Photrodes™ for physiological sensing

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ABSTRACT

This paper describes a paradigm shift in the technology for sensing electro-physiological signals. In recent years, SRICO has been developing small lithium niobate photonic electrodes, otherwise called "Photrodes™" for measuring EEG and ECG signals. These extrinsic fiber-optic sensing devices exploit the extremely high electrical input impedance of Mach-Zehnder Intensity (MZI) electro-optic modulators to detect microvolt and millivolt physiological signals. Voltage levels associated with electrocardiograms are typically on the order of several millivolts, and such signals can be detected by capacitive pickup through clothing, i.e., the Photrode™ may be used in a non-contact mode. Electroencephalogram signals, which typically have an amplitude of several microvolts, require direct contact with the skin. However, this contact may be dry, eliminating the need for conductive gels. The electrical bandwidth of this photonic electrode system stretches from below 0.1 Hz to many tens of kHz and is constrained mainly by the signal processing electronics, not by the Photrode™ itself. The paper will describe the design and performance of Photrode™ systems and the challenging aspects of this new technology.

Keywords: Photrode™, physiological sensing, lithium niobate, fiber optic, optical modulator, Mach-Zehnder Interferometer

1. INTRODUCTION

Serendipity has led a previously developed optical voltage sensor technology to emerge as a revolutionary approach to electrophysiological monitoring of military pilots and other combat personnel. Using light as its medium and innovative optical chip technology at its heart, the award-winning[1] Photrode™ represents a completely new paradigm in biopotential detection.

1.1 General Overview of Photrode™

The basic Photrode™ system consists of a laser source, optical input and output fibers, and an optical receiver and signal processing components as seen in Figure 1. A biopotential signal, a signal produced from a body, such as an electrocardiogram (ECG), a signal produced by various heart movements, is applied to the Photrode™. Light from a continuous wave (CW) laser source enters the Photrode™ and becomes intensity modulated by the biopotential signal. An optical receiver for detection and signal processing detects the output of the Photrode™.

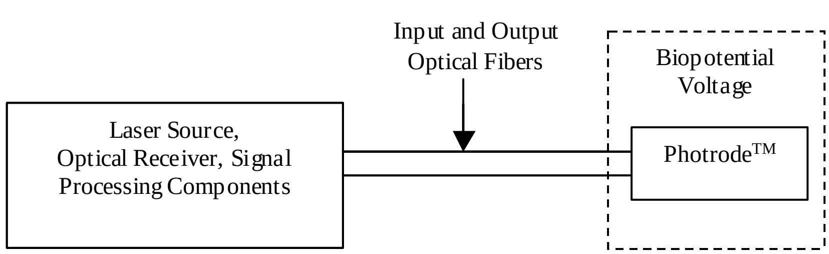

Figure 1. Basic Photrode™ System

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2. METHODOLOGY

The key operational component of the Photrode™ device is a miniature, specially designed, optical chip. The Photrode™ is based on integrated optic waveguide technology that has been used over the past two decades in demanding military and aerospace applications and, more recently, in telecommunications networks. The miniature, chip-size device consists of an integrated optical circuit referred to as a Mach-Zehnder Interferometer (MZI).

2.1 Photrode™ Design

The Mach-Zehnder Interferometer, shown in Figure 2, consists of an input light path, known as a waveguide, a Y-branch splitter, which divides the light path into two separate waveguides, and a Y-branch combiner, which recombines the two light paths into one waveguide at the output. The MZI is fabricated in a lithium niobate electro-optic crystal substrate. Optical input and output fibers are attached to the substrate using standard techniques from the manufacture of optical waveguide devices.[2] Thin-film gold electrodes are deposited on the crystal, which concentrate an ambient biopotential signal at the waveguides. The electrodes operate in a push-pull configuration, modulating the light via the electro-optic effect as the two legs of the interferometer are subjected to opposite voltages.

