Chapter 6

Conclusions and Future Work

The current chapter addresses the final conclusions regarding the developed work as well as suggestion and recommendation for future work. The main goal of this thesis was to develop a more advantageous system for bioelectric signal acquisition regarding wearable devices. The property of being wearable imposes for more flexible devices that are able to deliver comparable performances on bioelectric signal acquisition, regarding existent electrical acquisition systems. Photonic technologies have the required characteristics, although the use of signals with low–frequency and low–amplitude content still entails challenging demands. Figure 6.1 shows the milestones proposed in the present thesis towards the development of a photonic platform for bioelectric signal acquisition.

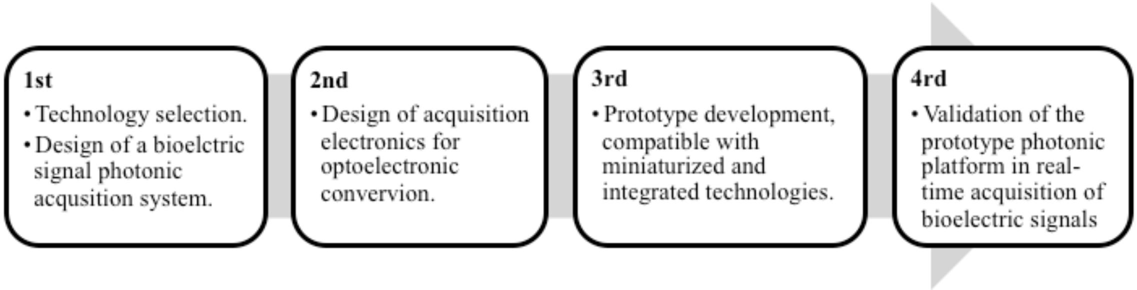

Figure 6.1. Thesis milestones towards the development of a photonic platform for bioelectric acquisition.

The resultant prototype is characterized by the possibility of miniaturization, compatibility with technology for integration into wearable materials and structure sensitivity to electric fields and in particular to bioelectric signals.

6.1 Photonic Platform Design

In the past few years, photonic technologies have become more popular in healthcare applications [1, 2]. Crosstalk and attenuation are the bottleneck of standard acquisition systems and photonic systems make possible to overcome these limitations. Other advantages are the easiness of integration into a widespread of materials and structures, multiplexing capacity towards the design of sensing networks and long lifetime (longer than 25 years).

The sensing solution investigated in this thesis is based on electro-optic (EO) methods that modulate light in response to an electric field. The designed sensor allows for multiple bioelectric signals to be extracted and recorded from several locations. The front-end acquisition is only composed by optical fibers as interconnections.

6.1.1 EO conversion module

Among the existent light modulation techniques, the intensity modulation was selected since it allows for differential measurements. The designed photonic stage combines an optical signal source, a Lithium Niobate ($LiNbO_3$) Mach-Zehnder Interferometer (MZI) modulator and a detection module, comprising a photoreceiver.

The optical power used in the developed prototype was provided by a broadband light source with a total optical input of 12 mW for the center wavelength of 1545 nm. The MZI input optical power should be stable regarding amplitude, since the interferometry measurements are based on intensity modulation. It was verified that the amplitude and frequency fluctuations of the broadband light source used in this prototype only produced TIA output voltage variations of 0.35% per volt. This result indicates that the optical source is still adequate for the type of measurements performed. However, it would be preferable to use a continuous wave (CW) light source, which has a constant optical amplitude and frequency.

