Towards Photonic Sensor based Brain-Computer Interface (BCI)

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***Abstract*—In any Internet of Things (IoT) application, the importance of a good and accurate sensor cannot be over emphasized. It is even more so in Brain-Computer Interface (BCI) systems wherein the most complex organ in the body is a component part. In this paper, we performed a study on photonic sensing and present a model of a specific photonic sensor for BCI applications as a preliminary effort in creating a better alternative to the conventional electroencephalography (EEG) and achieving smarter BCI systems. Photonic sensors are light-weight, consume less energy and provide low latency. These qualities and more endorse photonic sensing as a suitable candidate for achieving the desired smartness in BCI systems development. The modeled photonic sensor makes use of a dome-shaped micro-scale laser as a sensing element and its operation relies on the principle of morphology-dependent resonance (MDR) in which the wavelength at resonance is shifted based on the morphology of the micro-scale laser, as affected by its physical environment. The modeling is done using Simulink® and the modeled sensor produced the same results as the actual photonic sensor.**

***Index Terms*—Photonic Sensor, Brain Computer Interface, Brain Activity, Smart Healthcare, Stress Analysis, Modeling**

I. Introduction

Smart Healthcare is one of the subsets that make up a Smart City. One aspect of Smart Healthcare that is gaining tremendous attention in recent times is the Brain-Computer Interface (BCI) which also is the main subject of consideration in this paper.

The brain is the most complicated organ of the human body. It is an essential part of the central nervous system which also includes the spinal cord. It is estimated that it contains about 86 billion neurons [1]. The brain constantly produces electric currents originating in the neurons. These currents can be captured by an Electroencephalogram (EEG) which records variations in the electric currents occurring in different parts the brain. Different human activities result in different electric impulse patterns.

Extensive studies are currently underway with the use of these brain electrical signals in the emerging field called Brain-Computer Interface (BCI). These signals are extracted directly from the brain to a computer in order to make the computer or a machine carry out some human intentions in the same way the organs and body parts will do by mirroring the kind of communication and control that exist in the central nervous system. For example in [2], subjects could dial a phone number by merely gazing on the individual digits contained in the number as displayed on a computer screen. A smart and efficient sensing mechanism is at the core of successful BCI development. Photonic sensing is a candidate with great potential in this due to small form factor, high sensitivity, high accuracy, low cost, light weight, low power, robustness and resistance to electromagnetic interference [3]. Optical metrics such as wavelength and refractive index are used to examine changes in a photonic crystal or substance when exposed to certain physical conditions [4].

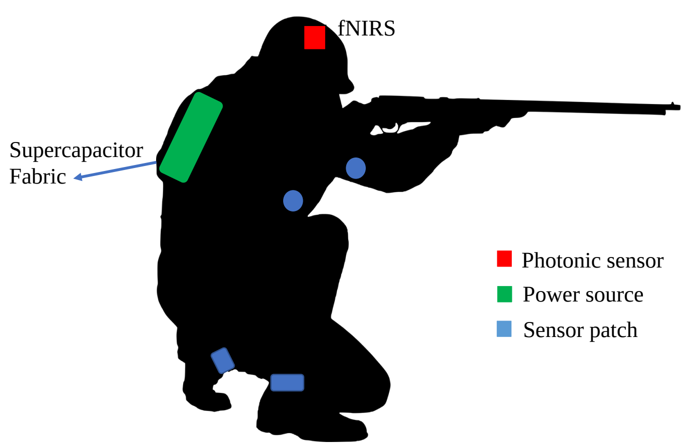


Fig. 1: Photonic neurological sensing in soldiers [5].

Laser wavelength via a photonic substance is measured through spectroscopy. When the wavelength of the laser used falls within the infrared region (IR) of the electromagnetic spectrum, it is called IR spectroscopy and is often used to measure the response of a photonic sensing element by observing the changes in the wavelength of the laser passing through it. This has led to the development of miniaturized spectrometers which are mainly fit for visible and near-IR wavelengths due to cost and performance concerns [6], giving rise to a new kind of spectroscopy called functional near-infrared spectroscopy (fNIRS). A military application of BCI where it is possible to monitor the brain states of each soldier on a battle field is shown in Fig. 1.