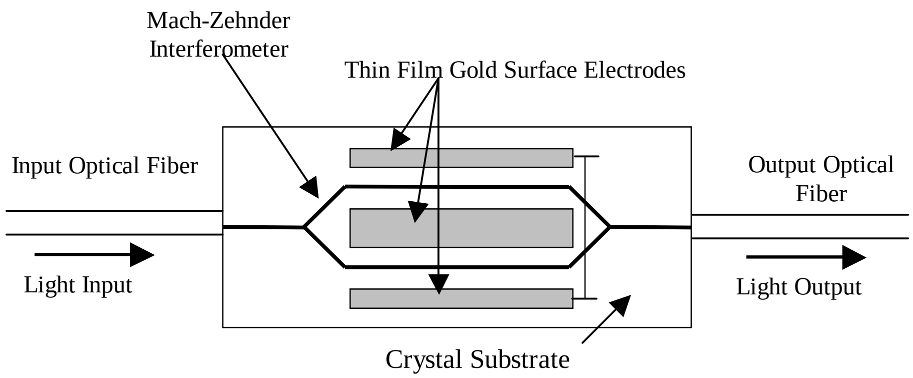


Figure 2. Photrode™ Schematic

Figure 3 shows the prototype Photrode™ package currently used for biopotential measurements although the actual commercial device would be much smaller. For instance, differential ECG measurements are made by placing the Photrode™ across the chest with the biopotential contacts touching the skin of the subject. The grounding tag is used as an extra ground reference, which is connected to the Photrode™ package.

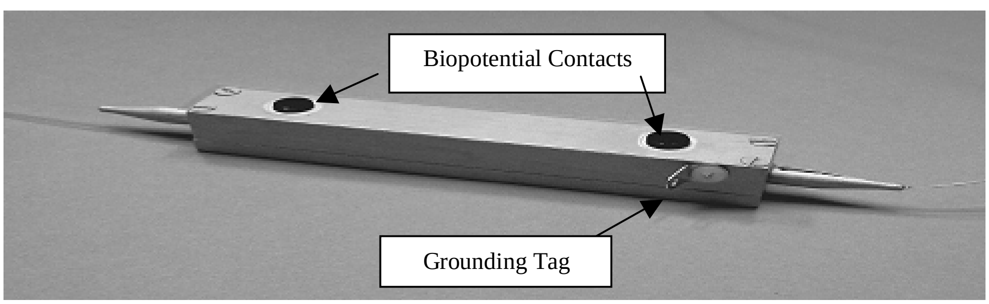


Figure 3. Photrode™ Package

2.2 Photrode™ Characteristics

This uniquely designed Photrode™ is ultra sensitive, functions as a high impedance device, and provides a high bandwidth especially capable of detecting low to high frequency ranged signals.

The response characteristic of the Mach-Zehnder interferometer Photrode™ is a cosine-squared function shown in Figure 4. To achieve the desired sensitivity needed to detect biopotential signals, Photrodes™ are selected to operate for small signal modulation, i.e. in the linear region of the cosine-squared curve, also known as quadrature. Therefore no further external dc bias voltage is needed for the device to operate with maximum sensitivity.

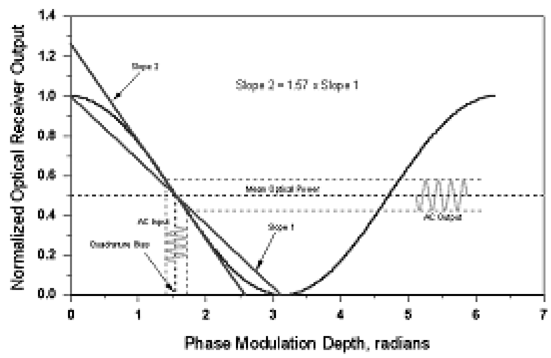


Figure 4. Mach Zehnder Cosine Squared Response

The simplified equivalent circuit for the Photrode™ is that of a very small capacitance (i.e., a few picofarads) in parallel with a very high resistance (i.e., 10^{14} Ohms). This is illustrated in Figure 5. It is this ultra-high electrical impedance that gives the Photrode™ one of its remarkable properties for measuring biopotentials, unlike the standard low impedance electrodes commonly used in medical device technology. To lessen the likelihood that Electro-Static Discharge (ESD) could damage the Photrode™ a resistive component is connected in parallel with the Photrode™.

