Chapter 3

Photonic Bioelectric Signal Sensor

This chapter addresses the whole photonic bioelectric signal sensor modeling and design, including optical and electrical component selection. The ultimate goal is to design a photonic platform that will perform electro-optic (EO) conversion of the bioelectric signal into an optical modulated signal. The EO stage herein described comprises the optical signal generation, EO modulation and photodetection.

3.1 Photonic Sensor Theory

In this section, the theory behind the EO effect will be described as well as the type of devices that exhibit this phenomena. The bioelectric signal is responsible to perform light modulation. Different devices can be use to perform EO sensing from which the most relevant
in this thesis is the Mach-Zehnder Interferometer (MZI) modulator. This device allows to perform differential measurements.

### 3.1.1 Linear Electro-Optic Effect

Certain materials exhibit a phenomenon called birefringence, where the orthogonal components of light polarization travel at different velocities. Therefore, for each of the two different perpendicular states of polarization, the light will travel in a different direction. This birefringence can be induced by an external electric field, giving origin to the EO effect [1], [2]. Through this effect, a time-varying applied electric field, i.e. the bioelectric signal, causes the time-dependency of refractive index of an EO substrate, by which light passes. The proportionality between the amount of change in refractive index (\( n \)) and the electric field strength (\( E \)) is described by [2], [3]:

\[
n(E) = n_0 - \frac{1}{2} r_p n E - \frac{1}{2} r_k n E^2
\]  \(3.1\)

where the coefficients \( r_p \) and \( r_k \) are called the linear (Pockels) EO and second order (Kerr) EO coefficients, which values depend on the direction of the applied electric field and the polarization of the light [1]. Equation 3.1 can be simplified considering only the linear EO effect, by eliminating the quadratic component.

Only noncentrosymetric crystals exhibit the Pockels effect since the difference between applying an electric field in reverse signal should not produce the same effect on the new \( n \). All materials display the Kerr effect, with varying magnitudes, but it is generally much weaker than the Pockels effect. These effects do not appear simultaneously, instead one of them becomes dominant [3].

### 3.1.2 Light Modulation Principle

The induced phase variation (\( \Delta \phi \)) of input light due to an external electric field can be expressed as [3, 4]:

\[
\Delta \phi(t) = \frac{\pi}{\lambda} n^3 r_p v_{in}(t)
\]  \(3.2\)

where \( \lambda \) is the wavelength of the input polarized light. The voltage needed to produce a phase shift of \( \pi \) is called half-wave voltage (\( v_{h} \)) and it influences the modulation depth. In fact, as
lower this parameter is, less voltage is required to produce a detectable change in light intensity. The $v_\pi$ is defined as:

$$v_\pi = \frac{\lambda d}{n^2 r_p L}$$

(3.3)

where $d$ is the electrode spacing and $L$ the electrode length. Therefore, $v_\pi$ is the standard measure of sensitivity of an EO modulator. Substituting equation (3.3) into (3.2) results in a simplification of $\Delta \phi$ produced by the modulation:

$$\Delta \phi(t) = \frac{\pi}{2v_\pi} v_{in}(t)$$

(3.4)

Phase variations can be manifested as intensity modulation if incorporating an interferometry design, which facilitates the conversion of the modulated optical signal into an electrical signal [3, 4]. The modulated power of the detected beam is described as:

$$P_{out} = \frac{P_{in} L}{2} \left(1 - \cos\left(\frac{\pi}{2v_\pi} v_{in}(t)\right)\right)$$

(3.5)

where $P_{in}$ is the input power of light and IL is the insertion loss of the EO modulator. The latter property is the result of the light loss within the modulator. The main contributors for IL are the fiber-crystal interface and propagation loss throughout the waveguides [4, 5].

### 3.1.3 EO Materials and Modulators

Materials that respond to an external electric field, with a change of the inherent $n$ are called EO materials. These include glasses, crystals, semiconductor and polymers. Most used materials for photonic devices are shown in Table 3.1 [3, 5–7].

The choice of the EO material depends on the final application and the required characteristics, since each one has advantages and disadvantages. Nevertheless, the most used material for photonic applications is the ferroelectric crystal Lithium Niobate (LiNbO$_3$) [4, 8]. These crystals have high EO coefficient and low optical loss as well as thermal, chemical and mechanical stability. In addition, waveguide fabrication and miniaturization techniques of EO modulators using this material have been widely explored [5, 8]. Although semiconductor EO materials are more compact and compatible with the majority of integrated devices, the linear EO effect shows weaker values when compared with LiNbO$_3$ [4].
Table 3.1 EO materials and main properties [3, 5–7].

