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ABSTRACT

Among all physiological functions, bioelectric activity may be considered one of the most important, since it is the backbone of many wearable technologies used for health condition diagnostic and monitoring. The existent bioelectric recording devices are difficult to integrate on wearable materials, mainly due to the number of electrical interconnections and components required at the sensing places. Photonic sensors have been presented in the medical field as a valuable alternative where features like crosstalk and attenuation, electromagnetic interference and integration constitute a challenge. Furthermore, photonic sensors have other advantages such as easy integration into a widespread of materials and structures, multiplexing capacity towards the design of sensing networks and long lifetime.

The aim of this work was to develop a multi-parameter bioelectric acquisition platform based on photonic technologies. The platform includes electro-optic (EO) and optoelectronic (OE) stages, as well as standard filtering and amplification. The core sensing technology is based on a Mach-Zehnder Interferometer (MZI) Modulator, which responds to the bioelectric signal by modulating the input light intensity. Only optical fibers are used as interconnections, and the subsequent signal conditioning and processing can be centralized in a common processing unit. The photonic and OE modules were designed to guarantee bioelectric signal detection using parameters compatible with existing technologies. Several considerations were made regarding noise-limiting factors, unstable operation and sensitivity. The EO modulator of choice was a Lithium Niobate ($LiNbO_3$) MZI modulator. The EO modulator was selected given its versatile geometry and potential to perform differential measurements and easiness to convert the resultant optical modulated signal into electrical values.

The OE conversion module developed includes a transimpedance amplifier (TIA), a notch and bandpass filter. In order to prevent a phenomenon called gain-peaking, the TIA was properly compensated, to insure a stable TIA operation and simultaneously avoid output signal oscillation. The performance of the TIA circuit was improved considering DC currents of 1.3 mA, which resulted in an additional high-pass filtering block. This allowed for a transimpedance gain of $1x10^5$ V/A. The filtering stage was designed for removing unwanted signal artifacts, and included two bandpass filters (0.2 – 40 Hz; 5 - 500 Hz) and a notch filtered centered at 50 Hz and with 34 dB of attenuation.

The photonic platform prototype performance was evaluated, covering linearity, frequency response and sensitivity. Results have shown that the combination of the photonic and OE stages had a flat 60 dB frequency over the frequency range of 0.3 Hz to 1 kHz. With regard to system linearity, it was verified a linear relationship between the voltage input and output signal, with a gain of 60 dB. These results indicated a correct biasing of the MZI modulator. In order to study the minimum detected fields that can be achieved using the developed prototype, the filtering and amplification stages were also considered. The characterization was performed with an overall gain of 4000 V/V (72 dB) and the photonic platform showed sufficient sensitivity to detect signals as low as 20 μV.

To assess the bioelectric signal acquisition performance, the developed photonic platform was tested in a real scenario through the acquisition of different bioelectric signals – Electrocardiogram (ECG), Electroencephalogram (EEG) and electromyogram (EMG). The results were compared with signals obtained from standard platforms using the same conditions. The developed photonic platform demonstrated the capability of recording signals with relevant and clinical content, providing enough sensitivity, frequency response and artifact removal. The photonic platform showed good results in various clinical scenarios, such as the evaluation of normal heart and muscle functions, as well as monitoring the consciousness state of patients.

As a final conclusion, a photonic platform for bioelectric signal acquisition was developed and tested; its application in wearable health systems was demonstrated.

RESUMO

De todas as funções fisiológicas, a actividade bioeléctrica é considerada uma das mais importantes, uma vez que representa a base para muitos sistemas vestíveis, utilizados para monitorização e diagnóstico no sector médico. Os dispositivos existentes - baseados em aquisição electronica - apresentam algumas desvantagens essencialmente relacionadas com a dificuldade de integração em materiais vestíveis, a quantidade de interligações e os componentes necessários nos locais de medição. Os sensores fotónicos têm vindo a ser cada vez mais utilizados no sector médico, uma vez que conseguem ultrapassar as desvantagens de atenuação e interferência electromagnética. Para além disso, este tipo de sensores apresenta uma fácil integração em diversos materiais, durabilidade e capacidade de multiplexagem, especialmente concebidas para redes de sensores.

O principal objectivo da presente tese foi desenvolver uma plataforma de aquisição de biopotenciais baseada em sensores fotónicos. A plataforma inclui um bloco responsável por efectuar a conversão electro-óptica (EO) do biopotencial medido, assim como a optoelectrónica (OE) necessária para transformar o sinal óptico para o domínio electrico.

