# Neural Signal Recording: Challenges & New Openings

Invited talk* by:
Dipankar Pal
Professor, Dept. of EEE and E&I
BITS-Pilani, K. K. Birla Goa Campus, NH 17B Bypass Rd.
Zuarinagar, Sancoale, Goa – 403726, INDIA

*Abstract*—**Acquisition of bio signals using a fully integrated design is needed in advanced medical applications [1]. Examples of recording of nerve signals (ENG) to control functional electrical stimulation (FES) prostheses, detection and localization of brain activity and acquisition of the electrocardiogram (ECG) or surface electromyogram (s-EMG) as part of a wearable or implantable monitoring system [2]-[6] establish this. The signals thus obtained are small, on the order of millivolts or less. Noise and interference therefore become key factors. Amplification near the recording site is desirable to reduce interference pickup.**

**Advances in CMOS technology, communication, and low power circuit design have spurred the development of wearable biomedical devices, leading to miniaturized and highly integrated systems for continuous monitoring of physiological parameters.**

**One of the crucial building blocks in a wearable device is the sensor interface picking up extremely small input signals and providing a preconditioned signal to the subsequent processing system. As stated, the amplitudes of the signals to be recorded are frequently on the order of tens of microvolts to tens of millivolts and the frequencies span from DC to a few kHz.**

***Keywords—nerve signals; implantable; low power; CMOS technology***

## I. INTRODUCTION

Amplifiers with controllable gain allow adjusting of gain to the optimum value during recording, providing maximum amplification without saturating the channel to become useful building blocks in multi parameter recording systems as well as multichannel recorders, which need matched gain between channels. The choice of input transistor, bipolar (BJT) or metal-oxide-semiconductor (MOS, CMOS), affects the noise and input impedance of the system. Whereas the latter yields very high input impedance, the former produces lower noise. The BJT stage, manufactured as a lateral structure in a conventional CMOS process technology, is a compromise solution proposed as an alternative to chopper-amplifier conventionally used to suppress low-frequency noise.

*** This talk is based on the paper: "Very Low-Noise ENG Amplifier System Using CMOS Technology", by Robert Rieger, Martin Schuettler, Dipankar Pal, Chris Clarke, Peter Langlois, John Taylor, and Nick Donaldson, published in IEEE Trans. Neural System & Rehabilitation Engg., vol. 14, No. 6, pp. 427-437, December 2006**.

A major current challenge in neuroprosthetics research concerns the use of naturally occurring neural signals (ENG) to provide sensory feedback to artificial devices. Neural afferent signals generated by natural sensors within the body can be used to obtain information such as skin contact, force, or limb position, so they may be used in closed-loop neuroprostheses. Evaluation of these acquisition front ends requires further effort since many parallel recording channels are required for certain approaches (e.g., for velocity discrimination), and interfacing to a live neuron is a delicate procedure.

These applications require stable responses from chronically implanted electrodes. Nerve cuff electrodes are currently the most well established nerve interfaces with safe implantation being reported for as long as 15 years. Consequently, nerve cuff electrodes have been used at sites in the limbs and on the nerves that innervate the bladder. A further advantage of these electrodes is that implantation is relatively easy, the cuff is either slit-and-reclosed, or is self-curling, to allow surgical placement without damage to the nerve. Typical nerve cuff fitted with three electrodes, its equivalent circuit and typical tripolar amplifier system are now reported in open literature.

In the tripolar nerve cuff typically, only one signal output is available and hence the information that can be obtained is limited. Because the large number of fibres in each peripheral nerve carry a great many neural signals with, generally, both afferent and efferent traffic, this reduction to only one output signal represents a huge loss of information. However, where fibres of different diameter carry various types of neural signal, it should be possible to extract more information from one cuff if fibre diameter-selective recording were possible. This is equivalent to measuring the level of activity in the velocity domain, because of the approximately linear relationship between axon diameter and action potential (AP) velocity. Methods of velocity-selective recording has also been described recently which relies on the use of a multi-electrode cuff (MEC). An MEC is an extension to N-tripoles of the single tripole arrangement shown, where N-is typically about 10. As a result, more than one ENG signal is available, which is the key to the proposed velocity selective recording (VSR) technique.