The main novel contribution of this paper is the modeling of a photonic sensor for the measurement of electrical activity from the brain for BCI applications. The focus in this work is to develop a Simulink® model of a specific photonic sensor so that a proper study of its reliability and relevance to BCI applications can be conducted. The ultimate goal is to provide a smart alternative to traditional electroencephalography (EEG) which makes use of electrodes to pick signals from the brain through the scalp. The presented approach promises to be lightweight and very accurate since micro-scale lasers are very light and highly sensitive. They also offer a lower latency since light is faster than electricity.

The rest of the paper is organized as follows: Section II highlights related research works. Section III discusses the brain state analysis using photonic sensor based systems. Section IV presents the proposed model of a photonic sensor. Experimental results are detailed in Section V. Section VI presents conclusions and directions for future work.

II. Related Research Work

Several studies on BCI have been conducted but the resulting BCI systems in most cases are not scalable or robust enough to be able to handle other types of brain signals or scenarios different from what was being originally intended [7]. BCI2000 was designed to address several issues in order to enhance better research and development of emerging BCI technologies [8]. The traditional non-invasive method of picking up electrical signals from the brain is by using some metal electrodes which are attached to the scalp as the sensing elements in an amplification technique called Electroencephalography (EEG). Efforts have been made to create a smarter EEG system that is portable, faster and less injury-prone. A wearable wireless EEG using dry copper electrodes without the use of gel has been proposed in [9]. However, it is believed that metal electrodes can cause skin irritation and discomfort [10]. A lightweight non skin-irritating, silicon-based dry EEG sensor is therefore designed in [10]. In [11], a hybrid functional Near-Infrared Spectroscopy (fNIRS) or Electroencephalography (EEG) recording device was proposed and experimental results show that the hybrid performs better than the individual systems. To the best of the authors' knowledge, there has not been a BCI system design with the use of photonic sensors in the literature. Photonic sensing combines the advantages of the previous methods with low power, light weight, low latency, and high sensitivity [12]. A linear relationship exists between electric field and the morphology dependent resonance (MDR) shift of a photonic micro-scale laser which is the basic operating principle of this system [3].

III. Brain State Analysis Using Photonic Sensor based Systems - A Big Picture

The field of photonics is particularly applicable in this domain because light is faster than electricity, which will make for faster communication and transmission of information. Photonic devices or substances such as optical fiber and dielectric microspheres have been used as sensing elements [4], [13]. Photonic devices have the ability to exhibit some optical characteristics such as refraction, reflection, and dispersion. Another good characteristic of an optical microsphere or micro-scale laser which enhances its suitability as a sensing element is its high quality factor [12] which can be as high as 10^{10} [4]. The morphology dependent resonance (MDR) shift of the microsphere is the inverse of the quality factor [4]. Hence, the higher the quality factor, the smaller the MDR shift and hence the better the sensitivity of the microsphere or micro-scale laser. The introduction of photonic sensors in BCI will prove invaluable especially in assisted living applications where speed and accuracy are very important. The big picture of photonic sensing and BCI synergy is illustrated in Fig. 2. The fNIR signal is converted to a Radio Frequency (RF) signal and then sent to the cloud for further analysis. The outcome of the analysis could result in actuation, communication, control or diagnosis depending on the intended goal at any point in time.

