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SIMULTANEOUS DETECTION OF ORGANIC AND INORGANIC SUBSTANCES IN A MIXED AQUEOUS SOLUTION USING A MICROWAVE DIELECTRIC SENSOR

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Abstract—This letter reports a new technique that enables simultaneous detection of concentrations of the organic and inorganic substances in a hybrid fluidic solution. The technique is based on a coplanar microwave distributed MEMS transmission line. Measurement results show that a hybrid aqueous solution with a mixture of 0 M–0.2 M NaCl and 0 mg/ml–350 mg/ml glucose can be easily detected simultaneously from measured one-port scattering parameter (S_{11}).

1. INTRODUCTION

Microwave dielectric sensors for measuring permittivity of aqueous solutions and for detecting the complex permittivity of liquid samples have been reported previously [1–4]. Periodic structures have clear advantages in biosensing applications since they offer more interactions between the electromagnetic waves and the measurands than normal straight waveguides. A theoretical investigation of using microwave periodic structures as biosensors was presented in [5]. Design, fabrication and characterisation of a novel flip-chip distributed MEMS transmission line (DMTL) biosensor [6] was reported by the author recently. This paper will show an experimental approach for distinguishing between organic and inorganic materials from a hybrid aqueous solution using the DMTL biosensor. This technique has great practical applications in biological and medical areas, as most of the real biological solutions are combinations of organic and inorganic materials, the examples of such solutions are rainwater, groundwater, food, and body tissue.

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2. DESIGN ABD FABRICATION OF THE SENSOR

The biosensor consists of a distributed DMTL and a microchannel shown schematically in Figure 1, the SEM photograph of the silicon based DMTL device is shown in Figure 2. The DMTL device was designed and fabricated based on a multi-layer MEMS foundry process — MetalMUMPs, which is suitable for prototyping microwave devices because it uses very high resistivity (> 5000 Ohm-cm) silicon as the substrate to reduce the insertion loss at high frequencies.

In the DMTL design, for the coplanar waveguide, the signal and ground lines of the coplanar waveguide (CPW) are constructed using a layer of nickel with thickness of 20 μm. The waveguide is

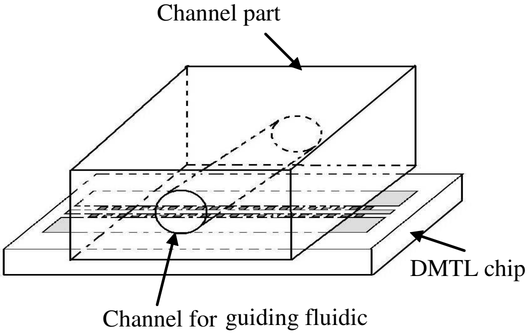

Figure 1. Schematic of the sensor. It consists of a DMTL device and a channel chip. The DMTL device was made by silicon microfabrication, and the channel part is made of acrylic material.

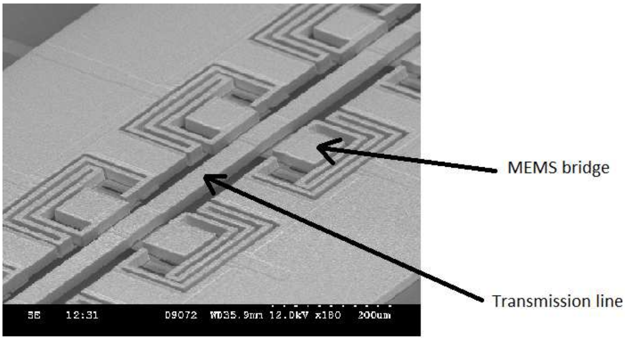

Figure 2. Scanning electron micrograph of the DMTL device. The device was fabricated by silicon micromachining process. The waveguides were made of Nickel.

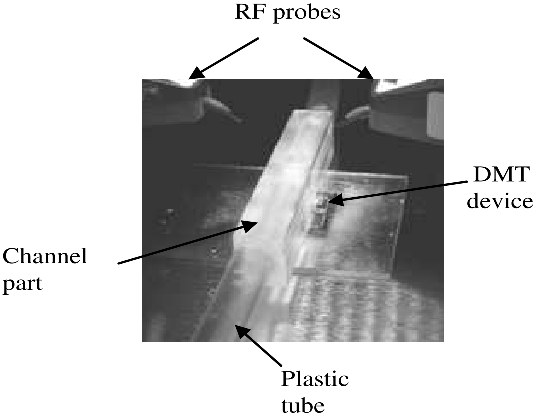

Figure 3. Photograph of the sensor under a RF probe station.