<table>
<thead>
<tr>
<th>Material</th>
<th>Type of Material</th>
<th>Refractive index</th>
<th>EO coefficient (Pockels) (x10^{-12} m/V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>Glass</td>
<td>n_o = 1.544</td>
<td>r_{41} = 0.2</td>
</tr>
<tr>
<td>LiNbO_3</td>
<td>Crystal/Ferroelectric</td>
<td>n_o = 2.297</td>
<td>r_{33} = 30.8</td>
</tr>
<tr>
<td>Potassium Dideuterium Phosphate (KD*P)</td>
<td>Crystal/ Ferroelectric</td>
<td>n_o = 1.5079</td>
<td>r_{63} = 26.8</td>
</tr>
<tr>
<td>Zinc Telluride (ZnTe)</td>
<td>Semiconductor</td>
<td>n_o = 2.99</td>
<td>r_{41} = 4.04</td>
</tr>
<tr>
<td>Cadmium Telluride (CdTe)</td>
<td>Semiconductor</td>
<td>n_o = 2.84</td>
<td>r_{41} = 6.8</td>
</tr>
<tr>
<td>Polycarbonate with CDL-1 chromophore (PC-CLD-1)</td>
<td>Polymer</td>
<td>n_o = 1.8</td>
<td>r_{33} = 70</td>
</tr>
<tr>
<td>Poly(methylmethacrylate) with CDL-1 chromophore (PMMA-CDL1)</td>
<td>Polymer</td>
<td>n_o = 5</td>
<td>r_{33} = 60</td>
</tr>
</tbody>
</table>

Regardless of the type of material/component used, as long as they modulate light, any of them can be considered an EO modulator. Nevertheless, the most common EO modulators nowadays are based on waveguide technologies (e.g., MZI Modulator) [5, 8]. In fact, using waveguide modulators allows to achieve lower v_π, which results in higher modulation efficiencies, when compared with bulk crystals.

In general, EO modulators can be divided into two categories according to the relation between light path and the measured field direction (Figure 3.1). Longitudinal modulators are those that apply the electric field along the propagation direction of light (Figure 3.1a). In this case, (3.3) can be re-written into [2, 3]:

\[
v_{\pi} = \frac{\lambda}{2n^3r_p} \tag{3.6}
\]

On the other hand, when the signal is applied in the perpendicular direction to the light propagation, the EO modulator is called transversal (Figure 3.1b). The v_π of this type of modulators is defined as in (3.3). In LiNbO_3 crystals, the strongest interaction occurs between the electric field applied in the z-direction and z-polarized light, i.e., with the electric field applied transversely to the z-cut surface of the crystal [3, 5].
Although EO conversion can be performed in free-space, considering a wearable application, the modulation geometry or scheme applied should be based on waveguide technologies and optical fiber connections.

### 3.1.5 Mach-Zehnder Interferometer

A MZI operates first by equally splitting an optical wave into two waveguide branches that will interact with a z-polarized electric field, inducing changes in the $n$ of the substrate material ($\text{LiNbO}_3$). When combining both waveguide legs of the interferometer, which in this case is made by a Y-branch, an interference pattern is created resulting in intensity modulation [3, 4]. Figure 3.2a) depicts this phenomenon by which the MZI modulates light intensity through the influence of an electric field.

The intensity modulation has a linear relationship with the electric field applied, if setting the modulator operation point at the linear region, i.e. quadrature point. A bias voltage ($v_{\text{bias}}$) is usually applied to set the MZI modulator at this point, which is the steepest part of the response curve. This means that a small change in voltage produces the maximum variation in output signal [2, 9]. The modulating signal can be applied in two ways as shown in Figure 3.2b): single drive, where only one arm of the MZI modulator is driven by the signal; or dual drive, where both paths are phase modulated.
The mechanism behind step 3 in Figure 3.2b), relies on the recombin
ation of both phase differences that are described by equation (3.5). The net phase difference is calculated, and transformed into intensity modulation. The mechanism and figures of merit of the MZI modulator will be further discussed in the design section.

### 3.2 Photonic Acquisition System Architecture

The configuration of the EO sensor includes three main functional stages: optical signal generation; EO modulation and optical detection. Light is carried using optical fibers that are responsible to maintain and preserve the lightwave properties, such as polarization. Figure 3.3 depicts the configuration of the EO sensor proposed.

![Figure 3.3 Photonic sensor design for bioelectric signal acquisition.](image-url)
The proposed bioelectric signal monitoring device is based on EO acquisition technology by which an electric field is used to intensity modulate the optical signal. The photonic acquisition system includes:

- An optical signal source;
- An optical transducer to modulate the optical signal in response to a bioelectric signal;
- A detection module comprising a photodiode or an optical spectrum analyzer (OSA)

The present system has several advantages facing the conventional systems already mentioned in Chapter 2, such as: require no electronic components on the wearable garment, reducing integration complexity and allowing the use of such wearable device on specific environments like Magnetic Resonance Imaging (MRI) rooms. Also, wearable requirements such as producing an electrical output for further processing, customization and resistance to adverse conditions (e.g. regular cleaning processes), are assured.

### 3.3 Photonic Acquisition Stage

The design of the photonic acquisition stage involves a series of performance issues that are dependent on the components used. The performance factors consist in high modulation efficiency, adequate bandwidth, good linearity and sensitivity. The following sub-sections will discuss the design of each photonic acquisition stage component.