The selection of the $LiNbO_3$ MZI modulator was made based on the possibility of performing differential measurements. This type of modulator also allows for a versatile geometry and multi-sensing structure, and the resultant optical modulated signal is easier to convert into an electrical value, when compared with the overall EO modulation solutions. Dual drive configuration is preferred over single-drive configuration. In fact, the modulation efficiency was 1.7 times better if using the dual-drive configuration. The performance of the MZI modulator was above the requirements for the measurements performed, although a smaller half-wave voltage (v_π) is recommended. In this way, the slope efficiency of the MZI modulator would be maximized, allowing for the detection of voltages with smaller amplitudes and, consequently, smaller bioelectric signals

The photoreceiver selected was a fiber-coupled PIN photodiode that enables the convertion of the optical modulated signal into an electrical current. The main drawback of the photodetection stage is the inherent noises of the device and the minimum detectable optical power that is represented by the Noise Equivalent Power (NEP). In terms of conversion efficiency, the photodiode used showed good performances allowing for a factor of 0.906 A/W.

Table 3.6 shows an overview of the photonic stage main parameters, including typical and recommended values for each of the components properties.

6.1.2 OE Conversion Module

The designed OE conversion module includes a transimpedance amplifier (TIA), a notch and bandpass filter. Bioelectric signal processing is one of the most important stages of a bioelectric sensor since it highlights the signal of interest, while preserving its content and integrity.

As expected, the main challenge was focused on designing high-sensitivity and stable TIA for the frequency components of interest. TIA needs to be properly compensated in order to avoid a phenomenon called gain-peaking, that ultimately results in unstable TIA operation and oscillation of the output signal. The design considerations (Table 4.1) to be taken into account during TIA circuit dimensioning were carefully followed. The resultant circuit was optimized considering DC currents of 1.3 mA, which imposed for an additional high-pass filtering block in order to reach the desired transimpedance gains of 10^5 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 attenuation factor of 34 dB.

6.1.3 Photonic Platform Performance and Validation

The main performance-driven parameters in the photonic stage are the frequency and amplitude stability of the light source, the MZI half-wave voltage and the photodetection efficiency. Regarding the OE conversion stage, the transimpedance gain and bandwidth, as well as stable operation are the main drivers for improving system performance. It should be noted that trade-offs between these performance-driven parameters must be established prior to the fabrication of photonic platform prototypes. In particular, levels of optical input and the photodetection amplification must be carefully adjusted in order to avoid saturation and output oscillation. Since the use of strong optical input powers involve high DC levels, it is imperative to reduce the DC transimpedance gain as much as possible without compromising the gain of the modulated signal.

The developed photonic platform was tested in terms of linearity, frequency response and sensitivity. Furthermore, after proper characterization, bioelectric signal acquisition was performed and the results obtained were compared with standard acquisition systems. Tests performed in the laboratorial environmental and using the prototype developed showed that the combination of the photonic stage with the TIA had a flat 60 dB response over the frequency range of 0.3 Hz to 1 kHz. The low cut-off frequency is adequate for detection of lower frequency signals, such as some components in the Electrocardiogram (ECG) and Electroencephalogram (EEG).

In respect to system linearity, this figure of merit represents the relationship between the modulating voltage, i.e., bioelectric signal, and the output voltage (at the TIA), and can be considered as the overall transfer function of the photonic stage (equation 3.17). It was demonstrated that there is a linear relationship between input and output with a gain of 60 dB, using the dual-drive configuration. This linearity suggests a correct biasing of the MZI modulator, being possible to perform OE conversion with trustful results.

In order to study the minimum detected fields that can be achieved using the developed prototype, the filtering and amplification stages were considered. The characterization was performed with an overall gain of 4000 V/V (72 dB) and the photonic platform showed sufficient resolution to detect signals as low as 20 μV. The major concern is for signal distortion, which occurs for sub-100 μV input signals. This may be related to the optical power source inherent fluctuations as well as to the photodetection limits. The signal-to-noise (SNR) needs to be improved in order to ensure signal integrity. The filtering stages are effective in removing power lines interferences and its harmonics, as well as other bioelectric signal artifacts, while maintaining signal integrity.