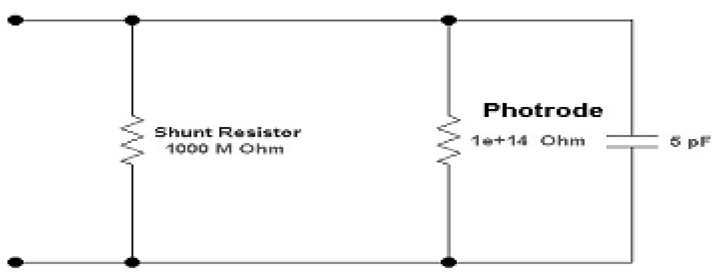
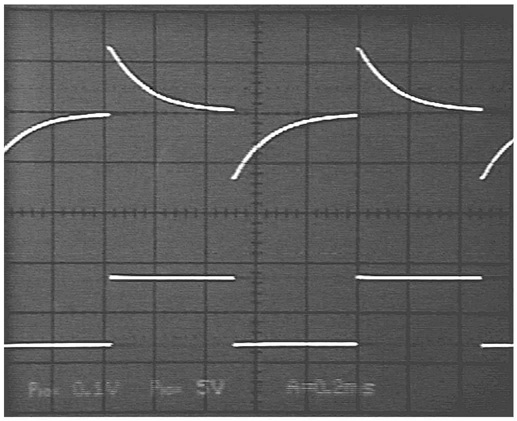


Figure 5. Equivalent Photrode™ circuit

Mach-Zehnder interferometer electro-optic modulators used in telecommunication networks are well known for their high frequency characteristics, but their low frequency response is typically limited to about 100 MHz. In order to detect biopotentials using MZI modulator devices, low frequency operation is imperative. In the case of the ECG signal, the frequency range is 0.1-150 Hz.[3] At 1kHz, typical commercially available integrated optic modulators produce considerable differentiation and tilt, as seen in Figure 6. The performance of the conventional modulator will affect the measurement of the ECG signal, causing severe distortion of the ECG waveform. This data was taken using a conventional high frequency Srico modulator, and an oscilloscope.



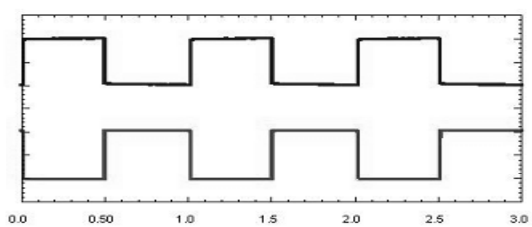
Conventional Modulator Response

Input Square Wave Signal

Time, 0.2ms/division

Figure 6. Conventional electro-optic modulator response at 1kHz

Figure 7 shows the low frequency capability characteristic of the Photrode™ system, represented in the top trace, driven with an input square wave signal at a frequency of 1Hz represented in the bottom trace. Data was obtained using a conventional oscilloscope. As shown in Figure 7 below, the Photrode™ faithfully reproduces the input signal data with no distortion or tilt, unlike the conventional high frequency modulator response of Figure 6. The Photrode™ will therefore be able to detect and reproduce biopotential data faithfully.



Detected Photrode Signal

Input Signal

Time, seconds

Figure 7. Low Frequency Photrode™ Characteristics

Figure 8 represents the biopotential signal levels and the contributions from the various noise sources associated with the Photrode™ system. The calculated optical carrier to noise ratio (CNR) of 154 dB/Hz is based on a received optical power of 1 mW at the operating wavelength of 1550 nm. The quantum noise refers to the noise associated with the statistical arrival of photons. Thermal noise, also referred to as conventional Johnston kT noise, is the noise produced by all electrical circuits above temperatures of absolute zero. An EEG signal, i.e. an electroencephalogram produced by the activity in the brain, is represented at a signal level of 1 μV over a frequency range of 1 to 60 Hz. The ECG signal is represented at a signal level of 1mV over a frequency range of 0.1 to 150 Hz. As seen in this graph the Photrode™ system noise is below that of the ECG and EEG signal levels. Therefore the Photrode™ is capable of measuring low-level biopotential signals.