#### 3.3.1 Optical signal source

The first component of the photonic system is an optical signal generator, or a light source, responsible to provide with a signal to modulate. The development of semiconductor optical devices is valuable in this field, since it allows to design more efficient and compact light sources [4, 10].

An optical signal source is characterized by several properties, being the most relevant ones the wavelength, intensity (optical power) and stability. In order to ensure the absence of optical damage on EO crystals (e.g. LiNbO$_3$), the light wavelength used should be above 800 nm, at which the photorefractive effect is generally negligible (@optical powers <100 mW) [5, 11]. The typical wavelength range used in photonic systems is around 1300 to 1550 nm (C-band), which is in the limits that prevent damage. The total power
spectrum \( (P_{in}) \) should be maximized in order to increase modulation efficiency \( (s_{MZI}) \) and in consequence sensor sensitivity. However, the upper limit of 100 mW should be taken into account. Ideally, the light source should produce a continuous wave (CW) light beam, i.e. with a stable light intensity, since it allows for a more stable operation. This is due to the influence of wavelength in the \( v_\pi \) of the EO modulator as translated in (3.6).

### 3.3.2 MZI Modulator

In this work, EO modulators perform intensity modulation since it’s easier to process the resultant data and to convert it to an electrical value. In addition, following this approach, differential measurements are easily achieved through the use of interferometry mechanism, such as MZI modulators. Waveguide technology should be applied since it facilitates integration and allows to produce MZI modulators with lengths reaching the range of \( \mu \text{m} \) [8, 9, 11]. An example of such small MZI modulator can be found in the work developed by developed by Xueying Wang et al. (2010), where a modulator with a length of 42.6 \( \mu \text{m} \) and and \( v_\pi \) of 1.25 V was presented [12]. The main MZI figures of merit driving its performance in bioelectric signal acquisition are: electrode configuration, EO material, EO crystal orientation, \( v_\pi \), \( s_{MZI} \) and linearity.

Since bioelectric signals have magnitudes from 5 \( \mu \text{V} \) to 10 mV and are usually recorded using a differential setup, the dual-drive configuration is recommended. By doing this, the bioelectric signal can be applied to both waveguide legs producing a push-pull effect on the light. The electric fields are opposite in effect in each path, i.e. the light traveling in one of the path is retarded, undergoing a negative phase change. On the other waveguide leg, light is advanced i.e. undergoes a positive phase change. As a result, the \( s_{MZI} \) is multiplied by a factor of two. In addition, pus-pull configuration contributes to cancel the laser-intensity noise common to both beams, improving the signal-to-noise ratio (SNR).

From the different EO materials, the material of choice is the LiNbO\(_3\) due to its combination of high EO coefficient, low optical loss and compatibility with common integrated-circuit (IC) processing technology. The appropriate orientation is a z-cut crystal, i.e. transversal mode that involves placing the electrodes such that the waveguides are below them and the electric field applied is perpendicular to the z-cut surface (Figure 3.4). The design of these devices is simplified and a good thermal stability is ensured. MZI modulators that use this type of electrode configuration are called travelling-wave modulators.
Linear relationship between the intensity modulation and the bioelectric signal is obtained when the $v_{\text{bias}}$ is set in the linear operating region, i.e. quadrature region. In order to determine the linear region, the transfer function needs to be represented in a plot (Figure 3.5) as a function of total input voltage ($V_{\text{in}}$). The transfer function of the dual-drive MZI modulator takes into account the overall phase change produced in each waveguide leg, and can be defined as:

$$P_{\text{out}} = \frac{ILP_i}{2} \left[ 1 + \cos \left( \frac{\pi V_{\text{in}}}{V_{\pi}} \right) \right]$$  \hspace{1cm} (3.7)$$

where $V_{\text{in}}$ is the sum of $v_{\text{bias}}$ with the bioelectric signal $v_{\text{bio}}$. The modulation or slope efficiency (W/V) of the MZI corresponds to the change in the optical output power for a given change in input current, and is defined as [4]:

$$S_{\text{MZI}} = \left. \frac{dP_{\text{out}}}{dv_i} \right|_{v_{\text{bias}}=0} = \frac{\pi ILP_i}{2V_{\pi}} \sin \left( \frac{\pi v_{\text{bias}}}{V_{\pi}} \right)$$  \hspace{1cm} (3.8)$$

The MZI $S_{\text{MZI}}$ depends on the $v_{\text{bias}}$, and can be increased by using stronger optical light sources, as shown in (3.8). However, $P_{\text{in}}$ is limited by size and cost of power light sources, and the threshold damage of the MZI modulator. Equation (3.8) also indicates the need to reduce $v_{\pi}$, in order to increase $S_{\text{MZI}}$ and in turn the gain of the photonic stage. Ideally, no external $v_{\text{bias}}$ should be required, since it contributes to the simplicity of the photonic setup, eliminating the need for an extra DC power source or bias-specific circuit.
As shown in Figure 3.5, the transfer function is characterized by periodic behaviour, showing that it’s possible to extend the regions of linear operation to more than one option. The optimum \( v_{bias} \) should be set to half the difference between the maximum and minimum transmission point in order to maximize \( s_{MZI} \). Also, \( v_{bias} \) can be located at any odd multiple (N) of the difference between transmission points, as in:

\[
v_{bias} = N \frac{v_{maxtrans} - v_{mintrans}}{2} = N \frac{v_{π}}{2}
\]  
(3.9)