IV. The Proposed Model of a Photonic Sensor

The photonic substance that is used as a sensing element in this paper is a dome-shaped micro-scale laser that is obtained from chemical combination of glycol and trimethylopropan at a predetermined ratio [12]. The main physical properties affecting the morphology of a photonic microsphere or micro-scale laser are the radius of the sphere and its refractive index is expressed as follows [4]:

$$\Psi = f(n, r) = \frac{\delta\lambda}{\lambda}, \tag{1}$$

where Ψ = MDR shift factor, n = refractive index of the sphere, r = radius of the sphere, λ is the wavelength of the incident radiation and $\delta\lambda$ is the shift in wavelength due to MDR. This implies that when the photonic micro-scale laser is subjected to a pressure strain or any other physical disturbance, the MDR shift, Ψ is a combined effect of the morphology change in the refractive index, n and the morphology change in the radius, r. Therefore, the following can be deduced:

$$\frac{\delta\lambda}{\lambda} = \frac{\delta n}{n} + \frac{\delta r}{r}. \tag{2}$$

As both changes in n and r are caused by the applied pressure, P, the above expression, can be re-written as:

$$\frac{\delta\lambda}{\lambda} = k\delta P + c\delta P = (k + c)\delta P, \tag{3}$$

where k and c are proportionality constants with respect to refractive index and radius respectively and δP is the change

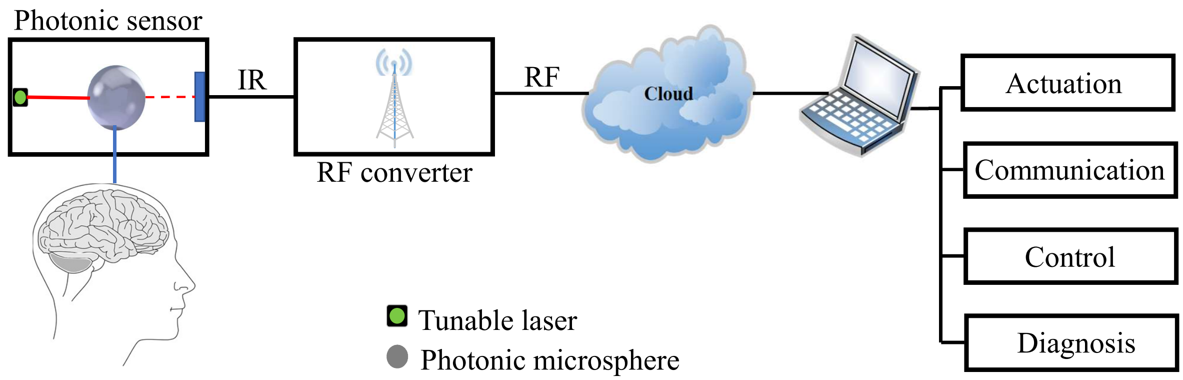


Fig. 2: A conceptual BCI system based on photonic sensing.

in pressure experienced by the micro-scale laser. If we set $k + c = \rho$, then the following expression is obtained:

$$\delta P = \frac{\Psi}{\rho}. \tag{4}$$

By modeling the effect of noise with ϵ, we finally have the following:

$$\Psi = \frac{\delta\lambda}{\lambda} = \rho\delta P + \epsilon. \tag{5}$$

Hence, for a given amount of pressure perturbation on the micro-scale laser, the corresponding MDR shift can be obtained and vice versa provided the sensitivity is known. The sensitivity for the specific photonic sensor being modeled in this work is 4×10^{-4} nm/Pa for a 4:1 polymeric ratio.

V. Experimental Results

When the photonic polymeric structure is subjected to certain strains such as pressure or electric field, they respond with some deformation which is interpreted as the MDR shift or the Whispering Gallery Mode (WGM) shift [3], [12], [14]. The relationship observed between the strain and the corresponding deformation is approximately linear [12].