Despite many advantages of the nerve cuff approach to ENG recording, the amplitude of the ENG recorded using this



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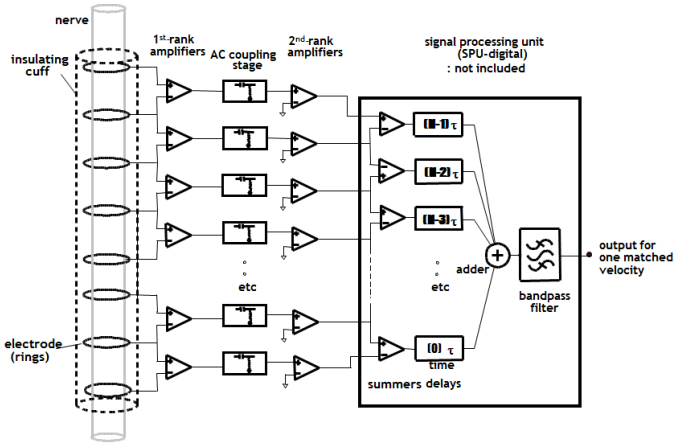
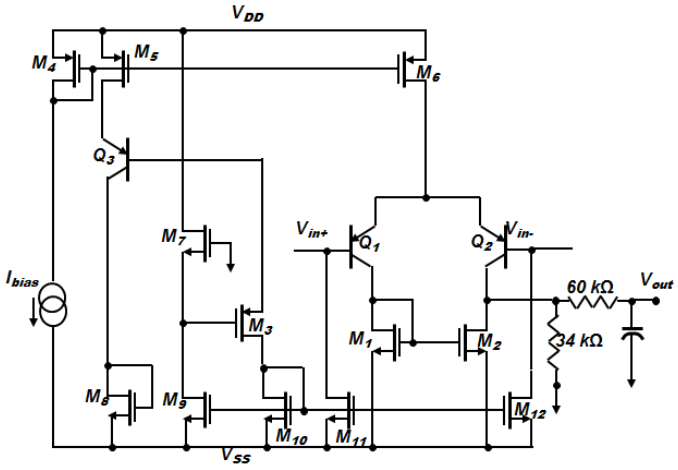
method is very small, on the order of a few microvolts, with most of the signal power in a bandwidth between about 300 Hz–5 kHZ. This problem is exacerbated in an MEC, since in this type of cuff the electrodes are spaced more closely than in a single-tripole cuff of the same length, resulting in even smaller signal amplitudes. In addition, the ENG signal recorded from nerve cuff electrodes is contaminated by significant amounts of noise. In the bandwidth of interest, for a single tripole, the most significant noise source is the axial (ohmic) resistance appearing between the electrodes and tissue. With MEC and with increasing N, the spreading resistances become dominant. These sources contribute thermal (additive white Gaussian) noise that, together with noise generated by the amplifiers, degrades the signal-to-noise ratio available at the tripole outputs. Therefore, ENG recording systems rely critically on the availability of very low-noise, high-gain amplifiers.




System Overview

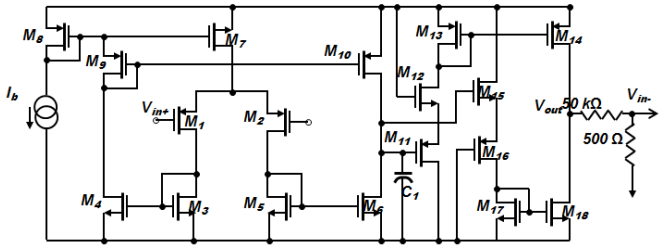
In this address, we present the design, fabrication and testing of the analogue signal-capture sections of a ten-channel amplifier system suitable for connection to an MEC. This is intended to be an implantable system to be mounted, ideally, directly on the MEC to take maximum advantage of the very low noise capabilities of the preamplifier stage of the system. We also describe preliminary *in vitro* experiments in frogs, which provide the first practical validation of the VSR process. The system has an overall gain of 10,000 and a total input-referred root mean square (rms) noise per channel of less than 300 nV in a band- width of 1 Hz–5 kHZ. In addition, a general description of the digital signal processing required to perform velocity selective recording is given.