Therefore, in order to properly bias the MZI modulator, a valid \( v_{bias} \) can be selected from (3.9), and equation (3.7) and (3.8) can be linearized, yielding:

\[
P_{out} = \frac{ILP_{i}}{2} \left[ 1 \pm \frac{\pi V_{BIO}}{V_{π}} \right]
\]  
(3.10)

\[
s_{MZI} = \frac{\pi ILP_{i}}{2V_{π}}
\]  
(3.11)

These equations allow to translate the bioelectric signal into an optical modulated signal, at the output of the MZI. Estimations and calculations for adequate and threshold values will be further detailed in section 3.5.
3.3.3 Photoreceiver

The fiber optic receiver used in the photonic sensor should be based on optoelectronic (OE) components in order to perform the reverse of EO conversion. The most common OE receiver used in photonics is the photodiode that produces an electrical current \( (i_{ph}) \) in response to the incident modulated light \( (P_{out}) \). This current signal can be further converted into a voltage signal that represents the bioelectric signal detected at the surface of the body.

Photodiodes, devices that perform photodetection, are characterized by a factor called responsivity \( (R) \), which corresponds to conversion efficiency \( (A/W) \). DC responsivity represents the slope of the characteristic transfer function of the OE conversion and in this case can be defined as [2, 10, 13]:

\[
R = \frac{i_{ph}}{P_{out}} = \eta \frac{q}{h f_c}
\]

where \( \eta \) is the quantum efficiency, \( q \) is the electron charge, \( h \) is Planck’s constant and \( f_c \) is the frequency of light \( (f_c = c/\lambda) \). This factor is dependent on the wavelength of the light source. With the increase of wavelength, the optical power is carried by more photons resulting in higher number of electrons. Since photoelectric detectors are responsive to the photon flux rather than to the incident optical power, \( R \) increases with wavelength. The \( R \) should then be as high as possible. The best strategy to raise this value is to choose a light source with the highest wavelength as possible, and at the same time inside the allowable range of the MZI modulator. Likewise, the damage threshold of the photodiode should be taken into account.

Fiber optic technology includes two types of photodetectors: PIN diode and avalanche photodiode (APD). The most used photodetectors in photonics and for the wavelengths of interest are PIN-based detectors, due to is simple fabrication and reduced costs. PIN photodiodes can be fabricated with several substrate materials, being the most common ones based in silicium (Si) and indium gallium arsenide (InGaAs) [1, 2, 10]. The photodiode may be used in the photoconductive or in photovoltaic mode. The latter works without biasing the photodiode, becoming the most appropriate for the photonic stage herein described since it allows to design low-power consumption systems. In fact, in the photovoltaic mode there’s no biasing, which means that no power is consumed for the photodetection of the intensity modulated light.
3.3.4 Other Optical Components

Since the EO effect is polarization dependent, the polarization state of the input light supplied to the modulator, must be controlled and maintained through using polarization maintaining (PM) optical fibers. In addition, single mode (SM) fibers are preferred over multimode (MM), since they provide better transmission with less distortion and cross-talk between fibers [14]. To minimize back-reflections from the fiber to the LiNbO₃ interface and ensure long-term stability and reliability, an angle cut and polished tube must be used to connect the input and output fibers to the modulator.

The connection between optical fibers is made through optical couplers, which operate by dividing light into two or more fibers, with possibility of selecting different coupling ratios. Nevertheless, power losses occur during each coupling mechanism, since it’s difficult to ensure proper matching and alignment between each fiber core [5, 14].

3.4 Photonic System Modeling and Performance Analysis

3.4.1 Electrical Equivalent Circuit

The photonic system can be represented by an electrical equivalent circuit in order to establish a full model of the photonic platform herein presented. The equivalent circuit is depicted in Figure 3.6.

![Figure 3.6 Equivalent electrical circuit of the LiNbO₃ MZI modulator.](image)

Here, the electrical model of the MZI modulator is similar to a common instrumentation amplifier, where the input impedance is represented by a capacitance \( C_{eo} \). The main contributors for the capacitive nature of the MZI are the insulation of the MZI terminals and
the ferroelectric nature of the LiNbO₃. This capacitance is dependent on the dimensional characteristics of the LiNbO₃ crystal and is expressed by:

\[ C_{eo} = \varepsilon_0 \varepsilon_r \frac{2wl}{d_{eo}} \]  

(3.13)

where \( \varepsilon_0 \) is the permittivity of the vacuum, \( \varepsilon_r \) is the relative dielectric constant of the LiNbO₃, and \( w, l \) and \( d_{eo} \) are the width, length and distance of the crystal, respectively.