suspended above the silicon substrate with a 25 µm air gap. The 0.7 µm polysilicon capacitor bridge is situated under the nickel waveguide with a 1.1 µm air gap. The width of the signal line and the gap between signal line and ground plane is designed to be 40 µm and 43 µm respectively The total length of the DMTL is approximately 8 mm. The channel part was machined from an acrylic cube. The size of the acrylic cube is 8 mm × 6 mm × 35 mm, in which the diameter and length of the channel are 2 mm and 5 mm respectively. The biosensor was completed by joining the DMTL device, the microchannel, and two plastic tubes. As there is no interface material between microchannel and the DMTL, the biological sample in the microchannel and the DMTL will be in direct contact during the measurement. The sidewall of the acrylic is around 2 mm, and source power of the vector network analyzer remains constant during all the measurements. A photograph of a completed biosensor is shown in Figure 3.

3. MEASUREMENT AND ANALYSIS

First of all, the DMTL device is characterized using a vector network analyzer (Agilent N5230A) and a microwave probe station (Cascade Microtech 9000 GSG). In the experiment, the device is firstly bonded on a PCB board, and then it is fixed on the stage of probe station. Before making any RF measurement, the probe station has been calibrated using standard calibration kits that came with the VNA and probe station RF data (S parameters) is read and saved to the computer after landing the coplanar probe onto the input and output

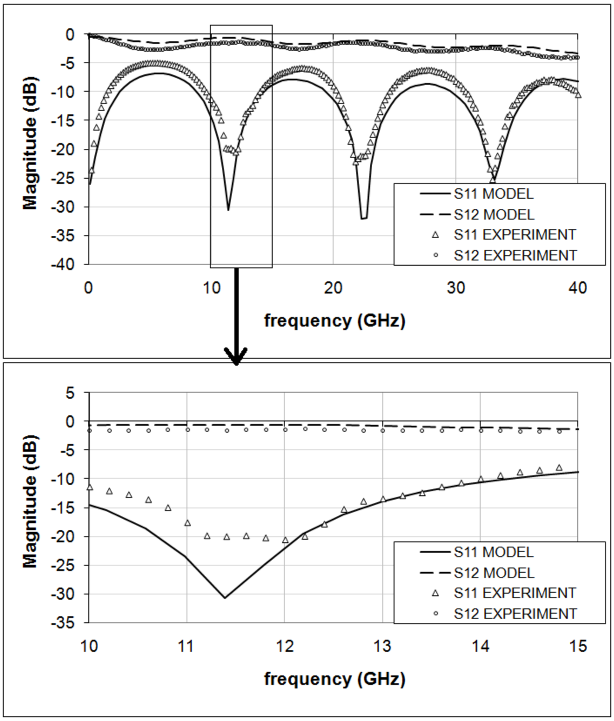

Figure 4. Microwave characteristics of the DMTL device.

of the device. Figure 4 shows the measured scattering parameters of the DMTL device. The device has been also simulated using discrete circuit model, and the results match well with experiments In the model, each section of the DMTL can be described equivalently by a series inductance, a transmission line capacitance, and a capacitance due to MEMS bridge. The values of these lumped elements can be calculated using dimensions of the device, which was presented in detail in reference [7]. After completion of the biosensor by bonding the DMTL device with the acrylic channel device, different concentrations (0 M–0.2 M) of pure NaCl aqueous solutions, different concentrations (0 mg/ml–348 mg/ml) of pure glucose solutions were prepared and measured with the VNA and the probe station. It is seen from Figure 4 that the resonant peaks in S_{11} are sharper and more readable than resonant peaks in S_{21}; therefore only S_{11} measurements are used to detect the changes of the dielectric property in the following experiments. Figure 5 shows that the NaCl concentrations are detected in the low frequency range of measured reflection parameters (S_{11})