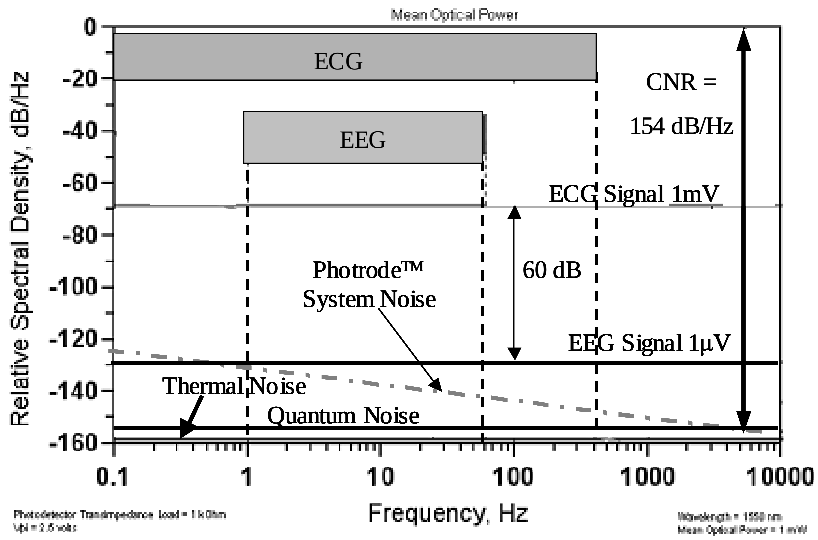


Figure 8. Signal and Noise Characteristics for Biopotential Measurements using the Photrode™

3. BIOPOTENTIAL MEASUREMENTS

The performance of the Photrode™ was characterized and compared with ECG and EEG waveforms collected using wet contact electrodes, of the typical silver-silver chloride variety. The Photrode™ signal was converted to an electrical signal, within the optical receiver, and the resulting data was acquired using a BIOPAC MP150 system simultaneously with the signals detected by conventional electrodes.

3.1 Results

Figure 9 shows ECG data collected using the Photrode™ along with data collected using a standard ECG electrode. The ECG signal is from one of the authors who has a known arrhythmia. The top trace corresponds to the Photrode™, and the bottom trace represents the electrode acquired biopotential ECG data. The data on both traces has been filtered using standard software provided with the acquisition unit (BIOPAC Acqknowledge version 4.7.3). Both responses are taken simultaneously, in close proximity to one another on the chest wall, and there is excellent agreement between the two signals. The arrhythmia is present in both traces and also the PQRST waveform, associated with the depolarization and repolarization of the various regions of the heart, of the ECG is prevalent in both traces.

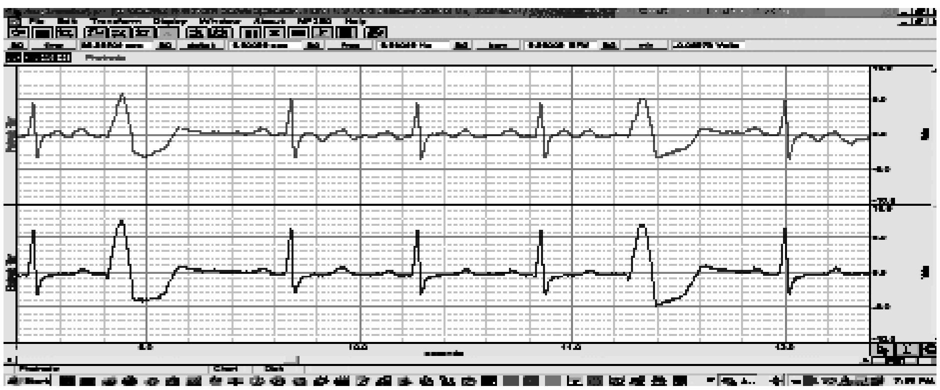


Figure 9. Photrode™ (top) vs. Electrode (bottom) ECG Response

Figure 10 shows the EEG response of the Photrode™ system compared to the response from standard electrodes. This data was collected on one of the authors. The electrode data was taken with a differential measurement on the C3 and C4 areas of the brain[4], the Photrode™ data was collected on the Cz region of the brain, between the C3 and C4 areas, with a return to ground on the earlobe. The raw data are shown in traces 1 and 2, and the traces below are filtered to show various standard signals of interest. The data acquisition rate was 10000 samples per second, using the BIOPAC MP150 System. Comparing charts 3 and 7 below, the delta waveform characteristics are represented in both the electrode (#7) and Photrode™ (#3) traces and are very similar. Any differences can be accounted for by the different placement regions of the devices, as well as the motional artifacts of the subject.