Considering our application, the capacitance should be as small as possible. In this way, the input impedance of the MZI modulator will be higher, and high quality differential measurements are more likely to be performed. To minimize \( C_{eo} \), as for any other application, the \( d_{eo} \) can be increased and \( w \) and the \( l \) decreased. This is actually a benefit for the present application, since it’s desired to minimize the size of the sensor for further use in wearable applications.

The conversion efficiency of the optical detector, which includes the transimpedance gain \( G_{TIA} \) and the \( R \) of the photodiode, as well as the coefficient for the \( IL \).

### 3.4.2 Photonic System Model

The electrical output value can be determined by a proportionality factor \( G_{TIA} \), regarding the output current of the photodiode:

\[ v_{out} = i_{ph} G_{TIA} = P_{out} R G_{TIA} \]  

(3.14)

Using equation (3.10) in (3.14), the full relationship between the modulation and the output electrical value can be determined as:

\[ v_{out} = \frac{G_{TIA} R P_{in} IL}{2} \cos^2 \left( \frac{\pi v_{BIO} (t)}{\nu} \right). \]  

(3.15)

Considering a MZI linear operation, i.e. setting \( v_{bias} = N \frac{\nu}{2} \), where \( n \) is an odd number, (3.15) can be simplified into:

\[ v_{out} = \frac{G_{TIA} R P_{in} IL}{2} \left( \frac{\pi v_{BIO} (t)}{\nu} \right). \]  

(3.16)
Taking into account the skin-interface impedance and the input impedance of the acquisition system as described in Chapter 2, a more complete transfer function of the overall photonic sensor can be derived:

\[
v_{out} = \frac{G_{TIA} R_{in}^{IL}}{2} \left( \frac{\pi v_{BIO}(t)}{v_{in}} \right) \left( \frac{z_{in}}{z_{in} + R_{sc} + j \omega C_{ep} R_{ep} + R_e} \right) \]

(3.17)

### 3.4.3 Limitation Factors

For the majority of EO applications, the noise currents in the photodetection stage determine the minimum electric field level that can be detected, i.e. the minimum optical power level. Thus, in order to maximize photodetection sensitivity (photodiode + TIA) it’s important to maintain a giving SNR. The SNR is defined as the simplest measure of the quality of reception and is represented as the ratio of the mean square of the power and the sum of the variances of the noise sources. The Carrier-to-noise Ratio (CNR) is the equivalent of the SNR of a modulated or Radiofrequency (RF) signal, and it can be represented by [14, 15]:

\[
CNR = \frac{\theta^2}{2} SNR = \frac{\text{carrier power}}{\text{source+photodiode+TIA}},
\]

(3.18)

where the carrier power (CP) represents the optical power developed at the photodiode. The denominator includes the noises from the source, photodiode and amplifier. The CP can be defined as:

\[
CP = \frac{1}{2} \left( \theta R G_{ph} P_{out} \right)^2
\]

(3.19)

where \( G_{ph} \) is the gain of the photodiode, which in the case of using PIN-based detectors has a unity value [14]. The main noise associated with the source is influenced by the laser relative intensity noise (RIN), which is associated with random spontaneous emissions that influence the laser intensity. The RIN is estimated by the following relationship [14], [16]:

\[
RIN = \frac{(\Delta P_{in})^2}{P_{in}},
\]

(3.20)
where the numerator is the mean square intensity fluctuations of the optical source and the
denominator corresponds to the average optical power generated. The overall source noise is
defined as:

$$\langle i^2_{\text{source}} \rangle = RIN (RP_{in})^2 BW,$$  \hfill (3.21)

where $BW$ is the bandwidth.

Regarding the photodiode-related noises, the most important effects result from the
statistical nature of the photon-to-electron conversion process, i.e. quantum or shot noise, as
well as the dark current ($i_{\text{dark}}$) noise. The overall photodetector noise that contributes to the
CNR can be described as [15]:

$$\langle i^2_{\text{phnoise}} \rangle = 2q (i_{\text{ph}} + i_{\text{dark}}) BW G_{\text{ph}} NF_{\text{ph}}$$  \hfill (3.22)

where $NF_{\text{ph}}$ is the noise figure associated with the photodetector, and for PIN diodes
$G_{\text{ph}} NF_{\text{ph}} = 1$.

The remaining limitation factor that contributes to CNR according to (3.18) is the noise
associated with the transimpedance stage. This noise is mainly due to thermal effects
introduced by the TIA, and can be defined as:

$$\langle i^2_{\text{TIA}} \rangle = \frac{4kB^T}{R_{\text{TIAeq}}} BW NF_{\text{TIA}}.$$  \hfill (3.23)

where $R_{\text{TIAeq}}$ is the effective resistance load of the photodetector, which in this case
represents the TIA, T is the temperature in K, $NF_{\text{TIA}}$ is the effective noise figure of the
TIA [15].