After characterizing the photonic platform, validation of the system in terms of bioelectric acquisition was achieved, using human subjects with normal bioelectric activity. Different bioelectric signals were acquired – ECG, EEG and electromyogram (EMG) – and compared with signals obtained from standard platforms. It was demonstrated that the developed photonic prototype is capable of recording signals with relevant and clinical content, providing enough sensitivities, frequency response and artifact removal. Although EEG recordings were more difficult to compare with the signals obtained with standard acquisition, the spectral components of each recording were analyzed and found to be similar. As a final conclusion on this subject, the photonic platform showed good results in possible clinical scenarios, such as the evaluation of normal heart and muscle functions, as well as monitoring the consciousness state of patients.

In general, the photonic platform resulted in a multi-parameter sensing structure mainly characterized by a linear response over the frequency range of interest. Furthermore, it became evident its potential by providing similar performances of standard bioelectric signal acquisition systems. The findings presented in this thesis show an important progress towards the design of wearable photonic systems for bioelectric signal acquisition.

6.2 Applications

A promising application of the developed photonic platform is towards wearable monitoring solutions for muscle, heart and brain functions. The aforementioned described platform can give origin to a material composed of different layers with photonic embedded components, as shown in Figure 6.3. In fact, current integration technologies allow to integrate most of the used optical components in the photonic platform herein described [3]. The smart material can comprise a substrate in which the optical components such as optical source, EO modulators and photodetectors are deposit. A sandwich structure can be designed towards different geometries and sizes. The main goal of the photonic smart material would be for monitoring and control of important physical parameters in relevant fields such as medicine, aeronautics, automative industry, military and defense sectors, among others.

Figure 6.2 shows a prospective solution of a smart material based on the photonic platform developed.

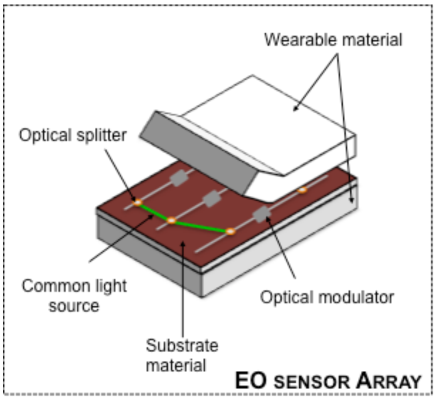

Figure 6.2 Smart material based on photonic platform technology developed in this thesis. Optical components can be embedded in a substrate material.

Regarding medical applications, the smart material can be assembled in order to give origin to different wearable monitoring solutions such as:

- Braincaps for EEG monitoring, that can be used both for long-term monitoring of brain-related diseases or in Brain-Computer Interface (BCI) applications.
- T-shirts or vests for ECG and EMG monitoring, with a variety of applications ranging from organ-related diseases monitoring to high-competitionathlete monitoring.
- Trousers or knee bands for EMG monitoring, which are recommended for situations like rehabilitation procedures (e.g., assessment of muscle force and contraction in within a rehabilitation context).

Figure 6.3 shows the full concept of the application of the photonic platform for wearable bioelectric signal monitoring.

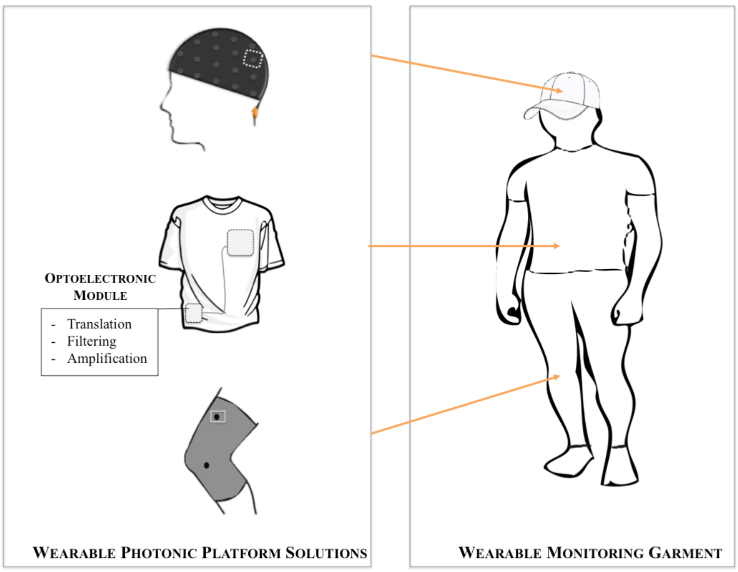

Figure 6.3 Schematic representation of the prospective integration of the photonic platform in a wearable monitoring garment. Three different solutions can be obtained with the photonic platform for monitoring EEG, ECG and EMG.