Chart 1: Cz- Raw Photrode™ Data
Chart 2: C3, C4 - Raw Electrode Data
Chart 3: Photrode™ - Delta Wave (1-4 Hz)
Chart 4: Photrode™ - Theta Wave (4-8 Hz)
Chart 5: Photrode™ - Alpha Wave (8-13 Hz)
Chart 6: Photrode™ - Beta Wave (13-30 Hz)
Chart 7: Electrode Delta Wave (1-4 Hz)
Chart 8: Electrode Theta Wave (4-8 Hz)
Chart 9: Electrode Alpha Wave (8-13 Hz)
Chart 10: Electrode Beta Wave (13-30 Hz)

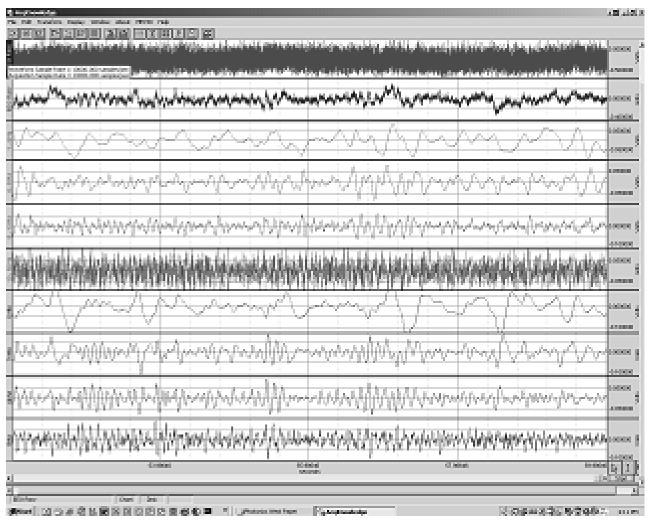


Figure 10. EEG response of Photrode™ and electrode

3.2 Application Areas

Standard electrode technology relies on a low impedance contact to the skin to detect the biopotential voltage of interest. The skin, composed of many different layers of cells, has an impedance range of 200000 Ω at 1 Hz to 200 Ω at 1 MHz in the epidermis layer.[5] It is in this epidermis layer that cells are constantly growing and dying – thus accounting for their different electrical characteristics. Typically, contact impedance values range from 30000 - 10 Ω, and are dependent on frequency, the electrode material, and the electrolyte used.[6] In order to maintain reliable contact, the skin is often vigorously cleaned, or even abraded in order to improve the stability of the signal during collection. This can be a time-consuming, messy, and somewhat uncomfortable process, depending upon the desired biopotential. For instance, in an EEG signal as many as 24 electrodes are attached to the scalp with a collodion adhesive which hardens and must be dissolved in acetone for removal. Some subjects find this electrode removal process to be irritating, uncomfortable, and painful, particularly if they have a full head of hair. Newer electrode technology, especially in ECG acquisition, offers pre-gelled electrodes that provide the low impedance and surrounds the electrode in adhesive to keep the contact in place on the skin. During long-term monitoring, the gel may dry out thereby losing the low impedance contact, after which the electrode is removed and a fresh electrode is reapplied. This of course consumes the time taken by the medical professional to reapply the electrode and obtain the low impedance contact, not to mention the aggravation to the patient who must endure the removal and reattachment routine.

Since the Photrode™ is a high impedance device, low-impedance skin contact is not required. Thus, the Photrode™ functions as a non-contact or a dry contact device. Unlike conventional electrode technology, the dry contact method requires no skin preparation, no conductive gels and no adhesives. In non-contact mode, the device does not even touch the body enabling even more flexible applications. Indeed, laboratory tests show the Photrode™ is capable of detecting an ECG signal through the subject's shirt. These results represent a significant advance in optical voltage sensing technology and suggest the possibility of placing the ECG Photrode™ over the patient's gown or clothing. In addition to ECG and EEG, this innovative technology can be applied to the study of other biopotential signals such as EMG, and EOG.