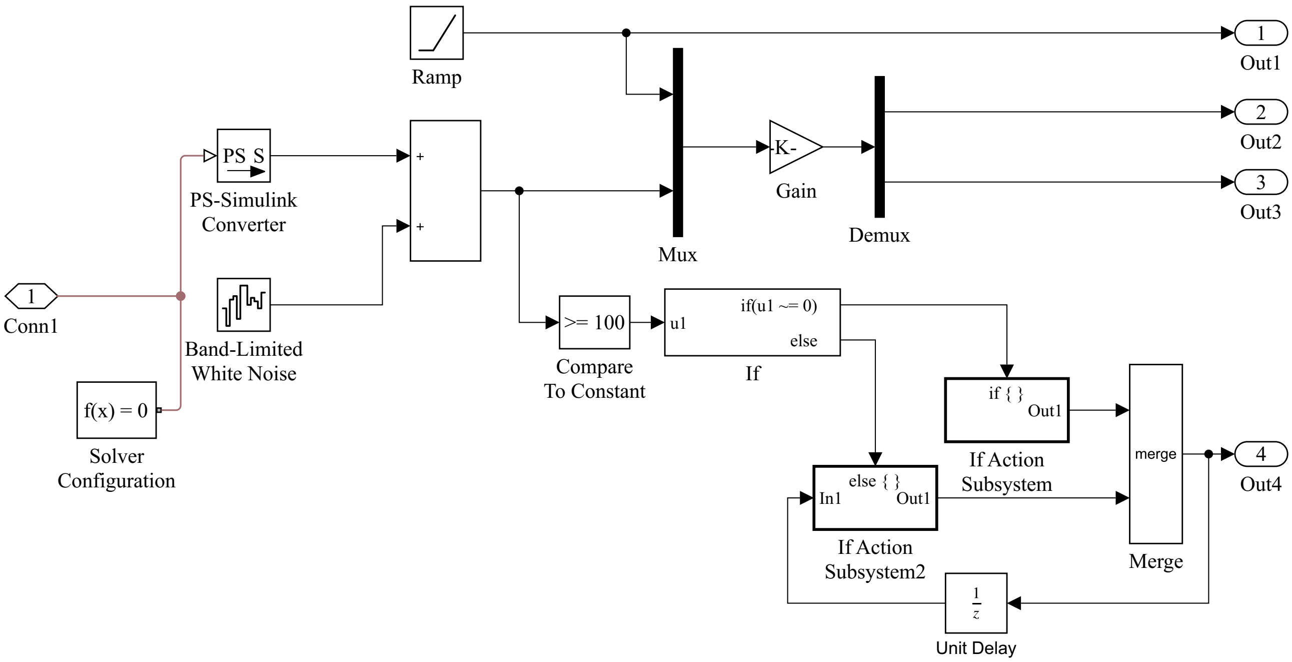
The proposed model is divided into three subsystems which are input block, functional block and output block. As shown in Fig. 3a, the input block consists of a pressure source that is assigned a given pressure value in Pascal (Pa) to simulate a physical pressure source (PS). The PS to Simulink® converter converts the physical signal from the input block to a Simulink® signal. The gain block consists of a value that is equal to the sensitivity of the photonic sensor which is 4×10^{-4} nm/Pa. A ramp signal is passed into the gain block to simulate a set of pressure values so that a plot of the MDR shift against the pressure can be obtained. The resulting plot is linear and an approximate replica of the plot obtained when the actual photonic sensor was used. The logic part of the model is used to simulate some level of actuation as a direct consequence of the input pressure. For example, if the pressure is greater that 100Pa, Scope1 will report a value of "1" representing a particular action and a value "0" otherwise, indicating that no action should take place. Another architecture of the functional block is shown in Fig. 3b, where instead of the "1" and "0", high and low frequency pulses were used respectively. For example, if the pressure is greater than 100Pa, a high frequency pulse is generated on the scope representing a particular action in the output block and a low frequency pulse is generated if otherwise. This could mean that when the doctor receives a high-frequency pulse signal from a patient, then the patient is at high risk and at low risk when a low-frequency pulse is received. On the other hand, a value of "1" received by a BCI component could signify that the BCI component should take an action and no action for a value of "0".