The wearable monitoring garment is able to sense the required bioelectric signals, using optical components and interconnections, and routing it to a central processing unit that may be placed at a convenient recording location. The processing unit, which includes the optoelectronic system (optical signal translation, filtering and amplification), can be used as a plug-in module, attached to the garment. In this way, the electronics can be left out of the garment and, therefore, more flexibility is given in terms of application, particularly for Magnetic Resonance Imaging (MRI) or laser therapy rooms.

Such photonic wearable monitoring solution presents a few advantages facing the conventional systems: no need for local electrical power supply and electrical components on the wearable garment itself, immunity to electromagnetic interference and easy integration into wearable materials.

6.3 Future Work

The development of the photonic platform has left some open issues for discussion, particularly regarding system miniaturization and integration into wearable materials.

6.3.1 Photonic System Clinical Validation

In order to validate the system for further application in wearable applications with clinical meaning, the tests performed with prototyped photonic platform should be extended to more subjects and in conditions similar to daily life routines. For instance, the system may be tested using several patients with different cardiac or brain diseases in order to assess the viability of the system to detect organ-related malfunctions. Also, in order to evaluate the performance of the photonic platform during daily life routines, tests can be performed during exercise, sleeping and house and work-related routines.

6.3.2 Miniaturization and Integration

After the photonic platform performance validation for bioelectric signals recording, the large scale deployment of such device would benefit if a more customizable system, featuring small-size, low-power consumption and more flexible structure solution. All this must be ensured while preserving system resolution and performance. Nevertheless, using other technologies may compromise the quality of the measurements performed, particularly in what concerns to EO material characteristics and photodetection stage. Merging electronics with photonics would allow to design integrated dual functional device, i.e., able to perform EO and OE conversion. Figure 6.4 shows the concept of integrating both technologies in a single structure, as well as the main limitations and subject of future work.

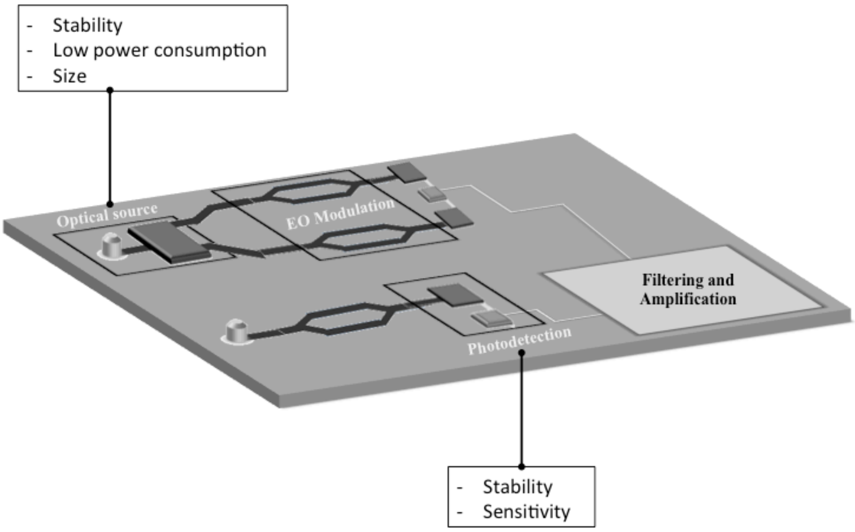

Figure 6.4 EO and OE functions merged into a single integrated device. Main limiting factors are optical signal generation and photodetection.

