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Glucose aqueous solution sensing by a near-field microwave microprobe

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ABSTRACT

We observed the glucose concentration of solutions using a near-field microwave microprobe (NFMM). Instead of the usual technique, we take advantage of the noncontact and label-free evaluation capabilities of a NFMM. A NFMM with a high Q dielectric resonator allows observation of small variations of the relative permittivity due to changes in the glucose concentration. By measuring the reflection coefficient S_{11} at an operating frequency near 4.5 GHz, we could observe the concentration of glucose with a detectable resolution of 0.5 mg/ml (0.05%). A glucose biosensor using a NFMM provides a unique approach to monitor glucose concentration.

1. Introduction

There is a wide spread need for highly sensitive and stable glucose biosensors in clinical monitoring, biological research and in the food processing industry [1,2]. Aqueous glucose solutions play a fundamental role in many chemical processes, in a variety of chemical and biological systems. Sensitive detection of glucose concentration in water may become a useful tool for studying the local electrical and biological properties of samples. Glucose biosensors have taken several forms, based on electrochemical, optical, piezoelectrical, thermal or mechanical principles [3–8]. Amperometric enzyme electrodes, based on the binding of glucose oxidase to electrode transducers, hold a leading position among present glucose biosensor systems and have already found a large commercial market. Thus, amperometric enzyme electrodes have been investigated in great detail. Recently, a number of mechanically based glucose biosensors based on the cantilever platform, have been demonstrated and found to respond specifically to the correct analyze over a wide concentration range. Commercial development of these devices has allowed measurement of glucose concentration with sufficient accuracy for some applications. However, the device is largely limited to monitoring patterns and trends and is invasive. Techniques with high sensitivity and efficiency for the detection of glucose concentration using a noninvasive technology are therefore of importance in biosensor construction. In order to better characterize the concentration of glucose instead of the usual method, we take advantage of the noncontact and label-free evaluation capabilities of a near-field microwave microscope (NFMM). NFMM techniques with high sensitivity have been developed for the microwave and millimeter-wave ranges [9–16]. An important ability of the NFMM is label-free and contactless characterization of glucose solutions.

In this paper, we monitored the glucose concentration using a NFMM technique. The glucose biosensor consisted of a dielectric resonator coupled to a probe tip at an operating frequency of about $f = 4.5$ GHz. The changes of glucose concentration due to a change of relative permittivity of the glucose solution were investigated by measuring the reflection coefficient S_{11} of the resonator. The change of the glucose concentration is directly related to the change of the reflection coefficient due to a near-field electromagnetic interaction between the probe tip and the glucose solution. In order to determine the probe selectivity, we measured a mixture solution of glucose and sodium chloride (NaCl).

2. Experimental setup

The experimental setup of NFMM with operating frequency of about 4.5 GHz is shown in Fig. 1(a). The NFMM probe consisted of a high Q dielectric resonator coupled to a probe tip with a distance control tuning fork sensor [13]. The resonance frequency of a given mode was TE_{011}. The $Ba(ZrTa)O_3$ dielectric cylindrical resonator with dielectric constant $\varepsilon = 29$ has inner and outer diameters of 2 mm and 14 mm, respectively, and a height of 5.8 mm. The diameter of the metal circular cylindrical cavity is 32 mm and the height is

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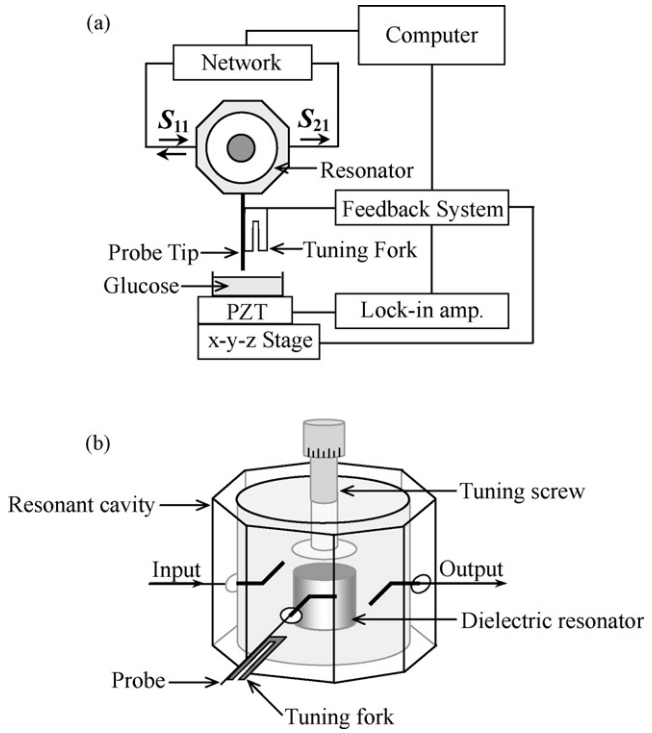

Fig. 1. (a) Block diagram of NFMM with tuning fork distance control and (b) NFMM microwave resonator and probe tip assembly.