The output block consists of all the output scopes and displays. An XY Graph scope displays the plot of MDR shift versus pressure. The Scope and the Display show a value of MDR shift that corresponds to the applied pressure while another scope displays a plot of the appropriate pulse depending on the pressure.

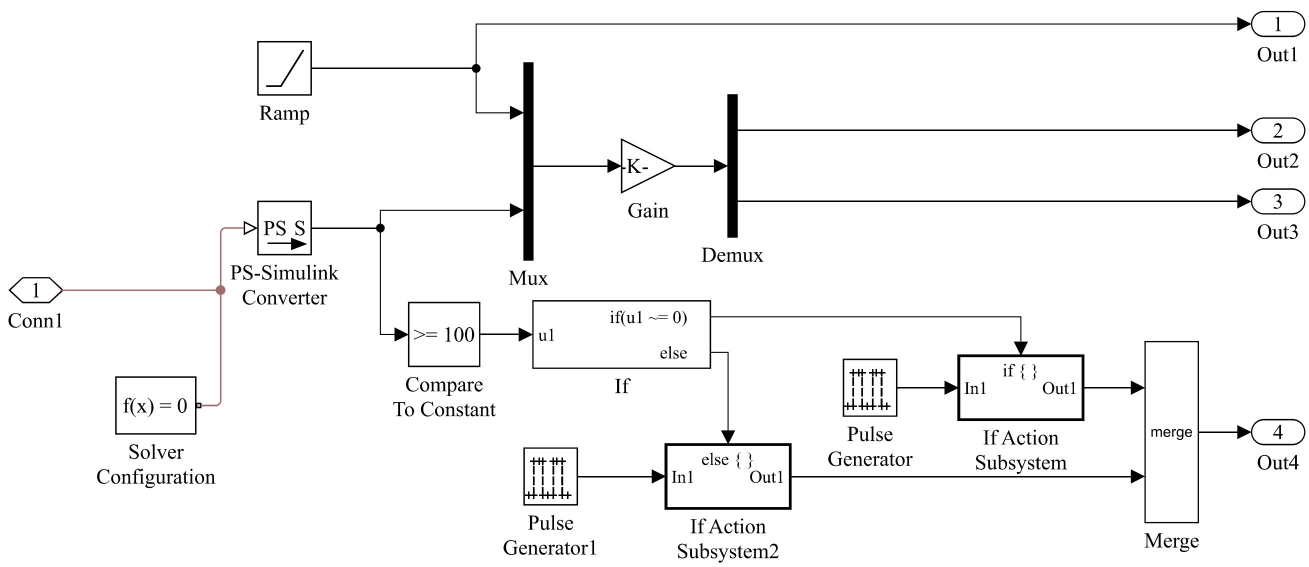
An experimental simulation was performed using the modeled photonic sensor by feeding in different pressure inputs. The corresponding MDR shifts were recorded and the results show an approximate replica of the values obtained using the actual photonic sensor that was modeled. The effect of the resulting MDR shift against the input pressure values is shown in Fig. 4. The pulse generated at pressures above and below a threshold of 100Pa are shown in Fig. 5a and 5b, respectively. The parameters of the photonic sensor are given in Table I. The characterization results of the sensitivity of the proposed sensor model along with the actual values are shown in Table II. It is evident from the results that the model closely matches the characteristics of the physical photonic sensor.

TABLE I: Characterization of the physical photonic sensor.

Metrics	Values
Sensitivity	4 x 10^{-4}nm/Pa
Resolution	50Pa
Dynamic range	5.5
Linearity	Linear



(a) Model - 1



(b) Model - 2

Fig. 3: Functional block of the photonic sensor model.

TABLE II: Characterization of photonic sensor model against the physical photonic sensor.