The CNR is defined according to the main limitation of the system, i.e., the source,
photodiode or TIA noise. The general expression for CNR, considering all the noise effects
described can be obtained substituting (3.19), (3.21), (3.22) and (3.23) into (3.18), yielding:

$$\text{CNR} = \frac{\frac{1}{2}(\beta R G_{\text{ph}} P_{\text{out}})^2}{[\text{RIN}(RP_{in})^2 BW] + [2q (i_{\text{ph}} + i_{\text{dark}}) BW] + \frac{4kB^T}{R_{\text{TIAeq}}} BW NF_{\text{TIA}}}.$$  \hfill (3.24)

For maximum sensitivity, the photodiode must be quantum noise limited, i.e. when the
quantum noise is higher than the thermal noise. In addition, more simplifications can be made
to (3.24), considering that the effect of the source noise and the dark current are negligible over the shot noise and TIA thermal noise. Therefore, equation (3.24) can be simplified into:

\[
CNR = \frac{\theta^2 P_{\text{out}}}{2h f_c BW},
\]

(3.25)

### 3.4.4 Performance-driven Parameters

Overall sensor performance is mainly driven by: characteristics of the input optical source (frequency stability and input power), MZI \(\nu_\pi\), gain of the current-to-voltage conversion and input impedance of the photonic sensor.

In order to increase overall sensitivity and acquire signals as low as 5 \(\mu\)V, a high \(P_{\text{in}}\) and a low \(\nu_\pi\) should be used. The \(\nu_\pi\) can be reduced by increasing the electrode length, since the EO interaction is augmented, improving the net \(\theta\). Nevertheless, there’s a limitation regarding the EO modulator settings, since they can’t be easily changed after assembly. In fact, opening a sealed MZI modulator could lead to damages in the waveguides due to air particles. Therefore, after designing the photonic sensor and seal the device, the main parameters influencing the overall performance are the \(P_{\text{in}}\) and \(G_{TIA}\). There’s a tradeoff between both parameters, since to compensate the DC levels introduced by a higher optical power, the the TIA components need to have higher values. This results in probable instability of the TIA and higher 50 Hz interference pick-up, due to an increase of the parasitic capacitance. The implemented solution consists in including a DC suppression block when designing the TIA, ensuring the sufficient gain and less probability of saturation. The feedback block low-cut frequency and attenuation depth are selected according to the value of the input optical power. This component will be discussed in Chapter 4.

Another important optimization consideration is to match the properties of the optical signal source used, e.g. wavelength and optical power, with the implemented MZI modulator specifications. In addition, since EO modulation used is based on intensity variations, it’s important to prevent optical power oscillations beyond those originated by the bioelectric signal, i.e. minimize RIN.

Table 3.2 includes the main parameters for each component that ultimately influence the overall photonic stage performance.
Table 3.2 Performance-driven parameters for each photonic sensor component.

<table>
<thead>
<tr>
<th>Element</th>
<th>Parameter</th>
<th>Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Source</td>
<td>$P_{in}$</td>
<td>As high as possible to improve EO $s_{MZI}$.</td>
</tr>
<tr>
<td></td>
<td>$RIN$</td>
<td>As low as possible to avoid artifacts external to bioelectric signal recording.</td>
</tr>
<tr>
<td>Photodiode</td>
<td>$R$</td>
<td>As high as possible to improve conversion efficiency.</td>
</tr>
<tr>
<td></td>
<td>$\langle i_{phnoise}^2 \rangle$</td>
<td>As low as possible to improve CNR.</td>
</tr>
<tr>
<td>MZI</td>
<td>$Z_{in}$</td>
<td>Sufficiently high to prevent signal attenuation.</td>
</tr>
<tr>
<td></td>
<td>$v_{\pi}$</td>
<td>As small as possible to increase $s_{MZI}$.</td>
</tr>
<tr>
<td></td>
<td>$IL$</td>
<td>This parameter should be improved as much as possible to avoid power losses during EO modulation.</td>
</tr>
</tbody>
</table>

3.5 Evaluation performance

In order to estimate the minimum required settings for the photonic sensor designed, a set of simulations and theoretical calculations can be performed. A direct way to understand the threshold values for each parameter is to analyze the transfer function of the photonic sensor described in (3.17), as well as the CNR (3.24). Some of the parameters involved in these equations can already be defined, as shown in Table 3.3.

Table 3.3 Photonic stage parameters used for theoretical calculations and simulations.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>LiNbO$_3$</td>
</tr>
<tr>
<td></td>
<td>$n = 2.208$</td>
</tr>
<tr>
<td></td>
<td>$r_p = 30.8 \times 10^{-12}$ m/V</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1550 nm ($f_c = 1.9 \times 10^{14}$ Hz)</td>
</tr>
<tr>
<td>MZI configuration</td>
<td>Dual drive/ Push-pull effect</td>
</tr>
<tr>
<td>Planck Constant</td>
<td>$h = 6.63 \times 10^{-34}$ J.s</td>
</tr>
<tr>
<td>Electron charge</td>
<td>$q = 1.602 \times 10^{-19}$ C</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>BW = 1 kHz</td>
</tr>
</tbody>
</table>
In the following sub-sections theoretical estimations on photonic stage performance, as well as simulations using a photonic-based software will be explored.

