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Quantifying Glucose Concentration in Aqueous Solutions via Microwave S-Parameters Analysis During Evaporation

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Abstract: ***This study investigates the use of high-frequency S-parameter analysis to monitor the evaporation kinetics of glucose solutions. By depositing a glucose-containing droplet on a coplanar waveguide transmission line and measuring S11 and S21 parameters in the 100 MHz to 16 GHz range, the authors identified time-dependent dielectric variations correlating with glucose concentration. Simulations confirm that during early evaporation stages, permittivity changes dominate response, enabling clear concentration discriminations, particularly at 15 minutes. These preliminary findings indicate the feasibility of an RF-based, non-invasive method for quantifying solutes in aqueous solutions, with potential applications in biomedical and food industries.***

Keywords: glucose concentration, RF sensing, coplanar waveguide, evaporation kinetic, S-parameters

1. Introduction

There is considerable interest in glucose measurement. For instance, diabetes is a chronic disease characterized by abnormally high blood sugar levels. In 2021, this pathology affected 537 million adults worldwide, a figure that is constantly rising [1]. Monitoring blood glucose levels is a crucial public health issue, requiring reliable methods of measuring glucose in solution. These include Raman spectroscopy [2], detection with resonant HF devices [3, 4], and the use of biosensors [5]. In addition to monitoring diabetes, glucose analysis is also very useful in the food industry, where controlling glucose levels is of importance, for example in dietetics. The high-performance liquid chromatography (HPLC) method is commonly used to quantify glucose in foods, particularly fruit. [6,7]

The aim of this work is to broaden the possibilities for characterizing liquid solutions. The originality of this study lies in the analysis of the evaporation kinetics of demineralized water solutions concentrated in glucose.

Monitoring S-parameters throughout the evaporation process reveals composition-dependent variations in the dielectric properties of the solutions. This approach offers an innovative way of discriminating glucose concentrations on the basis of variations in the electrical properties of the medium. To the best of our knowledge, we have not found any reference RF measurements for monitoring the evaporation kinetics of glucose solutions. This study aims to expand current methodologies for characterizing glucose concentrations in liquid solutions.

This research holds meaningful implications for biomedical sensing and food quality monitoring. By establishing a non-invasive, RF-based approach to solute quantification, the study offers a pathway toward faster, reagent-free diagnostics and real-time process control in industrial settings.

2. Measurement Setup and Experiment

The device used is a coplanar waveguide (CPW) transmission line as shown in figure 1. The line is excited using tips (Infinity GSG with a pitch of 1250 µm), connected to a PNA-X N5247B [10 MHz - 67 GHz] previously calibrated via an LRRM procedure.

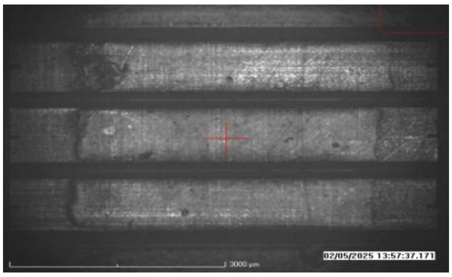


Figure 1: Photo of the varnished coplanar line on which the tips are deposited. A central ribbon and two external grounds.

2.1 CPW line

Using a conformal transformation calculation, we designed the line to have an impedance of 50 Ohms on a Rogers R04003 substrate of 815 µm thickness and a relative permittivity of 3.38, while making the dimensions compatible to ensure the fitting of the tips. The metallization is copper with 35 µm thick. With a 100 µm gap between the central ribbon and the ground lines, the widths of both the ribbon and the ground lines are set to 1.15 mm. The length of the CPW line is 6 mm. A coat of acrylic tropicalization varnish (-45°C to +145°C) was also applied in the central part. This makes the device waterproof during solution deposition and, above all, prevents any oxidation phenomena on the copper.

For the experiment, the drop is positioned so that it covers the gaps between the central ribbon and the two external masses, so that the electric field lines interact with the liquid. In this way, any change in the composition of the load directly influences the electric field. The addition of glucose to demineralized water fulfills this role by altering the dielectric permittivity of the mixture [8]. Evaporation of the drop results in variations that can be observed through analysis of the S-parameters measured using the PNA-X.

2.2 Test bench

The experiments were carried out in an air-conditioned room at 21°C, with humidity measured at 43% during our measurement campaign. For each test, S-parameters were measured every 2 minutes for a total duration of 30 minutes. The quantity of liquid forming the drop used for the experiments was 5 µL, thanks to a micro-pipetta for reproducibility. The position was controlled under microscope before analysis. Between each deposit, a clean-up with demineralized water and absorbent paper was carried out to ensure that the concentrations tested were not contaminated by previous ones. An additional measurement of the vacuum CPW transmission line was also carried out, in order to be able to determine at what value in dB of the transmission scattering parameter the drop can be considered as completely evaporated.