Pressure	Modelled Sensor MDR Shift	Physical Sensor MDR Shift
50 Pa	0.01993 nm	0.02000 nm
100 Pa	0.03950 nm	0.04000 nm
150 Pa	0.05950 nm	0.06000 nm
200 Pa	0.07953 nm	0.08000 nm
250 Pa	0.09993 nm	0.10000 nm

VI. Conclusion and Future Work

This paper explores the merits of photonic sensing and its prospects for BCI applications as a first step towards designing a complete system. A specific photonic sensor was also modeled so as to facilitate further studies of the field of photonics in relation to brain signal measurement for BCI systems development. This is only a preliminary effort on the relevance of photonics in BCI. Further research will be performed by using the modeled photonic sensor and a real photonic sensor on a BCI system while comparing their

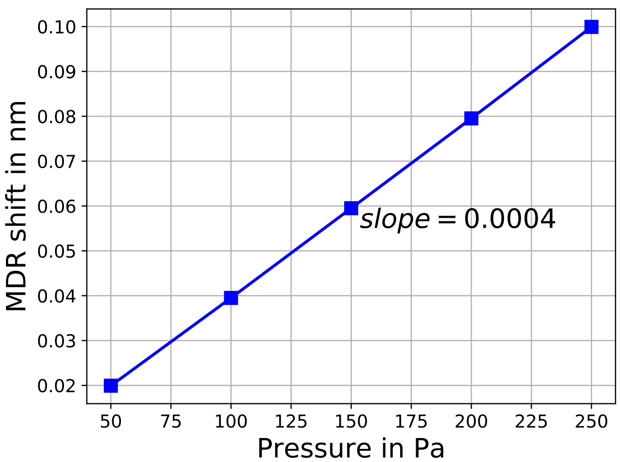
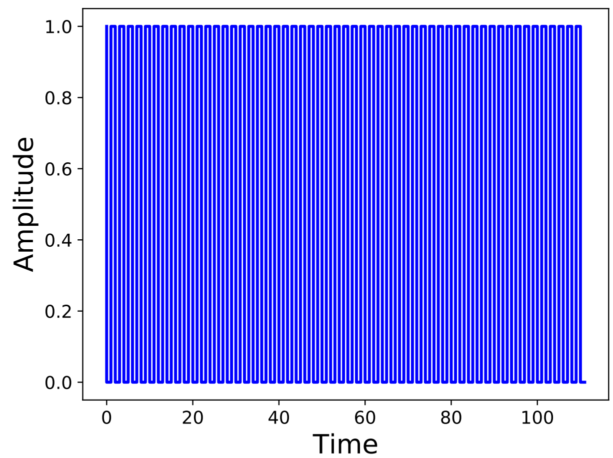
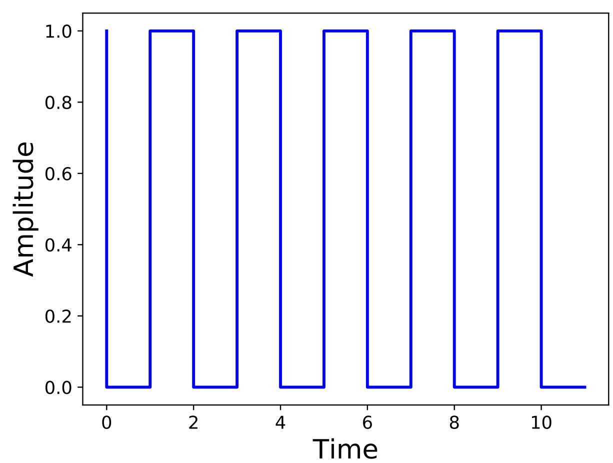


Fig. 4: Simulation of the modelled photonic sensor.



(a) Pulse generated when over 100Pa.



(b) Pulse generated when less than 100Pa.

Fig. 5: Simulation and Characterization of the photonic sensor.

performance with existing methods of collecting electrical impulses from the brain. Further studies will also be performed on the use of the photonic sensor for measuring and monitoring the intracranial pressure (ICP) of a subject. Stress analysis and management from these signals as well as alcohol content analysis for smart healthcare are long term goals [15].

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