/0.35	2	M1,M4	0.52/0.5
M3,M4	46.2/1	4.72	M3,M4	10/0.35	2	M2,M3	1.75/0.3
M5,M6	2.1/0.86	2.36	M5	40/0.35	8.17	M5	2.1/1.9
M7,M8	8/0.5	2.36	M6	20/0.7	8.17	M6	1.2/1.0
M9,M10	8/0.5	2.36	M7	10/0.7	4	M7	6.3/1.9
M13	8/0.5	0.295	M8	1.0/0.7	0.4	M8	3.6/1.0

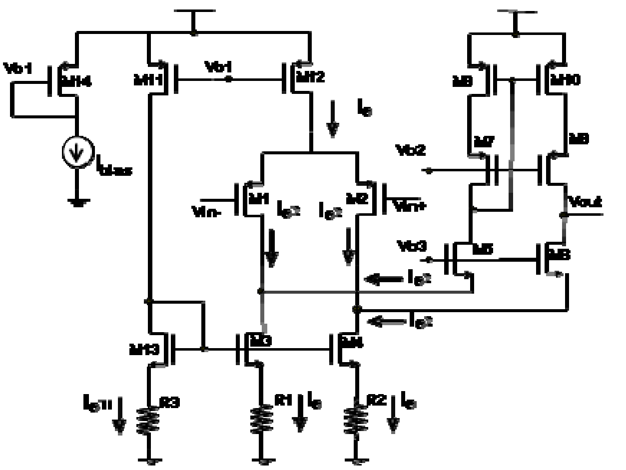

Fig. 5. OTA

C. Opamp & Schmitt trigger

Fig. 5 shows the schematic of the 2 stage opamp designed for a voltage gain over 30dB. The first stage and the second stage together consume a total supply current of 10 µA to provide an open loop gain of 70dB. Figure 6 shows the schematic of the Schmitt trigger circuit [5].

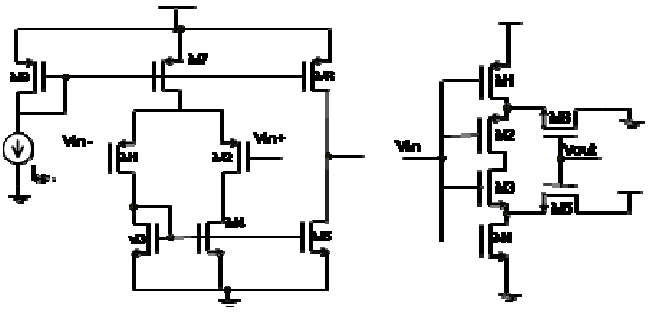

Fig. 6. (a) Opamp circuit, (b) Schmitt trigger circuit

High to low transition and low to high transition points for this design is found to be 1.28V and 1.65V respectively. This values are obtained from the simulation. Schmitt trigger consumes <5uA and produces 3V amplitude swing at its output for a valid input signal.

IV. Measurement Results

A fully integrated Analog front end circuit for the ultrasonic receiver was fabricated in 0.18µm CMOS process and the chip micrograph is shown in Fig.7. The chip occupies a silicon area of 1500 µm X 900 µm and the core circuit occupies an area of 800 µm X 600 µm. Test chip is packaged using a 16 pin SOIC package and a test board is designed and fabricated to characterize the design. When an input signal of 250 µV or higher is present at the input, the receiver chip produces a valid output. Full chip consumes only16 µA from a 3V power supply even when the input is at the minimum detectable level of the receiver.

Linear gain of this amplifier is observed to be 68dB in the simulation. Since we have only limited IO pins available in the chip, We measure the nonlinear gain and the time domain performance of the receiver to verify the chip functionality. We provide an input signal of 500µV and observe a 3V signal amplitude at the output. This condition indirectly tells us that the linear gain obtained by the circuit is about 70dB.

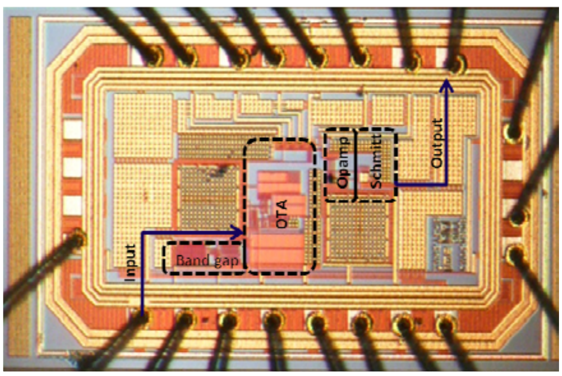

Fig. 7. (a)Chip Micrograph (b) Test PCB

Fig. 8 shows the nonlinear gain curve for the circuit and the gain at 40 KHz is found to be 8.41dB. Compared to the discrete transistor based PCB solution (Nonlinear gain of 6.5dB), this single chip design has an improvement in gain by 1.5dB for much lesser current (16µA in our chip as against >35 µA in case of discrete PCB receiver) drawn from the battery.

Fig. 8 shows the frequency spectrum at the output of the receiver chip for an input signal level of 250 µV.