A tecnologia que está na base do mecanismo de transdução desta plataforma consiste em moduladores Mach-Zehnder (MZI), cujo princípio é modular a intensidade da luz em resposta a um sinal electrico. As interconexões e transdução são efectuadas apenas por fibra óptica, sendo que o processamento e acondicionamento do sinal pode ser centralizado numa unidade de processamento transversal a todos os sinais.

Os módulos correspondentes aos blocos EO e OE foram desenvolvidos de forma a garantir a detecção do biopotencial utilizando características compatíveis com a tecnologia disponível. Foram efectuadas várias considerações relativamente aos factores que limitam o funcionamento adequado da plataforma fotónica, mais especificamente no que diz respeito a níveis de ruído, instabilidade e resolução. O modulador EO seleccionado foi um MZI de niobato de litio ($LiNbO_3$). A escolha deste modulador teve como principal motivo a possibilidade de efectuar medições diferenciais, geometria versátil e a facilidade de converter o sinal óptico resultante para o domínio eléctrico.

Os módulos de conversão OE desenvolvidos incluem um amplificador de transimpedância (TIA) e filtros passa-banda e notch. Para assegurar o funcionamento estável do TIA e evitar um fenóneno designado por *gain-peaking* (ganho de pico), foi necessário compensar devidamente o circuito. A performance do TIA desenvolvido foi optimizada para currentes DC na ordem dos 1.3 mA, resultando na adição de um filtro passa-alto de forma a atingir ganhos de transimpedância de $1\text{x}10^5$ V/A. Os blocos de filtragem para remover as componentes de interferencia indesejados incluiram dois filtros passa-banda (0.2 – 40 Hz; 5 – 500 Hz) e um filtro notch centrado nos 50 Hz filtered e com um factor de atenuação de 34 dB.

O protótipo da plataforma fotónica, mais especificamente o modulo EO e OE (saída do TIA) foi submetido a diferentes testes com o principal objectivo de caracterizar o desempenho do sistema ao nível da resposta em frequência, linearidade e resolução. Os resultados obtidos demonstratam uma resposta em frequência com um agama dos 0.3 Hz aos 1 kHz com um ganho de 60 dB. Relativamente à linearidade, foi demonstrado que a relação entre o sinal de entrada (biopotencial) e o sinal à saída do TIA apresentam uma relação linear. Os testes realizados para confirmar o mínimo sinal detectado pela plataforma fotónica desenvolvida foram efectuados incluindo os estágios de filtragem e amplificação, resultando num ganho global de 4000 V/V. O sinal minimo detectável foi de 20 μV, a uma frequência de 10 Hz.

Por último, a plataforma desenvolvida foi testada em cenários reais na aquisição de diferentes biopotenciais – Electrocardiograma (ECG), Electroencefalograma (EEG) e Electromiograma (EMG). Os resultados obtidos foram comparados com plataformas convencionais nas mesmas condições. A plataforma fotónica apresentou boa capacidade para adquirir biopotenciais com conteúdo clinico relevante, assegurando a sensibilidade, resposta em frequência e remoção de artefactos desejável.

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LIST OF SYMBOLS

Symbol	**Description**	**Unit**
A	Area of electrodes	m^2
A_{diff}	Differential gain	-
BW	Bandwidth	Hz
C	Cardiac equivalent vector	-
c	Speed of light	m/s
C_c	Virtual capacitor	F
$\mathrm{C_C}$	Compensation capacitor	F
$\mathrm{C_{cm}}$	Opamp common mode capacitance	F
$\mathrm{C_{diff}}$	Opamp differential capacitance	F
$\mathrm{C_{DL}}$	Double-layer capacitance	F
$\mathrm{C_{eo}}$	Electro-optic modulator capacitance	F
$\mathrm{C_{ep}}$	Epidermis capacitance	F
$\mathrm{C_f}$	Transimpedance amplifier feedback capacitor	F
C_i	Transimpedance amplifier input capacitance	F
$\mathrm{C_j}$	Photodiode junction capacitance	F
CNR	Carrier-to-noise Ratio	dB
CP	Carrier power	W
d	Electro-optic modulator electrode spacing	m
d_{eo}	Electro-optic crystal waveguide spacing	m
E	Electric-field	V/m
$\mathrm{E_{hc}}$	Half-cell potential	V
f_c	Frequency of light	Hz
(f_{GBW}):	Opamp gain-bandwidth product	Hz
f_n	Filter natural frequency	Hz
f_{notch}	Notch frequency	Hz
$\mathrm{f_p}$	High-frequency pole	Hz
G_{ph}	Photodiode gain	Hz
G_{TIA}	Transimpedance amplifier gain	V/A
h	Planck's constant	$J.s$
i_{bias}	Input bias current	A
$\mathrm{i_D}$	Photodiode current source	A
i_{dark}	Photodiode dark current	A