14 mm (Fig. 1(b)). The dielectric resonator has a fixed resonance frequency determined by the material, dimensions, and the shielding cavity conditions. In order to achieve the largest possible sensitivity, we tuned the resonance frequency and the impedance simultaneously by adjusting the tuning screw before scan over the sample. To obtain high near-field interaction of the NFMM, a gold probe tip with a diameter of 50 μm was used. To prevent the glucose solution from covering the tip due to the surface tension, the probe tip–sample distance was fixed at about 1 μm above the glucose solution by using a tuning fork feedback control system. Sample cells with different glucose concentrations and the mixture solution of glucose and NaCl were mounted on the *x*–*y*–*z* sample stage. The sample was mounted onto a *x*–*y*–*z* translation stage for coarse adjustment which was driven by a computer-controlled microstepping motor with a resolution of 0.1 μm, whereas fine movement of the sample was controlled by a PZT tube. The entire system was placed on a mechanical vibration isolation table and measurements were performed inside an electromagnetically shielded environment with an automated temperature and humidity control. To determine the glucose concentration changes, we measured the reflection coefficient S_{11} of the dielectric resonator of the NFMM using a network analyzer (NA). At the start of measurement the input loop and resonator impedances are matched, by adjustment of the tuning screw and positioning of the coupling loops, to minimize the reflection coefficient S_{11}. Subsequent changes in electromagnetic coupling between the probe tip and the sample cause an increase in S_{11} thus are forming the basis of sample characterization. All measurements were done at room temperature. At resonance, the mode we used was TE_{011} and the unloaded *Q* factor was 24,000. Fig. 2 presents (a) probe-sample schematic configuration and (b) its equivalent model, the probe with characteristic impedance $Z_0 = 50\,\Omega$ distanced from the sample (glucose on glass substrate with Z_{in}) by about 1 μm with an air gap of $Z_a = 377\,\Omega$.

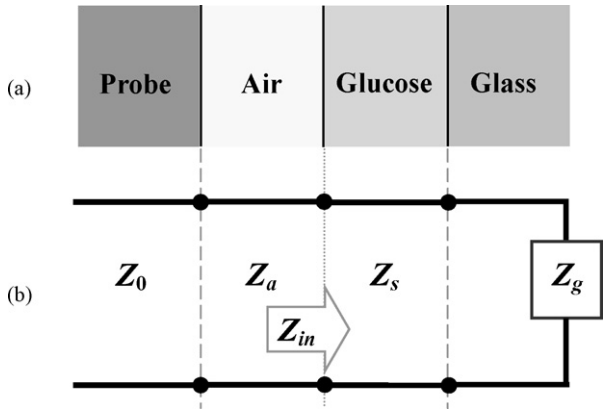

Fig. 2. Schematic diagram of (a) probe-sample and (b) its equivalent model.

3. Theory

An expression how the reflection coefficient S_{11} depends on permittivity of the glucose can be derived by using standard transmission line theory [17] and is given by assuming impedance matching between the probe and the microwave source for a λ/4 resonator

$$S_{11} = 20 \log \left| \frac{Z_{in}^{R} - Z_0}{Z_{in}^{R} + Z_0} \right|, \quad (1)$$

where Z_{in}^{R} is the real part of the complex impedance of the glucose solution with a cylindrical cell substrate and Z_0 is the effective impedance of the probe tip and is equal to 50 Ω (by tuning the resonance cavity we match to 50 Ω). Complex impedance of sample Z_{in} can be written by the transmission impedance equation as [17]

$$Z_{in} = Z_s \frac{Z_g + jZ_s \tan(k_s t_s)}{Z_s + jZ_g \tan(k_s t_s)}, \quad (2)$$

where t_s is the thickness of glucose solution ($t_s = 2$ mm) and k_s is the wave vector of glucose solution and it can be written as

$$k_s = k_a \sqrt{\varepsilon_s}, \quad (3)$$

where k_a is wave vector of free-space and it is equal to 94 m^{-1} at 4.5 GHz and ε_s is the relative permittivity of glucose solution. Z_g and Z_s are the impedance of glass substrate and glucose solution, respectively, and they are given by

$$Z_g = \frac{Z_a}{\sqrt{\varepsilon_g}}, \quad (4)$$

$$Z_s = \frac{Z_a}{\sqrt{\varepsilon_s}}, \quad (5)$$

where Z_a is the impedance of free-space ($Z_a = 377\,\Omega$) and ε_g is the relative permittivity of glass ($\varepsilon_g = 5$ at 4.5 GHz).

The dependence of relative permittivity ε_s on solute glucose concentration is approximately linear and is often expressed as the molar increment γ. The relative permittivity of glucose solution is complex with $\varepsilon_s = \varepsilon' - j\varepsilon''$ and it can be written as [18,19]

$$\varepsilon_s = (\varepsilon_0' + c\gamma') - j(\varepsilon_0'' + c\gamma''), \quad (6)$$

where ε_0 is the relative permittivity of water ($\varepsilon_0' = 74.53$ and $\varepsilon_0'' = 16.19$ for 4.5 GHz at 25 °C [20]), *c* is the concentration of the glucose solution, γ is the increase in permittivity when the glucose concentration is raised by 1 unit ($\gamma' = 0.0577\,(\text{mg/ml})^{-1}$ and $\gamma'' = 0.0015\,(\text{mg/ml})^{-1}$). Thus, the real part of the complex