The system presented indicating the principle of VSR while circuit topologies outline the architecture of the signal processing required by the system. The system consists of the interface to the MEC followed by two stages of amplification and a signal-processing unit (SPU). The first rank amplifiers are specially designed low noise, low power units (preamplifiers) each with a nominal voltage gain of 100. The superiority of this design as compared to other candidate designs is quantified by the benchmarking exercise described included in the presentation. Each preamplifier is followed by an alternating current (ac) coupling stage that, in addition to removing direct current (dc) offsets, shapes the frequency response of the system, setting the lower cutoff frequency of the pass band at 300 Hz.




Pre Amplifier Stage

This stage is followed by a second rank of much less tightly specified amplifiers, each also having a gain of 100 and an upper (i.e., low pass) cutoff frequency of 3.5 kHZ. The outputs of these second rank amplifiers are band pass filtered difference voltages taken between pairs of adjacent electrodes. They are called dipole signals. The dipole signals form the inputs to the SPU. The SPU contains elements (multiplexing, analogue to digital conversion) that are common to each chosen velocity band and some which (delay, summation, filtering) are duplicated for each band. The digitized dipole signals are subtracted in pairs to form tripole signals, before processing by the SPU as explained.




2nd Rank Amplifier

In order to demonstrate the VSR process, the system was used to measure electrically evoked ENG (i.e., compound action potentials) in the sciatic nerve from a *Xenopus Laevis* frog using an *in vitro* preparation. For these initial experiments, the dipole output signals were coupled directly to a PC fitted with a data acquisition card (DAC) and running MATLAB. This combination implemented the SPU, providing all the required signal processing. A description of the experimental



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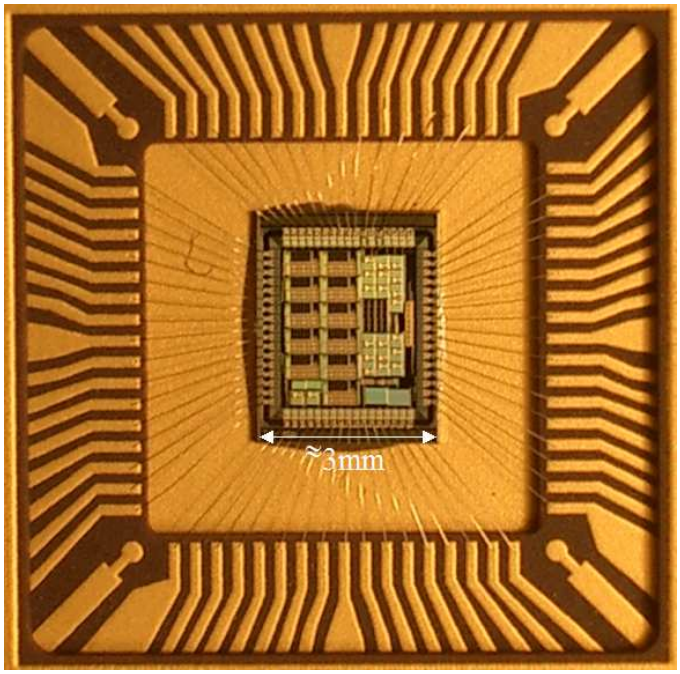
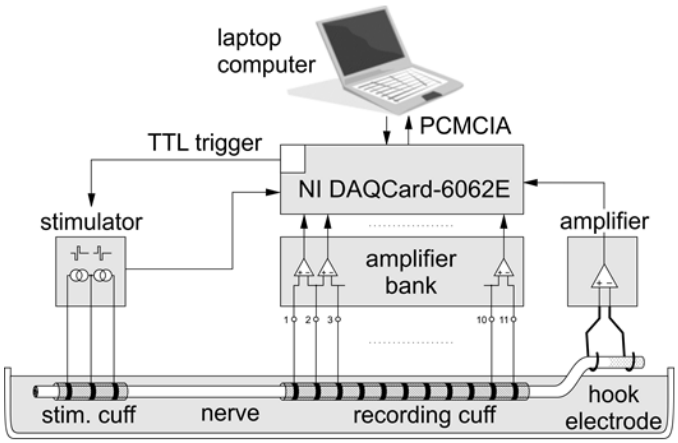
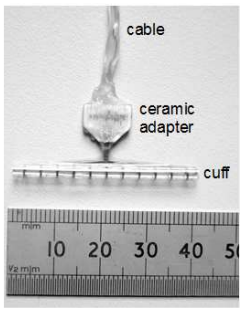
arrangement and details of the cuff construction are included.