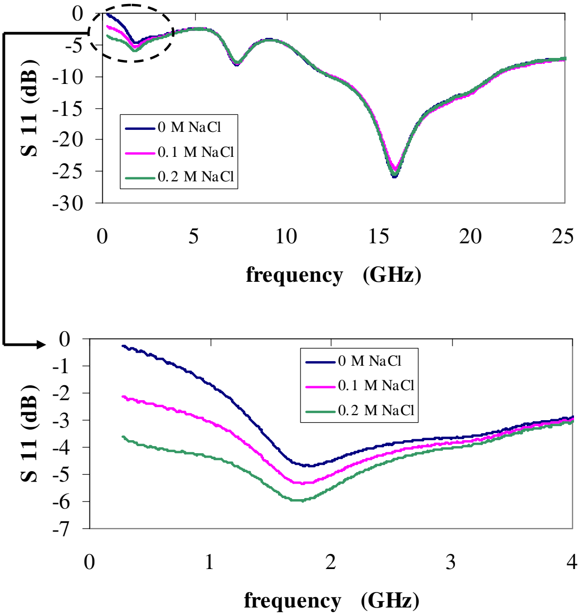

Figure 5. RF measurements for the pure NaCl solution.

where the S_{11} becomes smaller for the higher concentrations (the amplitude of the S_{11} at 300 MHz reduces from -0.36 dB to -3.77 dB while the NaCl concentration increases from 0 M to 0.2 M). There are three resonant peaks in the S_{11} graph shown in Figure 6. The Q factor of the first peak is low and the third peak is at very high frequency ($\sim$ 15 GHz) and is easily affected by environmental parameters such as temperature. It is also shown in the Figure 7 that out of three resonant peaks, the second one is more readable. Therefore the second peak is chosen for detecting concentration change of glucose solution. It is seen from Figure 6 that glucose concentrations can be detected from changes of the second resonant peak at frequencies around 8 GHz where the resonant frequency shifts upward for the higher concentrations (the resonant frequency increases from 7.66 GHz to 7.93 GHz while the glucose concentration increases from 0 mg/ml to 348 mg/ml). It can be seen from Figures 5 and 6 that there is no significant impact in the resonant peaks by the different NaCl concentrations and no significant impact in the low frequency range by the different glucose concentrations, therefore this biosensor is ideal to distinguish organic and inorganic concentrations from a mixed aqueous solution. It is worth noted that NaCl is a typical inorganic substances existing in

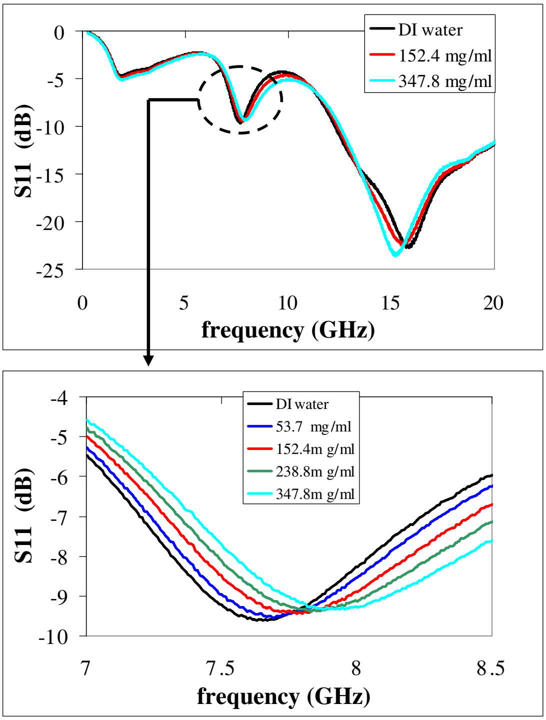

Figure 6. RF measurements for the pure glucose solution.

all of the animal bodies, and glucose is a very important organic carbohydrate used as a source of energy in the living cells. A solution that includes Deionized-Water, NaCl and glucose was prepared and measured using the proposed biosensor. RF Measurement results in Figure 7 shows that different glucose concentrations from a hybrid solution with the fixed 0.1 M NaCl concentration can be detected, the second resonant frequency increases from 7.29 GHz to 7.59 GHz while the glucose concentration increases from 50 mg/ml to 350 mg/ml. According to microwave theory, the loss of the transmission lines is due to conductivity of the dielectric, metal loss, and dielectric loss tangent. As for the dielectric formed by non-conducting materials like glucose, the change of concentration will mainly change the resonant frequency, and for the conducting materials such as NaCl, the change of concentration will affect the loss of the transmission lines. Therefore variation of the attenuation of the DMTL sensor in low frequency range is used to monitor materials like NaCl, and the change of resonant frequency in the higher frequency range is used to monitor