IL	Insertion loss	dB
$i_{leakage}$	Photodiode leakage current	A
(i_{ph})	Photodiode output current	A
L	Electro-optic modulator electrode length	m
l	Electro-optic crystal waveguide length	m
L_{AB}	Lead between point A and B	m
V_{AB}	Potential difference between point A and B	V
v_{BIO}	Electrical potential of bioelectric signal	V
n	Refractive index of an electro-optic medium	-
n_e	Refractive index of the extraordinary ray of light	-
NEP	Noise equivalent power	$V / Hz^{1/2}$
NF_{ph}	Noise figure associated with the photodetector	dB
NF_{TIA} is the	Effective noise figure of the transimpedance amplifier	dB
n_0	Refractive index of the ordinary ray of light	-
q	electron charge	C
P_{in}	Input power of light	W
P_{out}	Modulated output power	-
R	Responsivity	A/W
R_C	Compensation resistor	Ω
R_{CT}	Double-layer resistance	Ω
R_{ep}	Epidermis resistance	Ω
R_f	Transimpedance amplifier feedback resistor	Ω
r_k	Kerr coefficient	m/V
RIN	Relative intensity noise	Hz^{-1}
r_p	Pockels coefficient	m/V
R_{sh}	Photodiode shunt resistance	Ω
R_{TIAeq}	Effective resistance load of the photodetector	Ω
R_s	Resistance associated with electrolyte	Ω
R_{ut}	Resistance associated with underlying tissue	Ω
s_{MZI}	modulation efficiency	W/V
T	Temperature	K
T_f	Transmission factor	-
v_{bias}	Bias voltage	V
V_{cm}	Common-mode potential	V
v_{in}	Input modulating voltage	V
V_{it}	Elecro-optic modulator total input voltage	V
$v_{maxtrans}$	Bias voltage at maximum transmission	V

V_{min}	Minimum detected voltage	V
$v_{mintrans}$	Bias voltage at minimum transmission	V
v_{out}	Transimpedance amplifier output voltage	V
v_{th}	Thermal voltage	V
v_{+}	Noninverting electrical potential at the input of the amplifier	V
v_{-}	Inverting electrical potential at the input of the amplifier	V
v_{π}	Half-wave voltage	V
w	Electro-optic crystal width	m
Z_t	Total impedance	Ω
Z_{in}	Input impedance	Ω
$\Delta\phi$	Phase variation	rad
ε_o	Medium permittivity	-
ε_r	Relative static permittivity	-
η	Quantum efficiency	-
λ	Wavelength	m
ϕ	Phase shift	rad
ω_H	High–pass cut-off frequency	rad/s
ω_L	Low–pass cut-off frequency	rad/s

LIST OF TERMS

Term	**Designation**
Ag	Silver
ASE	Amplified spontaneous emission
AV	Atrioventricular node
BCI	Brain-computer interface
CdTe	Cadmium telluride
Cl	Chloride
CMMR	Common-mode rejection ratio
CMOS	Complementary metal-oxide-semiconductor
CW	Continuous wave
EAP	Electroactive polymer
ECG	Electrocardiogram
ECoG	Electrocortigram
EEG	Electroencephalograms
EMG	Electromyogram
EO	Electro-optic
EOG	Electroocculogram
ENG	Electroneurogram
ERG	Electroretinogram
GTWM	Georgia Tech Wearable Motherboard
IC	Integrated circuit
InGaAs	Indium gallium arsenide
KD*P	Potassium dideuterium phosphate
LA	Left arm
LL	Left leg
LED	Light-emitting devices
$LiNbO_3$	Lithium niobate
$LiTaO_3$	Lithium tantalite
MM	Multimode

MRI	Magnetic resonance imaging
MZI	Mach-Zehnder interferometer
MU	Motor units
OE	Optoelectronic
OSA	Optical spectrum analyzer
PCB	Printed circuit board
PC-CLD-1	Polycarbonate with CDL-1 chromophore
PDA	Personal digital assistant
PIC	Photonic integrated circuit
PM	Polarization maintaining
PMMA-CDL1	Poly(methylmethacrylate) with CDL-1 chromophore
PVDF	Polyvinylidene fluoride
RA	Right arm
RF	Radiofrequency
SA	Sinoatrial node
Si	Silicium
SLED	Superluminescent light-emitting diode
SM	Single mode
SNR	Signal-to-noise ratio
TF	Transfer function
TIA	Transimpedance amplifier
UV	Ultraviolet
WHO	World Health Organization
ZnTe	Zinc telluride