The five target solutions for this work are mixtures of demineralized water and glucose. Concentrations are respectively 1%, 5%, 15%, 20% and 30% of glucose. Measurements are taken on the frequency band [100MHz - 16GHz] every 2 minutes for 30 minutes.

The 30-minute evolution of a drop of demineralized water with a 30% glucose concentration can be seen in figure 2:

Figure 2: Illustration of demineralized water solution drops concentrated to 30% glucose, at 0 minutes, 10 minutes and 30 minutes.

Figure 2 shows that water evaporation modifies the shape of the drop over time. However, during the first ten minutes, the surface of the drop in contact with the device is only slightly modified. The photo of the drop at 30 minutes shows a reduced contact surface.

The drop on the surface of the CPW transmission line is responsible for local impedance mismatch. Its evaporation has therefore repercussions on both the reflexion parameter S_{11} and the transmission parameter S_{21}. The shape of the drop varies during the evaporation process. The permittivity of the real drop may vary due to concentration variation too. On that basis, we have carried out simulations of the transmission line loaded with the deposited drop at several evaporation steps (considering a constant permittivity in order to isolate the impact of the shape of the drop), two 3D modelling cases of which being presented in figure 3:

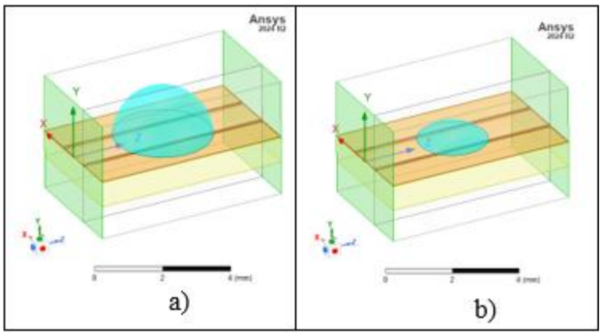
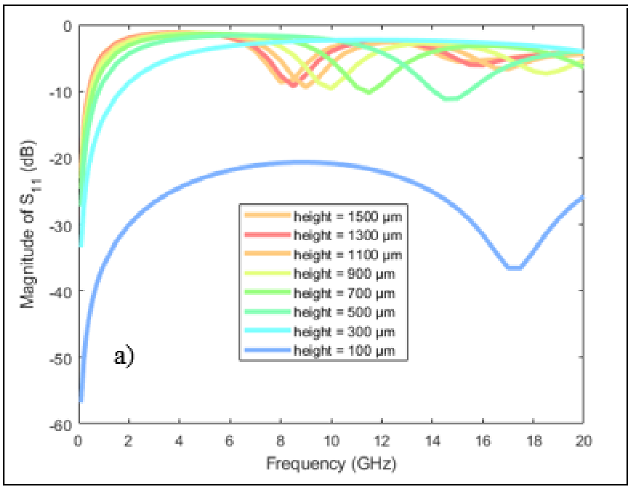


Figure 3: HFSS model design of drop evaporation on a CPW line. The drop height is 1500 µm (a) and 500 µm (b).

Two concomitant modifications of the drop geometry occur during its evaporation: on one hand, the height of the drop decreases, as does its volume, and on the other hand, the surface area in contact with the device begins to considerably shrink.

The uniform evaporation process of a water droplet can be conceptually divided into two phases. A first step in which the surface area on the line is considered stable while the height decreases, resulting in the displacement of the resonance with no big improvement of the impedance matching. A second step in which the surface area varies while the height continues decreasing, thus reducing drastically the impedance mismatch. These two steps are identifiable in figure 4 in the evolution of the parameters S_{11} and S_{21} depending on the height.



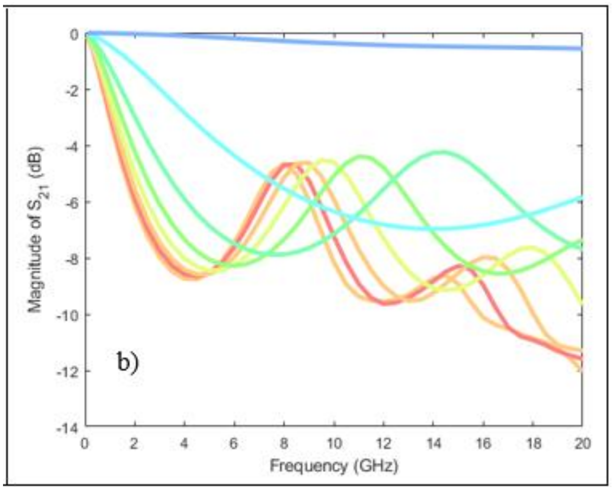


Figure 4: Variations of the magnitude of parameters (a) S_{11} and (b) S_{21} as a function of drop heights ranging from 1500 µm to 100 µm in HFSS simulation.