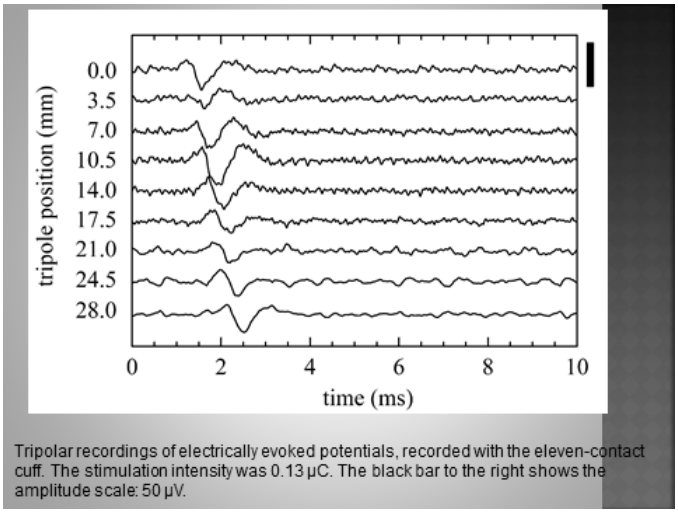



Chip Microphotograph

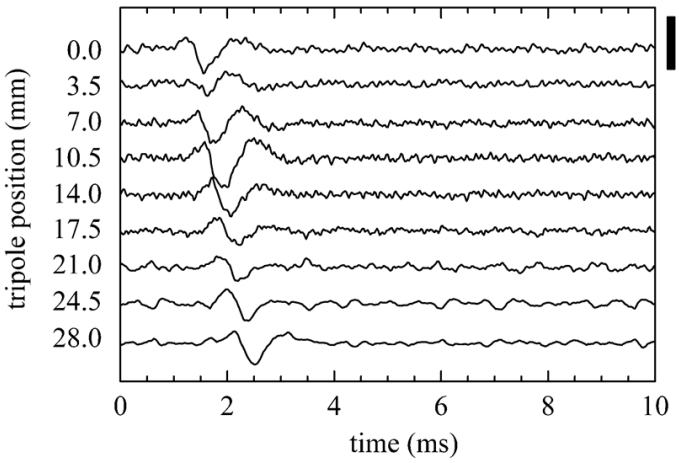



Final Set-Up




Tripolar recordings of electrically evoked potentials, recorded with the eleven-contact cuff. The stimulation intensity was 0.13 µC. The black bar to the right shows the amplitude scale: 50 µV.




Tripolar recordings of electrically evoked potentials, recorded with the eleven-contact cuff. The stimulation intensity was 1.01 µC. The black bar to the right shows the amplitude scale: 50 µV.

We have included some measured results, which is divided into two parts. The first part details the electrical measurements on the fabricated chips (including the benchmarking exercise already referred to) and compares them with CADENCE simulations while the second part describes the results of the in vitro frog experiments.

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