The photonic system's main performance bottlenecks are the optical signal generation and photodetection, as indicated in Figure 6.4. Since interferometry measurements are based on light intensity modulation, a highly stable power source must be used; for example, CW light sources. Furthermore, to be a competitive solution in existent wearable electronic technologies, photonic systems demand low power consumption. This is still a challenge that optical power sources pose, because the available solutions are either unstable or too power consuming.

To overcome this problems regarding optical signal generation, two different strategies could be followed as future work:

1) In a first approach, the optical signal source can be set to lower limits of input optical powers, although still over the threshold limits for proper operation. The CW operation, i.e., the stability of the source may have to be compromised according to the existent state of the art regarding light sources. An examples of such light source can be found in [4], which presents a CW light of 2 mW output power with a supply of 120mA. In [5], where a 1.5 μm light source with an optical output power of 1.6 mW and electrical consumptions of 4.8 mW.

2) Using Raman silicon lasers based on ring resonators that allows light amplification and stabilization such as the ones presented in [6]. Furthermore, broadband unstable source such as a Superluminescent LED (SLED) into a CW light source. The work developed by Rong et al. [6], shows a Raman silicon laser with µm dimensions, and showing an output power o 10 mW if using a pump power of 120 mW, with no biasing required. Therefore, the major contributor for power consumption would be the SLED used as an optical power pump. Although more components would be introduced to the overall system, a more stable operation would be guaranteed.

In respect to photodetection, future work should be focused in developing more stable circuits, since the main challenge is to warranty high-sensitivity and to avoid output oscillation. The problems are mainly related with the high-level DC currents introduced by the optical power source that ultimately leads to circuit saturation. Other circuits topologies may be studied in order to further reduce the DC component, while guaranteeing a good SNR and a stable OE conversion.

Although minimizing the half-wave voltage of the MZI may lead to more compact devices, the packaging of the device still imposes major challenges. Therefore, the desired is to include the components in the same package not only to reduce costs, but also to obtain more efficient interconnection between EO and OE stages. Therefore, a future recommendation would be to integrate the laser with the MZI modulator, saving space and costs in respect to the discrete approach. An attractive solution is to implement a Photonic Integrated Circuit (PIC), which is conceptually very similar to electronic IC, although the components integrated are lasers, modulators, photoreceivers, couplers, optical amplifiers [7]. $LiNbO_3$ isn't a suitable material for PICs since it offers little practical promise as a material platform for integration since it's a rigid substrate and it cannot be used to practically implement active OE components like detectors. Furthermore, $LiNbO_3$ often requires complex processing technologies that turn them economically and practically unsuitable. Thus, a suitable substrate for PIC is silicon that may be compatible with CMOS technologies. Silicon photonics have begin to rival traditional optical-communication photonics based on EO crystal and III-V semiconductor materials [8]. This opens the possibility of chip photonics built using standard CMOS processes [9]. Thus, the next step would be to implement a PIC based on silicon technology, comprising the necessary EO and OE components. Nevertheless, a careful study must be performed in order to assess the overall sensitivity of silicon-based devices over traditional $LiNbO_3$ ones. If possible, the fabrication of monolithic PICs is preferred over hybrid strategies, since a common substrate is used and thereby the photonic couplings occur and are consolidated into a single device[7].

The miniaturization is strongly related with the system integration and flexibility, since the use of smaller and integrated EO and OE components allows for more versatile solutions. A possible solution for improving system integration is to all-fiber MZIs, although the main challenge would be to guarantee a low half-wave voltage in order to detect low-amplitude signals as ECG, EEG or EMG. However, current fabricated all-fiber MZIs have half-wave voltages of a few V such as the one proposed by Xueying Wang et al., where an all-fiber MZI modulator with a length of 42.6 μm and drive voltage of 1.25 V was presented [10].The advantage of this solution is the design of more flexible devices with a higher sensor network density. Consequently, the integration of such structures in wearable materials would be facilitated, as well as the sensor location.

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