Figure 4 (a) and (b) suggest that the threshold between the two steps is at a height of 900 µm or lower, meaning that from 1500 µm to 900 µm at least, the circumference of the drop at the surface only slightly varies. Furthermore, during the time interval corresponding to the drop evaporation with few variations of the contact area, it can be assumed that the drop shape only slightly influences the parameters S_{11} and S_{21}. These parameters are very sensitive to the concentration variation of the liquid due to volume reduction. Specifically around 5 GHz, any change would be directly due to the variation in permittivity, *i.e.* in glucose concentration in the drop.

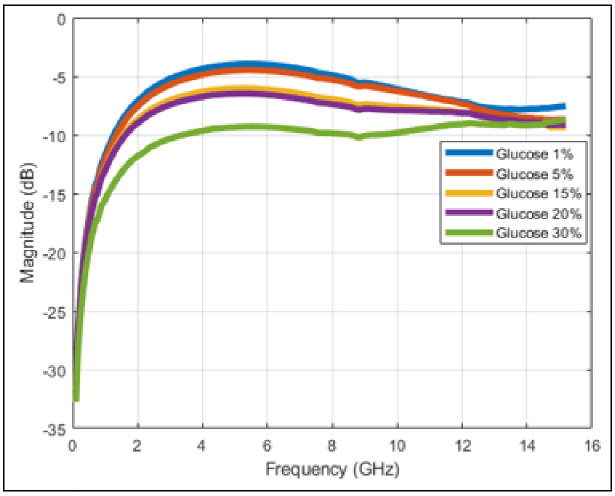


Figure 5: Parameter S_{11} of 1%, 5%, 15%, 20% and 30% glucose solutions at fixed time (t = 15 minutes)

The evolution of the S_{11}parameter at t = 15 minutes shown in Figure 5 enables the different glucose solutions to be discriminated over a wide band. However, when correlating the results obtained experimentally with the simulation results, we chose to set the frequency at 5 GHz to more easily distinguish the solutions from one another. We therefore chose to work at this fixed frequency and plot the evolution as a function of time, as shown in Figure 6.

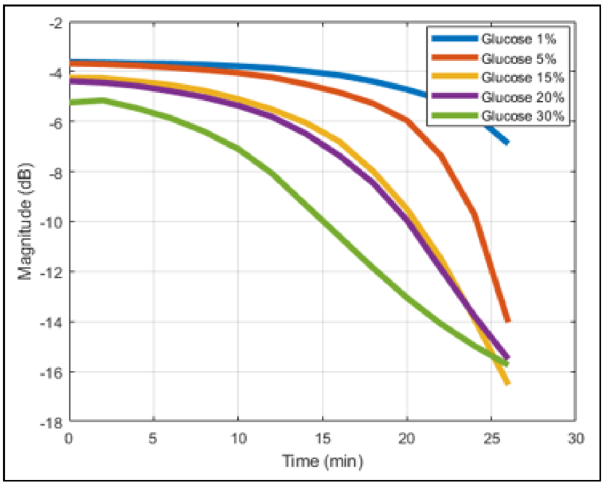


Figure 6: Parameter S_{11} of 1%, 5%, 15%, 20% and 30% glucose solutions at fixed frequency (5GHz) as a function of time

Figure 6 shows that it is difficult to distinguish between different concentrations until a certain time has elapsed. It is therefore necessary to wait for a certain amount of evaporation before obtaining satisfactory results. The distinction is clearest at t = 15 minutes. There is therefore an optimum time range for discriminating between solutions.

This methodology was also applied to parameter S_{21}. Figure 7 below illustrates the results obtained for parameter S_{21} at t = 15 minutes.

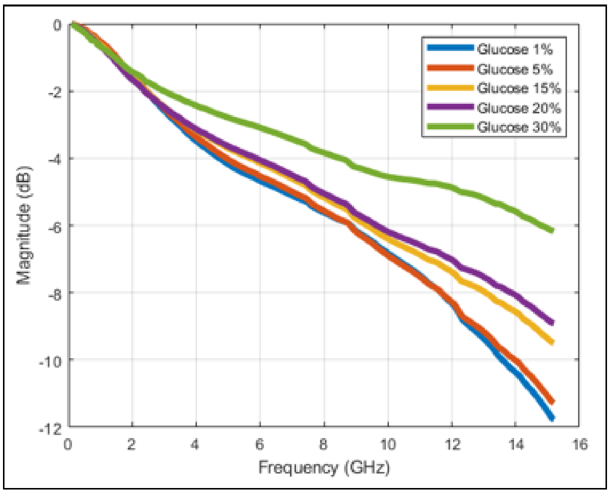


Figure 7: Parameter S_{21} of 1%, 5%, 15%, 20% and 30% glucose solutions at fixed time (t= 15 minutes)

In Figure 7, the differences between the curves are greatest at 15 GHz. Figure 8 shows the behaviour of the transmission parameter S_{21} as a function of time, at frequency f = 15 GHz.