3.5.1 Theoretical Calculations

Two different analysis can be performed: either define which is the minimum signal to be detected and re-define the EO sensor parameters according to (3.17); or determine the output voltage according to the pre-set values for each parameter.

Since the purpose of this device is to detect electric field or voltage signals, it’s important to define the minimum signal detected according to a specific set of parameters. Therefore, replacing (3.2) in (3.25) and solving the latter for $CNR = 1$, it’s possible to find the minimum detectable field, yielding:

$$V_{min} = \frac{\lambda \sqrt{f_c \Delta f}}{2\pi n^3 r_p}$$  \hspace{1cm} (3.26)

The necessary bandwidth for the system can be determined by the maximum frequency component of interest of the bioelectric signals measured. A sufficient bandwidth for the overall system would be 1 kHz, since EMG signals have the higher frequency components ($< 500$ Hz). However, before defining the minimum detectable field, it’s important to set the threshold values for each of the parameters involved in (3.26). Regarding the optical power used, the minimum measured optical power at the photodetector may be calculated through the use the noise equivalent power (NEP). NEP corresponds to the minimum detectable power per square root bandwidth ($f_c$) and is defined as:

$$NEP = \frac{\frac{I_{ph\text{noise}}^2}{R}}{\Delta f} = \sqrt{2qP_{out}BW}$$  \hspace{1cm} (3.27)

which solved for $P_{out}$ and considering $f_c = 1$ Hz, yields:

$$P_{out} = \frac{NEP^2}{2qBW}$$  \hspace{1cm} (3.28)

After having the minimum input power, as well as defined photonic stage parameters, it’s possible to estimate the minimum detectable field, and what would be the expected output for each desired bioelectric signal. Therefore, for the following calculations, some
assumptions need to be made, based on typical values existent in the literature and in typical commercialized devices (Table 3.4).

Table 3.4 Parameters assumptions for theoretical calculations.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Considerations</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input optical power</td>
<td>Minimize power consumption</td>
<td>100 µW – 10 mW</td>
</tr>
<tr>
<td>Half-wave voltage</td>
<td>Minimize sensor dimensions</td>
<td>1 – 6 V</td>
</tr>
<tr>
<td>Insertion loss</td>
<td>Minimize losses</td>
<td>6 dB</td>
</tr>
<tr>
<td>Responsivity</td>
<td>Optimize the OE conversion efficiency</td>
<td>0.8 A/W</td>
</tr>
<tr>
<td>NEP</td>
<td>Allow low power sources</td>
<td>1 x 10^{-12} W/Hz^{1/2}</td>
</tr>
<tr>
<td>Transimpedance Gain</td>
<td>Optimize the OE conversion efficiency</td>
<td>1 x 10^{5} V/A</td>
</tr>
</tbody>
</table>

The estimation of the minimum input power used in bioelectric signal measurements using the designed photonic stage can then be performed substituting values in Table 3.4. Therefore, the minimum detected power at the photodetection stage is:

\[
P_{\text{out}} = \frac{(1 \times 10^{-12})^2}{2 \times 1.602 \times 10^{-19} \times 1000} = 3.1211 \text{ nW}
\]

The equivalent input power \(P_{\text{in}}\) can be determined by subtracting the effect of the insertion loss throughout the MZI modulator:

\[
IL = 10 \log \left( \frac{P_{\text{in}}}{P_{\text{out}}} \right) \Rightarrow P_{\text{in}} = 3.1211 \times 10^{-9} \times 10^{6/10} = 12.45 \text{ nW}.
\]

Replacing parameters in (3.26) and considering the calculated minimum detectable optical power, the minimum detectable signal is determined as 0.1884 V, which is almost 40 times greater than the highest amplitude of bioelectric signals, i.e. EMG. However, this \(v_{\text{min}}\) represents the threshold voltage detected with the worst-case scenario, where the limits of photodetection are tested. If an input optical power in the ranges shown in Table 3.4 is considered, the minimum detected voltage can be increased and reach appropriate values for bioelectric signal acquisition applications. Therefore, considering an input optical power of 10 mW, the incident power at the photodetection stage is 2.5 mW. For this case, the minimum detected field is 210 µV, which is more adequate considering the typical amplitudes of bioelectric signals (5 µ to 10 mV).
Equation (3.16) can be used in order to find the expected output voltages for each type of bioelectric signal detected using pre-set values, or optimized parameters. Table 3.5 shows the results obtained for each bioelectric signal, considering a $P_{in} = 10 \text{ mW}$ and $v_\pi = 6 \text{ V}$.