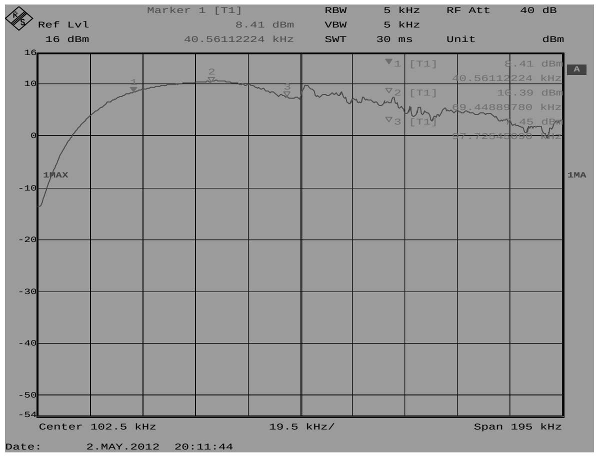

Fig. 8. Nonlinear gain measured at the receiver output

From the spectrum, we can calculate the Harmonic distortion(THD) and it is found to be around 5%.

Fig.10 shows the time domain signal output of the receiver chip for an input signal of 250 µV. The output voltage amplitude is found to have a swing of 0-3V as required by the system specification.

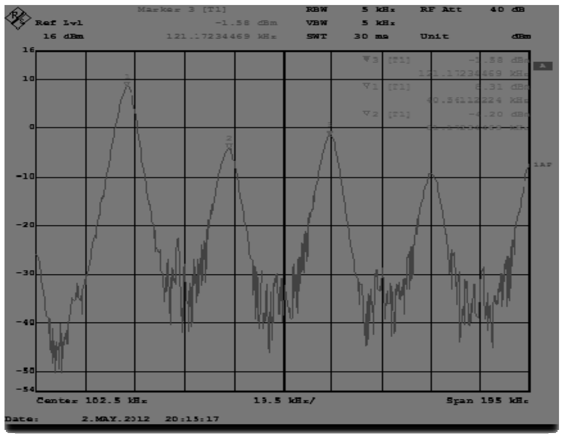

Fig. 9. Frequency spectrum

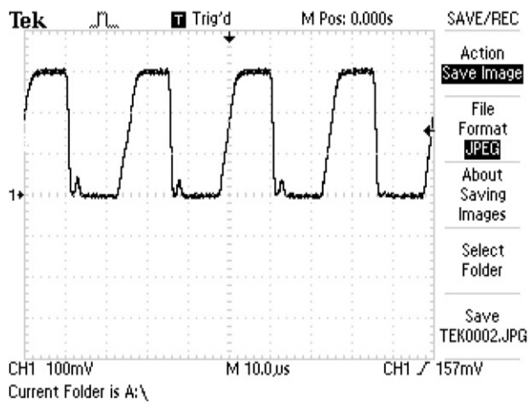

Fig. 10.Signal at the receiver output

V. Conclusion

In this paper we presented the design methodology and measurement results of an analog front end circuit for an ultrasonic receiver used in a battery powered wearable device of a zonal compliance sensor system. Measured results shows that the power consumption is much lesser than a discrete component based AFE receiver on PCB and being integrated to a single chip, this approach considerably reduces the number of components used and thereby the size of the wearable device.

ACKNOWLEDGMENT

The authors would like to acknowledge Agency for Science and Technology Research (A-STAR), Singapore for funding this project under grant number A*CIMIT 001. The authors would also like to thank Peh Ruey Feng from Science and Engineering Institutes and Sivakumar Viswanathan from Institute of Infocomm Research, Steve Schiefen from Hangenix and Mike Dempsey from CIMIT for the technical discussions.

REFERENCES

[1] F. Mazilly, etal., "In-Vitro Platform to Study Ultrasound as Source for Wireless Energy transfer and Communication for Implanted Medical devices," *IEEE Engineering in Medicine and Biology Society (EMBC) Proc.of Annual International conference*, Buenos Aires(Argentina), 31st August to 4th Sept. 2010.

[2] C. Kuratli and Q. Huang, "A CMOS Ultrasound Range finder Micro system," *IEEE ISSCC*, pp. 180-181, Feb. 2000, San Francisco, USA.

[3] Sverre Holm, "Airborne ultrasound data communication system: The core of an indoor positioning system," *IEEE Int. Ultrasonics symp.,* Sept. 18-21, 2005, Rotterdam, The Netherlands.

[4] M. P. Dempsey and R. S. Nowbower, "Ultrasonic Compliance Zone System," *U.S. Patent 8*, vol. 164,439 B2, Apr. 24, 2012.

[5] R. J. Baker, H. W. Li, and D. E. Boyce, "CMOS circuit design, layout and simulation," *IEEE press series on Microelectronic systems*, IEEE, 1998, ch. 17, pp. 356-359.

[6] W. Wattanapanitch, etal, "An Energy-Efficient Micropower Neural recording Amplifier," *IEEE Transactions on Biomedical Circuits and systems,* vol. 1, no.2, July 2007.

[7] R. R. Harrison and C. Charles, "A Low-Power Low-Noise CMOS amplifier for Neural recording applications," *IEEE Journal of Solid State Circuits*, vol. 38, no. 6, June 2003.

[8] *SenseComp Ceramic transducers Application note,* SenseComp Inc. USA.

.