G Model
SNA-8302; No. of Pages 6

ARTICLE IN PRESS

Sensors and Actuators A xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

A resonant co-planar sensor at microwave frequencies for biomedical applications

A. Mason*, O. Korostynska, M. Ortoneda-Pedrola, A. Shaw, A. Al-Shamma'a

School of Built Environment, BEST Research Institute, Liverpool John Moores University, UK

A R T I C L E I N F O

Article history:
Received 22 October 2012
Received in revised form 4 April 2013
Accepted 5 April 2013
Available online xxx

Keywords:
Microwave sensors
Medical sensing
Co-planar structure

A B S T R A C T

This work presents a novel electromagnetic sensor operating at microwave frequencies for real-time evaluation of fluid properties, which has been designed with biomedical applications in mind. The sensor has a resonant co-planar type structure, which has been recently patented by the authors, along with a unique tuning feature that allows full control over the sensitivity and selectivity of the system response to different analytes by adjusting the resonant peak frequency and the corresponding quality factor at that frequency. The sensor operates based on the contactless interaction of the non-thermal intensity microwave signal with the solution of interest. By monitoring the changes in reflected and/or transmitted signals, usually expressed by *S*-parameters, the system provides for a solution to real-time fluid analysis. To evaluate the sensor feasibility for use in clinical settings, the work considers the sensitivity of the sensor to glucose dilutions near to physiological levels (10–100 mmol), and reports a calibration curve at 3.64 GHz to demonstrate this sensitivity. The sensor's stable and repeatable response suggest that it can serve as a long-awaited alternative to currently used time-consuming laboratory based methods of bodily fluid analysis.

1. Introduction

Human bodily fluids (e.g. blood, spinal fluid and urine) contain a complex combination of compounds including water, glucose, salts, lactate, etc. This represents a challenging combination of materials for analysis and leads to an extensive time lapse between sample acquisition and associated diagnosis.

Accurate real-time measurements of the glucose concentrations in aqueous solutions are essential for both fundamental studies and biomedical applications, in particular for diabetic patients to monitor their condition and to test the efficiency of the drugs [1]. Diabetes is a metabolic disorder, which results from insulin deficiency and hyperglycemia and is reflected by blood glucose concentrations higher or lower than the normal range of 80–120 mg/dl (4.4–6.6 mmol) [2]. Self-monitoring and point-of-care monitoring of blood glucose levels is one of the important technical advances in the management of diabetes in the last few decades. It has given patients and providers remarkable insights into the day-to-day variability of blood glucose concentrations.

Optical techniques [3–5] are commonly employed for biomedical applications to assist when time is a critical factor. However, these methods can be bulky and expensive to implement and often there is still the requirement for an experienced operator to take time to consider the meaning of results obtained. The current devices on the market all require a sample of blood from the patient and then quantification of glycated haemoglobin (HbA1c). The chemical reaction between glucose and haemoglobin leads to an average blood sugar level and does not show any spikes in blood sugar level. There are also chemical systems, which directly measure the quantity of glucose, but these also require a sample of blood. Furthermore, the majority of methods for detecting glucose levels in the blood rely on *in vivo* methods utilising complex chemical processes [6,7] and/or sophisticated equipment, for example, impedance spectroscopy, mid-infrared spectroscopy and optical coherence tomography [8–11]. Notably, the spectroscopy methods utilise the interaction of the electromagnetic waves at various frequencies with a substance under test and these interactions are of three kinds: the absorption, the emission and the scattering [2]. Glucose biosensors can also be based on electrochemical principle of detection that employ enzymes for molecular recognition, as well as the optical, piezoelectrical, thermal, and mechanical principles [12–15]. An electromagnetic coupling approach for indirect measurement of glucose concentration in sodium chloride and Ringer–lactate solutions, which have similar to blood properties, was employed at low frequency of 40 kHz [16]. The sensor was able to detect the effect of glucose variations over a wide range of concentrations (~78–5000 mg/dl), with a sensitivity of ~0.22 mV/(mg/dl). However, special caution should be taken when

---

* Corresponding author. Tel.: +44 01512312847.
E-mail address: A.Mason1@ljmu.ac.uk (A. Mason).

0924-4247/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.sna.2013.04.015

Please cite this article in press as: A. Mason, et al., A resonant co-planar sensor at microwave frequencies for biomedical applications, Sens. Actuators A: Phys. (2013), http://dx.doi.org/10.1016/j.sna.2013.04.015

exploiting medical devices emitting signals at low frequencies, so as not to interfere with natural biological signals and other hospital diagnostic equipment, such as ECG, EEG, EMG [17].

Obviously, the current methods are inappropriate during a surgical procedure as time is often critical from the perspectives of patient well-being and hospital efficiency. Thus, there is a great desire for tools, which can be used at the point of care to assist medical practitioners in rapidly diagnosing patients. Previous work by the authors [18–20] with surgeons at local National Health Service (NHS) hospitals has indicated that there is a need for simple but rapid sensing techniques, which can be used during surgical procedures to detect parameters in a variety of patient bodily fluids. In the ideal case, surgeons would like tools, which are either (1) completely non-invasive or (2) minimally invasive. The nature of surgery however often means that invasive procedures are inevitable, so work by the authors has focused on tools, namely electromagnetic sensors, which can be on hand for real-time measurement of bodily fluids as they are extracted during surgical procedures. Future work to develop this sensor technology further will consider the use of the technique for completely non-invasive transcutaneous measurement, which will lead to the technology being used as a more general purpose medical tool.