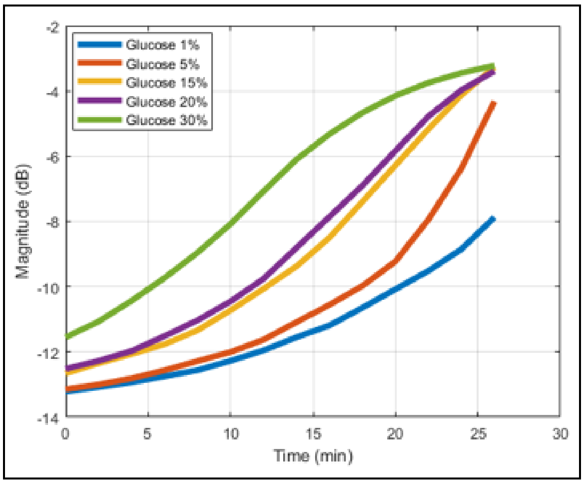


Figure 8: S_{21} parameter of 1%, 5%, 15%, 20% and 30% glucose solutions at fixed frequency (15GHz) as a function of time

As with parameter S_{11}, S_{21} distinctions between curves are most marked at t = 15 minutes. Once again, the benefits of evaporation are demonstrated.

Displaying S_{11}modulus values at 15 minutes and 5 GHz, and S_{21} values at 15 minutes and 15 GHz for different glucose concentrations, we obtain the curves plotted in figure 9:

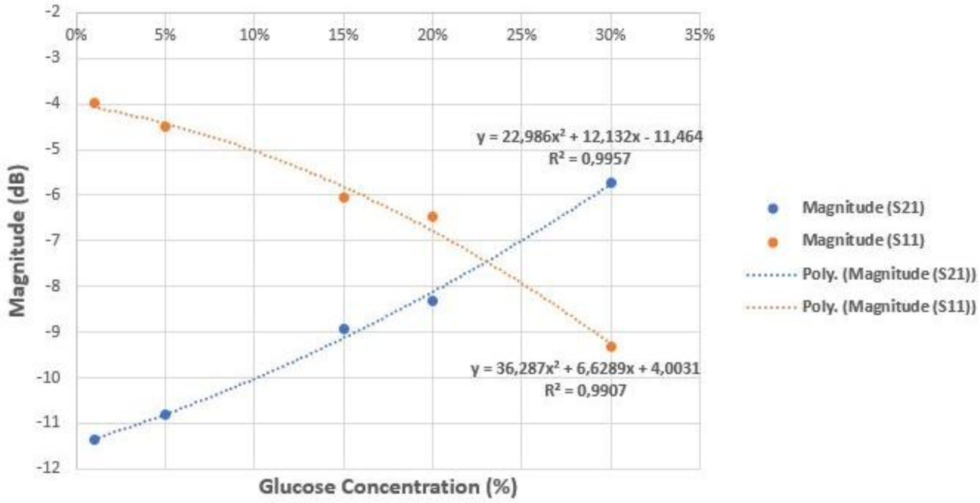


Figure 9: Modulus of S_{11} (red) and modulus of S_{21} (blue) as a function of glucose concentration, at t = 15 minutes.

The clear distinctions observed in the evaporation profiles of each of the solutions show that it is possible to quantify glucose solutions with this procedure, whereas direct measurement, i.e. without evaporation, gives inconclusive results. These promising results will be enhanced in the near future by measurements on lower glucose concentrations.

3. Conclusions and Outlook

We have shown here that it is possible to test several types of solution with different characteristics, depending on their glucose concentration.

Both the simulation results and the comparison of droplet images as a function of time show that in the first phase of evaporation, there is no change in the surface area in contact with the device. Only drop height and volume decrease. As soon as the surface in contact with the device starts to change, the measurements on parameters $S_{11}$and S_{21} are no longer usable for our study. In the initial phase, the variations observed in the measurements are therefore dependent on the variation in permittivity and therefore on the glucose concentration. Analysis at t=0, or too early, does not provide results consistent with the true concentration values of the solutions. It is only after a certain stage of evaporation (15 min here) that we can observe significant differentiation between solutions and a linear relationship between S-parameters and concentration. The repeatability, reproducibility and stability of CPW lines are currently being tested. Similarly, we will be aiming for much lower concentrations, to reach physiological values in blood (between 0.5 and 1.5 g/L).

Acknowledgments and Competing Interests

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