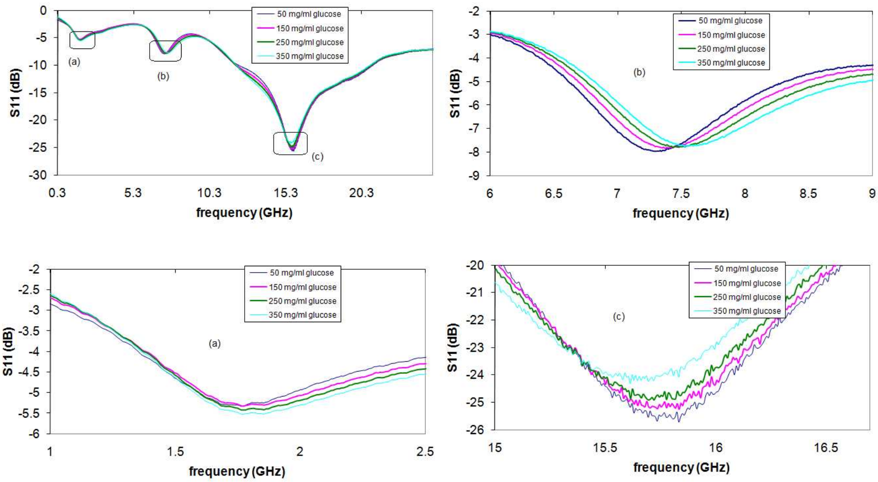

Figure 7. Measurement for the glucose concentration from a mixed NaCl and glucose solution.

concentration of materials such as glucose. It is shown in Figure 8 that different NaCl concentrations from a mixed solution with the fixed 350 mg/ml glucose can be detected, the S_{11} at 300 MHz decreases from -1.11 dB to -3.18 dB as the NaCl concentration increases from 0.1 M to 0.35 M. The temperature effect on the biosensor will be investigated in the future by integrating a heater and temperature sensor into the biosensor It is observed from the measurements that as the concentration of the NaCl increases, the insertion loss at low frequency decreases. This can be explained as follows: as soon as the NaCl is added into the DI water, the solution will have free Cl^- and Na^+ ions, causing an increase of the conductivity of the liquid sample and a decrease of S_{11}. As the concentration increases, more ions are generated; as a result, the conductivity value of the solution becomes higher. Therefore, the reflection coefficient further reduces as more RF signal is lost in the fluidic sample in the channel. It is also observed that the resonant frequency increases as the concentration of glucose increases, this is because the dielectric constant decreases as the concentration of the glucose increases, leading to increase of the transmission line capacitance and MEMS bridge capacitance, which results in increase of the resonant frequency.

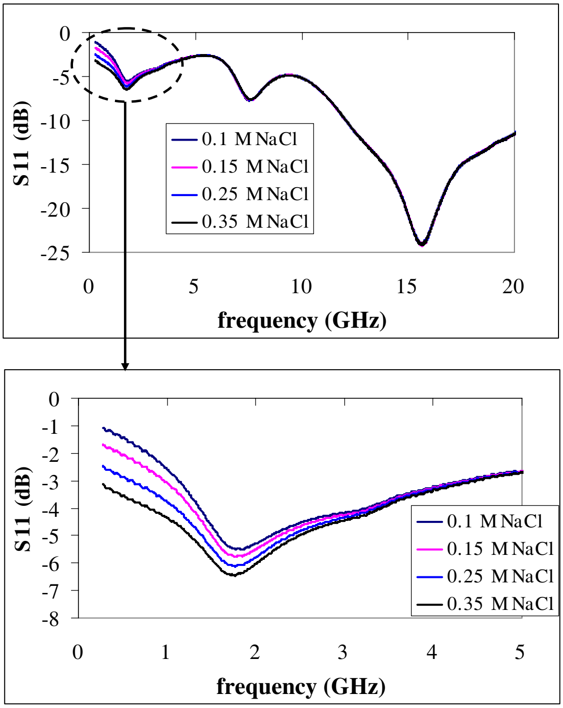

Figure 8. Measurement for the NaCl concentration from a mixed NaCl and glucose solution.

4. CONCLUSION

A technique that enables to detect organic and inorganic materials simultaneously has been reported based on microwave distributed transmission lines in this paper. Design and characterisation of a DMTL biosensor has been reported, and it is found that in a mixed NaCl and glucose solution, the second resonant peak of the measured reflective coefficient S_{11} varies from 7.29 GHz to 7.59 GHz as the concentration of the glucose changes from 50 mg/ml to 350 mg/ml. At 300 MHz of measured S_{11}, the attenuation decreases from -1.11 dB to -3.18 dB when the concentration of the NaCl varies from 0.1 M to 0.35 M.

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