This paper discusses a novel co-planar resonant structure, which is designed to have an area highly sensitive to changing analyte materials. The device has successfully been patented [21] recently, and improves on previous work, which concentrates on the use of highly sensitive but bulky cavity resonators [18–20]. While this work presents a proof of concept work, the eventual aim is to encapsulate this in a small hand-held or desktop diagnostic tool for rapid in situ analysis. This paper reports on the design of the sensor and shows laboratory based testing of this sensor's ability to distinguish between the solutions with varying glucose concentration levels. The paper concludes by alluding to future work to be conducted in this area using the proposed device.

2. Microwave analysis

Microwave sensing is a developing technology, which has shown vast potential in a number of industrial and medical areas [15,19,22–31]. This is a result of the technique being robust, requiring low power and having good depth of penetration in respect of analyte materials. Also, of particular interest in medical applications is the non-ionising nature of microwave radiation; the technique used in this paper has low power output at around 1 mW (0 dBm) but has good penetration depth and equipment could be made portable for use at the bedside. These are features which practitioners see as a significant benefit over existing technologies, particularly X-ray imaging [32].

The multi-parameter nature of broadband microwave analysis can provide unique signal spectrum signatures. In this work, captured microwave signals are presented in the form of scattering parameters (commonly referred to as *S*-parameters), with measurement of the reflected (S_{11}) and transmitted (S_{21}) microwave signal being possible. These signals vary depending upon properties of the analyte presented to the sensing structure, such as conductivity and permittivity [33]. Conductivity is a measurement of a material's ability to conduct an electric current. Permittivity is a measurement of how an electric field is affected by a dielectric medium, which is determined by the ability of a material to polarise in response to the field, and reduce the total electric field inside the material. Therefore, permittivity (ε_r) as defined in (1) relates to a material's ability to transmit an electric field and is a complex value which varies with changing frequency, and accounts for both the energy stored by a material (ε') as well as any losses of energy (ε'') which might occur.

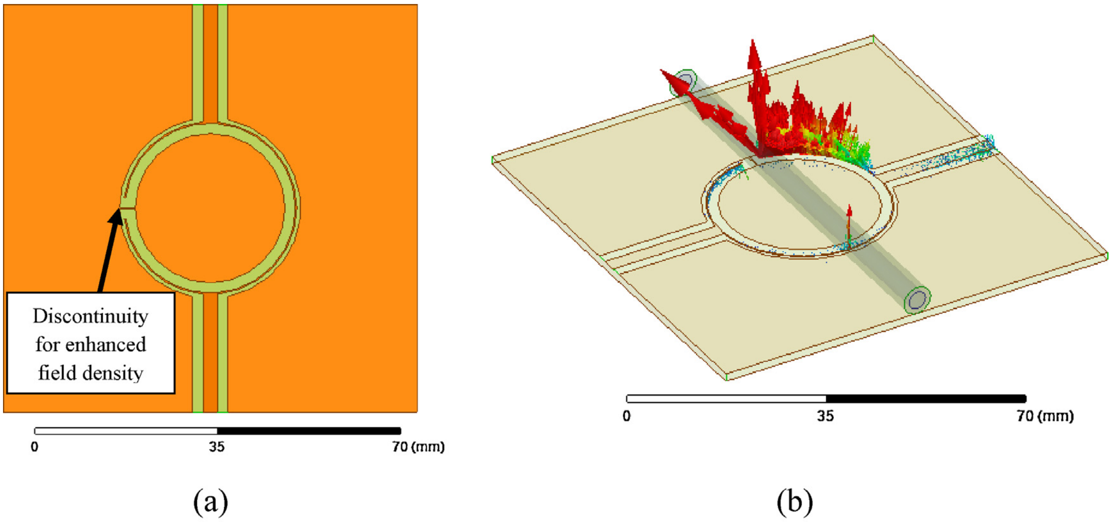
$$\varepsilon_r = \varepsilon' + j\varepsilon'' \tag{1}$$

As a material alters in concentration or type, it is likely that its permittivity will change leading to a change in response if the material is the target of microwave radiation. By measuring this response over a range of frequencies, one can characterise materials in order to infer their properties.

3. Co-planar sensor

The sensor used in this work is based upon a co-planar design. This design was chosen particularly since such devices are known to be resistant to losses and interferences induced from external sources, and thus offer a great deal of control in relation to how the sensor responds to analytes [34]. In particular, the sensor is constructed to ensure that only a small area is sensitive to dielectric change, which enhances significantly its robustness for potential biomedical use. The design of the sensor is shown in Fig. 1; the sensor has a footprint of approximately 80 mm^2.

The sensor, pictured in Fig. 2(a), in this system is also accompanied by a bespoke tuning system, which enables the user to



(a) (b)

Fig. 1. 3D software models of the co-planar sensor design showing (a) the sensor printed circuit board layout and (b) the electric vector field plot, showing maximum field around the embedded discontinuity. Note that a pipe is shown in (b), which is included to allow modelling of how dielectric change affects the sensor response.

Please cite this article in press as: A. Mason, et al., A resonant co-planar sensor at microwave frequencies for biomedical applications, Sens. Actuators A: Phys. (2013), http://dx.doi.org/10.1016/j.sna.2013.04.015