**Table 3.5** Theoretical output voltage for each bioelectric signal.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Range input amplitudes</th>
<th>Raw theoretical output voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECG</td>
<td>0.5 – 4 mV</td>
<td>0.5 – 5.0265 V</td>
</tr>
<tr>
<td>EEG</td>
<td>5 – 300 µV</td>
<td>0.0063 – 0.3770 V</td>
</tr>
<tr>
<td>EMG</td>
<td>0.1 – 10 mV</td>
<td>0.1257 – 12.5664 V</td>
</tr>
</tbody>
</table>

An important setting of the photonic stage, especially considering wearable applications, is the aspect ratio of the system, i.e. dimensions. In the case of the MZI modulator itself, this value can be determined through the $v_\pi$ definition, as described in equation (3.3), although an alteration needs to be performed giving dual drive configuration, yielding:

$$v_\pi = \frac{\lambda d}{2n^2r_pL}.$$  \hspace{1cm} (3.29)

Re-arranging (3.29) in order of the d/L ratio:

$$\frac{d}{L} = \frac{2n^2r_p v_\pi}{\lambda}$$  \hspace{1cm} (3.30)

The spacing between electrodes in this case corresponds to the spacing between waveguides in the MZI, which isn’t related with the electrode position in the body.

### 3.5.2 Photonic System Simulation

In this section, the main goal is to simulate a specific photonic platform, including also the OE conversion, i.e from an optical modulated signal to a readable output voltage. In this way, its possible to simulate the behavior of the designed photonic platform and verify the threshold voltage detected.
A photonic-based simulation software (OptiSystem 10.0, Optiwave) was used, and the considered setup is shown in Figure 3.7. Although the drive configuration shown here is for the single drive MZI operation, dual drive was also tested, substituting the 0 V signal (Sine Generator 2) by -5 µV.

![Photonic setup used in the simulation software OptiSystems.](image)

**Figure 3.7** Photonic setup used in the simulation software OptiSystems.

As shown in Figure 3.7, the characteristics used for each component are similar to the ones described in Table 3.3 and Table 3.4. The input test signal was a sinusoidal waveform with a peak-to-peak voltage of 10 µV. Results for single drive configuration are shown in Figure 3.8.

![Simulation results for MZI single drive configuration, in: a) Optical; and b) Electrical domain. Inset in b) represents the raw signal obtained at the output of the TIA.](image)

**Figure 3.8** Simulation results for MZI single drive configuration, in: a) Optical; and b) Electrical domain. Inset in b) represents the raw signal obtained at the output of the TIA.
The parameters used for dual-drive configuration were the same, although as explained before, a sinusoidal signal equal in amplitude, but with opposite phase, was used to drive the MZI second electrode. Respective results are shown in Figure 3.9.

![Figure 3.9 Simulation results for MZI dual drive configuration, in: a) Optical; and b) Electrical domain. Inset in b) represents the raw signal obtained at the output of the TIA](image)

$$P_{A:B} = 10.6\text{mW}$$  
$$V_{A:B} = 0.854\text{mV}$$

Analyzing both results, the effect of dual drive configuration (Figure 3.9) is obvious, resulting in twice the $s_{\text{MZI}}$ in respect to single drive (Figure 3.8). Thus, if using a photonic stage with the settings indicated in Figure 3.7, it’s possible to achieve satisfactory performances.

### 3.6 Photonic System Overview

This section presents the overview of the photonic system design. Table 3.6 shows the values for each parameter that determines component selection when designing the prototype for the photonic stage. In addition, these values are important to define the optoelectronic (OE) acquisition setup that will be subject of the next Chapter.
Table 3.6 Photonic System properties overview.

<table>
<thead>
<tr>
<th>System component</th>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Signal Source</td>
<td>Optical input Power</td>
<td>100 µW – 10 mW</td>
</tr>
<tr>
<td></td>
<td>Wavelength</td>
<td>1550 nm ($f_c = 1.9 \times 10^{14}$ Hz)</td>
</tr>
<tr>
<td>MZI Modulator</td>
<td>Material</td>
<td>LiNbO$_3$, $n = 2.208$, $\eta_p = 30.8 \times 10^{-12}$ m/V</td>
</tr>
<tr>
<td></td>
<td>Drive configuration</td>
<td>Dual drive/ Push-pull effect</td>
</tr>
<tr>
<td></td>
<td>Half-wave voltage</td>
<td>1 – 6 V</td>
</tr>
<tr>
<td></td>
<td>Insertion loss</td>
<td>6 dB</td>
</tr>
<tr>
<td>Photoreceiver</td>
<td>Responsivity</td>
<td>&gt; 0.8 A/W (@1550 nm)</td>
</tr>
<tr>
<td></td>
<td>NEP</td>
<td>$1 \times 10^{-12}$ W/Hz$^{1/2}$</td>
</tr>
<tr>
<td></td>
<td>TIA Gain</td>
<td>$1 \times 10^5$ V/A</td>
</tr>
</tbody>
</table>

References