The Photrode™ was developed especially for electrophysiological measurement applications in which conventional electrodes are deemed to be unsafe, unreliable, uncomfortable, or inconvenient. Motivation for such a system includes previous research demonstrating that soldiers who have been awake for 48-72 hours rapidly lose their ability to make correct judgments.[7, 8] Other applications of alertness monitoring include heavy equipment operators, such as truck drivers, who must be able to make decisions in order to avert possible accidents, or incidents.[9] The optical EEG and ECG technology was initially developed for the U.S. Army Aeromedical Research Laboratory for physiological status monitoring of Army pilots; the Walter Reed Army Institute of Research, Department of Neuropsychiatry, for ambulatory alertness monitoring; and the Walter Reed Army Institute of Research, Department of Surgery, for triage applications. Subsequent research and development efforts under NIH grants have focused on the use of EEG and ECG Photrode™ technology for functional magnetic resonance imaging. However, Photrode™ technology is not limited to these applications and may be used for any type of electrophysiological measurement. Examples include anesthesia awareness monitoring, sleep medicine, mobile medical monitoring for space flight, emergency patient care, and routine neurodiagnostics.

4. CONCLUSIONS

Current advances in the medical devices area have allowed a technology designed for the telecommunications industry to become a biopotential sensor. The Photrode™, which has high impedance characteristics, high bandwidth, and ultra high sensitivity, has proved to be a novel device for detection of biopotential signals. As shown, the Photrode™ is able to successfully detect ECG and EEG signals using dry contact methods, unlike conventional electrodes, which rely on low impedance, wet contact attachment to the skin. Although the Photrode™ technology has only been developed and tested for EEG and ECG, it may also be applied to other biopotential signals areas such as electromyography (EMG), and electrooculography (EOG). With such high demand application areas being important to the military and those undergoing patient monitoring, the Photrode™ technology has a promising future in years to come.

ACKNOWLEDGEMENTS

This work was sponsored by:
U.S. Army Contract # DAMD17-98-C-8009, 1998.
U.S. Army Contract # DAMD17-98-C-8008, 1998.
U.S. Army Contract # DAMD17-01-C-0021, 2001.
NIH Grant #1R43HL65823-01, 2001-2002.
NIH Grant #1R43NS40603-01, 2001-2002.

REFERENCES

[1] Srico's Photrodes™ for Electrophysiological Monitoring received a 2002 R&D-100 Award given by *Research & Development Magazine* for the top 100 innovations of the year.

[2] E. Wooten, K. Kissa, A. Yi-Yan, E. Murphy, D. Lafaw, P. Hallemeier, D. Maack, D. Attanasio, D. Fritz, G. McBrien, and D. Bossi, "A review of lithium niobate modulators for fiber-optic communication systems," *J. of Selected Topics in Quantum Electronics*, **vol. 6**, pp. 69-82, 2000.

[3] J. Webster, *Medical Instrumentation,* 3rd ed., pg. 262, John Wiley & Sons, Inc., New York, 1998.

[4] J. Webster, *Medical Instrumentation,* 3rd ed., pg. 169, John Wiley & Sons, Inc., New York, 1998.

[5] J. Webster, *Medical Instrumentation,* 3rd ed., pg. 198, John Wiley & Sons, Inc., New York, 1998.

[6] J. Webster, *Medical Instrumentation,* 3rd ed., pg. 195, John Wiley & Sons, Inc., New York, 1998.

[7] G. Belenky, D. M. Penetar, D. Thorne, K. Popp, J. Leu, M. Thomas, H. Sing, T. Balkin, N. Wesensten, and D. Redmond, "The effects of sleep deprivation on performance during continuous combat operations," in *Marriott*, B.M. (Editor), Food Components to Enhance Performance, National Academy Press, Washington, DC, 1994.

[8] E. Schmitt, "After the War: Inquiry. Report Says Errors and Fatigue Led to Ambush of Convoy," *New York Times*, Late Edition – Final, Section A, Page 12, Column 3, July 10, 2003.

[9] T. A. Dinges, H. L. Hardee, and W. W. Wierwille, "Development of models for on-board detection of driver impairment," *Accident Analysis and Prevention,* **vol. 19**, pp. 271-283, 1987.